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(71) **Applicant: WAVEFRONT TECHNOLOGY, INC.** [US/US]; 7350 Somerset Blvd., Paramount, California 90723 (US).

(72) **Inventors: RICH, Christopher, Chapman**; 7350 Somerset Blvd., Paramount, California 90723 (US). **PHILLIPS, Roger, Winston**; 466 Jacqueline Drive, Santa Rosa, California 95405 (US). **PETERSEN, Joel, Mikael**; 7350 Somerset Blvd., Paramount, California 90723 (US).

(74) **Agent: ALTMAN, Daniel, E.**; KNOBBE, MARTENS, OLSON & BEAR, LLP , 2040 Main Street , 14th Floor, Irvine, California 92614 (US).

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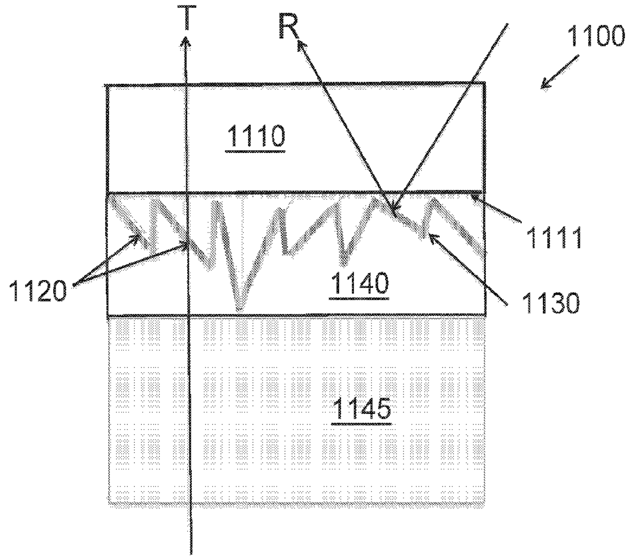

FIG. 5

(57) **Abstract:** An optical product can be configured, when illuminated, to reproduce an image that appears to be a 3D image of at least a part of a 3D object. The optical product can include a surface comprising a plurality of portions. Each portion can correspond to a point on a surface of the 3D object. One or more non-holographic features can be disposed within each portion configured to produce at least part of the image without relying on diffraction. An interference optical structure can be disposed on one or more features. A gradient in the features can correlate to a surface normal of the surface of the 3D object at the corresponding point. An orientation of the features can correlate to an orientation of the surface of the 3D object at the corresponding point.

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OPTICAL PRODUCTS, MASTERS FOR FABRICATING OPTICAL PRODUCTS, AND METHODS FOR MANUFACTURING MASTERS AND OPTICAL PRODUCTS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority to U.S. Provisional Application No. 63/088,937, entitled "OPTICAL PRODUCTS, MASTERS FOR FABRICATING OPTICAL PRODUCTS, AND METHODS FOR MANUFACTURING MASTERS AND OPTICAL PRODUCTS," filed October 7, 2020. The entirety of each application referenced in this paragraph is incorporated herein by reference.

TECHNICAL FIELD

[0002] The present application generally relates to optical products, masters (e.g., master and/or daughter shims) for fabricating an optical product, and methods for manufacturing the masters and optical products. In particular, the optical products can be configured, when illuminated, to reproduce by reflected and/or transmitted (or refracted) light, a 3D image (e.g., an image that appears three-dimensional) of at least a part of a 3D object. The optical products can include one or more non-holographic features with thin interference structures, films, coatings, and pigments potentially configured to produce color in both reflection mode and transmission mode. These structures, films, coatings, and pigments can possibly exhibit color shifting properties with changes in reflection and/or transmission with a change in the angle of incidence or the viewing angle.

DESCRIPTION OF THE RELATED TECHNOLOGY

[0003] Optical products can be used for a variety of purposes such as to reproduce a 3D image. Such products can be placed on decorative signs, labels, packaging, and consumer goods. Counterfeiting continues at a high level and poses risks. Given the level of counterfeiting, an easy identifiable image on a tag or on the actual item is desirable for the public at large so individuals can tell if they are receiving a genuine article or a fake one. Accordingly, some optical products can be used as an anti-counterfeit feature, for example, on goods (e.g., handbags, watches, clothing, cosmetics, pharmaceuticals, etc.) or on currency (e.g., a banknote). Holograms have traditionally been used as a counterfeit deterrent. However, this technology has become so widespread with hundreds if not thousands of holographic shops around the world that holograms are now viewed as having poor security. Optically variable inks and optically variable magnetic inks have also enjoyed for the past decade a high security place on banknotes. However, these products have now been simulated or have been even made from similar materials as the originals that these security elements are now being questioned as a high security feature. Motion type security elements have been adopted into banknotes, but even here, security has been compromised as this feature has also been used on commercial products. Thus, what is needed is a new security feature that the average person readily recognizes, has no resemblance to holograms or inks, is readily verified as to its authenticity, is difficult to counterfeit, is easily manufactured in quantity and can be readily incorporated into an item such as packaging, a tag, a consumer product, or a banknote.

[0004] Color shifting features can be used to prevent counterfeiting. The color shifting effect produced by color shifting materials can be easy for the common person to observe. The color shifting effect produced by the color shifting features, however, can be impractical to recreate using counterfeit copies produced by color copiers, printers and/or photographic equipment. Color copiers, printers and/or photographic equipment use pigments based on dyes having absorption and as such the printed colors can be insensitive to a change in the viewing angle. Therefore, the difference between an authentic item comprising color shifting features and a fake one can be detected by tilting the item to observe if there is a color shift. Some color shifting features that are available are opaque and exhibit a color shift for reflection mode. Additionally, counterfeiters have developed sophisticated methods that compromise the effectiveness of the existing reflective color shifting features as counterfeit protection. Thus, a new anti-counterfeit optical product that is difficult to counterfeit and can be readily incorporated into an item such as packaging, a tag, a consumer product, or a banknote is desirable.

[0005] Manufacturing such optical products, e.g., in relatively large quantities for commercial use, can utilize a master to fabricate the optical product. A master can be either a negative or positive master. For example, a negative master can form a surface of the optical product that is complementary to the surface of the master. As another example, a positive master can provide a surface for the optical product that is substantially similar to the surface of the master.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] Figure 1A schematically illustrates an example master and optical product in accordance with certain embodiments described herein.

[0007] Figure 1B schematically illustrates a top view of the surface of a master for fabricating an optical product in accordance with certain embodiments described herein.

[0008] Figure 1C schematically illustrates the inclination and orientation of a surface of a 3D object at a point on the surface.

[0009] Figure 1D is another example optical product 10′ in accordance with certain embodiments described herein.

[0010] Figure 1E is another example optical product 10′ in accordance with certain embodiments described herein.

[0011] Figure 2 illustrates an example method to manufacture a master for fabricating an optical product in accordance with certain embodiments described herein.

[0012] Figure 2A illustrates an example method that can be used to manufacture a surface relief diffuser.

[0013] Figures 2B-2C illustrate example methods to manufacture a master for fabricating an optical product in accordance with certain embodiments described herein.

[0014] Figures 3A-3B illustrate example 2D data files in accordance with certain embodiments disclosed herein.

[0015] Figures 3C-3D illustrate example features on a data file and the corresponding features on the surface of a master for fabricating an optical product in accordance with certain embodiments disclosed herein.

[0016] Figure 4A illustrates another example 2D data file in accordance with certain embodiments disclosed herein.

[0017] Figure 4B illustrates an example normal map used to generate the data file shown in Figure 4A.

[0018] Figure 4C illustrates the 3D image reproduced by an optical product generated from a master produced using the data file shown in Figure 4A.

[0019] Figure 5 schematically illustrates a cross-sectional view of an example optical product with an interference optical structure disposed on non-holographic features.

[0020] Figure 6 schematically illustrates an example optical product producing colored depth perception in an image.

[0021] Figure 7A shows an example planar view of a reproduced object and background.

[0022] Figure 7B shows another example planar view of a reproduced object and background.

[0023] Figure 8 shows another example planar view of a reproduced object and background.

[0024] Figure 9 shows another example planar view of a reproduced object and background.

[0025] Figure 10 shows another example view of a reproduced object and background.

[0026] Figure 11 schematically illustrates a side view of an optical structure configured to be used as a security feature.

[0027] Figures 12A-1 and 12A-2 schematically illustrate side views of optical structures configured to be used as a security feature in the form of a platelet encapsulated with an encapsulating layer, comprising, for example, a SiO_2 layer and silica spheres.

[0028] Figures 12B-1 and 12B-2 illustrates a plurality of platelets dispersed in a polymer which can comprise an ink or a paint medium.

[0029] Figure 13 illustrates the silane coupling agent bonded to an exposed surface of the encapsulation layer of a platelet. Another side of the silane coupling agent can also bond to a medium such as a polymer in which the platelets are dispersed.

[0030] Figure 14 is a schematic illustration showing propagation light incident on the optical structure and the resultant nodes in field strength at the metal layers.

[0031] Figures 15A and 15B illustrate transmission and reflection spectra of examples of optical structures.

[0032] Figures 16A-16D and 17A-17D are a* b* plots showing the color travel or change in reflection and transmission respectively for four different example optical structures.

[0033] Figures 18A and 18B respectively illustrate the transmittance and reflectance spectra for an example of the optical structure.

[0034] Figures 18C and 18D respectively illustrate the transmittance and reflectance spectrum for an example of the optical structure.

[0035] Figures 18E and 18F respectively illustrate the transmittance and reflectance spectrum for an example of the optical structure.

[0036] Figure 18G illustrates the a*b* values in the CIE L*a*b* color space for an example of the optical structure for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the example of the optical structure in transmission mode.

[0037] Figure 18H illustrates the a*b* values in the CIE L*a*b* color space for an example of the optical structure for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the example of the optical structure in reflection mode.

[0038] Figure 19A schematically illustrates a cross-sectional view of an embodiment of an optical structure configured to be used as a security feature. Figure 19B schematically illustrates a cross-sectional view of another embodiment of an optical structure configured to be used as a security feature.

[0039] Figure 20 is a schematic illustration of a laminate structure comprising an optical structure that is affixed to a banknote.

[0040] Figure 21A shows a banknote with two windows, each window including a different optical structure. Figure 21B shows a security device with two at least partially overlapping windows, each window comprising a different optical structure.

[0041] Figures 22 and 23 illustrate examples of a security device comprising an optical structure disposed under or over a text, symbol or number. The text, symbol or number becomes visible when the viewing angle is changed.

[0042] Figure 24A schematically illustrates a side view of an implementation of an optical structure comprising a stack of layers that can be used as a security feature.

[0043] Figure 24B illustrates a cross-sectional view of an implementation of an optical structure including a first region comprising a first metallic material which is surrounded by a second region comprising a dielectric material which in turn is surrounded by a third region comprising a second metallic material.

[0044] Figure 25A is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light transmitted through a first example of the optical structure shown in Figure 24A or 24B for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure.

[0045] Figure 25B is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light reflected from the first example of the optical structure shown in Figure 24A or 24B for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure.

[0046] Figure 25C illustrates the a*b* values in the CIE L*a*b* color space when the first example of the optical structure shown in Figure 24A or 24B is viewed in the transmission mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the first example of the optical structure.

[0047] Figure 25D illustrates the a*b* values in the CIE L*a*b* color space when the first example shown in Figure 24A or 24B of the optical structure is viewed in the reflection mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the first example of the optical structure.

[0048] Figure 26A is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light transmitted through a second example of the optical structure shown in Figure 24A or 24B for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure.

[0049] Figure 26B is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light reflected from the second example of the optical structure shown in Figure 24A or 24B for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure.

[0050] Figure 26C illustrates the a*b* values in the CIE L*a*b* color space when the second example of the optical structure shown in Figure 14A or 14B is viewed in the transmission mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the second example of the optical structure.

[0051] Figure 26D illustrates the a*b* values in the CIE L*a*b* color space when the second example of the optical structure shown in Figure 24A or 24B is viewed in the reflection mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the second example of the optical structure.

[0052] Figure 27A shows the variation of the transmittance with wavelength for a third example of the optical structure shown in Figure 24A or 24B at a viewing angle of about 0 degrees with respect to a normal to the surface of the optical structure 300a/300b.

[0053] Figure 27B shows the variation of the reflectance with wavelength for the third example of the optical structure shown in Figure 24A or 24B at a viewing angle of about 0 degrees with respect to a normal to the surface of the optical structure.

[0054] Figure 27C is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light transmitted through the third example of the optical structure shown in Figure 24A or 24B for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure.

[0055] Figure 27D illustrates the a*b* values in the CIE L*a*b* color space when the third example of the optical structure shown in Figure 24A or 24B is viewed in the transmission mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the third example of the optical structure.

[0056] Figure 27E is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light reflected from the third example of the optical structure shown in Figure 24A or 24B for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure.

[0057] Figure 27F illustrates the a*b* values in the CIE L*a*b* color space when the third example of the optical structure shown in Figure 24A or 24B is viewed in the reflection mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the third example of the optical structure.

[0058] Figure 28A shows the variation of the transmittance with wavelength for a fourth example of the optical structure shown in Figure 24A or 24B at a viewing angle of about 0 degrees with respect to a normal to the surface of the optical structure.

[0059] Figure 28B shows the variation of the reflectance with wavelength for the fourth example of the optical structure shown in Figure 24A or 24B at a viewing angle of about 0 degrees with respect to a normal to the surface of the optical structure.

[0060] Figure 28C is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light transmitted through the fourth example of the optical structure for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure.

[0061] Figure 28D illustrates the a*b* values in the CIE L*a*b* color space when the fourth example of the optical structure shown in Figure 24A or 24B is viewed in the transmission mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fourth example of the optical structure.

[0062] Figure 28E is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light reflected from the fourth example of the optical structure shown in Figure 24A or 24B for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure. Figure 28F illustrates the a*b* values in the CIE L*a*b* color space when the fourth example of the optical structure is viewed in the reflection mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fourth example of the optical structure 300a/300b.

[0063] Figure 29A shows the variation of the transmittance, reflectance and absorptance with wavelength for a fifth example of the optical structure shown in Figure 24A or 24B at a viewing angle of about 0 degrees with respect to a normal to the surface of the optical structure.

[0064] Figure 29B is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light transmitted through the fifth example of the optical structure shown in Figure 24A or 24B for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure.

[0065] Figure 29C illustrates the a*b* values in the CIE L*a*b* color space when the fifth example of the optical structure shown in Figure 24A or 24B is viewed in the transmission mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fifth example of the optical structure.

[0066] Figure 29D is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light reflected from the fifth example of the optical structure shown in Figure 24A or 24B for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure.

[0067] Figure 29E illustrates the a*b* values in the CIE L*a*b* color space when the fifth example of the optical structure shown in Figure 24A or 24B is viewed in the reflection mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fifth example of the optical structure.

[0068] Figures 30A and 30B are CIE 1931 color space chromaticity diagrams respectively showing the x and y chromaticity coordinates of light transmitted through and reflected from various implementations of an optical structure having a geometry similar to the geometry of the implementations illustrated in Figures 24A and 24B.

[0069] Figures 31A and 31B respectively illustrate the transmittance and reflectance spectra for example optical structures with and without protective layers. .

DETAILED DESCRIPTION

[0070] In various embodiments, a master (e.g., a master and/or daughter shim) for fabricating an optical product is provided. The optical product, when illuminated, can reproduce an overt 3D image (e.g., an image that appears 3D to the naked eye) of a 3D object. Compared to ink printed images, the reflective surface of various embodiments of the optical product can produce a brighter mirror-like image produced by reflecting (or refracting) light incident on the surface. In certain such embodiments, the surface normals of the 3D object are mimicked as surface relief on the master and/or optical product. The surface relief on the master and/or optical product can be thinner than the 3D object, yet produce the same appearance of the 3D object. This property is similar to

Fresnel lenses, where the surface relief allows a lens to be produced that is thinner than a comparable non-Fresnel lens. Unlike Fresnel lenses, however, certain embodiments disclosed herein are not limited in the type of 3D object that can be reproduced (e.g., linear and regularly shaped objects). As such, realistic and bright 3D images can be produced on relatively thin films (e.g., 300 μm and less in thickness, 250 μm and less in thickness, 200 μm and less in thickness, 150 μm and less in thickness, 100 μm and less in thickness, 75 μm and less in thickness, 50 μm and less in thickness, 30 μm and less in thickness, 25 μm and less in thickness, 15 μm and less in thickness, or any ranges in between these values or any ranges formed by these values). In various implementations, the optical product can comprise one or more thin films. Thin films may be advantageous for different applications. In addition, special effects can be integrated into the image. In various embodiments described herein, the optical product can advantageously be used in applications for flexible packaging, brand identification, tamper evident containers, currency (e.g., a banknote), decoding messages, authenticity, and security, etc. Some security applications include incorporation of small detailed features, incorporation of non-symmetrical features, incorporation of machine readable features, etc.

[0071] In certain embodiments, the optical product can be incorporated into an item as an embedded feature, a laminated feature, a hot stamp feature, a windowed thread feature, or a transparent window feature. For example, on an item such as a banknote, the optical product can be a patch, a window, or a thread. The optical product can have a thickness of less than 350 μm, less than 300 μm, less than 250 μm, less than 200 μm, less than 150 μm, less than 100 μm, less than 75 μm, less than 50 μm, less than 30 μm, less than 25 μm, or less than 15 μm or any ranges in between these values or any ranges formed by these values. In various embodiments, the image can appear 3D by the naked eye.

[0072] In some embodiments, the image can be seen at a viewing angle between 20 degrees to 160 degrees, between 15 degrees to 165 degrees, between 10 degrees to 170 degrees, between 5 degrees to 175 degrees, or between 0 degrees to 180 degrees relative to the plane of the item (e.g., relative to the banknote plane) as the item is tilted. For example, the image can be viewable within one or more of these viewing angle ranges relative to the plane of the item.

[0073] In some embodiments, the image can be seen at a viewing angle between 20 degrees to 90 degrees, between 15 degrees to 90 degrees, between 10 degrees to 90 degrees, between 5 degrees to 90 degrees, or between 0 degrees to 90 degrees relative to the normal of the item as the item is rotated the normal of the item (e.g., in the plane of the item). For example, the image can be viewable and/or visible within one or more of these viewing angle ranges as the item is rotated (e.g., rotated at least throughout the range of 90 degrees, rotated at least throughout the range of 180 degrees, rotated at least throughout the range of 270 degrees, or rotated at least throughout the range of 360 degrees) about the normal of the item (e.g., in the plane of the item).

[0074] Figure 1A schematically illustrates an example master 10 for fabricating an optical product 10′ in accordance with certain embodiments described herein. In various embodiments, the master 10 can include a first surface 11 and a second surface 12 opposite the first surface 11. As shown in Figure 1A, the second surface 12 can include a plurality of portions P_1, P_2, … P_n. Each portion P_n can correspond to a plurality of portions P'_1, P'_2, … P'_n on the optical product 10′. The plurality of portions P'_1, P'_2, … P'_n on the optical product 10′ can also be referred to as a cell, pixel, or a tile. Each portion P'_n can have a length between 1 μm and 100 μm, between 7 μm and 100 μm, or any range within these ranges (e.g., between 20 μm and 100 μm, between 7 μm and 50 μm, between 7 μm and 35 μm, between 10 μm and 55 μm, between 12.5 μm and 100 μm, between 12.5 μm and 50 μm, between 12.5 μm and 35 μm, between 20 μm and 50 μm, between 35 μm and 55 μm, between 40 μm and 50 μm, etc.). Each portion P'_n can have a width between 1 μm and 100 μm, between 7 μm and 100 μm, or any range within these ranges (e.g., between 20 μm and 100 μm, between 7 μm and 50 μm, between 7 μm and 35 μm, between 10 μm and 55 μm, between 20 μm and 50 μm, between 12.5 μm and 100 μm, between 12.5 μm and 50 μm, between 12.5 μm and 35 μm, between 35 μm and 55 μm, between 40 μm and 50 μm, etc.). Accordingly, in various embodiments, the aspect ratio of each portion P'_n can be 1:1 or 1:1.1.

[0075] Each portion P_n of the master 10 (and each portion P'_n of the optical product 10′) can correspond to a point S_1, S_2, … S_n on a surface S of the 3D object 50.

Each portion P_n can include features F_1, F_2, … F_n corresponding to elements E_1, E_2, … E_n, e.g., non-holographic elements, on the optical product 10′. A gradient (e.g., slope) in the features F_1, F_2, … F_n can correlate to an inclination (e.g., slope) of the surface S of the 3D object 50 at the corresponding point S_1, S_2, … S_n. For example, in various implementations, for individual ones of the portions, a gradient of the features can correlate to an inclination of the surface of the 3D object at the corresponding point. In addition, an orientation of the features F_1, F_2, … F_n can correlate to an orientation of the surface S of the 3D object 50 at the corresponding point S_1, S_2, … S_n. For example, in various implementations, for individual ones of the portions, an orientation of the features can correlate to an orientation of the surface of the 3D object at the corresponding point. Accordingly, with certain embodiments disclosed herein, an optical product 10′ fabricated using the example master 10 can be configured, when illuminated, to reproduce by reflected (or refracted) light, a 3D image 50′ (e.g., an image that appears 3D) of at least a part of a 3D object 50. The image can be observed by the naked eye and under various lighting conditions (e.g., specular, diffuse, and/or low light conditions).

[0076] In various implementations, the features on the master and/or optical product can be different than the 3D object, yet produce the same appearance of the 3D object. In addition, certain implementations disclosed herein are not limited in the type of 3D object that can be reproduced (e.g., an irregularly shaped object, a regularly shaped object, a non-symmetrical shaped object, a symmetrical shaped object, an object in nature, a man-made object, etc.). In various optical products, the features (e.g., non-holographic elements) can reproduce at least part of the 3D image without use of lenses. In some implementations, as described herein, lenses can be used to improve contrast and/or sharpness of the image.

[0077] The optical product 10′ can be used on a variety of products to reproduce a 3D image 50′ of at least a part of a 3D object 50. For example, the optical product 10′ can be placed on decorative signs, advertisements, labels (e.g., self-adhesive labels), packaging (e.g., consumer paper board packaging and/or flexible packaging), consumer goods, collectible cards (e.g., baseball cards), etc. The optical product 10′ can also be advantageously used for authenticity and security applications. For example, the optical product 10′ can be placed on currency (e.g., a banknote), credit cards, debit cards, stock certificates, passports, driver's licenses, identification cards, documents, tamper evident containers and packaging, consumer packaging, bottles of pharmaceuticals, etc.

[0078] In various implementations, the optical product 10′ can be a reflective or transmissive device. For example, the optical product 10′ can include reflective material (e.g., reflective metal such as aluminum, copper, or silver disposed on the plurality of elements E_1, E_2, … E_n, or a transparent, relatively high refractive index material such as ZnS or TiO_2 disposed on the plurality of elements E_1, E_2, … E_n creating a semi-transmitting/partially reflective boundary). In some instances, the relatively high refractive index material can have a refractive index from 1.65 to 3.0. In some instances, the relatively high refractive index material can have a refractive index from 1.8 to 3.0. Depending on the thickness of the reflective material, the optical product 10′ can be reflective or transmissive. Depending on the thickness of the reflective material, the optical product 10′ can be partially reflective or partially transmissive. The thickness of the reflective material at which the optical product 10′ is reflective or transmissive can depend on the chemical composition of the reflective material.

[0079] Accordingly, in some embodiments, the optical product 10′ can include a reflective surface 12′ from which light can reflect from the elements E_1, E_2, … E_n to reproduce the image 50′ of the 3D object 50 or at least part of the 3D object 50. For example, the optical product 10′ can be made of a reflective metal (e.g., aluminum, copper, or silver), a semi-transparent metal, or a material (e.g., polymer, ceramic, or glass) coated with a reflective metal. Reflective coatings that employ non-metallic material can also be employed.

[0080] In some embodiments where the elements E_1, E_2, … E_n are coated with a reflective metal, the thickness of the coating layer can be greater than or equal to 40 nm such that the layer is opaque. Alternatively, the thickness of the reflective metal can be less than 40 nm such that the layer is semi-transparent (e.g., 30% transparent 40% transparent, 50% transparent, 60% transparent, 70% transparent, or any ranges formed by any of these values, etc.). In reflective embodiments, the elements E_1, E_2, … E_n can reflect light towards or away from the observer's eye to reproduce the image 50′ the 3D object 50. For example, the elements E_1, E_2, … E_n can reflect light towards the observer's eye in bright areas, and reflect light away from the observer's eye in dark areas. In some embodiments, the slopes of the elements E_n can be configured to create the 3D depth perception of the image. For example, elements E_n with less steep slopes can cause light to reflect toward the observer's eye creating more brightness, while elements E_n with steeper slopes can cause light to reflect away from the observer's eye creating more darkness.

[0081] In some other embodiments (e.g., for a transmissive device), the optical product 10′ can include a layer (e.g., a coating) of a transparent, relatively high refractive index material such as, for example, ZnS or TiO_2. In some such embodiments, light can transmit through the material and can also reflect at each of the elements E_1, E_2, … E_n due to the presence of the relatively high index layer which can create index mismatch and results in Fresnel reflection. The relatively high index material can be up to a full visible wavelength in thickness in some embodiments. If a color tint is used, the relatively high index material can be up to a ¼ of a visible wavelength in thickness in some embodiments.

[0082] Furthermore, the optical product 10′ can include a protective covering, e.g., an organic resin, to protect the elements E_1, E_2, … E_n and/or any coating layer from corrosion from acidic or basic solutions or organic solvents such as gasoline and ethyl acetate or butyl acetate. In various implementations, the protective covering can also provide protection during subsequent processing steps and use of the optical product 10′ (e.g., during the manufacturing of currency and/or by general handling by the public).

[0083] In various embodiments, the optical product 10′ can be placed on or in another surface (e.g., as an embedded feature, a hot stamped feature such as a patch, a windowed thread feature, or a transparent window feature). In other embodiments, the optical product 10′ can be placed under another surface (e.g., a laminated feature laminated under a film and/or cast cured). In some embodiments, the optical product 10′ can be placed between two other surfaces (e.g., hot stamped on another surface and laminated under a film). Additional features associated with the optical product 10′ will become apparent with the disclosure herein of the master 10 for fabricating the optical product 10′.

[0084] The image 50′ of at least part of the 3D object 50 can be reproduced when the optical product 10′ is illuminated. In various embodiments, the image 50′ can be reproduced by a multitude of relatively small mirrors (e.g., each of the elements E_1, E_2, … E_n having both a length and width between 30 μm and 100 μm, between 35 μm and 55 μm, or between 40 μm and 50 μm) which can be curved (e.g., have a freeform curvature) or planar. For example, in some embodiments, a reflective surface of the optical product 10′ can provide a surface for specular reflection, such that the image 50′ can be produced by the reflected light (e.g., like a mirror). Accordingly, various embodiments can produce a bright, high quality image. Some embodiments can also utilize techniques for producing diffuse reflection, e.g., for special or desired effects. Furthermore, the image 50′ can be a substantially similar reproduction (e.g., with similar details), an approximate reproduction (e.g., with less details), a not scaled copy (e.g., not scaled up or down in size), and/or a scaled copy (e.g., scaled up or down in size) of the 3D object 50 or part of the 3D object 50.

[0085] In general, the 3D object 50 to be reproduced is not particularly limited and can advantageously include rotationally non-symmetrical and/or irregularly shaped objects, as well as symmetrical and/or regularly shaped objects. For example, the 3D object 50 can include one or more alphanumeric characters and/or symbols. For example, the 3D object 50 can include one or more text, one or more alphabetic characters, one or more numeric characters, one or more letters, one or more numbers, one or more symbols, one or more punctuation marks, one or more mathematical operators, etc. The 3D object 50 can also include one or more graphical images or logos, e.g., a company logo, a team logo, product branding designs, etc. Accordingly, the 3D object 50 can include irregularly shaped features in addition to planar and curved features. In some embodiments, the 3D object 50 can comprise animals, humans, plants or trees, landscapes, buildings, cars, boats, airplanes, bicycles, furniture, office equipment, sports equipment, foods, drinks, personal care items, flags, emblems, symbols like country, company or product symbols including trademarks, or parts thereof or groups or combination of these items with or without other items. The objects may be cartoon or artistic renditions. A wide range of other objects are possible. In some implementations, the produced image can be a Quick Response or QR code.

[0086] As set forth herein, in various embodiments, the image 50′ can be seen at various viewing angles (e.g., between 20 degrees to 160 degrees, between 15 degrees to 165 degrees, between 10 degrees to 170 degrees, between 5 degrees to 175 degrees, or between 0 degrees to 180 degrees relative to the plane of the item (e.g., relative to the banknote plane). For example, when the example optical product 10′ is tilted, upon viewing the example optical product 10′ at different viewing angles (or upon different angles of illumination), different sets of elements E_1, E_2, … E_n can be seen by the observer to provide the different images of the 3D object.

[0087] In some embodiments, the image can be seen at a viewing angle between 20 degrees to 90 degrees, between 15 degrees to 90 degrees, between 10 degrees to 90 degrees, between 5 degrees to 90 degrees, or between 0 degrees to 90 degrees relative to the normal of the item as the item is rotated about the normal of the item. For example, the image can be viewable within one or more of these viewing angle ranges as the item is rotated (e.g., rotated at least throughout the range of 90 degrees, rotated at least throughout the range of 180 degrees, rotated at least throughout the range of 270 degrees, or rotated at least throughout the range of 360 degrees) about the normal of the item.

[0088] Furthermore, in certain embodiments, the image 50′ can be substantially without iridescence or change in color with angle. For example, in various embodiments, there are substantially no colors (e.g., rainbow effect), other diffractive colors, or ghosting effects in the image 50′. For example, in certain embodiments, the size of the portions P'_1, P'_2, … P'_n can have a length and width between 1 µm and 200 µm, between 7 µm and 200 µm, or any range within these ranges (e.g., between 20 µm and 100 µm, between 7 µm and 50 µm, between 7 µm and 35 µm, between 10 µm and 55 µm, between 12.5 µm and 100 µm, between 12.5 µm and 50 µm, between 12.5 µm and 35 µm, between 20 µm and 50 µm, between 35 µm and 55 µm, between 40 µm and 50 µm, between about 65 µm and 80 µm, between about 50 µm and 100 µm, between about 60 µm and 90 µm, between about 100 µm and 200 µm, etc.). In some such embodiments (e.g., between 20 µm and 50 µm), the portions P'_n may be small enough such that the portions P'_n are not resolvable by a human observer under normal viewing conditions (e.g., a reading distance of 18 to 24 inches between the eye and the item to be viewed). In addition, without being bound by theory, the portions P'_n may be big enough such that the cone of light passing through the pupil (e.g., 5 mm in diameter) is small enough such that the eye may see a majority of the colors mixed as white light at a distance of 18-24 inches.

[0089] As another example, in some embodiments, a majority (e.g., greater than 50%, greater than 55%, greater than 60%, greater than 65%, greater than 70%, greater than 80%, greater than 90%, and any ranges in between these values) of the plurality of portions P'_1, P'_2, … P'_n on the optical product 10′ can include a single non-holographic element E_1 (as opposed to a plurality of spaced apart non-holographic elements E_n that may resemble a grating-like feature). Without being bound by theory, grating-like features can cause light to be dispersed with some of the light collected by the pupil of the eye. If the period of the grating-like feature is small enough, the light captured by the pupil may appear as a color. Accordingly, in various embodiments of the optical product 10′ that have a majority of the plurality of portions P'_1, P'_2, … P'_n having not more than a single non-holographic reflective or refractive element E_1, unwanted color caused by grating-like features may possibly be substantially reduced and/or eliminated. Similarly, color change with angle of tilt can be reduced. In some embodiments, at least 20%, at least 30%, at least 40%, at least 50%, at least 60%, at least 70%, at least 80%, at least 90%, or any ranges in between these values) of the plurality of portions P'_1, P'_2, … P'_n on the optical product 10′ can include a single non-holographic element E_1. In various embodiments, the single element may be slowly varying and/or substantially flat. In certain embodiments, the maximum average slope per portion with a single feature is less than ½, less than 1/3, less than ¼, less than 1/5, less than 1/6, potentially flat, and any ranges in between these values depending on feature height and width.

[0090] In addition, in portions P'_n having a plurality of non-holographic elements E_1, E_2, … E_n (e.g., grating-like features), the elements E_n can be discontinuous and/or having different orientation with non-holographic elements E_1, E_2, … E_n in surrounding adjacent portions P'_n. Without being bound by theory, the discontinuity and/or different orientations between grating-like features can cause a lateral shift of the grating-like feature. The lateral shift may cause the color spectrum to shift as well (e.g., from red to blue to green). The colors may combine on the retina providing an average white irradiance distribution. Accordingly, in embodiments of the optical product 10′

that have a plurality of portions P'_1, P'_2, … P'_n including a plurality of non-holographic element E_n, unwanted color cause by grating-like features may possibly be substantially reduced and/or eliminated. Similarly, color change with angle of tilt can be reduced.

[0091] In some implementations, a majority of the portions can comprise non-holographic features with discontinuities. In some instances, a majority of portions can comprise features discontinuous with features in surrounding adjacent portions. In some instances, a majority of features can be discontinuous at boundaries between adjacent portions.

[0092] Accordingly, certain embodiments of the optical product 10′ can utilize a certain portion P'_n size, a single non-holographic element E_1 in a portion P'_n, discontinuous and/or differently orientated elements E_n to produce images that may be substantially without iridescence or change in color with angle. The application of these features can be dependent on the image to be formed.

[0093] Various embodiments described herein can create a 3D image primarily by the reflection of light without relying on diffraction (e.g., without relying on holographic or grating diffraction). In other embodiments, the optical product 10′ can include surfaces which additionally include features from which light can diffract, e.g., at surface defects, at discontinuities at borders, and/or via incorporation of diffractive or holographic elements. Such diffractive or holographic features can be combined with the surface features disclosed herein that produce an image of a 3D object using reflection (or possibly refraction, e.g., in transmission) without relying on diffraction.

[0094] In various embodiments, the master 10 can be either a negative or positive master. Whether as a negative or positive master, the method to produce the master 10 is not particularly limited. For example, the features F_1, F_2, … F_n on surface 12 of the master 10 can be produced using any technique known in the art or yet to be developed, including but not limited to photolithography (e.g., UV or visible light), electron beam lithography, and ion beam lithography to name a few. Additionally, the materials that can be used to manufacture the master 10 are not particularly limited and can include glasses, ceramics, polymers, metals, etc.

[0095] As a negative master, the master 10 can form a surface 12′ of the optical product 10′ that is complementary to the surface 12 of the master 10. For example, as shown in Figure 1A, the features $F_1, F_2, \ldots F_n$ on the surface 12 of the master 10 can be the inverse of the elements $E_1, E_2, \ldots E_n$ on the surface 12′ of the optical product 10′. In such embodiments, the master 10 can be used to form the optical product 10′. For example, the master 10 can be used to emboss the elements $E_1, E_2, \ldots E_n$ onto a metal sheet, a polymeric substrate such as a thermoformable polymer, or a UV curable photoresist layer such as a UV curable resin, or to injection mold the elements $E_1, E_2, \ldots E_n$ onto a polymer.

[0096] As another example, as a positive master, the master 10 can provide a surface 12′ for the optical product 10′ that is substantially similar to the surface 12 of the master 10. The features $F_1, F_2, \ldots F_n$ on the surface 12 of the master 10 can be substantially similar to the elements $E_1, E_2, \ldots E_n$ on the surface 12′ of the optical product 10′. In some such embodiments, the positive master 10 can provide a model for the optical product 10′. In other such embodiments, the positive master 10 can be used to create an inverse image of the 3D object 50. In addition, the positive master 10 can be used to fabricate one or more negative masters.

[0097] Although the master 10 is shown producing a product directly, in certain embodiments the master 10 is employed to produce one or more other masters (e.g., daughter shims) or intermediate surfaces that can in turn be used to produce a product. For example a first negative master can be used to produce a second master that is a positive master. The second positive master can be used to make a third negative master. The third negative master can be used to produce a fourth positive master. The fourth positive master can be used to produce a product. Accordingly, a tooling tree of masters (e.g., four, five, six, etc. generations deep) can be produced.

[0098] Certain embodiments of the optical product 10′ disclosed herein can be advantageously manufactured on a large industrial scale. Some embodiments can be manufactured by embossing the elements $E_1, E_2, \ldots E_n$ into an UltraViolet (UV) curable resin coated onto various polymeric substrates, such as, for example, polyethylene terephthalate (PET), oriented polypropylene (OPP), biaxially oriented polypropylene (BOPP), low density polyethylene (LDPE), linear low density polyethylene (LLDPE), polypropylene (PP), polyvinyl chloride (PVC) polycarbonate (PC) or any other type of plastic film or carrier. For thermoformable plastics such as PVC and PC, the elements

E_1, E_2, … E_n can be embossed directly into the substrate without the UV curable layer. In various embodiments, the polymeric substrate can be clear. The polymeric substrates can have a thickness less than or equal to 300 microns (e.g., less than or equal to 250 microns, less than or equal to 200 microns, less than or equal to 150 microns, less than or equal to 100 microns, less than or equal to 50 microns, less than or equal to 25 microns, less than or equal to 15 microns, etc.). Some such polymeric substrates having elements E_1, E_2, … E_n can be formed into security threads that can be incorporated into a banknote having a paper or polymer thickness of 100 microns, 150 microns, or any thickness up to 300 microns. Other thicknesses are also possible.

[0099] With continued reference to Figure 1A, the master 10 can include a first surface 11 and a second surface 12. The first surface 11 is shown for simplicity as a planar surface. However, the shape of the first surface 11 is not particularly limited. The second surface 12 can be opposite the first surface 11. In various implementations, the second surface can be planar. However, the shape of the second surface in not particularly limited. The second surface 12 can include a plurality of portions P_1, P_2, … P_n. In some embodiments, the plurality of portions P_1, P_2, … P_n can form a single cell (e.g., a mono-cell). In other embodiments, the plurality of portions P_1, P_2, … P_n can form a plurality of cells. For example, each of the plurality of portions P_1, P_2, … P_n can form a cell of the plurality of cells. The number of cells is not particularly limited and can depend on factors such as size and resolution of the image to be reproduced. In various embodiments, the portions P_1, P_2, … P_n can form a pixelated surface. For simplicity, only one row of portions P_1, P_2, … P_n is shown in Figure 1A. However, certain embodiments can include additional rows and columns of portions P_1, P_2, … P_n. For example, as shown in Figure 1B, the portions P_1, P_2, … P_n can include a plurality of rows and columns spanning across the surface 12 of the master 10. For simplicity, only the first row is labeled as P_1, P_2, … P_n. Futhermore, although Figure 1B shows a 4x4 array of portions P_1, P_2, … P_n, the numbers of rows, columns, and portions P_1, P_2, … P_n are not particularly limited. In some instances, the portions can form at least a 4x4 array of rows and columns. In some instances, the portions can comprise from 10 to 20 portions. In some instances, the portions can comprise more than 20 portions (e.g., up to

50 portions, up to 100 portions, up to 200 portions, up to 300 portions, up to 400 portions, up to 500 portions, etc. or any ranges formed by any of these values).

[0100] As also shown in Figure 1B, in some embodiments, borders 13 can surround at least part of the portions P_1, P_2, … P_n. The borders 13 can substantially surround a portion P_n, or can surround just part of a portion P_n. In some embodiments, discontinuities can extend around all or substantially all of the portion P_n. In other embodiments, discontinuities may extend on just a part of the portion P_n. In various implementations, the portions can be defined by the borders. The borders 13 can help define the size and shape of the portions P_1, P_2, … P_n in some embodiments. However, the size and shape of the portions P_1, P_2, … P_n are not particularly limited. For example, some of the portions P_1, P_2, … P_n can comprise a symmetrical shape. For example, the symmetrical shape can include a rectangle, a square, a rhombus, an equilateral triangle, an isosceles triangle, a regular polygon (e.g., a regular pentagon, a regular hexagon, a regular octagon, etc.), to name a few. In various instances, the portions can be defined by linear borders. The symmetrical shape can also include curvature, e.g., a circle, an ellipse, etc. In other embodiments, some of the portions P_1, P_2, … P_n can comprise a non-symmetrical shape, e.g., a non-rotationally symmetrical shape, and/or an irregular shape. In some embodiments, some of the portions P_1, P_2, … P_n can have a shape that is substantially the same as other portions P_1, P_2, … P_n. In some embodiments, at least 20%, at least 30%, at least 40%, at least 50%, at least 60%, at least 70%, at least 80%, at least 90% (or any range in between these percentages) of the portions P_1, P_2, … P_n can have the same shape, size, or both. In other embodiments, some of the portions P_1, P_2, … P_n can have a shape that is different from other portions P_1, P_2, … P_n.

[0101] Arrangement of the portions P_1, P_2, … P_n is not particularly limited. For example, whether with or without borders, whether symmetrically shaped or non-symmetrically shaped, or whether regularly or irregularly shaped, the portions P_1, P_2, … P_n can form a periodic array. In other embodiments, whether with or without borders, whether symmetrically shaped or non-symmetrically shaped, or whether regularly or irregularly shaped, the portions P_1, P_2, … P_n can form an aperiodic array. In yet other embodiments, the portions P_1, P_2, … P_n can form a combination of periodic and aperiodic arrays.

[0102] With continued reference to Figure 1A, each portion P_n can correspond to a point S_1, S_2, … S_n on the surface S of the 3D object 50, and each portion P_n can include one or more features F_1, F_2, … F_n. For simplicity, the features F_1, F_2, … F_n shown in Figure 1A appear linear and substantially similar to each other. However, the features F_1, F_2, … F_n can vary in number, size, shape, and orientation.

[0103] In certain embodiments, the features F_1, F_2, … F_n can include linear and/or curved features, for example as seen from a top or front view. In some embodiments, the features F_1, F_2, … F_n can include facets, such as linear or curved saw tooth shaped features. The size of the features F_1, F_2, … F_n are not particularly limited. However, from a manufacturing and economic perspective, in some embodiments, a smaller height (e.g., 0 μm to 10 μm) can be advantageous to reduce the amount of material used. Accordingly, in some embodiments, the heights of the features F_1, F_2, … F_n can be from close to 0 μm to 0.1 μm (e.g., 0 nm to 100 nm, 1 nm to 75 nm, or 1 nm to 50 nm), from close to 0 μm to 1 μm (e.g., 0 nm to 1000 nm, or 1 nm to 500 nm), from close to 0 μm to 5 μm (e.g., 1 nm to 5 μm, 10 nm to 5 μm, 50 nm to 5 μm, 75 nm to 5 μm, 0.1 μm to 5 μm, 0.5 μm to 5 μm, or 1 μm to 5 μm), or from close to 0 μm to 8 μm (e.g., 1 nm to 8 μm, 10 nm to 8 μm, 50 nm to 8 μm, 75 nm to 8 μm, 0.1 μm to 8 μm, 0.5 μm to 8 μm, or 1 μm to 8 μm), or from close to 0 μm to 10 μm (e.g., 1 nm to 10 μm, 10 nm to 10 μm, 50 nm to 10 μm, 75 nm to 10 μm, 0.1 μm to 10 μm, 0.5 μm to 10 μm, or 1 μm to 10 μm). In other embodiments, the heights of the features F_1, F_2, … F_n can go up to 15 μm, up to 20 μm, up to 25 μm, or any ranges from 1 μm, 2 μm, or 3 μm up to 25 μm . In yet other embodiments, the heights of the features F_1, F_2, … F_n can go up to 50 μm if needed, e.g., depending on the desired size of the 3D image to be reproduced.

[0104] Furthermore, in some embodiments, the lateral dimensions of the features F_1, F_2, … F_n are not particularly limited, but can depend on the details of the 3D object. For example, for text, the lateral dimensions of the features F_1, F_2, … F_n can be less than 1 μm. Accordingly, the lateral dimensions of the features F_1, F_2, … F_n can be from close to 0 μm to 0.1 μm (e.g., 0 nm to 100 nm, 1 nm to 75 nm, or 1 nm to 50 nm), from close to 0 μm to 1 μm (e.g., 0 nm to 1000 nm, or 1 nm to 500 nm), from close to 0 μm to 5 μm (e.g., 1 nm to 5 μm, 10 nm to 5 μm, 50 nm to 5 μm, 75 nm to 5 μm, 0.1 μm to 5 μm, 0.5 μm to 5 μm, or 1 μm to 5 μm), or from close to 0 μm to 8 μm (e.g., 1 nm to

8 μm, 10 nm to 8 μm, 50 nm to 8 μm, 75 nm to 8 μm, 0.1 μm to 8 μm, 0.5 μm to 8 μm, or 1 μm to 8 μm), or from close to 0 μm to 10 μm (e.g., 1 nm to 10 μm, 10 nm to 10 μm, 50 nm to 10 μm, 75 nm to 10 μm, 0.1 μm to 10 μm, 0.5 μm to 10 μm, or 1 μm to 10 μm).

[0105] In various embodiments, a lateral distance between two features can be defined in some embodiments as a pitch. In some embodiments, the pitch between features within a portion P_n can be substantially the same within the portion P_n. For example, in various embodiments, in portion P_1 of the portions P_1, P_2, … P_n, the feature F_1 can comprise a plurality of features that form a periodic array such that the pitch is substantially the same within portion P_1. In addition, in some embodiments, the features F_1, F_2, … F_n among the multiple portions P_1, P_2, … P_n, can form a periodic array such that the pitch is substantially the same among the portions P_1, P_2, … P_n. In other embodiments, the features could be chirped and form an aperiodic array such that the pitch may be different among multiple portions P_1, P_2, … P_n. However, although the pitch may be different for different portions P_1, P_2, … P_n, the pitch can be slowly varying (e.g., less than 15% change per lateral distance, less than 12% change per lateral distance, less than 10% change per lateral distance, less than 8% change per lateral distance, less than 5% change per lateral distance, less than 3% change per lateral distance, or less than 1% change per lateral distance) among the portions P_1, P_2, … P_n. In some embodiments, the pitch may uniformly change across multiple portions P_1, P_2, … P_n. In other embodiments, the features could be chirped within a portion P_n such that the pitch may be different within the portion P_n. In some such embodiments, the pitch within the portion P_n may slowly vary (e.g., less than 15% change per lateral distance, less than 12% change per lateral distance, less than 10% change per lateral distance, less than 8% change per lateral distance, less than 5% change per lateral distance, less than 3% change per lateral distance, or less than 1% change per lateral distance). In some embodiments, the pitch may uniformly change with the portion P_n. The pitch in certain embodiments can be between 1 μm and 100 μm, between 1 μm and 75 μm, between 1 μm and 50 μm, or between 1 μm and 25 μm.

[0106] With continued reference to Figure 1A, the features F_1, F_2, … F_n can correspond to elements E_1, E_2, … E_n on the optical product 10′, and since the optical product 10′ is configured to reproduce the 3D object 50, aspects of the features F_1, F_2, …

F_n can correlate to aspects of the surface S of the 3D object 50 at the corresponding point S_1, S_2, … S_n. For example, a gradient (e.g., slope) in the features F_1, F_2, … F_n can correlate to an inclination of the surface S of the 3D object 50 at the corresponding point S_1, S_2, … S_n. For example, in various embodiments, each feature can include a slope. A slope of the feature F_1 can correlate to the inclination of the surface S of the 3D object 50 at the corresponding point S_1. As shown in Figure 1C, the slope of the feature F_1 can correlate to the polar angle θ_1 from reference line R_1 of the 3D object 50. Accordingly, the slopes of the features F_1, F_2, … F_n can mimic the surface normals of the 3D object 50.

[0107] Various embodiments can advantageously have a uniform gradient (e.g., uniform slope) within each portion P_n such that the gradient is a single value (e.g., a single polar angle θ_n) at the corresponding point S_n on the surface S of the 3D object 50. In other embodiments, the feature F_n within a portion P_n includes a plurality of features, and the features within the portion P_n may have more than one gradient (e.g., different slopes). In such embodiments, the average gradient (e.g., average slope) of the features within the portion P_n can correlate to the inclination of the surface S of the 3D object 50 at the corresponding point S_n.

[0108] In some embodiments, varying the slopes within and/or among portions P_1, P_2, … P_n can create contrast on the surface and therefore, on the image 50′. Furthermore, varying at least one of the height of features, pitch between features (e.g., lateral distance between two features), and slope of the features in one or more portions P_1, P_2, … P_n can be used in authenticity and security applications. For example, one can intentionally vary the pitch within one or more portions P_n, but maintain the given slopes. The image 50′ of the 3D object 50 would be reproduced, yet upon closer inspection of the presence of the intentional variation within one or more portions P_1, P_2, … P_n, authenticity can be verified. Other variations are possible.

[0109] In various embodiments, the orientation of features F_1, F_2, … F_n can correlate to an orientation of the surface S of the 3D object 50 at the corresponding point S_1, S_2, … S_n. For example, an orientation of the feature F_1 can correlate to the orientation of the surface S of the 3D object 50 at the corresponding point S_1. As shown in Figure 1C, the orientation of the feature F_1 can correlate to the azimuth angle φ_1 from reference line R_2 of the 3D object 50. Various embodiments can advantageously have a uniform orientation within each portion P_n, such that the orientation is a single value (e.g., a single azimuth angle φ_n) at the corresponding point S_n on the surface S of the 3D object 50. In other embodiments, the feature F_n within a portion P_n includes a plurality of features, and the features within the portion P_n may have more than one orientation (e.g., different orientations). In such embodiments, the average orientation of the features within the portion P_n can correlate to the orientation of the surface S of the 3D object 50 at the corresponding point S_n. Furthermore, the orientation of the features within and among the portions P_1, P_2, … P_n, can slowly vary (e.g., less than 15% change per lateral distance, less than 12% change per lateral distance, less than 10% change per lateral distance, less than 8% change per lateral distance, less than 5% change per lateral distance, less than 3% change per lateral distance, or less than 1% change per lateral distance) within and among the portions P_1, P_2, … P_n.

[0110] In some embodiments, where a feature F_1 includes multiple features within a portion, the features can appear discontinuous with other features within the portion. In some embodiments where the surface 12 of the master 10 is pixelated (e.g., having a plurality of cells), the features F_1, F_2, … F_n can appear discontinuous with features in surrounding adjacent portions. In other embodiments, the portions P_1, P_2, … P_n can form a single cell or a mono-cell. In some such embodiments, the features F_1, F_2, … F_n can appear continuous and smoothly varying depending on the shape. In other such embodiments, the features F_1, F_2, … F_n can appear discontinuous due to discontinuities in the 3D object 50.

[0111] In some instances, the features F_1, F_2, … F_n can comprise one or more linear and/or non-linear features when viewed in a cross-section orthogonal to the first and second surfaces. In some embodiments, the features F_1, F_2, … F_n can comprise linear features corresponding to a substantially smooth region of the surface S of the 3D object 50. The features F_1, F_2, … F_n can also comprise non-linear features, e.g., curved features as seen from a top or front view, corresponding to a curved region of the surface S of the 3D object 50, e.g., instead of flat facets. In some embodiments, features F_1, F_2, … F_n that are linear can be used to correspond to a curved region of the surface S of the 3D object 50. In some such embodiments, linear features on a master 10 can be used to represent a curved region by using a piecewise approximation function (e.g., a piecewise linear function such as a function comprising straight line sections). In some other embodiments, features F_1, F_2, … F_n that are non-linear can be used to correspond to a substantially smooth region of the surface S of the 3D object 50. In some such embodiments, non-linear features on a master 10 can be used to represent smooth regions on the surface S of the 3D object because the features F_1, F_2, … F_n can correspond to relatively small sized features on the optical product 10′. For example, the pitch and/or texture on the optical product 10′ can be between 1 μm and 100 μm, between about 1 μm and about 75 μm, between about 1 μm and about 50 μm, or between about 1 μm and about 25 μm.

[0112] With continued reference to Figure 1A, as described herein, the features F_1, F_2, … F_n can correspond to aspects of the surface S of the 3D object 50 and can also correspond to elements E_1, E_2, … E_n on the optical product 10′ such that the optical product 10′ can reproduce an image 50′ of the 3D object 50. In various embodiments, the elements E_1, E_2, … E_n on the optical product 10′ can be non-holographic. For example, the elements E_1, E_2, … E_n do not need to rely on holography (e.g., effects based on diffraction and/or based on optical interference) to render a 3D image 50′ of the 3D object 50. In some such embodiments, the features F_1, F_2, … F_n on the surface 12 of the master 10 can include non-sinusoidal features or non-quasi-sinusoidal features. In general, sinusoidal or quasi-sinusoidal features can be diffractive with +/- orders of equal intensity that generate a twin image. One positive order and one negative order can share the incident light and result in a simultaneous twin image with counter-intuitive movement of one image with respect to the other. Such effects may be non-ideal. In some embodiments that include non-sinusoidal or non-quasi-sinusoidal features, the features F_1, F_2, … F_n on the surface 12 of the master 10 can include other shapes, such as saw toothed shapes as described herein.

[0113] Although various embodiments described herein do not necessarily rely on holography to reproduce an image, some embodiments can include diffractive or holographic features (e.g., less than about 50% of the surface area, less than about 40% of the surface area, less than about 30% of the surface area, less than about 20% of the surface area, less than about 10% of the surface area, less than about 5% of the surface area, less than about 3% of the surface area, less than about 2% of the surface area, or less than about 1% of the surface area) to be used in conjunction with the non-holographic elements E_1, E_2, … E_n described herein. For example, in some embodiments, the second surface 12 of the master 10 can further comprise features corresponding to holographic elements on the optical product 10′ in one or more portions P_1, P_2, … P_n. In other embodiments, a holographic layer can be added over or under the surface 12′ of the optical product 10′.

[0114] Figure 1D is another example optical product 10′ in accordance with certain embodiments described herein. As shown in Figure 1D, the optical product 10′ can include a plurality of portions P'_1, P'_2, … P'_n. Each portion P'_n can include elements E_1, E_2, … E_n, e.g., non-holographic elements, on the optical product 10′. In some such embodiments, the elements E_1, E_2, … E_n can be embossed on the bottom surface of the substrate, e.g. UV curable resin having a refractive index of 1.5. The elements E_1, E_2, … E_n can be coated with a reflective coating. The elements E_1, E_2, … E_n may then be embedded between the substrate and the item to which the optical product 10′ is attached. As described herein, the slopes of the elements E_1, E_2, … E_n can be configured to create the 3D depth perception of the image. For example, elements E_1, E_2, … E_n with less steep slopes can cause light to reflect toward the observer's eye creating more brightness, while elements E_1, E_2, … E_n with steeper slopes can cause light to reflect away from the observer's eye creating more darkness. In this example of an embedded optical product 10′, elements E_1, E_2, … E_n with steep enough slopes can cause light to be totally internally reflected within the substrate (which has a higher index than the surrounding medium), and creating even more darkness.

[0115] Figure 1E is another example optical product 10′ in accordance with certain embodiments described herein. As shown in Figure 1E, the optical product 10′ can include a plurality of portions P'_1, P'_2, … P'_n. Each portion P'_n can include elements E_1, E_2, … E_n, e.g., non-holographic elements, on the optical product 10′. As described herein, utilizing embodiments of the optical product 10′ having elements E_1, E_2, … E_n (or masters having features F_1, F_2, … F_n) with smaller height can be advantageous to reduce the amount of material used. However in cases where height is less important, certain embodiments can utilize elements E_1, E_2, … E_n with slowly varying surfaces (e.g., slopes) creating a substantially contiguous surface from one portion P'_n to another. In various embodiments, the number of substantially contiguous portions can include at least two, three, four, five, eight, ten, fifteen, twenty, or more, or be in any range in between these values.

[0116] Various methods can be used to manufacture the master 10 for fabricating an optical product 10′. An example method 100 is shown in Figure 2. As shown in operational block 110, the method 100 can include providing a data file, e.g., a 2D data file, configured to describe, characterize, and/or record features the 3D object and/or 3D image 50′. The data file can provide the pattern of the features F_1, F_2, … F_n on the surface 12 of the master 10.

[0117] For example, the data file can comprise a plurality of portions (as will be described further herein). Each portion can correspond to one or more points on a surface S of the 3D object 50. Each portion can comprise features of intensity corresponding to non-holographic elements on the optical product 10′. A gradient in intensity can correlate to an inclination of the surface S of the 3D object 50 at the one or more corresponding points. In addition, an orientation of the features can correlate to an orientation of the surface S of the 3D object 50 at the one or more corresponding points. As shown in operational block 120, the method 100 can further include manufacturing the master 10 based at least in part on the 2D data file.

[0118] As described herein, certain embodiments of the optical product 10′ can produce a bright, mirror-like image. In some implementations, a matte finish may be desired. Figure 2A illustrates an example method that can be used to manufacture a surface relief diffuser and also to determine a height displacement file used to manufacture the diffuser. In the method 200 shown in Figure 2A, an input image 210 of the 3D object 50 (e.g., a 2D photograph of the 3D object) is entered into the recording loop 220 of the main program 225 of the processor 230. Other information, such as user parameters 211 (e.g., angle, scale, zoom, etc.), exposure compensation curve 212, intensity compensation mask 213, and apodizing mask 214 can also be entered into the recording loop 220. The processor 230 can produce a height displacement file 240 that is configured to describe the intensities of the 3D object 50. This height displacement file 240 can be used as a map to generate the pattern of the diffuser. In some examples of the height displacement file 240, the intensities of the 3D object can be correlated to a depth for the diffuser. For example, the black sections of the 3D object 50 can correlate to the surface of the diffuser, white sections of the 3D object 50 can correlate to a lower depth (e.g., down 10 µm), and grey sections of the 3D object 50 can correlate to some depth in between. Other variations are possible.

[0119] In the example method 200 shown in Figure 2A, a digital micromirror device (DMD) video projector 250 can be used along with the photoresist recording plate 260, each receiving the inputted information from the recording loop 220. The DMD video projector 250 includes a DMD chip that includes a plurality of micromirrors that in certain embodiments can correspond to the pixels of the height displacement file 240. The pixels of the height displacement file 240 can also correspond to the regions on the X-Y stage of the photoresist recording plate 260 in some embodiments. Each micromirror of the DMD chip can be used as a spatial light modulator that, for example, reflects light from a light source in the video projector 250 in the on-state, and that does not reflect light in the off-state. Varying the amount of light intensity can be produced by varying the time the micromirror is in the on- and off-states (e.g., pulse width modulation, etc.). As shown in Figure 2A, demagnification optics 255 can be used to produce the pattern of the diffuser in a light sensitive material, e.g., a photoresist, on the resist recording plate 260. In some embodiments, the resist can be used as the diffuser. As disclosed herein, other techniques, such as electron beam lithography on electron sensitive material and ion beam lithography on ion sensitive material can also be used. Certain embodiments of the diffuser can be used with certain embodiments of the optical product 10′ to produce a diffuse or hazy layer over the reflected image 50′ to produce an image with a matte finish.

[0120] Figure 2B illustrates an example method that can be used to manufacture the master 10 and also to determine the data file to be used to manufacture the master 10, e.g., to determine the pattern of the features F_1, F_2, … F_n on the surface 12 of the master 10. Certain such embodiments can be advantageous as a 3D physical object and/or a 3D model utilizing physical dimensions of the 3D object (e.g., topographical calculations) are not required. For example, in the method 300 shown in Figure 2B, the input image 305 can be a 2D input image (e.g., a 2D photograph of the 3D object) or 2D image converted from a 3D image. In some embodiments, the input image 305 can be converted into a 2D interpolated image 308 and produced as a 2D converted image 310. The 2D image of the 3D object can be translated into a gray scale image (e.g., a normal map 315 wherein black, white, and gray regions correlate to different heights of the 3D object). In the method 300 shown in Figure 2B, the converted image 310 (or a normal map 315) is entered into the recording loop 320 of the main program 325 of the processor 330 in accordance with certain embodiments described herein. Similar to the method 200 in Figure 2A, other information, such as user parameters 311 (e.g., angle, scale, zoom, etc.), exposure compensation curve 312, intensity compensation mask 313, and apodizing mask 314 can also be entered into the recording loop 320. The processor 330 can produce a data file 340, e.g., a 2D data file, that is configured to describe the 3D image 50′ of at least a part of the 3D object 50. In some embodiments, the intensities in the data file 340 can be assigned based on gray scale. For example, the data file 340 can comprise a plurality of portions. Each portion can correspond to one or more points on a surface S of the 3D object 50. Each portion can comprise features of intensity corresponding to non-holographic elements on the optical product 10′. A gradient in intensity can correlate to a gradient or an inclination of the surface S of the 3D object 50 at the one or more corresponding points. In addition, an orientation of the features can correlate to an orientation of the surface S of the 3D object 50 at the one or more corresponding points. This data file 340 can be used as a map to generate the pattern of features F_1, F_2, … F_n on the surface 12 of the master 10. An example data file is discussed with respect to Fig. 3A.

[0121] Similar to method 200 in Figure 2A, a digital micromirror device (DMD) video projector 350 can be used along with the photoresist recording plate 360, each receiving the inputted information from the recording loop 320. The plurality of micromirrors in the DMD video projector 350 in certain embodiments can correspond to the pixels of the data file 240. The pixels of the data file 340 can also correspond to one or more portions P_1, P_2, … P_n of the surface 12 of the master 10 in some embodiments. As shown in Figure 2B, the demagnification optics 355 can be used to produce the pattern of features F_1, F_2, … F_n in a light sensitive material, e.g., a photoresist, on the resist recording plate 360. In some embodiments, the resist can be used as the surface 12 of the master 10. As disclosed herein, other techniques, such as electron beam lithography on electron sensitive material and ion beam lithography on ion sensitive material can also be used.

[0122] In some embodiments, the method 300 can further include adding on the master 10 features corresponding to holographic elements on the optical product 10′. For example, an optical recording (e.g., a planar optical recording) for the holographic elements can be superimposed onto the master 10 to add the holographic elements on the master 10. As another example, in some embodiments, the data file 340 can include features corresponding to holographic elements on the optical product 10′. In other embodiments, a separate data file comprising the features of intensity corresponding to holographic elements on the optical product 10′ can be provided. Manufacturing the master 10 can be based at least in part on the data file 340 including features corresponding to non-holographic elements and on the data file including features corresponding to holographic elements on. In some such embodiments, the data file 340 including the features corresponding to non-holographic elements and the data file including the features corresponding to holographic elements can be used sequentially or simultaneously to manufacture the master 10. In some other embodiments, a needle, such as from an atomic force microscope, can be used to produce the features corresponding to the holographic elements on the optical product 10′. Other methods can be employed to add holographic features or elements.

[0123] Figure 2C illustrates yet another example method that can be used to determine the pattern of the features F_1, F_2, … F_n on the surface 12 of the master 10. The method 400 shown in Figure 2C is similar to the method 300 shown in Figure 2B except that a normal map 415 can be provided instead of the input image 310. The normal map 415 can be inputted into the main program 425 of the processor 430 to produce the data file 440.

[0124] Figure 3A illustrates an example 2D data file 540 in accordance with certain embodiments disclosed herein. The data file 540 can include a plurality of portions p_1, p_2, … p_n. In some embodiments, the plurality of portions p_1, p_2, … p_n can form a single cell (e.g., a mono-cell). In other embodiments, as shown in Figure 3A, the plurality of portions p_1, p_2, … p_n can form a plurality of cells. In various embodiments, the portions p_1, p_2, … p_n can form a pixelated surface corresponding to the portions P_1, P_2, … P_n of the surface 12 of the master 10. For example, as shown in Figure 3A, the portions p_1, p_2, … p_n can include a plurality of rows and columns.

[0125] As also shown in Figure 3A, in some embodiments, borders 13′ can surround at least part of the portions p_1, p_2, … p_n. The borders 13′ can substantially surround a portion p_n or can surround just part of a portion p_n. As with the master 10, the size and shape of the portions p_1, p_2, … p_n on the data file 540 are not particularly limited. Some of the portions p_1, p_2, … p_n can comprise a symmetrical shape. For example, the symmetrical shape can include a rectangle, a square, a rhombus, an equilateral triangle, an isosceles triangle, a regular polygon (e.g., a regular pentagon, a regular hexagon, a regular octagon), etc. The shape can also include curvature, e.g., a circle, an ellipse, etc. In other embodiments, some of the portions p_1, p_2, … p_n can comprise a non-symmetrical shape, e.g., a non-rotationally symmetrical shape, and/or an irregular shape. For example, Figure 3B illustrates an example embodiment of a data file 545 with irregularly shaped portions p_1, p_2, … p_n. In some embodiments, some of the portions p_1, p_2, … p_n can have a shape that is substantially the same as other portions p_1, p_2, … p_n. In other embodiments, e.g., as shown in Figure 3B, some of the portions p_1, p_2, … p_n can have a shape that is different from other portions p_1, p_2, … p_n.

[0126] As with the master 10, the arrangement of the portions p_1, p_2, … p_n in the data file 540 is not particularly limited. For example, whether with or without borders, whether symmetrically shaped or non-symmetrically shaped, or whether regularly or irregularly shaped, the portions p_1, p_2, … p_n can form a periodic array. For example, in Figure 3A, the portions p_1, p_2, … p_n form a periodic array. In other embodiments, whether with or without borders, whether symmetrically shaped or non-symmetrically shaped, or whether regularly or irregularly shaped, the portions p_1, p_2, … p_n can form an aperiodic array. For example, in Figure 3B, the portions p_1, p_2, … p_n form an aperiodic array. In yet other embodiments, the portions p_1, p_2, … p_n can form a combination of periodic and aperiodic arrays.

[0127] With continued reference to Figure 3A, each portion p_n can include features f_1, f_2, … f_n that correspond to features F_1, F_2, … F_n on the surface 12 of the master 10. Portion p_a has a single feature f_1, while portion p_b has multiple features f_n.

The features $f_1, f_2, \ldots f_n$ of the data file 540 can include features of intensity (varying dark and light lines). In some embodiments, the intensity can correlate to the height of a feature on the surface S of the 3D object 50.

[0128] In various embodiments, a lateral distance between two features can be defined in some embodiments as a pitch. In some embodiments, the pitch between features within a portion p_n can be substantially the same within the portion p_n. For example, in various embodiments, in portion p_1 of the portions $p_1, p_2, \ldots p_n$, the feature f_1 can comprise a plurality of features that form a periodic array such that the pitch is substantially the same within portion p_1. In addition, in some embodiments, the features $f_1, f_2, \ldots f_n$ among multiple portions $p_1, p_2, \ldots p_n$, can form a periodic array such that the pitch is substantially the same among multiple portions $p_1, p_2, \ldots p_n$.

[0129] In other embodiments, the features can form an aperiodic array such that the pitch may be different among multiple portions $p_1, p_2, \ldots p_n$. However, although the pitch may be different for different portions $p_1, p_2, \ldots p_n$, in some embodiments, the pitch can be slowly varying (e.g., less than 15% change per lateral distance, less than 12% change per lateral distance, less than 10% change per lateral distance, less than 8% change per lateral distance, less than 5% change per lateral distance, less than 3% change per lateral distance, or less than 1% change per lateral distance) among the portions $p_1, p_2, \ldots p_n$. In some embodiments, the pitch may uniformly change across multiple portions $p_1, p_2, \ldots p_n$.

[0130] In other embodiments, the features could be chirped within a portion p_n such that the pitch may be different within the portion p_n. In some such embodiments, the pitch within the portion p_n may slowly vary (e.g., less than 15% change per lateral distance, less than 12% change per lateral distance, less than 10% change per lateral distance, less than 8% change per lateral distance, less than 5% change per lateral distance, less than 3% change per lateral distance, or less than 1% change per lateral distance).

[0131] Figure 3A shows an example data file 540 with linear features where the pitch is substantially uniform within a portion p_n, and Figure 3B shows an example data file 545 with curved features where the pitch is substantially uniform within a portion p_n. Figure 3A is also an example of features having a pitch that slowly changes (e.g., less than 10% change per lateral distance) across multiple portions $p_1, p_2, \ldots p_n$.

[0132] In various embodiments, each feature of intensity can include a slope. Various embodiments can advantageously have a uniform gradient (e.g., uniform slope) within each portion p_n such that the gradient is a single value (e.g., a single polar angle θ_n) at the corresponding point S_n on the surface S of the 3D object 50. The gradient in the features $f_1, f_2, \ldots f_n$ can correlate to an inclination of the surface S of the 3D object 50 at the corresponding point $S_1, S_2, \ldots S_n$. In other embodiments, the feature f_n within a portion p_n includes a plurality of features, and the features within the portion p_n may have more than one gradient (e.g., different slopes). In such embodiments, the average gradient (e.g., average slope) of the features within the portion p_n can correlate to the inclination of the surface S of the 3D object 50 at the corresponding point S_n.

[0133] Various embodiments can also advantageously have a uniform orientation within each portion p_n, such that the orientation is a single value (e.g., a single azimuth angle φ_n) at the corresponding point S_n on the surface S of the 3D object 50. In various embodiments, the orientation of features $f_1, f_2, \ldots f_n$ can correlate to an orientation of the surface S of the 3D object 50 at the corresponding point $S_1, S_2, \ldots S_n$. In other embodiments, the feature f_n within a portion p_n includes a plurality of features, and the features within the portion p_n may have more than one orientation (e.g., different orientations). In such embodiments, the average orientation of the features within the portion p_n can correlate to the orientation of the surface S of the 3D object 50 at the corresponding point S_n. Furthermore, the orientation of the features within and among the portions $p_1, p_2, \ldots p_n$, can slowly vary (e.g., less than 15% change per lateral distance, less than 12% change per lateral distance, less than 10% change per lateral distance, less than 8% change per lateral distance, less than 5% change per lateral distance, less than 3% change per lateral distance, or less than 1% change per lateral distance) within and among the portions $p_1, p_2, \ldots p_n$.

[0134] In some embodiments, where a feature f_1 includes multiple features within a portion, the features can appear discontinuous with other features within the portion. In some embodiments where the surface 12 of the master 10 is pixelated (e.g., having a plurality of cells), the features $f_1, f_2, \ldots f_n$ can appear discontinuous with features in surrounding adjacent portions. Based on pixel or cell size and/or tolerances in creating the data file 540, some embodiments may include random discontinuities with substantially no (relatively little if any) negative impact in image reproduction. Such discontinuity can reduce iridescence. In other embodiments, the portions p_1, p_2, … p_n can form a single cell or a mono-cell. In some such embodiments, the features f_1, f_2, … f_n can appear continuous and smoothly varying depending on the shape. In other such embodiments, the features f_1, f_2, … f_n can appear discontinuous due to discontinuities in the 3D object 50.

[0135] In some embodiments, as shown in Figure 3C, the features f_1, f_2, … f_n can comprise linear features corresponding to a substantially smooth region of the surface S of the 3D object 50. The features f_1, f_2, … f_n can be used to produce linear features F_1, F_2, … F_n on the surface 12 of the master 10. The features f_1, f_2, … f_n can also be used to produce non-linear features F_1, F_2, … F_n on the surface 12 of the master 10. In some embodiments, features f_1, f_2, … f_n that are linear can be used to correspond to a curved region of the surface S of the 3D object 50. In some such embodiments, linear features f_1, f_2, … f_n in the data file can be used to represent a curved region by using a piecewise approximation function.

[0136] As shown in Figure 3D, in some embodiments, although linear features f_1, f_2, … f_n in the data file can correspond to a substantially smooth region of the surface S of the 3D object 50, non-linear features on the master 10 (e.g., curved facets shown in left profile) can be used. As described herein, in some such embodiments, non-linear features on the master 10 can be used to produce elements E_1, E_2, … E_n on an optical product 10′ that can appear smooth because the corresponding features on the optical product 10′ can be relatively small (e.g., between 1 μm and 100 μm, between 1 μm and 75 μm, between 1 μm and 50 μm, or between 1 μm and 25 μm).

[0137] As the features f_1, f_2, … f_n of the data file 540 correspond to aspects of the surface S of the 3D object 50, the features f_1, f_2, … f_n of the data file 540 can be used to produce the features F_1, F_2, … F_n on the surface 12 of the master 10. As described herein, the features F_1, F_2, … F_n on the surface 12 of the master 10 can be used to fabricate the elements E_1, E_2, … E_n on the surface 12′ of the optical product 10′. As described herein, in various embodiments, the elements E_1, E_2, … E_n on the optical product 10′ can be non-holographic. For example, the elements E_1, E_2, … E_n do not need to rely on holography to render a 3D image 50′ of the 3D object 50.

[0138] Figure 4A is another example 2D data file 640 prepared in accordance with certain embodiments described herein. The data file 640 was generated by the normal map 650 shown in Figure 4B. As an example, the lower left portion 645 of the data file 640 represents the center of the hemispherical object 655 in the lower left portion of the normal map 650. The data file 640 was used to generate the features F_1, F_2, … F_n on the surface 12 of a master 10, which was used to fabricate the elements E_1, E_2, … E_n on the surface 12′ of an optical product 10′. The optical product 10′ was configured, when illuminated, to reproduce by reflected light, the 3D image 650′ shown in Figure 4C.

[0139] In certain embodiments, an optical product 10′ is also disclosed herein. As described herein, the optical product 10′ can be configured, when illuminated, to reproduce by reflected light, a 3D image 50′ of at least a part of a 3D object 50. As shown in Figure 1A, similar to the master 10, the optical product 10′ can include a surface 12′ comprising a plurality of portions P'_1, P'_2, … P'_n. Each portion P'_n can correspond to a point S_n on a surface S of the 3D object 50. Each portion P'_n can comprise features, e.g., non-holographic elements E_1, E_2, … E_n. In certain embodiments, the non-holographic elements E_1, E_2, … E_n can be configured to produce at least part of the 3D image 50′ without relying on diffraction. In various embodiments, the portions P'_1, P'_2, … P'_n can form a single cell (e.g., a mono-cell). In other embodiments, the portions P'_1, P'_2, … P'_n can form a plurality of cells. Each portion P'_n can form a cell of the plurality of cells. The optical product 10′ can include borders surrounding at least part of the portions P'_1, P'_2, … P'_n.

[0140] A gradient (e.g., uniform slope or average slope) in the non-holographic features E_1, E_2, … E_n can correlate to an inclination of the surface S of the 3D object 50 at the corresponding point S_1, S_2, … S_n. In addition, the orientation (e.g., uniform orientation or average orientation) of the non-holographic features E_1, E_2, … E_n can correlate to an orientation of the surface S of the 3D object 50 at the corresponding point S_1, S_2, … S_n.

[0141] Furthermore, since the master 10 can be used to fabricate an optical product 10′, aspects disclosed herein with reference to the master 10 can apply to certain embodiments of the optical product 10′. For example, disclosure with respect to the shapes (e.g., symmetrical, non-symmetrical, irregular, curved, etc.) and arrangements (e.g., periodic, aperiodic, etc.) of the portions P_1, P_2, … P_n for the master 10 can apply to the shapes and arrangements of the portions P'_1, P'_2, … P'_n of the optical product 10′. As another example, disclosure with respect to the features F_1, F_2, … F_n (e.g., linear, curved, periodic, aperiodic, slowly varying, continuous, discontinuous, non-sinusoidal, etc.) for the master 10 can apply to the features E_1, E_2, … E_n of the optical product 10′. Furthermore, as described herein with respect to the master and the method of manufacturing the master, the optical product 10′ of certain embodiments can further comprise features corresponding to holographic features.

[0142] In addition, small features can be imbedded in the optical product 10′ that do not contribute to the formation of the image. Such imbedded features can be used in authenticity and security applications. Furthermore, as described herein, certain embodiments can incorporate intentional variations within one or more portions P'_1, P'_2, … P'_n of the optical product 10′ for security applications.

<u>Optical Products Comprising Non-Holographic Features and Interference Optical Structures</u>

[0143] Although some implementations described herein include optical products configured, when illuminated, to reproduce by reflected or transmitted light, a 3D image, various implementations can reproduce a 3D image in both reflection and transmission. In particular, some implementations can reproduce the 3D image in a first color in transmission mode and a second color in reflection mode. The second color can be different from the first color. In addition, although some implementations described herein include optical products configured to reduce and/or eliminate color change with angle of tilt (e.g., reducing and/or eliminating iridescence by using non-holographic features), in some instances, it may be desired to provide a color change with viewing angle. Accordingly, various implementations can comprise an interference optical structure disposed on one or more non-holographic features described herein. Various implementations can have color shifting properties. The optical product can be configured to provide authenticity verification on an item for anti-counterfeiting or security. The item can be a banknote, a credit card, a debit card, a stock certificate, a passport, a driver's license, an identification card, a document, a tamper evident container or packaging, consumer packaging, a bottle of pharmaceuticals, etc. The item can be electronics, apparel, jewelry, cosmetics, a handbag, etc.

[0144] To curtail counterfeiting, currency, documents (e.g., banknotes) as well as other items such as products and packaging can be provided with security features that can be inspected by the general public to verify authenticity. In many cases, it can be advantageous if the security features can be easily seen under a variety of light conditions and without the need for special lighting conditions. It can also be desirable that the security features have distinct characteristics that can be easily identified by the public within a 1-10 second time frame. In addition, it is advantageous in general, if the security feature is not susceptible to copying by electronic or photographic equipment, such as, for example, printers, copiers, cameras, etc.

[0145] One example of a security feature employed in banknotes is the watermark, which has a fairly high degree of awareness among the general public. An example of a watermark can be an image comprising light and dark regions that can be easily seen by holding up the banknote to see the watermark in light transmission. However, watermarks may be susceptible to be copied and thus are not very secure. Other examples of security features may use inks and motion type features that are not readily seen under low light conditions (e.g., at low lit bars, restaurants, etc.), have poor image resolution, and/or have slow optical movement relative to the movement of the banknote. Accordingly, some existing security features tend to be more complicated structures having more complex color changing effects. This approach, however, can be disadvantageous when the complicated security devices are applied to banknotes or currency, as these complicated security devices may confuse an average person who is looking for a distinctive security feature.

[0146] Having a security feature (e.g., an anti-counterfeit feature) that has high contrast with respect to the background that can be easily identified by the general public under a variety of light conditions, including low light, can be advantageous.

Accordingly, various optical products disclosed can reproduce a 3D image in color in reflection and/or transmission. In various instances, the image can appear to have one color in reflection and another different color in transmission. These security features can be incorporated in a consumer product, packaging, or a document (e.g., banknote). A consumer, merchant, or a bank teller can holdup such a banknote to light to readily verify the authenticity of the banknote. Additionally or alternatively, in some implementations, the security feature can be configured to exhibit color shift and/or movement of identifiable features when the viewing angle is varied to enhance security. These and other features are described in further detail herein.

[0147] Accordingly, various security features contemplated herein can comprise optical stacks and/or structures that are at least partially reflective and at least partially transmissive. The security features contemplated herein can be configured as coatings, threads, laminates, foils, films, hot stamps, windows, patches, labels, pigments and/or inks disposed on one or more non-holographic features and incorporated with documents (e.g., banknotes), packaging, or other items. The innovative aspects described in this application also include systems and methods of fabricating optical products comprising one or more non-holographic features with optical structures and/or stacks that are at least partially reflective and at least partially transmissive. In some embodiments, such optical structures may be fabricated on support or base layers or sheets such as webs (e.g., roll coated webs). Processes described herein may also include removing the fabricated optical structures and/or stacks from a support or base layer (e.g., roll or sheet). The innovative aspects described in this application further include methods and systems for including the optical structures and/or stacks that are at least partially reflective and at least partially transmissive in pigment and inks having a desired amount of durability and mechanical strength to be disposed on one or more non-holographic features and to be further used in or on or incorporated into banknotes and other security devices/documents. The innovative aspects described in this application further include methods and systems for including the optical structures and/or stacks (e.g., in the form of a hot stamp coating, a foil coating, or an ink coating) to be disposed on one or more non-holographic features and to be further used in or on or incorporated into documents or packaging. In some implementations, a document or packaging can include a main body and the optical structure can be disposed on the main body. The main body can comprise cloth, paper, plastic, cardboard, etc.

[0148] Figure 5 schematically illustrates a cross-sectional view of an example optical product 1100 with an interference optical structure 1130 (e.g., a coating, film, pigment, etc.) disposed on non-holographic features 1120. The optical product 1100 can be configured, when illuminated, to reproduce an image that appears 3D of at least a part of a 3D object (e.g., a regularly or irregularly shaped object). The optical product 1100 can include a surface 1111 (e.g., a surface of a substrate 1110 described herein) comprising a plurality of portions, each portion corresponding to a point on a surface of the 3D object (e.g., as described with respect to Figs. 1A-4C). The optical product 1100 can also include one or more non-holographic features 1120 (e.g., linear and/or curved facets with various angles, orientations, and heights) disposed within each portion configured to produce at least a part of the image without relying on diffraction (e.g., as described with respect to Figs. 1A-4C). An interference optical structure 1130 (e.g., a coating, film, pigment, etc.) can be disposed on one or more non-holographic features 1120. In various implementations, the interference optical structure 1130 can be disposed with respect to one or more non-holographic features 1120 such that the optical product 1100, when illuminated, reproduces color in transmission mode T and/or reflection mode R. As an example, the interference optical structure 1130 can be disposed with respect to one or more non-holographic features 1120 such that the optical product 1100, when illuminated, reproduces the image in a first color in transmission mode T and a second color in reflection mode R. The second color in reflection mode R can be different from the first color in transmission mode T. In some instances, the first and second colors can be complementary colors. In some instances, the first and second colors are not complementary colors.

[0149] In some instances, the optical product 1100 can include a transparent or optically transmissive window 1145 in an item such as a document. The window 1145 can be adhered to the non-holographic features 1120 and interference optical structure 1130 with an adhesive 1140 in various implementations.

[0150] Figure 6 schematically illustrates the non-holographic features 1120 and interference optical structure 1130 of the example optical product 1100 producing colored depth perception in the reproduced image of the object. As described herein, the non-holographic features 1120 can include discontinuities (e.g., discontinuous with other features). In some instances, the discontinuous features can correspond to a continuous region of the object. As described herein, the non-holographic features 1120 with less steep slopes can be configured to reflect light toward an observer's eye, and the non-holographic features 1120 with steeper slopes are configured to reflect light away from the observer's eye. In section 1121, the non-holographic features 1120 include multi-angled facets with different slopes, orientations, and heights. For individual ones of the portions in section 1121, a gradient in the non-holographic features 1120 can correlate to a surface normal of the surface of the 3D object at the corresponding point. For individual ones of the portions in section 1121, an orientation of the non-holographic features 1120 can correlate to an orientation of the surface of the 3D object at the corresponding point. Accordingly, the non-holographic features 1120 can produce the appearance of the 3D image and the interference optical structure 1130 can provide color in the image. In section 1122, the non-holographic features 1120 have the same (e.g., substantially the same) slopes which may produce no image and the interference optical structure 1130 can provide the same (e.g., substantially the same) color to the observer. In section 1122, no image in the same (e.g., substantially the same) color can also be produced with the interference optical structure 1130 disposed on a flat area (e.g., no facets).

[0151] Various implementations can create various optical effects utilizing a combination of non-holographic features 1120 with interference optical structures 1130 along with other features described herein (and/or other features known in the art or yet to be developed). For example, some implementations can also utilize reflective structures and/or demetallized structures.

[0152] Figure 7A shows an example planar view 1150A of a reproduced object 1151A and background 1152A. The image that appears three dimensional can be formed by the non-holographic features 1120 described herein. As described herein, the non-holographic features 1120 can be coated with a reflective material. In this example, the non-holographic features 1120 and surrounding areas were coated with aluminum. The non-holographic features 1120 can be de-metallized (e.g., leaving the surrounding areas metallized) and coated with an interference optical structure 1130. In this example, the non-holographic features 1120 were de-metallized and coated with an interference optical structure 1130. In Figure 7A, the image of the object 1151A (e.g., a mustang in this example) is produced in color with an aluminum background. In some instances, the interference optical structure 1130 can be partially transmissive and partially reflective such that the object 1151A appears one color in tranmission and another color in reflection. For example, when viewing the optical product from the other side, the object 1151A may be produced in a different color. In some implementations, the background 1152A, e.g., instead of the object 1151A, can also be produced with an interference optical structure 1130. In some implementations, the background 1152A, e.g., in addition to the object 1151A, can also be produced with an interference optical structure 1130 (e.g., another interference optical structure).

[0153] Figure 7B shows another example planar view 1150B of a reproduced object 1151B and background 1152B. In this example, the color in the image of the object 1151B (e.g., a mustang in this example) is produced by an aluminum coating and the background 1152B is produced with an interference optical structure 1130 deposited onto flat or non-holographic features 1120 with the same (e.g., substantially the same) slopes, orientations, and heights. In Figure 7B, the background 1152B is produced in color. In some instances, the interference optical structure 1130 can be partially transmissive and partially reflective such that the background 1152B appears one color in tranmission and another color in reflection. For example, when viewing the optical product from the other side, the background 1152B may be produced in a different color.

[0154] Figure 8 shows another example planar view 1150C of a reproduced object 1151C and background 1152C. The color in the image of the object 1151C (e.g., mustang in this example) is produced by an interference optical structure 1130 (e.g., similar to Fig. 7A) and the background 1152C is produced with an aluminum coating deposited onto flat or non-holographic features 1120 with the same (e.g., substantially the same) slopes, orientations, and heights. In addition, portions of the background 1152C can include de-metallized regions 1153C. In this example, portions of the aluminum was de-metallized to produce alphanumeric characters. The de-metallized regions 1153C can also be formed into other objects (regular or irregularly shaped objects), patterns, or images, etc.

[0155] Figure 9 shows another example planar view 1150D of a reproduced object 1151D and background 1152D. In this example, the colors in the image of the object 1151D and the background 1152D are produced by one or more interference optical structures (e.g., one or more interference optical structures). As described herein, various interference optical structures 1130 can operate in reflection and/or transmission modes. In some implementations, the optical structure 1130 can produce color in reflection and/or transmission. In some instances, the optical structure 1130 can produce a first color in transmission mode and a second color in reflection mode. In the example shown in Fig. 9, the color of the image of the object 1151D (e.g., a "10" in this example) is produced by an interference optical structure 1130 in reflection mode, and the color of the background 1152D is produced by the interference optical structure 1130 in transmission mode. In this example, at a certain viewing angle, the color in reflection is different from the color in transmission. In some instances, the interference optical structure 1130 can be partially transmissive and partially reflective such that the object 1151D and the background 1152D appear one color in tranmission and another color in reflection. For example, when viewing the optical product from the other side, the object 1151D and the background 1152D may be produced in different colors.

[0156] In some instances, the optical structure 1130 can have color shifting properties. For example, the color in transmission and/or reflection can change with a change in viewing angle. With respect to Fig. 9, at a different viewing angle, the optical structure can produce another different color in transmission mode and another different color in reflection mode. In some instances, the optical structure 1130 can have non-color shifting properties. For example, the color in transmission and/or reflection might not change with a change in viewing angle.

[0157] Figure 10 shows another example view 1150E of a reproduced object and background. This example illustrates the optical effect of a color outline or halo 1155 that appear to be on the surface of the object, which provides another difficulty of being counterfeited. Such effect can be produced by an interference optical structure 1130 disposed on non-holographic features 1120.

[0158] Some implementations can utilize reflective structures, demetallized structures, and/or interference optical structures in combination. For example, the non-holographic features and the surrounding areas can be coated with a reflective material (e.g., metallized). Some portions of the non-holographic features and/or surrounding areas can be de-metallized. Portions metallized and de-metallized can then be coated with an interference optical structure.

[0159] Various interference optical structures will now be described.

[0160] The interference structures described herein may comprise structures that produce optical interference. Such structures may include a plurality of reflective surfaces from which light reflects. Light from one such reflective surface may, for example interfere with light from another such reflective surface and produce optical interference.

[0161] In certain implementations, the optical structure 1130 can comprise a Fabry-Perot or an etalon structure. The etalon structure may comprise for example two (e.g., first and second) reflective surfaces separated by a distance. Light incident on the etalon may reflect off the two reflective surfaces. The distance between the first and second reflective surfaces may introduce phase shift between the light reflected from the first reflected surface and light reflected from the second reflective surfaces. This phase shift may produce optical interference. Accordingly, light reflectd from the etalon may have properties associated with interference. For example, the light reflected may have a particular wavelength spectrum and may for example be a particular color. In some implementations, the etalon may exhibit color shifting, the color of reflected light changing color with the angle of the incident light and/or the angle of viewing the etalon. Etalons may also produce interference in transmission as well. Likewise the light transmitted through the etalon may have properties associated with interference such as a characteristic wavelength or spectral character (e.g., a particular spectral band or color), change in color with angle of incidence of light and/or angle of viewing, etc. In some implementations the etalon comprises a plurality of layer stacked on top of each other the for the first and second reflective surfaces spaced apart by a distance (e.g., the thickness of one of the layers).

[0162] Light reflected from more than two reflective surfaces can also interfere with each other to produce an optical interference effect. Accordingly, in various implementations, the optical structure may comprise a plurality of layers such as two or more. Without subscribing to any particular scientific theory, in some cases the plurality of layers may provide a plurality of reflective surfaces, for example, at the interface between the layer. Similarly, in various implementations, the optical structure 1130 can comprise an interference optical stack. In some implementations, the optical stack may include pairs of high (H) and low (L) index layers comprising materials having higher and lower reflective index, respectively. In various implementations the different layer have thickness to provide interference and the desired interference effect.

[0163] In various implementations, for example, the optical structure 1130 can comprise a A/D/M multilayer thin film optical stack, where A is an absorber layer, D is a transparent dielectric layer, and M is a metal layer, for example, that is opaque. In some instances, the absorber layer can have a ratio of the real part (n) of the refractive index to the imaginary part (k) of the refractive index near unity. In some implementations, the optical structure can comprise a A/D/M/D/A multilayer thin film optical stack. As another example, the optical structure can comprise a A/D/M/M*/M/D/A multilayer thin film optical stack, where M* is a magnetic layer. Some such structures can include those described in U.S. Patent No. 4,705, 300 and U.S. Patent No. 6,838,166, each of which is incorporated herein by reference in its entirety.

[0164] The optical structure 1130 can also comprise, for example, a M/D/M or D/M/D/M/D multilayer thin film optical stack, where D is a transparent or optically transmissive dielectric layer and M is a metal layer. In some implementations, the metal layer can have a ratio of the real part (n) of the refractive index to the imaginary part (k) of the refractive index greater than or equal to 0.01 and less than or equal to 0.5, 0.4, or 0.2.

[0165] In various implementations, the optical structure 1130 can comprise a D/M/D or M/D/M/D/M multilayer thin film optical stack, where D is a transparent or optically transmissive dielectric layer and M is a metal layer. In some instances, the metal layer can have a ratio of the real part (n) of the refractive index to the imaginary part (k) of the refractive index greater than or equal to 0.01 and less than or equal to 0.5, 0.4, or 0.2. In some instances, individual ones of the metal layers can have a thickness of about 20 nm, 30 nm, 40 nm, 50 nm, 60 nm, 70 nm, 80 nm, 90 nm, 100 nm, or any ranges formed by such values, e.g., from about 20 nm to about 100 nm.

[0166] The metal layers can, for example, be any of those described herein, e.g., one or more of the metal layer can comprise aluminum, silver, gold, silver alloy, or gold alloy. The dielectric layers can, for example, be any of those described herein, e.g., one or more of the dielectric layers can comprise magnesium fluoride, silicon dioxide, zinc oxide, zinc sulfide, zirconium dioxide, titanium dioxide, tantalum pentoxide, ceric oxide, yttrium oxide, indium oxide, tin oxide, indium tin oxide, aluminum oxide, tungsten trioxide, or combinations thereof. In some instances, one or more of the dielectric layers can comprise an organic layer.

[0167] In various implementations, the optical structure 1130 can comprise a H/L/H/L/H multilayer thin film optical stack, where H and L are layers with a refractive index and the H layers have a higher refractive index than the L layers. In some designs, the L layers have a refractive index less than 1.65 and the H layers have a refractive index greater than or equal to 1.65. Some such structures can, for example, include those described in U.S. Patent No. 6,838,166, which is incorporated herein by reference in its entirety.

[0168] Some such optical structures 1130 will be described further herein.

<u>Optical Structures Comprising Metal Layers Surrounded by Dielectric Layers (e.g., D/M/D/M/D optical stack)</u>

[0169] Figure 11 schematically illustrates an optical structure 10 comprising a stack of layers that can be used as a security feature. The optical structure 10 comprises at least two metal layers 13 and 15. The at least two metal layers 13 and 15 can comprise metals having a ratio of the real part (n) of the refractive index to the imaginary part (k) of the refractive index (k) that is less than 1. For example, the at least two metal layers 13 and 15 can comprise metals that have an n/k value between about 0.01 and about 0.6, between about 0.015 and about 0.6, between about 0.01 and about 0.5, between about 0.01 and about 0.2, between about 0.01 and about 0.1, or any value in a range or sub-range defined by these values. Accordingly, the at least two metal layers 13 and 15 can comprise silver, silver alloys, gold, aluminum or copper and their respective alloys. Nickel (Ni) and Palladium (Pd) can be used in some implementations. In some cases, however, the at least two metal layers 13 and 15 do not comprise chromium, titanium, and/or tungsten or any metal having an n/k ratio greater than 0.6. In some cases, the metal layer 13 and 15 can have a thickness greater than or equal to about 3 nm and less than or equal to about 35 nm. For example, thickness of the metal layer 13 and 15 can be greater than or equal to about 10 nm and less than or equal to about 30 nm, greater than or equal to about 15 nm and less than or equal to about 27 nm, greater than or equal to about 20 nm and less than or equal to about 25 nm, or any value in a range or sub-range defined by these values. The thickness of the metal layer 13 can be equal to the thickness of the metal layer 15. Alternately, the thickness of the metal layer 13 can be greater than or less than the thickness of the metal layer 15.

[0170] A transparent dielectric layer 14 is sandwiched between the at least two metal layers 13 and 15. The dielectric layer 14 can have a refractive index greater than, less than or equal to 1.65. Materials with an index greater than or equal to 1.65 can be considered as high refractive index materials for the purpose of this application and materials with an index less than 1.65 can be considered as low index materials for the purpose of this application. The transparent dielectric layer 14 can comprise inorganic materials including but not limited to silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), magnesium fluoride (MgF_2), cerium fluoride (CeF_3), lanthanum fluoride (LaF_3), zinc oxide (ZnO), zinc sulfide (ZnS), zirconium dioxide (ZrO_2), titanium dioxide (TiO_2), tantalum pentoxide (Ta_2O_5), ceric oxide (CeO_2), yttrium oxide (Y_2O_3), indium oxide (In_2O_3), tin oxide (SnO_2), indium tin oxide (ITO) and tungsten trioxide (WO_3) or combinations thereof. The transparent dielectric layer 14 can comprise polymers including but not limited to parylene, acrylates, and/or methacrylate. Without any loss of generality, the transparent dielectric layer 14 can comprise a material having an index of refraction greater than, less than, or equal to 1.65 and an extinction coefficient between 0 and about 0.5 such that it has low absorption of light in the visible spectral range.

[0171] The dielectric layer 14 can have a thickness that is greater than or equal to about 75 nm and less than or equal to about 2 micron. For example, the dielectric layer 14 can have a thickness that is greater than or equal to about 150 nm and less than or equal to about 650 nm, greater than or equal to about 200 nm and less than or equal to about 600 nm, greater than or equal to about 250 nm and less than or equal to about 550 nm, greater than or equal to about 300 nm and less than or equal to about 500 nm, greater than or equal to about 350 nm and less than or equal to about 450 nm, greater than or equal to about 700 nm and less than or equal to about 1 micron, greater than or equal to about 900 nm and less than or equal to about 1.1 micron, greater than or equal to about 1 micron and less than or equal to about 1.2 micron, greater than or equal to about 1.2 micron and less than or equal to about 2.0 microns or any value in a range/sub-range defined by these values. Without subscribing to any particular theory, in various implementations, the thickness of the dielectric layer 14 can be approximately a quarter wavelength of light (e.g., visible light) incident thereon or an integer multiple of a quarter wavelength. In various implementations, the thickness of the dielectric layer 14 may be, for example, 1/4, 3/4, 5/4, 7/4, 9/4, 10/4, etc. of the wavelength of visible light incident on the dielectric layer 14.

[0172] The optical structure 10 further comprises a transparent dielectric layer 12 that is disposed on a side of the metal layer 13 that is opposite to the dielectric layer 14 and a transparent dielectric layer 16 that is disposed on a side of the metal layer 15 that is opposite to the dielectric layer 14. In some cases, layers 12 and 16 can comprise materials having a refractive index greater than or equal to 1.65. For example, layers 12 and 16 can comprise ZrO_2, TiO_2, ZnS, ITO (indium tin oxide), CeO_2 or Ta_2O_3. Dielectric layers 12 and 16 can have a thickness that is greater than or equal to about 100 nm and less than or equal to about 400 nm, greater than or equal to about 150 nm and less than or equal to about 350 nm, greater than or equal to about 200 nm and less than or equal to about 300 nm, or any value in a range/sub-range defined by these values. The thickness of the dielectric layer 12 can be equal to the thickness of the dielectric layer 16. Alternately, the thickness of the dielectric layer 12 can be greater than or less than the thickness of the dielectric layer 16. The optical structure 10 can have a thickness that is less than or equal to about 2 microns.

[0173] Fabricating the optical structure 10 can include providing the layer of dielectric material 12 (or the layer of dielectric material 16) and depositing the metal layer 13 (or the metal layer 15) over the layer of dielectric material 12 (or the layer of dielectric material 16). The metal layer 13 (or the metal layer 15) can be deposited over the layer of dielectric material 12 (or the layer of dielectric material 16) using an electroless method discussed in further detail below. The metal layer 13 (or the metal layer 15) can be deposited as a continuous thin film, as small spheres, metallic clusters or island like structures. The other dielectric layer 14 can be subsequently disposed over the metal layer 13 (or the metal layer 15). The initial layer of dielectric material 12 (or the layer of dielectric material 16) can be disposed and/or formed over a support. The support is also referred to herein as a base layer. The support can comprise a carrier. The support can comprise a sheet such as a web. The support can comprise a substrate. The substrate can be a continuous sheet of PET or other polymeric web structure. The support can comprise a non-woven fabric. Non-woven fabrics can be flat, porous sheets comprising fibers. In some implementations, the non-woven fabric can be configured as a sheet or a web structure that is bonded together by entangling fiber or filaments mechanically, thermally, or chemically. In some implementations, the non-woven fabric can comprise perforated films (e.g., plastic or molten plastic films). In some implementations, the non-woven fabric can comprise synthetic fibers such as polypropylene or polyester or fiber glass.

[0174] The support can be coated with a release layer comprising a release agent. The release agent can be soluble in solvent or water. The release layer can be polyvinyl alcohol, which is water soluble or an acrylate which is soluble in a solvent. The release layer can comprise a coating, such as, for example, salt (NaCl) or cryolite (Na_3AlF_6) deposited by evaporation before the layers of the optical structure are deposited/formed.

[0175] In some implementations of the support configured as a non-woven fabric, the non-woven fabric can be coated with a release layer. Such implementations can be dipped or immersed in a solvent or water that acts as a release agent to dissolve or remove the release layer. The release agent (e.g., the solvent or water) is configured to penetrate from a side of the non-woven fabric opposite the side on which the optical structure is disposed to facilitate release of the optical structure instead of having to penetrate through the optical structure. The optical structure is recovered from the solvent or water after dissolution of the release layer. In some manufacturing approaches, the recovered optical structure can then be processed into a pigment.

[0176] In one method of fabrication, the optical structure 10 can be fabricated, for example, deposited or formed on a coated web, a coated base layer, a coated carrier or a coated substrate. The coating on the web, the base layer, the substrate or the carrier can be configured as a release layer to facilitate easy removal of the optical structure 10.

[0177] The optical structure 10 can be configured as a film or a foil by disposing over a substrate or other support layer having a thickness, for example, greater than or equal to about 10 microns and less than or equal to about 25 microns. For example, a substrate or support layer such as a polyester substrate or support layer can have a thickness greater than or equal to 12 microns and less than or equal to 22.5 microns, greater than or equal to 15 microns and less than or equal to about 20 microns. The substrate or support layer can comprise materials, such as, for example, polyethylene terphthalate (PET), acrylate, polyester, polyethylene, polypropylene, or polycarbonate. The support or support layer itself can be dissolvable. The support or support layer, for example, can also comprise polyvinyl alcohol, which can be dissolved, for example, in water. Accordingly, instead of using a release layer on a insoluble support web, the support web itself may comprise soluble material. Accordingly, the support or support layer can be dissolved leaving the optical coating remaining. The optical structure 10 configured as a film or a foil can be encapsulated with a polymer, such as, for example a UV cured polymer.

[0178] The optical structure 10 can comprises additional layers. For example, a thin protective layer may be disposed between the metal layer 13 and the dielectric layer 12 and/or between the metal layer 15 and the dielectric layer 16. The protective layer can comprise materials, such as, for example, $NiCrO_x$,Si_3N_4, $CeSnO_4$ and $ZnSnO_4$. The protective layers can have a thickness between about 3-5 nm. The protective layers can advantageously increase the durability of the metal layers 13 and 15.

[0179] Instead of a film, the optical structure, 10, may be removed from the substrate, web, carrier, or support layer on which it is fabricated and divided into platelets having a size that is suitable for a pigment or printing ink. Platelets having a size that is suitable for a pigment or printing ink can have an area, length, and/or width that is about

5-10 times the thickness of the platelet, in some implementations. Accordingly, the platelets having a thickness of about 1 micron, and/or can have a width and/or a length that is between approximately 5 micron and about 50 microns. For example, the width and/or a length can be greater than or equal to about 5 micron and less than or equal to about 15 microns, greater than or equal to about 5 microns and less than or equal to about 10 microns, greater than or equal to about 5 micron and less than or equal to about 40 microns, greater than or equal to about 5 microns and less than or equal to about 20 microns, or any value in the ranges/sub-ranges defined by these values. Platelets having a length and/or width that is less than about 5-10 times the thickness of the platelet, such as, for example having a length and/or width that is equal to the thickness of the platelet can be oriented along their edges in the printing ink or pigment. This can be disadvantageous since pigment or printing ink comprising platelets that are oriented along their edges may not exhibit the desired colors in reflection and transmission modes. Dimensions such as, thicknesses, lengths and/or widths outside these ranges are also possible.

[0180] Figure 12A-1 illustrates an example of a platelet 20. The optical structure, 10 is fractured, cut, diced or otherwise separated to obtain the separate, for example, microns sized, pieces or platelets. In some implementations, the obtained platelets may be surrounded by an encapsulating layer 21. The encapsulating layer 21 can comprise a moisture resistant material, such as, for example silicon dioxide. The encapsulating layer 21 can also comprise silica spheres 22 and 23. The silica spheres 22 and 23 can be of the same size or have different sizes. The encapsulating layer 21 can help protect the at least two metal layers 13 and 15 from corrosion. The encapsulating layer 21 can additionally and/or alternatively reduce the occurrence of delamination of the at least two metal layers 13 and 15 from the other layers of the optical structure 10. The optical structures 10 surrounded by the encapsulating layer 21, and potentially comprising the silica spheres 22 and 23, can be configured as platelets 20 that are suitable for a pigment or printing ink. The silica spheres 22 and 23 of the encapsulating layer 21 can help prevent the platelets from adhering to one another. Without the spheres the platelets may stick together like two microscope slides stick together. The spheres 22 and 23 can also prevent the platelets 20 from sticking to the print rollers in the printing machine. One method of surrounding the optical structure 10 with an encapsulating layer 21 can rely on sol-gel technology using tetraethylorthosilicate (TEOS). In one method of forming the encapsulating layer 21, an alcohol based solution of TEOS can be added in small quantities (e.g., one or more drops at a time) to a dispersion of the platelets in alcohol or water. A catalyst, such as, for example, an acid or sodium hydroxide solution can be added into the a dispersion of the platelets in alcohol or water in small quantities (e.g., one or more drops at a time). The dispersion of the platelets in alcohol or water can be heated to a temperature of about 50-70°C, while stirring to transform TEOS to a silica coating. Other processes, however, may be employed.

[0181] In some embodiments, a plurality of platelets 20 can form a pigment. Such a pigment may be color shifting (e.g., the color reflected and/or transmitted changes with angle of view or angle of incidence of light), in some cases. In some embodiments, non-color shifting pigment or dye may be mixed with the pigment. In some embodiments other materials may be included with the platelets 20 to form the pigment. Although some of the pigments discussed herein can provide color shift with change in viewing angle or angle of incidence of light, pigments that do not exhibit color shift with change in viewing angle or angle of incidence of light or that produce very little color shift with change in viewing angle or angle of incidence of light are also contemplated.

[0182] In some embodiments, the platelets 20 can be added to a medium such as a polymer 25 (e.g., a polymeric resin) to form a dichroic ink, a pigment, or paint as shown in Figure 12B-1. The platelets can be suspended in the medium (e.g., polymer) 25. The platelets can be randomly oriented in the medium (e.g., polymer) 25 as shown in Figure 12B-1. During the printing process, in some cases, the individual platelets can be oriented parallel to the surface of the object (e.g., paper) to which the pigment, the paint, or the dichroic ink is being applied as a result of, for example, the printing action, gravity, and/or surface tension of the normal drying process of the pigment, the paint, or the dichroic ink as shown in Figure 12B-2. The medium 25 can comprise material including but not limited to acrylic melamine, urethanes, polyesters, vinyl resins, acrylates, methacrylate, ABS resins, epoxies, styrenes and formulations based on alkyd resins and mixtures thereof. In some implementations, the medium 25, e.g., polymer, can have a refractive index that closely matches the refractive index of the encapsulating silica layer

21 and/or silica balls such that the encapsulating layer and/or the silica balls do not adversely affect the optical performance of the pigment, the paint, or the dichroic ink in the medium.

[0183] In various implementations, the platelets 20 need not be surrounded by an encapsulating layer. In such implementations, one or more platelets 20 that are not encapsulated by an encapsulating layer can be added or mixed with an ink or a pigment medium (e.g., varnish, polymeric resin, etc.) to obtain a dichroic ink or pigment as discussed above. In various implementations, the dichroic ink or pigment can comprise a plurality of platelets 20. The optical structures 10 that are configured as the plurality of platelets 20 can have different distributions of shapes, sizes, thicknesses and/or aspect ratios. The optical structures 10 that are configured as the plurality of platelets 20 can also have different optical properties. For example, the optical structures 10 that are configured as the plurality of platelets 20 can also have different color properties.

[0184] In some implementations, an optical structure comprising only the metal layers 13 and 15 and the transparent dielectric layer 14 without the high refractive index dielectric layers 12 and 16 as depicted in Figure 12A-2 can be configured as platelets as discussed above and dispersed in the medium 25 as shown in Figure 12B-2 to manufacture a dichroic printing ink, paint or pigment as discussed above. In some implementations, the platelets including an optical structure comprising only the metal layers 13 and 15 and the transparent dielectric layer 14 without the high refractive index dielectric layers 12 and 16 need not be encapsulated in an encapsulating layer as discussed above.

[0185] A silane coupling agent can be bonded to the encapsulating layer 21 to form a functionalized platelet 30 as shown in Figure 13. Bonding of the silane coupling agent to the encapsulating layer can occur through a hydrolyzing reaction. The silane coupling agent can bind to the polymer (e.g., polymeric resin) of the printing ink or paint medium so that the heterogeneous mixture of pigment and the polymer do not separate during the printing process and substantially function in much the same way as a homogeneous medium would function. The printing ink or paint medium can comprise material including but not limited to acrylic melamine, urethanes, polyesters, vinyl resins, acrylates, methacrylate, ABS resins, epoxies, styrenes and formulations based on alkyd resins and mixtures thereof. The silane coupling agents used can be similar to the silane coupling agents sold by Gelest Company (Morristown, PA USA). In some implementations, the silane coupling agent can comprise a hydrolyzable group, such as, for example, an alkoxy, an acyloxy, a halogen or an amine. Following a hydrolyzing reaction (e.g., hydrolysis), a reactive silanol group is formed, which can condense with other silanol groups, for example, with the silica spheres of the encapsulating layer 21 or the encapsulating layer of silica to form siloxane linkages. The other end of the silane coupling agent comprises the R-group 31. The R-group 31 can comprise various reactive compounds including but not limited to compounds with double bonds, isocyanate or amino acid moieties. Reaction of the double bond via free radical chemistry can form bonds with the ink polymer(s) such as those based on acrylates, methacrylates or polyesters based resins. For example, isocyanate functional silanes, alkanolamine functional silanes and aminosilanes can form urethane linkages.

[0186] Without any loss of generality, in various implementations of the optical structure 10 configured as a platelet that do not comprise the encapsulating layer, the silane coupling agent can be bonded to one or both of the high refractive index dielectric layers 12 and 16 comprising a dielectric material (e.g., TiO_2) suitable to be bonded with the silane coupling agent.

[0187] Without any loss of generality, the optical structure 10 can be considered as an interference stack or cavity. Ambient light incident on the surface of the optical structure 10 is partially reflected from the various layers of the optical structure 10 as shown by rays 47 and 48 in Figure 14 and partially transmitted through the various layers of the optical structure 10 as shown by ray 49 in Figure 14. Figure 14 illustrates an embodiment of an optical structure 10 comprising the high refractive index dielectric layer 12 and 16, metal layers 13 and 15 and a dielectric layer 14 encapsulated in the encapsulating layer 21. Some wavelengths of the ambient light reflected from the various layers may interfere constructively and some other wavelengths of the ambient light reflected from the various layers may interfere destructively. Similarly, some wavelengths of light transmitted through the various layers may interfere constructively and some other wavelengths of the ambient light transmitted through the various layers may interfere destructively. As a result of which, the optical structure 10 appears colored when viewed in transmission and reflection mode. In general, the color and the intensity of light reflected by and transmitted through the optical structure 10 can depend on the thickness and the material of the various layers of the optical structure 10. By changing the material and the thickness of the various layers, the color and intensity of light reflected by and transmitted through the optical structure 10 can be varied. Without subscribing to any particular scientific theory about the operation of the optical structures 10, in general, the material and the thickness of the various layers can be configured such that some or all of the ambient light reflected by the various layers interfere such that a node 45 in the field 42 occurs at the two metal layer 13 and 15. Without subscribing to any particular scientific theory, it is noted that in some cases those wavelengths that are substantially equal to the thickness of the spacer layer (e.g., wavelengths within about ±10% of the thickness of the spacer layer) will interfere such that a node 45 in the field 42 occurs at the two metal layer 13 and 15. For other wavelengths, a node 45 might not occur. Accordingly, in some implementations, the two metal layers 13 and 15 might not be visible in the reflection mode. Again, without subscribing to a particular scientific theory, based on the thickness of the two metal layers 13 and 15 and the transparent dielectric layer 14, a portion of the incident light may be transmitted through the optical structure 10 as a result of the phenomenon of "induced transmittance" or "induced transmission". The reflection and transmission spectral characteristics are discussed below.

[0188] Figure 15A shows a spectral plot in both transmission (curve 501a) and reflection (curve 503a) for a first example of the optical structure 10. The materials of the various layers of the first example of the optical structure 10 and the thickness of the various layers of the first example of the optical structure 10 are provided in Table 1 below. As indicated in Table 1, the first example of the optical structure 10 comprises two metal layers comprising silver. The two silver layers correspond to the at least two metal layer 13 and 15 of the optical structure 10 shown in Figure 11. Both the silver layers have the same thickness of 25 nm. A dielectric layer having a thickness of 300 nm is sandwiched between the two silver layers. The dielectric layer comprises SiO_2 which has a refractive index of 1.47011. The dielectric layer comprising SiO_2 corresponds to the transparent layer 14 having a low refractive index (i.e., refractive index less than

1.65). A layer of ZrO_2 is disposed on the side of each of the two silver layers that is opposite the side facing the SiO_2 layer. Each of the two layers comprising ZrO_2 has a thickness of 150 nm. As noted from Table 1 below, ZrO_2 has a refractive index of 2.27413. The two layers comprising ZrO_2 corresponds to the transparent layers 12 and 16 having a high refractive index (i.e., refractive index greater than or equal to 1.65). The first example of the optical structure 10 is encapsulated in a SiO_2 matrix as indicated in Table 1. The SiO_2 matrix is used to simulate the printing medium or ink which has a similar refractive index.

[0189] The transmission and reflection of light observed at an angle of 0 degrees with respect to a normal to the first example of the optical structure 10 is shown in Figure 15A. The reflection spectrum 503a (indicated as curve #1 in Figure 15A) and the transmission spectrum 501a (indicated as curve #0 in Figure 15A) in the spectral range between about 400 nm and about 700 nm which includes the visible spectral range were obtained using a simulation software from http://thinfilm.hansteen.net.

Parameters

Curve #0

```
#
#    Slab:
#    SIO2                        N=(1.47011      ,0)         mynkdb/SIO2.NK
#    ZRO2       d=1.5e-07        N=(2.27413      ,0)         mynkdb/ZRO2.NK
#    AG         d-2.5e-08        N=(0.173038     ,1.94942)   mynkdb/AG.NK
#    SIO2       d=3e-07          N=(1.47011      ,0)         mynkdb/SIO2.NK
#    AG         d=2.5e-08        N=(0.173038     ,1.94942)   mynkdb/AG.NK
#    ZRO2       d=1.5e-07        N=(2.27413      ,0)         mynkdb/ZRO2.NK
#    SIO2                        N=(1.47011      ,0)         mynkdb/SIO2.NK
#
#    Beam:
#    Wavelength=(4e-07,0)    Angle=0.0174533    Polarization=1    N=(1.47011,0)
#
#    Supported spectral range:  2.5e-07m – 8.5e-07m.
#    -----------------------------------------------------------------------------
#    Lambda[nm]    R[ ]
#    -----------------------------------------------------------------------------
```

Curve #1

```
#
#    Slab:
#    SIO2                        N=(1.47011      ,0)         mynkdb/SIO2.NK
#    ZRO2       d=1.5e-07        N=(2.27413      ,0)         mynkdb/ZRO2.NK
#    AG         d=2.5e-08        N=(0.173038     ,1.94942)   mynkdb/AG.NK
#    SIO2       d=3e-07          N=(1.47011      ,0)         mynkdb/SIO2.NK
#    AG         d=2.5e-08        N=(0.173038     ,1.94942)   mynkdb/AG.NK
#    ZRO2       d=1.5e-07        N=(2.27413      ,0)         mynkdb/ZRO2.NK
#    SIO2                        N=(1.47011      ,0)         mynkdb/SIO2.NK
#
#    Beam:
#    Wavelength=(4e-07,0)    Angle=0.0174533    Polarization=1    N=(1.47011,0)
#
#    Supported spectral range:  2.5e-07m – 8.5e-07m.
#    -----------------------------------------------------------------------------
#    Lambda[nm]    T[ ]
#    -----------------------------------------------------------------------------
```

Table 1: Parameters of a first example of the optical structure that has the reflection and transmission spectra as shown in Figure 15A.

[0190] It can be seen from Figure 15A that the transmission curve 501a (curve#0) has a peak with a maximum value occurring at a wavelength of about 520 nm and the reflection curve 503a has two peaks with a first maximum value occurring at a wavelength of 420 nm and a second maximum value occurring at a wavelength of about 650 nm. The maximum value of the transmission and reflection peaks is greater than 0.5 which indicates that the transmission and reflection peaks have high intensities.

Furthermore, the transmission and reflection peaks have a bandwidth as measured at 50% of the maximum value of the peak greater than about 20 nm. The bandwidth as measured at 50% of the maximum value of the peak is referred to as full width at half maximum (FWHM). It is observed from Figure 15A that the FWHM of the transmission peak is about 75 nm.

[0191] Based on the position of the transmission and reflection peaks and the bandwidth of the transmission and reflection peaks, the optical structure 10 can be perceived as having a first color in the reflection mode and a second color in the transmission mode by an average human eye. In some cases, the first color and the second color can be complimentary colors. In some cases, the transmission and reflection peaks comprising a range of wavelengths of the visible spectral range can have a high intensity and a FWHM greater than 2 nm (e.g., FWHM greater than or equal to about 10 nm, FWHM greater than or equal to about 20 nm, FWHM greater than or equal to about 30 nm, FWHM greater than or equal to about 40 nm, FWHM greater than or equal to about 50 nm, FWHM greater than or equal to about 60 nm, FWHM greater than or equal to about 70 nm, FWHM greater than or equal to about 100 nm, FWHM greater than or equal to about 200 nm, FWHM less than or equal to about 300 nm, FWHM less than or equal to about 250 nm, or any value in a range/sub-range defined by these values).

[0192] The one or more reflection peaks can be considered to have a high intensity if the reflectivity or reflectance of the peak in a range of visible wavelengths is greater than or equal to about 50% and less than or equal to about 100%. For example, the one or more reflection peaks can be considered to have a high intensity if the amount of light reflected or reflectivity or reflectance in a range of visible wavelengths is greater than or equal to about 55% and less than or equal to about 99%, greater than or equal to about 60% and less than or equal to about 95%, greater than or equal to about 70% and less than or equal to about 90%, greater than or equal to about 75% and less than or equal to about 85%, or any value in a range/sub-range defined by these values.

[0193] The one or more transmission peaks can be considered to have a high intensity if the transmissivity or transmittance of the peak in a range of visible wavelengths is greater than or equal to about 50% and less than or equal to about 100%.

For example, the one or more transmission peaks can be considered to have a high intensity if the amount of light transmitted or transmissivity or transmittance in a range of visible wavelengths is greater than or equal to about 55% and less than or equal to about 99%, greater than or equal to about 60% and less than or equal to about 95%, greater than or equal to about 70% and less than or equal to about 90%, greater than or equal to about 75% and less than or equal to about 85%, or any value in a range/sub-range defined by these values.

[0194] The first example of the optical structure 10 having a design as depicted in Table 1 and having a reflection spectrum and a transmission spectrum as shown in Figure 15A appears green in transmission mode and as magenta in reflection mode to an average human eye. Without any loss of generality, it can be advantageous, in various implementations, for the peaks in the reflection and transmission spectra to be non-overlapping as shown in Figures 15A and 15B such that a reflection peak having a highest possible reflectance or reflectivity can be obtained in one region of the visible spectral range and a transmission peak having a highest possible transmittance or transmissivity can be obtained in a non-overlapping region of the visible spectral range. Accordingly, the reflected color and the transmitted color can be different and potentially complementary to each other, such as, for example, red and green, yellow and violet, blue and orange, green and magenta, etc.

[0195] The shape of the transmission and reflection peaks, the position of the maximum of the transmission and reflection peaks, the FWHM of the transmission and reflection peaks, etc. can be varied by varying the materials and/or thickness of the various layers of the optical structure 10. This can be observed from Figure 15B which depicts the reflection spectrum 503b and transmission spectrum 501b of a second example of the optical structure 10 which has the same material composition as the first example of the optical structure 10 but different thickness for the various layers. The parameters of the second example of the optical structure 10 are provided in Table 2 below. As noted from Table 2, the thickness of the dielectric layer comprising SiO_2 and having a refractive index of 1.47011 in the second example of the optical structure 10 is 400 nm instead of 300 nm in the first example of the optical structure 10. Furthermore, the thickness of the two ZrO_2 disposed on either side of each of the two silver layers is

225 nm in the second example of the optical structure 10 instead of 150 nm in the first example of the optical structure 10.

Parameters

Curve #0

```
#
#   Slab:
#   SIO2                         N=(1.47011     ,0)          mynkdb/SIO2.NK
#   ZRO2        d=2.25e-07       N=(2.27413     ,0)          mynkdb/ZRO2.NK
#   AG          d=2.5e-08        N=(0.173038    ,1.94942)    mynkdb/AG.NK
#   SIO2        d=4e-07          N=(1.47011     ,0)          mynkdb/SIO2.NK
#   AG          d=2.5e-08        N=(0.173038    ,1.94942)    mynkdb/AG.NK
#   ZRO2        d=2.25e-07       N=(2.27413     ,0)          mynkdb/ZRO2.NK
#   SIO2                         N=(1.47011     ,0)          mynkdb/SIO2.NK
#
#   Beam:
#   Wavelength=(4e-07,0)   Angle=0.0174533   Polarization=1   N=(1.47011,0)
#
#   Supported spectral range:  2.5e-07m – 8.5e-07m.
#   ------------------------------------------------------------------------------
#   Lambda[nm]   R[ ]
#   ------------------------------------------------------------------------------
```

Curve #1

```
#
#   Slab:
#   SIO2                         N=(1.47011     ,0)          mynkdb/SIO2.NK
#   ZRO2        d=2.25e-07       N=(2.27413     ,0)          mynkdb/ZRO2.NK
#   AG          d=2.5e-08        N=(0.173038    ,1.94942)    mynkdb/AG.NK
#   SIO2        d=4e-07          N=(1.47011     ,0)          mynkdb/SIO2.NK
#   AG          d=2.5e-08        N=(0.173038    ,1.94942)    mynkdb/AG.NK
#   ZRO2        d=2.25e-07       N=(2.27413     ,0)          mynkdb/ZRO2.NK
#   SIO2                         N=(1.47011     ,0)          mynkdb/SIO2.NK
#
#   Beam:
#   Wavelength=(4e-07,0)   Angle=0.0174533   Polarization=1   N=(1.47011,0)
#
#   Supported spectral range:  2.5e-07m – 8.5e-07m.
#   ------------------------------------------------------------------------------
#   Lambda[nm]   T[ ]
#   ------------------------------------------------------------------------------
```

Table 2: Parameters of a second example of the optical structure that has the reflection and transmission spectra as shown in Figure 15B.

[0196] As a result of the change in the thickness of the dielectric layers comprising SiO_2 and ZrO_2 between the second example of the optical structure and the first example of the optical structure, an average eye would perceive the second example of the optical structure to appear green in reflection mode and a magenta in transmission mode when viewed along a direction normal to the surface of the second example of the optical structure.

[0197] The color of the first example and the second example of the optical structure 10 as perceived by the average human eye in reflection mode and transmission mode can shift from the above described magenta and green colors at different viewing angles with respect to the normal to the surface of the first example and the second example of the optical structure 10. For example, the first example of the optical structure 10 can appear yellowish green in reflection mode and blue in transmission mode when viewed at an angle of about 35 degrees with respect to the normal to the surface of the first example of the optical structure 10. As another example, the second example of the optical structure 10 can appear pale purple in reflection mode and yellowish in transmission mode when viewed at an angle of about 35 degrees with respect to the normal to the surface of the second example of the optical structure 10. Without any loss of generality, the reflection and the transmission peaks can exhibit a blue shift towards shorter wavelengths as the viewing angle with respect to the normal to the surface of the first example and the second example of the optical structure 10 increases.

Incident Angle	L*	a*	b*
0.0	66.0433	-91.9989	11.4335
5.0	65.5578	-91.5328	9.3070
10.0	64.0035	-89.0283	2.6936
15.0	61.1497	-81.1844	-8.9303
20.0	56.8304	-63.3282	-25.7758
25.0	51.2146	-32.8229	-46.6651
30.0	44.8902	5.7777	-67.7337
35.0	38.6590	39.5335	-81.9630
40.0	33.4474	53.5162	-81.6652
45.0	30.4059	43.0007	-64.1869

Design: First Example of the Optical Structure
Polarization: P
Source: D65
Observer: CIE 1931
Mode: Transmittance

Table 3: CIELab values for transmission mode when the first example of the optical structure having parameters as described in Table 1 is viewed at different viewing angles in the presence of a D65 light source.

Incident Angle	L*	a*	b*
0.0	79.2753	51.6407	-11.0765
5.0	79.6541	50.6966	-9.6957
10.0	80.8290	47.4222	-5.3025
15.0	82.8379	40.8204	2.7687
20.0	85.5358	30.2258	15.3945
25.0	88.5026	16.2157	33.3659
30.0	91.2316	1.0176	55.5312
35.0	93.4068	-11.0169	70.1468
40.0	94.9289	-14.7597	57.7563
45.0	95.7892	-10.6419	32.4479

Design: First Example of the Optical Structure
Polarisation: P
Source : D65
Observer : CIE 1931
Mode :Reflectance

Table 4: CIELab values for reflection mode when the first example of the optical structure having parameters as described in Table 1 is viewed at different viewing angles in the presence of a D65 light source.

[0198] Tables 3 and 4 above provide the CIELa*b* values for transmission mode and reflection mode respectively when the first example of the optical structure having parameters as described in Table 1 is viewed at different viewing angles in the presence of a D65 light source. Tables 5 and 6 below provide the CIELa*b* values for transmission mode and reflection mode respectively when the second example of the optical structure having parameters as described in Table 2 is viewed at different viewing angles in the presence of a D65 light source. The CIELab color closely represent the colors perceived by an average human eye. The CIELab color space mathematically describe various colors perceived by an average human eye in the three dimensions L for lightness, a for the color component green–red, and b for the color component from blue–yellow. The a-axis extends longitudinally in a plane from green (represented by -a) to red (represented by +a). The b-axis extends along a transverse direction in the plane perpendicular to the a-axis from blue (represented by -b) to yellow (represented by +b). The brightness is represented by the L-axis which is perpendicular to the a-b plane. The brightness increases from black represented by L=0 to white represented by L=100. The CIELab values for different viewing angles using a D65 illuminant were calculated using Essential Macleod Thin Film Software.

Incident Angle	L*	a*	b*
0.0	35.3624	87.7761	-73.0966
5.0	35.9375	88.1214	-71.4170
10.0	37.8504	88.3232	-65.5105
15.0	41.5481	86.2320	-53.1339
20.0	47.3489	79.0290	-32.0276
25.0	54.8227	62.6584	-2.6495
30.0	62.6567	31.6730	29.2861
35.0	68.8117	-13.6155	53.1104
40.0	70.1939	-60.8762	56.3246
45.0	63.8734	-83.2865	29.4710

Design: Second Example of the Optical Structure
Polarization: P
Source: D65
Observer: CIE 1931
Mode: Transmittance

Table 5: CIELab values for transmission mode when the second example of the optical structure having parameters as described in Table 2 is viewed at different viewing angles in the presence of a D65 light source.

Incident Angle	L*	a*	b*
0.0	95.0631	-31.7647	48.4548
5.0	94.9402	-32.7902	47.4892
10.0	94.5010	-35.8118	43.8268
15.0	93.5195	-40.5801	35.7606
20.0	91.6012	-45.9635	22.4005
25.0	88.3120	-46.8681	5.3389
30.0	83.5384	-31.2961	-12.0407
35.0	78.2978	5.6475	-26.1375
40.0	76.3297	41.2278	-30.5320
45.0	81.1875	43.5513	-17.6926

Design: Second Example of the Optical Structure
Polarisation: P
Source: D65
Observer : CIE 1931
Mode: Reflectance

Table 6: CIELab values for reflection mode when the second example of the optical structure having parameters as described in Table 2 is viewed at different viewing angles in the presence of a D65 light source.

[0199] The optical performance of two additional examples of optical structures having parameters provided in Tables 7 and 8 were analyzed. The additional examples of optical structures were designed using Essential Macleod Thin Film Software. The material composition and the thickness of the various layers for the third example of the optical structure are provided in Table 7 and the material composition and the thickness of the various layers for the fourth example of the optical structure are provided in Table 8.

Layer		Material	Refractive Index	Extinction Coefficient	Optical Physical Thickness (Full Wavelength Optical Thickness)	Thickness (nm)
	SiO2		1.46180	0.00000		
1	ZrO2	1.00000	2.06577	0.00004	1.00000000	246.88
2	Ag	1.00000	0.05100	2.96000	0.00250000	25.00
3	SiO2	1.00000	1.46180	0.00000	0.50000000	174.44
4	Ag	1.00000	0.05100	2.96000	0.00250000	25.00
5	ZrO2	1.00000	2.06577	0.00004	1.00000000	246.88
Substrate		Glass	1.52083	0.00000		
Total Thickness					2.50500000	718.21

Table 7: Material Composition and thickness of the various layers of the third example of the optical structure 10.

	Medium	Material	Refractive Index	Extinction Coefficient	Optical Physical Thickness (Full Wavelength Optical Thickness)	Thickness (nm)
		SiO2	1.46180	0.00000		
1	ZrO2	1.00000	2.06577	0.00004	0.50000000	123.44
2	Ag	1.00000	0.05100	2.96000	0.00250000	25.00
3	SiO2	1.00000	1.46180	0.00000	0.75000000	261.66
4	Ag	1.00000	0.05100	2.96000	0.00250000	25.00
5	ZrO2	1.00000	2.06577	0.00004	0.50000000	123.44
Substrate		Glass	1.52083	0.00000		
Total Thickness					1.75500000	558.55

Table 8: Material Composition and thickness of the various layers of the fourth example of the optical structure 10.

[0200] The material composition of the various layers of the third and the fourth example of the optical structure 10 is the same as the material composition of the various layers of the first and the second example of the optical structure 10. For example, similar to the first and the second example of the optical structure 10, the third and the fourth examples of the optical structure 10 comprise a SiO_2 layer sandwiched by two silver layers with ZrO_2 layers disposed on the side of the two silver layers opposite the side facing the SiO_2 layer. However, the thickness of the various layers is different for each of the first, second, third and fourth examples of the optical structure 10.

[0201] The third example of the optical structure 10 comprises two silver layers having a thickness of 25 nm each sandwiching a dielectric layer having a thickness of 174.44 nm and comprising SiO_2. The third example of the optical structure 10 comprises a layer of ZrO_2 on the side of the silver layers opposite the side facing the SiO_2 layer. Each ZrO_2 layer has a thickness of 246.88 nm. The total thickness of the third example of the optical structure 10 is 718.21 nm.

[0202] The fourth example of the optical structure 10 comprises two silver layers having a thickness of 25 nm each sandwiching a dielectric layer having a thickness of 261.66 nm and comprising SiO_2. The fourth example of the optical structure 10 comprises a layer of ZrO_2 on the side of the silver layers opposite the side facing the SiO_2 layer. Each ZrO_2 layer has a thickness of 123.44 nm. The total thickness of the fourth example of the optical structure 10 is 558.55 nm.

[0203] Figure 16A illustrates the a*b* values in the CIELa*b* color space for the first example of the optical structure 10 having parameters as described in Table 1 for different viewing angles between 0 degrees and 45 degrees with respect to the normal to the surface of the first example of the optical structure 10 in reflection mode. It is observed from Figure 16A that at a viewing angle of 0 degrees with respect to the normal to the surface of the first example of the optical structure 10, the first example of the optical structure 10 appears magenta to an average human eye in reflection mode. As the viewing angle increases the color reflected by the first example of the optical structure 10 shifts along the curve 601a in the direction of the arrow towards yellow.

[0204] Figure 16B illustrates the a*b* values in the CIELa*b* color space for the second example of the optical structure 10 having parameters as described in Table 2 for different viewing angles between 0 degrees and 45 degrees with respect to the normal to the surface of the second example of the optical structure 10 in reflection mode. It is observed from Figure 16B that at a viewing angle of 0 degrees with respect to the normal to the surface of the second example of the optical structure 10, the second example of the optical structure 10 appears yellowish green to an average human eye in reflection mode. As the viewing angle increases the color reflected by the second example of the optical structure 10 shifts along the curve 601b in the direction of the arrow towards magenta.

[0205] Figure 16C illustrates the a*b* values in the CIELa*b* color space for the third example of the optical structure 10 having parameters as described in Table7 for different viewing angles between 0 degrees and 45 degrees with respect to the normal to the surface of the third example of the optical structure 10 in reflection mode. It is observed from Figure 16C that at a viewing angle of 0 degrees with respect to the normal to the surface of the third example of the optical structure 10, the third example of the optical structure 10 appears green to an average human eye in reflection mode. As the viewing angle increases the color reflected by the third example of the optical structure 10 shifts along the curve 601c in the direction of the arrow towards blue at 35°. The transmission color moves from red to orange as the viewing angle increases to 35°. It is noted that the various reflection and transmission color curves move counterclockwise in the various a* b* plots of Figures 16A-16D and 17A-17D.

[0206] Figure 16D illustrates the a*b* values in the CIELa*b* color space for the fourth example of the optical structure 10 having parameters as described in Table 8 for different viewing angles between 0 degrees and 45 degrees with respect to the normal to the surface of the fourth example of the optical structure 10 in reflection mode. It is observed from Figure 16D that at a viewing angle of 0 degrees with respect to the normal to the surface of the fourth example of the optical structure 10, the fourth example of the optical structure 10 appears yellow to an average human eye in reflection mode. As the viewing angle increases the color reflected by the fourth example of the optical structure 10 shifts along the curve 601d in the direction of the arrow towards grey. In transmission the color seen at zero degrees is blue moving to magenta at 35°. This sample is configured as a dichroic film/pigment that has a very small color shift as the angle of view changes.

[0207] Figure 17A illustrates the a*b* values in the CIELa*b* color space for the first example of the optical structure 10 having parameters as described in Table 1 for different viewing angles between 0 degrees and 45 degrees with respect to the normal to the surface of the first example of the optical structure 10 in transmission mode. It is observed from Figure 17A that at a viewing angle of 0 degrees with respect to the normal to the surface of the first example of the optical structure 10, the first example of the optical structure 10 appears green to an average human eye in transmission mode. As the viewing angle increases the color transmitted by the first example of the optical structure 10 shifts along the curve 701a in the direction of the arrow towards violet.

[0208] Figure 17B illustrates the a*b* values in the CIELa*b* color space for the second example of the optical structure 10 having parameters as described in Table 2 for different viewing angles between 0 degrees and 45 degrees with respect to the normal to the surface of the second example of the optical structure 10 in transmission mode. It is observed from Figure 17B that at a viewing angle of 0 degrees with respect to the normal to the surface of the second example of the optical structure 10, the second example of the optical structure 10 appears purple to an average human eye in transmission mode. As the viewing angle increases the color reflected by the second example of the optical structure 10 shifts along the curve 701b in the direction of the arrow towards green.

[0209] Figure 17C illustrates the a*b* values in the CIELa*b* color space for the third example of the optical structure 10 having parameters as described in Table 7 for different viewing angles between 0 degrees and 45 degrees with respect to the normal to the surface of the third example of the optical structure 10 in transmission mode. It is observed from Figure 17C that at a viewing angle of 0 degrees with respect to the normal to the surface of the third example of the optical structure 10, the third example of the optical structure 10 appears red to an average human eye in transmission mode. As the viewing angle increases the color reflected by the third example of the optical structure 10 shifts along the curve 701c in the direction of the arrow towards orange.

[0210] Figure 17D illustrates the a*b* values in the CIELa*b* color space for the fourth example of the optical structure 10 having parameters as described in Table 8 for different viewing angles between 0 degrees and 45 degrees with respect to the normal to the surface of the fourth example of the optical structure 10 in transmission mode. It is observed from Figure 17D that at a viewing angle of 0 degrees with respect to the normal to the surface of the fourth example of the optical structure 10, the fourth example of the optical structure 10 appears blue to an average human eye in transmission mode. As the viewing angle increases the color reflected by the fourth example of the optical structure 10 shifts along the curve 701d in the direction of the arrow towards magenta.

[0211] The optical structures 10 are considered to be illuminated by D65 illumination for generating the curves of Figures 16A-16D and 17A-17D.

[0212] Figures 18A and 18B respectively illustrate the transmittance and reflectance spectra for the third example of the optical structure 10 having parameters as described in Table 7. As noted, from Figures 18A and 18B, the third example of the optical structure 10 has a peak transmittance at about 650 nm while the reflectance is substantially uniform in the spectral region between about 400 nm and about 600 nm and a dip around 650 nm.

[0213] Figures 18C and 18D respectively illustrate the transmittance and reflectance spectrum for the fourth example of the optical structure 10 having parameters as described in Table 8. As noted, from Figures 18C and 18D, the fourth example of the optical structure 10 has a peak transmittance between about 470 nm and about 480 nm while the reflectance is substantially uniform in the spectral region between about 520 nm and about 700 nm and a dip around 470 nm.

[0214] The optical performance of an additional fifth example of the optical structure 10 are analyzed. The fifth example of the optical structure 10 comprised a glass substrate, a first dielectric layer comprising CeO_2 over the substrate, a first metal layer comprising aluminum over the first dielectric layer, a second dielectric layer comprising CeO_2 over the first metal layer, a second metal layer comprising aluminum over the second dielectric layer, and a third dielectric layer comprising CeO_2 over the second metal layer. The thickness of various metal and dielectric layers can be configured to appear blue/violet in transmission at a viewing angle between about 0 degrees and about 40 degrees with respect to a normal to the surface of the fifth example of the optical structure 10 and yellow/green in reflection at viewing angles between 0 degrees and about 40 degrees with respect to a normal to the surface of the fifth example of the optical structure 10.

[0215] Figures 18E and 18F respectively illustrate the transmittance and reflectance spectrum for the fifth example of the optical structure 10 discussed above. Figure 18G illustrates the a*b* values in the CIELa*b* color space for the fifth example of the optical structure 10 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fourth example of the optical structure 10 in transmission mode. It is observed from Figure 18G that at a viewing angle of 0 degrees with respect to the normal to the surface of the fifth example of the optical structure 10, the fifth example of the optical structure 10 appears blue to an average human eye in transmission mode. As the viewing angle increases the color reflected by the fifth example of the optical structure 10 shifts along the curve 751a in the direction of the arrow towards violet.

[0216] Figure 18H illustrates the a*b* values in the CIELa*b* color space for the fifth example of the optical structure 10 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fifth example of the optical structure 10 in reflection mode. It is observed from Figure 18H that at a viewing angle of 0 degrees with respect to the normal to the surface of the fifth example of the optical structure 10, the fifth example of the optical structure 10 appears yellow to an average human eye in reflection mode. As the viewing angle increases the color reflected by the fifth example of the optical structure 10 shifts along the curve 751b in the direction of the arrow towards green.

[0217] Various implementations of an optical structure that can be used as a security feature can comprise a dielectric region comprising one or more dielectric materials surrounded by a partially optically transmissive or partially reflective metal layer (e.g., partially reflective and partially transmissive metal layer). For example, the optical structure can comprise a dielectric region having first and second major surfaces (e.g., top and bottom) and edges (or sides) therebetween. The partially reflective and partially transmissive metal layer can be disposed on the edges (or sides) in addition to being disposed on the first and second major surfaces (e.g., top and bottom). In various implementations, the dielectric region comprising the one or more dielectric materials is optical transmissive and in some configurations may be optically transparent. In certain implementations, the region comprising the one or more dielectric materials is surrounded by a partially optically transmissive and partially reflective metal layer. In various implementations, the one or more dielectric materials can comprise polymer, glass, oxides (e.g., SiO_2, TiO_2) or other dielectric materials. In various implementations, the dielectric region can comprise a dielectric substrate coated with a one or more dielectric materials (e.g., layers) having a refractive index equal to, less than or greater than the refractive index of the dielectric substrate. In various implementations, the dielectric region can comprise a first dielectric material (e.g., first dielectric layer) having a first refractive index surrounded by a second dielectric material (e.g., second dielectric layer) having a second refractive index. The second refractive index can be equal to, less than or greater than the first refractive index.

[0218] Figures 19A and 19B illustrate different embodiments of such optical structures. Figure 19A schematically illustrates a cross-sectional view of an embodiment of an optical structure 70a comprising a dielectric region 30a surrounded by a partially reflective and partially transmissive metal layer 35a. The optical structure 70a shown in Figure 19A has a rectilinear (e.g., rectangular) cross-section. Figure 19B schematically illustrates a cross-sectional view of another embodiment of an optical structure 70b comprising a dielectric region 30b surrounded by a partially reflective and partially transmissive metal layer 35b. The optical structure 70b shown in Figure 19B has a circular cross-section.

[0219] The dielectric region 30a and/or 30b can comprise one or more dielectric materials such as, for example, polymer, magnesium fluoride, silicon dioxide, aluminum oxide, titanium oxide, cerium oxide, any transparent oxide material, any transparent nitride material, any transparent sulfide material, glass, combinations of any of these materials or any other inorganic or organic material. The refractive index of the one or more dielectric materials in the dielectric region 30a and/or 30b can have a value between about 1.35 and about 2.5. For example, the refractive index of the one or more dielectric materials in the dielectric region 30a and/or 30b can have a value between about 1.38 and 1.48, between about 1.48 and about 1.58, between about 1.58 and about 1.78, between about 1.75 and about 2.0, between about 2.0 and about 2.25, between about 2.25 and about 2.5, or any value in any range/sub-range defined by these values. Values outside these ranges are also possible, in some implementations. The dielectric region 30a and/or 30b can comprise a dielectric substrate coated with a one or more dielectric materials having a refractive index equal to, less than or greater than the refractive index of the dielectric substrate. In various implementations, the dielectric region 30a and/or 30b can comprise a first dielectric material having a first refractive index surrounded by a second dielectric material having a second refractive index. The second refractive index can be equal to, less than or greater than the first refractive index.

[0220] In various implementations, the dielectric region 30a and/or 30b can be configured as a slab, flake, a sphere, spheroid, ellipsoid, disc, or any other 3-dimensional shape enclosing a volume. The dielectric region 30a and/or 30b may have a regular or irregular shape. For example, as shown in Figure 19A, the dielectric region 30a can be configured as a slab having two major surfaces 31a and 31b and one or more edge surfaces disposed between the two major surfaces 31a and 31b. In some implementations, a number of edges surfaces may be disposed between the two major surfaces 31a and 31b. The number of edge surfaces may, for example, be one, two, three, four, five, six, seven, eight, nine, ten, twelve, twenty, thirty, fifty, etc. or in any range between any of these values. Values outside these ranges are also possible. The major surfaces 31a and 31b can have a variety of shapes. For example, one or both of the major surfaces 31a and 31b can have a rectilinear or curvilinear shape in certain implementations. The shape may be regular or irregular in certain implementations. For example, one or both of the major surfaces 31a and 31b can have a square shape, a rectangular shape, a circular shape, an oval shape, an elliptical shape, pentagonal shape, a hexagonal shape, an octagonal shape or any polygonal shape. In various implementations, one or both of the major surface 31a and 31b can have jagged edges such that the lateral dimensions (e.g., length or width) of the one or both of the major surface 31a and 31b varies across the area of the one or both of the major surface 31a and 31b. Other configurations are also possible. Additionally, other shapes are also possible. One or more of the edge surfaces can have a variety of shapes (e.g., as viewed from the side), such as, for example, a square shape, a rectangular shape, an oval shape, an elliptical shape, a pentagonal shape, a hexagonal shape, an octagonal shape or any a polygonal shape.

[0221] The shape of the one or more of the edge surfaces (e.g., as viewed from the side) can be rectilinear or curvilinear in certain implementations. The shape may be regular or irregular in certain implementations. Similarly, the cross-section through the dielectric region 30a and/or 30b parallel to one of the major surfaces 31a and 31b, can be rectilinear or curvilinear in certain implementations and can be regular or irregular in certain implementations. For example, the cross-section can have a square shape, a rectangular shape, a circular shape, an oval shape, an elliptical shape, pentagonal shape, a hexagonal shape, an octagonal shape or any a polygonal shape. Other shapes are also possible. Likewise, the cross-section through the dielectric material or region 30a and/or 30b perpendicular to one of the surfaces 31a and 31b, can be rectilinear or curvilinear in certain implementations and can be regular or irregular implementations. For example, the cross-section can have a square shape, a rectangular shape, a circular shape, an oval shape, an elliptical shape, pentagonal shape, a hexagonal shape, an octagonal shape or any a polygonal shape. Other shapes are also possible. In various implementations, an area, a length and/or a width of the major surfaces 31a and 31b of the dielectric region 30a can be greater than or equal to about 2, 3, 4, 5, 6, 8, or 10 times the thickness of the dielectric region 30a and less than or equal to about 50 times the thickness of the dielectric region 30a, or any value in a range/sub-range between any of these values. Accordingly, the dielectric region 30a can have a large aspect ratio.

[0222] In some implementations, a thickness (T) of the dielectric region 30a can correspond to the distance between the two major surfaces 31a and 31b along a vertical direction as shown in Figure 19A. As another example, as shown in Figure 19B, the dielectric material 30b can be configured as a sphere. A thickness of the dielectric material 30b configured as a sphere can correspond to the diameter of the sphere. In other implementations, the dielectric material 30a and/or 30b can be configured as a cube, a rectangular cuboid, a cylinder, an ellipsoid, an ovoid or any other three-dimensional shape. The shape may be curvilinear or rectilinear in certain implementations. The shape may be regular or irregular in certain implementations. Accordingly, in some implementations, the dielectric region 30a and/or 30b can be configured as an irregularly shaped object enclosing a volume of one or more dielectric materials.

[0223] In various implementations, light can be transmitted through the optical structure 70a or 70b and reflected by surfaces of the optical structure 70a or 70b. Moreover, in various implementations, the dielectric region 30a and/or 30b can have a thickness that allows light incident on one side of the metal layer 35a and/or 35b to constructively or destructively interfere. For example, in various implementations, the thickness of the dielectric region 30a and/or 30b can be approximately a quarter wavelength of light (e.g., visible light) incident thereon or an integer multiple of a quarter wavelength. In various implementations, the thickness of the dielectric region 30a and/or 30b may be, for example, 1/4, 3/4, 5/4, 7/4, 9/4, 10/4, etc. of the wavelength of visible light incident on the dielectric material 30a or 30b. As a result various wavelengths of incident light can constructively or destructively interfere as it is transmitted through the optical structure 70a or 70b or reflected by the optical structure 70a or 70b. Accordingly, in some configurations, color light is reflected by and/or transmitted through the optical structure when white light is incident thereon. In some implementations, a first color is reflected and a second different color is transmitted when white light is incident on the optical structure. In some case, the first color and the second color can be complementary.

[0224] In various implementations, for example, to obtain constructive interference of incident visible light, a thickness (or lateral dimension) of the dielectric region 30a and/or 30b can have a value between about 90 nm and about 2 microns. In various implementations, a thickness (or lateral dimension) of the dielectric region 30a and/or 30b can be greater than or equal to about 90 nm and less than or equal to about 1 microns, greater than or equal to about 100 nm and less than or equal to about 1.0 microns, greater than or equal to about 300 nm and less than or equal to about 1.0 microns, greater than or equal to about 400 nm and less than or equal to about 900 nm, greater than or equal to about 500 nm and less than or equal to about 800 nm, greater than or equal to about 600 nm and less than or equal to about 700 nm, or any thickness in any range/sub-range defined by these values. Values outside these ranges are also possible, in some implementations.

[0225] The dielectric material 30a and/or 30b can be purchased from various suppliers (e.g., Tyndall Institute, Glassflake, Ltd., Sigma Technologies) or custom made by synthesizing in a laboratory or a manufacturing facility. In some implementations, the optical structure 70a (or 70b) and/or the dielectric region 30a (or 30b) can comprise flakes (e.g., glass flakes available from Glassflake, Ltd. http://www.glassflake.com/pages/home). In some implementations, the flakes can comprise glass such as, for example, borosilicate flakes having an average thickness between about 90 nm and about 2 microns (e.g., an average thickness of about 1.2 microns) that may or may not be coated with coatings (e.g., high refractive index metal oxides such as TiO_2 and/or silica). In various implementations, lateral dimensions (e.g., length and a width) of the flakes can be between about 5 microns and about 20 microns. Values outside these ranges are also possible, in some implementations.

[0226] As discussed above, the dielectric region 30a or 30b can be surrounded by a partially reflective and a partially transmissive metal layer 35a or 35b. In some implementations, the metal layer 35a or 35b can comprise a metal having a ratio of the real part (n) of the refractive index to the imaginary part (k) of the refractive index (k) that is less than 1 as discussed above. For example, the metal layer 35a or 35b can comprise metals that have an n/k value between about 0.01 and about 0.6, between about 0.015 and about 0.6, between about 0.01 and about 0.5, between about 0.01 and about 0.2, between about 0.01 and about 0.1, or any value in a range or sub-range defined by these values. Values outside these ranges are also possible, in some implementations. Accordingly, the metal layer 35a or 35b can comprise silver, silver alloys, gold, aluminum or copper and their respective alloys, nickel (Ni) and palladium (Pd).

[0227] In various implementations, a thickness of the metal layer 35a or 35b can be configured such that the metal layer 35a or 35b is at least partially transmissive and partially reflective to light in the visible spectral region between about 400 nm and about 800 nm. For example, the thickness of the metal layer 35 can be configured such that the metal layer 35a or 35b is at least partially transmissive to light in a wavelength range between about 400 nm and about 500 nm, between about 430 nm and about 520 nm, between about 450 nm and about 530 nm, between about 520 nm and about 550 nm, between about 540 nm and about 580 nm, between about 550 nm and about 600 nm, between about 600 nm and about 680 nm, between about 630 nm and about 750 nm, or any wavelength in a range/sub-range defined by any of these values. Values outside these ranges are also possible, in some implementations. Alternatively or in addition, the thickness of the metal layer 35a or 35b can be configured such that the metal layer 35a or 35b is at least partially reflective to light in a wavelength range between about 400 nm and about 500 nm, between about 430 nm and about 520 nm, between about 450 nm and about 530 nm, between about 520 nm and about 550 nm, between about 540 nm and about 580 nm, between about 550 nm and about 600 nm, between about 600 nm and about 680 nm, between about 630 nm and about 750 nm, or any wavelength in a range/sub-range defined by any of these values. Values outside these ranges are also possible, in some implementations.

[0228] The thickness of the metal layer 35a or 35b can vary depending on the type of metal. For example, in implementations of the optical structure 70a or 70b comprising a metal (e.g., silver) layer 35a or 35b, the thickness of the metal (e.g., silver) layer 35a or 35b can be greater than or equal to about 10 nm and less than or equal to about 35 nm such that the metal (e.g., silver) layer 35a or 35b can be partially transmissive to light in the visible spectral range. In some implementations, the thickness of the metal layer 35a or 35b can be less than about 10 nm or greater than about 35 nm depending possibly on the type of metal used and the wavelength range in which transmissivity or transmittance is desired. Accordingly, in various implementations, the metal layer 35a or 35b can have a thickness greater than or equal to about 3 nm and less than or equal to about 40 nm. Values outside these ranges are also possible, in some implementations. As discussed above, with reference to Figure 14, the thickness of the metal layer 35a or 35b and the dielectric region 30a or 30b can be configured such that interference of some or all of the incident light reflected by the metal layer 35a or 35b and the one or more layers of the dielectric region 30a or 30b can produce a node at or in the metal layer 35a or 35b. Accordingly, the transmittance through the metal layer 35a or 35b can be greater than the transmittance expected for a certain thickness of the metal layer 35a or 35b. Without subscribing to any particular scientific theory, this effect is known as induced transmittance. As a result of induced transmittance or induced transmission, the optical structure 70a or 70b may in some implementation, be configured to exhibit a first color in reflection mode and a second color in transmission mode.

[0229] Depending on the shape of the dielectric region 30a or 30b, the dielectric region 30a or 30b can have one or more outer surfaces. The metal layer 35a or 35b can cover or substantially cover all the outer surfaces of the dielectric region 30a or 30b or a fraction thereof. Accordingly, in various implementations, the metal layer 35a or 35b can be disposed over at least 50% of the one or more outer surfaces of the dielectric region 30a or 30b. For example, metal layer 35a or 35b can be disposed over at least 50%, over at least 60%, at least 75%, at least 80%, at least 85%, at least 90%, at least 95%, at least 99%, 100%, or any range between any of these values of the one or more outer surfaces of the dielectric region 30a or 30b. In some implementations, the metal layer 35a or 35b can be disposed over the entire area (e.g., 100%) of the one or more outer surfaces of the dielectric region 30a or 30b. Without subscribing to any particular theory, the optical properties of the optical structure 70a or 70b can vary based on the amount of outer surface of the dielectric region 30a or 30b that is covered by the metal layer 35a or 35b. For example, the reflectivity or reflectance and/or the transmissivity or transmittance of the optical structure 70a or 70b can vary based on the amount of outer surface of the dielectric region 30a or 30b that is covered by the metal layer 35a or 35b.

[0230] In various implementations, the shape of the metal layer 35a or 35b can conform to the shape of the underlying dielectric material 30a or 30b. For example, in the optical structure 70a shown in Figure 19A, the dielectric material 30a has a rectangular cross-section. Accordingly, the metal layer 35a which is disposed over the major surfaces 31a and 31b and the edge surfaces also has a rectangular cross-section. As another example, in the optical structure 70b shown in Figure 19B, the dielectric material 30b has a circular cross-section. Accordingly, the metal layer 35b which is disposed over the circumference of the dielectric material 30b also has a circular cross-section. However, in other implementations, the shape of the metal layer 35a or 35b can be different from the shape of the underlying dielectric material 30a or 30b.

[0231] In various implementations, the optical structure 70a or 70b comprising a dielectric region 30a or 30b surrounded by a metal layer 35a or 35b can be configured as particles, slabs, filaments, flakes, beads (e.g., spherical beads) or platelets as discussed above. In some implementations, the optical structure 70a or 70b comprising a dielectric region 30a or 30b surrounded by a metal layer 35a or 35b can have the same shape as the shape of the dielectric region 30a or 30b. For example, the optical structure 70a can be configured as a cube or a rectangular cuboid when the dielectric region 30a is configured as a cube or a rectangular cuboid as shown in Figure 19A. As another example, the optical structure 70b can be configured as a sphere when the dielectric region 30b is configured as a sphere as shown in Figure 19B. In some cases, the optical structure 70a or 70b configured as a particle, a slab, a flake, a filament, or a platelet can be suitable for a pigment or a printing ink. In some implementations, the optical structure 70a or 70b configured as a particle, a slab, a flake, a filament, or a platelet can have an area (or a lateral dimension) that is about 5 to 10 times or more the thickness of the optical structure 70a or 70b configured as a particle, a slab, a flake, a filament, or a platelet. Accordingly, an optical structure 70a or 70b configured as a particle, a slab, a flake, a filament, or a platelet can have a thickness between about 100 nm and about 1 micron. In some such implementations, the area (or a lateral dimension) can be greater than or equal to about 500 nm and less than or equal to about 1 micron, greater than or equal to about 1 micron and less than or equal to about 5 microns, greater than or equal to about 5 microns and less than or equal to about 10 microns, greater than or equal to about 5 micron and less than or equal to about 40 microns, greater than or equal to about 5 microns and less than or equal to about 20 microns, or any value in the ranges/sub-ranges defined by these values. In various embodiments, the optical structure 70a or 70b configured as a particle, a slab, a flake, a filament, or a platelet can be configured such that an area, a length and/or a width of a major surface of the optical structure 70a or 70b is greater than or equal to about 2, 3, 4, 5, 6, 8, or 10 times the thickness of the optical structure 70a or 70b and less than or equal to about 50 times the thickness of the optical structure 70a or 70b or any value in any range formed by any of these values.

[0232] In various implementations, surrounding the dielectric region 30a or 30b with the metal layer 35a or 35b can advantageously increase the reflectivity or reflectance of the dielectric material 30a or 30b at one or more wavelengths of the visible spectral range in some implementations. In some implementations, surrounding the dielectric material 30a or 30b with the metal layer 35a or 35b can advantageously enhance or change the color appearance of the dielectric material 30a or 30b at one or more wavelengths of the visible spectral range in reflection and transmission mode.

[0233] In various implementations, the optical structure 70a or 70b comprising the dielectric region 30a or 30b surrounded by the metal layer 35a or 35b can have a reflection spectrum with one or more reflection peaks in the visible spectral region and a transmission spectrum with one or more transmission peaks in the visible spectral region. Without any loss of generality, the one or more reflection peaks and the one or more transmission peak do not overlap with each other. Accordingly, the optical structure 70a or 70b comprising the dielectric region 30a or 30b surrounded by the metal layer 35a or 35b can have a first color in the reflection mode and a second color different from the first color in the transmission mode. In certain implementations, the first color and the second color can be complementary colors, such as, for example, red and green, yellow and violet, blue and orange, green and magenta, etc.

[0234] In various implementations, there may be little to no shift in the first color in the reflection mode for any viewing angle between a first angle with respect to a normal to the surface of the optical structure 70a or 70b and a second angle with respect to a normal to the surface of the optical structure 70a or 70b. Likewise, in some implementations, there may be little to no shift in the second color in the transmission mode for any viewing angle between a first angle with respect to a normal to the surface of the optical structure 70a or 70b and a second angle with respect to a normal to the surface of the optical structure 70a or 70b. In various implementations, the first angle can have a value between 0 degrees and 10 degrees (e.g., 0 degrees, 1 degree, 2 degrees, 3 degrees, 4 degrees, 5 degrees, 6 degrees, 7 degrees, 8 degrees, 9 degrees or 10 degrees). In various implementations, the second angle can have a value between 20 degrees and 90 degrees (e.g., 20 degrees, 30 degrees, 40 degrees, 50 degrees, 60 degrees, 70 degrees, 80 degrees or 90 degrees). Accordingly, for any viewing angle between a first angle (e.g., 0 degrees, 1 degree, 2 degrees, 3 degrees, 4 degrees, 5 degrees, 6 degrees, 7 degrees, 8 degrees, 9 degrees or 10 degrees) with respect to a normal to the surface of the optical structure 70a or 70b and a second angle (e.g., 20 degrees, 30 degrees, 40 degrees, 50 degrees, 60 degrees, 70 degrees, 80 degrees or 90 degrees) with respect to a normal to the surface of the optical structure 70a or 70b, the color of the optical structure 70a or 70b in the reflection mode and/or the transmission mode may remain substantially the same. Likewise, in some implementations, there may be little to no shift color shift in the color of the optical structure 70a or 70b in the reflection mode and/or the transmission mode for tilt of 10 degrees, 20 degrees, 30 degrees, 40 degrees, 50 degrees, 60 degrees, 70 degrees, 80 degrees or 90 degrees or any value in a range/sub-range defined by any of these values.

[0235] In some implementations, it may be desirable to have a color shift in the first color in the reflection mode as the viewing angle changes from a first angle with respect to a normal to the surface of the optical structure 70a or 70b to a second angle with respect to a normal to the surface of the optical structure 70a or 70b. Similarly, in various implementations, it may be desirable to have a color shift in the second color in the transmission mode as the viewing angle changes from a first angle with respect to a normal to the surface of the optical structure 70a or 70b to a second angle with respect to a normal to the surface of the optical structure 70a or 70b. In various implementations, the first angle can have a value between 0 degrees and 10 degrees (e.g., 0 degrees, 1 degree, 2 degrees, 3 degrees, 4 degrees, 5 degrees, 6 degrees, 7 degrees, 8 degrees, 9 degrees or 10 degrees). In various implementations, the second angle can have a value between 20 degrees and 90 degrees (e.g., 20 degrees, 30 degrees, 40 degrees, 50 degrees, 60 degrees, 70 degrees, 80 degrees or 90 degrees) depending on the design. Accordingly, as the viewing angle changes from a first angle (e.g., 0 degrees, 1 degree, 2 degrees, 3 degrees, 4 degrees, 5 degrees, 6 degrees, 7 degrees, 8 degrees, 9 degrees or 10 degrees) with respect to a normal to the surface of the optical structure 70a or 70b to a second angle with respect to a normal to the surface of the optical structure 70a or 70b and a second angle (e.g., 20 degrees, 30 degrees, 40 degrees, 50 degrees, 60 degrees, 70 degrees, 80 degrees or 90 degrees) with respect to a normal to the surface of the optical structure 70a or 70b, the color of the optical structure 70a or 70b in the reflection mode and/or the transmission mode may change (e.g., dark blue to light blue, purple to pink, dark green to light green, etc.). Likewise, in some implementations, there may be a shift in the color of the optical structure 70a or 70b in the reflection mode and/or the transmission mode for tilt of 10 degrees, 20 degrees, 30 degrees, 40 degrees, 50 degrees, 60 degrees, 70 degrees, 80 degrees or 90 degrees or any value in a range/sub-range defined by any of these values.

[0236] Without subscribing to any particular theory, the one or more reflection peaks of the reflection spectrum of the optical structure 70a or 70b comprising the dielectric region 30a or 30b surrounded by the metal layer 35a or 35b can have high reflectivity or reflectance. For example, the reflectivity or reflectance of the one or more reflection peaks can be greater than or equal to 30%, greater than or equal to 40%, greater than or equal to 50%, greater than or equal to 55%, greater than or equal to 60%, greater than or equal to 65%, greater than or equal to 70%, greater than or equal to 75%, greater than or equal to 80%, greater than or equal to 85%, greater than or equal to 90%, greater than or equal to 95% and less than or equal to 100%, or a value in any range/sub-range defined by these values.

[0237] Without subscribing to any particular theory, the one or more transmission peaks of the transmission spectrum of the optical structure 70a or 70b comprising the dielectric region 30a or 30b surrounded by the metal layer 35a or 35b can have high transmissivity or transmittance. For example, the transmissivity or transmittance of the one or more transmission peaks can be greater than or equal to 30%, greater than or equal to 40%, greater than or equal to 50%, greater than or equal to 55%, greater than or equal to 60%, greater than or equal to 65%, greater than or equal to 70%, greater than or equal to 75%, greater than or equal to 80%, greater than or equal to 85%, greater than or equal to 90%, greater than or equal to 95% and less than or equal to 100%, or a value in any range/sub-range defined by these values.

[0238] The optical structures 70a and 70b comprising the dielectric region 30a or 30b surrounded by the metal layer 35a or 35b can produce many or all the optical effects that are described above with reference to optical structure 10 where the two metal layers 13 and 15 do not surround the dielectric layer 14 (e.g., as shown in Figure 11).

[0239] The metal layer 35a or 35b can be disposed around the dielectric material 30a or 30b using a variety of chemical methods. For example, metal layer 35a or 35b can be disposed around the dielectric region 30a or 30b using electroless method. Various implementations of an electroless method of depositing the metal layer 35a or 35b can comprise depositing the metal layer 35a or 35b without applying electrical current or voltage. Various metals such as, for example, gold, silver, or nickel can be deposited using electroless methods. An example of depositing metal layer 35a or 35b comprising silver around the dielectric region 30a or 30b using an electroless method is discussed below. The electroless method of depositing silver can also be referred to as electroless silver plating. Electroless silver plating comprises immersing the dielectric region 30a or 30b in a silvering bath comprising chemical compounds of silver (e.g., silver nitrate, silver-ammonia compounds, sodium argento cyanide, etc.) and at least one of ammonia, water, potassium hydroxide or sodium hydroxide. The chemical compounds of silver are reduced to metallic silver using a reducing agent which is added to the silvering bath. The metallic silver adheres to the exposed surfaces of the dielectric region 30a or 30b. The reducing agent can comprise glucose, sucrose, invert sugar, stannous chloride, hydrazine, Rochelle salt, formaldehyde, or organic borane (e.g., dimethylamine borane in various implementations). In certain implementations, the silvering bath and the reducing agent can be sprayed on the dielectric region 30a or 30b. In some implementations, the outer surface of the dielectric region 30a or 30b can be activated using stannous chloride ($SnCl_2$) in preparation for the electroless deposition of the metal layer. Other methods of depositing the metal layer 35a or 35b on the outer surface of the dielectric region 30a or 30b can also be used. For example, the metal layer 35a or 35b can be disposed around the dielectric region 30a or 30b using methods such as, for example, chemical vapor deposition (CVD), sputtering or electroplating. In some implementations, the metal layer 35a or 35b can be patterned around the dielectric region 30a or 30b.

[0240] In various implementation, a second dielectric region 40a or 40b comprising one or more dielectric materials may be disposed around the metal coated dielectric region 30a or 30b. The second dielectric region 40a or 40b may comprise high refractive index materials such as ZrO_2, TiO_2, ZnS, ITO (indium tin oxide), CeO_2 or Ta_2O_3. In various implementations, the second dielectric region 40a or 40b may comprise dielectric materials having refractive index greater than 1.65 and less than or equal to 2.5. For example, the refractive index of the one or more dielectric material in the second dielectric region 40a or 40b can be greater than or equal to 1.65 and less than or equal to 1.75, greater than or equal to 1.75 and less than or equal to 1.85, greater than or equal to 1.85 and less than or equal to 1.95, greater than or equal to 1.95 and less than or equal to 2.05, greater than or equal to 2.0 and less than or equal to 2.2, greater than or equal to 2.1 and less than or equal to 2.3, greater than or equal to 2.25 and less than or equal to 2.5, or any value in any range/sub-range defined by these values. Other values outside these ranges are also possible in some implementations. In various implementations, the refractive index of the one or more materials of the second dielectric region 40a or 40b can be greater than the refractive index of the one or more materials of the dielectric region 30a or 30b. The thickness of the second dielectric region 40a or 40b can be between 75 nm and 700 nm. For example, the thickness of the second dielectric region 40a or 40b can be greater than or equal to 75 nm and less than or equal to 100 nm, greater than or equal to 100 nm and less than or equal to 150 nm, greater than or equal to 150 nm and less than or equal to 200 nm, greater than or equal to 200 nm and less than or equal to 250 nm, greater than or equal to 300 nm and less than or equal to 350 nm, greater than or equal to 400 nm and less than or equal to 450 nm, greater than or equal to 450 nm and less than or equal to 500 nm, greater than or equal to about 500 nm and less than or equal to 650 nm, greater than or equal to 650 nm and less than or equal to 700 nm, or any value in any range/sub-range defined by these values. The second dielectric region 40a or 40b can be disposed to cover at least 50% of the outer surface of the metal layer 35a or 35b. For example, the second dielectric region 40a or 40b can be disposed to cover at least 80%, at least 90%, at least 95%, or 100% of the outer surface of the metal layer 35a or 35b, or any value in a range/sub-range defined by these values.

[0241] The reflected color and/or the transmitted color of the optical structure 70a or 70b comprising the second dielectric region 40a or 40b surrounding the metal coated dielectric region 30a or 30b can be different from the reflected color and/or the transmitted color of the optical structure 70a or 70b comprising only the metal coated dielectric region 30a or 30b. For example, the reflected color and/or the transmitted color of the optical structure 70a or 70b comprising the second dielectric region 40a or 40b surrounding the metal coated dielectric region 30a or 30b can be more vibrant than the reflected color and/or the transmitted color of the optical structure 70a or 70b comprising the metal coated dielectric region 30a or 30b without the second dielectric region 40a or 40b having suitable thickness and/or materials with suitable refractive index. The shape of the transmission and/or reflection peaks, the position of the maximum of the transmission and/or reflection peaks and/or the width (e.g., full width at half maximum (FWHM)) of the transmission and/or reflection peaks of the optical structure 70a or 70b comprising the second dielectric region 40a or 40b surrounding the metal coated dielectric region 30a or 30b can be different from the shape of the transmission and/or reflection peaks, the position of the maximum of the transmission and/or reflection peaks and/or the width of the transmission and reflection peaks of the optical structure 70a or 70b comprising the metal coated dielectric region 30a or 30b without the second dielectric region 40a or 40b having suitable thickness and/or materials with suitable refractive index. For example, the width of one or more of the reflection peaks of the optical structure 70a or 70b comprising the second dielectric region 40a or 40b surrounding the metal coated dielectric region 30a or 30b can be broader than the width of a corresponding reflection peak of the optical structure 70a or 70b comprising the metal coated dielectric region 30a or 30b without the second dielectric region 40a or 40b having suitable thickness and/or materials with suitable refractive index. As another example, the width (e.g., FWHM) of one or more of the reflection peaks of the optical structure 70a or 70b comprising the second dielectric region 40a or 40b surrounding the metal coated dielectric region 30a or 30b can be greater than or equal to about 50 nm and less than or equal to about 300 nm, in some implementations.

[0242] Various implementations of the of the optical structure 70a or 70b comprising the second dielectric region 40a or 40b surrounding the metal coated dielectric region 30a or 30b can have a reflection spectrum with one or more reflection peaks having a width (e.g., FWHM) greater than or equal to about 10 nm, greater than or equal to about 20 nm, greater than or equal to about 30 nm, greater than or equal to about 40 nm, greater than or equal to about 50 nm, greater than or equal to about 60 nm, greater than or equal to about 70 nm, greater than or equal to about 100 nm, greater than or equal to about 200 nm, less than or equal to about 300 nm, less than or equal to about 250 nm, or any value in a range/sub-range defined by these values. Various implementations of the optical structure 70a or 70b comprising the second dielectric region 40a or 40b surrounding the metal coated dielectric region 30a or 30b can have higher reflectivity or reflectance at one or more wavelengths in the visible spectral range as compared to the reflectivity or reflectance of the optical structure 70a or 70b comprising the metal coated dielectric region 30a or 30b without the second dielectric region 40a or 40b having suitable thickness and/or materials with suitable refractive index at those one or more wavelengths in the visible spectral range.

[0243] Various implementations of the of the optical structure 70a or 70b comprising the second dielectric region 40a or 40b surrounding the metal coated dielectric region 30a or 30b can have a transmission spectrum with one or more transmission peaks having a width (e.g., FWHM) greater than or equal to about 10 nm, greater than or equal to about 20 nm, greater than or equal to about 30 nm, greater than or equal to about 40 nm, greater than or equal to about 50 nm, greater than or equal to about 60 nm, greater than or equal to about 70 nm, greater than or equal to about 100 nm, greater than or equal to about 200 nm, less than or equal to about 300 nm, less than or equal to about 250 nm, or any value in a range/sub-range defined by these values.

[0244] Without subscribing to any particular theory, the one or more reflection peaks of the reflection spectrum of the optical structure 70a or 70b comprising the second dielectric region 40a or 40b surrounding the metal coated dielectric region 30a or 30b can have high reflectivity or reflectance. For example, the reflectivity or reflectance of the one or more reflection peaks can be greater than or equal to 30%, greater than or equal to 40%, greater than or equal to 50%, greater than or equal to 55%, greater than or equal to 60%, greater than or equal to 65%, greater than or equal to 70%, greater than or equal to 75%, greater than or equal to 80%, greater than or equal to 85%, greater than or equal to 90%, greater than or equal to 95% and less than or equal to 100%, or a value in any range/sub-range defined by these values.

[0245] Without subscribing to any particular theory, the one or more transmission peaks of the transmission spectrum of the optical structure 70a or 70b comprising the second dielectric region 40a or 40b surrounding the metal coated dielectric region 30a or 30b can have high transmissivity or transmittance. For example, the transmissivity or transmittance of the one or more transmission peaks can be greater than or equal to 30%, greater than or equal to 40%, greater than or equal to 50%, greater than or equal to 55%, greater than or equal to 60%, greater than or equal to 65%, greater than or equal to 70%, greater than or equal to 75%, greater than or equal to 80%, greater than or equal to 85%, greater than or equal to 90%, greater than or equal to 95% and less than or equal to 100%, or a value in any range/sub-range defined by these values.

[0246] Additionally, the second dielectric region 40a or 40b can advantageously insulate the metal layer 35a or 35b from the ink varnish when the optical structures 70a or 70b are configured as pigments.

[0247] In some implementations, the second dielectric region 40a or 40b can be disposed around the metal coated dielectric materials 30a or 30b using a sol-gel process. For example, the metal coated dielectric materials 30a or 30b can be coated with a dielectric material comprising titanium di-oxide (TiO_2) using a sol–gel process, involving the hydrolysis of titanium(IV) isopropoxide. As another example, a precursor comprising the dielectric material 40a or 40b is transformed to form a colloidal suspension (or a "sol") by a series of hydrolysis and polymerization reactions. In some implementations, the colloidal suspension comprising the dielectric material of the second dielectric region 40a or 40b can be disposed on the metal coated first dielectric region 30a or 30b by a coating, gelling or precipitation. The metal coated first dielectric region 30a or 30b comprising the colloidal suspension comprising the dielectric material of the second dielectric region 40a or 40b can be heated or dried to obtain the metal coated first dielectric region 30a or 30b coated with second dielectric region 40a or 40b. In some implementations, the one or more materials of the second dielectric region 40a or 40b can be disposed around the metal coated first dielectric region 30a or 30b using deposition methods such as, for example, chemical vapor deposition method, e-beam, sputtering. In some implementations, the various deposition methods can be combined with vibrating the metal coated first dielectric region 30a or 30b.

[0248] As discussed above, various embodiments of the optical structures 10, 70a or 70b are configured to partially reflect light and partially transmit light. In various implementations, the reflectivity or reflectance of the optical structures 10, 70a or 70b at one or more wavelengths in the visible spectral range can be greater than or equal to 10%, greater than or equal to 20%, greater than or equal to 30%, greater than or equal to 40%, greater than or equal to 50%, greater than or equal to 60%, greater than or equal to 70%, greater than or equal to 80%, greater than or equal to 90%, greater than or equal to 95% and/or less than or equal to 100%, or any value in any range/sub-range defined by these value. In various implementations, the transmissivity or transmittance of the optical structures 10, 70a or 70b at one or more wavelengths in the visible spectral range can be greater than or equal to 10%, greater than or equal to 20%, greater than or equal to 30%, greater than or equal to 40%, greater than or equal to 50%, greater than or equal to 60%, greater than or equal to 70%, greater than or equal to 80%, greater than or equal to 90%, greater than or equal to 95% and/or less than or equal to 100%, or any value in any range/sub-range defined by these value. In various implementations, the reflectivity or reflectance of the optical structures 10, 70a or 70b at one or more first set of wavelengths can be approximately equal to the transmissivity or transmittance of the optical structures 10, 70a or 70b at one or more second set of wavelengths different from the first set of wavelengths.

[0249] The optical structures 10, 70a or 70b can have a size, such as, for example, a lateral dimension, an area, a length or a width of the optical structure (e.g., a length, a width or an area of a major surface of the optical structure) greater than or equal to about 1 micron and less than or equal to about 50 microns. For example, the size of the optical structures 10, 70a or 70b can be greater than or equal to about 1 micron and less than or equal to 10 microns, greater than or equal to 2 microns and less than or equal to 12 microns, greater than or equal to 3 microns and less than or equal to 15 microns, greater than or equal to 4 microns and less than or equal to 18 microns, greater than or equal to 5 microns and less than or equal to 20 microns, greater than or equal to 10 microns and less than or equal to 20 microns, greater than or equal to 15 microns and less than or equal to 25 microns, greater than or equal to 20 microns and less than or equal to about 30 microns, greater than or equal to 25 microns and less than or equal to 35 microns, greater than or equal to 30 microns and less than or equal to 40 microns, greater than or equal to 35 microns and less than or equal to 45 microns, greater than or equal to 40 microns and less than or equal to 50 microns, or a value in any range/sub-range defined by these values.

[0250] The optical structures 10, 70a or 70b can have a size, such as, for example, a lateral dimension, an area, a length or a width of the optical structure (e.g., a length, a width or an area of a major surface of the optical structure) greater than or equal to about 1 micron and less than or equal to about 50 microns can be between 0.1 microns and 2.0 microns. For example, the thickness of the optical structures 10, 70a or 70b having a size, such as, for example, a lateral dimension, an area, a length or a width of the optical structure (e.g., a length, a width or an area of a major surface of the optical structure) greater than or equal to 0.1 micron and less than or equal to 0.3 microns, greater than or equal to 0.2 microns and less than or equal to 0.5 microns, greater than or equal to 0.3 microns and less than or equal to 0.6 microns, greater than or equal to 0.4 microns and less than or equal to 0.7 microns, greater than or equal to 0.5 microns and less than or equal to 0.8 microns, greater than or equal to 0.6 microns and less than or equal to 0.9 microns, greater than or equal to 0.7 microns and less than or equal to 1.0 micron, greater than or equal to 1.0 micron and less than or equal to 1.2 microns, greater than or equal to 1.2 microns and less than or equal to 1.5 microns, greater than or equal to 1.5 microns and less than or equal to 2.0 microns, or a value in any range/sub-range defined by these values.

[0251] One or more of the optical structures 10, 70a or 70b discussed above can be incorporated with or in a document (e.g., a banknote), package, product, or other item. Optical products such as a film, a thread, a laminate, a foil, a pigment, or an ink comprising one or more of the optical structures 10, 70a or 70b discussed above can be incorporated with or in documents such as banknotes or other documents to verify authenticity of the documents, packaging materials, etc. For example, the optical structures 70a or 70b can be configured as an ink or a pigment which is disposed on a base comprising at least one of a polymer, a plastic, a paper or a fabric. The base may be flexible in some implementations. The base comprising the ink or a pigment or pigment comprising the optical structures 70a or 70b can be cut or diced to obtain a thread or a foil. A plurality of optical structures 10, 70a or 70b discussed above can be incorporated in a particular optical product (e.g., ink, pigment, thread, filament, paper, security ink, security pigment, security thread, security filament, security paper, etc.). The shapes, sizes and/or aspect ratios of the plurality of optical structures 10, 70a or 70b discussed above that are incorporated in a particular optical product (e.g., ink, pigment, thread, filament, paper, security ink, security pigment, security thread, security filament, security paper, etc.) can vary. Accordingly, a particular optical product (e.g., ink, pigment, thread, filament, paper, security ink, security pigment, security thread, security filament, security paper, etc.) can comprise optical structures 10, 70a or 70b with different distributions of shapes, sizes and/or aspect ratios of the optical structures. For example, a particular optical product (e.g., ink, pigment, thread, filament, paper, security ink, security pigment, security thread, security filament, security paper, etc.) can comprise optical structures 10, 70a or 70b with sizes distributed around one or more mean sizes.

As another example, a particular optical product (e.g., ink, pigment, thread, filament, paper, security ink, security pigment, security thread, security filament, security paper, etc.) can comprise optical structures 10, 70a or 70b with aspect ratios distributed around one or more aspect ratios.

[0252] Figure 20 shows, for example, a banknote 80 comprising a laminated film 83. The laminated film 83 comprises the optical structure 10, 70a or 70b. The laminated film 83 can be fabricated by disposing the optical structure 10, 70a or 70b over a base or support layer or substrate such as polymer base layer (e.g., a polyester film). The optical structure 10, 70a or 70b can be disposed over the polymer base layer by a variety of methods including but not limited to coating methods, vacuum deposition on a surface of the polymer base layer, etc. The optical structure 10, 70a or 70b may be disposed over a first side of the surface of the polymer base layer (e.g., polyester film). The laminated film 83 can be adhered to the "paper" (e.g., cellulose, cotton/linen, polymer or fabric) 81 of the banknote 80, for example, by a transparent and/or an optically clear adhesive. In various cases, a second surface of the polymer base layer opposite the first surface of the base layer is disposed closer to the banknote paper 81 comprising the banknote and may be in contact with the adhesive. In some cases, the adhesive can be a two component adhesive with one component disposed onto the banknote paper and the other component disposed on the second surface of the polymer base layer opposite the first surface of the base layer on which the optical structure 10, 70a or 70b is disposed. The banknote 80 and the laminated film 83 can be brought together for bonding. The laminated film 83 can also be attached to the banknote 80 using a cross-linking thermoset adhesive. A transparent protective barrier coating 82 (e.g., UV curable cross-linked resin) can be disposed over the laminated film 83. The protective barrier coating 82 can extend over the edges of the laminated film 83 onto the paper (e.g., fabric) 81 of the banknote. The protective barrier coating 82 can be configured to protect the laminated film 83 against corrosion, abrasive wear and liquids that may commonly come in contact with the banknote 80 without sacrificing the optical effects provided by the laminated film 83. The optical structure 10 can be disposed facing the protective barrier coating 82 or the adhesive layer between the laminated film 83 and the "paper" 81.

[0253] In some embodiments, the optical structure 10, 70a or 70b can be configured as a thread (e.g., a windowed thread) instead of a laminated film. A windowed thread can be manufactured by a variety of methods. For example, the thread can be woven up and down within the paper and to the surface of the paper during the papermaking process. As another example, the windowed thread can be disposed within the paper itself so that no part of the thread reaches the surface of the banknote. As yet another example, open spaces within the paper can be provided in the regions of the paper comprising the thread.

[0254] The thread can be fabricated by cutting a strip of the optical structure 10, for example the web, sheet, or base layer on which the layers comprising the optical structure 10 are formed and passing the strip through a bath of UV curable resin. The rate at which the strip is passed through the UV curable resin bath can be controlled to coat the sides and the edges of the strip uniformly. The strip coated with the UV curable resin can be cured to obtain the thread. The obtained thread comprising the optical structure 10 can be inserted (e.g., weaved) in the banknote. In some implementations, any fringe (e.g., the jagged or ragged edge of the thread) of the thread (due to hot stamping or chatter from any cutting operation) can be hidden from an observer by printing an opaque border around the hot stamp patch. Another way to affix the optical structure 10, 70a or 70b to the banknote can include die cutting a portion of the optical structure, for example, the web, sheet, or base layer on which the layers comprising the optical structure 10, 70a or 70b are formed and applying the portion to the banknote using an adhesive. Various implementations of the examples of optical structure described above can be configured as a thread, a hot stamp, or a laminate and incorporated with or in a document (e.g., a banknote), package, product, or other item.

[0255] Without any loss of generality, the optical structure 10, 70a or 70b or a material (e.g., an ink, a paint or a pigment, a varnish) comprising the optical structure 10, 70a or 70b can be disposed on a base comprising at least one of a polymer, a plastic, a paper or a fabric. The base comprising the optical structure 10, 70a or 70b or the material comprising the optical structure 10, 70a or 70b can be cut or diced into a smaller portions having a variety of shapes and/or sizes. The smaller portions can be disposed on or inserted into or onto a substrate (e.g., a bank note, paper, packaging material, fabric, etc.)

using various methods. For example, the smaller portions can be configured as strips or threads which can be woven into the substrate. As another example, the smaller portions can be configured as foils which can be hot stamped on the substrate. As yet another example, the smaller portions can be laminated to the substrate using adhesives.

[0256] Figure 21A depicts a banknote 90a having two transparent windows 91a and 92a inserted into or attached on the paper (e.g., fabric) of the banknote. Each window comprises the optical structure 10, 70a or 70b. In some implementations, the reflection and/or transmission spectra of the optical structure 10 of the window 91a may be configured to be different from the reflection and/or transmission spectra of the optical structure 10, 70a or 70b of the window 92a. Thus, a person viewing the banknote 90a will perceive a first reflected color when viewing the window 91a along a viewing direction (e.g., normal to the surface of the banknote 90a) and a second reflected color different from the first reflected color when viewing the window 92a along the viewing direction. The person may also perceive a third transmitted color different from the first reflected color when viewing through the window 91a along the viewing direction. The person may additionally perceive a fourth transmitted color different from the first, second and third colors when viewing through the window 92a along the viewing direction. Furthermore, upon folding the banknote 90a over itself so that the two windows 91a and 92a are at least partially aligned with respect to one another, the person will perceive a different color, different from the first, second, third and/or fourth colors in reflection and transmission modes when viewing the banknote 90a along the viewing direction. For example, upon folding the banknote 90a over itself so that the two windows 91a and 92a are at least partially aligned with respect to one another, the person will perceive a reflected color that is a combination of the effects of the reflectivity or reflectance spectrums of the two windows 91a and 92a and a transmitted color that is a combination of the effects of the transmission spectrums of the two windows 91a and 92a. Additionally, the person can perceive color shift of the various colors seen in the reflection and transmission modes as the viewing angle changes. The amount of color shift may be different from the different windows as well as for the combination of the two windows.

[0257] Figure 21B depicts an implementation of a security device 90b (e.g., a banknote) comprising two windows 91b and 92b (a first and a second) inserted into or attached to the surface of the security device 90b. The two windows 91b and 92b at least partially overlap in the overlapping region 93b. The two windows 91b and 92b are transparent and comprise the optical structure 10, 70a or 70b. The configuration (e.g., thickness or other design parameters) of the optical structures 10, 70a or 70b in the respective windows 91a and 91b can be such that the reflection and/or transmission spectra of the optical structure 10, 70a or 70b of the window 91b is different from the reflection and/or transmission spectra of the optical structure 10 of the window 92b.

[0258] Thus, a person viewing the security device 90b along a viewing direction (e.g., normal to the surface of the security device 90b) will perceive (i) a first reflected color when viewing the portion of the window 91b that does not overlap with the window 92b, (ii) a second reflected color different from the first color when viewing the portion of the window 92b that does not overlap with the window 91b; and (iii) a third second reflected color that is a combination of the effects of the reflectivity or reflectance spectrums of the two windows 91b and 92b when viewing the overlapping region 93b.

[0259] A person viewing the security device 90b along a viewing direction (e.g., normal to the surface of the security device 90b) will perceive (i) a fourth transmitted color different from the first color when viewing through the portion of the window 91b that does not overlap with the window 92b, (ii) a fifth transmitted color different from the second and the fourth color when viewing through the portion of the window 92b that does not overlap with the window 91b; and (iii) a sixth transmitted color that is a combination of the effects of the transmission spectrums of the two windows 91b and 92b when viewing through the overlapping region 93b.

[0260] Additionally, in various embodiments, a person viewing the security device 90b can perceive color shift of the various colors seen in the reflection and transmission modes as the viewing angle changes. The amount of color shift may be different from the different windows.

[0261] Although, the two windows 91b and 92b are shown as partially overlapping in Figure 21B, the two windows 91b and 92b can be completely overlapping.

Various implementations of the security device 90b can comprise two or more different pigments. The two or more different pigments can comprise optical structures 10. A respective optical structure of one of the two or more different pigments can have reflectance and transmittance characteristics that are different from the respective optical structure of another of the two or more different pigments. The two or more different pigments can partially or completely overlap with each other. As discussed above, the color perceived by a person viewing an overlapping region of the two or more different pigments can depend on a combination of the effects of the reflection/transmission spectra of the different optical structures of the two or more different pigments. Some implementations of the security device 90b can comprise two or more at least partially overlapping foils, films, threads or laminates comprising different optical structures. The color perceived by a person viewing an overlapping region of the two or more at least partially overlapping foils, films, threads or laminates can depend on a combination of the effects of the reflection/transmission spectra of the different optical structures of the two or more foils, films, threads or laminates.

[0262] Figure 22 illustrates a side view of an object 100 with a security device comprising a main body 103 of the object and a layer 102 comprising the optical structure 10, 70a or 70b. The object can be a banknote. The main body may comprise paper comprising the banknote. The layer 102 can be a laminate, a thread, or a label. When the layer 102 is configured as a label, an adhesive (e.g., a varnish) can be applied to the main body 103 and the layer 102 can be adhered to the adhesive of the main body 103 using a polymeric adhesive. Alternatively, the adhesive can be applied to the layer 102 before being affixed to the main body 103. When the layer 102 is configured as a laminate, the layer 102 can be adhered to the main body 103 using a polymer.

[0263] The layer 102 can be adhered to the main body103 using adhesives, such as, for example optical clear adhesive and/or a cross-linking thermoset adhesive. The security device 100 further comprises a layer 101 comprising a message that is composed using a text, a symbol, a number or any combination thereof that is disposed on the side of the main body (e.g., paper /fabric) 103 of the object (e.g., banknote) opposite the side on which the layer 102 as shown in Figure 22. Alternately, the layer 101 can be disposed between the main body (e.g., paper/fabric) 103 and the layer 102 or over the layer 102. The layer 101 can comprise, for example, a dye, a pigment or a phosphorescent material that has the same color characteristics as the color reflected or transmitted by the optical structure 10 when viewed along a direction normal to the surface of the layer 102. Accordingly, the message is not visible to an observer (or hidden) when the security device 100 is viewed along a direction normal to the surface of the layer 102. However, when the security device 100 is tilted such that viewing angle changes, the color reflected by and/or transmitted through the optical structure 10 changes such that the message become visible to the observer. In certain cases, the layer 101 comprising a message printed with a phosphorescent material can be made visible when illuminated by UV. The resultant color of the phosphorescent material can be the combined color of the fluoresence and the dichroic color.

[0264] Figure 23 shows the effect of changing the viewing angle in transmission of the security device 100 from 0 to about 45 degrees. When the viewing angle is 0 degrees, the message comprising a combination of a number, text or a symbol is not visible in the transmission mode because the color of the text is the same as the color of the optical structure in transmission mode (e.g., orange). However, as the viewing angle increases, the color of the optical structure in transmission mode shifts. For example, the message 203 becomes visible as the color of the optical structure in transmission mode shifts from orange to yellow as the angle of observation increases. The color of the message has sufficient contrast with respect to the transmitted color of the optical structure 10 so as to be visible to the observer.

[0265] In other embodiments, the security device 100 can be configured to operate in reverse to that described above such that for example the message is visible at normal incidence and not visible when the security device is tilted. Other variations are possible.

[0266] As describe above, the optical structures 10, 70a or 70b may be used in different forms, such as a laminate, a foil, a film, a hot stamp, a thread, pigment, ink, or paint. In some implementations, a laminate, a foil, a film, or a thread can comprise a pigment, ink or paint comprising the optical structures 10, 70a or 70b. A laminate may be adhered to a document, product or package using adhesive. A thread may be threaded or woven through an opening, for example, in the document. A foil can be hot stamped on the document, product or package. Pigment, ink, or paint may be deposited on the document, product or package or the material (e.g., paper, cardboard, or fabric) used to form the document, product, or package. For example, the document, product, or package may be exposed to (e.g., contacted with) the pigment, ink, or paint to color the document, product or packages in process similar to those used for non-color shifting pigments, dyes, paints and inks.

[0267] A plurality of optical structures 10, 70a or 70b such as described herein collected together as a pigment (as well as inks, and paints) can have similar optical characteristics as the optical structure 10, 70a or 70b configured as a film/laminate. As described above, optical structures 10, 70a or 70b collected together to form a pigments can exhibit as a collection of platelets or separate pieces the same optical characteristics as the bulk optical film from which the platelets were made. An added advantage of the optical structures 10, 70a or 70b configured as a pigment is that color can be blended according to desired specification. The color of the optical structure 10 can be designed by using computer software to calculate the thickness of the various layers of the optical structure 10, 70a or 70b that would provide a desired reflection and/or transmission characteristics. Optical structures 10, 70a or 70b that can provide specific colors can be designed using the computer software and then fabricated. Additionally, different color shifting optical structures 10, 70a or 70b that produce different colors can be included together and/or color shifting optical structures such as described herein can be combined with non-color shifting pigments or dyes to produce different colors.

[0268] The optical structure 10, 70a or 70b can be fabricated using a variety of methods including but not limited to vacuum deposition, coating methods, etc. One method of fabrication of the optical structures 10 described herein uses a vacuum coater that employs batch or roll coating. In one method of fabricating the optical structure 10, a first transparent high index layer (e.g., layer 12 or layer 16 of Figure 11) is deposited onto carrier or base layer such as a sheet or web or other substrate. The carrier, web, base layer or substrate can comprise materials such as, for example, polyester or a polyester with release characteristics such that the optical structure can be readily separated from the web or base layer. A release layer between the base layer and the plurality of other optical layers the form the optical structure may be used to permit separation of the optical layers comprising the optical structure from the base layer or web. A first metal layer (e.g., layer 13 or layer 15), a transparent dielectric layer comprising high or low refractive index material (e.g., layer 14), a second metal layer (e.g., layer 15 or layer 13), and a second transparent high index layer (e.g., layer 16 or layer 12) is deposited over the first transparent high index layer in sequence (e.g., layer 12 or layer 16 of Figure 11). The various layers can be deposited in sequence in some embodiments. However, in other embodiments, one or more intervening layers can be disposed between any of the first metal layer, the transparent dielectric layer comprising high or low refractive index material, the second metal layer, and the second transparent high index layer. As examples, in some cases the transparent high index layers and the dielectric layer can be deposited using electron gun while the first and the second metal layers can be deposited by using electron gun or sputtering.

[0269] Some materials, like ZnS or MgF_2, can be evaporated from a resistance source. In instances wherein the transparent dielectric layer comprising high or low refractive index material comprises a polymer, a process known as PML (Polymer Multi-Layer) as described in US 5,877,895 can be used. The disclosure of US 5,877,895 is incorporated by reference herein in its entirety.

<u>Optical Structures Comprising Dielectric Layers Surrounded by Metal Layers (e.g., M/D/M/D/M optical stack)</u>

[0270] Figure 24A schematically illustrates an implementation of an optical structure 300a comprising a stack of layers that can be used as a security feature. The optical structure 300a comprises at least two dielectric layers 303a and 303b and at least three metal layers 301a, 301b, and 301c. In various implementations, the at least three metal layers 301a, 301b, and 301c can comprise a material selected from a group consisting of silver (Ag), silver alloys, gold (Au), and gold alloys. In some implementations, the at least three metal layers 301a, 301b, and 301c can comprise palladium (Pd). For example, the at least three metal layers 301a, 301b, and 301c can comprise silver alloys with palladium. The amount of palladium in some such implementations can be less than or equal to about 10% by weight.

[0271] In various implementations, different metal layers (e.g. metal layers 301a, 301b, and 301c) can have a thickness in a range between about 3 nm and about 120 nm. For example, the thickness of the different metal layers (e.g. metal layers 301a, 301b, and 301c) can be greater than or equal to about 3 nm and less than or equal to about 20 nm, greater than or equal to about 7.5 nm and less than or equal to about 25 nm, greater than or equal to about 10 nm and less than or equal to about 27.5 nm, greater than or equal to about 12.5 nm and less than or equal to about 30 nm, greater than or equal to about 15 nm and less than or equal to about 35 nm, greater than or equal to about 17.5 nm and less than or equal to about 37.5 nm, greater than or equal to about 20 nm and less than or equal to about 40 nm, greater than or equal to about 25 nm and less than or equal to about 50 nm, greater than or equal to about 30 nm and less than or equal to about 60 nm, greater than or equal to about 35 nm and less than or equal to about 55 nm, greater than or equal to about 45 nm and less than or equal to about 75 nm, greater than or equal to about 60 nm and less than or equal to about 80 nm, greater than or equal to about 75 nm and less than or equal to about 100 nm, greater than or equal to about 90 nm and less than about 120 nm, or any thickness in a range/sub-range defined by any of these values.

[0272] In various implementations, the different metal layers 301a, 301b and 301c can have the same thickness. However, in some implementations, the different metal layers 301a, 301b and 301c can have different thickness. In some implementations, two of the three metal layers 301a, 301b and 301c have different thicknesses while in others all three metal layers have different thicknesses. In some implementations, the metal layer 301b can have a thickness greater than the thickness of the metal layer 301a and/or metal layer 301c. For example, the thickness of the metal layer 301b can be in a range between about 1.1 times and about 2 times the thickness of the metal layer 301a and/or the metal layer 301c.

[0273] In various implementations, one or more of the metal layers 301a, 301b and 301c can be configured as a continuous layer. However, in some implementations, one or more of the metal layers 301a, 301b and 301c can be discontinuous. Accordingly, any of the metal layers 301a, 301b and 301c can comprise separate regions comprising the metallic material separated by regions comprising a non-metallic material. For example, any of the metal layers 301a, 301b and 301c can comprise one or more islands comprising the metallic material spaced apart by regions comprising dielectric material such as the dielectric material of one or both of the layers 303a and 303b. In various implementations, one or more of the metal layers 301a, 301b and 301c need not be a continuous layer or film. Instead, any of the metal layers 301a, 301b and 301c can be configured in the form of spheres or half-domes. In some implementations, one or more of the metal layers 301a, 301b and 301c configured in the form of spheres or half-domes can coalesce into a continuous film during or following the fabrication process.

[0274] In various implementations, the different metal layers 301a, 301b, and 301c can have a ratio of the real part (n) of the refractive index of the different metal layers 301a, 301b, and 301c to the imaginary part (k) of the refractive index that is greater than or equal to about 0.01 and less than or equal to about 0.2. For example, the different metal layers 301a, 301b, and 301c can comprise metals that have an n/k value between about 0.01 and about 0.2, between about 0.015 and about 0.2, between about 0.01 and about 0.15, between about 0.01 and about 0.1, between about 0.1 and about 0.2, or any value in a range or sub-range defined by any these values. As another example, the different metal layers 301a, 301b, and 301c can comprise metals that have an n/k value of about 0.0166. As yet another example, the different metal layers 301a, 301b, and 301c can comprise metals that have an n/k value of about 0.158.

[0275] The different dielectric layers 303a and 303b can have a thickness between about 40 nm and about 850 nm. For example, the different dielectric layers 303a and 303b can have a thickness greater than or equal to about 50 nm and less than or equal to about 800 nm, greater than or equal to about 75 nm and less than or equal to about 750 nm, greater than or equal to about 100 nm and less than or equal to about 700 nm, greater than or equal to about 150 nm and less than or equal to about 650 nm, greater than or equal to about 200 nm and less than or equal to about 600 nm, greater than or equal to about 250 nm and less than or equal to about 550 nm, greater than or equal to about 300 nm and less than or equal to about 500 nm, greater than or equal to about 350 nm and less than or equal to about 450 nm, or a thickness having a value in any range/sub-range defined by any of these values.

[0276] In various implementations, the different dielectric layers 303a and 303b can have the same thickness. However, in some implementations, the different dielectric layers 303a and 303b can have different thickness. For example, the thickness of one of the dielectric layers 303a or 303b can be in a range between about 1.5 times – 10 times the thickness of another one of the dielectric layers 303a or 303b.

[0277] The different dielectric layers 303a and 303b can have a refractive index between about 1.38 and about 2.4. For example, the refractive index of the different dielectric layers 303a and 303b can be greater than or equal to about 1.38 and less than or equal to about 2.4, greater than or equal to about 1.5 and less than or equal to about 2.3, greater than or equal to about 1.6 and less than or equal to about 2.2, greater than or equal to about 1.7 and less than or equal to about 2.1, greater than or equal to about 1.8 and less than or equal to about 2.1, greater than or equal to about 1.9 and less than or equal to about 2.0, or any values in a range/sub-range defined by any of these values.

[0278] The imaginary part (k) of the refractive index of the different dielectric layers 303a and 303b can be sufficiently low such that the different dielectric layers 303a and 303b are substantially transparent to light in the visible spectral range. For example the imaginary part (k) of the refractive index of the different dielectric layers 303a and 303b can be equal to zero (0) or be close to zero (0). In various implementations, the imaginary part (k) of the refractive index of the different dielectric layers 303a and 303b can be sufficiently low such that very little of the incident visible light is absorbed by the different dielectric layers 303a and 303b. For example, in various implementations the composition and the thickness of the different dielectric layers 303a and 303b can be configured such that less than about 5% of the incident visible light is absorbed by the different dielectric layers 303a and 303b. In various implementations, the different dielectric layers can comprise a material that is water white.

[0279] In some implementations, the dielectric layers 303a and 303b can comprise materials including but not limited to silicon dioxide (SiO_2), magnesium fluoride (MgF_2), zirconium dioxide (ZrO_2), ceric oxide (CeO_2), titanium dioxide (TiO_2), tantalum pentoxide (Ta_2O_5), yttrium oxide (Y_2O_3), indium oxide (In_2O_3), tin oxide

(SnO_2), indium tin oxide (ITO), aluminum oxide (Al_2O_3) , or tungsten trioxide (WO_3), organic polymer layers or combinations thereof.

[0280] Various implementations of the optical structure 300a can comprise optional passivation layers (or protective layers or "flash" layers) 305a and 305b disposed on a side of the metal layers 301a and 301c that is opposite to the side facing the dielectric layers 303a and 303b. Metal surfaces can oxidize and/or corrode, which may affect optical performance. As an example, when exposed silver oxidizes and corrodes, silver sulfide can form and compromise optical performance. Finely divided metal particles, particulates, or pieces may also spontaneously combust under the right conditions. For example, fires may occur in a coating machine when the machine is brought up to atmosphere. Explosions can also occur during the milling process, e.g., when milling is performed in air, using a cyclone type classifier. The passivation layers 305a and 305b can provide protective layers to enhance durability, potentially reduce or prevent oxidation and/or corrosion of the metal layers 301a and 301b, and allow possibly for safer processing.

[0281] Various embodiments of the optical structure 300a can be configured as platelets that are suspended in an ink medium to form a pigment. In some such embodiments, the passivation layers 305a and 305b can comprise a material having a refractive index that is matched (e.g., substantially equal or equal) to the refractive index of the ink medium. By choosing the material of the passivation layers 305a and 305b to have a refractive index that is matched (e.g., substantially equal or equal) to the refractive index of the ink medium, the passivation layers 305a and 305b can be configured to reduce or prevent oxidation or corrosion of the metal layers 301a and 301b without affecting or substantially affecting the overall optical properties of the optical structure 300a. For example, silicon dioxide can be used to closely or substantially optically match the ink medium (e.g., a medium comprising resin). Various implementations of the optical structure 300a can be configured as films, foils, threads, laminates, hot stamps, window patches, labels, etc. In some instances, the passivation layers 305a and 305b can comprise a material having a high refractive index (e.g., greater than or equal to about 1.65). In some implementations, zinc sulfide can be used outside of a non-shifting optical stack with negligible effect on the optical performance in either reflection or transmission.

[0282] The passivation layers 305a and 305b can have a thickness in a range from about 2 nm to about 500 nm. For example, the thickness of the passivation layers 305a and 305b can be greater than or equal to about 2 nm and less than or equal to about 10 nm, greater than or equal to about 2 nm and less than or equal to about 20 nm, greater than or equal to about 5 nm and less than or equal to about 10 nm, greater than or equal to about 5 nm and less than or equal to about 20 nm, greater than or equal to about 10 nm and less than or equal to about 20 nm, greater than or equal to about 20 nm and less than or equal to about 40 nm, greater than or equal to about 30 nm and less than or equal to about 50 nm, greater than or equal to about 40 nm and less than or equal to about 60 nm, greater than or equal to about 50 nm and less than or equal to about 70 nm, greater than or equal to about 60 nm and less than or equal to about 80 nm, greater than or equal to about 70 nm and less than or equal to about 90 nm, greater than or equal to about 80 nm and less than or equal to about 100 nm, greater than or equal to about 90 nm and less than or equal to about 110 nm, greater than or equal to about 100 nm and less than or equal to about 150 nm. greater than or equal to about 125 nm and less than or equal to about 175 nm, greater than or equal to about 150 nm and less than or equal to about 200 nm, greater than or equal to about 175 nm and less than or equal to about 225 nm, greater than or equal to about 200 nm and less than or equal to about 250 nm, greater than or equal to about 225 nm and less than or equal to about 275 nm, greater than or equal to about 300 nm and less than or equal to about 350 nm, greater than or equal to about 325 nm and less than or equal to about 375 nm, greater than or equal to about 350 nm and less than or equal to about 400 nm, greater than or equal to about 400 nm and less than or equal to about 450 nm, greater than or equal to about 450 nm and less than or equal to about 500 nm, or any thickness in any range/sub-range defined by any of these values.

[0283] In some instances, the passivation layers 305a and 305b can comprise a material having a refractive index between about 1.45 and about 1.6. For example, the passivation layers 305a and 305b can comprise a material having a refractive index greater than or equal to about 1.45 and less than or equal to about 1.55, greater than or equal to about 1.48 and less than or equal to about 1.57, greater than or equal to about 1.5

and less than or equal to about 1.58, greater than or equal to about 1.53 and less than or equal to about 1.6, or any value in any range/sub-range defined by any of these values. In various implementations, the passivation layers 305a and 305b can comprise silicon dioxide, a transparent dielectric material or a ultraviolet (UV) curable polymer.

[0284] In some instances, the passivation layers 305a and 305b can comprise a material having an refractive index greater than or equal to about 1.65. In various implementations, the passivation layers 305a and 305b can comprise ZrO_2, TiO_2, ZnS, ITO (indium tin oxide), CeO_2 or Ta_2O_3.

[0285] Many implementations of the optical structure 300a may comprise no more than three metal layers 301a, 301b, and 301c and no more than two dielectric layers 303a and 303b. For example, various implementations of the optical structure 300a may comprise exactly three metal layers 301a, 301b, and 301c and exactly two dielectric layers 303a and 303b. Some such implementations of the optical structure 300a can have a thickness that is less than or equal to about 2.5 microns.

[0286] Fabricating the optical structure 300a can include providing a first layer 303a comprising dielectric material and depositing a layer of metal 301b on one side of the first dielectric layer 303a. A second layer 303b comprising dielectric material can be disposed over the metal layer 301b. A layer of metal 301a can be further disposed over the side of the first dielectric layer 303a that is opposite the side of the metal layer 301b. A layer of metal 301c can be further disposed over the side of the second dielectric layer 303b that is opposite the side of the metal layer 301b. The metal layers 301a, 301b, and 301c can be deposited as a continuous thin film, as small spheres, metallic clusters or island like structures. The first dielectric layer 303a can be disposed and/or formed over a support. The support is also referred to herein as a base layer. The support can comprise a carrier. The support can comprise a sheet such as a web. The support can comprise a substrate. The substrate can be a continuous sheet of PET, acrylate, or other polymeric web structure. The support can comprise a non-woven fabric. Non-woven fabrics can be flat, porous sheets comprising fibers. In some implementations, the non-woven fabric can be configured as a sheet or a web structure that is bonded together by entangling fiber or filaments mechanically, thermally, or chemically. In some implementations, the non-woven fabric can comprise perforated films. In some implementations, the non-woven fabric can comprise synthetic fibers such as polypropylene or polyester or fiber glass.

[0287] The support can be coated with a release layer comprising a release agent. The release agent can be soluble in solvent or water. The release layer can be polyvinyl alcohol, which is water soluble or an acrylate which is soluble in a solvent. The release layer can comprise a coating, such as, for example, salt (NaCl) or cryolite (Na_3AlF_6) deposited by evaporation before the layers of the optical structure are deposited/formed.

[0288] In some implementations using a support configured as a non-woven fabric, the non-woven fabric can be coated with a release layer. Such implementations can be dipped or immersed in a solvent or water that acts as a release agent to dissolve or remove the release layer. The release agent (e.g., the solvent or water) is configured to penetrate from a side of the non-woven fabric opposite the side on which the optical structure is disposed to facilitate release of the optical structure instead of having to penetrate through the optical structure.

[0289] One method of fabricating the optical structure 300a shown in Figure 24A utilizes a vacuum roll coater. In this method, the optical structure 300a is fabricated by depositing the metallic and dielectric materials of the various layers on a web using vacuum deposition methods, such as, for example, electron beam (e-beam) deposition, sputtering and/or resistive heating. The web can comprise a polymeric material, such as for example polyethylene terephthalate (PET) or acrylate. If the optical structure is configured to be used as a foil or a film, then the various layers of the optical structure 300a can be deposited directly on a surface of the web. However, in other implementations, a release coating can be applied to the surface of the web prior to the vacuum deposition of the various layers. For example, if the optical structure 300a is configured to be used as a pigment, then the optical structure can be applied on the release coating. In some implementations, the various layers of the optical stack 300a can be deposited in series. For example, in certain implementations, the metal layer 301c can be deposited first followed by the dielectric layer 303b, followed by the metal layer 301b, followed by the dielectric layer 303a, followed by the metal layer 301a. In various implementations of the optical structure can include the passivation layers 305a and

305b, for example, the passivation layer 305b can be deposited prior to the deposition metal layer 301c and the passivation layer 305a can be deposited over the metal layer 301a.

[0290] In some implementations, the optical structure 300a fabricated using the vacuum roll coater can be released from the web by immersing the web comprising the release layer and the deposited optical structure in a bath of a solvent comprising salt (NaCl) or cryolite (Na_3AlF_6) to remove or dissolve the release layer and release the optical structure 300a. In some cases, the optical structure 300a can break or shatter in pieces having various shapes and sizes when released from the web. The solvent can be removed and the various pieces of the optical structure 300a can be dried and subsequently milled to form platelets having desired size and thickness for use as a pigment (e.g., in Intaglio ink).

[0291] Figure 24B illustrates a cross-sectional view of an implementation of an optical structure 300b including a first region 310 comprising a first metallic material which is surrounded by a second region 312 comprising a dielectric material. The second region 312 comprising the dielectric material can be surrounded by a third region 314 comprising a second metallic material. The third region 314 can be optionally surrounded by a fourth region 316 comprising a dielectric material having a refractive index between about 1.45 and about 1.6 configured as a passivation region to reduce or prevent oxidation of the second metallic material. Such a structure can be considered to have three metal layers, two dielectric layers and two optional passivation layers as noted from the cross-sectional view shown in Figure 24B. The optical structure 300b can be fabricated by providing a substrate comprising the first metallic material and disposing the dielectric material on the exposed surfaces of the substrate using physical and/or chemical deposition methods. The exposed surfaces of the dielectric material can be covered by the second metallic material using physical and/or chemical deposition methods. For example, the optical structure 300b can be fabricated using various methods described in U.S. Patent No. 6,524,381 which is incorporated herein by reference in its entirety.

[0292] The chemical composition and various physical characteristics (e.g., thickness) of the first region 310 can be similar to the chemical composition and various physical characteristics (e.g., thickness) of the metal layer 301b discussed above. The chemical composition and various physical characteristics (e.g., thickness) of the second region 312 can be similar to the chemical composition and various physical characteristics (e.g., thickness) of the dielectric layers 303a and 303b discussed above. The chemical composition and various physical characteristics (e.g., thickness) of the third region 314 can be similar to the chemical composition and various physical characteristics (e.g., thickness) of the metal layers 301a and 301c discussed above. The chemical composition and various physical characteristics (e.g., thickness) of the fourth region 316 can be similar to the chemical composition and various physical characteristics (e.g., thickness) of the passivation layers 305a and 305b discussed above.

[0293] Accordingly, in various implementations, the first region 310 can comprise silver, silver alloys, gold and/or gold alloys. The thickness of the first region 310 can be between about 3 nm and about 100 nm. The second region 312 can comprise materials including but not limited to silicon dioxide (SiO_2), magnesium fluoride (MgF_2), zirconium dioxide (ZrO_2), ceric oxide (CeO_2), titanium dioxide (TiO_2), tantalum pentoxide (Ta_2O_5), yttrium oxide (Y_2O_3), indium oxide (In_2O_3), tin oxide (SnO_2), indium tin oxide (ITO), aluminum oxide (Al_2O_3) , or tungsten trioxide (WO_3), or organic polymer layers. or combinations thereof. The second region 312 can extend to a height between about 50 nm and 800 nm from an outermost surface of the first region 310. The third region 314 can comprise silver, silver alloys, gold and/or gold alloys and extend to a height between about 3 nm and about 100 nm from an outermost surface of the first region 310. The fourth region 316 can comprise a dielectric material having a refractive index between about 1.45 and about 1.6 and extend to a height between about 10 nm and about 100 nm from an outermost surface of the third region 314.

[0294] In various implementations, the first region 310 can be configured as a slab, flake, a sphere, spheroid, ellipsoid, disc, or any other 3-dimensional shape enclosing a volume. The first region 310 may have a regular or irregular shape. For example, as shown in Figure 24B, the first region 310 can be configured as a slab (e.g., a slab having nanometer scale thickness and micrometer scale lateral dimensions) having two major surfaces and one or more edge surfaces disposed between the two major surfaces. In some implementations, a number of edge surfaces may be disposed between the two major surfaces of the slab. The number of edge surfaces may, for example, be one, two, three, four, five, six, seven, eight, nine, ten, twelve, twenty, thirty, fifty, etc. or in any range between any of these values. Values outside these ranges are also possible. The major surfaces of the slab can have a variety of shapes. For example, one or both of the major surfaces 310a and 310b can have a rectilinear or curvilinear shape in certain implementations. The shape may be regular or irregular in certain implementations. For example, one or both of the major surfaces can have a square shape, a rectangular shape, a circular shape, an oval shape, an elliptical shape, pentagonal shape, a hexagonal shape, an octagonal shape or any polygonal shape. In various implementations, one or both of the major surface can have jagged edges such that the lateral dimensions (e.g., length or width) of the one or both of the major surface varies across the area of the one or both of the major surface. Other configurations are also possible. Additionally, other shapes are also possible. One or more of the edge surfaces can have a variety of shapes (e.g., as viewed from the side), such as, for example, a square shape, a rectangular shape, an oval shape, an elliptical shape, a pentagonal shape, a hexagonal shape, an octagonal shape or any a polygonal shape.

[0295] The shape of the one or more of the edge surfaces (e.g., as viewed from the side) can be rectilinear or curvilinear in certain implementations. The shape may be regular or irregular in certain implementations. Similarly, the cross-section through the first region 310 parallel to one of the major surfaces, can be rectilinear or curvilinear in certain implementations and can be regular or irregular in certain implementations. For example, the cross-section can have a square shape, a rectangular shape, a circular shape, an oval shape, an elliptical shape, pentagonal shape, a hexagonal shape, an octagonal shape or any a polygonal shape. Other shapes are also possible. Likewise, the cross-section through the first region 310 perpendicular to one of the major surfaces, can be rectilinear or curvilinear in certain implementations and can be regular or irregular implementations. For example, the cross-section can have a square shape, a rectangular shape, a circular shape, an oval shape, an elliptical shape, pentagonal shape, a hexagonal shape, an octagonal shape or any a polygonal shape. Other shapes are also possible. In various implementations, an area, a length and/or a width of the major surfaces of the first region 310 can be greater than or equal to about 2, 3, 4, 5, 6, 8, or 10 times the thickness of the first region 310 and less than or equal to about 50 times the thickness of the first region 310, or any value in a range/sub-range between any of these values. Accordingly, the first region 310 can have a large aspect ratio. Other sizes and shapes, however, are possible.

[0296] The optical structure 300a and 300b can be configured as a film or a foil by disposing over a substrate or other support layer having a thickness, for example, greater than or equal to about 10 microns and less than or equal to about 25 microns. For example, a substrate or support layer can have a thickness greater than or equal to 12 microns and less than or equal to 22.5 microns, greater than or equal to 15 microns and less than or equal to about 20 microns. The substrate or support layer can comprise materials, such as, for example, polyethylene terephthalate (PET), acrylate, polyester, polyethylene, polypropylene, or polycarbonate. The support or support layer itself can be dissolvable. The support or support layer, for example, can also comprise polyvinyl alcohol, which can be dissolved, for example, in water. Accordingly, instead of using a release layer on a insoluble support web, the support web itself may comprise soluble material. Accordingly, the support or support layer can be dissolved leaving the optical coating remaining. The optical structure 300a configured as a film or a foil can be encapsulated with a polymer, such as, for example a UV cured polymer.

[0297] Instead of a film or a foil, the optical structure 300a or 300b can be divided into platelets having a size that is suitable for a pigment or printing ink. Platelets having a size that is suitable for a pigment or printing ink can have an length, and/or width that is about 5-10 times, 10-20 times or 30-40 times the thickness of the platelet, in some implementations. Accordingly, the platelets can have a thickness of about 1 micron, and/or can have a width and/or a length that is between approximately 5 micron and about 50 microns. For example, the width and/or a length can be greater than or equal to about 5 micron and less than or equal to about 15 microns, greater than or equal to about 5 microns and less than or equal to about 10 microns, greater than or equal to about 5 micron and less than or equal to about 40 microns, greater than or equal to about 5 microns and less than or equal to about 20 microns, or any value in the ranges/sub-ranges defined by these values. Platelets having a length and/or width that is less than about 5-10 times the thickness of the platelet, such as, for example having a length and/or width that is equal to the thickness of the platelet can be oriented along their edges in the printing ink or pigment. This can be disadvantageous in some implementations since pigment or printing ink comprising platelets that are oriented along their edges may not exhibit the desired colors in reflection and transmission modes. Dimensions such as, thicknesses, lengths and/or widths outside these ranges, however, are also possible.

[0298] In some implementations, the optical structure 300a or 300b can be fractured, cut, diced or otherwise separated to obtain the separate, for example, pieces or platelets. These pieces or platelets can have micron scale sizes in certain embodiments. In some implementations, the obtained platelets may be surrounded by an encapsulating layer similar to the encapsulating layer 21 discussed above. For example, the optical structures 300a and 300b including the passivation layers 305a and 305b can further comprise an encapsulating layer similar to the encapsulating layer 21 discussed above. In some implementations, the encapsulating layer can comprise a moisture resistant material, such as, for example silicon dioxide. The encapsulating layer can also comprise silica spheres similar to silica spheres 22 and 23 discussed above. The encapsulating layer can additionally and/or alternatively reduce the occurrence of delamination of the different layers of the optical structure 300a/300b. The optical structures 300a/300b with the surrounding encapsulating layer, which may potentially comprise the silica spheres, can be configured as platelets that are suitable for a pigment or printing ink. The silica spheres of the encapsulating layer can help prevent the platelets from adhering to one another. For example, in some cases, without the spheres the platelets may stick together. The silica spheres can also prevent or reduce the likelihood of the platelets sticking to the print rollers in the printing machine. One method of surrounding the optical structure 300a/300b with the encapsulating layer comprising silica spheres can rely on sol-gel technology using tetraethylorthosilicate (TEOS) discussed above. Other processes, however, may be employed.

[0299] The pigment can be formed by a plurality of optical structures 300a/300b configured as platelets. Such a pigment may be color shifting (e.g., the color reflected and/or transmitted changes with angle of view or angle of incidence of light), in some cases. In some embodiments, non-color shifting pigment or dye may be mixed with the pigment. In some embodiments other materials may be included with the plurality of optical structures 300a/300b configured as platelets to form the pigment. Although some of the resultant pigments discussed herein can provide color shift with change in viewing angle or angle of incidence of light, pigments that do not exhibit color shift with change in viewing angle or angle of incidence of light or that produce very little color shift with change in viewing angle or angle of incidence of light are also contemplated.

[0300] In some embodiments, the plurality of optical structures 300a/300b configured as platelets can be added to a medium such as a polymer (e.g., a polymeric resin) to form a dichroic ink, a pigment, or paint as discussed above with reference to Figure 12B-1. In some implementations, the medium can be an organic resin. The refractive index of the medium can be in a range between about 1.4 and about 1.6 (e.g. 1.5). The medium can comprise an optical material that is substantially clear. The medium can be substantially transparent to visible light. The platelets can be suspended in the medium (e.g., polymer). The platelets can be randomly oriented in the medium (e.g., polymer) as discussed above with reference to Figure 12B-1. During the printing process, in some cases, the individual platelets (e.g., the majority of the platelets) can be oriented parallel to the surface of the object (e.g., paper) to which the pigment, the paint, or the dichroic ink is being applied as a result of, for example, the printing action, gravity, and/or surface tension of the normal drying process of the pigment, the paint, or the dichroic ink as discussed above with reference to Figure 12B-2. The medium can comprise material including but not limited to acrylic melamine, urethanes, polyesters, vinyl resins, acrylates, methacrylate, ABS resins, epoxies, styrenes and formulations based on alkyd resins and mixtures thereof. In some implementations, the passivation layer 305a and 305b, the encapsulating layer and/or the silica balls can have a refractive index that closely matches the refractive index of the medium, e.g., polymer, in which the optical structures 300a/300b configured as platelets are suspended such that the passivation layers 305a/305b, the encapsulating layer and/or the silica balls do not adversely affect the optical performance of the pigment, the paint, or the dichroic ink in the medium.

[0301] In various implementations, the optical structures 300a/300b configured as platelets need not be surrounded by an encapsulating layer. In such implementations, one or more platelets that are not encapsulated by an encapsulating layer can be added or mixed with an ink or a pigment medium (e.g., varnish, polymeric resin, etc.) to obtain a dichroic ink or pigment as discussed above. In various implementations, the dichroic ink or pigment can comprise a plurality of platelets. The optical structures 300a/300b that are configured as the plurality of platelets can have different distributions of shapes, sizes, thicknesses and/or aspect ratios. The optical structures 300a/300b that are configured as the plurality of platelets can also have different optical properties. For example, the optical structures 300a/300b that are configured as the plurality of platelets can also have different color properties.

[0302] In various implementations, a silane coupling agent can be bonded to the encapsulating layer of the optical structures 300a/300b as discussed above with reference to Figure 13. As discussed above, bonding of the silane coupling agent to the encapsulating layer can occur through a hydrolyzing reaction. The silane coupling agent can bind to the polymer (e.g., polymeric resin) of the printing ink or paint medium so that the heterogeneous mixture of pigment and the polymer do not separate during the printing process and substantially function in much the same way as a homogeneous medium would function. The printing ink or paint medium can comprise material including but not limited to acrylic melamine, urethanes, polyesters, vinyl resins, acrylates, methacrylate, ABS resins, epoxies, styrenes and formulations based on alkyd resins and mixtures thereof. The silane coupling agents used can be similar to the silane coupling agents sold by Gelest Company (Morristown, PA USA). In some implementations, the silane coupling agent can comprise a hydrolyzable group, such as, for example, an alkoxy, an acyloxy, a halogen or an amine. Following a hydrolyzing reaction (e.g., hydrolysis), a reactive silanol group is formed, which can condense with other silanol groups, for example, with the silica spheres of the encapsulating layer or the encapsulating layer of silica to form siloxane linkages. The other end of the silane coupling agent comprises the R-group. The R-group can comprise various reactive compounds including but not limited to compounds with double bonds, isocyanate or amino acid moieties. Reaction of the double bond via free radical chemistry can form bonds with the ink polymer(s) such as those based on acrylates, methacrylates or polyesters based resins. For example, isocyanate functional silanes, alkanolamine functional silanes and aminosilanes can form urethane linkages.

[0303] Without any loss of generality, in various implementations of the optical structure 300a/300b configured as a platelet that do not comprise the encapsulating layer, the silane coupling agent can be bonded to one or both of the passivation layers 305a/305b comprising a dielectric material (e.g., TiO_2) suitable to be bonded with the silane coupling agent.

[0304] An ink comprising various implementations of the optical structure 300a/300b configured as platelets can be applied to a substrate (e.g., a polyester web) and dried. In some implementations, the substrate comprising the ink can be cut in strips to form a security thread having the optical characteristics of the various implementations of the optical structure 300a/300b. For example, depending on the thickness and composition of the various layers of the various implementations of the optical structure 300a/300b included in the ink, the ink can produce a color in transmission mode and a different color in reflection mode. As discussed above, in some implementations, the color in the transmission mode can be a complementary color of the color in the reflection mode. Additionally, in some implementations, the color in the transmission mode and the reflection mode can vary with viewing angle. The security thread can be integrated with products and/or packaging to improve security of the products and/or packaging. In some implementations, the substrate comprising the ink including various implementations of the optical structure 300a/300b can be configured as a laminate and adhered to a security document (e.g., a banknote). In some implementations, the ink comprising various implementations of the optical structure 300a/300b applied to a releasable carrier web can be configured as a hot stamp having the optical characteristics of the various implementations of the optical structure 300a/300b.

[0305] Without any loss of generality, the optical structure 300a/300b can be considered as an interference stack or cavity. Ambient light incident on the surface of the optical structure 300a/300b is partially reflected from the various layers of the optical structure 300a/300b and partially transmitted through the various layers of the optical structure 300a/300b. Some wavelengths of the ambient light reflected from the various layers may interfere constructively and some other wavelengths of the ambient light reflected from the various layers may interfere destructively. Similarly, some wavelengths of light transmitted through the various layers may interfere constructively and some other wavelengths of the ambient light transmitted through the various layers may interfere destructively. As a result of which, the optical structure 300a/300b appears colored when viewed in transmission and reflection mode. In general, the color and the intensity of light reflected by and transmitted through the optical structure 300a/300b can depend on the thickness and the material of the various layers of the optical structure 300a/300b. By changing the material and the thickness of the various layers, the color and intensity of light reflected by and transmitted through the optical structure 300a/300b can be varied.

[0306] Without subscribing to any particular scientific theory about the operation of the optical structures 300a/300b, in general, the material and the thickness of the various layers can be configured such that some or all of the ambient light reflected by the various layers interfere such that a node in the field occurs at one or more of the three metal layers 301a, 301b, and 301c for some of the wavelengths of the ambient light. For example, some or all of the ambient light reflected by the various layers interfere such that a node in the field occurs at all the three metal layers 301a, 301b, and 301c for some of the wavelengths of the ambient light. Again, without subscribing to a particular scientific theory, based on the thickness of the three metal layers 301a, 301b, and 301c and the dielectric layers 303a and 303b, a portion of the incident light may be transmitted through the optical structure 300a/300b as a result of the phenomenon of "induced transmittance" or "induced transmission". The reflection and transmission spectral characteristics are discussed below.

[0307] Figure 25A is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light transmitted through a first example of the optical structure 300a or 300b for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure 300a or 300b. Figure 25B is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light reflected from the first example of the optical structure 300a or 300b for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure 300a or 300b. The first example of the optical structure 300a or 300b comprises a layer of silver (Ag) (corresponding to the layer 301b of Figure 24A or the region 310 of Figure 24B) having a thickness of about 100 nm surrounded by two layers of a dielectric material comprising zinc sulfide (ZnS) (corresponding to the layers 303a and 303b of Figure 24A or the region 312 of Figure 24B) having an individual thickness of about 66 nm. The first example further comprises two additional silver layers disposed over the two dielectric layers (corresponding to the layers 301a and 301c of Figure 24A or the region 314 of Figure 24B) having an individual thickness of about 50 nm. To obtain the chromaticity of x and y chromaticity coordinates of light reflected from and transmitted through the first example of the optical structure 300a or 300b, the optical structure 300a or 300b is encapsulated in a SiO_2 matrix, which is used to simulate the printing medium or ink which has a similar refractive index.

[0308] As noted from Figures 25A and 25B, the first example of the optical structure 300a or 300b appears in different shades of green when viewed in the transmission mode at different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure 300a or 300b and appears greyish purple when viewed in the reflection mode at different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure 300a or 300b. The color in the transmission mode and the color in the reflection mode are complementary to each other. It is observed from Figure 25B that the color in the reflection mode does not vary significantly when viewed in the reflection mode at different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure 300a or 300b. It is observed from Figure 25A that there is a slight variation of the color in the transmission mode when viewed in the transmission mode at different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure 300a or 300b.

[0309] Figure 25C illustrates the a*b* values in the CIE L*a*b* color space when the first example of the optical structure 300a/300b is viewed in the transmission mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the first example of the optical structure 300a/300b. As the viewing angle increases the color of the first example of the optical structure 300a/300b in the transmission mode shifts in the direction of the arrow 1501. For example, the color of the first example in the transmission mode can have a lightness (L*) value between approximately 12.5 and approximately 17.0 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the first example of the optical structure 300a/300b. The color of the first example in the transmission mode can have an (a*) value between approximately -44.5 and approximately -51.5 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the first example of the optical structure 300a/300b. The color of the first example in the transmission mode can have a (b*) value between approximately 20.5 and approximately 27.0 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the first example of the optical structure 300a/300b.

[0310] Figure 25D illustrates the a*b* values in the CIE L*a*b* color space when the first example of the optical structure 300a/300b is viewed in the reflection mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the first example of the optical structure 300a/300b. It is noted that as the viewing angle increases the color of the first example of the optical structure 300a/300b in the reflection mode does not shift significantly. The color of the first example in the reflection mode can have a lightness (L*) value between approximately 92.7 and approximately 92.8 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the first example of the optical structure 300a/300b. The color of the first example in the reflection mode can have an (a*) value between approximately 18.0 and approximately 19.1 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the first example of the optical structure 300a/300b. The color of the first example in the reflection mode can have a (b*) value between approximately -8.7 and approximately -9.9 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the first example of the optical structure 300a/300b.

[0311] Figure 26A is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light transmitted through a second example of the optical structure 300a or 300b for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure 300a or 300b. Figure 26B is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light reflected from the second example of the optical structure 300a or

300b for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure 300a or 300b. The second example of the optical structure 300a or 300b comprises a layer of silver (Ag) (corresponding to the layer 301b of Figure 24A or the region 310 of Figure 24B) having a thickness of about 10 nm surrounded by two layers of a dielectric material comprising zinc sulfide (ZnS) (corresponding to the layers 303a and 303b of Figure 24A or the region 312 of Figure 24B) having an individual thickness of about 66 nm. The second example further comprises two additional silver layers disposed over the two dielectric layers (corresponding to the layers 301a and 301c of Figure 24A or the region 314 of Figure 24B) having an individual thickness of about 5 nm. To obtain the chromaticity of x and y chromaticity coordinates of light reflected from and transmitted through the second example of the optical structure 300a or 300b, the optical structure 300a or 300b is encapsulated in a SiO_2 matrix which is used to simulate the printing medium or ink which has a similar refractive index.

[0312] As noted from Figures 26A and 26B, the second example of the optical structure 300a or 300b appears greenish grey when viewed in the transmission mode at different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure 300a or 300b and appears blue or deep purple when viewed in the reflection mode at different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure 300a or 300b.

[0313] Figure 26C illustrates the a*b* values in the CIE L*a*b* color space when the second example of the optical structure 300a/300b is viewed in the transmission mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the second example of the optical structure 300a/300b. As the viewing angle increases the color of the second example of the optical structure 300a/300b in the transmission mode shifts in the direction of the arrow 1601. The color of the second example in the transmission mode can have a lightness (L*) value between approximately 96.0 and approximately 98.5 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the second example of the optical structure 300a/300b. The color of the second example in the transmission mode can have an (a*) value between approximately -6.2 and approximately -9.0 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the second example of the optical structure 300a/300b. The color of the second example in the transmission mode can have a (b*) value between approximately 12.9 and approximately 25.7 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the second example of the optical structure 300a/300b.

[0314] Figure 26D illustrates the a*b* values in the CIE L*a*b* color space when the second example of the optical structure 300a/300b is viewed in the reflection mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the second example of the optical structure 300a/300b. As the viewing angle increases the color of the second example of the optical structure 300a/300b in the reflection mode shifts in the direction of the arrow 1603. The color of the second example in the reflection mode can have a lightness (L*) value between approximately 11.0 and approximately 26.5 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the second example of the optical structure 300a/300b. The color of the second example in the reflection mode can have an (a*) value between approximately 44.5 and approximately 63.8 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the second example of the optical structure 300a/300b. The color of the second example in the reflection mode can have a (b*) value between approximately -69.0 and approximately -72.0 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the second example of the optical structure 300a/300b.

[0315] Figure 27A shows the variation of the transmittance with wavelength for a third example of the optical structure 300a/300b at a viewing angle of 0 degrees with respect to a normal to the surface of the optical structure 300a/300b. Figure 27B shows the variation of the reflectance with wavelength for the third example of the optical structure 300a/300b at a viewing angle of 0 degrees with respect to a normal to the surface of the optical structure 300a/300b. The third example of the optical structure 300a or 300b comprises a layer of silver (Ag) (corresponding to the layer 301b of Figure 24A or the region 310 of Figure 24B) having a thickness of about 40 nm surrounded by two layers of a dielectric material comprising magnesium fluoride (MgF_2) (corresponding to the layers 303a and 303b of Figure 24A or the region 312 of Figure 24B) having an individual thickness of about 185 nm. The third example further comprises two additional silver layers disposed over the two dielectric layers (corresponding to the layers 301a and 301c of Figure 24A or the region 314 of Figure 24B) having an individual thickness of about 23 nm. The third example of the optical structure 300a or 300b is encapsulated in a SiO_2 matrix which is used to simulate the printing medium or ink which has a similar refractive index.

[0316] It is observed from Figure 27A that the transmittance through the third example of the optical structure 300a/300b is less than 10% in a wavelength range between about 400 nm and about 600 nm. The transmittance is greater than about 10% for wavelengths greater than about 600 nm and less than about 700 nm. The maximum value of the transmittance occurs at a wavelength between about 630 nm and about 650 nm. It is observed from Figure 27B that the reflectance from the third example of the optical structure 300a/300b is less than 30% for wavelengths between about 630 nm and about 680 nm. It is observed from the transmittance and the reflectance spectra that the third example of the optical structure 300a/300b will appear red/orange in the transmission mode and grey/blue in the reflection mode.

[0317] Figure 27C is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light transmitted through the third example of the optical structure 300a or 300b for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure 300a or 300b. As the viewing angle increases, the color of the optical structure 300a or 300b changes from red towards green in the direction of the arrow 1701. Figure 27D illustrates the a*b* values in the CIE L*a*b* color space when the third example of the optical structure 300a/300b is viewed in the transmission mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the third example of the optical structure 300a/300b. As the viewing angle increases the color of the third example of the optical structure 300a/300b in the transmission mode shifts in the direction of the arrow 1703. The color of the third example in the transmission mode can have a lightness (L*) value between approximately 26.8 and approximately 77.2 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the third example of the optical structure 300a/300b. The color of the third example in the transmission mode can have an (a*) value between approximately -19.2 and approximately 66.0 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the third example of the optical structure 300a/300b. The color of the third example in the transmission mode can have a (b*) value between approximately 35.9 and approximately 98.8 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the third example of the optical structure 300a/300b.

[0318] Figure 27E is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light reflected from the third example of the optical structure 300a or 300b for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the third example of the optical structure 300a or 300b. As the viewing angle increases, the color of the optical structure 300a or 300b changes from grey towards blue in the direction of the arrow 1705. Figure 27F illustrates the a*b* values in the CIE L*a*b* color space when the third example of the optical structure 300a/300b is viewed in the reflection mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the third example of the optical structure 300a/300b. As the viewing angle increases the color of the third example of the optical structure 300a/300b in the reflection mode shifts in the direction of the arrow 1707. The color of the third example in the reflection mode can have a lightness (L*) value between approximately 63.3 and approximately 97.2 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the third example of the optical structure 300a/300b. The color of the third example in the reflection mode can have an (a*) value between approximately -48.0 and approximately 15.5 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the third example of the optical structure 300a/300b. The color of the third example in the reflection mode can have a (b*) value between approximately -1.0 and approximately -57.9 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the third example of the optical structure 300a/300b.

[0319] Figure 28A shows the variation of the transmittance with wavelength for a fourth example of the optical structure 300a/300b at a viewing angle of 0 degrees with respect to a normal to the surface of the optical structure 300a/300b. Figure 28B shows the variation of the reflectance with wavelength for the fourth example of the optical structure 300a/300b at a viewing angle of 0 degrees with respect to a normal to the surface of the optical structure 300a/300b. The fourth example of the optical structure 300a or 300b comprises a layer of gold (Au) (corresponding to the layer 301b of Figure 24A or the region 310 of Figure 24B) having a thickness of about 40 nm surrounded by two layers of a dielectric material comprising magnesium fluoride (MgF_2) (corresponding to the layers 303a and 303b of Figure 24A or the region 312 of Figure 24B) having an individual thickness of about 185 nm. The fourth example further comprises two additional gold layers disposed over the two dielectric layers (corresponding to the layers 301a and 301c of Figure 24A or the region 314 of Figure 24B) having an individual thickness of about 23 nm. The fourth example of the optical structure 300a or 300b is encapsulated in a SiO_2 matrix which is used to simulate the printing medium or ink which has a similar refractive index.

[0320] It is observed from Figure 28A that the transmittance through the fourth example of the optical structure 300a/300b is less than 10% in a wavelength range between about 400 nm and about 600 nm. The transmittance is greater than about 10% for wavelengths greater than about 600 nm and less than about 700 nm. The maximum value of the transmittance occurs at a wavelength between about 650 nm and about 675 nm. It is observed from Figure 28B that the reflectance from the fourth example of the optical structure 300a/300b is greater than 30% for wavelengths between about 480 nm and about 650 nm. It is observed from the transmittance and the reflectance spectra that the fourth example of the optical structure 300a/300b will appear red/orange in the transmission mode and yellow-green/aquamarine in the reflection mode.

[0321] Figure 28C is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light transmitted through the fourth example of the optical structure 300a or 300b for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure 300a or 300b. As the viewing angle increases, the color of the optical structure 300a or 300b changes from red towards orange in the direction of the arrow 1801. Figure 28D illustrates the a*b* values in the CIE L*a*b* color space when the fourth example of the optical structure 300a/300b is viewed in the transmission mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fourth example of the optical structure 300a/300b. As the viewing angle increases the color of the fourth example of the optical structure 300a/300b in the transmission mode shifts in the direction of the arrow 1803. The color of the fourth example in the transmission mode can have a lightness (L*) value between approximately 27.1 and approximately 62.1 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fourth example of the optical structure 300a/300b. The color of the fourth example in the transmission mode can have an (a*) value between approximately 20.5 and approximately 47.2 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fourth example of the optical structure 300a/300b. The color of the fourth example in the transmission mode can have a (b*) value between approximately 29.5 and approximately 74.3 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fourth example of the optical structure 300a/300b.

[0322] Figure 28E is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light reflected from the fourth example of the optical structure 300a or 300b for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure 300a or 300b. As the viewing angle increases, the color of the optical structure 300a or 300b changes from yellow-green towards aquamarine in the direction of the arrow 1805. Figure 28F illustrates the a*b* values in the CIE L*a*b* color space when the fourth example of the optical structure 300a/300b is viewed in the reflection mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fourth example of the optical structure 300a/300b. As the viewing angle increases the color of the fourth example of the optical structure 300a/300b in the reflection mode shifts in the direction of the arrow 1807. The color of the fourth example in the reflection mode can have a lightness (L*) value between approximately 53.3 and approximately 88.5 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fourth example of the optical structure 300a/300b. The color of the fourth example in the reflection mode can have an (a*) value between approximately -13.9 and approximately -65.5 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fourth example of the optical structure 300a/300b. The color of the fourth example in the reflection mode can have a (b*) value between approximately -13.0 and approximately 59.9 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fourth example of the optical structure 300a/300b.

[0323] Figure 29A shows the variation of the transmittance, reflectance and absorptance with wavelength for a fifth example of the optical structure 300a/300b at a viewing angle of 0 degrees with respect to a normal to the surface of the optical structure 300a/300b. In Figure 29A, curve 1901 shows the variation of transmittance with wavelength, curve 1903 shows the variation of reflectance with wavelength, and curve 1905 shows the variation of absorptance with wavelength. The fifth example of the optical structure 300a or 300b comprises a layer of gold (Au) (corresponding to the layer 301b of Figure 24A or the region 310 of Figure 24B) having a thickness of about 40 nm surrounded by two layers of a dielectric material comprising zinc sulfide (ZnS) (corresponding to the layers 303a and 303b of Figure 24A or the region 312 of Figure 24B) having an individual thickness of about 80 nm. The fifth example further comprises two additional gold layers disposed over the two dielectric layers (corresponding to the layers 301a and 301c of Figure 24A or the region 314 of Figure 24B) having an individual thickness of about 23 nm. The fifth example of the optical structure 300a or 300b is encapsulated in a SiO_2 matrix which is used to simulate the printing medium or ink which has a similar refractive index.

[0324] It is observed from Figure 29A that the transmittance through the fifth example of the optical structure 300a/300b is greater than about 10% for wavelengths greater than about 550 nm and less than about 700 nm. The maximum value of the transmittance occurs at a wavelength between about 600 nm and about 650 nm. It is further observed from Figure 29A that the reflectance from the fifth example of the optical structure 300a/300b is greater than 30% for wavelengths between about 430 nm and about 580 nm. The fifth example of the optical structure 300a/300b has significant absorptance (e.g., greater than about 10%) for wavelengths between about 400 nm and about 700 nm. Accordingly, the color in the transmission mode is not expected to be complementary to the color in the reflection mode.

[0325] Figure 29B is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light transmitted through the fifth example of the optical structure 300a or 300b for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure 300a or 300b. Figure 29C illustrates the a*b* values in the CIE L*a*b* color space when the fifth example of the optical structure 300a/300b is viewed in the transmission mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fifth example of the optical structure 300a/300b. As the viewing angle increases the color of the fourth example of the optical structure 300a/300b in the transmission mode shifts in the direction of the arrow 1907. The color of the fifth example in the transmission mode can have a lightness (L*) value between approximately 54.0 and approximately 58.5 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fifth example of the optical structure 300a/300b. The color of the fifth example in the transmission mode can have an (a*) value between approximately 35.0 and approximately 40.3 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fifth example of the optical structure 300a/300b. The color of the fifth example in the transmission mode can have a (b*) value between approximately 62.8 and approximately 74.9 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fifth example of the optical structure 300a/300b.

[0326] Figure 29D is a CIE 1931 color space chromaticity diagram showing the x and y chromaticity coordinates of light reflected from the fifth example of the optical structure 300a or 300b for different viewing angles between 0 degrees and 40 degrees with respect to a normal to a surface of the optical structure 300a or 300b. Figure 29E illustrates the a*b* values in the CIE L*a*b* color space when the fifth example of the optical structure 300a/300b is viewed in the reflection mode at different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fifth example of the optical structure 300a/300b. As the viewing angle increases the color of the fifth example of the optical structure 300a/300b in the reflection mode shifts in the direction of the arrow 1909. The color of the fifth example in the reflection mode can have a lightness (L*) value between approximately 64.5 and approximately 77.3 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fifth example of the optical structure 300a/300b. The color of the fifth example in the reflection mode can have an (a*) value between approximately -60.1 and approximately -63.7 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fifth example of the optical structure 300a/300b. The color of the fifth example in the reflection mode can have a (b*) value between approximately -0.1 and approximately 6.6 for different viewing angles between 0 degrees and 40 degrees with respect to the normal to the surface of the fifth example of the optical structure 300a/300b.

[0327] Without relying on any particular theory, the color in the reflection and the transmission mode is dependent on the thickness and the composition of the different layers of the optical structure 300a or 300b. For example, in some implementations little to no light is transmitted through an implementation of an optical structure 300a or 300b in which the dielectric layers 303a and 303b are absent. The brightness of the color in the reflection mode can increase as the thickness of the metal layers 301a, 301b, and 301c increases while the brightness of the color in the transmission mode can decrease as the thickness of the metal layers 301a, 301b, and 301c increases in certain implementations.

[0328] Without subscribing on any particular theory, various implementations of the optical structure 300a or 300b can exhibit variation in the reflected and/or transmitted color as the viewing angle changes. The variation in the reflected and/or transmitted color with change in the viewing angle can be large (or significant) if the refractive index of the dielectric material of the layers 303a and 303b has a refractive index less than about 2.0. For example, the variation in the reflected and/or transmitted color with change in the viewing angle can be large (or significant) if the layers 303a and 303b comprises silica (SiO_2) having a refractive index of about 1.5 or magnesium fluoride (MgF_2) having a refractive index of about 1.39. The variation in the reflected and/or transmitted color with change in the viewing angle can be small (or insignificant) if the refractive index of the dielectric material of the layers 303a and 303b has a refractive index greater than about 2.0. For example, the variation in the reflected and/or transmitted color with change in the viewing angle can be small (or insignificant) if the layers 303a and 303b comprises zinc sulfide (ZnS) having a refractive index of about 2.38 or other high refractive index materials such as, for example, zirconium dioxide (ZrO_2) or ceric oxide (CeO_2). In various implementations, the variation in the reflected and/or transmitted color with change in the viewing angle can depend on the thickness of the dielectric layers 303a and 303b.

[0329] The optical structures 300a/300b configured as foil, film or platelets can be incorporated with or in a document (e.g., a banknote), package, product, or other item. Optical products such as a film, a thread, a laminate, a foil, a pigment, or an ink comprising one or more of the optical structures 300a/300b discussed above can be incorporated with or in documents such as banknotes or other documents to verify authenticity of the documents, packaging materials, etc. For example, the optical structures 300a/300b can be configured as an ink or a pigment which is disposed on a base comprising at least one of a polymer, a plastic, a paper or a fabric. The base may be flexible in some implementations. The base comprising the ink or a pigment or pigment comprising the optical structures 300a or 300b can be cut or diced to obtain a thread or a foil. A plurality of optical structures 300a or 300b discussed above can be incorporated in a particular optical product (e.g., ink, pigment, thread, filament, paper, security ink, security pigment, security thread, security filament, security paper, etc.). The shapes, sizes and/or aspect ratios of the plurality of optical structures 300a or 300b discussed above that are incorporated in a particular optical product (e.g., ink, pigment, thread, filament, paper, security ink, security pigment, security thread, security filament, security paper, etc.) can vary. Accordingly, a particular optical product (e.g., ink, pigment, thread, filament, paper, security ink, security pigment, security thread, security filament, security paper, etc.) can comprise optical structures 300a or 300b with different distributions of shapes, sizes and/or aspect ratios of the optical structures. For example, a particular optical product (e.g., ink, pigment, thread, filament, paper, security ink, security pigment, security thread, security filament, security paper, etc.) can comprise optical structures 300a or 300b with sizes distributed around one or more mean sizes. As another example, a particular optical product (e.g., ink, pigment, thread, filament, paper, security ink, security pigment, security thread, security filament, security paper, etc.) can comprise optical structures 300a or 300b with aspect ratios distributed around one or more aspect ratios.

[0330] As discussed above, the color in the reflection mode and the transmission mode of an implementation of an optical structure 300a or 300b depends on the thickness and the composition of the various metal layers and the various dielectric layers that form the implementation of the optical structure 300a or 300b. Accordingly, the reflected and/or transmitted color of a particular optical product (e.g., ink, pigment, thread, filament, paper, security ink, security pigment, security thread, security filament, security paper, etc.) can be tailored by incorporated plurality of optical structures 300a or 300b having different thicknesses and/or compositions of the various constituent layers. By combining plurality of optical structures 300a or 300b having different thicknesses and/or compositions of the various constituent layers, optical products (e.g., ink, pigment, thread, filament, paper, security ink, security pigment, security thread, security filament, security paper, etc.) having different reflected and/or transmitted colors can be manufactured.

[0331] Figures 30A and 30B are CIE 1931 color space chromaticity diagrams respectively showing the x and y chromaticity coordinates of light transmitted through and reflected from various implementations of an optical structure having a geometry similar to optical structure 300a or 300b. The various implementations of the optical structure include three metal layers comprising silver (Ag) and two dielectric layers comprising zinc sulfide (ZnS). The thickness of a central metal layer comprising silver (Ag) (e.g., corresponding to layer 301b in Figure 24A or region 310 in Figure 24B) can be about 40 nm in the various implementations of the optical structure. The thickness of the surrounding metal layers comprising silver (Ag) (e.g., corresponding to layers 301a and 301c in Figure 24A or region 314 in Figure 24B) can be about 25 nm in the various implementations of the optical structure. The thickness of the two dielectric layers (e.g., corresponding to layers 303a and 303b in Figure 24A or region 312 in Figure 24B) can be in a range between about 40 nm and about 183 nm in the various implementations of the optical structure.

[0332] For example, the region 2001 in Figure 30A shows the x and y chromaticity coordinates of light transmitted through an implementation of an optical structure with two dielectric layers comprising zinc sulfide (ZnS) having an individual thickness of about 95 nm. The region 2003 in Figure 30B shows the corresponding x and y chromaticity coordinates of light reflected from the implementation of the optical structure with two dielectric layers comprising zinc sulfide (ZnS) having an individual thickness of about 95 nm. As another example, the region 2005 in Figure 30A shows the x and y chromaticity coordinates of light transmitted through an implementation of an optical structure with two dielectric layers comprising zinc sulfide (ZnS) having an individual thickness of about 66 nm. The region 2007 in Figure 30B shows the corresponding x and y chromaticity coordinates of light reflected from the implementation of the optical structure with two dielectric layers comprising zinc sulfide (ZnS) having an individual thickness of about 66 nm.

[0333] As noted from Figures 30A and 30B implementations of optical structures with different thickness of the dielectric layers produce different colors in the transmission and reflection mode. For example, other regions corresponding to other designs are also shown in the CIE 1931 color space chromaticity diagrams of Figures 30A and 30B. Accordingly, pigments and/or inks that are configured to produce a wide variety of colors in a color space can be obtained by varying the thickness of the individual dielectric layers of the constituent optical structures. Other variations, for example, of the material composition and/or thickness of the other layers (metal and/or dielectric) are possible. Such different designs may provide different colors and/or other characteristics such as amount of color shift with angle, etc.

[0334] The optical performance of example optical structures with and without protective dielectric layers having parameters provided in Tables 9 and 10 were analyzed. The material composition and the thickness of the various layers for the example optical structure without protective layers are provided in Table 9 and the material composition and the thickness of the various layers for the example optical structure with protective layers are provided in Table 10.

Layer	Material	Refractive Index	Extinction Coefficient	Optical Physical Thickness (Full Wavelength Optical Thickness)	Thickness (nm)
	SiO2	1.46180	0.00000		
1	Ag	0.05100	2.96000	0.00250000	25.00
2	ZnS	2.37920	0.00000	0.30789645	66.00
3	Ag	0.05100	2.96000	0.00400000	40.00
4	ZnS	2.37920	0.00000	0.30789645	66.00
5	Ag	0.05100	2.96000	0.00250000	25.00
Substrate	Glass	1.52083	0.00000		

Table 9: Material Composition and thickness of the various layers of an example optical structure without protective layers.

	Medium	Refractive Index	Extinction Coefficient	Optical Physical Thickness (Full Wavelength Optical Thickness)	Thickness (nm)
	SiO2	1.46180	0.00000		
1	ZnS	2.37920	0.00000	0.04665098	10.00
2	Ag	0.05100	2.96000	0.00250000	25.00
3	ZnS	2.37920	0.00000	0.30789645	66.00
4	Ag	0.05100	2.96000	0.00400000	40.00
5	ZnS	2.37920	0.00000	0.30789645	66.00
6	Ag	0.05100	2.96000	0.00250000	25.00
7	ZnS	2.37920	0.00000	0.04665098	10.00
Substrate	Glass	1.52083	0.00000		

Table 10: Material Composition and thickness of the various layers of an example optical structure with protective layers.

[0335] The material composition of the various layers of the example optical structure with protective layers is the same as the material composition of the various layers of the example optical structure without protective layers but with the additional protective layers. For example, the example optical structures comprise an Ag layer having a thickness of 40 nm sandwiched by two ZnS layers each having a thickness of 66 nm. Two Ag layers each having a thickness of 25 nm are disposed on the side of the two ZnS layers opposite the side facing the Ag layer having a 40 nm thickness. The example optical structure with the protective layers included additional ZnS layers each having a thickness of 10 nm. The SiO_2 layer and glass layer represent the medium (e.g., refractive indices of approximately 1.4-1.6) in which the optical stack is immersed (e.g., organic vehicle for pigment). In both examples, when outputting a spectral scan, SiO_2 and glss can index match the organic vehicle and in effect disappear with respect to the optical performance of the optical stack.

[0336] Table 11 provides the CIELa*b* values for transmission mode when the example optical structure without protective layers (e.g., having parameters as described in Table 9) is viewed at different viewing angles in the presence of a D65 light source. Table 12 provides the CIELa*b* values for transmission mode when the example optical structure with protective layers (e.g., having parameters as described in Table 10) is viewed at different viewing angles in the presence of a D65 light soure.

Design ZnS with 3 layers of Ag dichroic design
Polarisation P
Source D65
Observer CIE 1931
Mode Transmittance

Incident Angle	L*	a*	b*
Wht Pt	100.0000	0.0000	0.0000
0.0	75.0871	-72.4036	71.2058
5.0	75.0948	-72.6351	71.1003
10.0	75.1162	-73.3251	70.7800
15.0	75.1464	-74.4601	70.2335
20.0	75.1770	-76.0180	69.4423
25.0	75.1956	-77.9679	68.3802
30.0	75.1849	-80.2708	67.0130
35.0	75.1217	-82.8794	65.2976
40.0	74.9748	-85.7385	63.1796

Table 11: CIELab values for transmission mode when the example optical structure without protective layers (e.g., having parameters as described in Table 9) is viewed at different viewing angles in the presence of a D65 light source.

Design ZnS with 3 layers of Ag dichroic design
Polarisation P
Source D65
Observer CIE 1931
Mode Transmittance

Incident Angle	L*	a*	b*
Wht Pt	100.0000	0.0000	0.0000
0.0	78.6293	-69.6413	69.0996
5.0	78.6168	-69.9121	69.0059
10.0	78.5767	-70.7180	68.7193
15.0	78.5019	-72.0398	68.2237
20.0	78.3805	-73.8464	67.4936
25.0	78.1956	-76.0948	66.4964
30.0	77.9258	-78.7316	65.1949
35.0	77.5441	-81.6934	63.5499
40.0	77.0167	-84.9067	61.5232

Table 12: CIELab values for transmission mode when the example optical structure with protective layers (e.g., having parameters as described in Table 10) is viewed at different viewing angles in the presence of a D65 light source.

[0337] Figures 31A and 31B respectively illustrate the transmittance and reflectance spectra for the example optical structures with and without protective layers. With additional protective layers, the color in transmssion or reflection (e.g., as indicated by the peaks and dips) is not greatly impacted. Hence, in various implementations, protective layers can be used to enhance durability, allow for safer processing, reduce oxidation and/or corrosion with negligible effect on optical performance in transmission and/or reflection.

[0338] The disclosure set forth herein describes a wide variety of structures and methods but should not be considered to be limited to those particular structures or methods. For example, although many of the example optical structures 10, 300a, or 300b are symmetrical, asymmetric structures are also possible. For example, instead of having a pair of similar or identical dielectric layers sandwiching the pair of metallic layers, either dielectric or metal layers having different characteristics (e.g., thickness or material) may be used on opposite sides of the structure or alternatively, maybe only one side of the pair of metal layers has a dielectric layer thereon. Similarly, the metal layers need not be identical and may have different characteristics such as different thicknesses or materials. As described above, intervening layers may also be included. One or more such intervening layer may be include such that the optical structure is not symmetric. For example, one or more intervening layers may be included between the dielectric layer 12 and metal layer 13 (or the dielectric layer 303a and the metal layer 301a) and not between that metal layer 15 and the dielectric layer 16 (or the dielectric layer 303b and the metal layer 301c) or vice versa. Similarly, one or more intervening layers may be included between the metal layer 13 and the dielectric layer 14 and not between the dielectric layer 14 and the metal layer 15, or vice versa. Likewise, one or more intervening layers having different characteristics (e.g., material or thickness) may be included on different sides of the optical structure 10, 300a, or 300b. Or more intervening layers may be included on one side of the optical structure 10, 300a or 300b than on the other side of the optical structure. For example, the metal layer 13, the metal layer 15, the metal layer 301a, the metal layer 301b and/or the metal layer 301c can comprise metal sub-layers. In some implementations, the metal layer 13 and/or the metal layer 15 can comprise a first metal (e.g., silver) facing the high refractive index transparent layers 12 or 16 and a second metal (e.g., gold) facing the dielectric layer 14. In some implementations, the metal layer 301a and the metal layer 301c can comprise a first metal (e.g., gold) and the metal layer 301b can comprise a second metal (e.g., silver). Other variations are possible.

[0339] Likewise, although this disclosure describes applications of the structures and method describe herein to include security applications, e.g., countering successful use of counterfeit currency, documents, and products, this disclosure should not be considered to be limited to those particular applications. Alternatively or in addition, such features could, for example, be used for providing an aesthetic effect, to create appealing or attractive features on products or packaging for marketing and advertisement, or for other reasons.

[0340] Dimensions, such as, thickness, length, width of various embodiments described herein can be outside the different ranges provided in this disclosure. The values of refractive indices for the various materials discussed herein can be outside the different ranges provided in this disclosure. The values for reflectance and/or transmittance of the different structures can be outside the different ranges provided herein. The values for spectral widths and peak locations for the reflection and transmission spectra can be outside the different ranges provided herein.

[0341] The entirety of each application below is incorporated herein by reference:.U.S. Patent Application No. 14/921,933 (Attorney Docket No. WVFRNT.011A) filed on October 23, 2015, which claims the benefit of priority of U.S. Provisional Application No. 62/068,540 (Attorney Docket No. WVFRNT.011PR) filed on October 24, 2014; U.S. Patent Application No. 16/054,898 (Attorney Docket No. WVFRNT.017A) filed on August 3, 2018, which claims the benefit of priority of U.S. Provisional Application No. 62/568,711 (Attorney Docket No. WVFRNT.017PR) filed on October 05, 2017; and U.S. Patent Application No. 16/780,777 (Attorney Docket No. WVFRNT.019A) filed on February 3, 2020, which claims the benefit of priority of U.S. Provisional Application No. 62/829,572 (Attorney Docket No. WVFRNT.019PR) filed on April 4, 2019.

Examples

[0342] The following is a numbered list of example embodiments that are within the scope of this disclosure. The example embodiments that are listed should in no way be interpreted as limiting the scope of the embodiments. Various features of the example embodiments that are listed can be removed, added, or combined to form additional embodiments, which are part of this disclosure.

1. An optical product configured, when illuminated, to reproduce an image that appears 3D of at least a part of a 3D object, said optical product comprising:

a surface comprising a plurality of portions, each portion corresponding to a point on a surface of said 3D object;

one or more non-holographic features disposed within each portion configured to produce at least part of said image without relying on diffraction;

an interference optical structure disposed with respect to said one or more non-holographic features;

wherein for individual ones of the portions, a gradient in said non-holographic features correlates to a surface normal of said surface of said 3D object at said corresponding point, and wherein for individual ones of the portions, an orientation of said non-holographic features correlates to an orientation of said surface of said 3D object at said corresponding point.

2. The optical product of Example 1, when illuminated, reproduces the image in a first color in transmission mode or a second color in reflection mode.

3. The optical product of any of Examples 1-2, when illuminated, reproduces the image in a first color in transmission mode and a second color in reflection mode, wherein the second color is different from the first color.

4. The optical product of any of Examples 1-3, wherein the first color and/or the second color changes with a change in a viewing angle.

5. The optical product of any of Example 1-3, wherein the first color and/or the second color does not change with a change in a viewing angle.

6. The optical product of any of Examples 1-5, wherein said optical structure comprises an interference optical stack.

7. The optical product of any of Examples 1-6, wherein said optical structure comprises a D/M/D/M/D multilayer thin film optical stack, where D is a transparent or optically transmissive dielectric layer and M is a metal layer.

8. The optical product of Example 7, wherein the metal layers have a ratio of the real part (n) of the refractive index to the imaginary part (k) of the refractive index greater than or equal to 0.01 and less than or equal to 0.5.

9. The optical product of any of Examples 1-6, wherein said optical structure comprises a M/D/M/D/M multilayer thin film optical stack, where D is a transparent or optically transmissive dielectric layer and M is a metal layer.

10. The optical product of Example 9, wherein the metal layers have a ratio of the real part (n) of the refractive index to the imaginary part (k) of the refractive index greater than or equal to 0.01 and less than or equal to 0.2.

11. The optical product of any of Examples 9-10, wherein individual ones of the metal layers have a thickness from about 20 nm to about 100 nm.

12. The optical product of any of Examples 7-11, wherein at least one of the metal layers comprises aluminum, silver, gold, silver alloy, or gold alloy.

13. The optical product of any of Examples 7-12, wherein at least one of the dielectric layers comprises magnesium fluoride, silicon dioxide, zinc oxide, zinc sulfide, zirconium dioxide, titanium dioxide, tantalum pentoxide, ceric oxide, yttrium oxide, indium oxide, tin oxide, indium tin oxide, aluminum oxide, tungsten trioxide, or combinations thereof.

14. The optical product of any of Examples 7-12, wherein at least one of the dielectric layers comprises an organic layer.

15. The optical product of any of Examples 1-6, wherein said optical structure comprises a H/L/H/L/H multilayer thin film optical stack, wherein H and L are layers with a refractive index, and wherein the H layers have a higher refractive index than the L layers.

16. The optical product of Example 15, wherein the L layers have a refractive index less than 1.65 and the H layers have a refractive index greater than or equal to 1.65.

17. The optical product of any of Examples 1-6, wherein said optical structure comprises a A/D/M multilayer thin film optical stack, where A is an absorber layer, D is a transparent dielectric layer, and M is a metal layer that is opaque.

18. The optical product of Example 17, wherein the metal layer has a ratio of the real part (n) of the refractive index to the imaginary part (k) of the refractive index near unity.

19. The optical product of any of Examples 17-18, wherein said optical structure comprises a A/D/M/D/A multilayer thin film optical stack.

20. The optical product of any of Examples 17-19, wherein said optical structure comprises a A/D/M/M*/M/D/A multilayer thin film optical stack, where M* is a magnetic layer.

21. The optical product of any of Examples 1-6, wherein said optical structure comprises a Fabry-Perot or etalon structure.

22. The optical product of any of the preceding examples, wherein said non-holographic features comprise facets.

23. The optical product of any of the preceding examples, wherein said non-holographic features comprise linear or curved facets.

24. The optical product of any of the preceding examples, wherein said non-holographic features with less steep slopes are configured to reflect light toward an observer's eye, and wherein said non-holographic features with steeper slopes are configured to reflect light away from the observer's eye.

25. The optical product of any of the preceding examples, wherein said portions comprise non-holographic features with discontinuities corresponding to a continuous region of said 3D object.

26. The optical product of any of the preceding examples, wherein said 3D object comprises an irregularly shaped object.

27. The optical product of any of the preceding examples, wherein the optical structure is in the form of a hot stamp coating, a foil coating, or an ink coating.

28. The optical product of any of the preceding examples, wherein the optical product is in the form of a thread, patch, laminate, hot stamp, or window.

29. The optical product of any of the preceding examples, wherein said optical product is configured to provide authenticity verification on an item for anti-counterfeiting or security.

30. The optical product of Example 29, wherein said item is a banknote, a credit card, a debit card, a passport, a driver's license, an identification card, a document, a tamper evident container or packaging, or a bottle of pharmaceuticals.

31. The optical product of Example 29, wherein said item is electronics, apparel, jewelry, cosmetics, or a handbag.

32. The optical product of any of the preceding examples,

wherein an inclination of said surface of said 3D object comprises a polar angle from a first reference line of said 3D object, and

wherein said orientation of said surface of said 3D object comprises an azimuth angle from a second reference line orthogonal to said first reference line of said 3D object.

33. The optical product of any of the preceding examples, wherein said image is a substantially similar reproduction of said 3D object and not scaled up in size.

34. The optical product of any of the preceding examples, wherein said non-holographic features form a shape different from said 3D object.

35. The optical product of any of the preceding examples, wherein a majority of said plurality of portions comprises non-holographic features with discontinuities.

36. The optical product of any of the preceding examples, wherein said portions of said plurality of portions are defined by borders.

37. The optical product of any of the preceding examples, wherein said portions of said plurality of portions are defined by linear borders.

38. The optical product of any of the preceding examples, wherein a majority of said plurality of portions comprises features discontinuous with features in surrounding adjacent portions.

39. The optical product of any of the preceding examples, wherein a majority of said non-holographic features is discontinuous at linear boundaries between adjacent portions.

40. The optical product of any of the preceding examples, wherein said plurality of portions comprises non-holographic features with discontinuities corresponding to a continuous region of said 3D object.

41. The optical product of any of the preceding examples, further comprising holographic features.

42. The optical product of any of the previous examples, wherein portions of the plurality of portions have a length and width between 10 μm and 55 μm.

43. The optical product of any of the preceding examples, wherein portions of the plurality of portions have a length and width between 20 μm and 50 μm.

44. The optical product of any of the preceding examples, wherein the optical product comprises a first surface and a second surface opposite said first surface, wherein said plurality of portions are disposed on the second surface, wherein the non-holographic features comprise one or more non-linear features when viewed in a cross-section orthogonal to said first and second surfaces.

45. The optical product of any of the preceding examples, wherein said 3D object comprises a non-symmetrical shaped object.

46. The optical product of any of the preceding examples, wherein said 3D object comprises an object in nature.

47. The optical product of any of the preceding examples, wherein said 3D object comprises a man-made object.

48. The optical product of any of the preceding examples, wherein the non-holographic features are configured to produce at least part of the image without lenses.

49. The optical product of any of the preceding examples, wherein the optical product comprises a first surface and a second surface opposite said first surface, wherein said plurality of portions are disposed on said second surface, and wherein said first surface is planar.

50. The optical product of any of Examples 1-6, wherein said optical structure comprises a M/D/M multilayer thin film optical stack, where D is a transparent or optically transmissive dielectric layer and M is a metal layer.

51. The optical product of any of Examples 1-6, wherein said optical structure comprises a D/M/D multilayer thin film optical stack, where D is a transparent or optically transmissive dielectric layer and M is a metal layer.

[0343] Various embodiments of the present invention have been described herein. Although this invention has been described with reference to these specific embodiments, the descriptions are intended to be illustrative of the invention and are not intended to be limiting. Various modifications and applications may occur to those skilled in the art without departing from the true spirit and scope of the invention.

What is Claimed is:

1. An optical product configured, when illuminated, to reproduce an image that appears 3D of at least a part of a 3D object, said optical product comprising:

a surface comprising a plurality of portions, each portion corresponding to a point on a surface of said 3D object;

one or more non-holographic features disposed within each portion configured to produce at least part of said image without relying on diffraction;

an interference optical structure disposed with respect to said one or more non-holographic features;

wherein for individual ones of the portions, a gradient in said non-holographic features correlates to a surface normal of said surface of said 3D object at said corresponding point, and

wherein for individual ones of the portions, an orientation of said non-holographic features correlates to an orientation of said surface of said 3D object at said corresponding point.

2. The optical product of Claim 1, when illuminated, reproduces the image in a first color in transmission mode or a second color in reflection mode.

3. The optical product of Claim 2, when illuminated, reproduces the image in a first color in transmission mode and a second color in reflection mode, wherein the second color is different from the first color.

4. The optical product of Claim 2, wherein the first color and/or the second color changes with a change in a viewing angle.

5. The optical product of Claim 2, wherein the first color and/or the second color does not change with a change in a viewing angle.

6. The optical product of Claim 1, wherein said optical structure comprises an interference optical stack.

7. The optical product of Claim 1, wherein said optical structure comprises a D/M/D/M/D multilayer thin film optical stack, where D is a transparent or optically transmissive dielectric layer and M is a metal layer.

8. The optical product of Claim 7, wherein the metal layers have a ratio of the real part (n) of the refractive index to the imaginary part (k) of the refractive index greater than or equal to 0.01 and less than or equal to 0.5.

9. The optical product of Claim 1, wherein said optical structure comprises a M/D/M/D/M multilayer thin film optical stack, where D is a transparent or optically transmissive dielectric layer and M is a metal layer.

10. The optical product of Claim 9, wherein the metal layers have a ratio of the real part (n) of the refractive index to the imaginary part (k) of the refractive index greater than or equal to 0.01 and less than or equal to 0.2.

11. The optical product of Claim 9, wherein individual ones of the metal layers have a thickness from about 20 nm to about 100 nm.

12. The optical product of Claim 1, wherein the optical structure comprises a multilayer thin film optical stack comprising metal layers and transparent or optically transmissive dielectric layers, wherein at least one of the metal layers comprises aluminum, silver, gold, silver alloy, or gold alloy.

13. The optical product of Claim 1, wherein the optical structure comprises a multilayer thin film optical stack comprising metal layers and transparent or optically transmissive dielectric layers, wherein at least one of the dielectric layers comprises magnesium fluoride, silicon dioxide, zinc oxide, zinc sulfide, zirconium dioxide, titanium dioxide, tantalum pentoxide, ceric oxide, yttrium oxide, indium oxide, tin oxide, indium tin oxide, aluminum oxide, tungsten trioxide, or combinations thereof.

14. The optical product of Claim 1, wherein the optical structure comprises a multilayer thin film optical stack comprising metal layers and transparent or optically transmissive dielectric layers, wherein at least one of the dielectric layers comprises an organic layer.

15. The optical product of Claim 1, wherein said optical structure comprises a H/L/H/L/H multilayer thin film optical stack, wherein H and L are layers with a refractive index, and wherein the H layers have a higher refractive index than the L layers.

16. The optical product of Claim 15, wherein the L layers have a refractive index less than 1.65 and the H layers have a refractive index greater than or equal to 1.65.

17. The optical product of Claim 1, wherein said optical structure comprises a A/D/M multilayer thin film optical stack, where A is an absorber layer, D is a transparent dielectric layer, and M is a metal layer that is opaque.

18. The optical product of Claim 17, wherein the metal layer has a ratio of the real part (n) of the refractive index to the imaginary part (k) of the refractive index near unity.

19. The optical product of Claim 17, wherein said optical structure comprises a A/D/M/D/A multilayer thin film optical stack.

20. The optical product of Claim 17, wherein said optical structure comprises a A/D/M/M*/M/D/A multilayer thin film optical stack, where M* is a magnetic layer.

21. The optical product of Claim 1, wherein said optical structure comprises a Fabry-Perot or etalon structure.

22. The optical product of Claim 1, wherein said non-holographic features comprise facets.

23. The optical product of Claim 1, wherein said non-holographic features comprise linear or curved facets.

24. The optical product of Claim 1, wherein said non-holographic features with less steep slopes are configured to reflect light toward an observer's eye, and wherein said non-holographic features with steeper slopes are configured to reflect light away from the observer's eye.

25. The optical product of Claim 1, wherein said portions comprise non-holographic features with discontinuities corresponding to a continuous region of said 3D object.

26. The optical product of Claim 1, wherein said 3D object comprises an irregularly shaped object.

27. The optical product of Claim 1, wherein the optical structure is in the form of a hot stamp coating, a foil coating, or an ink coating.

28. The optical product of Claim 1, wherein the optical product is in the form of a thread, patch, laminate, hot stamp, or window.

29. The optical product of Claim 1, wherein said optical product is configured to provide authenticity verification on an item for anti-counterfeiting or security.

30. The optical product of Claim 29, wherein said item is a banknote, a credit card, a debit card, a stock certificate, a passport, a driver's license, an identification card, a document, a tamper evident container or packaging, consumer packaging, or a bottle of pharmaceuticals.

31. The optical product of Claim 29, wherein said item is electronics, apparel, jewelry, cosmetics, or a handbag.

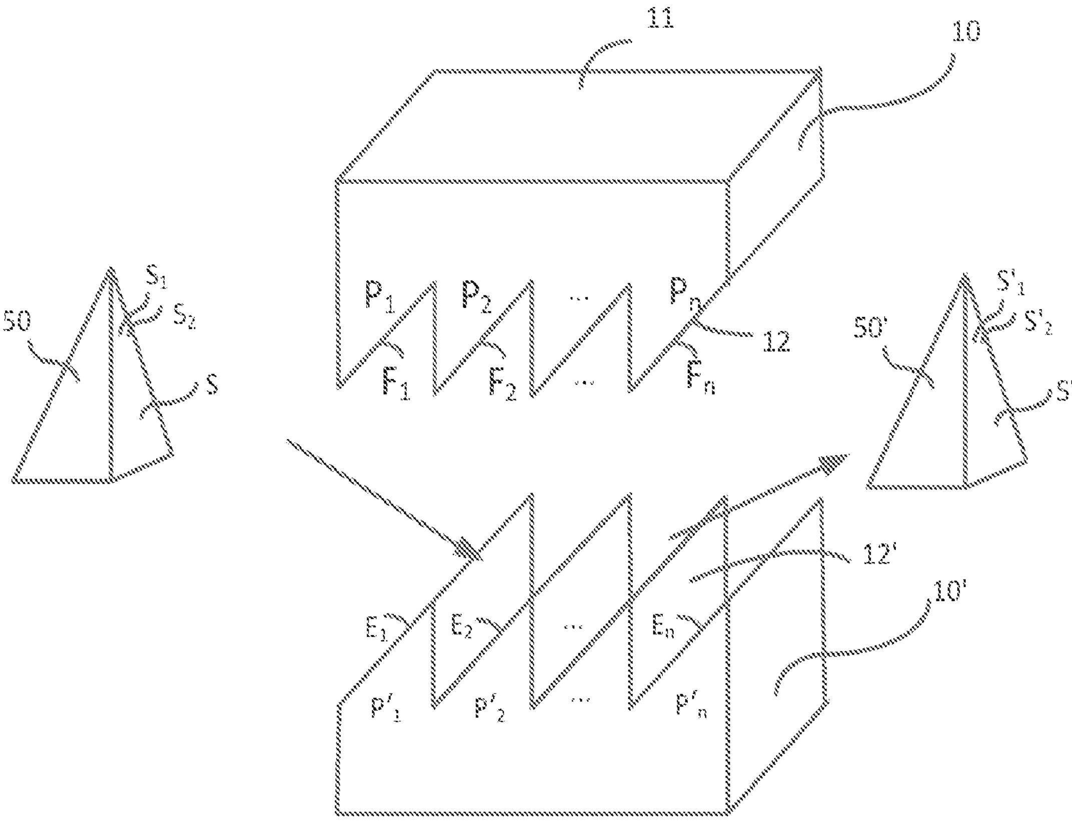

FIG. 1A

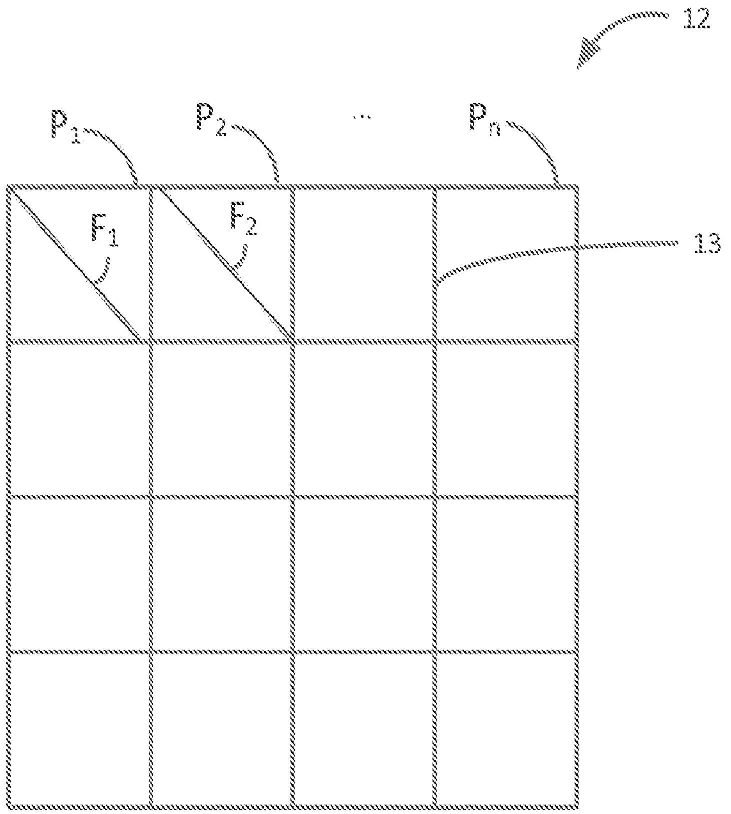

FIG. 1B

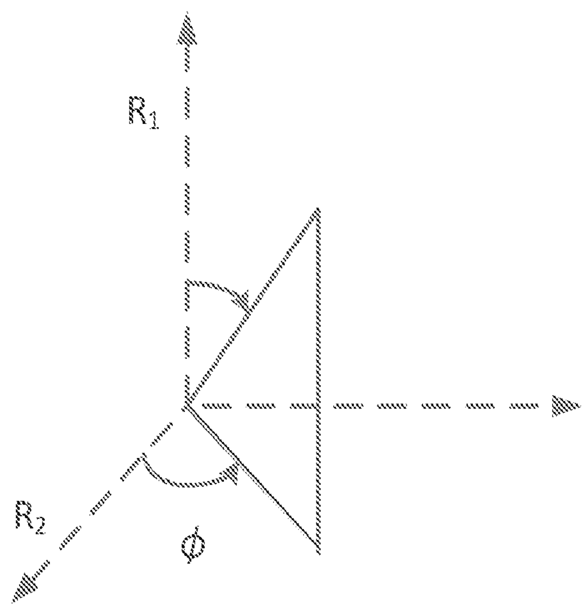

FIG. 1C

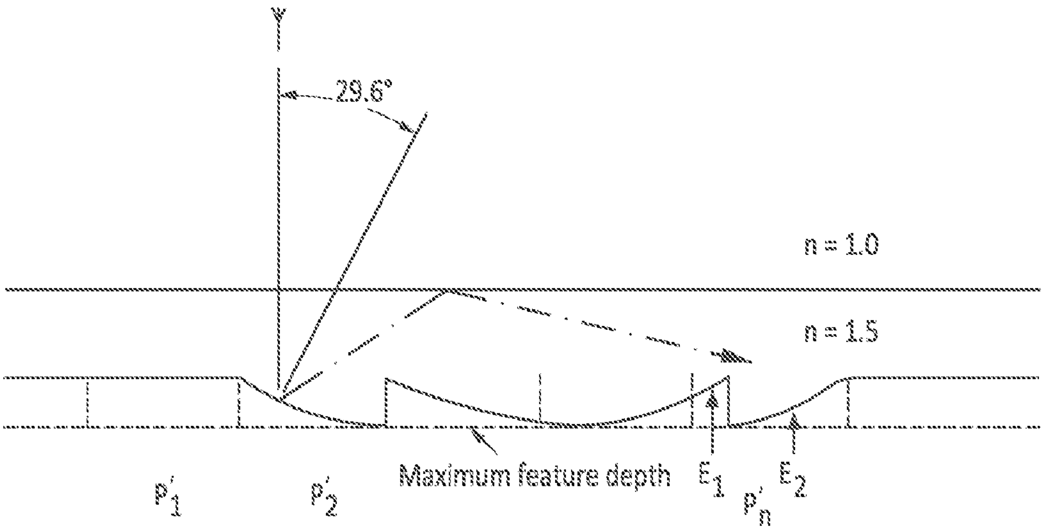
29.6°
n = 1.0
n = 1.5
Maximum feature depth
E_1
E_2
P'_1
P'_2
P'_n

FIG.1D

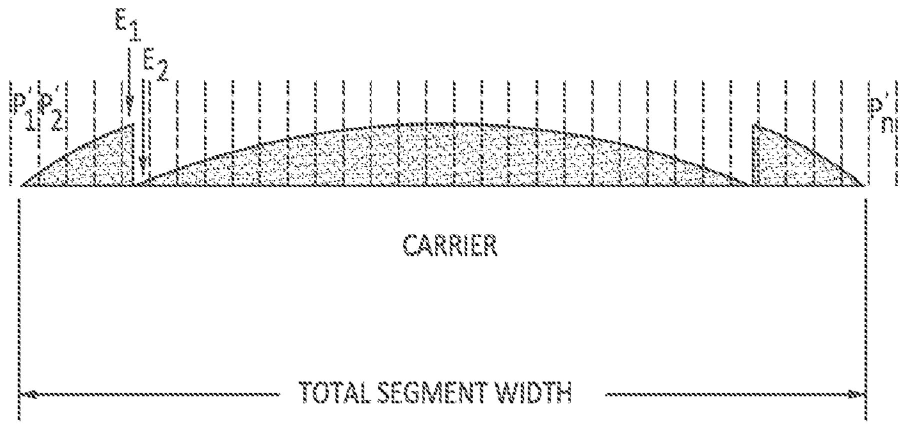
E_1
E_2
P'_1
P'_2
P'_n
CARRIER
TOTAL SEGMENT WIDTH

FIG.1E

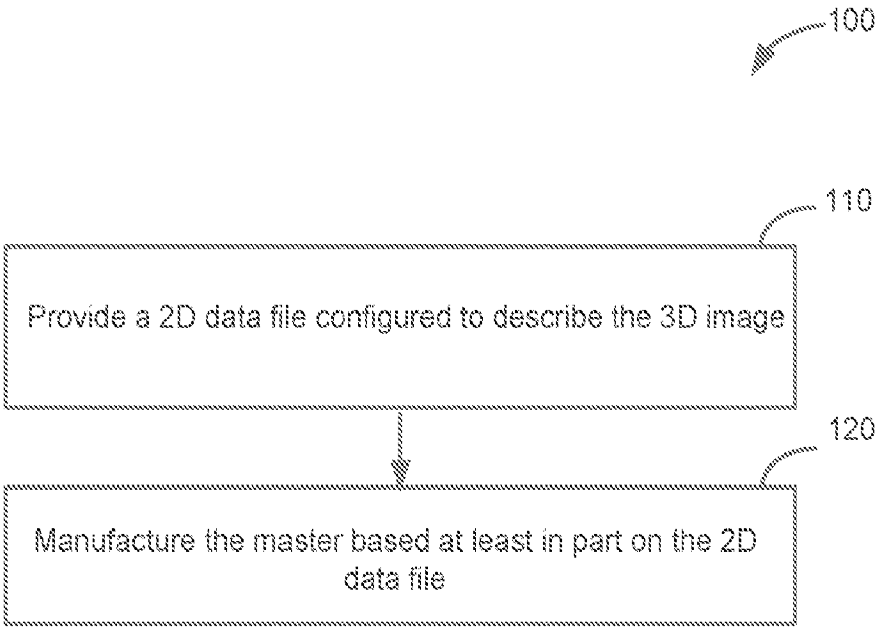
100
110
Provide a 2D data file configured to describe the 3D image
120
Manufacture the master based at least in part on the 2D data file

FIG. 2

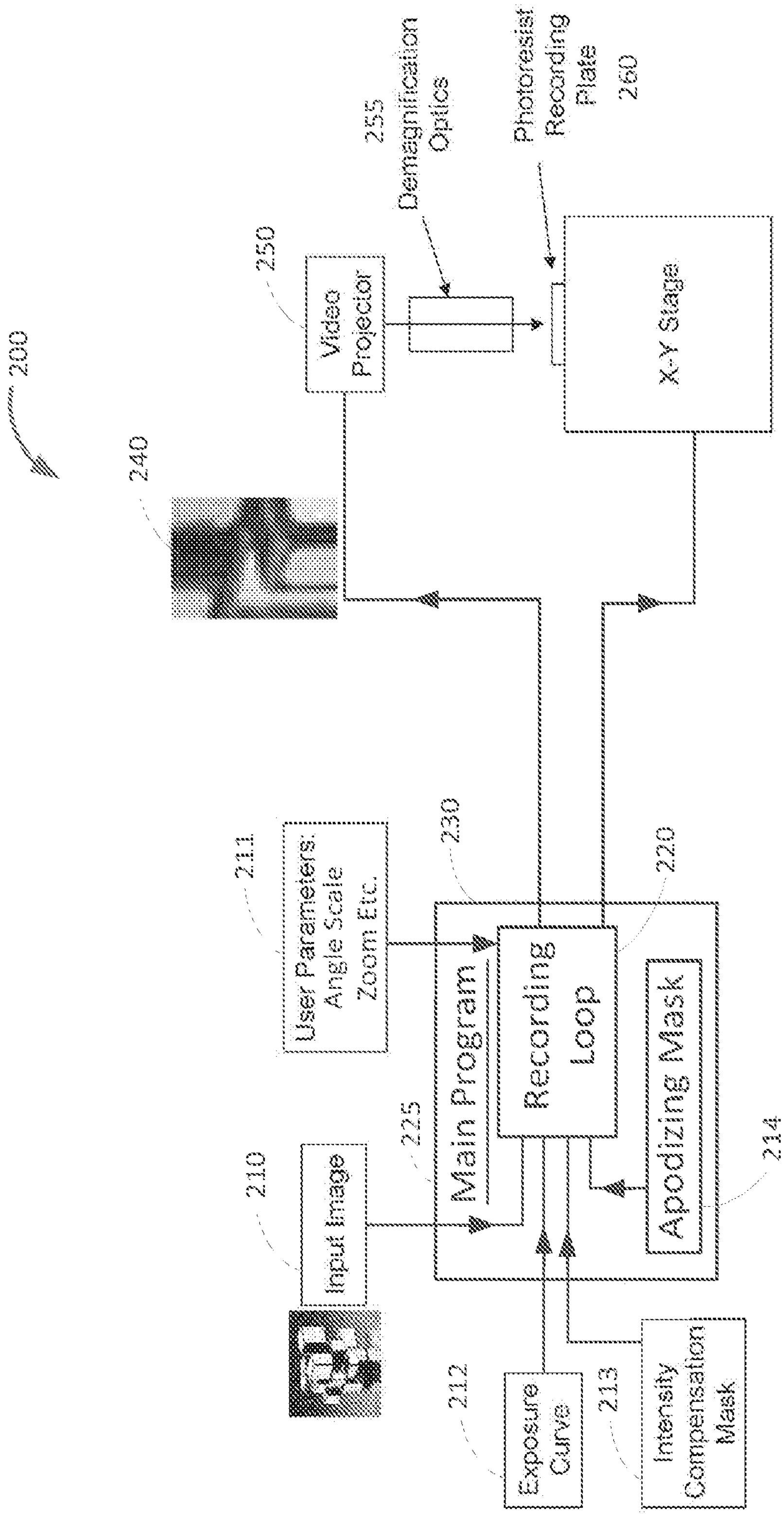
200
240
250
Video Projector
255
Demagnification Optics
Photoresist Recording Plate
260
X-Y Stage
211
User Parameters: Angle Scale Zoom Etc.
230
220
Main Program
Recording Loop
Apodizing Mask
225
210
Input Image
214
212
Exposure Curve
213
Intensity Compensation Mask

FIG. 2A

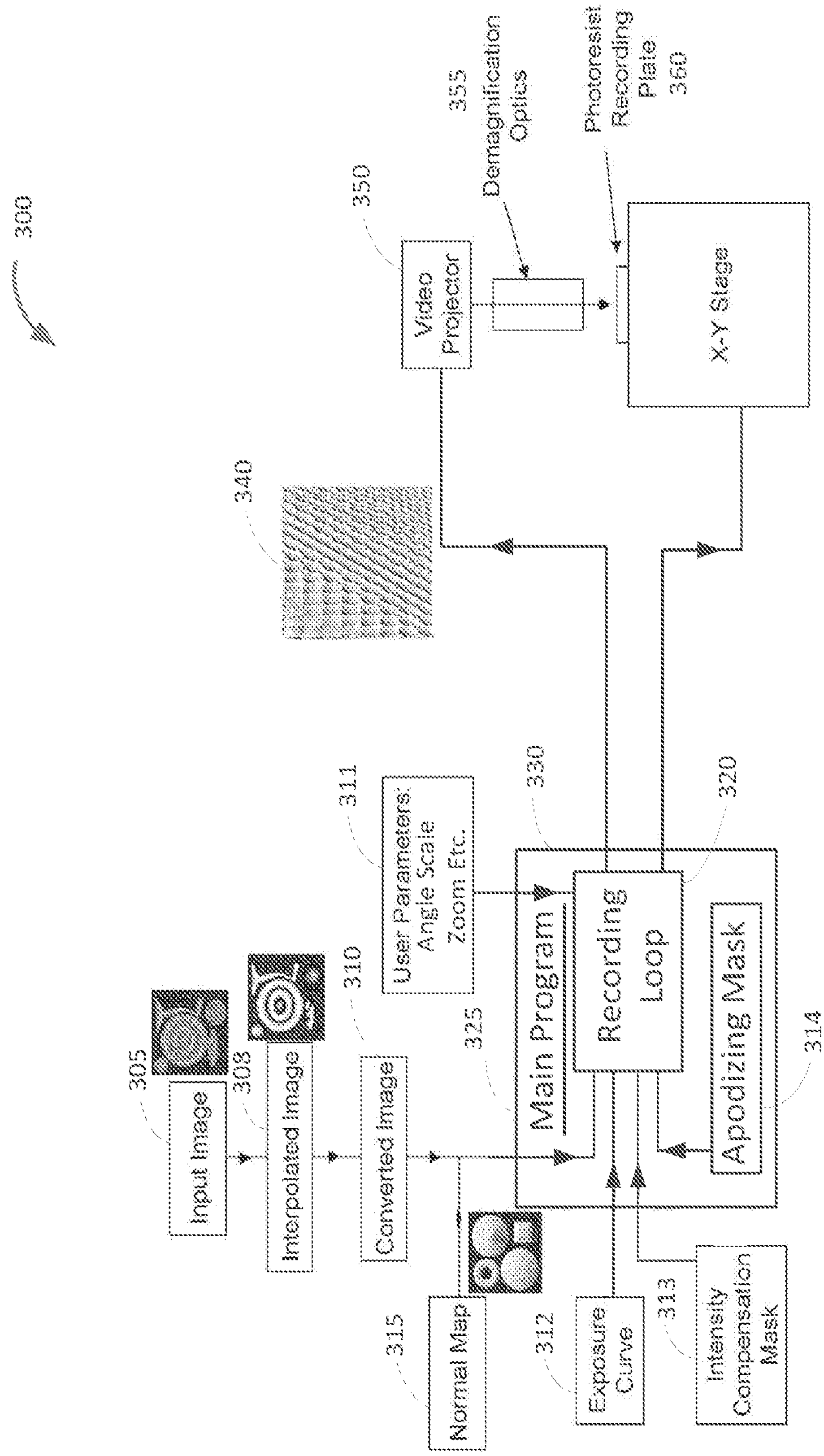
300
Input Image
305
Interpolated Image
308
Converted Image
310
User Parameters: Angle Scale Zoom Etc.
311
Main Program
325
330
Recording Loop
320
Apodizing Mask
314
Normal Map
315
Exposure Curve
312
Intensity Compensation Mask
313
340
Video Projector
350
Demagnification Optics
355
Photoresist Recording Plate
360
X-Y Stage

FIG. 2B

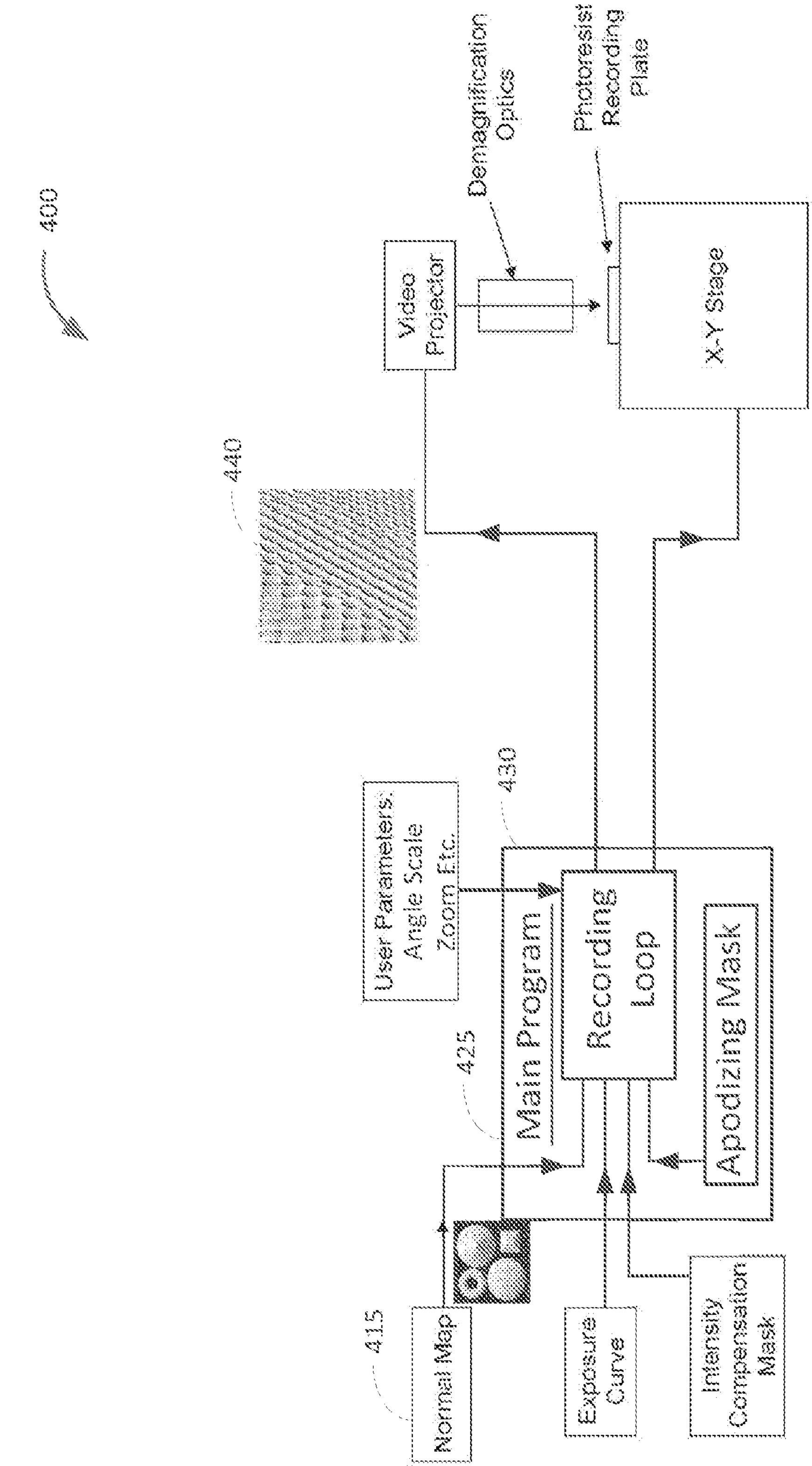
400
Demagnification Optics
Photoresist Recording Plate
Video Projector
X-Y Stage
440
430
User Parameters: Angle Scale Zoom Etc.
Main Program
Recording Loop
Apodizing Mask
425
415
Normal Map
Exposure Curve
Intensity Compensation Mask

FIG. 2C

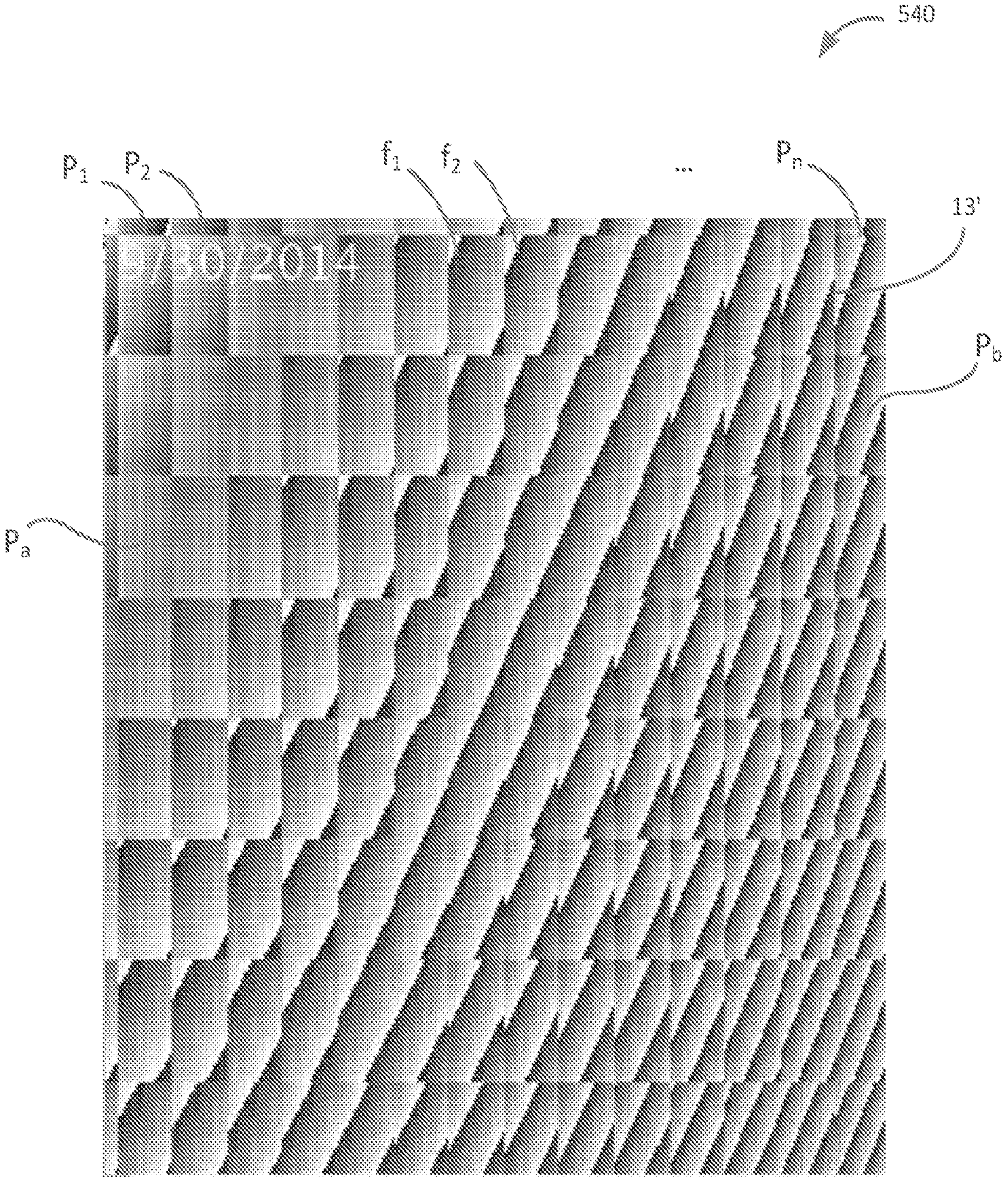

FIG. 3A

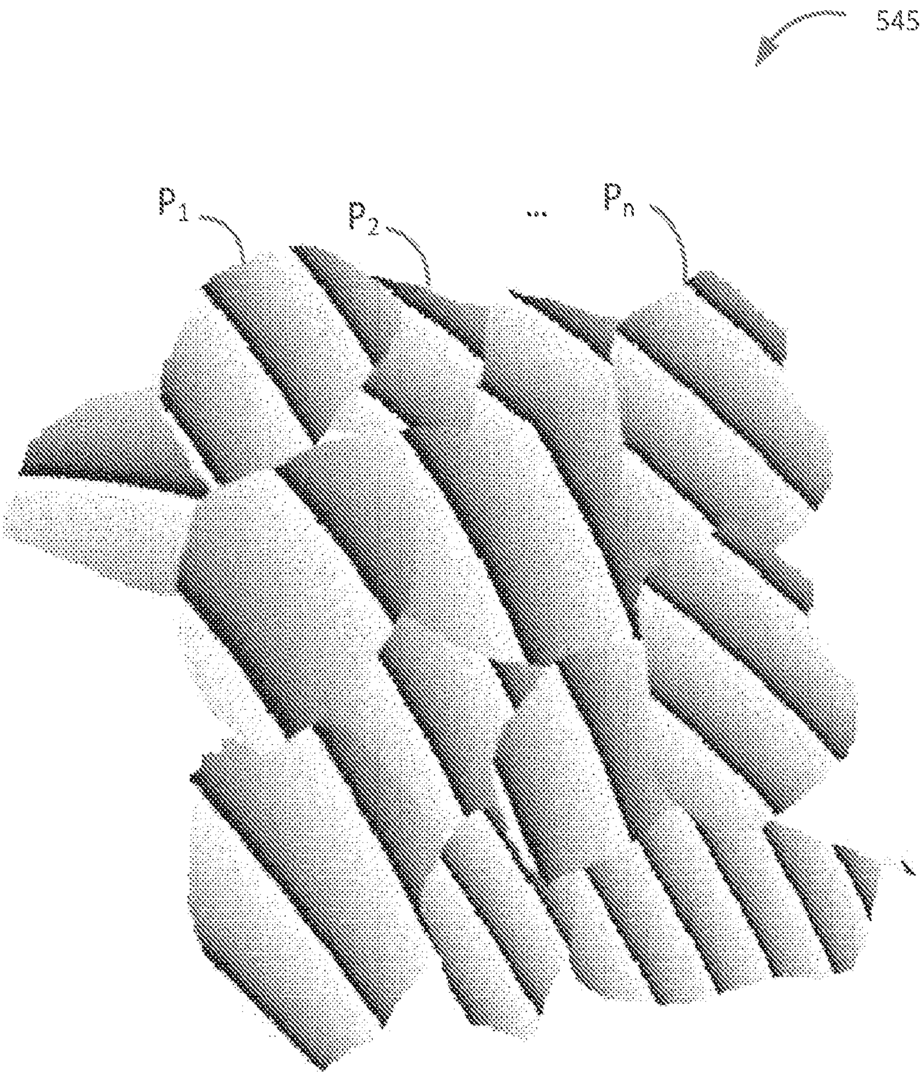

FIG. 3B

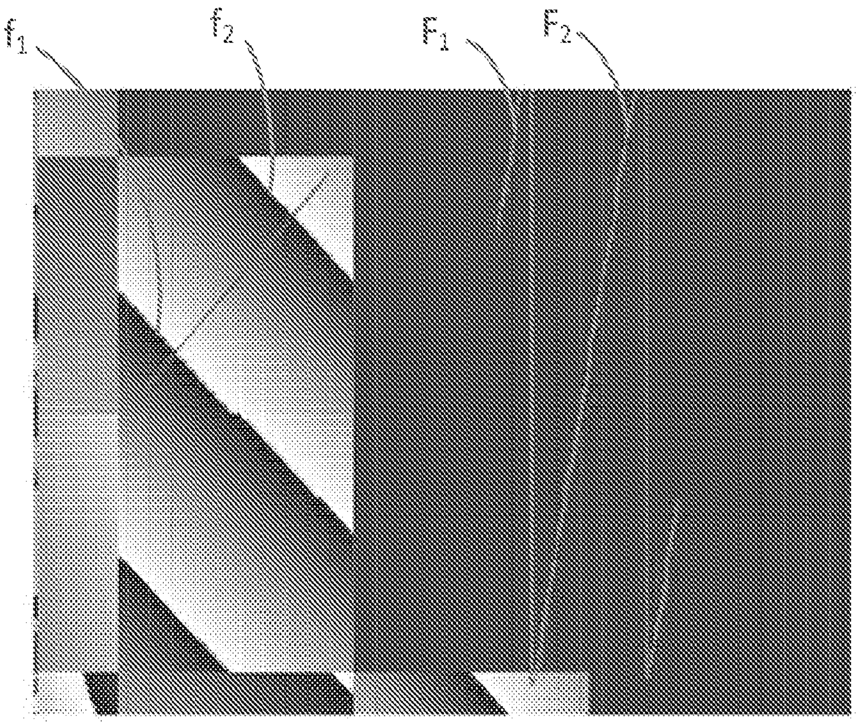

FIG. 3C

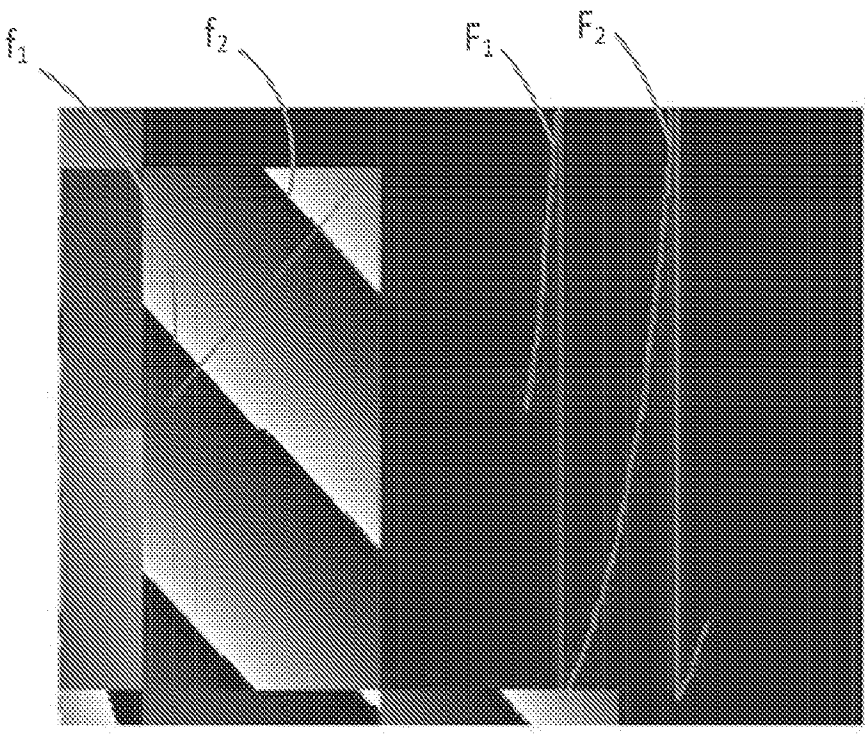

FIG. 3D

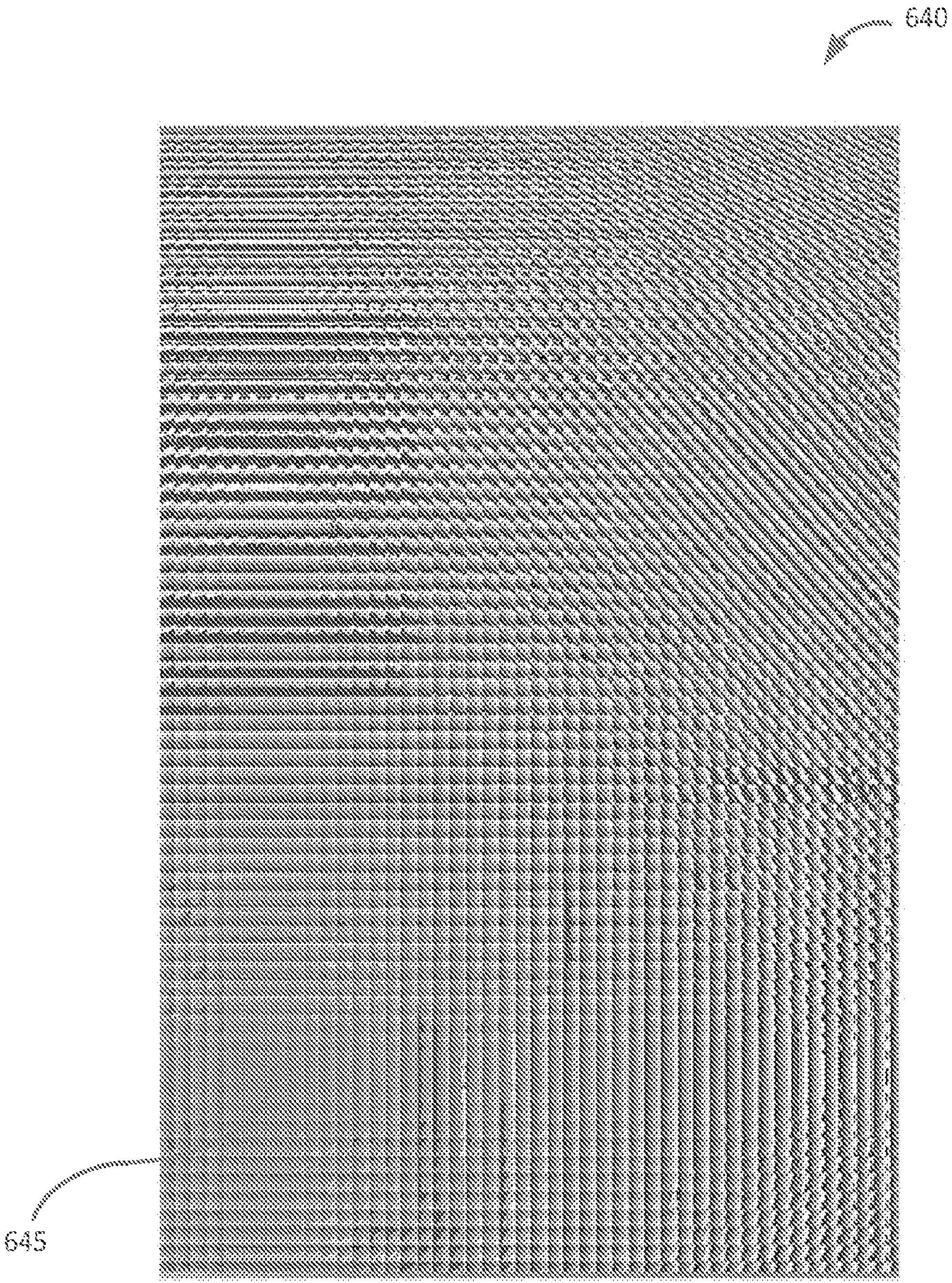

FIG. 4A

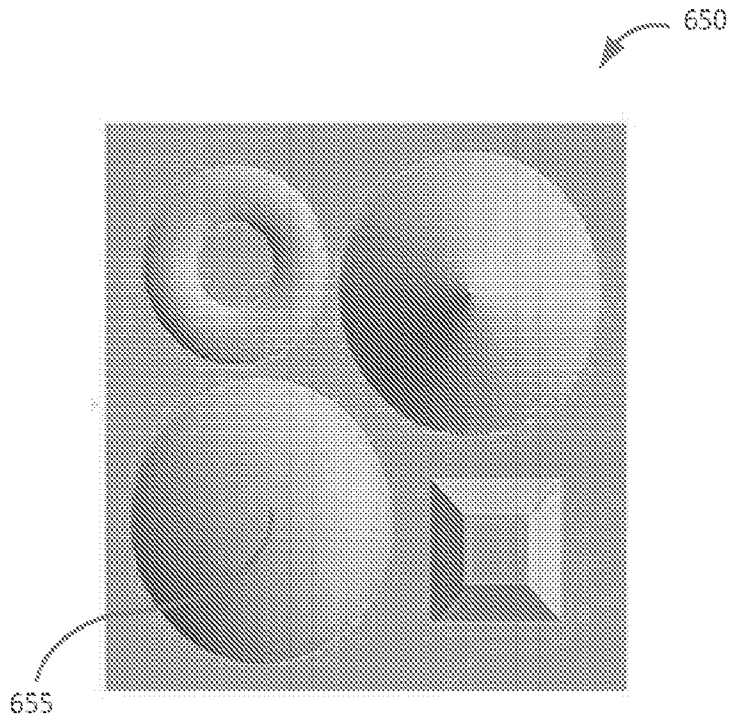

FIG. 4B

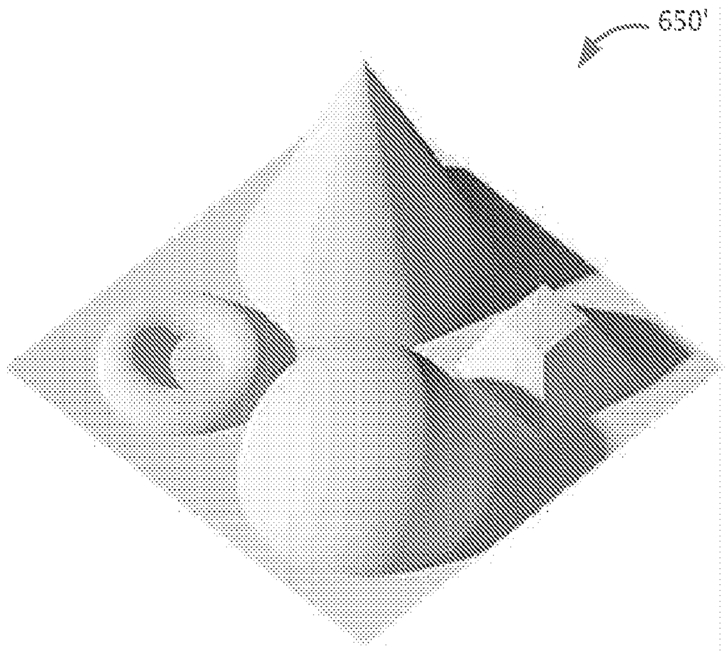

FIG. 4C

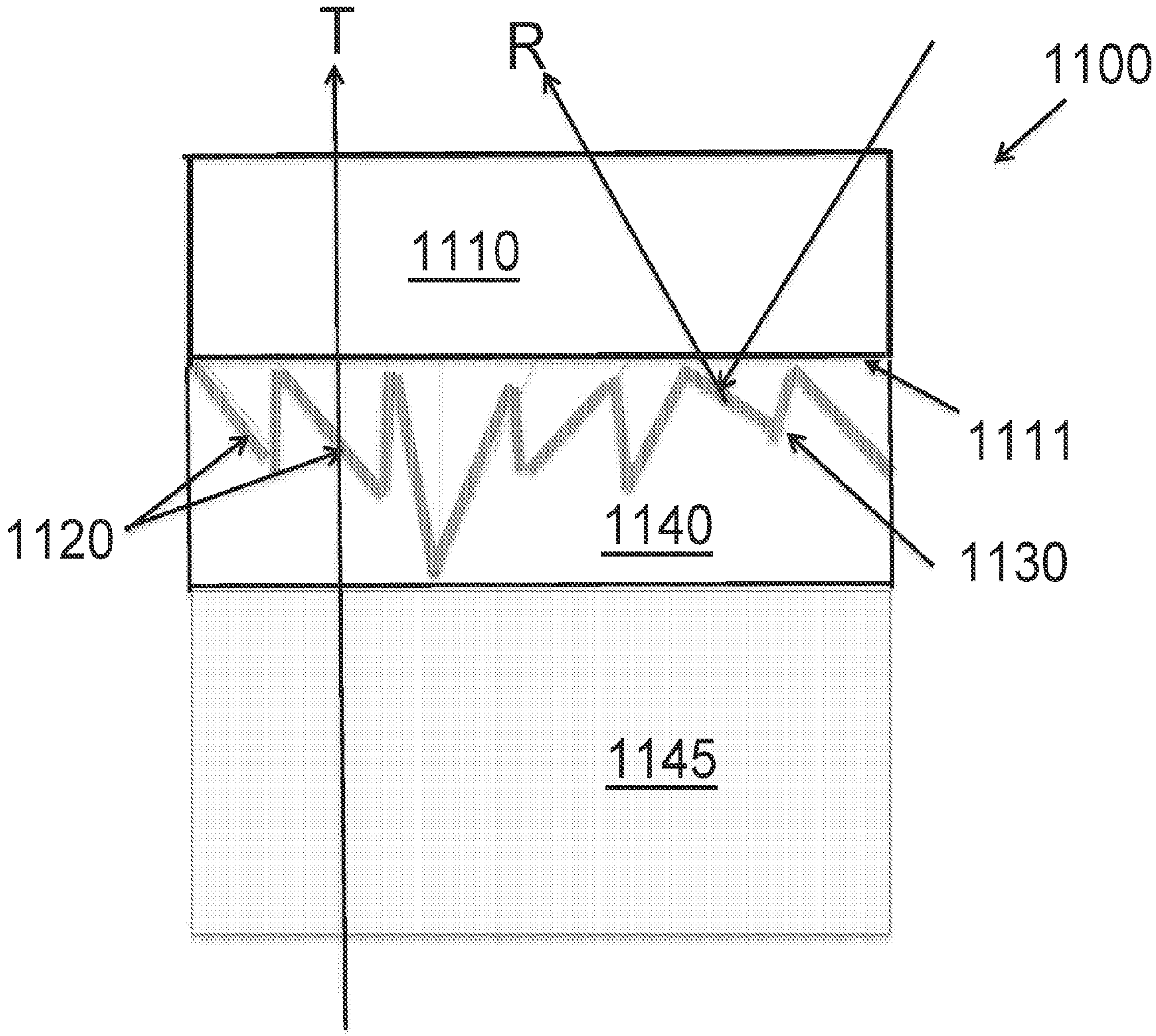

FIG. 5

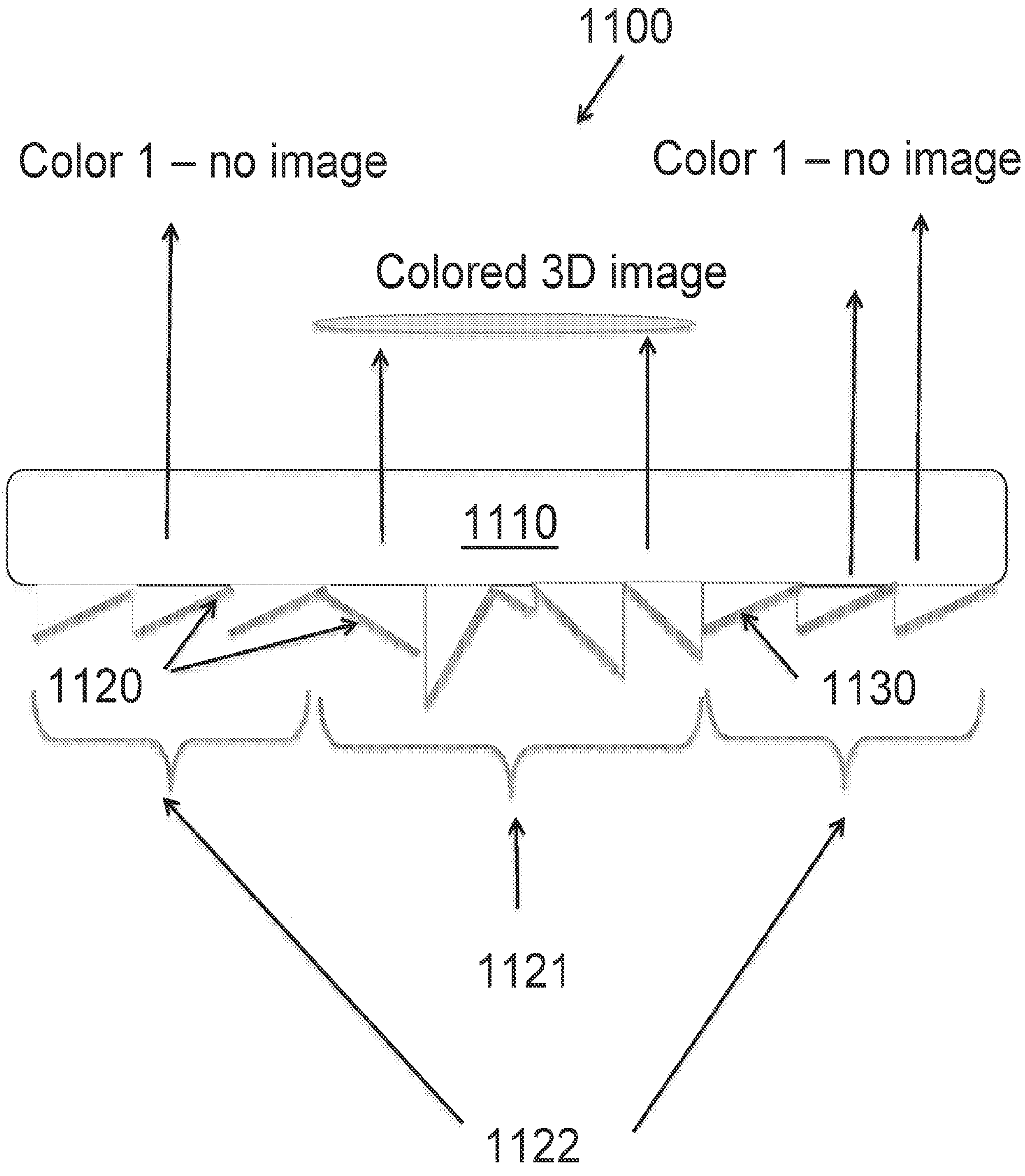
1100
Color 1 – no image
Color 1 – no image
Colored 3D image
1110
1120
1130
1121
1122

FIG. 6

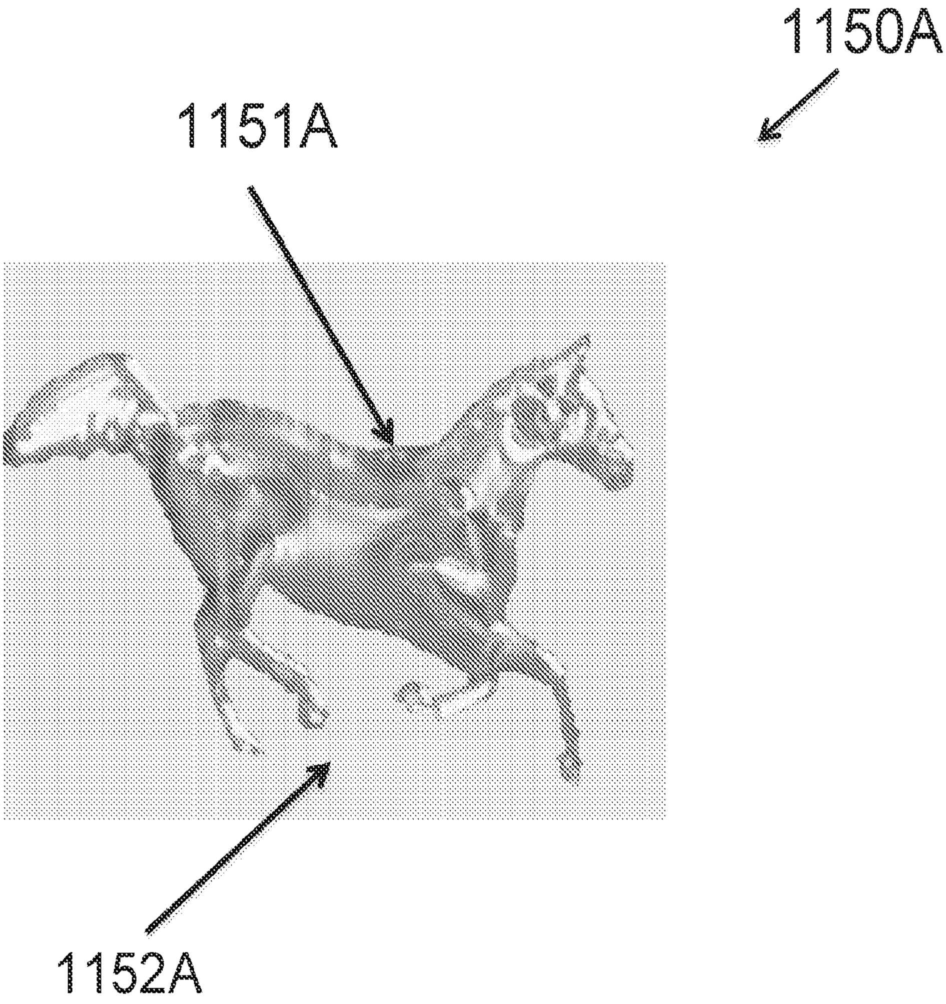

FIG. 7A.

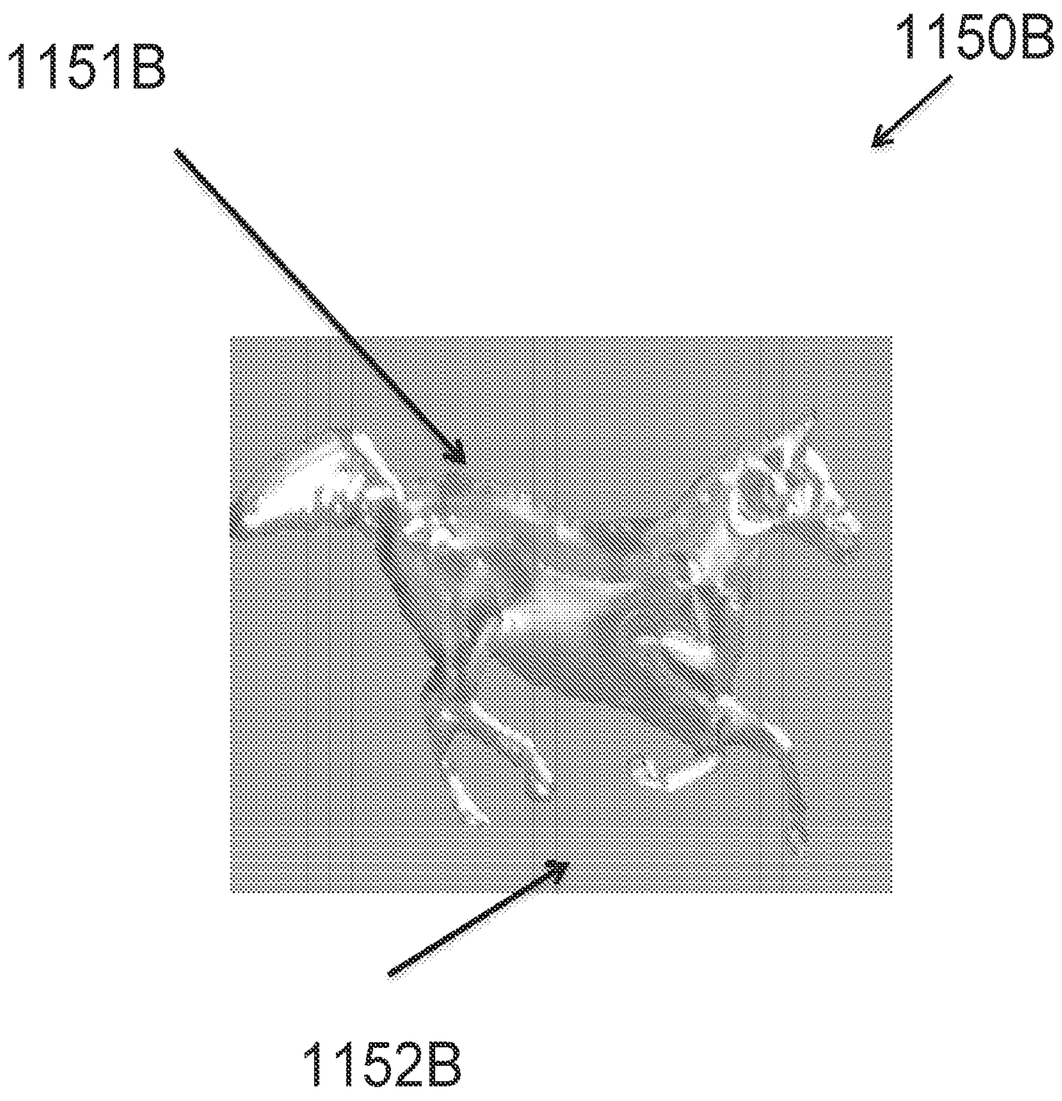

FIG. 7B

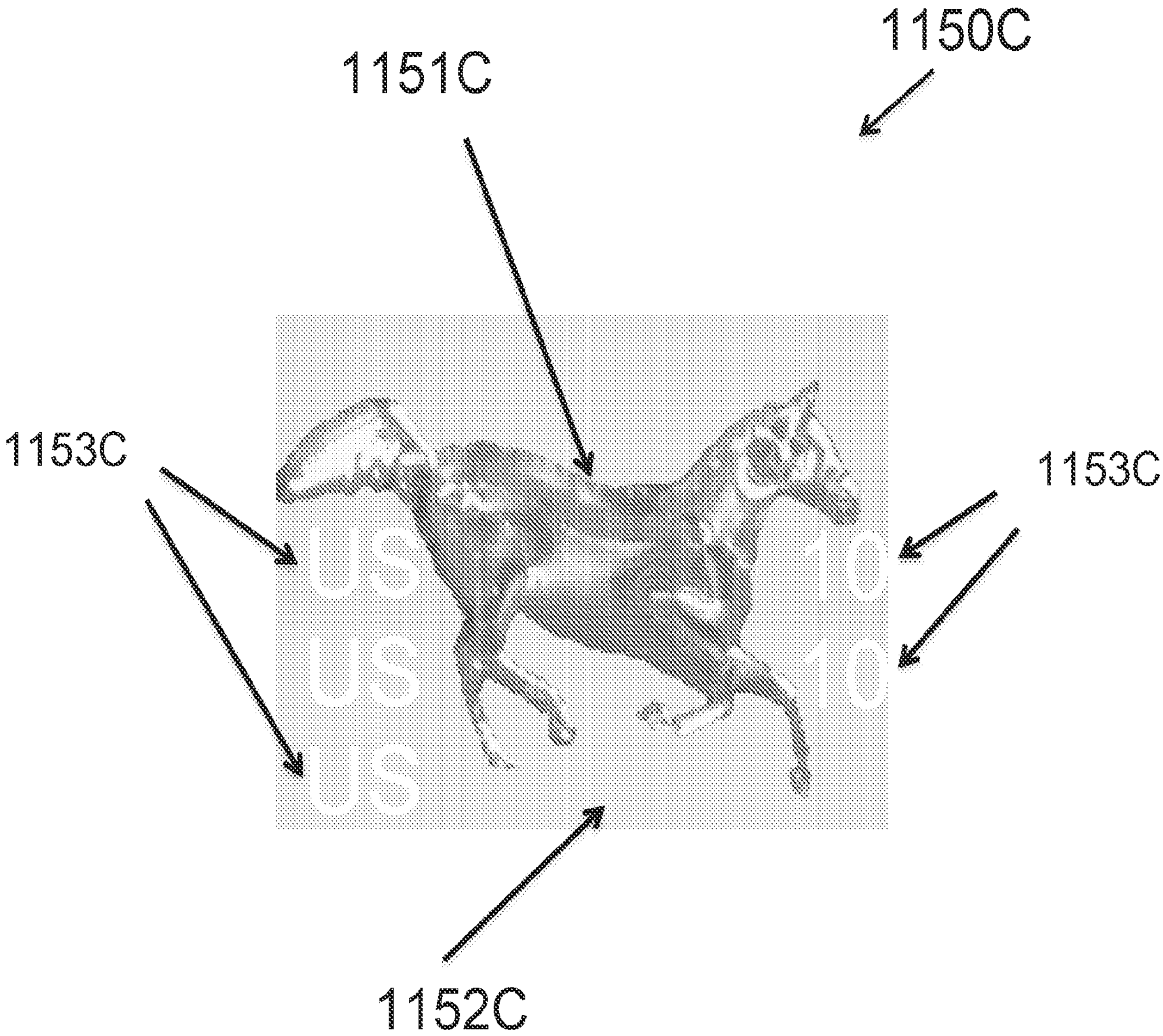

FIG. 8.

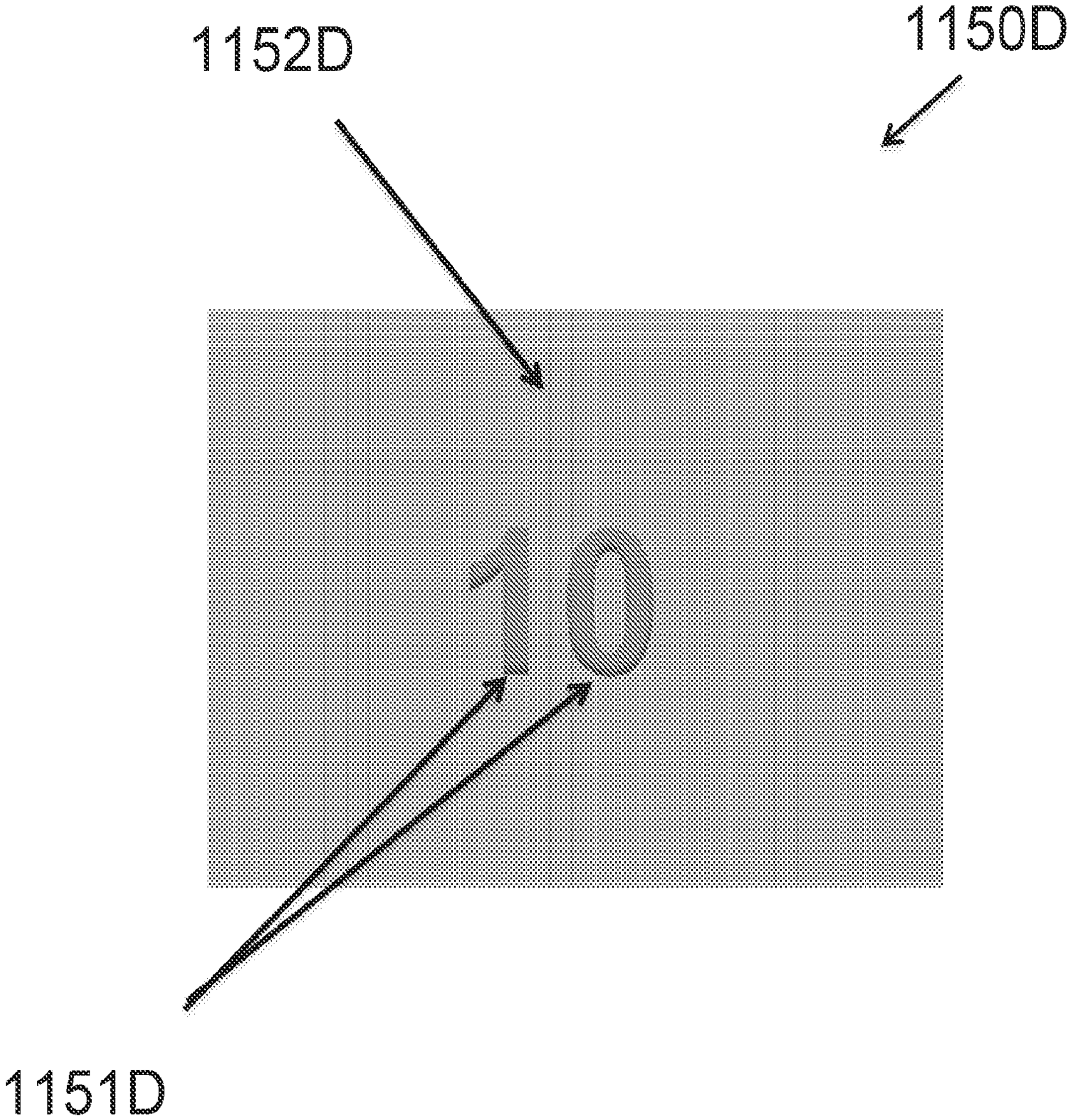

FIG. 9.

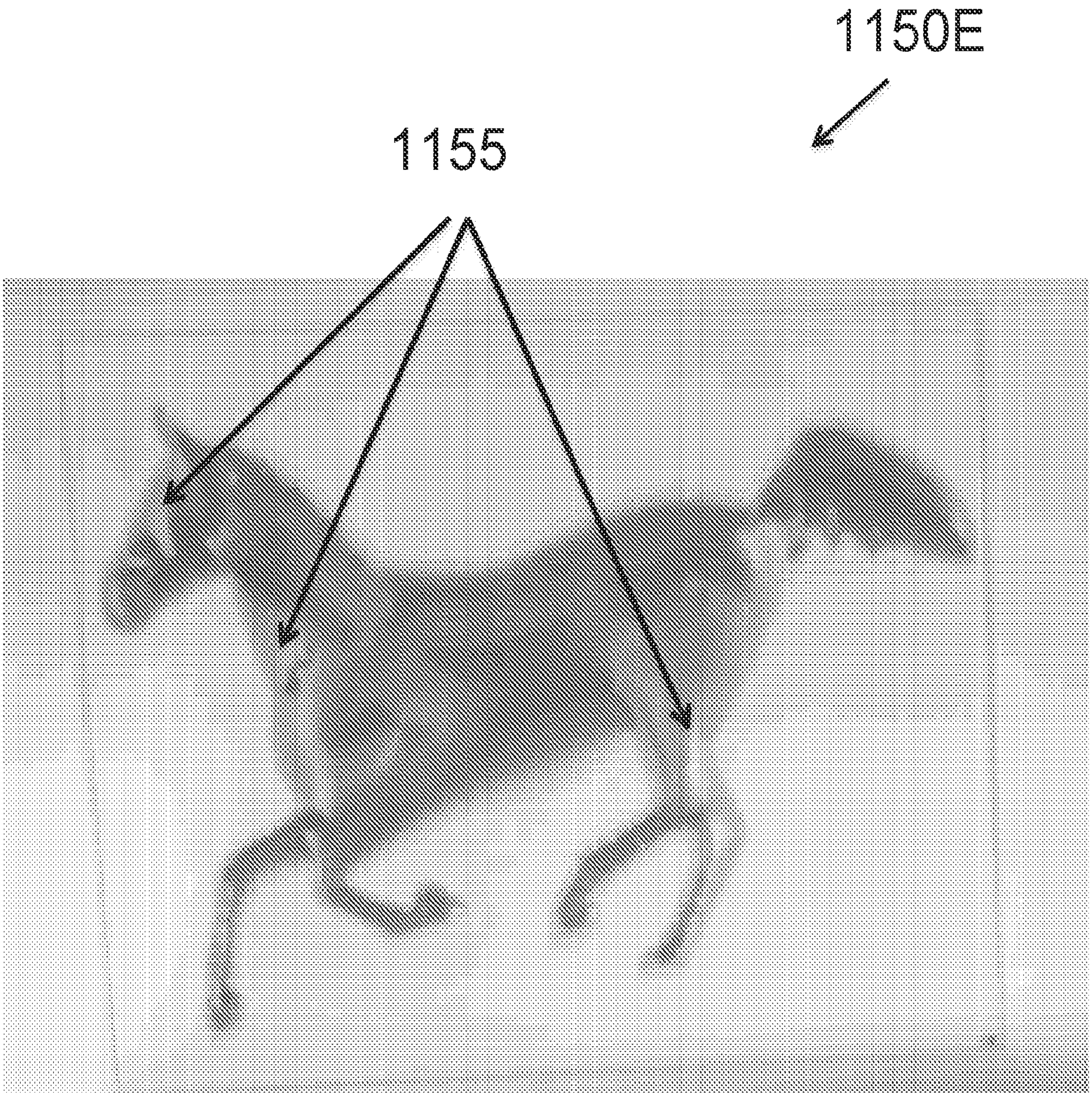

FIG. 10.

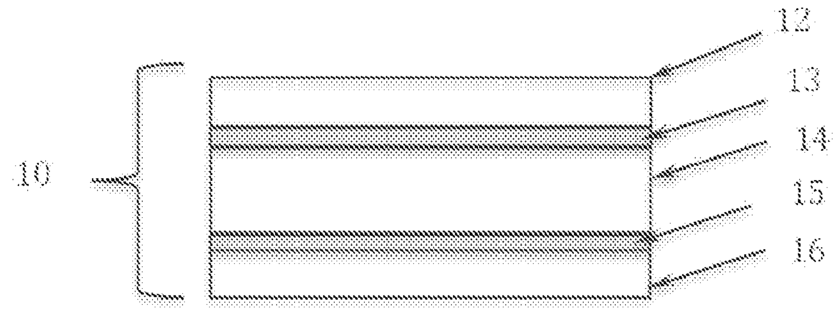

Fig. 11

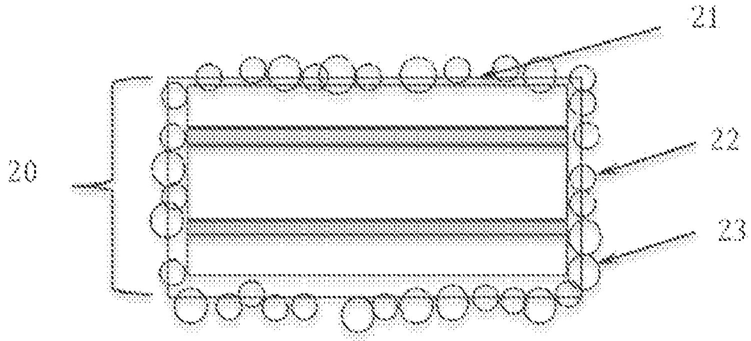

Fig. 12A-1

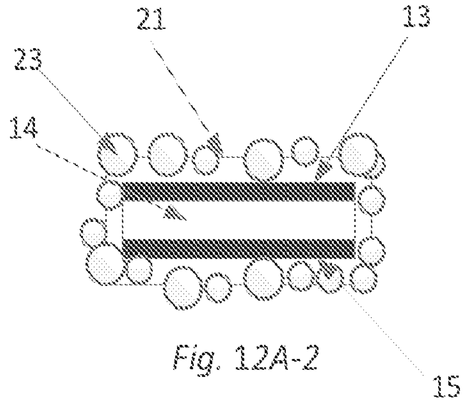

Fig. 12A-2

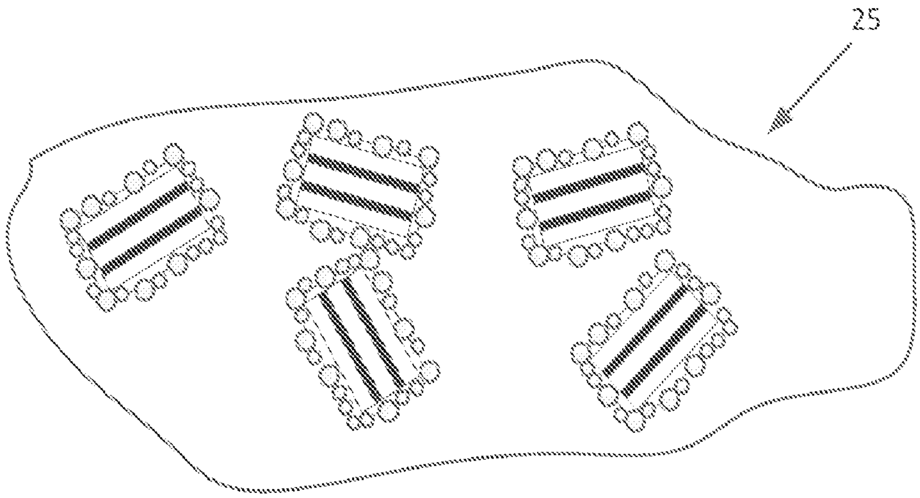

Fig. 12B-1

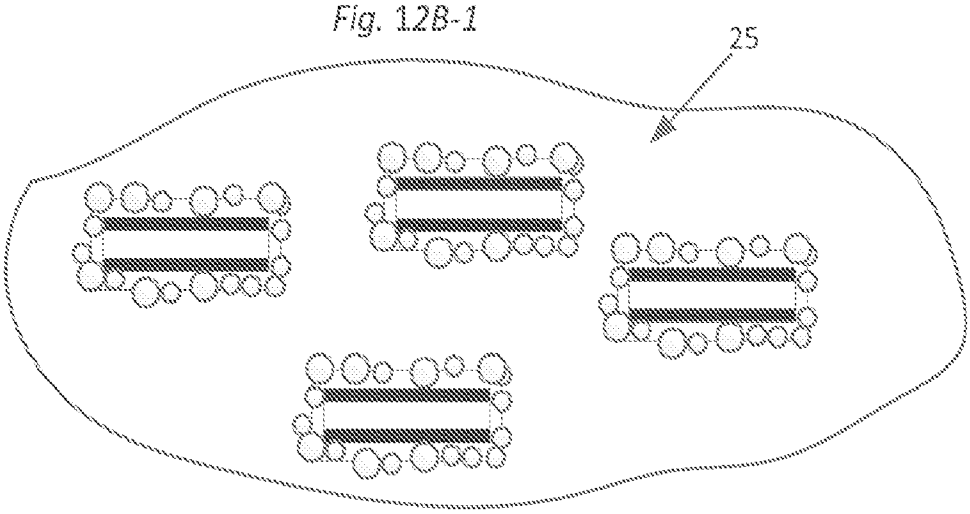

Fig. 12B-2

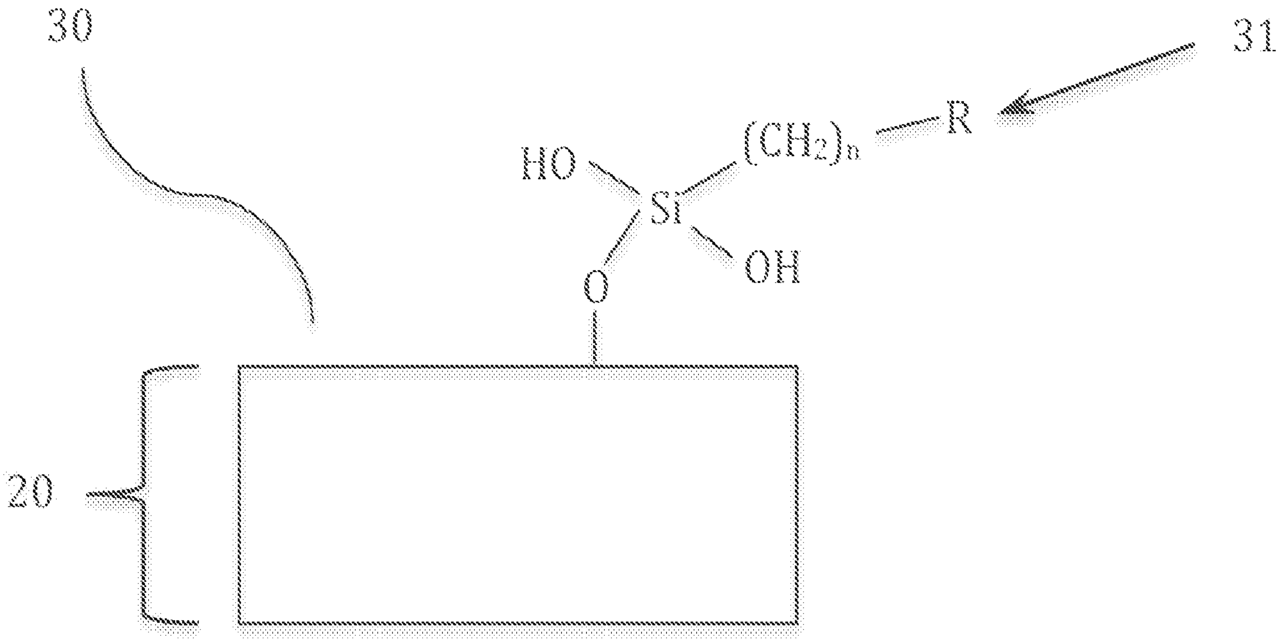

Fig13.

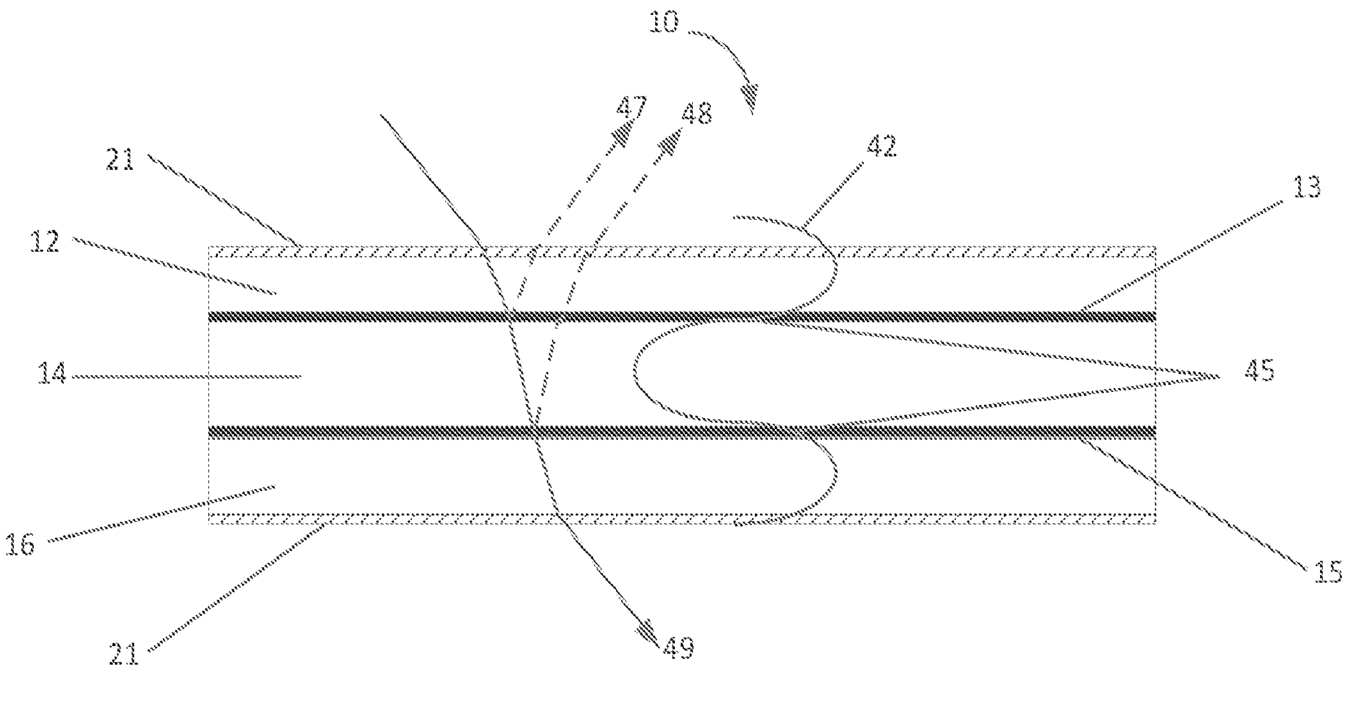

Fig. 14

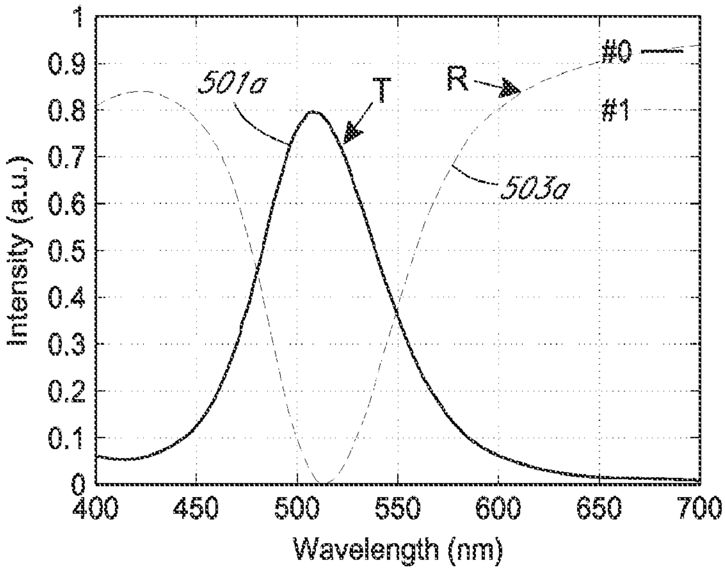

FIG. 15A

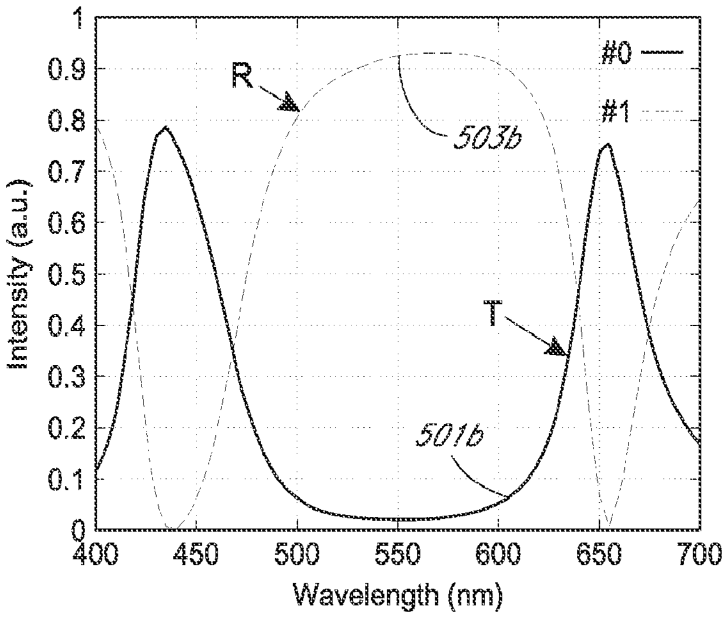

FIG. 15B

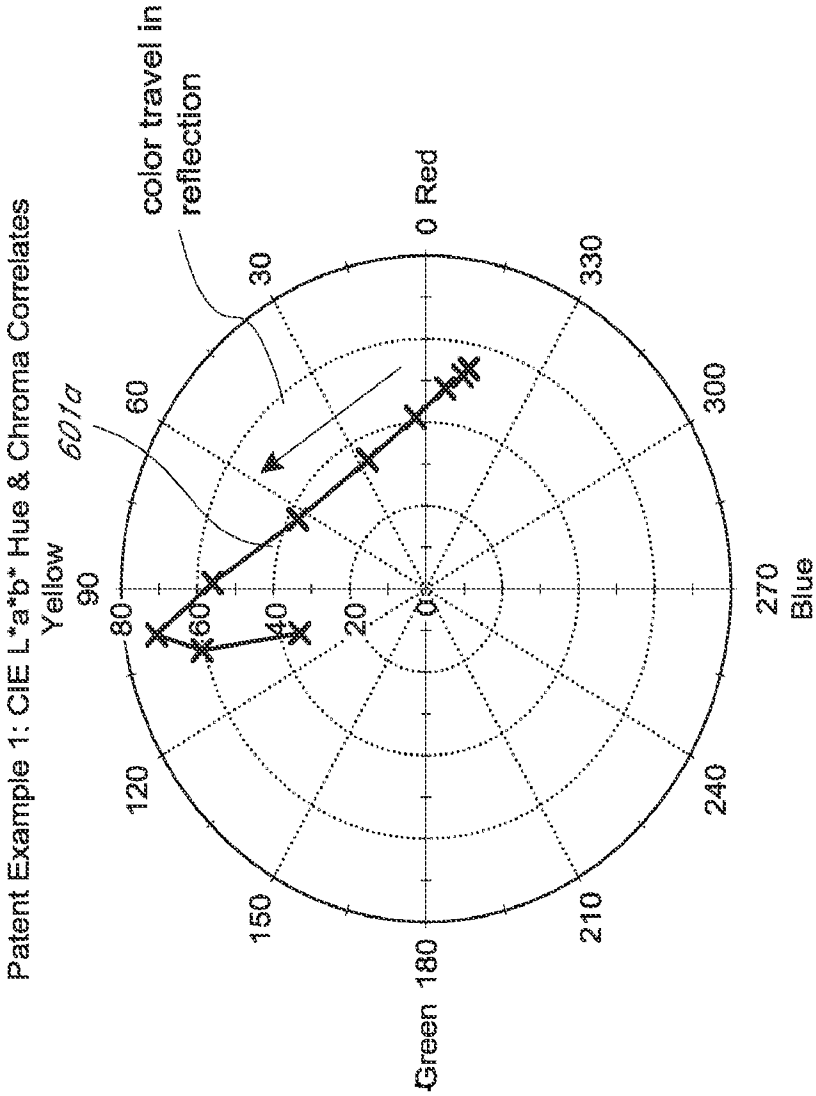

FIG. 16A

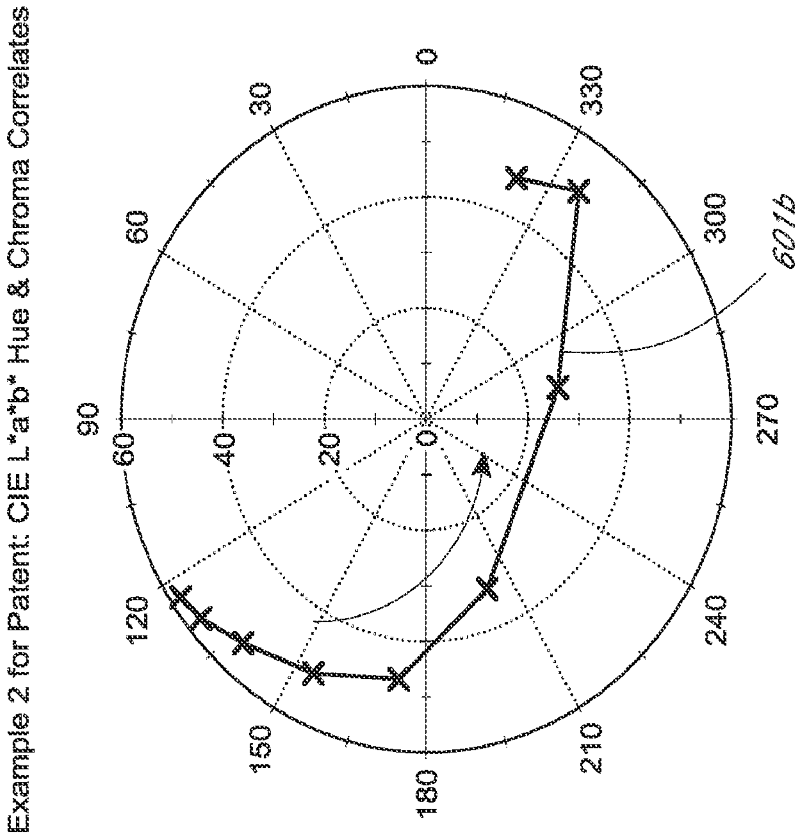

FIG. 16B

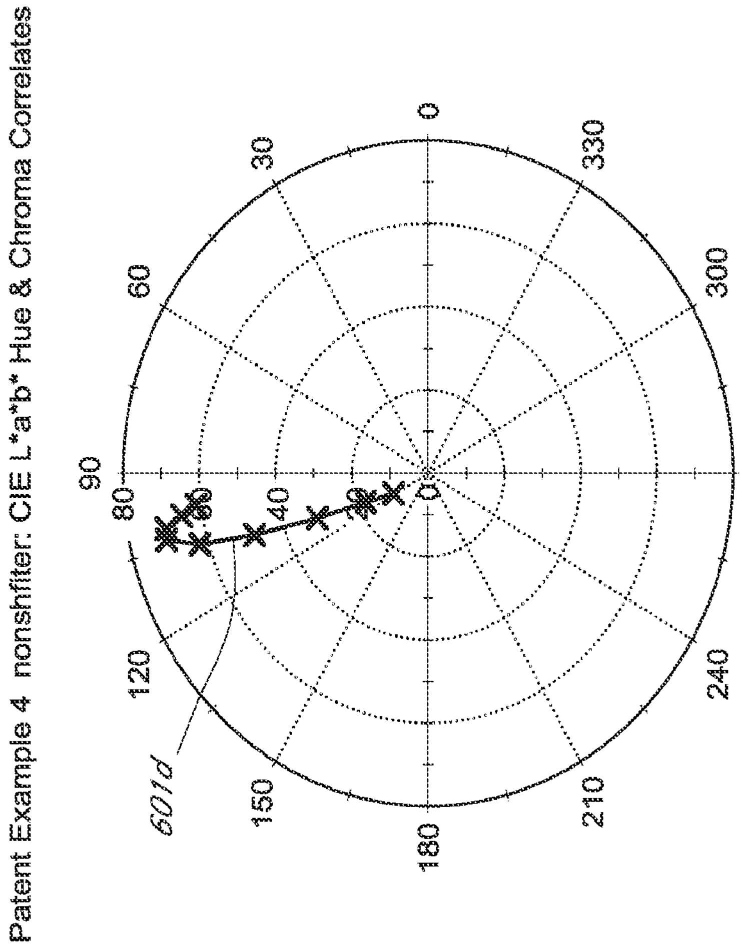

FIG. 16D

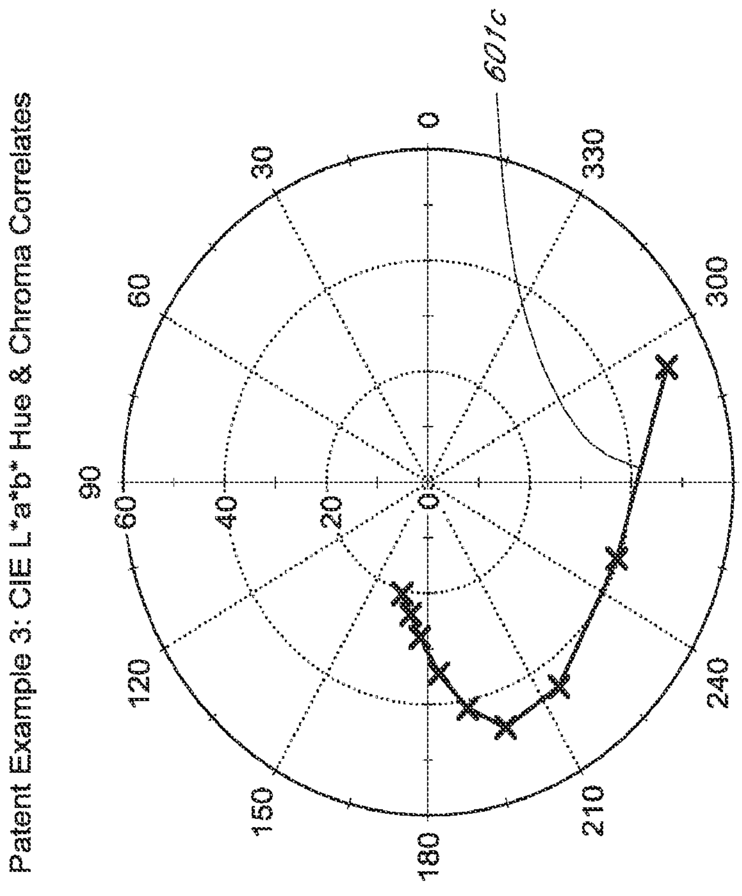

FIG. 16C

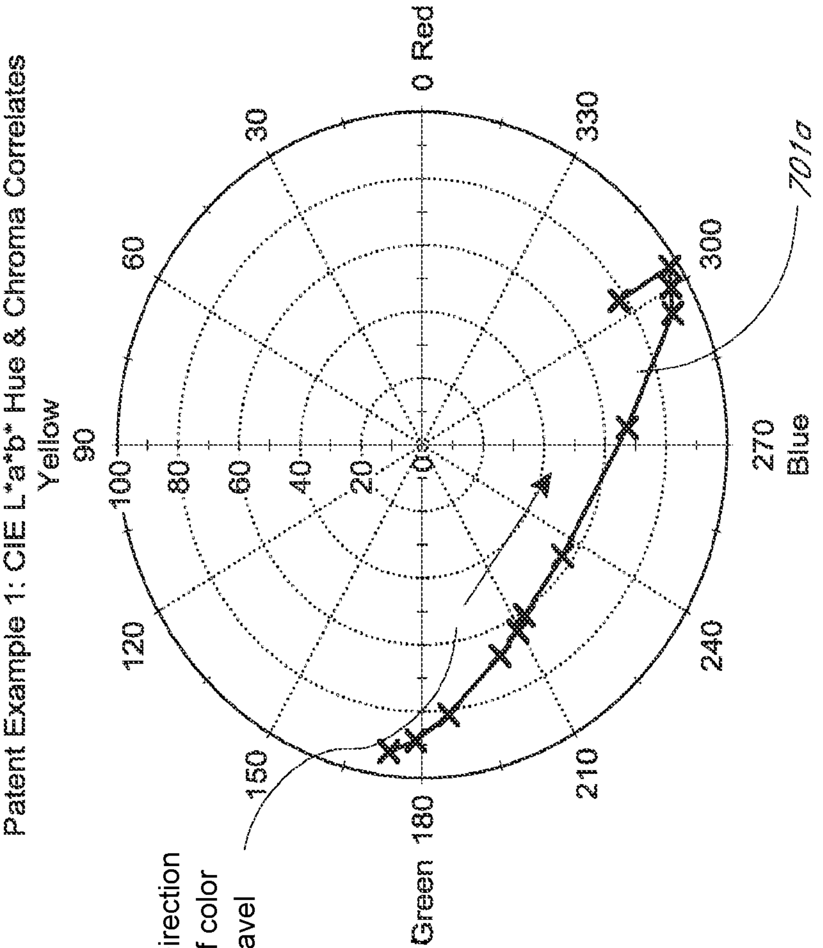

FIG. 17A

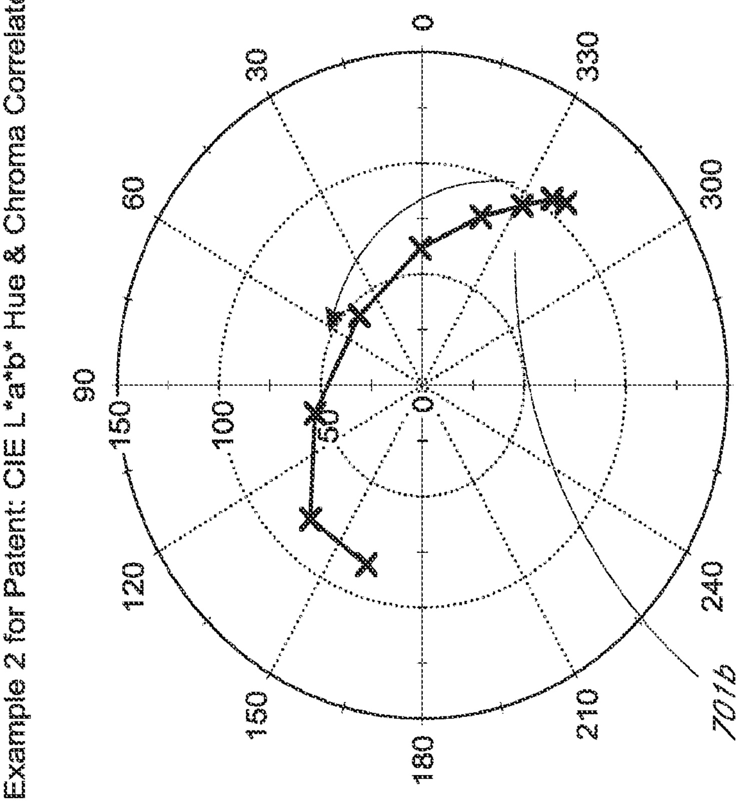

FIG. 17B

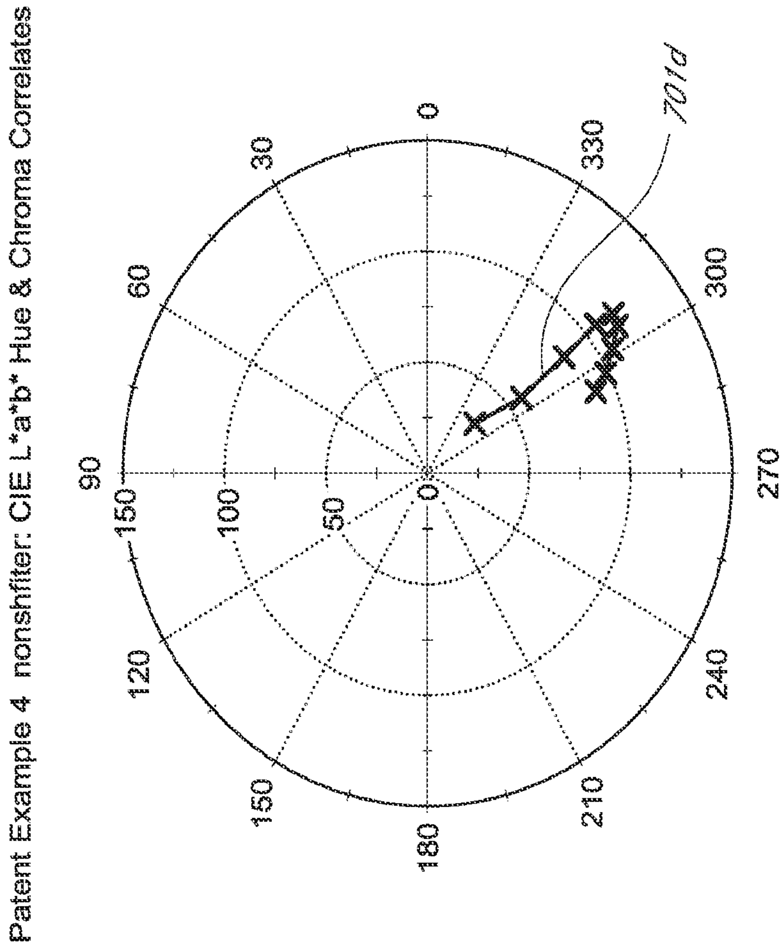

FIG. 17D

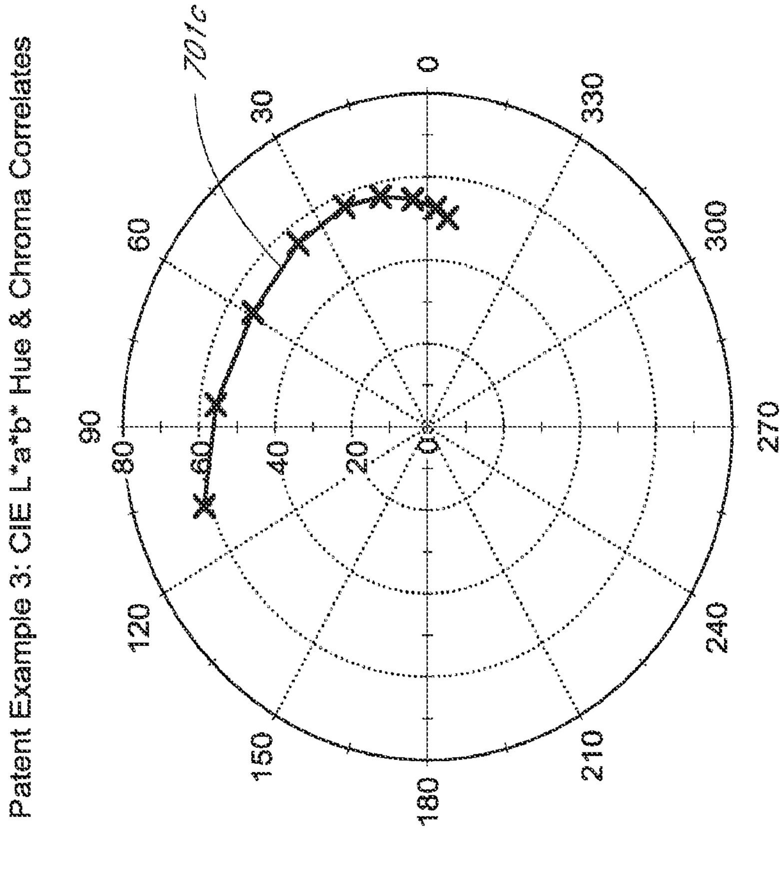

FIG. 17C

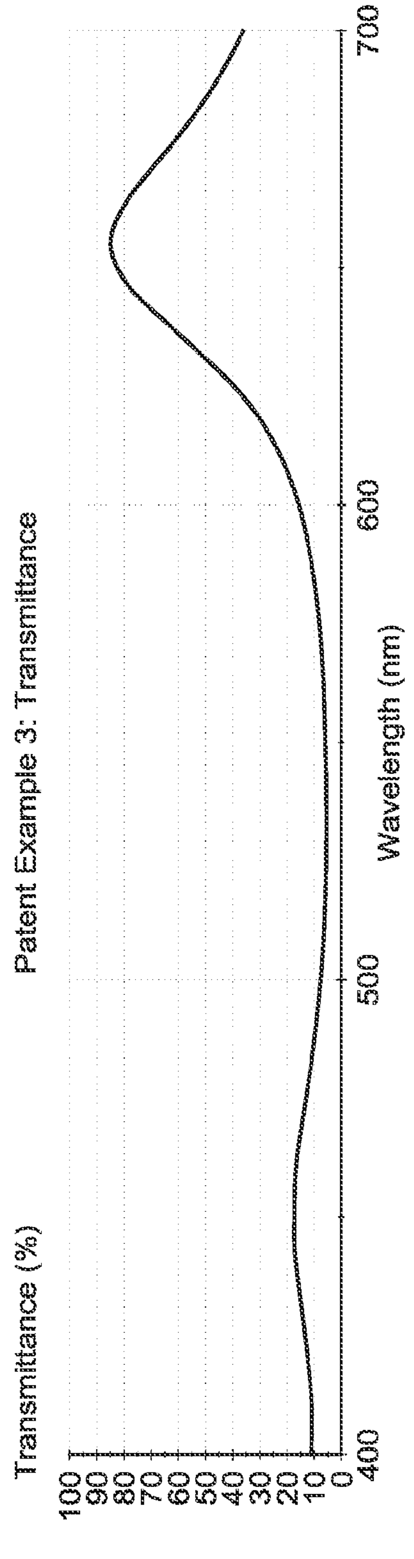

FIG. 18A

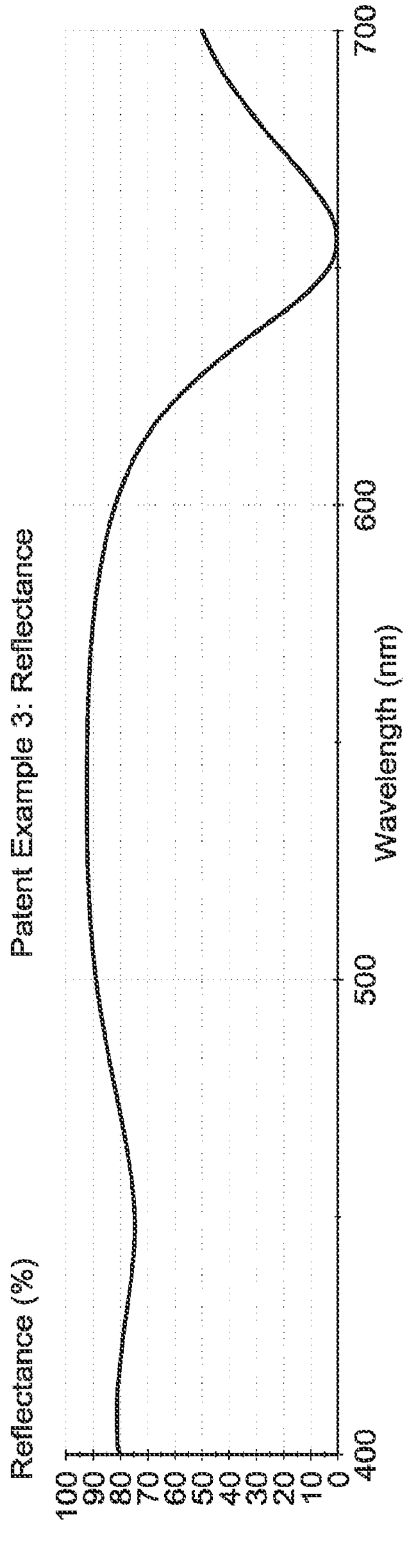

FIG. 18B

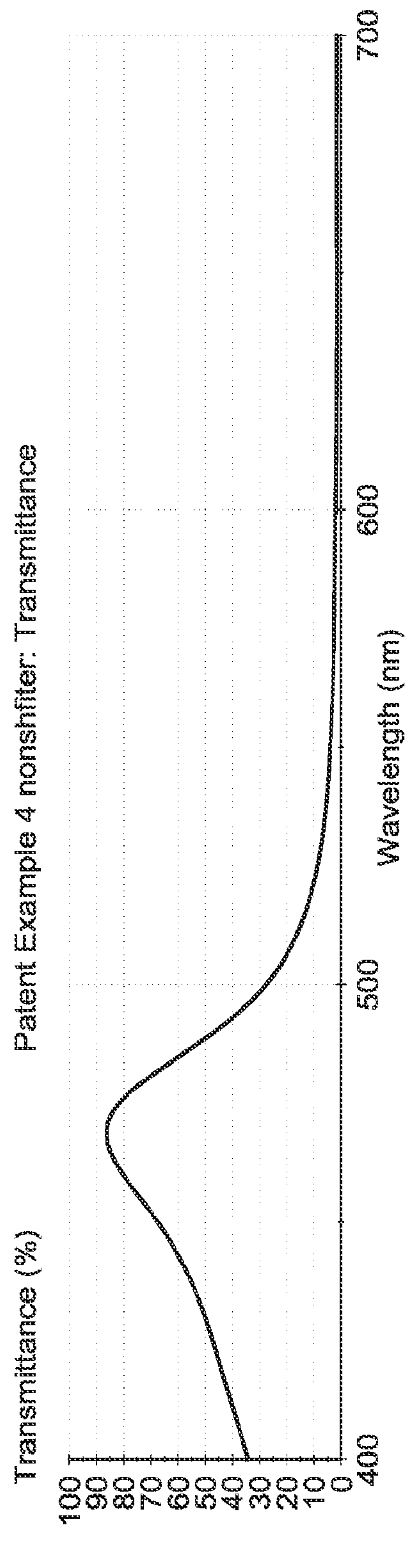

FIG. 18C

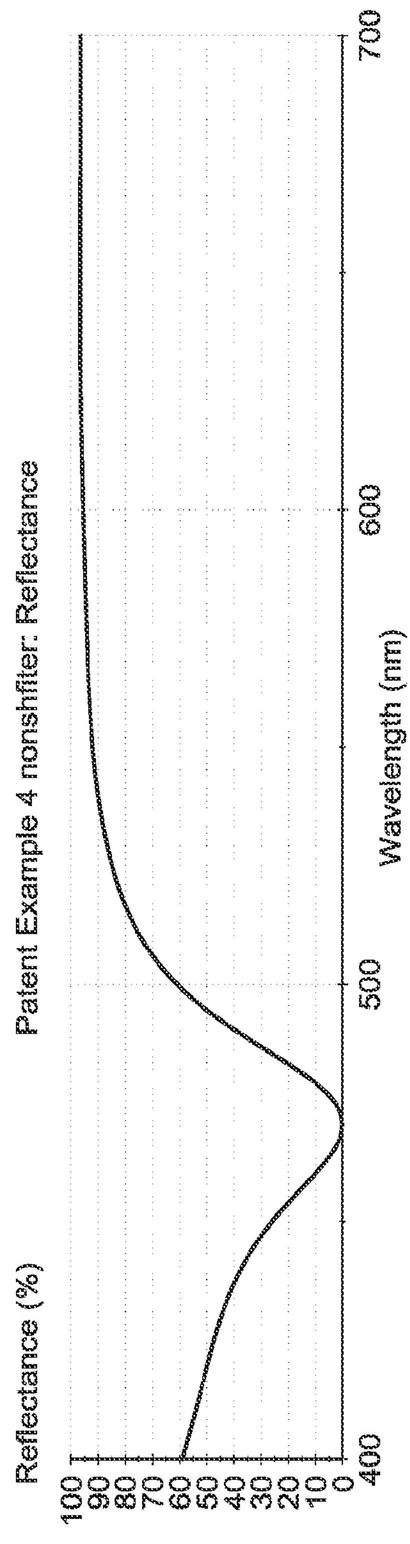

FIG. 18D

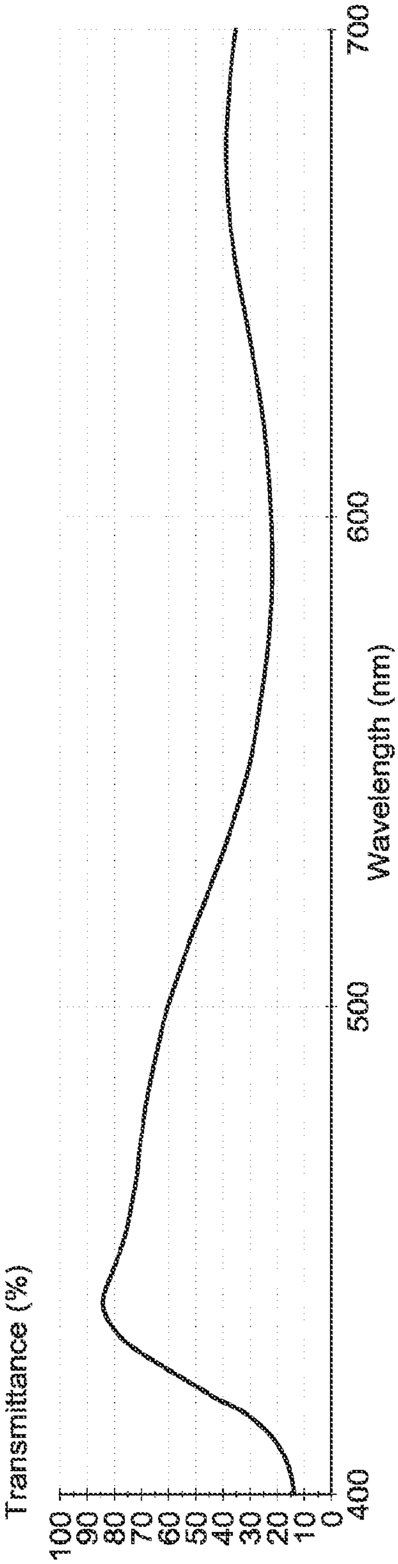

FIG. 18E

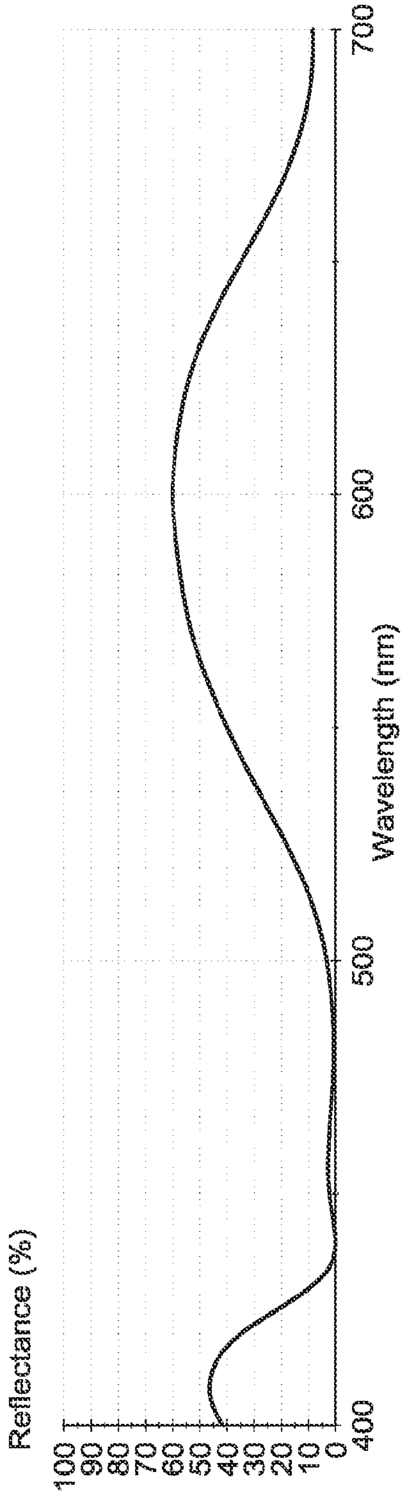

FIG. 18F

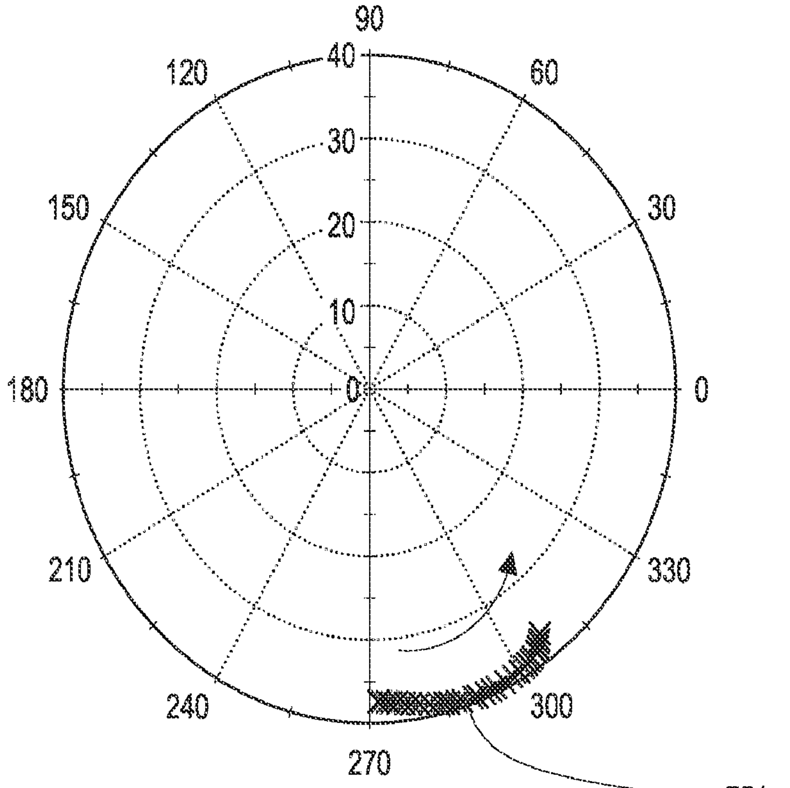

FIG. 18G

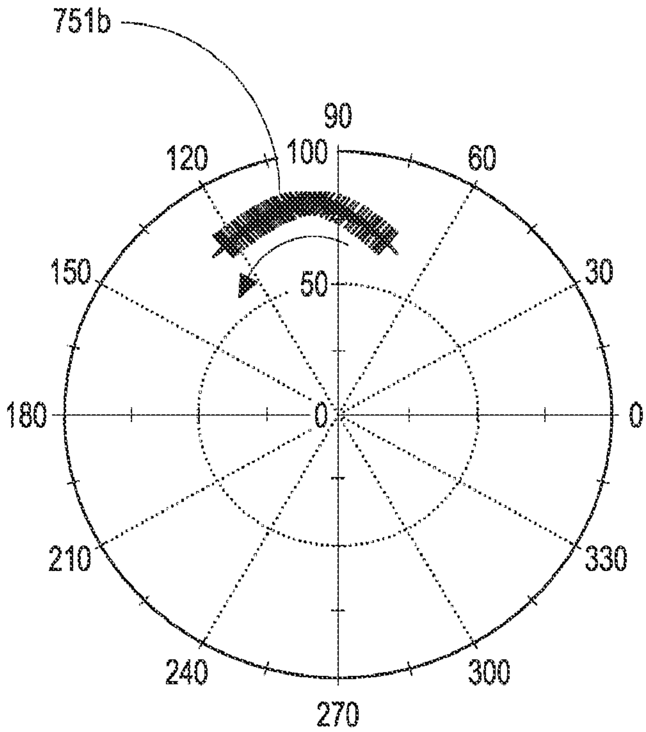

FIG. 18H

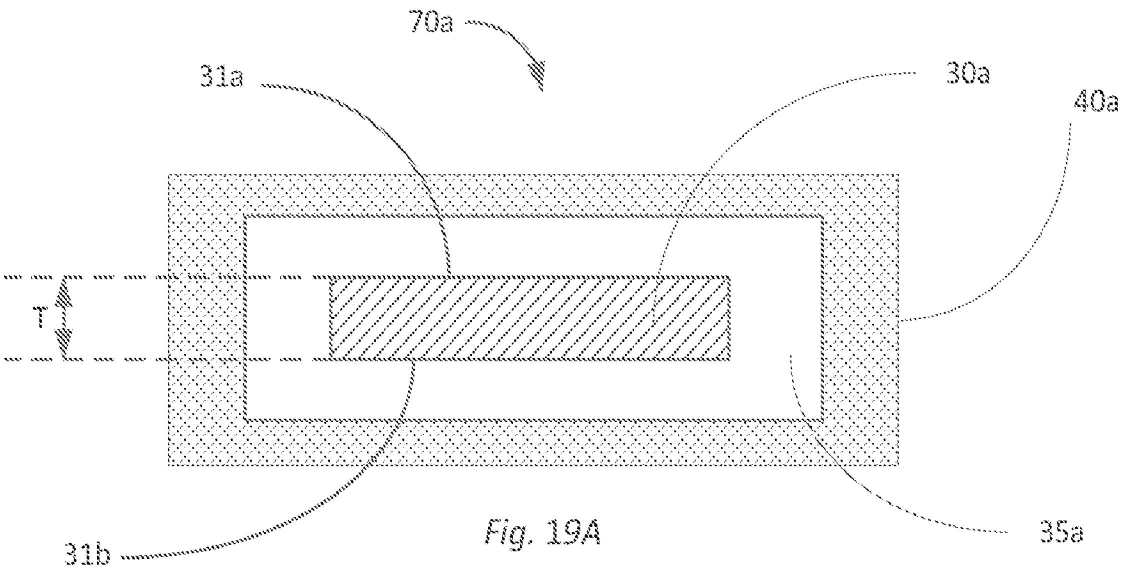

Fig. 19A

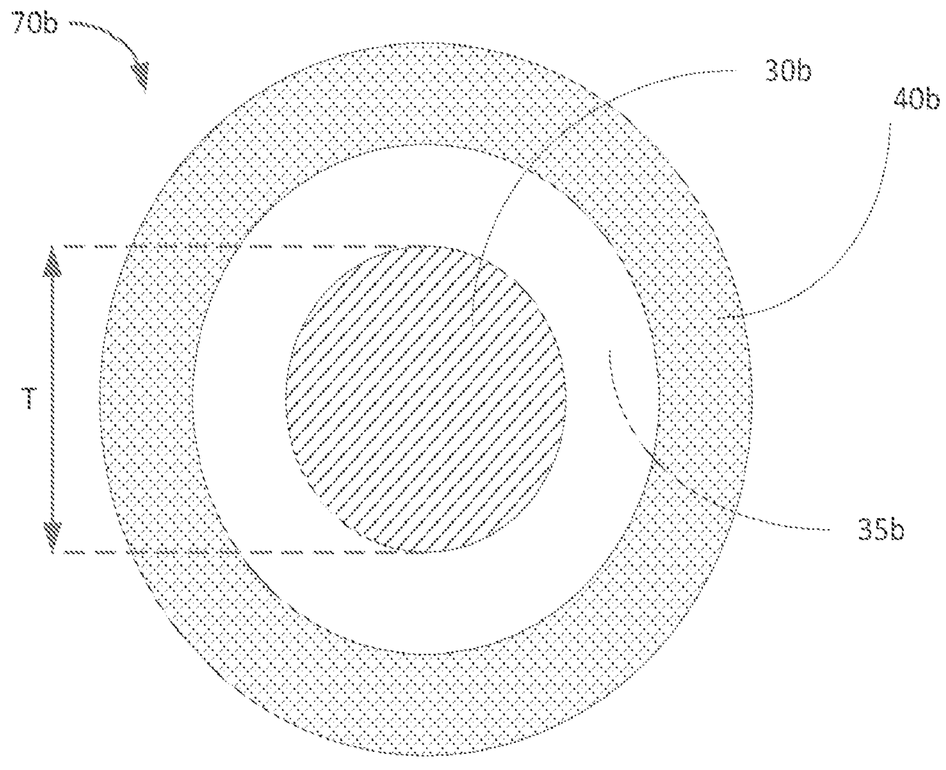

Fig. 19B

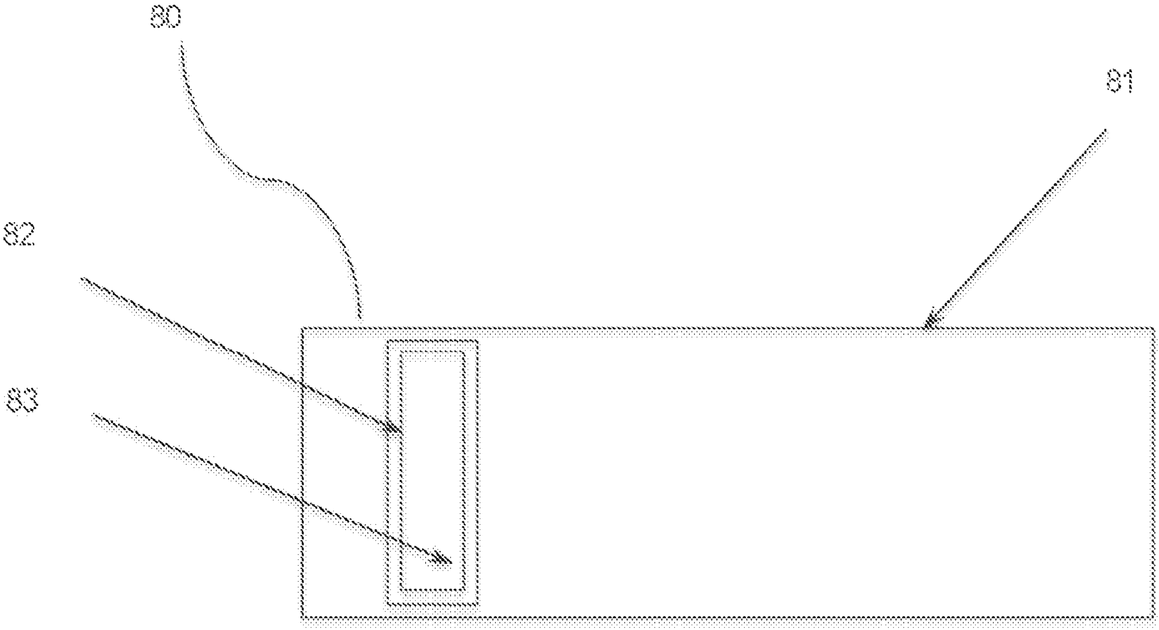

Fig. 20

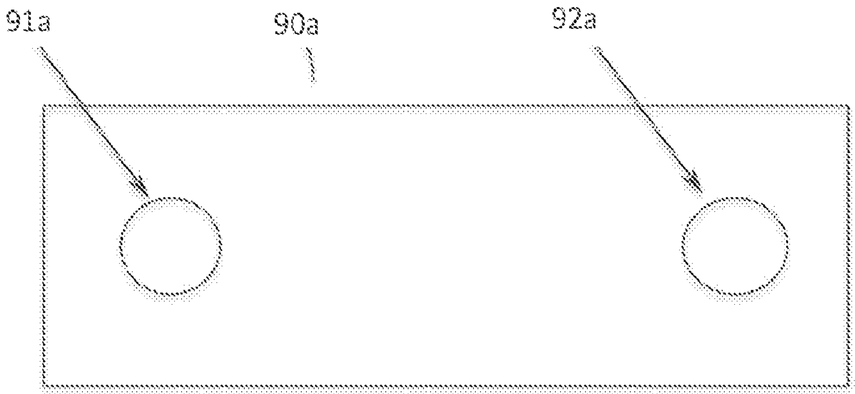

Fig. 21A

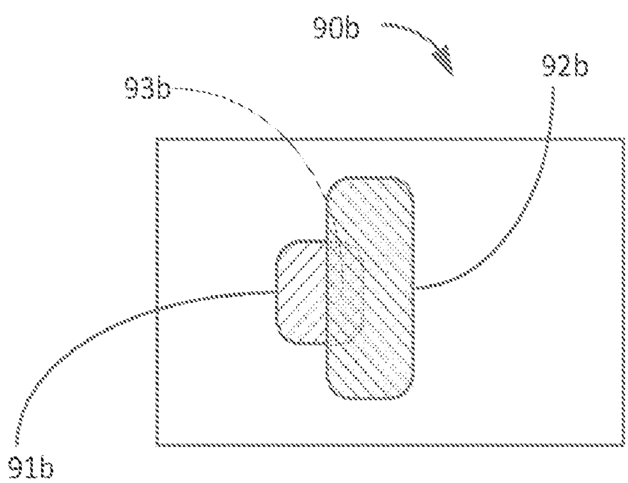

Fig. 21B

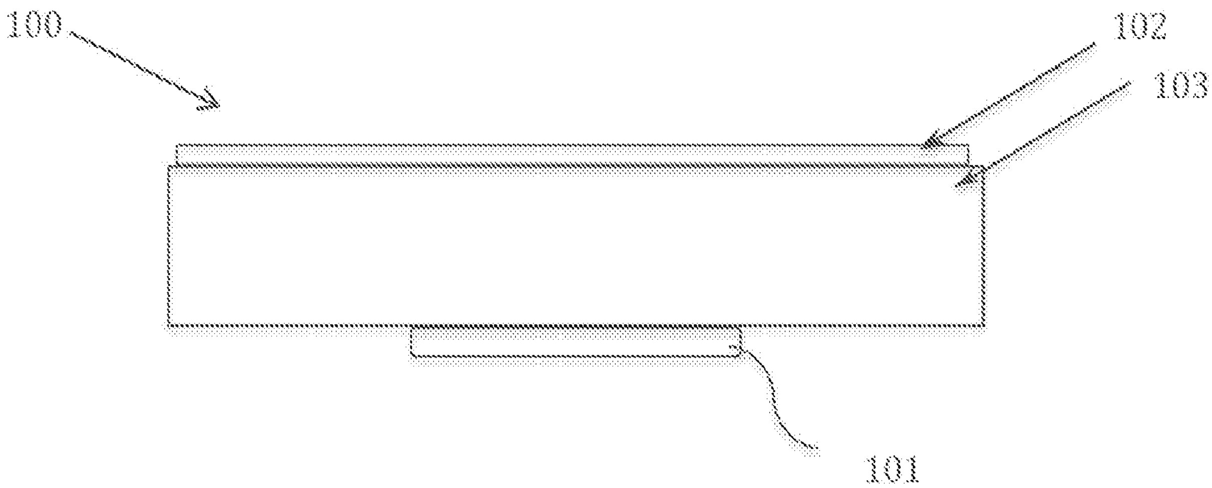
100
102
103
101

Fig. 22

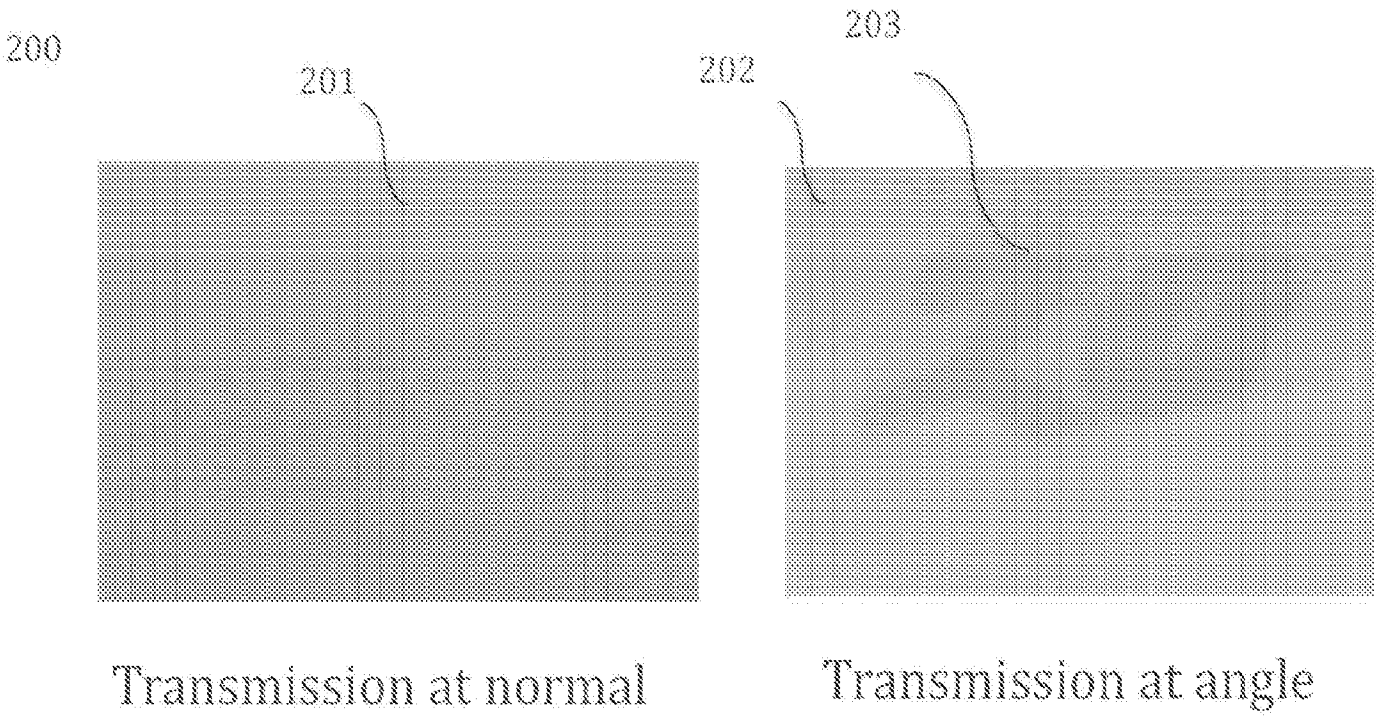
200
201
202
203
Transmission at normal
Transmission at angle

Fig. 23

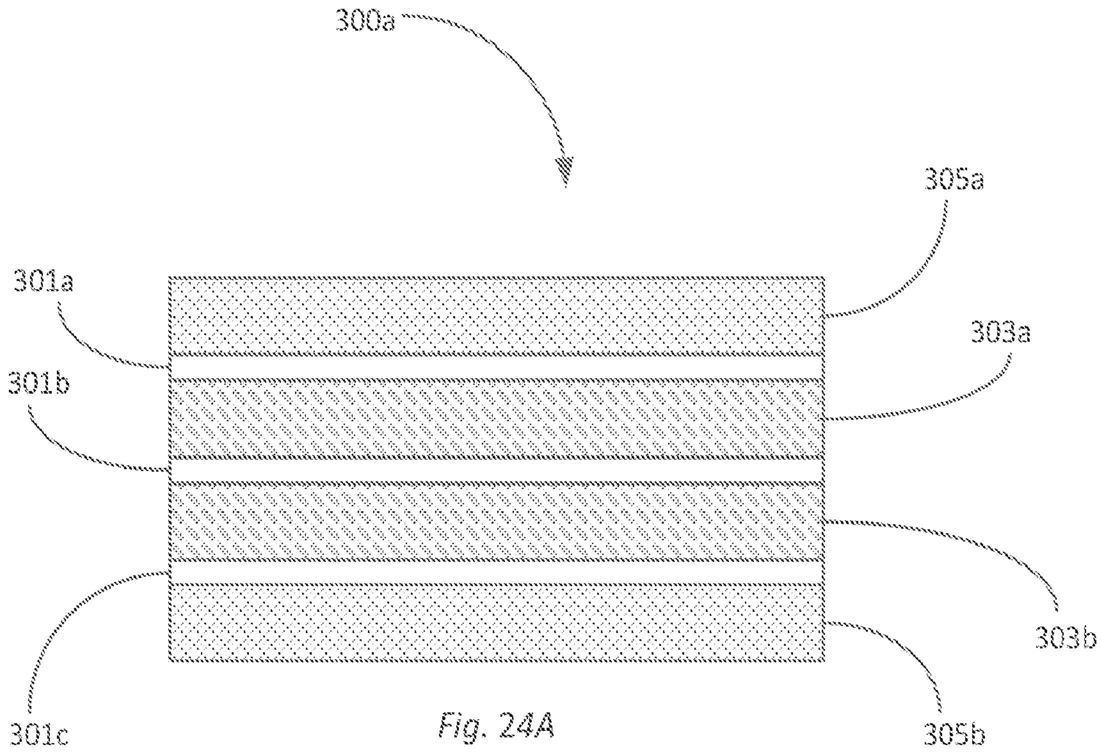

Fig. 24A

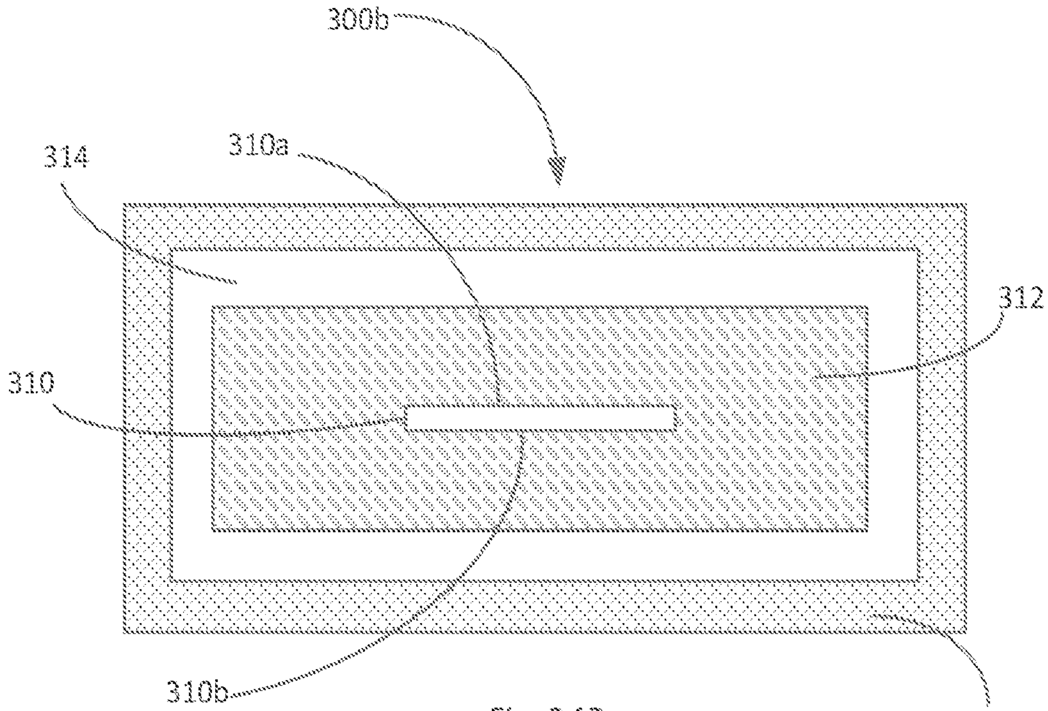

Fig. 24B

CIE 1931 Chromaticity Diagram

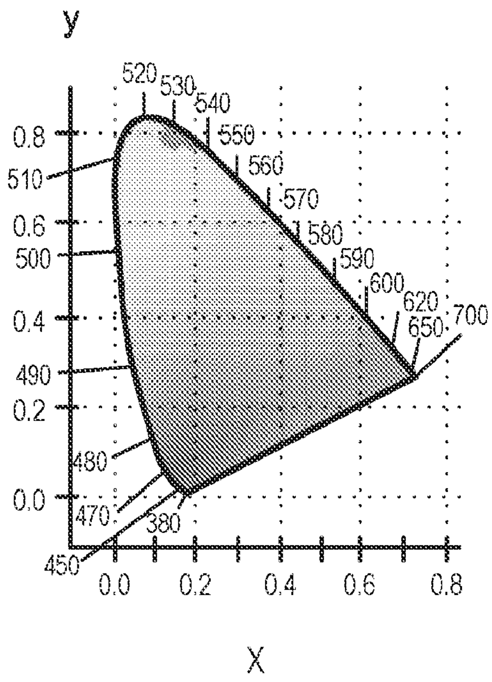

FIG. 25A

CIE 1931 Chromaticity Diagram

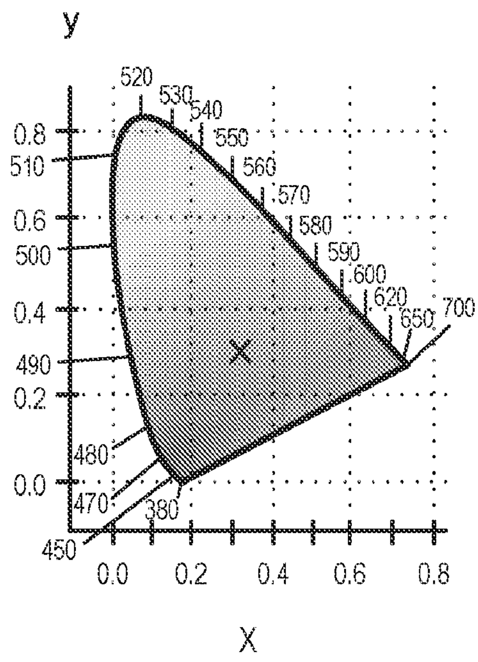

FIG. 25B

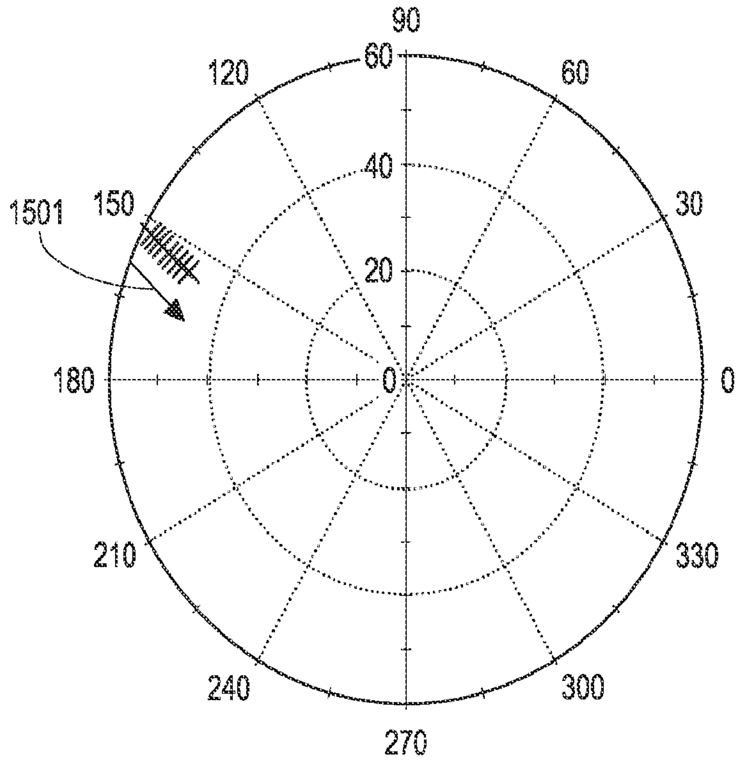

FIG.25C

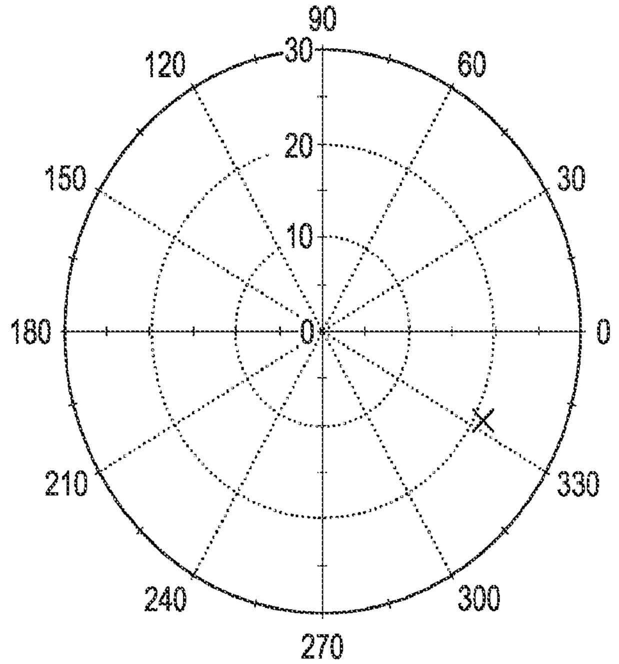

FIG.25D

CIE 1931 Chromaticity Diagram

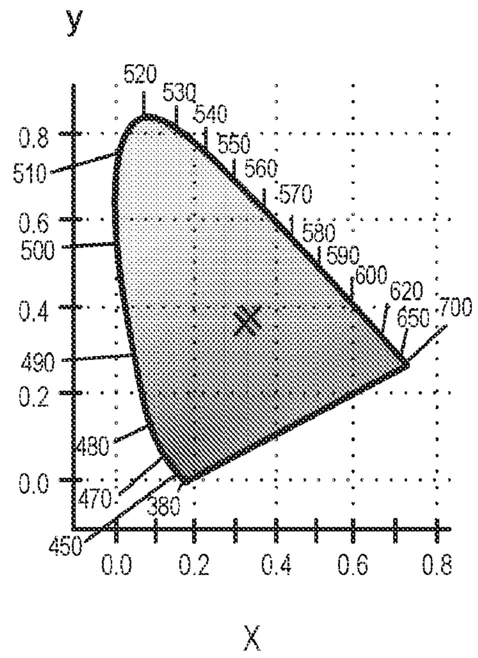

FIG.26A

CIE 1931 Chromaticity Diagram

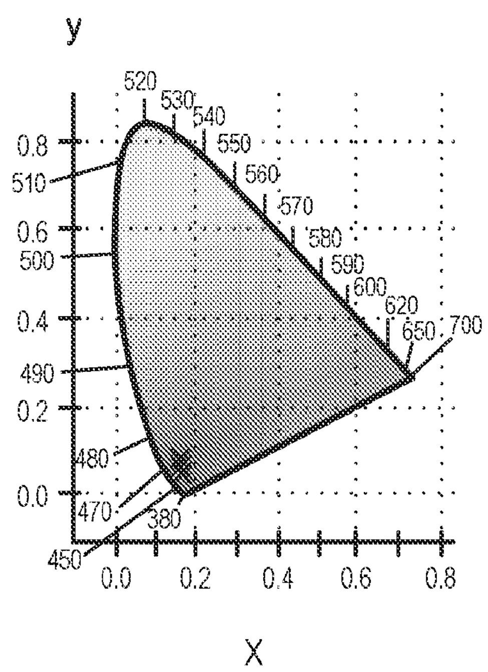

FIG.26B

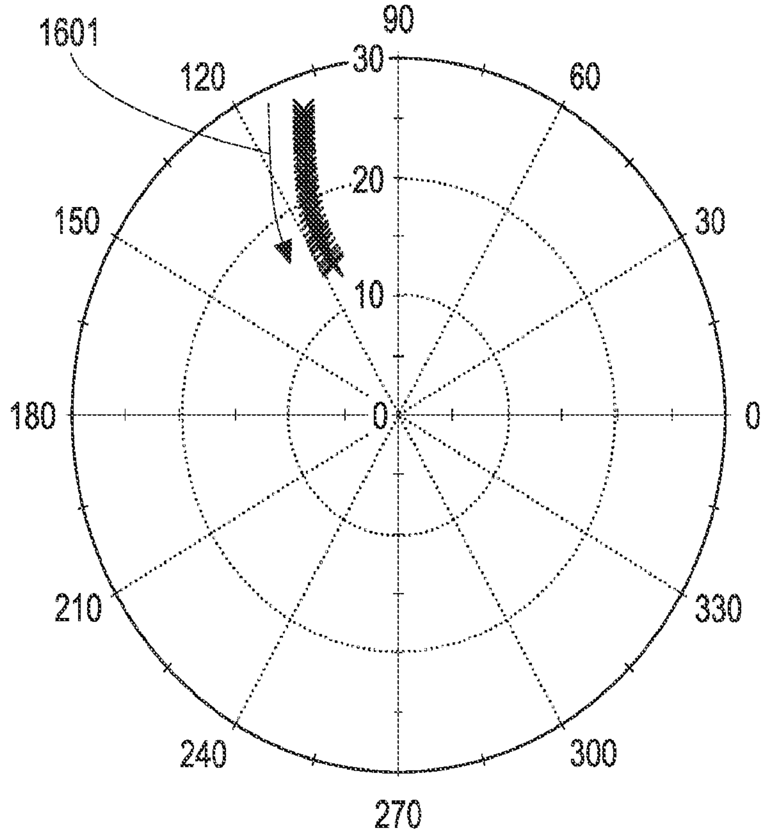

FIG.26C

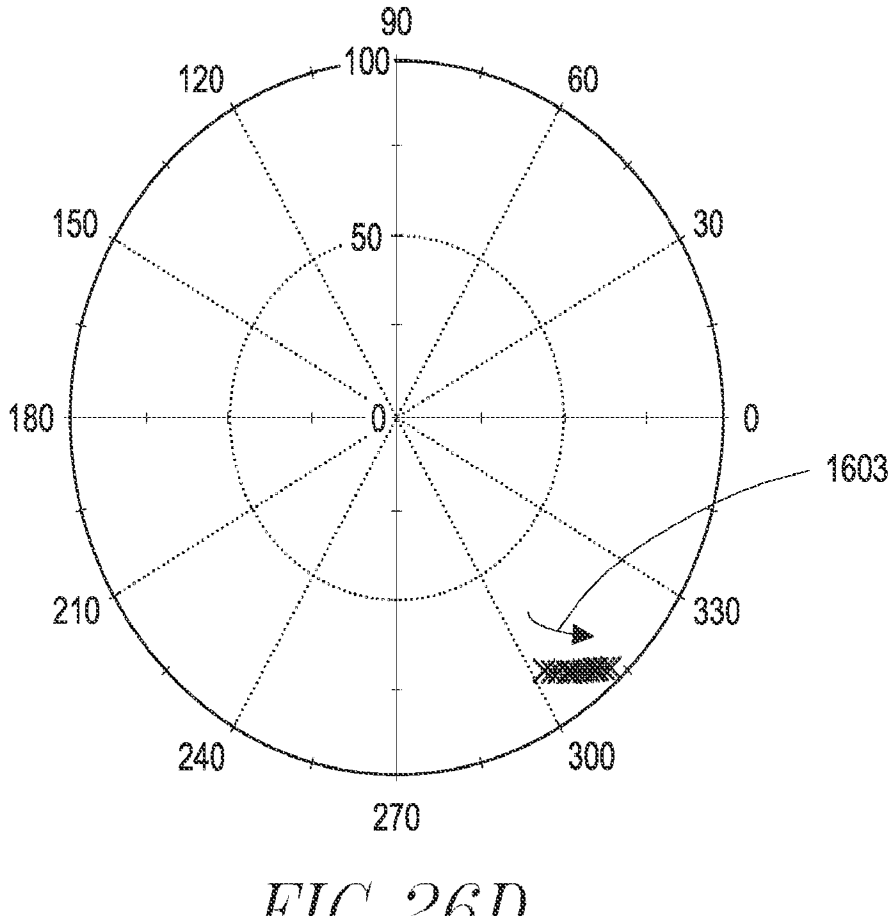

FIG.26D

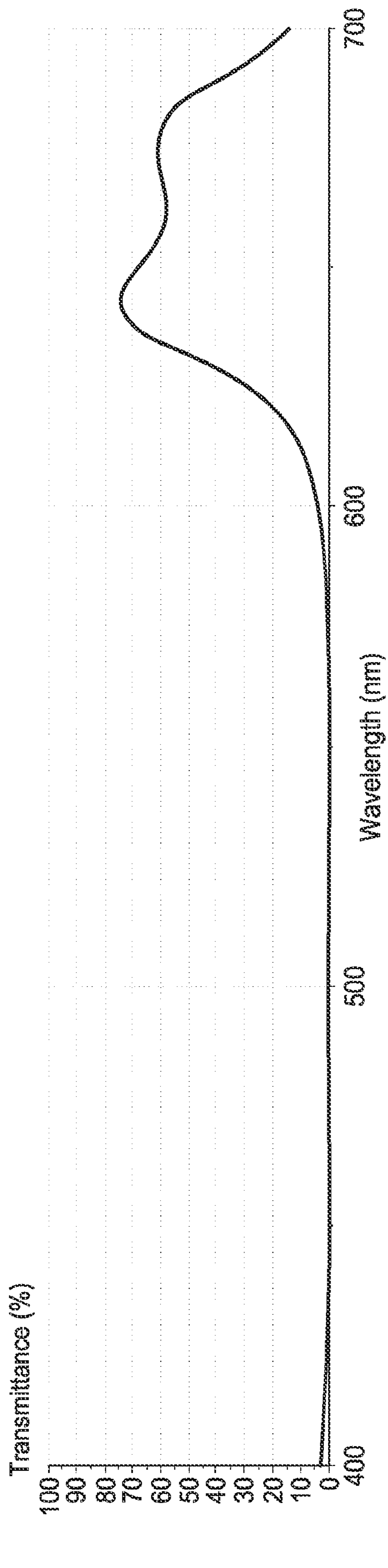

FIG. 27A

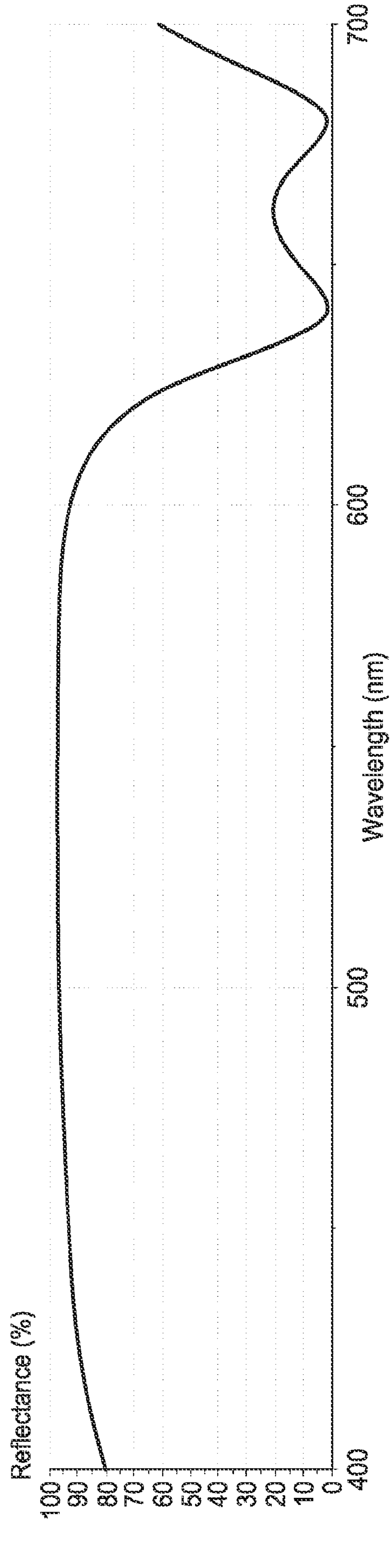

FIG. 27B

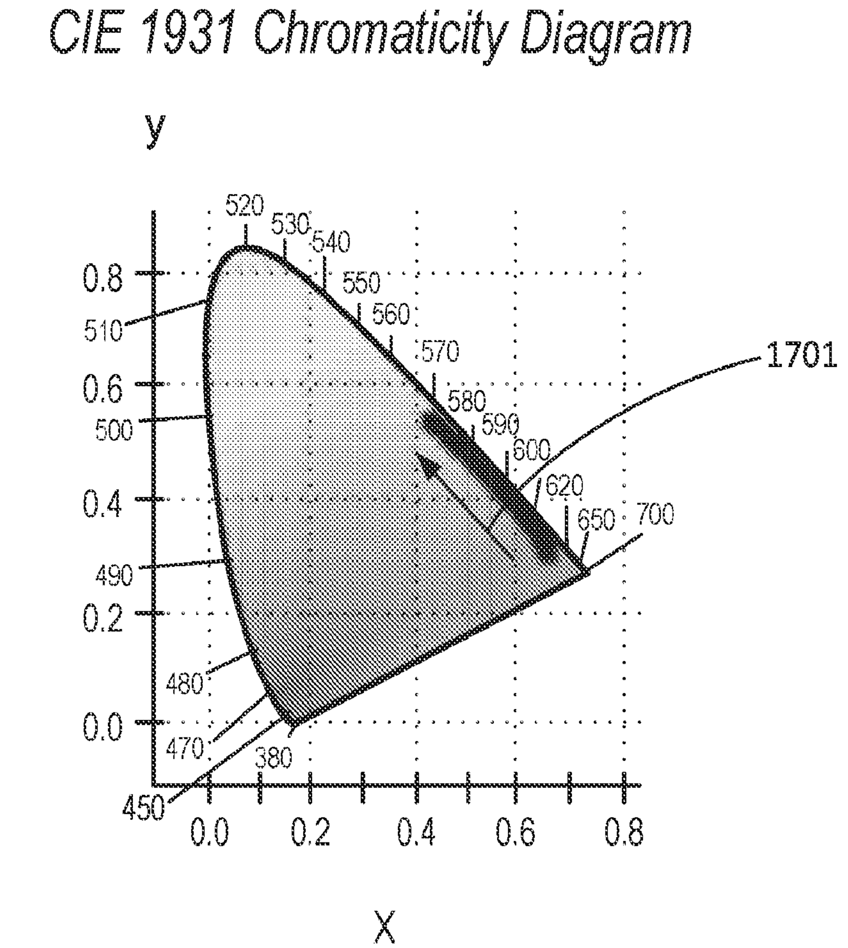

FIG.27C

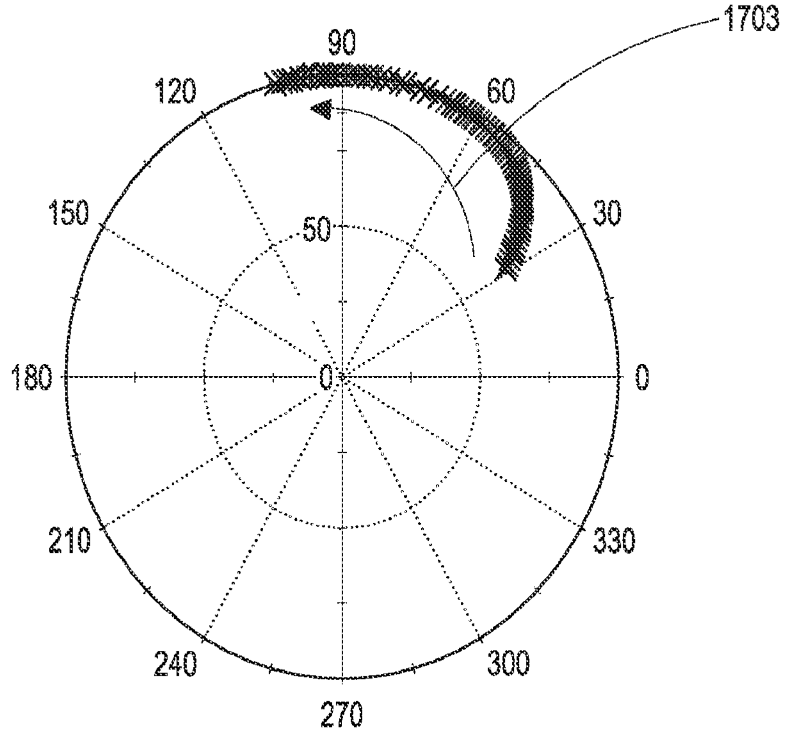

FIG.27D

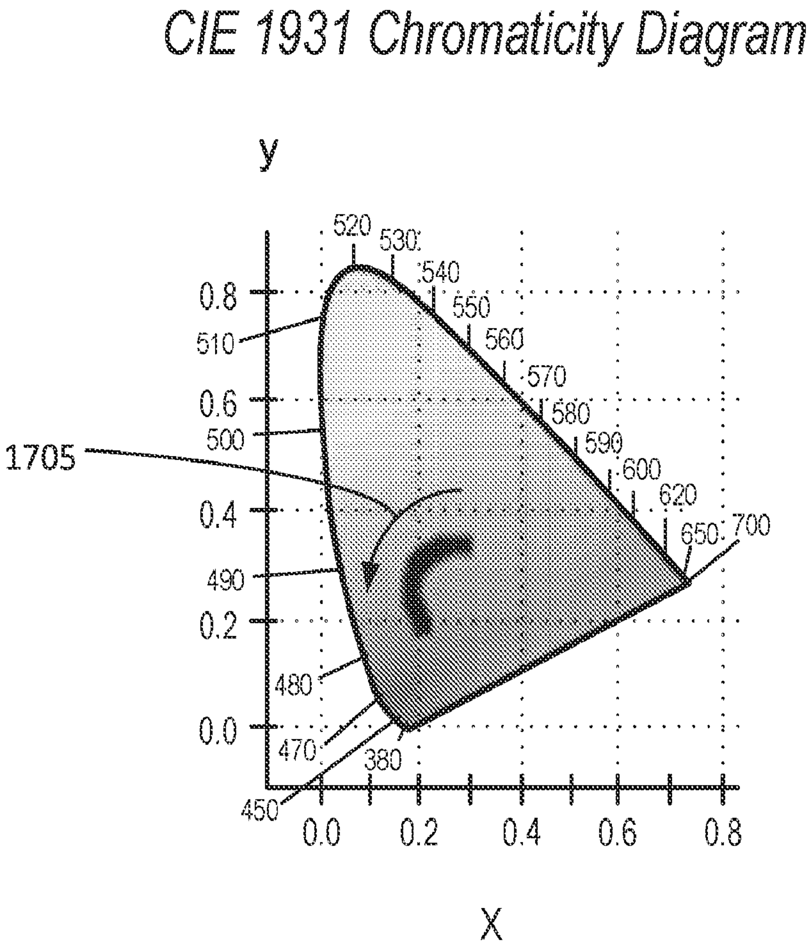

FIG.27E

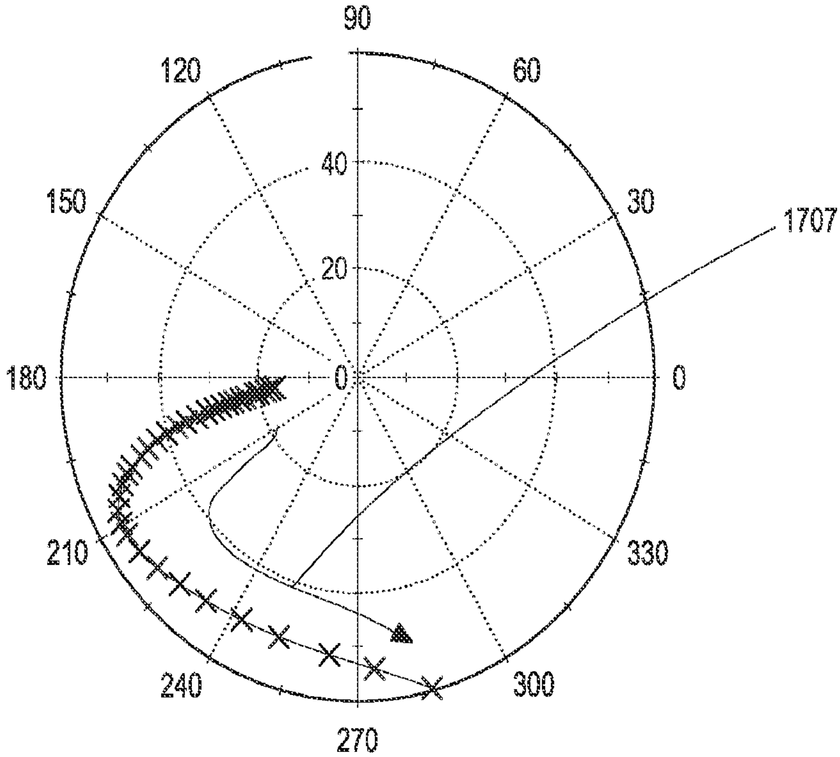

FIG.27F

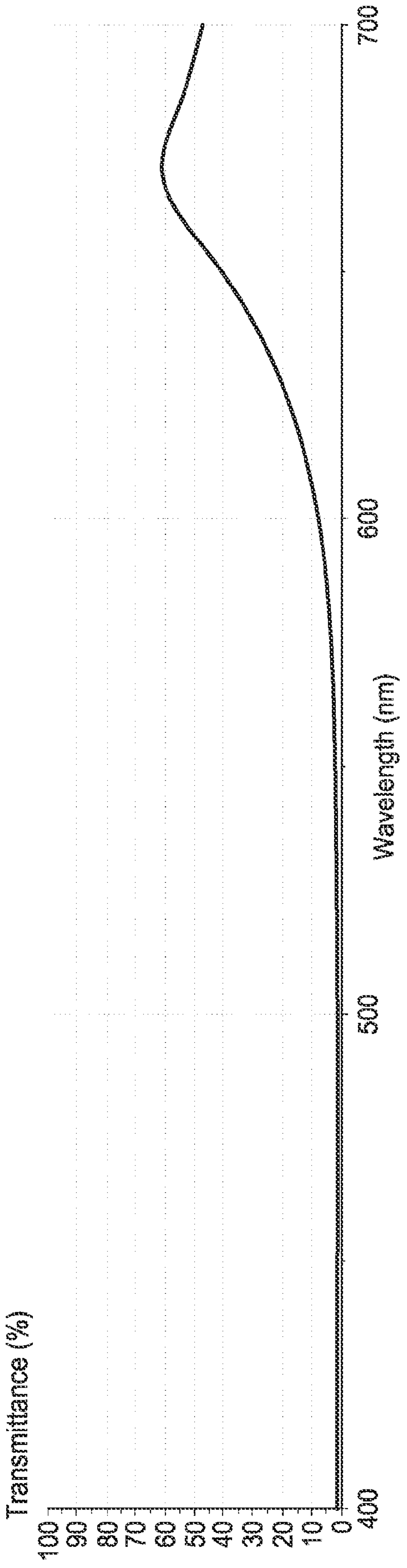

FIG. 28A

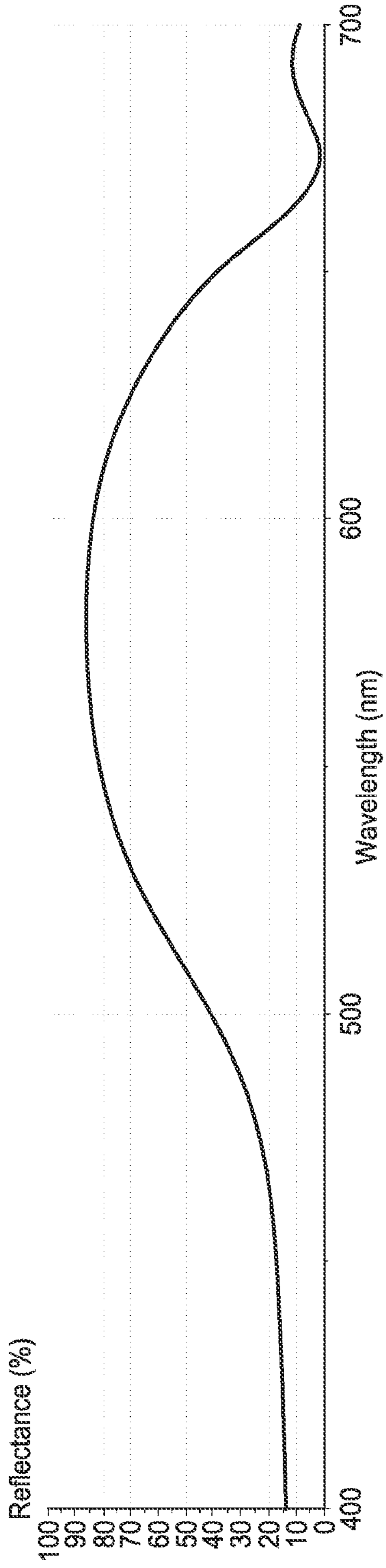

FIG. 28B

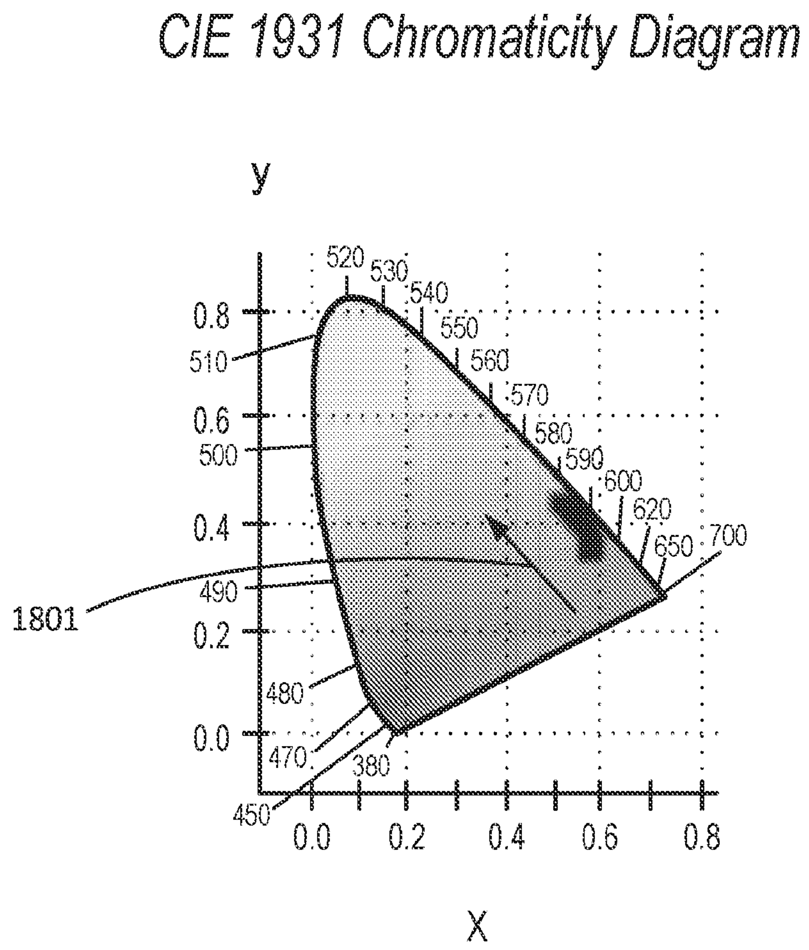

FIG. 28C

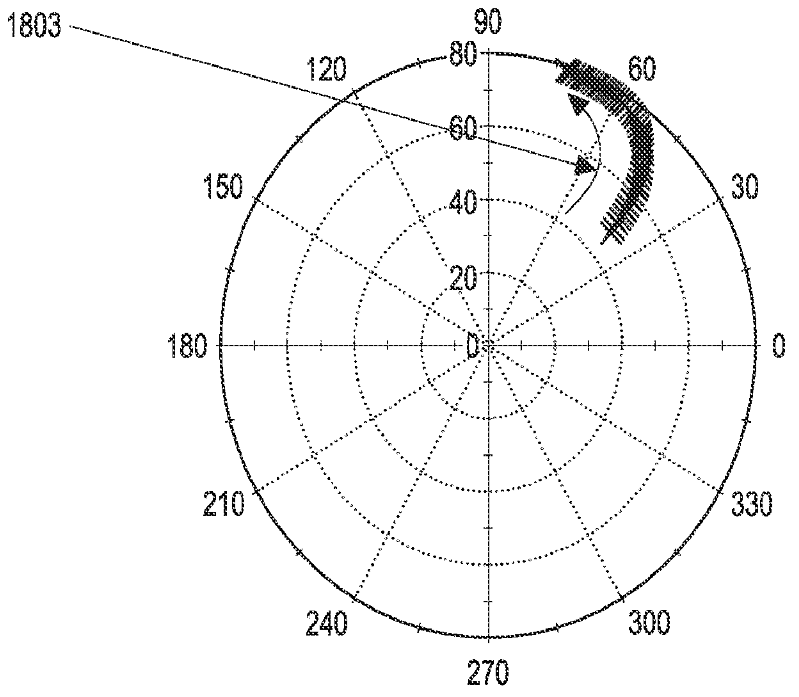

FIG. 28D

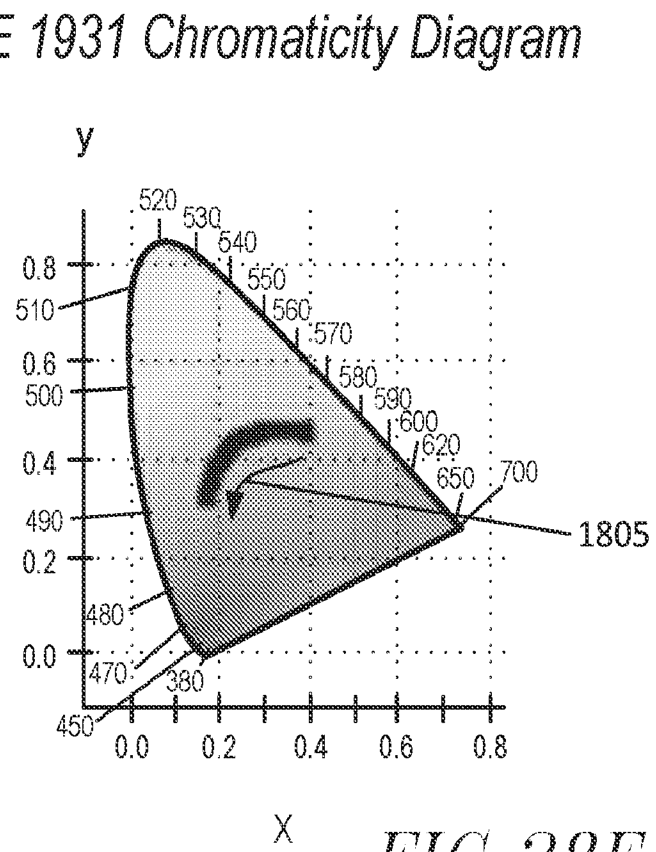

FIG. 28E

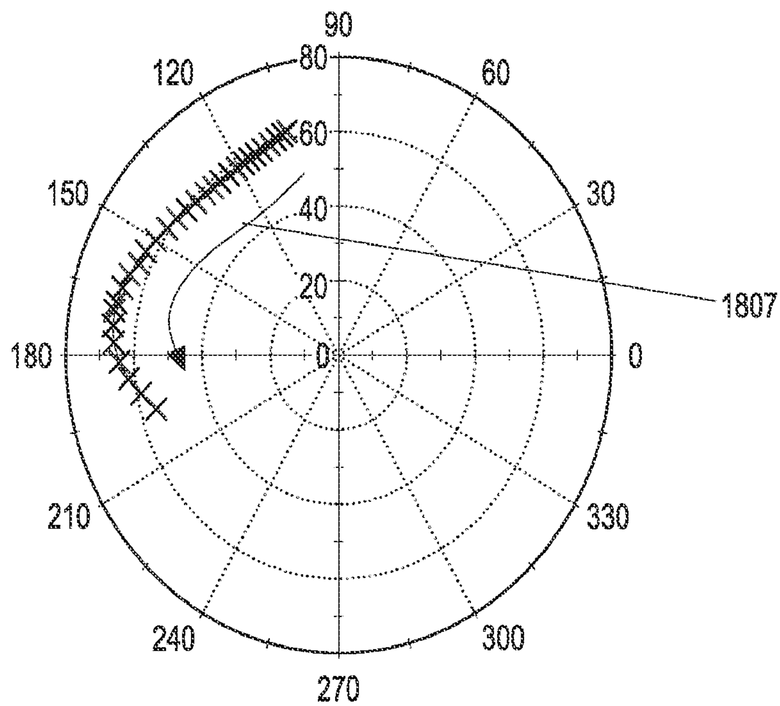

FIG. 28F

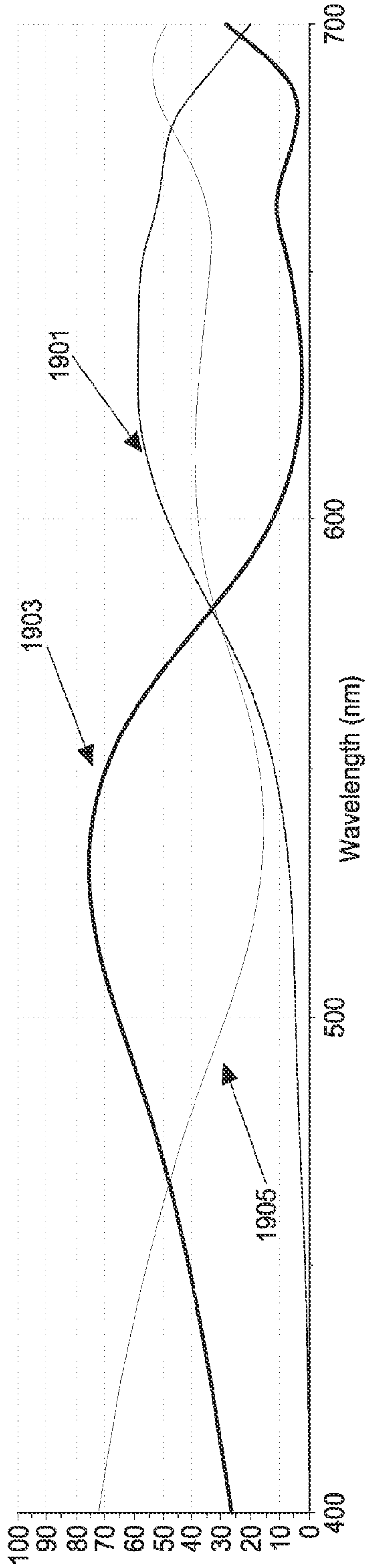

FIG. 29A

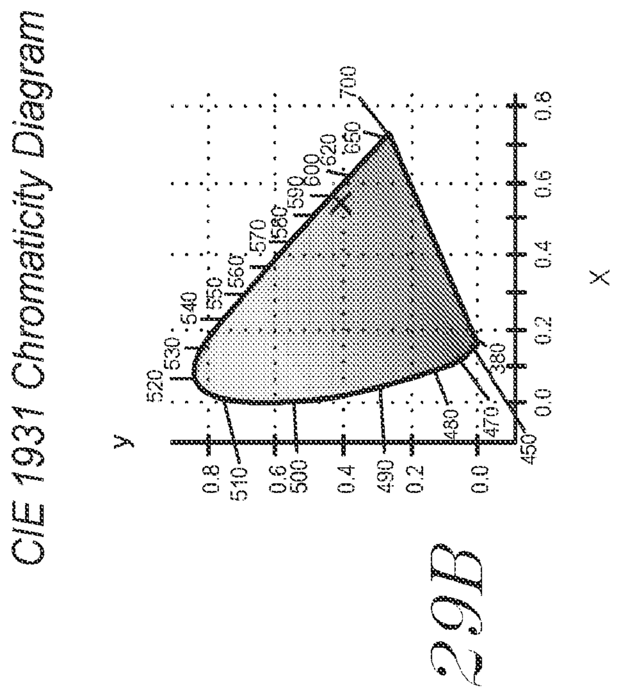

FIG. 29B

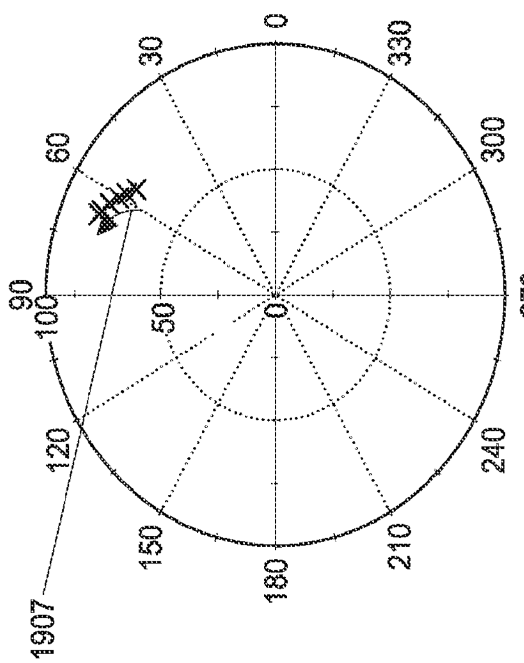

FIG. 29C

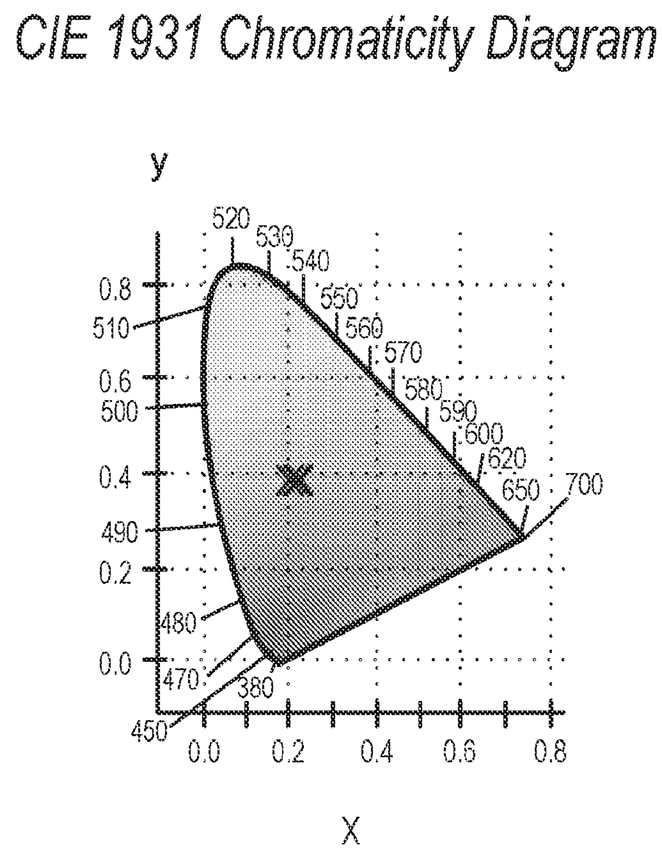

FIG.29D

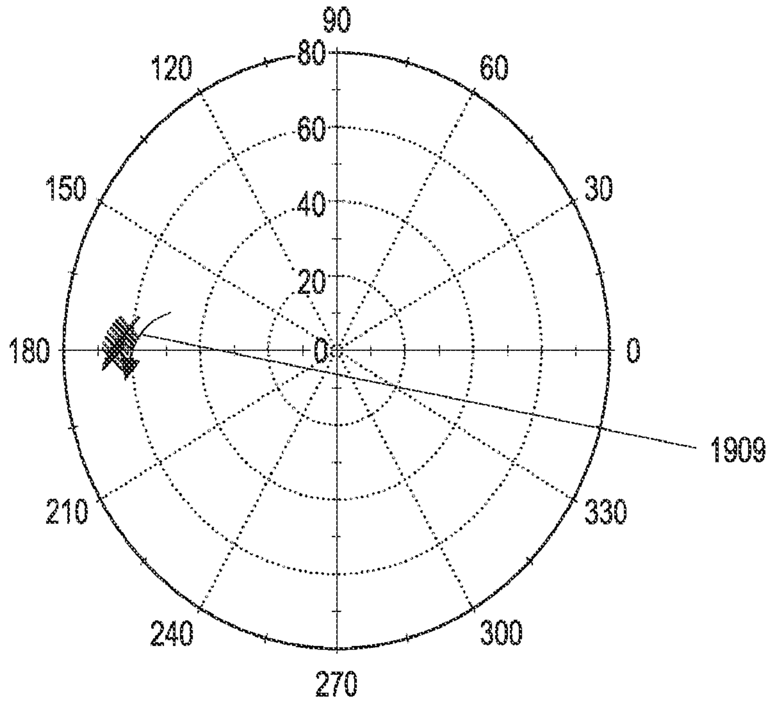

FIG.29E

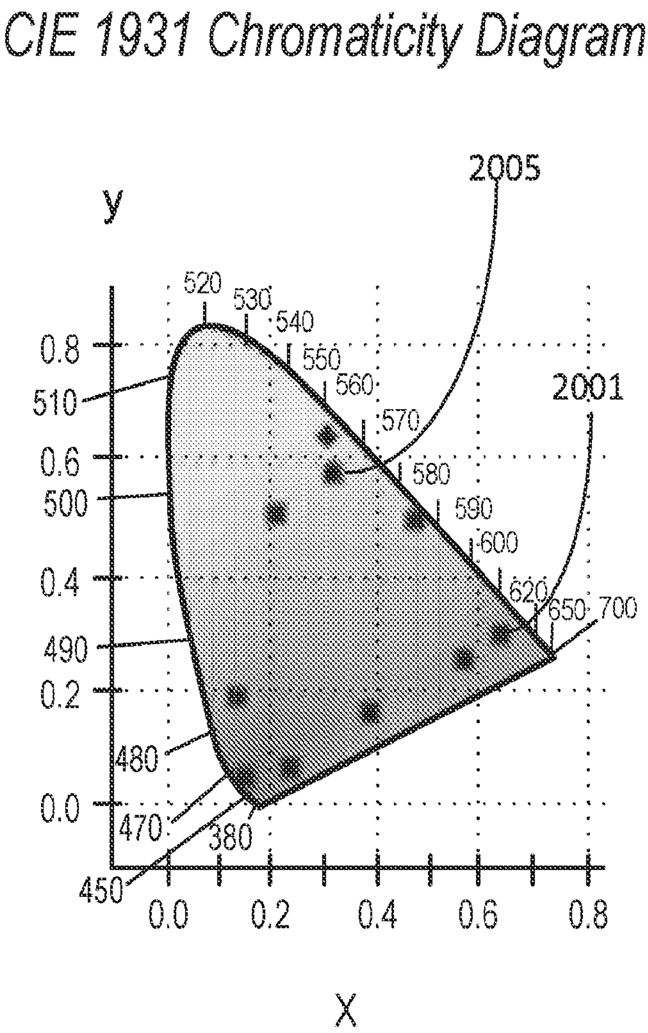

FIG. 30A

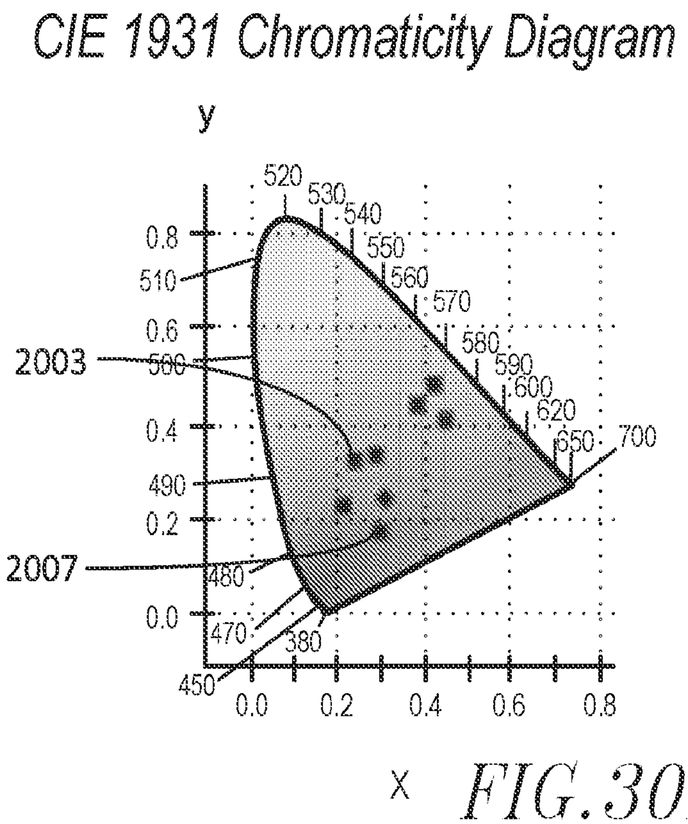

FIG. 30B

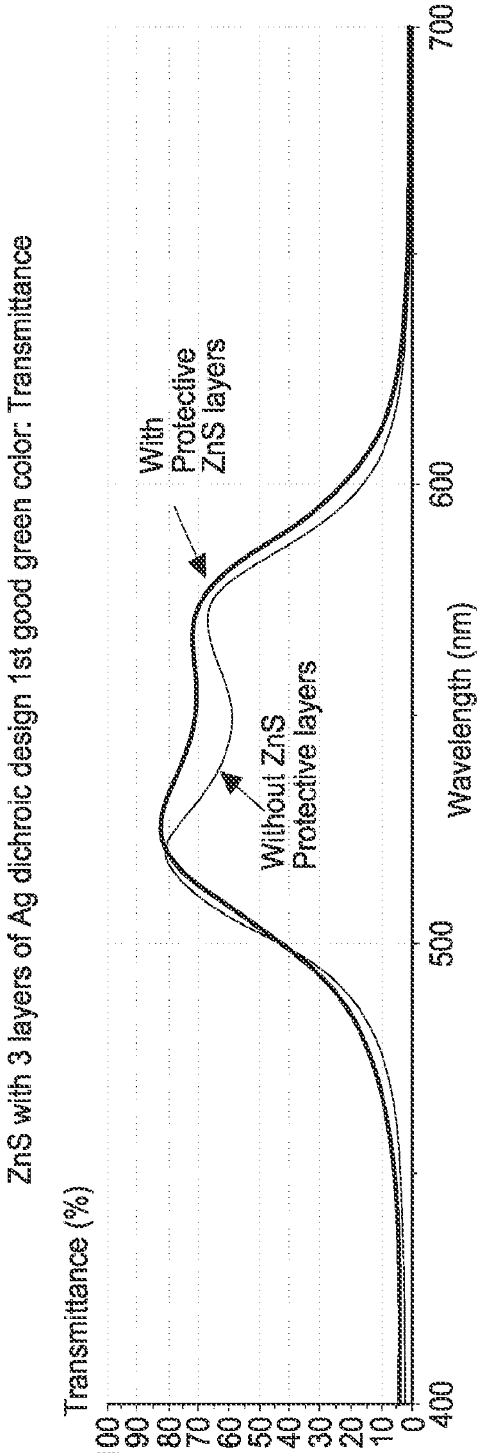

FIG. 31A

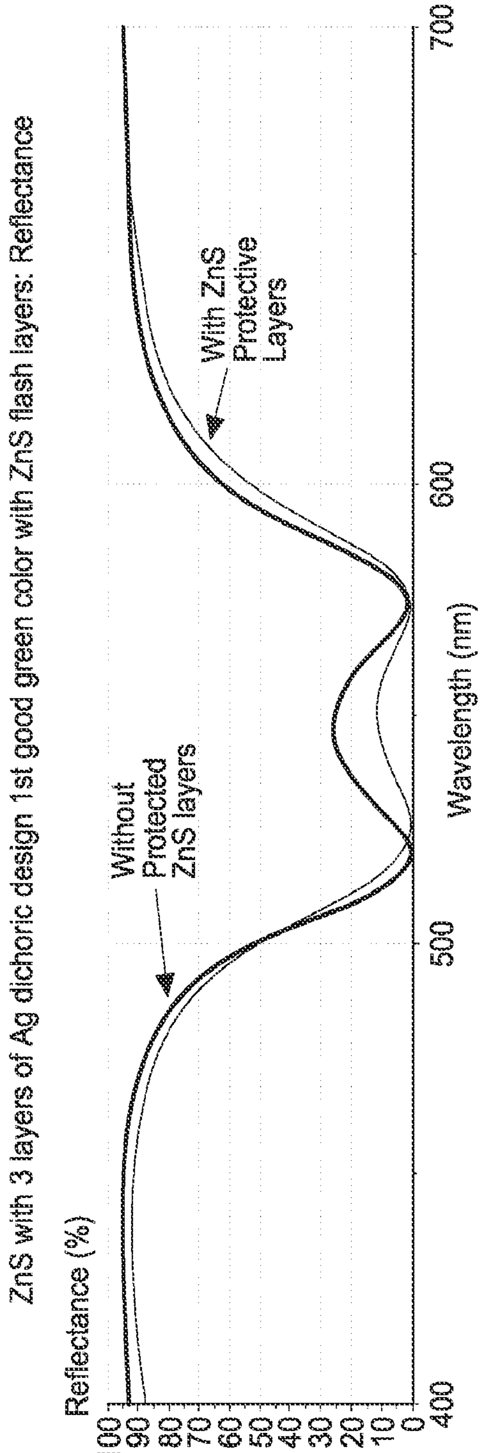

FIG. 31B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US21/71765

A. CLASSIFICATION OF SUBJECT MATTER

IPC - G02B 30/40; B42D 25/324; B42D 25/328; B42D 25/373; B42D 25/425; B42D 25/45; G02B 30/56; B42D 25/23 (2021.01)

CPC - G02B 30/40; B42D 25/328; B42D 25/324; B42D 25/373; B42D 25/425; B42D 25/45; G02B 30/56; G03H 1/0011; G02B 5/09; B42D 25/23; B42D 25/24; B42D 25/29

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
See Search History document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2005/0180020 A1 (STEENBLIK et al) 18 August 2005; figures 1a, 1b, 3a-3i, 4, 12a, 12b; paragraphs [0077], [0078], [0080], [0081], [0118], [0131].	1-31
Y	US 2013/0093172 A1 (FUHSE et al) 18 April 2013; figures 1, 3, 4; paragraphs [0097], [0105], [0106], [0112], [0114], [0142].	1-31
Y	JP 5132540 B2 (FLEX PRODUCTS INC) 30 January 2013; pages 17, 20-22; figure 8; see machine translation.	7-8
Y	LIN ET AL. "Design and fabrication of an alternating dielectric multi-layer device for surface plasmon resonance sensor" pp 169-176. Sensors and Actuators B 113. Online. 16 March 2005; [retrieved 01 December 2021]. Retrieved from the Internet: <URL: https://warwick.ac.uk/fac/sci/eng/research/grouplist/sensorsanddevices/mbl/database/fbar_references/design_and_fabrication_of_an_alternating_dielectric_multi-layer__device_for_surface_plasmon_resonance_sensor.pdf>; DOI: 10.1016/j.snb.2005.02.044	8, 10, 18
Y	US 2007/0098989 A1 (RAKSHA et al.) 03 May 2007; figure 2; paragraphs [0053], [0063].	9-11, 14-16, 20
Y	CN 105291630 B (CHINA BANKNOTE PRINTING AND MINTING CORP) page 5, 1st para; see machine translation.	21

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
01 December 2021 (01.12.2021)	JAN 26 2022

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