(19) **United States**

(12) **Patent Application Publication** (10) Pub. No.: **US 2014/0211195 A1**

BARCELO et al. (43) **Pub. Date:** **Jul. 31, 2014**

(54) **PLASMON RESONANCE BASED STRAIN GAUGE**

(71) Applicant: **HEWLETT-PACKARD DEVELOPMENT COMPANY, L.P.,** Houston, TX (US)

(72) Inventors: **STEVEN J BARCELO**, Palo Alto, CA (US); **ZHIYONG LI**, Redwood City, CA (US); **GARY GIBSON**, Palo Alto, CA (US); **MINEO YAMAKAWA**, Campbell, CA (US); **ANSOON KIM**, Palo Alto, CA (US)
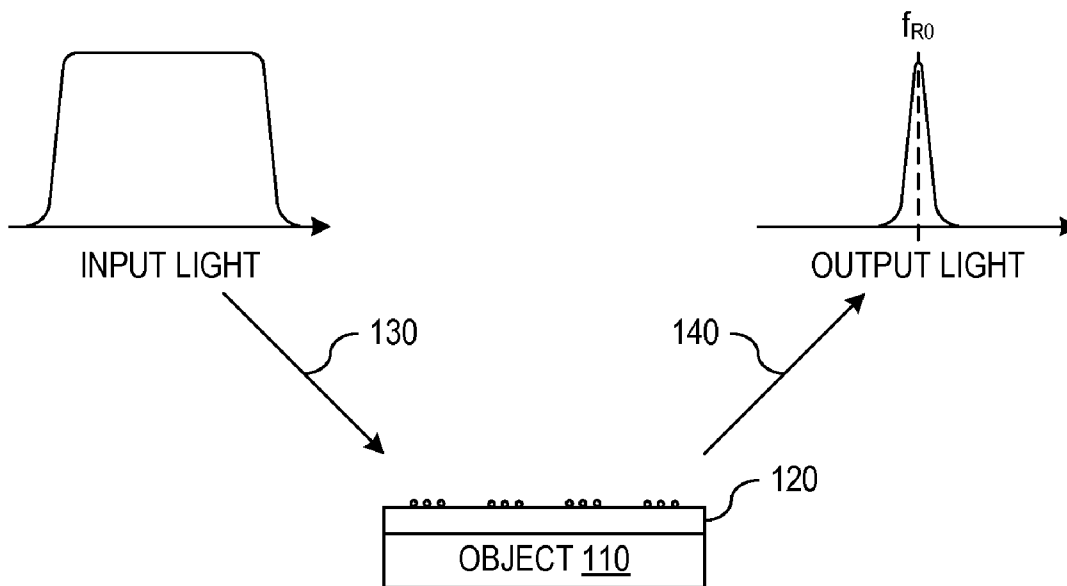
(73) Assignee: **HEWLETT-PACKARD DEVELOPMENT COMPANY, L.P.,** Houston, TX (US)

(21) Appl. No.: **13/755,801**

(22) Filed: **Jan. 31, 2013**

Publication Classification

(51) **Int. Cl.**
 G01L 1/24 (2006.01)

(52) **U.S. Cl.**
 CPC ***G01L 1/24*** (2013.01)
 USPC **356/33**; 356/32

(57) **ABSTRACT**

A strain gauge or other device may include a deformable medium and discrete plasmon supporting structures arranged to create one or more plasmon resonances that change with deformation of the medium and provide the device with an optical characteristic that indicates the deformation of the medium.
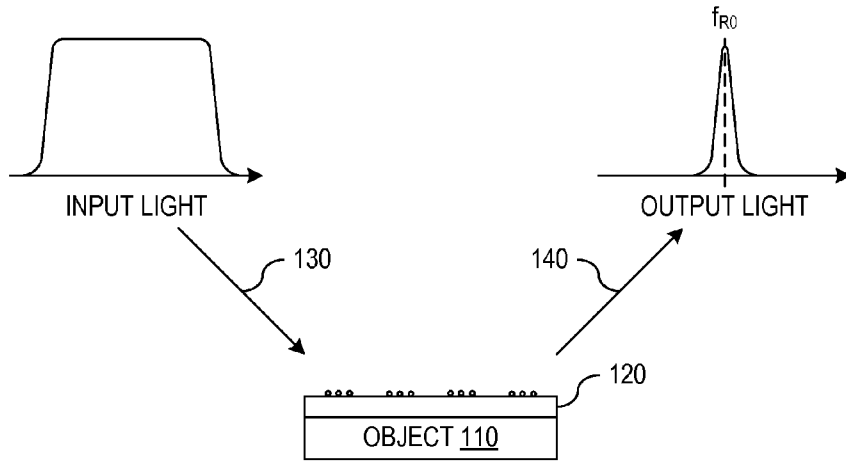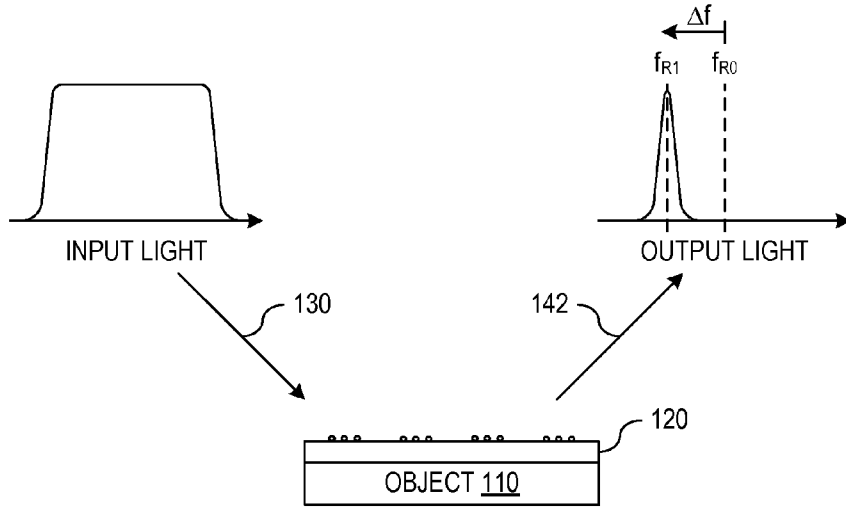
f_{R0}

INPUT LIGHT

OUTPUT LIGHT

130

140

120

OBJECT 110

f_{R0}

INPUT LIGHT

OUTPUT LIGHT

130

140

120

OBJECT 110

FIG. 1A

Δf

f_{R1} f_{R0}

INPUT LIGHT

OUTPUT LIGHT

130

142

120

OBJECT 110

ΔX

FIG. 1B

LIGHT 210

120

OBJECT 110

FIG. 2A

200

CONTROLLER 250

230

LIGHT SOURCE

130

140

OPTICAL SENSOR

120

240

OBJECT 110

FIG. 2B

300

320

MEASURE OUTPUT LIGHT WHILE THE ARRAY IS ILLUMINATED

330

DERIVE DEFORMATIONS OR QUANTITY DEPENDENT ON DEFORMATIONS

FIG. 3A

300

310

CHARACTERIZE OUTPUT LIGHT AS A FUNCTION OF DEFORMATIONS OF ARRAY

320

322

ILLUMINATE ARRAY WITH SELECTED INPUT LIGHT

324

MEASURE SELECTED OUTPUT LIGHT

326

ANOTHER MEASUREMENT?   YES

NO

330

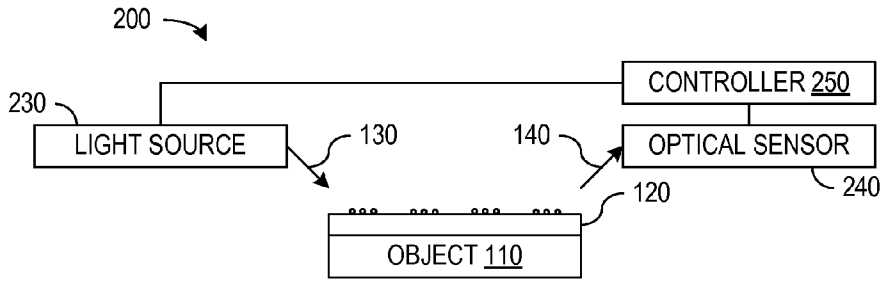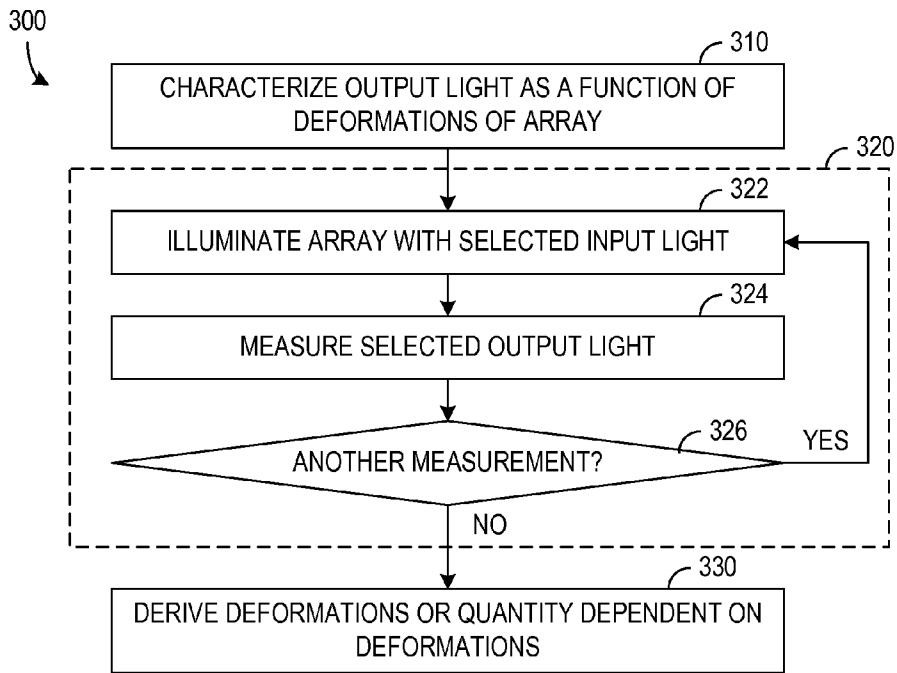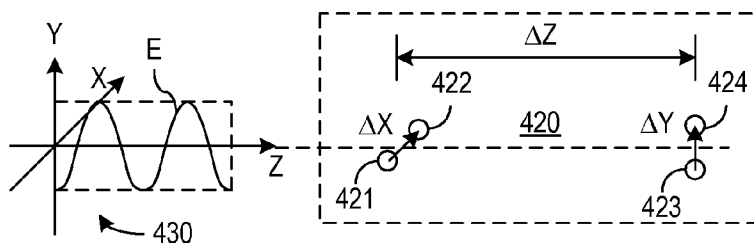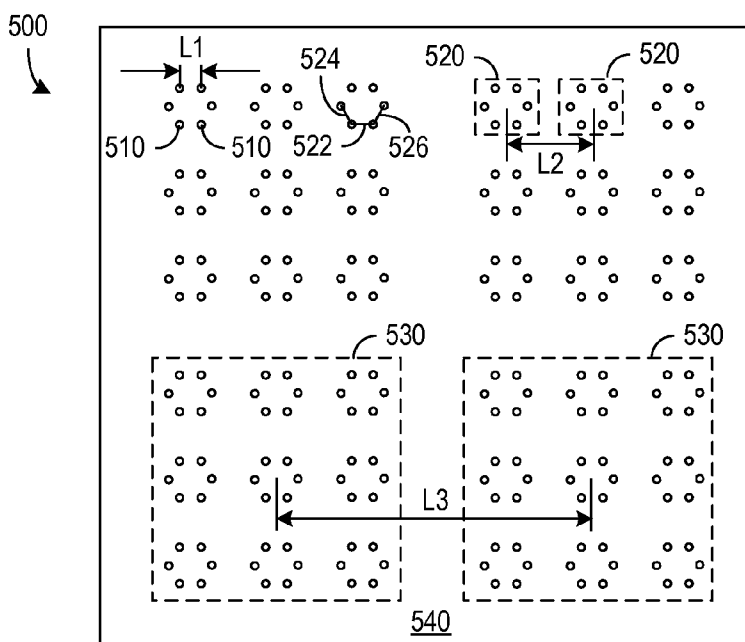DERIVE DEFORMATIONS OR QUANTITY DEPENDENT ON DEFORMATIONS
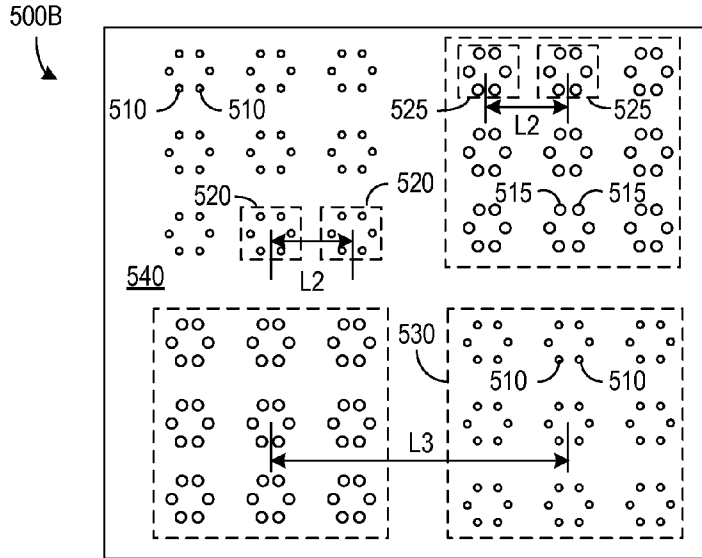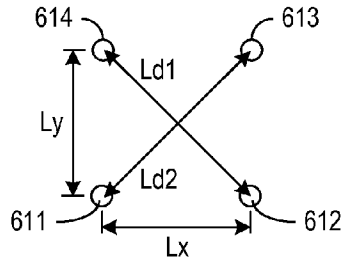
FIG. 3B

FIG. 4A

FIG. 4B

FIG. 5A

FIG. 5B

FIG. 6A
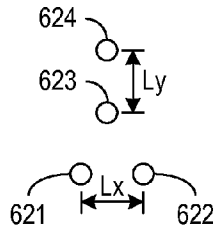

FIG. 6B

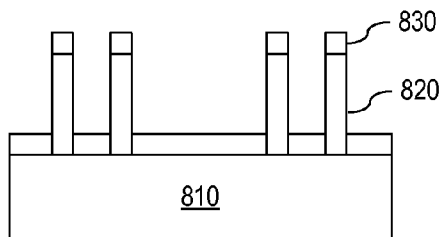FIG. 6C

FIG. 7

830

820

810

FIG. 8A

830

820

810

FIG. 8B

810

820

830

840

FIG. 8C

810

820

830

840

FIG. 8D

900

230

LIGHTING SYSTEM

CONTROLLER 950

MAGNETIC SENSOR

920

930

OPTICAL SENSOR

240

130

140

OBJECT 110

Ω

910
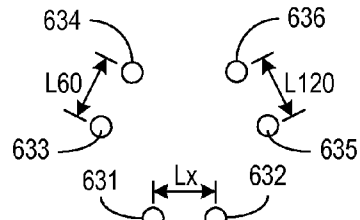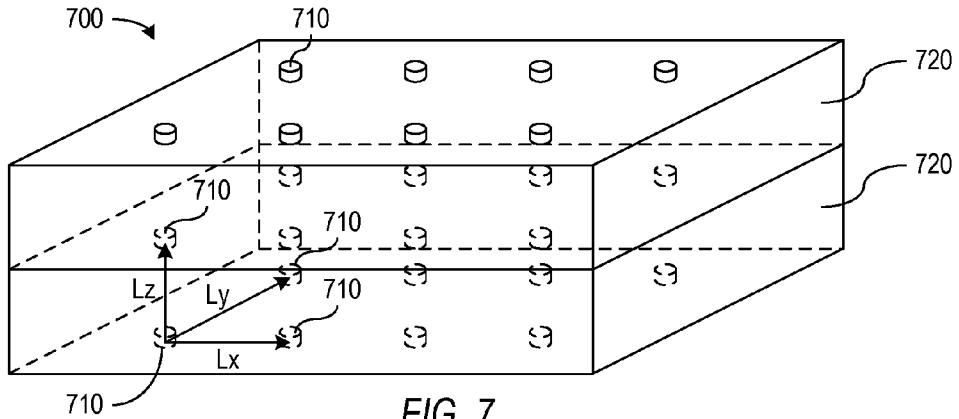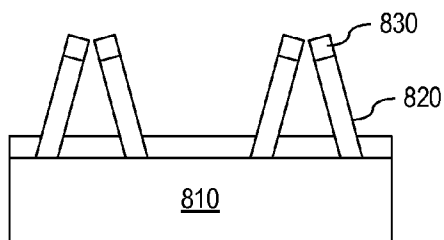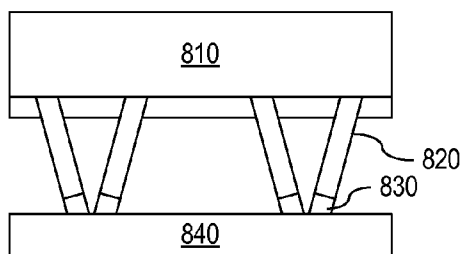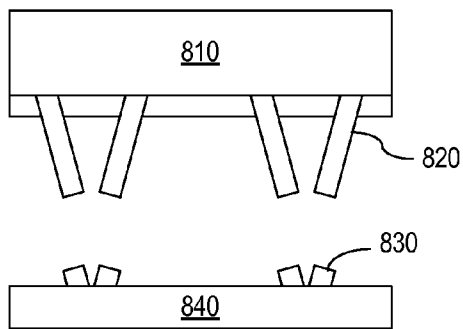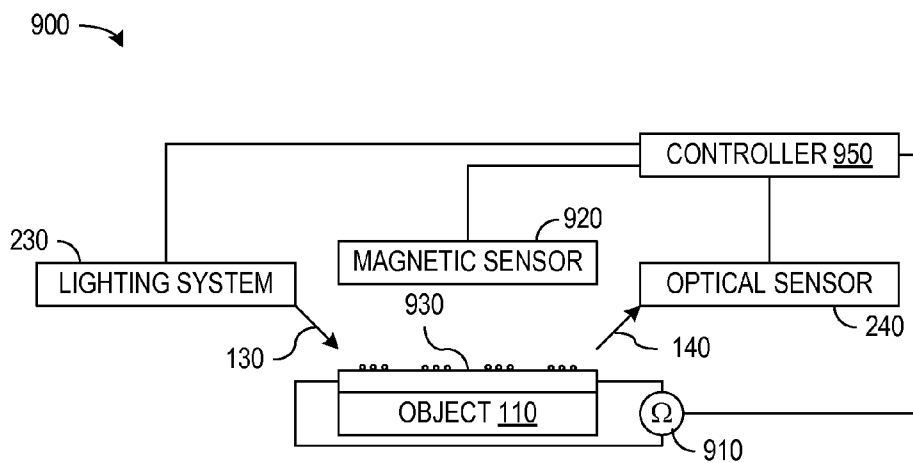
FIG. 9

PLASMON RESONANCE BASED STRAIN GAUGE

BACKGROUND

[0001] A strain gauge can measure the strain or deformation of an object. Typical strain gauges are based on the change in resistance of a metal undergoing strain. For example, one type of strain gauge includes a metallic foil pattern that may be attached to an object, so that deformation of the object deforms and changes the electrical resistance of the foil. A measurement of the change in the electrical resistance can thus provide a measure of the strain or deformation of the object. Strain gauges can measure other physical quantities such as force, acceleration, pressure, torque, or even temperature by placing the strain gauge on an object that has known deformations in response to the physical quantity being measured. In particular, a measurement of the strain may indicate an ambient or applied physical quantity.

BRIEF DESCRIPTION OF THE DRAWINGS

[0002] FIGS. 1A and 1B illustrate general principles of one implementation of a strain measurement.

[0003] FIGS. 2A and 2B illustrate alternative implementations of measurement systems.

[0004] FIGS. 3A and 3B illustrate respective implementations of measurement processes using arrays of discrete plasmon supporting structures.

[0005] FIGS. 4A and 4B illustrate interactions of polarized light in an implementation of a strain measurement.

[0006] FIGS. 5A and 5B show hierarchical arrangements of plasmon supporting structures in respective implementations of strain gauges.

[0007] FIGS. 6A, 6B, and 6C respectively illustrate three different assemblies of plasmon supporting structures capable of indicating strain in at least two independent directions.

[0008] FIG. 7 illustrates an implementation of a strain gauge including a three-dimensional array of plasmon supporting structures.

[0009] FIGS. 8A, 8B, 8C, and 8D illustrate a fabrication process for a strain gauge in accordance with one implementation.

[0010] FIG. 9 is a block diagram of an implementation of a strain gauge that combines optical, electrical, and magnetic measurements when measuring strain.

[0011] The drawings illustrate examples for the purpose of explanation and are not of the invention itself. Use of the same reference symbols in different figures indicates similar or identical items.

DETAILED DESCRIPTION

[0012] A strain gauge can employ a deterministic arrangement or array of discrete plasmon supporting structures such as plasmonic nanoparticles. The deterministic arrangement of the plasmon supporting structures can create relationships between deformation of the object and resulting changes in optical characteristics such as the number, frequencies, widths, and relative magnitudes associated with plasmon resonances in the strain gauge. For example, one or more frequencies, widths, or relative magnitudes of plasmon resonances may change in response to changes in separations of the plasmon supporting structures that the deformation of an object or a medium may cause. Similarly, one or more plas-

mon resonances may appear or disappear in response to changes in separations of the plasmon supporting structures. Optical measurement of light interactions with the plasmon resonances in a strain gauge can measure changes such as changes in the frequencies of the plasmon resonances, and the measured changes can then be converted into a quantitative measurement of strain, torsion, or other physical quantity that may depend on the strain or torsion of an array. Alternatively, a strain gauge including an array of discrete plasmon supporting structures may exhibit color changes in visible wavelengths that can be detected with the human eye or with a relatively simple interface.

[0013] The arrays within a strain gauge may be hierarchical, for example, by arraying assemblies of plasmon supporting structures. A lowest level assembly may include an array of discrete plasmon supporting structures with separations arranged so that plasmon resonances that the structures collectively support within an assembly have frequencies that depend on the separations of the particles within the assembly. The separations of assemblies from other assemblies may be larger and create other plasmon resonances that are collectively supported in multiple assemblies. The plasmon resonances associated with longer separations often have lower frequencies than plasmon resonances associated with shorter separations. However, changing the separation between plasmonic structures can result in hybrid resonances that are not apparent in structures with other separations, so that optical characteristics resulting from different separations are not always simply a shifting of the same resonances. Still, an array with multiple hierarchical levels can thus create plasmon resonances with frequencies at multiple scales respectively associated with the multiple hierarchical levels. A strain sensor with such assemblies may thus display plasmon resonances with a wide dynamic range of plasmon frequencies.

[0014] Arrays of discrete plasmon supporting structures can be created with a wide variety of specific geometries or patterns to create sensors with different sensitivities to strain and different color or spectral responses to strain. In particular, arrays or assemblies may have multiple symmetry axes, and a single sensor can measure multiple dimensions or components of a physical quantity such as strain or torsion, where the measured components are related to the symmetry axes. These strain gauges can also be configured to yield measurements of many physical quantities including but not limited to pressure, force, acceleration, torque, and any other physical quantities that may be related to the measured strain, torsion, or other deformation of the sensor.

[0015] FIGS. 1A and 1B illustrate general principles of one implementation of a strain measurement. As shown in FIG. 1A, an object 110 may have a surface with an attached deterministic array 120 of discrete plasmon supporting structures that collectively have one or more plasmon resonance. FIG. 1A is intended to illustrate an example where array 120 has a single plasmon resonance with a frequency f_{R0} when array 120 has no deformation. Input light 130 that is incident on array 120 can have any desired spectral content or polarization characteristics, but as one example, input light 130 may be unpolarized light and include electromagnetic radiation with a range of wavelengths, e.g., white light. Input light 130 can interact with array 120 or object 110, so that output light 140, which may be reflected, scattered, diffracted, or otherwise radiated from object 110, may have a spectral content, an angular distribution, or polarization characteristics that differ

from input light **130** in a manner that depends on the deformation of array **120**. For example, if object **110** or a medium of array **120** is a strong absorber of the wavelengths in input light **130**, array **120** may absorb or scatter most of input light **130**. FIG. 1A shows an example in which most frequencies of input light **130** may be strongly absorbed, but a plasmon resonance of array **120** makes object **110** highly efficient at scattering light having frequency f_{RO}. Alternatively, a resonance of array **120** may primarily absorb light with frequency f_{RO}, and object **110** reflects the remainder of input light **130** so that output light **140** is similar to input light **130** but has a 'spectral hole' at resonance frequency f_{RO}. In both examples, input light **130**, which in different implementations may have many different spectral distributions, can consistently produce output light **140** having spectral distribution with a prominent feature at frequency f_{RO}. This spectral feature depends on the pattern of array **120** and may give object **110** a color characteristic of frequency f_{RO} if frequency f_{RO} corresponds to a visible frequency of light.

[0016] FIG. 1B illustrates an effect that may result from strain on object **110**. For example, strain may change the shape, e.g., stretch or compress one or more dimensions, of object **110**, and the separations of the discrete plasmon supporting structures in array **120** may correspondingly change. Such changes are known to change the collective plasmon resonance frequencies, and FIG. 1B illustrates an example where stretching of object **110** and array **120** shifts the plasmon resonance from the unstressed frequency f_{RO} to a frequency f_{R1}. As a result, even with the same input light **130** as used in the example of FIG. 1A, output light **142** when object **110** is under strain has a different spectral content, even a different color if frequency f_{RO} or f_{R1} is in the visible range. As shown in FIG. 1B, a feature in the spectral distribution of output light **140** may have a frequency shift Δf corresponding to the difference between plasmon resonance frequencies f_{RO} and f_{R1}. Frequency shift Δf is related to a strain ΔX in object **110**. As a result, strain ΔX in object **110** can be observed or measured by observing or measuring the spectral content of output light **140** and **142**.

[0017] The differences in output light **140** and **142** of FIGS. 1A and 1B illustrate relatively simple techniques for observing deformation of object **110** by observing optical response of array **120** and particularly by observing a frequency shift in a spectral feature corresponding to a plasmon resonance. Observing the optical response of an array of plasmons supporting structures in some other implementations may include observing other optical effects caused by plasmon resonances. For example, deformations can be detected by observing frequency shifts in features (e.g., peaks or holes) of the output light, observing changes in the relative amplitude of features in the output light, observing changes in the widths of one or more features in the output light, or observing the emergence or disappearance of a spectral peak or hole in the output light, or observing any combination of these.

[0018] FIG. 2A illustrates how strain in object **110** can be simply observed using the naked eye in any available lighting **210**. For example, object **110** may be a mechanical member such as a beam, joint, or cantilever in a structure such as a bridge, building, or other edifice that is coated with an array of discrete plasmon supporting structures. A simple visible inspection of member/object **110** can indicate an amount of strain in the object from the color of the object **110**. In a working environment, an inspector can simply look at object **110** and determine the level of strain in object **110**. Light **210**

may be any available lighting in the environment of object **110** or may or may not be a source of light with known spectral or polarization characteristics.

[0019] The principles or techniques illustrated in FIG. 2A can be employed to detect strain on any object **110**. For example, object **110** may be a mechanical member or part, a container, a pipe, a valve, a tool, a panel, a plate, a casing, or a handle that may be coated with arrays of discrete plasmon supporting structures that change color when strain is present, for example, when object **110** may be close to a mechanical failure. Alternatively, the principles or techniques illustrated in FIG. 2A can be employed to effect a cosmetic change in object **110**, e.g., when object **110** is a toy or decorative item, having a color that changes to a desired color in response to the application of a strain.

[0020] FIG. 2B illustrates a system **200** for obtaining a quantitative measurement of strain on an object **110** with an attached array **120** of discrete plasmon supporting structures. System **230** uses a lighting system **230** that produces input light **130** for illumination of array **120**. Lighting system **230** may include any type of light source such as ambient light, an incandescent or fluorescent lighting fixture, a light emitting diode (LED), or a laser used with or without additional optical elements such as color or polarization filters. In one implementation, lighting system **230** has known spectral and polarization characteristics, which may be characteristic of the light source that lighting system **230** uses or characteristic of filters or other optical components that light source **230** applies to produce input light **130**, and a controller **250** may operate lighting system **230** to alter input light **130** in a controlled manner. In one implementation described below, controller **250** may alter the operation of a light source or other optical components within lighting system **230** to change the polarization of input light **130**.

[0021] An optical sensor **240** in system **200** measures output light **140** and may particularly measure the spectral content of output light **140** as a whole, within a specific or selectable angular range, or having a specific or selectable polarization. Optical sensor **240** may, for example, include a spectrometer, spectrophotometer, an image detector, or one or more photodiodes with or without polarization filters. (A photodiode used with color filters could act as a crude spectrometer, or if the wavelength shift is large enough a color filter may not be necessary). Polarization filters may be employed when selective measurement, e.g., spectral measurement, of one or more particular light polarizations is desired. As noted above, strain in object **110** can change the frequencies of plasmon resonances in array **120** and correspondingly change the optical response of array **120** and the optical characteristics of output light **140**. Optical sensor **240**, in general, can measure any optical characteristics of output light **140** that deformation of array **120** changes.

[0022] Controller **250** may include one or more processors capable of executing instructions or may be entirely a hardware controller. Controller **250** generally controls light source **230** and optical sensor **240** during measurement of output light **140** and can further analyze the measured characteristics of output light **140** and determine one or more measurements of a physical quantity such as the strain in object **110**.

[0023] FIG. 3A illustrates one implementation of a measurement process **300** that can be performed with system **200**. Process **300** basically includes measuring **320** of output light **140** during illumination of array **120** and based on the mea-

sured optical characteristics of output light **140**, deriving or inferring **330** the strain or a physical quantity that depends on the strain.

[0024] In one specific implementation of system **200** and process **300**, lighting system **230**, optical sensor **240**, and controller **250** of system **200** may be in a handheld measuring device, while object **110** is relatively immobile. For example, if object **110** is a large object such as components in a factory, building, or bridge, an inspector may employ the handheld device to illuminate a portion, e.g., a joint, of object **110** and measure light from the array **120** on object **110** as in step **320**. The measuring device can then process the optical measurements to produce a measurement result.

[0025] FIG. **3B** shows a more specific implementation of measurement process **300**, which further includes characterization **310** of the optical response of array **120** as a function of deformation in array **120**. Characterization **310** may, for example, provide a mapping from a set of frequencies corresponding to peaks (maxima) or valleys (minima) in the spectral content of output light **140** to a combination of one or more components of deformation of object **110** or array **120** that would produce the measured frequencies. In a simple case, only one component of strain is of interest, e.g., stretching or compression along a linear direction or torsion about an axis, and characterization **310** may provide a simple function or lookup table that maps a frequency of a spectral peak to a value of the measurement result of interest. Characterization **310** of the output light from an array **120** may involve more complicated formulations that may require multiple functions or look-up tables for derivation of a measurement result from a spectral distribution. Characterization **310** of array **120** may possibly be derived from first principles based on the geometry and composition of array **120** or may be determined empirically from a calibration of array **120** or an archetype of array **120**. Characterization **310** may be performed before or after fabrication of array **120**.

[0026] The characteristics of output light **140** from array **120** may depend on the characteristics of input light **130**. Characterization **310** may be for specific input light characteristics, and illumination may be controlled during optical measurement **330**. In particular, variations in input lighting **130** can be used during optical measurement **320** to provide more information for derivation of a measurement result. Additionally, the characteristics of output light **140** may differ for different polarization components of output light **140**, and optical measurement **320** may select and measure a particular polarization component. FIG. **3B** illustrates an implementation of process **300** in which optical measurement **320** includes one or more illuminations **322** of array with input light **130** having different characteristics for each illumination **322** and with respective optical measurements **324** of output light **140**.

[0027] An even more specific implementation of optical measurement **320** uses different polarizations for input light **130**. Light with different polarizations may interact differently with different plasmon resonant modes in array **120**. FIG. **4A**, for example, shows an example in which linearly polarized input light **410** interacts with an array **420** of plasmon supporting structures **421-424**. In array **420**, plasmon supporting structures **421** and **422** are separated by a distance ΔX along a horizontal or X direction, and plasmon supporting structures **423** and **424** are separated by a distance ΔY along a vertical or Y direction. In FIG. **4A**, linearly polarized input light **410** has the electric field directed in an X direction and

may interact most strongly with horizontal plasmon oscillations and therefore with a plasmon resonant mode associated with structures **421** and **422**, collectively. Deformations of array **420** that change separation ΔX may thus significantly change the frequency of the plasmon resonant mode that input light **410** tends to excite. In contrast, plasmon resonant modes that structures **423** and **424** support may more weakly interact with horizontally polarized input light **410**, or deformations of array **420** that change separation ΔX may not significantly change the frequency of the plasmon resonant modes that primarily reside in structures **423** and **424**. In either case, horizontally polarized input light **410** may provide output light **140** that includes a strong peak associated with the resonances primarily associated with structures **421** and **422** or that changes most with deformations of array **420** in the X direction.

[0028] FIG. **4B** shows the example of linearly polarized input light **430** having an electric field directed in the vertical or Y direction, so that input light **430** may interact most efficiently with a plasmon resonant mode associated with plasmon oscillations in the Y direction such as a plasmon resonance supported collectively in structures **423** and **424**. Deformations of array **420** that change separation ΔY may thus significantly change the frequency of the plasmon resonant modes that input light **420** tends to excite, and vertically polarized input light **420** may provide output light that includes strong peaks associated with the plasmon resonances primarily associated with structures **423** and **424** or that change most with deformations of an array in the Y direction.

[0029] Light radiated or output from the resonance associated with plasmon oscillations in the X or Y direction may similarly have characteristic polarization. Accordingly, selectively filtering the polarization of the output light **140** may help to distinguish plasmon resonances associated with oscillations in the X and Y directions.

[0030] The polarization dependence of light-plasmon interactions can thus be used to measure specific components of deformation of an object or media containing an array of discrete plasmon supporting structures. Returning to FIG. **3B**, optical measurement **320** can thus include: illumination **322** of array **120** with input light having selected and controlled characteristics, e.g., a selected linear polarization; optical measurement **324** of a selected component of output light **140**, e.g., a selected linear polarization, while input light **130** has the selected characteristics; and repetition **326** of illumination **322** and measurement **324** until all desired illumination and measurement profiles have been exhausted, e.g., after illumination **322** and measurement **324** have been performed with all of the linear polarizations associated with symmetry axes in array **120**. Optical measurement **320** may thus provide more data that derivation **330** can use to determine measurement results, e.g., to determine multiple components of the strain in object **110**. Further, rapid alternation of the excitation light sources or rapid rotation or switching of polarization filters can lead to essentially continuous deformation measurement along multiple axes.

[0031] The specific configurations of arrays of discrete plasmon supporting structures can be varied widely according to the desired measurements and one implementation of a strain gauge uses a hierarchical array, which may provide a wide dynamic range of measurement results. FIG. **5A** shows a plan view of one implementation of a strain gauge **500** including a hierarchical array of discrete plasmon supporting

4

structures **510**. Strain gauge **500** can be used to measure or indicate deformation of an object or any quantity that may be related to the deformation of the object. Gauges that measure quantities that are dependent on such deformations are sometimes referred to herein as strain gauges in the general sense that a strain gauge may measure strain, torsion, or any physical quantity that is related to the deformation of an object. Strain gauge **500** includes discrete structures **510** that are in or on a medium **540** and arranged to form assemblies **520** and **530** of different sizes. In the illustrated implementation, each assembly **530** is an array of smaller assemblies **520**, and each assembly **520** is an array of discrete plasmon supporting structures **510**. The implementation of FIG. **5A** is thus one example of a three-level hierarchical arrangement of discrete plasmon supporting structures **510**, but more generally, a strain gauge may have any number of hierarchical levels, including just a single level or arrangement of discrete plasmon supporting structures **510**.

[0032] Each discrete plasmon supporting structure **510** is a structure in which plasmons may reside. The plasmons in structures **510** may interact to varying degrees across the separations between structures **510**. The interaction of structures **510** depend upon the sizes, geometries, and material characteristics of structures **510** and the surrounding materials (in particular the dielectric properties of the materials between structures **510**). The interaction as noted above can shift the frequencies of plasmon resonances or create additional, hybrid resonances. Plasmon supporting structures **510** are discrete in that, absent structures **510**, the gaps or separating material between plasmon supporting structures **510** do not support strong plasmon resonances. For example, each plasmon supporting structure **510** may be a plasmonic nanoparticle surrounded by dielectric materials. However, plasmon supporting structures **510** may be connected to each other in some fashion to form arrays. For example, plasmon supporting structures **510** may be the tops of pillars or bumps that isolate or separate areas in which plasmons reside even though the pillars or bumps themselves are connected to each other through their bases.

[0033] In one implementation of strain gauge **500**, medium **540** is a stretchable medium made of a material such as a suitable plastics, rubber, biopolymers, flexible metals, or fabric. Medium **540** may further be an insulator or dielectric material and may be transparent to frequencies of electromagnetic radiation corresponding to the frequencies of some plasmon resonances used in strain gauge **500** or may have a color, for example, black to absorb visible input light. Medium **540** may be selected to attach to or cover a surface of an object that undergoes a strain to be measured. For example, medium **540** may be a thin layer of material or tape with an adhesive that allows medium **540** to be attached to the object so that medium **540** is able to stretch, compress, or twist as the object undergoes the strain to be measured. Alternatively, medium **540** may itself be the object that undergoes the strain to be measured, or equivalently, medium **540** may be eliminated and discrete structures **510** may be directly attached to or deterministically positioned in or on an object for which strain is to be measured or identified.

[0034] Discrete plasmon supporting structures **510** collectively provide one or more useful plasmon resonances. In general, a plasmon is a quantum of plasma oscillation, and one type of plasma is made up of the free electrons near the surface of materials such as a metal. Plasmons at the surfaces of metals or at interfaces are commonly referred to as surface

plasmons. A plasmon resonance of a structure corresponds to a frequency of plasmon oscillation at which the structure has a resonance for energy absorption or radiation. The plasmon resonances of discrete structures **510** generally depend on the material, size, and shape of discrete structures **510**. Smaller structures, e.g., metal discs or spheres having diameters less than about 200 nm, tend to have fewer resonances and may have only one resonance in a desired frequency range, e.g., the frequencies corresponding to visible light, or have a few discrete resonances that are easily distinguishable. Particles having linear dimensions smaller than a few hundred nanometers, which may sometimes be referred to as nanoparticles, are one example of discrete structures that may collectively provide a suitable plasmon resonance. In particular, particles of a metal such as platinum, gold, silver, copper, aluminum, or nickel smaller than about 200 nm in width can be used to provide plasmon resonances with frequencies corresponding to the frequencies of visible light, but plasmon resonances may also be created at suitable semiconductor interfaces, e.g., a silicon-air interface. Discrete structures **510** thus may be separated semiconductor interfaces or any plasmon supporting structures with separations that can be determined during fabrication.

[0035] In the implementation of FIG. **5A**, discrete structures **510** are arranged within assemblies **520** to have smallest inter-particle gaps L1 aligned along a number of axes of interest, e.g., axes **522**, **524**, and **526**. Assemblies **520** are arranged with smallest center-to-center separations L2 in a rectangular grid in a corresponding assembly **530**, and assemblies **530** are arranged with smallest center-to-center separations L3 in a rectangular grid on medium **540**. The plasmon resonances of discrete plasmon supporting structures such as metallic nanoparticles have been shown to be strongly dependent on interparticle spacing ranging from less than a few nanometers up to hundreds of nanometers. The implementation of strain gauge **500** of FIG. **5A** can achieve a high dynamic range of the plasmon resonance variation by providing critical dimensions on a number of length scales. The different length scales in turn may correspond to different scales of resonance frequencies. In array **500**, separations L1 between discrete structures **510** within a single assembly **520** are smallest, and separations L2 between adjacent assemblies **520** may be larger than separation L1. In general, each length scale will be most sensitive to changes on the order of that length scale, and the existence of larger assemblies on smaller scale resonances, e.g., higher frequency resonances, may primarily be changes in the width of the higher frequency resonances.

[0036] In one specific implementation, discrete structures **510** are about 5 to 200 nm in width, and separation L1 between closest neighboring structures **510** is about 1 to 50 nm. Separation L2 between assemblies **520** may be about 100 to 300 nm. As a result, strain gauge **500** may have plasmon resonance frequencies respectively corresponding to separations L1 and L2. When array **500** has a plasmon resonance that corresponds to a frequency of light, array **500** can become highly efficient at absorption or radiation of light having that frequency and therefore have a color that depends on the plasmon resonance. Changes in the plasmon resonances of strain gauge **500** that result from changes in separation L1 and L2 can be measured as described above by illuminating strain gauge **500** and observing the resulting output light.

[0037] Assemblies **530** in one implementation are separated by separations L3 that are larger than separations L1 or

5

L2, and in one implementation of strain gauge 500, separation L3 may be on the order of the wavelength of light used for observation of strain gauge 500. As a result, in addition to variation of the plasmon resonance, the spacing of assemblies 530 may provide grating effects, and the grating effect may vary with deformation of medium 540. The grating effect may, for example, shift the direction of diffraction of specific wavelengths of light. Optical measurement of output light 140 may thus include measuring angular differences in output light 140, or wavelength of output light 140 at a given angle. Such grating effects may also be used to effectively focus or direct more of output light at a detector.

[0038] The plasmon resonances of individual structures 510 can interact over distances on the order of their size or greater, but typically the strongest interactions are over smaller length scales. In array 500, the smallest plasmon supporting structures 510 may be some sort of particle that is less than or on the order of a couple of hundred nanometers (e.g., down to about 5 or 10 nm). For strong interactions, smallest separations of structures 510 (at least when at their closest approach) may be less than the size of a single structure 510. The interactions between assemblies 520 at larger length scales would typically be weaker. Consequently, dynamic range may improve by having some assemblies contain plasmon supporting structures that are smaller and some other assemblies contain plasmon supporting structures that are larger. FIG. 5B, for example, shows an example of a hierarchical array 500B including assemblies 520 of discrete plasmon supporting structures 510 as described with reference to FIG. 5A and also assemblies 525 of discrete plasmon supporting structures 515. Plasmon supporting structures 515 may generally differ in size from plasmon supporting structures 510 and may be of the same or different composition. As a result, the plasmon resonances primarily in plasmon supporting structures 515 may expected to be different from the plasmon resonances primarily in plasmon supporting structures 510, whether or not structures 510 and 515 have the same or similar separations. The use of different size plasmon supporting structures 510 and 515 may provide array 500B with greater dynamic range in measurement of deformations of media 540.

[0039] Strain gauges 500 and 500B of FIGS. 5A and 5B as described above provides examples of an arrangements of discrete structures 510 or 515 to provide a measurement or indication of the strain or deformation of an object. Many different types of arrangements are possible. FIGS. 6A, 6B, and 6C illustrate respective two-dimensional arrangements of discrete plasmon supporting structures 611-614, 621-624, and 631-634 within respective assemblies that provide sets of symmetry axes. In FIGS. 6A, 6B, and 6C, discrete structures 611-614, 621-624, and 631-634 may be but are not required to be substantially identical. For example, in FIG. 6A, discrete structures 611-614 may all be metal nanoparticles, separated regions of a suitable interface, or assemblies of such structures, and discrete structures 611-614 may all have the same size and composition. Alternatively, different types of plasmon supporting structures may be used within each assembly of FIG. 6A, 6B, or 6C.

[0040] FIG. 6A shows an assembly with a rectangular arrangement of plasmon supporting structures 611-614. Structures 611 and 612 are separated from each other by a separation Lx in an X direction as are structures 613 and 614. Similarly, structures 611 and 614 are separated from each other by a separation Ly in a Y direction as are structures 612

and 613. Separations Lx and Ly may be the same or be different from each other. If separations Lx and Ly are different, a plasmon resonance associated primarily with X-direction oscillations and separation of structures may have a different frequency from the frequency of a plasmon resonance associated primarily with Y-direction oscillations and separations of the structures. As described above, input and output light with a linear polarization in the X-direction may most effectively interact with plasmon resonances that oscillate along the X-direction and that are supported by structures 611 and 612 or 613 and 614 separated in the X direction. Similarly, input and output light with a linear polarization in the Y-direction may most effectively interact with plasmon resonances that oscillate along the Y-direction and are supported by structures 611 and 614 or 612 and 613 separated in the Y direction. Polarization filtering of input or output light may thus be used to separately measure deformation components.

[0041] FIG. 6B shows another example of a T-shaped arrangement of discrete plasmon supporting structures 621-624 that provide plasmon resonances corresponding to oscillation along orthogonal X and Y axes. With the T-shaped configuration, discrete structures 621 and 622 are separated along the X axis by a separation Lx, and discrete structures 623 and 624 are separated along the Y axes by a separation Ly. If desired, structures 621 and 622 may be different in size or composition or separation Lx may differ from Ly, so that a plasmon resonance associated primarily with structures 621 and 622 has a different frequency from the frequency of a plasmon resonance associated primarily with structures 623 and 624. Arrays or assemblies of plasmon supporting structures with the arrangement of FIG. 6B may thus provide information about two corresponding components of strain.

[0042] FIG. 6C shows an arrangement of six discrete plasmon supporting structures 631-636 that are arranged to provide separations Lx, L60, and L120 along three directions within the same plane. In particular, structures 631 and 632 are separated by a distance Lx along the X axis. Structures 633 and 634 are separated by a distance L60 along a direction 60° from the X axis. Structures 635 and 636 are separated by a distance L120 along a direction 120° from the X axis. Accordingly, three different polarizations of input light and/or separate measurements of output light having different polarizations can provide information for determining separate components of strain within the assembly of FIG. 6C.

[0043] FIGS. 6A, 6B, and 6C are examples of two-dimensional patterns of plasmon support structures for assemblies that may be used in two-dimensional arrays. However, three-dimensional arrays of discrete plasmon supporting structures could alternatively be employed and may be able to provide information about additional strain components. FIG. 7 shows an example of an array of discrete plasmon supporting structures 710 that are arranged at interfaces of multiple layers 720 in order to form a three-dimensional array. For example, plasmon supporting structures 710 can be plasmonic nanoparticles and may be arranged in multiple flat deterministic arrays such as described above, but in array 700, the flat deterministic arrays are stacked to create a three dimensional arrangement. In particular, separation Lx and Ly in X and Y directions may be between structures 710 in one layer of structures 710, and each layer may be separated by a separation Lz in a Z direction from an overlying or underlying layer of structures 710. The plasmon resonances of array 700 will generally depend on separations Lx, Ly, and Lz, so that

deformation of array **700** in three different directions may have measurable effects on the plasmon resonances of array **700**.

[0044] FIGS. **8A**, **8B**, **8C**, and **8D** illustrate a process for fabrication of an array of discrete plasmon supporting structures. The illustrated fabrication process can begin as shown in FIG. **8A** with fabrication of pillars **820** on a substrate **810** and deposition of metal caps **830** on the tops of pillars **820**. In general, substrate **810** can be made of any desired material but in one implementation is a semiconductor substrate of a material such as silicon. Pillars **820** can be formed on substrate **810** using any fabrication techniques that are capable of producing pillars of the desired widths, which would typically be smaller than about 200 nm. For example, known integrated circuit fabrication techniques such as nanoimprint lithography can be used to achieve the desired feature size and a pattern for pillars **820** corresponding to the array of plasmon supporting structures to be created. Metal caps **830** can be made of any metal capable of supporting surface plasmons, e.g., platinum, gold, silver, copper, aluminum, or nickel caps, can be deposited on pillars using physical vapor deposition (PVD), chemical vapor deposition (CVD), electrochemical deposition, or sputtering, for example. As an alternative to deposition of metal on top surface of pillars **830**, metal regions **830** may be formed from a layer of metal formed overlying a layer from which pillars **820** are formed and patterned at the same time pillars **820** are created.

[0045] Pillars **820** may be closely spaced, e.g., less than 200 nm from a closest neighboring pillar **820** when originally formed, but the spacing between pillars **820** (and therefore between metal caps **830**) can be further closed or reduced as shown in FIG. **8B**. For example, when the pillars **820** are exposed to a volatile liquid which is allowed to evaporate, microcapillary forces between pillars **820** or metal caps **830** can pull metal caps toward their nearest neighbors and reduce their separation, e.g., down to less than about 1 nm. Molecules on the pillar surfaces can be used to maintain the gaps between the tips of pillars **820** in the range of 1-10 nm. These molecules can either be coated on pillars **820** before exposure to the volatile liquid, e.g. through vapor-phase self-assembly, or can be contained in the volatile liquid itself, coating the pillar surface before evaporation is completed.

[0046] A nanoimprinting process illustrated in FIGS. **8C** and **8D** can be used to bond metal caps **830** with a new substrate **840**. Substrate **840** is a flexible or deformable substantially flat substrate. Transfer of metal caps **830** to substrate **840** occurs after separating pillars **820** and substrate **810**, provided that adhesion of caps **830** to substrate **840** is greater than the adhesion of caps **830** to pillars **820**. This bonding can be achieved in a number of ways, such as through a chemical adhesive or through a curable polymer. Suitable adhesive layers include chemicals which bind strongly to substrate **840** while leaving one or more free groups to bond to metal caps **830**. For example, mercaptopropyl-trimethoxysilane (MPTMS) can be used to bind to oxide substrates, leaving a free thiol group to bind to gold, silver or other suitable metals. Suitable polymers include thermally curable materials such as polymethyl methacrylate (PMMA) and polymide and UV curable materials such as polydimethylsiloxane (PDMS). Substrate **840** with attached metal caps **830** can thus form a desired array for use in a strain sensor as described above or may be bonded to another layer on which further metal caps **830** are bonded, e.g., during fabrication of a three-dimensional array. In the case of transfer to a curable

polymer, for example PDMS, a thick enough layer may be formed to peel off and apply to a new substrate if desired. Substrate **810** and pillars **820** can be discarded or reused as a template for fabrication of another array.

[0047] An article of Steven J. Barcelo, Ansoon Kim, Wei Wu, and Zhiyong Li, entitled "Fabrication of Deterministic Nanostructure Assemblies with Sub-nanometer Spacing Using a Nanoimprinting Transfer Technique," VOL. 6, NO. 7, 6446-6452, ACSNano (2012) further describes some suitable fabrication techniques and is hereby incorporated by reference in its entirety.

[0048] The above described stress sensors that use optical measurements of light output from an array of discrete plasmon supporting structures can further employ additional techniques for measuring strain. In particular, when an array includes the plasmon supporting structures are metal or otherwise conductive, the electrical resistance of the array may also depend on deformation of the array and therefore may provide a secondary indication of the deformation of the object. Also, when an array includes the plasmon supporting structures that are ferromagnetic, the magnetic properties of the array may depend on deformation of the array and therefore may provide a different or a further secondary indication of the deformation of the object. FIG. **9** is a block diagram of a strain sensor **900** that employs an array **930** of discrete plasmon supporting structure for measurement of strain in an object **110** or within array **930**. Array **930** may be substantially identical to array **130** described above, but for the particular implementation of FIG. **9**, array **930** uses ferromagnetic conductive particles, e.g., nickel nanoparticles, as the discrete plasmon supporting structures. Array **930** may further include additional structures such electrical contacts for measurement of resistance in array **930**.

[0049] Strain sensor **900** may employ lighting system **230** and an optical sensor **240** in the same manner described above to measure output light **140** and determine the optical response of array **930** to input light **130**. However, sensor **900** further includes an ohm meter or other resistance measuring device **910** that measures the electrical resistance across array **930**. In general, the electrical resistance may be expected to increase as the separations between conductive structures in array increase. Sensor **920** also includes a magnetic sensor **920** that detects the magnetic properties of array **930**. The magnetic sensor **920** could scan the surface to measure the magnetic field in a given area. In general, the magnetic field in a given area may be expected to decrease as the material is stretched, decreasing the effective density of magnetic nanoparticles. Controller **950** in addition to performing the functions of controller **250** described above can combine strain measurements based on optical, resistive, and magnetic characteristics of array **930** to improve accuracy of measurements of strain or another physical quantity that depends on the strain in array **930**.

[0050] Although particular implementations have been disclosed, these implementations are only examples and should not be taken as limitations. Various adaptations and combinations of features of the implementations disclosed are within the scope of the following claims.

1. A strain gauge comprising:
a medium that is deformable; and
a plurality of discrete plasmon supporting structures arranged with the medium to create one or more plasmon resonances that change with deformation of the

medium so that a color of light scattered from the strain gauge visibly changes with the deformation of the medium.

2. The strain gauge of claim **1**, wherein the medium is a surface of or is attached to a surface of an object that is subject to strain to be observed.

3. (canceled)

4. The strain gauge of claim **6**, wherein each of the first optical characteristic and the second optical characteristic is selected from a group consisting of a frequency, an amplitude, and a width of a feature that the one or more plasmon resonances create in a spectral distribution of light scattered from the strain gauge.

5. A strain gauge comprising:

a medium that is deformable; and

a plurality of discrete plasmon supporting structures arranged with the medium to create one or more plasmon resonances that change with deformation of the medium and provide the strain gauge with an optical characteristic that depends on the deformation of the medium, wherein the discrete plasmon supporting structures are arranged to form a hierarchical structure that includes:

a plurality of first assemblies of the discrete plasmon supporting structures, wherein the plasmon supporting structures have first separations within the first assemblies; and

one or more second assemblies containing the first assemblies, wherein the first assemblies have second separations within the one or more second assemblies.

6. The strain gauge of claim **5**, wherein:

a first of the one or more plasmon resonance that has a first optical characteristic that depends on the first separations; and

a second of the one or more plasmon resonances has a second optical characteristic that depends on the second separations.

7. The strain gauge of claim **5**, wherein the one or more second assemblies comprises a plurality of the second assembles arranged in an array with third separations, wherein:

the first separations are less than about 50 nm;

the second separations are more than 100 nm; and

the third separations are larger than the second separations and cause a diffraction pattern that depends on deformation of the medium.

8. The strain gauge of claim **1**, wherein the discrete plasmon supporting structures include:

a plurality of discrete plasmon supporting structures that have a first size; and

a plurality of discrete plasmon supporting structures that have a second size that is larger than the first size.

9. A strain gauge comprising:

a medium that is deformable; and

a plurality of discrete plasmon supporting structures arranged with the medium to create one or more plasmon resonances that change with deformation of the medium and provide the strain gauge with an optical characteristic that depends on the deformation of the medium, wherein the plasmon supporting structures comprise a ferromagnetic material and provide the strain gauge with a measureable magnetic characteristic that depends on deformation of the medium.

10. The strain gauge of claim **1**, wherein the plasmon supporting structures comprise a conductive material and provide the strain gauge with a measureable electrical resistance that depends on deformation of the medium.

11. The strain gauge of claim **5**, further comprising a lighting system that is controllable to switch between illuminating the discrete plasmon supporting structures with light having a first polarization corresponding to a first symmetry axis of an arrangement of the discrete plasmon supporting structures and illuminating the discrete plasmon supporting structures with light having a second polarization corresponding to a second symmetry axis of the arrangement of the discrete plasmon supporting structures.

12. The strain gauge of claim **5**, further comprising:

an optical sensor; and

a controller coupled to the optical sensor and configured to derive a measurement result from measurements that the optical sensor provides of output light from the discrete plasmon supporting structures.

13. The strain gauge of claim **12**, wherein the optical sensor is operable to separately measure light having first and second polarizations, wherein the first polarization corresponds to a first symmetry axis of an arrangement of the discrete plasmon supporting structures and the second polarization corresponds to a second symmetry axis of the arrangement of the discrete plasmon supporting structures.

14. The strain gauge of claim **1**, wherein the discrete plasmon supporting structures are arranged in a hierarchical array that provides multiple spacing length scales including a spacing length scale less than 50 nm.

15. A measuring method comprising:

providing a plurality of discrete plasmon supporting structures on an object and arranged to create a plasmon resonance that depends on deformation of the object; and

observing, with a naked eye, a change in an optical characteristic of the object to detect a deformation of the object, wherein the optical characteristic observed is caused by the plasmon resonance.

16. The method of claim **15**, wherein observing the change in the optical characteristic comprises visually observing a change in color of light scattered from the object.

17. The method of claim **18**, wherein observing the change comprises measuring and analyzing a spectral content of light reflected from the plasmon supporting structures.

18. A measuring method comprising:

providing a plurality of discrete plasmon supporting structures on an object and arranged to create a plasmon resonance that depends on deformation of the object;

observing a change in optical characteristics of the object to detect a deformation of the object, wherein the optical characteristic observed is caused by the plasmon resonance;

measuring a secondary characteristic that the discrete plasmon supporting structures provide across an area of the object, wherein the secondary characteristic is one of an electrical resistance and a magnetic characteristic; and

using the secondary characteristic measured in determination of the deformation of the object.

19. (canceled)

20. (canceled)

21. The strain gauge of claim **9**, further comprising:

an optical sensor;

a magnetic sensor; and

a controller to derive a measurement result using a measurement of the optical characteristic from the optical sensor and a measurement of the magnetic characteristic from the magnetic sensor.

* * * * *