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(54) APPARATUS COMPRISING A WAVEGUIDE FOR RADIO FREQUENCY SIGNALS

(57) Apparatus comprising a waveguide for radio frequency signals and at least one active element comprising a transition metal oxide material and two electrodes for applying a control voltage to the transition metal oxide material.

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Description

Field of the Disclosure

[0001] Exemplary embodiments relate to an apparatus comprising a waveguide for radio frequency, RF, signals.

Background

[0002] Apparatus of the aforementioned type can be used to transmit RF signals, e.g. from a source to a sink.

Summary

[0003] The scope of protection sought for various embodiments of the invention is set out by the independent claims. The exemplary embodiments and features, if any, described in this specification, that do not fall under the scope of the independent claims, are to be interpreted as examples useful for understanding various exemplary embodiments of the invention.

[0004] Exemplary embodiments relate to an apparatus comprising a waveguide for radio frequency signals and at least one active element comprising a transition metal oxide material and two electrodes for applying a control voltage to the transition metal oxide, TMO, material. This enables to effect a change of electric characteristics of the portion of the waveguide where the active element is located, e.g. by altering the control voltage, so that a propagation of electromagnetic waves associated with the RF signal may be influenced.

[0005] According to further exemplary embodiments, the TMO material may comprise at least one of: tungsten trioxide (WO_3), titanium dioxide (TiO_2), vanadium dioxide (VO_2), nickel oxide (NiO), manganese dioxide (MnO_2).

[0006] According to further exemplary embodiments, the at least one active element may be arranged at least partly within or at the waveguide, preferably such that the active element or at least a portion of the TMO material of the active element may interact with at least a portion of the RF signal(s) propagating within the waveguide.

[0007] According to further exemplary embodiments, arranging the at least one active element at least partly within or at the waveguide may comprise arranging the at least one active element relative to the waveguide such that the active element or at least a portion of the TMO material of the active element may at least interact with a portion of RF signals propagating outside of the waveguide.

[0008] According to further exemplary embodiments, the at least one active element is configured to change, depending on the control voltage, between a dielectric state, in which the at least one active element is not electrically conductive, and a conductive state, in which the at least one active element is electrically conductive.

[0009] According to further exemplary embodiments, the at least one active element may be configured to perform a phase transition and/or metal-nonmetal transition depending on an electric field applied to the TMO material, e.g. in the form of the control voltage, e.g. a Mott-transition. This way, by applying a specific control voltage, the active element may be influenced to exhibit electric properties similar to a metallic conductor or to a dielectric material, i.e. isolator. According to further exemplary embodiments, this behavior may also be gradually or continuously changed by gradually or continuously changing the control voltage, which e.g. enables to selectively attenuate the RF signal(s) propagating within the waveguide.

[0010] According to further exemplary embodiments, the at least one active element is at least partly arranged within a) a core of the waveguide, and/or within b) a cladding (or at least one cladding, respectively) of the waveguide.

[0011] According to further exemplary embodiments, the waveguide comprises at least in sections a) a circular cross-section or b) a non-circular cross-section, e.g. elliptical or polygonal, e.g. rectangular, cross-section.

[0012] According to further exemplary embodiments, the waveguide may comprise or consist of one or more dielectric materials.

[0013] According to further exemplary embodiments, the core of the waveguide may comprise or consist of dielectric material.

[0014] According to further exemplary embodiments, at least one cladding of the waveguide may comprise or consist of dielectric material.

[0015] According to further exemplary embodiments, the dielectric material may comprise polymer material, which is cost-effective and enables efficient manufacturing.

[0016] According to further exemplary embodiments, the waveguide comprises or is at least one polymer fiber.

[0017] According to further exemplary embodiments, the waveguide is a polymer fiber having a core of polymer material and a cladding, which surrounds the core, wherein the cladding preferably also comprises a polymer material. According to further exemplary embodiments, an optional coating may be provided, which may e.g. surround the cladding.

[0018] According to further exemplary embodiments, the at least one active element comprises a stack of layers stacked, preferably upon each other, along a first axis, wherein the stack comprises a first layer formed by a first electrode of the two electrodes, a second layer formed by a second electrode of the two electrodes, and a third layer formed by the transition metal oxide (TMO) material, the third, e.g. TMO, layer being arranged between the first layer and the second layer.

[0019] According to further exemplary embodiments, the first axis of the stack extends substantially parallel to a longitudinal axis of the waveguide. According to further exemplary embodiments, "substantially parallel" means that an angle between the longitudinal axis of the waveguide and the first axis of the stack may range between 0 degrees and 20 degrees.

[0020] According to further exemplary embodiments, at least one of the first electrode and the second electrode comprises a metallic layer ("electrode layer").

[0021] According to further exemplary embodiments, at least one of the first electrode and the second electrode comprises a thickness smaller than a skin depth of at least one frequency component of the radio frequency signals. This enables the RF signal(s) propagating within the waveguide to propagate (at least partly) through the at least one active element (and its electrode(s)), especially if the at least one active element or the TMO material of which is in its dielectric, i.e. non-metallic, state, which, according to further exemplary embodiments, may also be considered as an "OFF"-state.

[0022] According to further exemplary embodiments, in the OFF-state, the TMO material of the active element exhibits a dielectric, i.e. electrically non-conductive, behavior, thus in principle enabling propagation of RF signals and the associated electromagnetic (EM) waves through the TMO material layer (and also through the electrode layer(s), if they are sufficiently thin according to further preferred embodiments).

[0023] According to further exemplary embodiments, in an "ON"-state, the TMO material of the active element exhibits a metallic, i.e. electrically conductive, behavior, thus in principle preventing propagation of RF signals and the associated electromagnetic (EM) waves through the TMO material layer, i.e. attenuating the RF signals, as seen from a transmission point of view. According to further exemplary embodiments, however, the degree of attenuation may be controlled by selecting a layer thickness of the TMO material layer. Particularly, if the TMO material layer has sub-skin depth thickness values, similar to the electrode layers according to further exemplary embodiments, at least a portion of the RF signal(s) may propagate through the TMO material layer, even in the ON-state.

[0024] According to further exemplary embodiments, at least one of the first electrode and the second electrode comprises a thickness smaller than a skin depth of the highest frequency component of the radio frequency signals. This enables the highest frequency component of the radio frequency signals to at least partly be transmitted, i.e. propagate, through the at least one active element.

[0025] According to further exemplary embodiments, at least one of the first electrode and the second electrode comprises a thickness smaller than 1 micrometer, μm, preferably smaller than 500 nanometer, nm.

[0026] According to further exemplary embodiments, the third layer comprises a thickness greater than a skin depth of at least one frequency component of the radio frequency signals, in some embodiments greater than 300 percent of the skin depth, such as greater than 500 percent of the skin depth.

[0027] According to further exemplary embodiments, the apparatus comprises at least one control device configured to provide at least one control voltage for the at least one active element, whereby the (di)electric properties of the TMO material may be influenced as exemplarily explained above, thus enabling to control a degree of attenuation or propagation of the radio frequency signal(s).

[0028] According to further exemplary embodiments, the at least one control device is configured to at least temporarily provide the at least one control voltage a) with a plurality of discrete voltage values, or b) with continuous voltage values.

[0029] According to further exemplary embodiments, providing a plurality of e.g. two different discrete voltage values may be used for switching on and switching off the at least one active element, i.e. toggling the at least one active element between the conductive state of its TMO material and the dielectric state of its TMO material.

[0030] According to further exemplary embodiments, providing continuous voltage values for the active element may be used for continuously changing the at least one active element between the conductive state of its TMO material and the dielectric state of its TMO material, thus e.g. effecting a continuously changing degree of attenuation.

[0031] According to further exemplary embodiments, the apparatus comprises at least one impedance transformer, wherein preferably the at least one impedance transformer is arranged adjacent to the at least one active element. As an example, the at least one impedance transformer may be used to perform impedance matching between the waveguide and the at least one active element, especially if the at least one active element is in the OFF-state, whereby reflections of the RF signals at the interface between the waveguide and the at least one active element may be avoided or at least be reduced.

[0032] According to further exemplary embodiments, an impedance transformer with an electric length of quarter-wavelength at the frequency of operation (i.e., (center) frequency of the RF signal(s)) may be provided, with a characteristic impedance Z_{match} that can be characterized by e.g.:

$$Z_{\mathrm{match}} = \frac{Z_{\mathrm{free\ space}}}{\sqrt[4]{\varepsilon_{\mathrm{r\ OFF}}\varepsilon_{\mathrm{r\ PMF}}}} \quad \texttt{[equation 1],}$$

wherein $Z_{\text{free space}}$ characterizes an impedance of free space, wherein $\varepsilon_{r\,OFF}$ characterizes the relative permittivity of the at least one active element in the OFF-state, wherein $\varepsilon_{r\,PMF}$ characterizes the relative permittivity of the waveguide. As an example, the at least one active element may be in its OFF-state if the control voltage has a value of zero.

[0033] According to further exemplary embodiments, the at least one impedance transformer may comprise a section of the waveguide having a predetermined length.

[0034] According to further exemplary embodiments, providing the at least one impedance transformer, e.g. based on [equation 1], enables that in the OFF-state of the at least one active element, there are (at least substantially) no unwanted reflections at the interface waveguide/active element, and that the propagation of RF signals between the input and output is unhindered.

[0035] According to further exemplary embodiments, the situation may change once a non-vanishing control voltage is applied to the at least one active element or its TMO material, respectively. Now, the layer containing the transition metal oxide becomes conductive (ON-state), particularly highly conductive, with indirect contact with the conductive electrodes ("biasing pads"), which are, according to further exemplary embodiments, sub-skin depth conductors.

[0036] According to further exemplary embodiments, a composite electrical thickness of the at least one active element or its TMO material (layer) may now, e.g. in the ON-state, significantly be increased (compared to the OFF-state) thus resulting in significant reflections of RF signals at the boundary or interface between the waveguide and the at least one active element.

[0037] According to further exemplary embodiments, this may result in a significantly attenuated RF signal at an "output" of the apparatus, i.e. on an output side of the at least one active element, assuming the RF signal has been supplied to the at least one active element on its "input" side.

[0038] According to further exemplary embodiments, the composite electrical thickness of the at least one active element or its active (e.g., TMO) region may e.g. be in the range of a few skin-depths of the RF signal(s), so that the RF signal at the output may be (particularly fully) annihilated. According to further exemplary embodiments, the composite electrical thickness of the at least one active element may depend on a physical thickness of the transition metal oxide layer, and potentially also on a mode of operation of the at least one active elements.

[0039] According to further exemplary embodiments, two modes may be distinguished:

1. According to an exemplary first mode, the active (e.g., TMO) layer thickness in the ON-state is several skin-depths thick,

2. According to an exemplary second mode, the active layer thickness in the ON- state is sub skin-depth thick.

[0040] According to further exemplary embodiments, in the first mode, the apparatus may e.g. be operable by the application of a continuous DC (direct current) control voltage (i.e., a control voltage that can be varied from 0 V (Volt) to a maximum value of Vmax > 0 V), where for example the conductivity and hence the skin-depth of the transition metal oxide layer may be a function of the voltage value of the applied control voltage. This (exemplary first) mode of operation may also be referred to "analogue waveguide or transmission line attenuator".

[0041] According to further exemplary embodiments, in the second mode, one active region or TMO layer may not be enough to fully annihilate an input RF signal even when the highest allowable control voltage (value Vmax) is applied to the at least one active element or its TMO material (layer). Hence, in order to provide a full controllability of the magnitude of the output RF signal, according to further exemplary embodiments, several TMO material layers may be provided, e.g. in the form of a plurality of, preferably adjacent, active elements.

[0042] In other words, according to further exemplary embodiments, a plurality of active elements may be provided in the waveguide, wherein at least two of the active elements may be arranged adjacent to each other.

[0043] According to further exemplary embodiments, the plurality of active elements may be arranged in series along a or the longitudinal axis of the waveguide, wherein preferably adjacent active elements share one common electrode. As an example, a second electrode of a first active element may also form the first electrode of a second active element arranged adjacent to the first active element.

[0044] According to further exemplary embodiments, the plurality of active elements may be provided in a length section of the waveguide that corresponds with 20 percent or less of a total length of the waveguide, preferably with 10 percent or less, more preferably with 5 percent or less. In other words, compared to the total length of the waveguide, regions of the waveguide comprising one or more active elements according to the embodiments may form a comparatively small fraction.

[0045] According to further exemplary embodiments, the at least one active element or the plurality of active elements may be arranged at a first and/or second axial end section of the waveguide.

[0046] According to further exemplary embodiments, the apparatus may comprise a coupler, wherein the at least one active element is connected to at least one port of the coupler.

[0047] According to further exemplary embodiments, at least a first active element or a first group of active elements is connected to a first port of the coupler, and at least a second active element or a second group of active elements is connected to a second port of the coupler.

[0048] Further exemplary embodiments relate to a method of using an apparatus comprising a waveguide for radio frequency signals and at least one active element comprising a transition metal oxide material and two electrodes for applying a control voltage to the transition metal oxide material, the method comprising at least one of the following steps: a) processing a radio frequency signal, b) influencing a radio frequency signal, particularly a radio frequency signal propagating within the waveguide, c) attenuating a radio frequency signal,

d) reflecting a radio frequency signal, e) selecting one or more modes of a radio frequency signal, f) modulating a radio frequency signal.

Brief description of the figures

[0049] Some exemplary embodiments will now be described with reference to the accompanying drawings in which:

Fig. 1	schematically depicts a simplified block diagram of an apparatus according to exemplary embodiments,
Fig. 2A, 2B	each schematically depict a simplified side view of an apparatus according to further exemplary embodiments,
Fig. 3A	schematically depicts a simplified cross-sectional front view of a waveguide according to further exemplary embodiments,
Fig. 3B	schematically depicts a simplified cross-sectional front view of a waveguide according to further exemplary embodiments,
Fig. 4	schematically depicts a simplified side view of an active element according to further exemplary embodiments,
Fig. 5	schematically depicts a simplified side view of an apparatus according to further exemplary embodiments,
Fig. 6	schematically depicts a simplified side view of an apparatus according to further exemplary embodiments,
Fig. 7	schematically depicts a simplified perspective view of an apparatus according to further exemplary embodiments,
Fig. 8	schematically depicts a simplified perspective view of an apparatus according to further exemplary embodiments, and
Fig. 9	schematically depicts a block diagram of an apparatus according to further exemplary embodiments.

Description of exemplary embodiments

[0050] Figure 1 schematically depicts a simplified block diagram of an apparatus 100 according to exemplary embodiments. The apparatus 100 includes a waveguide 110 for radio frequency, RF, signals, RF1, RF1’ and at least one active element 120 including a transition metal oxide, TMO, material and two electrodes for applying a control voltage CV to the TMO material. This enables to effect a change of electric characteristics of the portion of the waveguide 110 where the active element 120 is located, e.g. by altering the control voltage CV, so that a propagation of electromagnetic waves associated with the RF signal RF may be influenced, cf. the further RF signal RF’.

[0051] According to further exemplary embodiments, the at least one active element 120 may be arranged at least partly within or at the waveguide 110, preferably such that the active element 120 or at least a portion of the TMO material of the active element 120 may interact with at least a portion of the RF signal(s) RF1, RF1’ propagating within the waveguide 110.

[0052] According to further exemplary embodiments, arranging the at least one active element 120 at least partly within or at the waveguide 110 may include arranging the at least one active element 120 relative to the waveguide 110 such that the active element 120 or at least a portion of the TMO material of the active element 120 may at least interact with a portion of RF signals RF1, RF1’ propagating outside of the waveguide.

[0053] According to further exemplary embodiments, the at least one active element 120 is configured to change, depending on the control voltage CV, between a dielectric state, in which the at least one active element 120 (or its TMO material, respectively) is not electrically conductive, and a conductive state, in which the at least one active element 120 (or its TMO material, respectively) is electrically conductive.

[0054] According to further exemplary embodiments, the at least one active element 120 may be configured to perform a phase transition and/or metal-non-metal transition depending on an electric field applied to the TMO material, e.g. in the form of the control voltage CV, e.g. a Mott-transition. This way, by applying a specific control voltage CV, the active element 120 may be influenced to exhibit electric properties similar to a metallic conductor or to a dielectric material, i.e. isolator.

[0055] According to further exemplary embodiments, this behavior may also be gradually or continuously be changed by gradually or continuously changing the control voltage CV, which e.g. enables to selectively attenuate the RF signal(s) RF1, RF1’ propagating within the waveguide 110.

[0056] According to further exemplary embodiments, cf. the schematic side view of apparatus 100a of Fig. 2A, the at least one active element 120 is at least partly arranged within a) a core 112 of the waveguide 110, and/or within b) a cladding 114 (or at least one cladding, respectively) of the waveguide 110.

[0057] According to the example of Fig. 2A, a cross-section of the at least one active element 120 basically corresponds with the cross-section of the waveguide 110, i.e. including the core 12 and the cladding 114.

[0058] According to further exemplary embodiments, cf. the schematic side view of apparatus 100b of Fig. 2B, the at least one active element 120 is at least partly arranged within the core 112 of the waveguide 110, but not within the cladding 114 of the waveguide 110.

[0059] According to further exemplary embodiments, cf. the cross-sectional front view of Fig. 3A, the waveguide 110a includes at least in sections a) a circular cross-section with a core 112a and a cladding 114a.

[0060] According to further exemplary embodiments, cf. the cross-sectional front view of Fig. 3B, the waveguide 110b includes a non-circular cross-section, e.g. elliptical or, as depicted by Fig. 3B, polygonal, e.g. rectangular, cross-section. Presently, the waveguide 110b of Fig. 3B includes a core 112b with rectangular cross-section exemplarily embedded (e.g., "sandwiched") between two claddings 114a, 114b (top and bottom claddings).

[0061] According to further exemplary embodiments, waveguide configurations having a non-circular cross-section, wherein the core is fully circumferentially surrounded by cladding(s) (not shown) are also possible.

[0062] Similar to the waveguide 110, 110a, 110b, according to further exemplary embodiments, the at least one active element 120 may have a) a circular cross-section or b) a non-circular cross-section, e.g. elliptical or polygonal, e.g. rectangular, cross-section.

[0063] According to further exemplary embodiments, the at least one active element 120 may be fully embedded within at least one cladding or may be partly embedded within at least one cladding, e.g. sandwiched between top and bottom claddings.

[0064] According to further exemplary embodiments, the waveguide 110, 110a, 110b may include or consist of one or more dielectric materials.

[0065] According to further exemplary embodiments, the core 112, 112a, 112b of the waveguide 110, 110a, 110b may include or consist of dielectric material.

[0066] According to further exemplary embodiments, at least one cladding 114, 114a, 114b of the waveguide 110, 110a, 110b may include or consist of dielectric material.

[0067] According to further exemplary embodiments, the dielectric material may include polymer material, which is cost-effective and enables efficient manufacturing.

[0068] According to further exemplary embodiments, the waveguide 110, 110a, 110b includes or is at least one polymer fiber.

[0069] According to further exemplary embodiments, the waveguide 110, 110a, 110b is a polymer fiber having a core 112, 112a, 112b of polymer material and a cladding 114, 114a, 114b which surrounds the core, wherein the cladding preferably also includes a polymer material. According to further exemplary embodiments, an optional coating (not shown) may be provided, which may e.g. surround the cladding 114, 114a, 114b.

[0070] According to further exemplary embodiments, cf. Fig. 4, the at least one active element 120a includes a stack S of layers stacked, preferably upon each other, along a first axis a1, wherein the stack S includes a first layer 122 formed by a first electrode 122 of the two electrodes 122, 123, a second layer 123 formed by a second electrode 123 of the two electrodes, and a third layer 121 formed by the transition metal oxide (TMO) material, the third, e.g. TMO, layer 121 being arranged between the first layer 122 and the second layer 123.

[0071] According to further exemplary embodiments, cf. the apparatus 100c of Fig. 5, the first axis a1 of the stack S extends substantially parallel to a longitudinal axis LA (also cf. Fig. 1) of the waveguide 110. According to further exemplary embodiments, "substantially parallel" means that an angle between the longitudinal axis LA of the waveguide 110 and the first axis a1 (Fig. 4) of the stack S may range between 0 degrees and 20 degrees.

[0072] According to further exemplary embodiments, at least one of the first electrode 122 and the second electrode 123 includes a metallic layer ("electrode layer").

[0073] According to further exemplary embodiments, at least one of the first electrode 122 and the second electrode 123 includes a thickness t1 smaller than a skin depth of at least one frequency component of the radio frequency signals RF1, RF1' (Fig. 1). This enables the RF signal(s) propagating within the waveguide 110 to propagate (at least partly) through the at least one active element 120 (and its electrode(s)), especially if the at least one active element 120 or the TMO material 121 of which is in its dielectric, i.e. non-metallic, state, which, according to further exemplary embodiments, may also be considered as an "OFF"-state.

[0074] According to further exemplary embodiments, in the OFF-state, the TMO material 121 (Fig. 4) of the active element 120 exhibits a dielectric, i.e. electrically non-conductive, behavior, thus in principle enabling propagation of RF signals RF1, RF1' and the associated electromagnetic (EM) waves through the TMO material layer 121 (and also through the electrode layer(s) 122, 123, if they are sufficiently thin according to further preferred embodiments).

[0075] According to further exemplary embodiments, in an "ON"-state, the TMO material 121 of the active element 120 exhibits a metallic, i.e. electrically conductive, behavior, thus in principle preventing propagation of RF signals RF1, RF1' and the associated electromagnetic (EM) waves through the TMO material layer 121, i.e. attenuating the RF signals RF1, RF1', as seen from a transmission point of view. According to further exemplary embodiments, however, the degree of attenuation may be controlled by selecting a layer thickness t2 (Fig. 4) of the TMO material layer 121. Particularly, if the TMO material layer 121 has sub-skin depth thickness values, similar to the electrode layers 122, 123 according to further exemplary embodiments, at least a portion of the RF signal(s) may propagate through the TMO material layer 121, even in the ON-state.

[0076] According to further exemplary embodiments, at least one of the first electrode 122 and the second electrode 123 includes a thickness t1 smaller than a skin depth of the highest frequency component of the radio frequency signals RF1, RF1'. This enables the highest frequency component of the radio frequency signals RF1, RF1' to at least partly be transmitted, i.e. propagate, through the at least one active element 120.

[0077] According to further exemplary embodiments, at least one of the first electrode 122 and the second electrode 123 includes a thickness t1 less than 1 micrometer, μm, preferably less than 500 nanometer, nm.

[0078] According to further exemplary embodiments, the third layer 121 comprises a thickness t2 greater than a skin depth of at least one frequency component of the radio frequency signals, in some embodiments greater than 300 percent of the skin depth, such as greater than 500 percent of the skin depth.

[0079] According to further exemplary embodiments, cf. Fig. 1, the apparatus 100 includes at least one control device 130 configured to provide the at least one control voltage CV for the at least one active element 120, whereby the (di)electric properties of the TMO material 121 may be influenced as exemplarily explained above, thus enabling to control a degree of attenuation or propagation of the radio frequency signal(s) RF1, RF1'.

[0080] According to further exemplary embodiments, the at least one control device 130 is configured to at least temporarily provide the at least one control voltage CV a) with a plurality of discrete voltage values, or b) with continuous voltage values.

[0081] According to further exemplary embodiments, providing a plurality of e.g. two different discrete voltage values may be used for switching on and switching off the at least one active element 120, i.e. toggling the at least one active element 120 between the conductive state of its TMO material 121 and the dielectric state of its TMO material 121.

[0082] According to further exemplary embodiments, providing continuous voltage values for the active element 120 may be used for continuously changing the at least one active element 120 between the conductive state of its TMO material 121 and the dielectric state of its TMO material 121, thus e.g. effecting a continuously changing degree of attenuation.

[0083] Figure 6 schematically depicts a simplified side view of an apparatus 100d according to further exemplar embodiments. The apparatus 100d includes a plurality of active elements, two of which are exemplarily depicted by Fig. 6 and denoted with reference signs 120_1, 120_2.

[0084] According to further exemplary embodiments, a plurality of active elements 120_1, 120_2, ... may be provided in the waveguide 110, wherein at least two of the active elements may be arranged adjacent to each other, cf. Fig. 6.

[0085] According to further exemplary embodiments, each of the plurality of active elements 120_1, 120_2, ... may be controlled by an individual control voltage CV_1, CV_2, ... which may e.g. be provided by the control device 130 (Fig. 1) .

[0086] According to further exemplary embodiments (not shown), each of the plurality of active elements 120_1, 120_2, ... may be controlled with a same, i.e. common, control voltage which may also be provided by the control device 130 (Fig. 1).

[0087] According to further exemplary embodiments, cf. the perspective view of Fig. 7, the apparatus 100e includes at least one, presently exemplarily two, impedance transformer(s) 140_1, 140_2.

[0088] According to further exemplary embodiments, the at least one impedance transformer is arranged adjacent to the at least one active element. As exemplarily depicted by Fig. 7, both impedance transformers 140_1, 140_2 are arranged adjacent to the at least one active element 120, thus e.g. enabling impedance transformation, particularly impedance matching, from both sides of the active element 120.

[0089] As an example, the at least one impedance transformer 140_1, 140_2 may be used to perform impedance matching between the waveguide 110 (Fig. 1) (or a respective section 110_1, 110_2 of the waveguide) and the at least one active element 120, especially if the at least one active element 120 is in the OFF-state, whereby reflections of the RF signals RF1 at the interface between the waveguide 110, 110_1 and the at least one active element 120 may be avoided or at least be reduced.

[0090] According to further exemplary embodiments, the apparatus 100e of Fig. 7 can be considered as an attenuator for RF signals RF1 propagating within the waveguide 110, wherein the waveguide has a first waveguide section 110_1, which is followed by the first impedance transformer 140_1, the at least one active element 120, the second impedance transformer 140_2, and a second waveguide section 110_2. The attenuation of the RF signal RF1 is controllable by the control voltage CV, wherein the RF signal RF1' represents an attenuated RF signal.

[0091] According to further exemplary embodiments, signal transmission by the waveguide sections 110_1, 110_2 may roughly be described as achieved by different dielectric behaviour (e.g., different relative permittivity) of the core 112 and the cladding, resulting in a kind of-mirror, reflecting the RF signal RF1 fed into the core 112 (particularly total reflexion) for specific frequencies. This also applies to the further exemplary waveguides explained above with reference to Fig. 1 to Fig. 6.

[0092] According to further exemplary embodiments, if no control voltage CV is applied to the active element 120, which corresponds with an OFF-state of the active element 120, the active element 120 or its active, i.e. TMO, region 121, behaves as a dielectric, e.g., with a dielectric constant given by ε_{rOFF} , which, in general may be substantially different from a composite dielectric constant of the waveguide 110_1, 110_2, denoted as ε_{rPMF}.

These different dielectric constants may give rise to characteristic impedances of the waveguide,

$$Z_{\mathrm{PMF}} = \sqrt{\frac{\mu_0}{\varepsilon_0 \varepsilon_{\mathrm{r\ PMF}}}} = \frac{Z_{\mathrm{free\ space}}}{\sqrt{\varepsilon_{\mathrm{r\ PMF}}}},$$

and of the active region

$$Z_{\mathrm{OFF}} = \sqrt{\frac{\mu_0}{\varepsilon_0 \varepsilon_{\mathrm{r\ OFF}}}} = \frac{Z_{\mathrm{free\ space}}}{\sqrt{\varepsilon_{\mathrm{r\ OFF}}}}.$$

[0093] According to further exemplary embodiments, an impedance transformer 140_1, 140_2 with an electric length of quarter-wavelength at the frequency of operation (i.e., (center) frequency of the RF signal(s) RF1, RF1') may be provided, with a characteristic impedance Z_{match} that can be characterized by e.g.:

$$Z_{\mathrm{match}} = \frac{Z_{\mathrm{free\ space}}}{\sqrt[4]{\varepsilon_{\mathrm{r\ OFF}} \varepsilon_{\mathrm{r\ PMF}}}} \quad \texttt{[equation 1],}$$

wherein $Z_{\mathrm{free\ space}}$ characterizes an impedance of free space, wherein $\varepsilon_{r\,OFF}$ characterizes the relative permittivity of the at least one active element 120 in the OFF-state, wherein $\varepsilon_{r\,PMF}$ characterizes the relative permittivity of the waveguide 110 or its sections 110_1, 110_2. As an example, the at least one active element 120 may be in its OFF-state if the control voltage CV has a value of zero, i.e. 0 V.

[0094] According to further exemplary embodiments, the at least one impedance transformer 140_1, 140_2 may include a section of the waveguide having a predetermined length. In other words, the at least one impedance transformer 140_1, 140_2 may be formed by a section of the waveguide of the predetermined length.

[0095] According to further exemplary embodiments, providing the at least one impedance transformer, e.g. based on [equation 1], enables that in the off-state of the at least one active element 120, there are (at least substantially) no unwanted reflections at the interface waveguide/active element, and that the propagation of RF signals between the input and output is unhindered.

[0096] According to further exemplary embodiments, the situation may change once a non-vanishing control voltage CV is applied to the at least one active element 120 or its TMO material 121, respectively. Now, the layer 121 containing the transition metal oxide becomes conductive (ON-state), particularly highly conductive, with indirect contact with the conductive electrodes ("biasing pads"), which are, according to further exemplary embodiments, sub-skin depth conductors.

[0097] According to further exemplary embodiments, a composite electrical thickness of the at least one active element 120 or its TMO material (layer) 121 may now, e.g. in the ON-state, significantly be increased (compared to the OFF-state) thus resulting in significant reflections of RF signals RF1, RF1' at the boundary or interface between the waveguide 110, 110_1, 110_2 and the at least one active element 120.

[0098] According to further exemplary embodiments, this may result in a significantly attenuated RF signal RF1' at an "output" of the apparatus 100e (Fig. 7), i.e. on an output side of the at least one active element 120, assuming the RF signal RF1 has been supplied to the at least one active element on its "input" side.

[0099] According to further exemplary embodiments, the apparatus may exhibit reciprocity, i.e. may behave (preferably at least substantially) identical regarding a direction of signal transmission. In other words, according to further exemplary embodiments, an input signal may be provided at either side of the apparatus or the waveguide, respectively.

[0100] According to further exemplary embodiments, the composite electrical thickness of the at least one active element 120 or its active (e.g., TMO) region 121 may e.g. be in the range of a few skin-depths of the frequency of the RF signal(s), so that the RF signal RF' at the output may be (particularly fully) annihilated.

[0101] According to further exemplary embodiments, the composite electrical thickness of the at least one active element 120 may depend on a physical thickness t2 (Fig. 4) of the transition metal oxide layer 121, and potentially also on a mode of operation of the at least one active elements 120.

[0102] According to further exemplary embodiments, two modes of operation may be distinguished:

1. According to an exemplary first mode, the active layer thickness in the ON-state is several skin-depths thick,

2. According to an exemplary second mode, the active layer thickness in the ON- state is sub skin-depth thick.

[0103] According to further exemplary embodiments, in the first mode, the apparatus may e.g. be operable by the application of a continuous DC (direct current) control voltage CV (i.e., a control voltage that can be varied from 0 V (Volt) to a maximum value of Vmax > 0 V), where for example the conductivity and hence the skin-depth of the transition metal oxide layer 121 may be a function of the voltage value of the applied control voltage CV. This (exemplary first) mode of operation may also be referred to "analogue waveguide or transmission line attenuator".

[0104] According to further exemplary embodiments, in the second mode, one active region or TMO layer may not be enough to fully annihilate an input RF signal even when the highest allowable control voltage (value Vmax) is applied to the at least one active element 120 or its TMO material (layer) 121. Hence, in order to provide a full controllability of the magnitude of the output RF signal RF1', according to further exemplary embodiments, several TMO material layers may be provided, e.g. in the form of a plurality 120' of, preferably adjacent, active elements, cf. e.g. the simplified perspective view of the apparatus 100f of Fig. 8.

[0105] In other words, according to further exemplary embodiments, a plurality 120' of active elements 120_1, 120_2, ..., 120_n may be provided in the waveguide, wherein at least two of the active elements may be arranged adjacent to each other.

[0106] According to further exemplary embodiments, the plurality 120' of active elements may be arranged in series along a or the longitudinal axis LA (Fig. 1) of the waveguide, wherein preferably adjacent active elements 120_1, 120_2 share one common electrode. As an example, a second electrode 123_1 of a first active element 120_1 may also form the first, common, electrode CE of a second active element 120_2 arranged adjacent to the first active element 120_1. The first electrode of the first active element 120_1 is denoted with reference sign 122_1, and the TMO layer of the first active element 120_1 is denoted with reference sign 121_1 in Fig. 8.

[0107] As exemplarily depicted by Fig. 8, n many active elements 120' may be provided, wherein n > 2, particularly n > 10 is possible according to further embodiments.

[0108] According to further exemplary embodiments, the n many active elements may be provided with a respective individual control voltage CV (not shown).

[0109] According to further exemplary embodiments, the n many active elements may collectively be provided with a common control voltage CV (not shown).

[0110] According to further exemplary embodiments, at least one of the n many active elements may be provided with a control voltage CV (also cf. Fig. 1) according to at least one of the following aspects:

(a) gradually (continuous control voltage, e.g. dc bias), which may e.g. result in a sectorized analog attenuation, or

(b) the control voltage CV can be made to have e.g. two states, for example b1) OFF (e.g., 0 V) and b2) ON (e.g., Vmax), for example in order to switch the respective active element(s) ON or OFF, e.g. resulting in a "digitally controlled" attenuation - attenuation is controlled by discrete attenuation values, or

(c) combination of (a) and (b), resulting e.g. in a coarse "digital" attenuation setting supplemented by "analog" fine tuning of attenuation.

[0111] According to further exemplary embodiments, and particularly regardless of the exemplary operation mode, the number n of active elements can be varied, e.g. depending on a desired level of attenuation for a specific field of application.

[0112] According to further exemplary embodiments, further degrees of freedom for the apparatus according to the embodiments are provided by the thickness(es) of the active, i.e. TMO, regions 121 (and hence a granularity of attenuation), the corresponding conductivity of the active region 121, and the frequency of operation, i.e. of the RF signals RF1, RF1'.

[0113] For example, according to further exemplary embodiments, if a composite conductivity of the active region 121 in the ON-state at a control voltage CV of V_{max} is $\sigma = 10^7 \, S/m$ (Siemens per meter), a thickness t2 (Fig. 4) of the active region 121 is about 500 nm and a frequency of operation f_0 is 100 GHz, the skin depth, using the below stated equation 2

$$\delta = \sqrt{\frac{1}{\sigma \pi f_0 \mu_r \mu_0}} \quad \texttt{[equation 2],}$$

[0114] is 500 nm, wherein μ_0 is the permeability of free space, and wherein μ_r is the relative permeability of the active region 121 in the ON-state. The skin depth is defined as the thickness of the conductor at which the signal is about 37% (1/e, e being Euler's constant) of the value it had at the surface of the conductor. As such, in the present example, a single active region thickness of t2 = 500 nm may result in a signal that is -20log(0.37)=8.6 dB attenuated compared to its input. Increasing the number of stages (i.e., n>1, cf. Fig. 8) according to further exemplary embodiments, may increase the overall level of attenuation of the RF signal(s) RF1. For example, according to further exemplary embodiments, two stages 120_1, 120_2 (Fig. 8) may yield an attenuation level of -20log(0.37*0.37)=17.2 dB, three stages (n=3) -20log(0.37*0.37*0.37)=25.9 dB, and so on.

[0115] According to further exemplary embodiments, in some cases, aspect (a) as mentioned above may also be referred to as "analog sub-skin depth waveguide or transmission line attenuator", aspect (b) as "digital sub-skin depth waveguide or transmission line attenuator", and aspect (c) as "analogue-digital sub-skin depth waveguide or transmission line attenuator".

[0116] According to further exemplary embodiments, the plurality 120' of active elements may be provided in a length section (not shown) of the waveguide that corresponds with 20 percent or less of a total length of the waveguide, preferably with 10 percent or less, more preferably with 5 percent or less, more preferably even less than 1 percent. In other words, compared to the total length of the waveguide, regions of the waveguide including one or more active elements according to the embodiments may form a comparatively small fraction of the overall length of the waveguide, which may e.g. be a few meters or e.g. up to 50m.

[0117] According to further exemplary embodiments, the regions of the waveguide including one or more active elements according to the embodiments may not be adjacent, i.e. may be separated by waveguide sections not having active elements.

[0118] According to further exemplary embodiments, the at least one active element 120 or the plurality 120' of active elements may be arranged, particularly concentrated, at a first and/or second axial end section of the waveguide.

[0119] According to further exemplary embodiments, cf. Figure 9, the apparatus 100g may include a coupler 150, wherein the at least one active element 120_1, 120_2 is connected to at least one port of the coupler 150.

[0120] Presently, at least a first active element 120_1 or a first group of active elements is connected to a first port 151 of the coupler 150, and at least a second active element 120_2 or a second group of active elements is connected to a second port 152 of the coupler 150.

[0121] According to further exemplary embodiments, at least one of the further ports 153, 154 of the coupler 150 may e.g. be used as an input port and/or an output port for a radio frequency signal RF1 (cf. Fig. 1).

[0122] According to further exemplary embodiments, each of the active elements 120_1, 120_2 may be provided with an individual control voltage CV_1, CV_2.

[0123] According to further exemplary embodiments, the active elements 120_1, 120_2 may alternatively be provided with a common control voltage (not shown), which enables or facilitates symmetrical biasing of the active elements 120_1, 120_2, which may be preferred for some reflective-type configurations.

[0124] The configuration 100g of Fig. 9 enables a reflection-type attenuation of RF signals, whereas the configurations of Fig. 1 to Fig. 8 may be, according to further exemplary embodiments, considered as transmission-type attenuators.

[0125] According to further exemplary embodiments, the coupler 150 (Fig. 9) may be a 3-dB hybrid coupler that splits an input signal (e.g. provided at the port 154) into two equal magnitude signals with phases in quadrature in a coupled and a direct arm. The coupler 150 may include waveguide sections s1, s2, s3, s4, s5, s6, s7, s8, wherein preferably the sections s1, s3, s4, s6, s7, s8 have a characteristic impedance Z_{PMF}, and wherein the sections s2, s5 have a characteristic impedance $Z_{PMF}/\sqrt{2}$.

[0126] The scattering (S)-parameters of this structure, provided that the active elements 120_1, 120_2, which may be considered as reflective loads for the coupler 150, are identical, are: $S_{11} = 0$ and $S_{21} = j\Gamma$ [equation 3], where Γ characterizes a reflection coefficient at the loads 120_1, 120_2. As can be seen from equation 3, and as opposed to a "transmission line" attenuator (cf. e.g. Fig. 7), the "reflective type" attenuator of Fig. 9 is impedance matched at the input ($S_{11} = 0$), particularly regardless of the control voltage(s) CV_1, CV_2 applied to the active region(s) 121 of the loads 120_1, 120_2.

[0127] According to further exemplary embodiments, the apparatus 100g may, particularly significantly, reflect an input RF signal from its reflective loads 120_1, 120_2 for a case when the active region(s) is/are switched ON (i.e., having conductive state).

[0128] According to further exemplary embodiments, an exact amount of the reflected signal may be dependent on the physical thickness t2 (Fig. 4) of the transition metal oxide layers 121 of the loads 120_1, 120_2, similar to above explained exemplary embodiments with "transmission line" or waveguide attenuators, cf. e.g. Fig. 7. This exemplary case corresponds to the case of the device 100g (Fig. 9) being in a low-loss state.

[0129] According to further exemplary embodiments, by e.g. reducing the control voltages CV_1, CV_2, the conductivity of the active regions 121 of the loads 120_1, 120_ may be reduced. At a point when the resistance of the active regions 121 becomes equal to a resistance (or characteristic impedance, respectively) of the waveguide, Z_{PMF}, the entire RF signal may be absorbed and dissipated as heat in the resistor formed using the active regions 121 of the loads 120_1, 120_2.

[0130] According to further exemplary embodiments, resistors (not shown) may be added at the coupler and through ports. The resistance of the resistors may e.g. be chosen as $Z_{PMF} - Z_{TMO\_ON}$. In this case, once the TMO layers are fully activated, they represent the resistance Z_{PMF_ON}, which together with the termination resistor may provide conditions for high signal attenuation.

[0131] According to further exemplary embodiments, in order to ensure a low-loss performance, and in order to have an incident signal fully reflected, it may be beneficial for the active regions 121 to be at least a few skin-depths thick. This may e.g. be attained by providing a plurality of active elements (e.g., similar to element 120' of Fig. 8), instead of a single active element as the loads 120_1, 120_2. In other words, a group of several active elements 120 may be connected to each port 151, 152 of the coupler 150 to increase reflective properties in the case of the conductive state of the TMO layers.

[0132] Further exemplary embodiments relate to a method of using an apparatus according to the embodiments, the method including at least one of the following steps: a) processing a radio frequency signal RF1, RF1', b) influencing a radio frequency signal RF1, particularly a radio frequency signal propagating within the waveguide, c) attenuating a radio frequency signal RF1, d) reflecting a radio frequency signal RF1, e) selecting one or more modes of a radio frequency signal, f) modulating a radio frequency signal.

[0133] According to further exemplary embodiments, the apparatus according to the embodiments may be used for processing RF signals RF1, RF1' in the GHz range, up to 100 GHz or more, i.e. even into the THz range.

Claims

1. Apparatus (100) comprising a waveguide (110) for radio frequency signals (RF1, RF1') and at least one

active element (120) comprising a transition metal oxide material (121) and two electrodes (122, 123) for applying a control voltage (CV) to the transition metal oxide material (121).

2. Apparatus (100) according to claim 1, wherein the at least one active element (120) is configured to change, depending on the control voltage, between a dielectric state, in which the at least one active element (120) is not electrically conductive, and a conductive state, in which the at least one active element (120) is electrically conductive.

3. Apparatus (100) according to claim 1 or 2, wherein the at least one active element (120) is at least partly arranged within a) a core (112) of the waveguide (110; 110a; 110b), and/or within b) a cladding (114; 114a, 114b) of the waveguide (110; 110a; 110b; 110c).

4. Apparatus (100) according to at least one of the preceding claims, wherein the waveguide (110; 110a; 110b) comprises at least in sections a) a circular cross-section or b) a non-circular cross-section, e.g. elliptical or polygonal, e.g. rectangular, cross-section.

5. Apparatus (100) according to at least one of the preceding claims, wherein the waveguide (110) comprises or is at least one polymer fiber.

6. Apparatus (100) according to at least one of the preceding claims, wherein the at least one active element (120) comprises a stack (S) of layers stacked, preferably upon each other, along a first axis (a1), wherein the stack (S) comprises a first layer (122) formed by a first electrode (122) of the two electrodes (122, 123), a second layer (123) formed by a second electrode (123) of the two electrodes (122, 123), and a third layer (121) formed by the transition metal oxide material (121), the third layer being arranged between the first layer (122) and the second layer (123).

7. Apparatus (100) according to claim 6, wherein the first axis (a1) of the stack (S) extends substantially parallel to a longitudinal axis (LA) of the waveguide (110) .

8. Apparatus (100) according to at least one of the claims 6 to 7, wherein at least one of the first electrode (122) and the second electrode (123) comprises a thickness (t1) smaller than a skin depth of at least one frequency component of the radio frequency signals (RF, RF').

9. Apparatus (100) according to at least one of the claims 6 to 8, wherein the third layer (121) comprises a thickness (t2) greater than a skin depth of at least one frequency component of the radio frequency signals (RF, RF').

10. Apparatus (100) according to at least one of the claims 6 to 9, wherein at least one of the first electrode (122) and the second electrode (123) comprises a thickness (t1) smaller than 1 micrometer, preferably smaller than 500 nanometer.

11. Apparatus (100) according to at least one of the preceding claims, comprising at least one control device (130) configured to provide at least one control voltage (CV; CV_1, CV_2, ..) for the at least one active element (120) .

12. Apparatus (100) according to claim 11, wherein the at least one control device (130) is configured to at least temporarily provide the at least one control voltage (CV; CV_1, CV_2, ..) a) with a plurality of discrete voltage values, or b) with continuous voltage values.

13. Apparatus (100) according to at least one of the preceding claims, comprising at least one impedance transformer (140_1, 140_2), wherein preferably the at least one impedance transformer (140_1, 140_2) is arranged adjacent to the at least one active element (120), and wherein the at least one impedance transformer (140_1, 140_2) comprises a section of the waveguide (110) having a predetermined length.

14. Apparatus (100) according to at least one of the preceding claims, wherein a plurality (120') of active elements (120_1, 120_2,) is provided in the waveguide (110).

15. Method of using an apparatus (100) comprising a waveguide (110) for radio frequency signals (RF1, RF1') and at least one active element (120) comprising a transition metal oxide material (121) and two electrodes (122, 123) for applying a control voltage (CV) to the transition metal oxide material (121), the method comprising at least one of the following steps: a) processing a radio frequency signal, b) influencing a radio frequency signal, particularly a radio frequency signal propagating within the waveguide, c) attenuating a radio frequency signal, d) reflecting a radio frequency signal, e) selecting one or more modes of a radio frequency signal, f) modulating a radio frequency signal.

Fig. 1

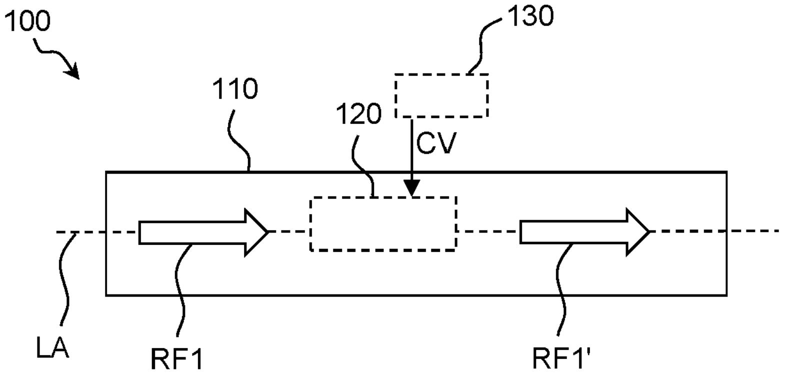


Fig. 2A

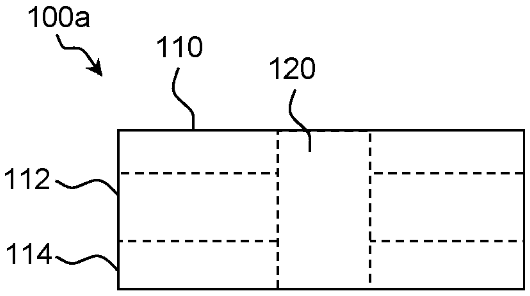


Fig. 2B

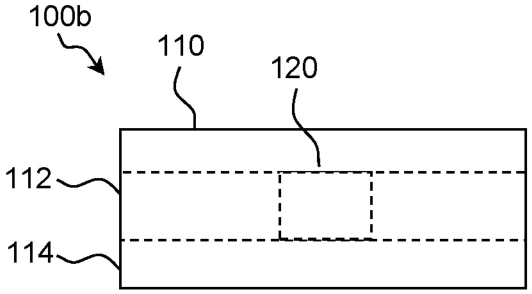


Fig. 3A

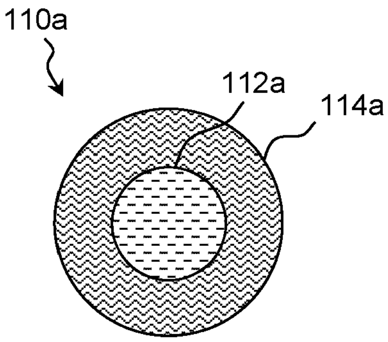


Fig. 3B

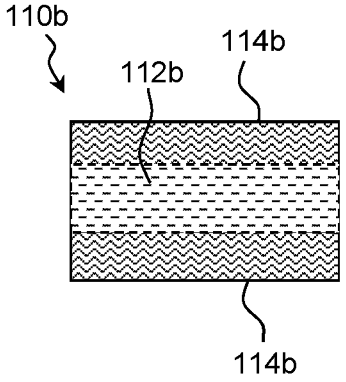


Fig. 4

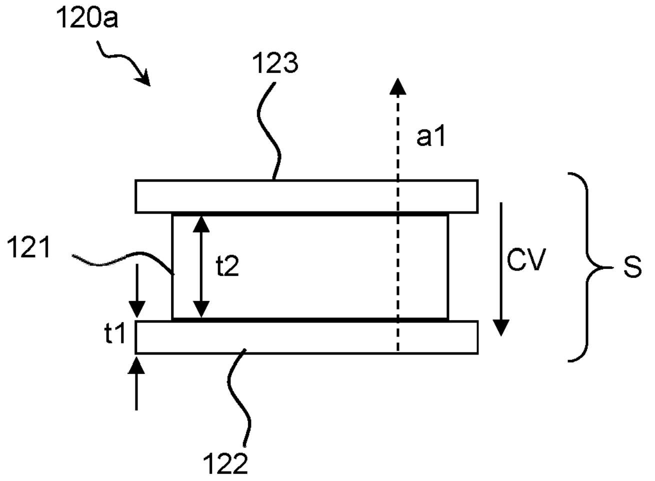


Fig. 5

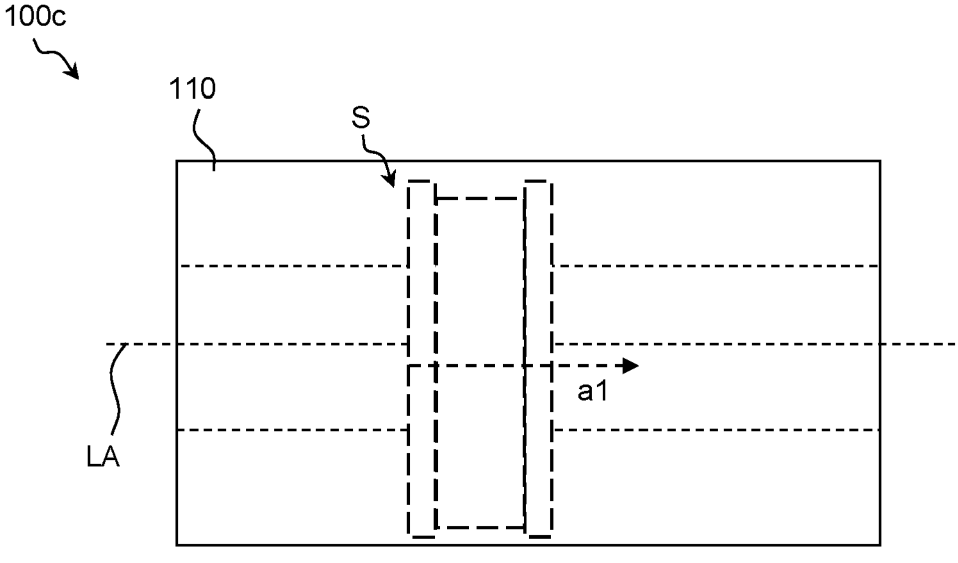


Fig. 6

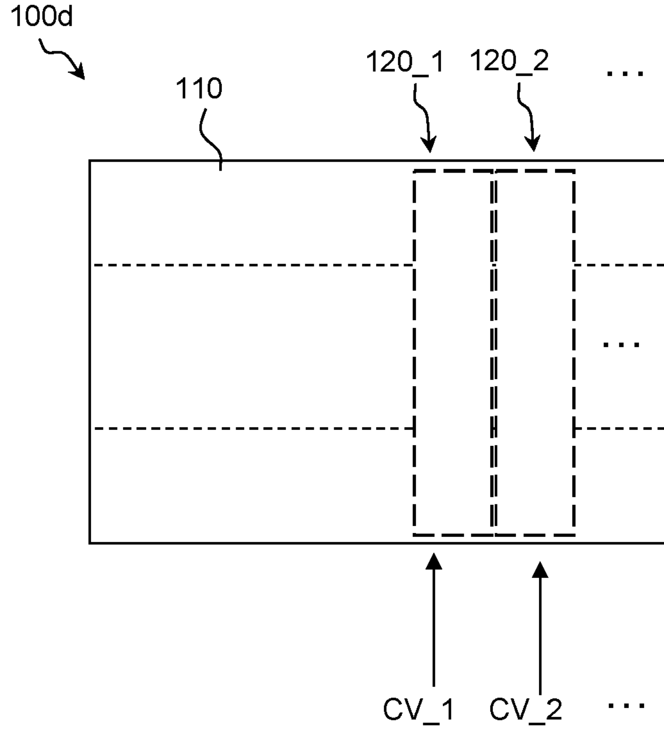
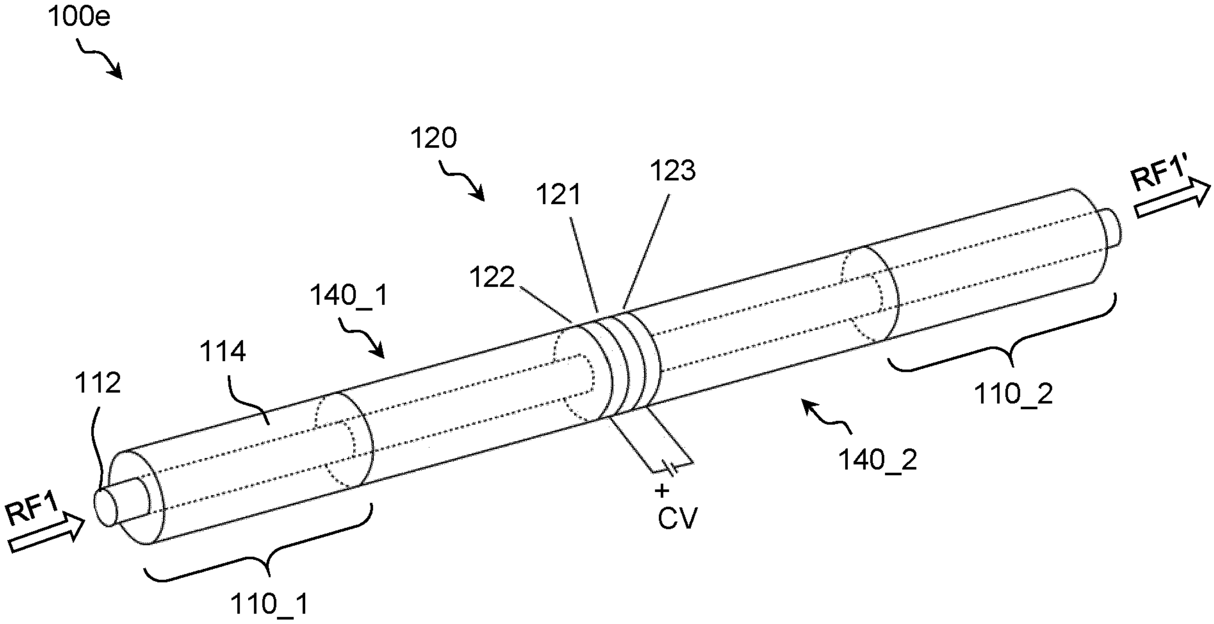

100d
110
120_1
120_2
...
...
CV_1
CV_2
...

Fig. 7


100e
120
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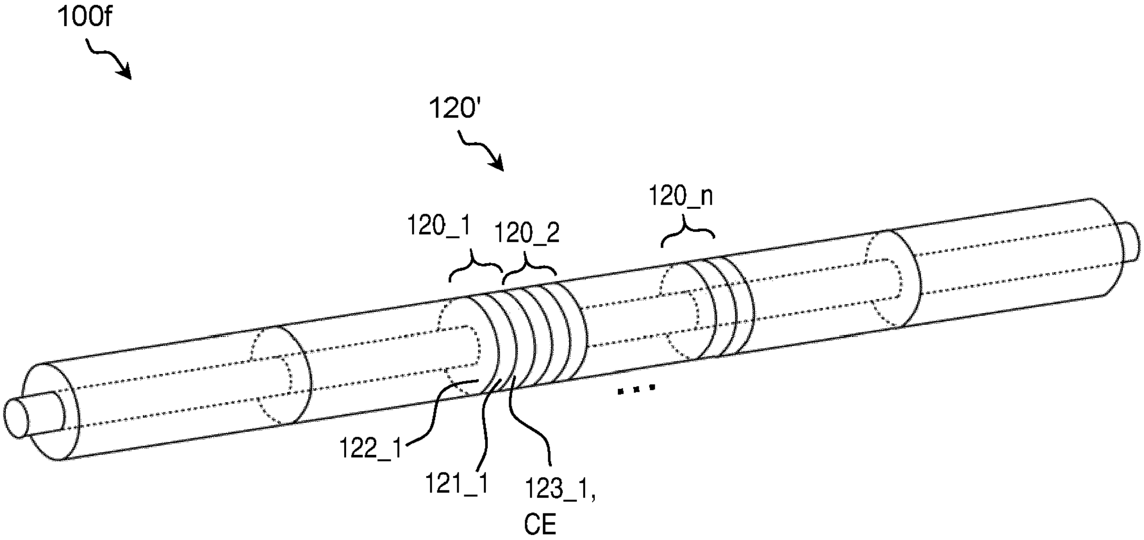
123
RF1'
122
140_1
114
112
RF1
+
CV
140_2
110_2
110_1

Fig. 8


100f
120'
120_n
120_1
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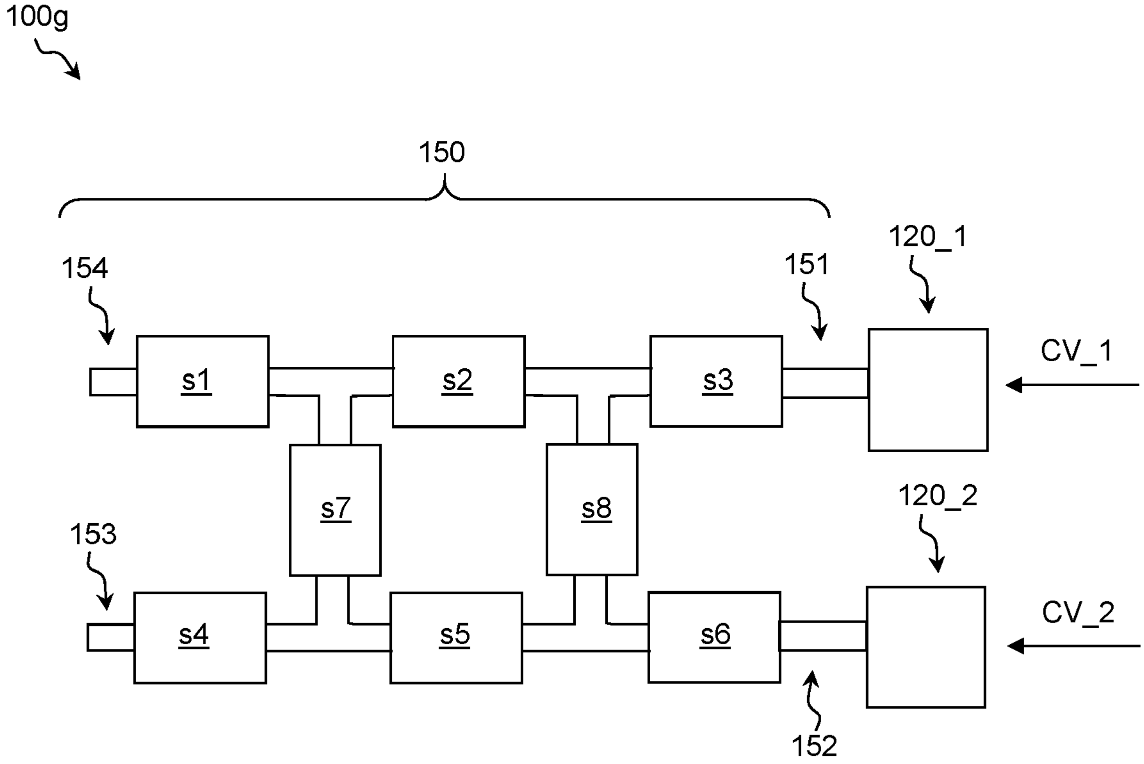
...
122_1
121_1
123_1,
CE

Fig. 9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CV_2
152

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EUROPEAN SEARCH REPORT

Application Number
EP 20 16 8129

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The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
The Hague	18 September 2020	Pastor Jiménez, J

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18-09-2020

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