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Han et al.

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(54) **OPTICAL MODULATING DEVICE HAVING GATE STRUCTURE**

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(30) **Foreign Application Priority Data**

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G02F 1/03 (2006.01)
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(Continued)

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CPC ***G02F 1/0121*** (2013.01); ***G02B 5/008*** (2013.01); ***G02F 1/0102*** (2013.01); ***H01L 33/06*** (2013.01); ***H01L 33/44*** (2013.01)

(58) **Field of Classification Search**
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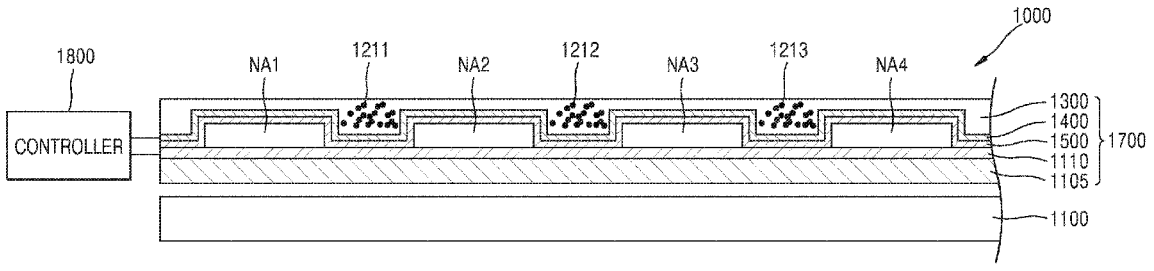
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Primary Examiner — Tuyen Tra
(74) *Attorney, Agent, or Firm* — Sughrue Mion, PLLC

(57) **ABSTRACT**

An optical modulating device includes a permittivity change layer having a variable permittivity, a dielectric layer disposed on the permittivity change layer, a nanoantenna disposed on the dielectric layer, and a light-emitting structure disposed adjacent to the permittivity change layer.

21 Claims, 9 Drawing Sheets



(51) **Int. Cl.**

G02F 1/01	(2006.01)
H01L 33/06	(2010.01)
G02B 5/00	(2006.01)
H01L 33/44	(2010.01)

(58) **Field of Classification Search**
USPC 359/244, 241, 240, 238, 237
See application file for complete search history.

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FIG. 1

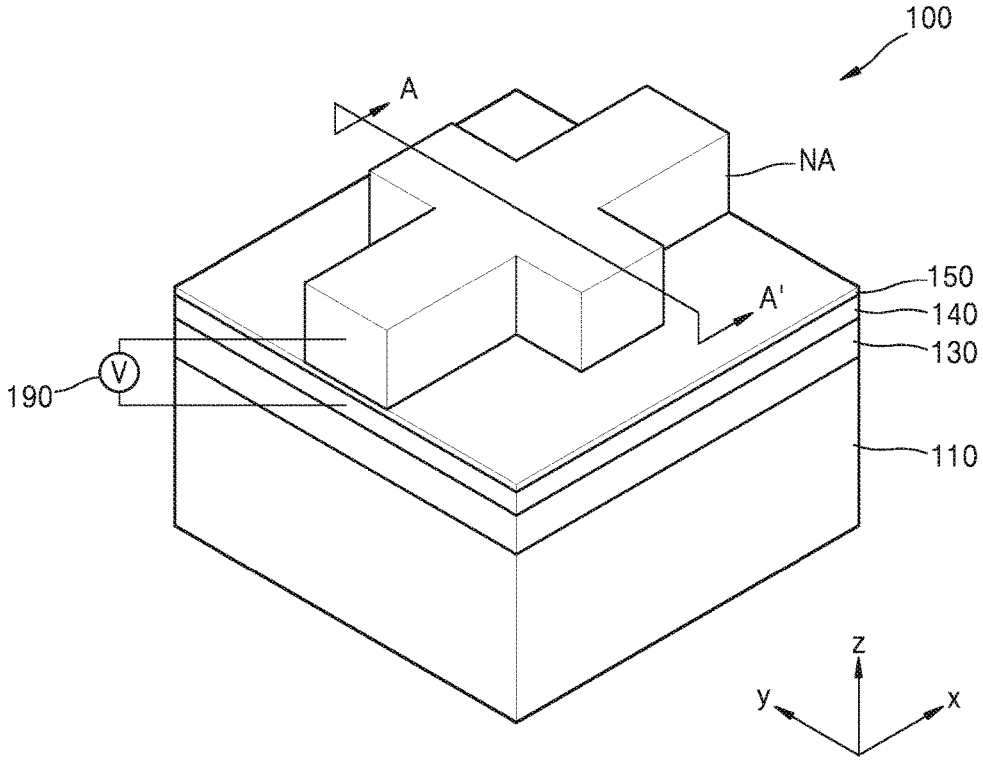


FIG. 2

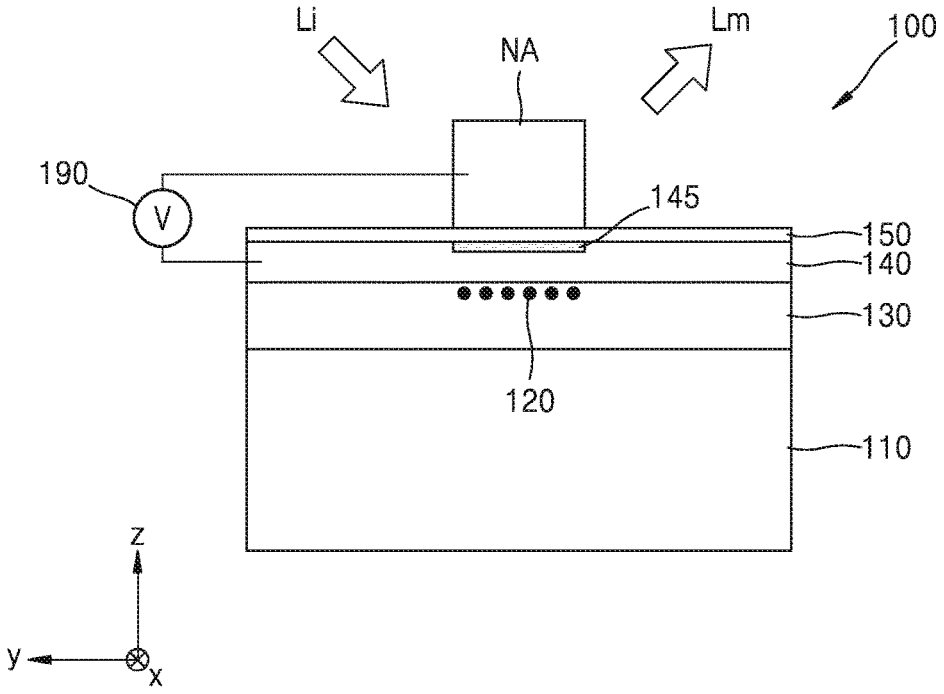

Li
NA
Lm
100
190
V
145
150
140
130
120
110
z
y
x

FIG. 3

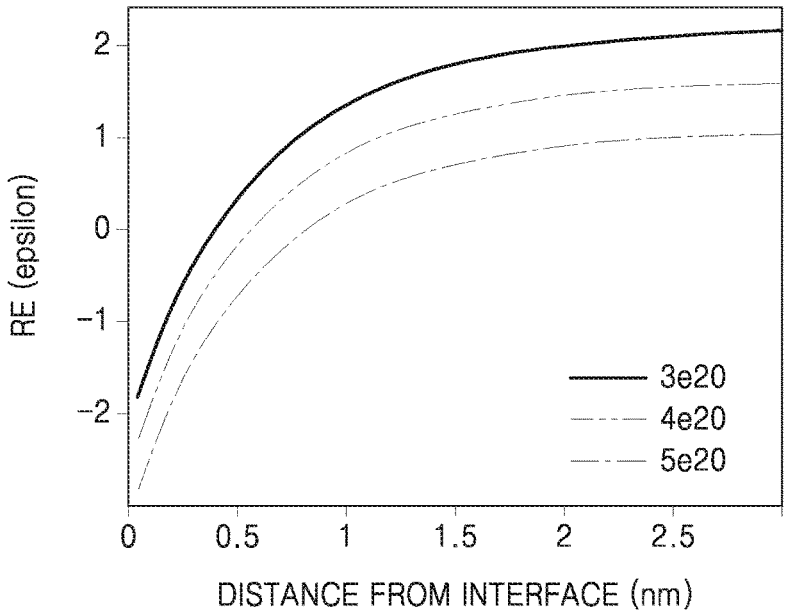

RE (epsilon)
2
1
0
−1
−2
0
0.5
1
1.5
2
2.5
DISTANCE FROM INTERFACE (nm)
3e20
4e20
5e20

FIG. 4

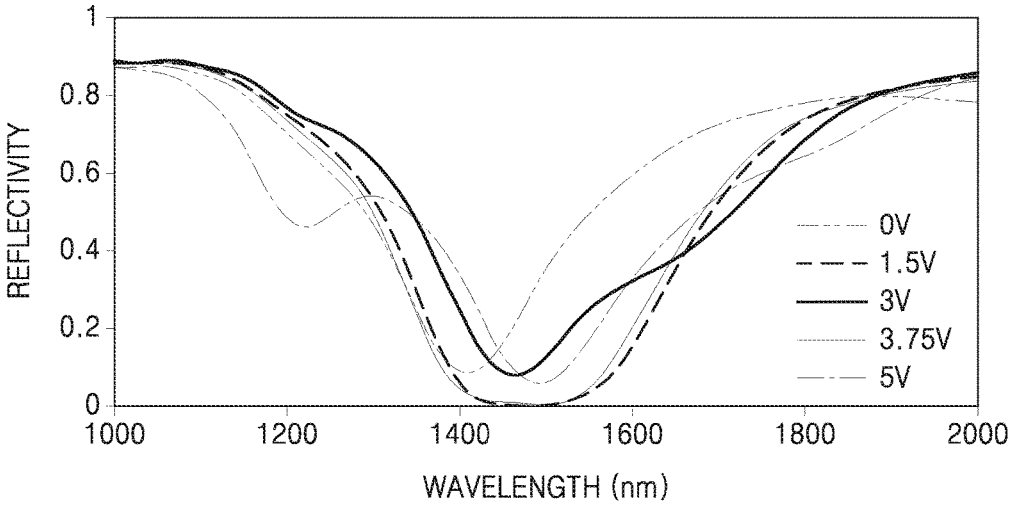

REFLECTIVITY
1
0.8
0.6
0.4
0.2
0
1000
1200
1400
1600
1800
2000
WAVELENGTH (nm)
0V
1.5V
3V
3.75V
5V

FIG. 5

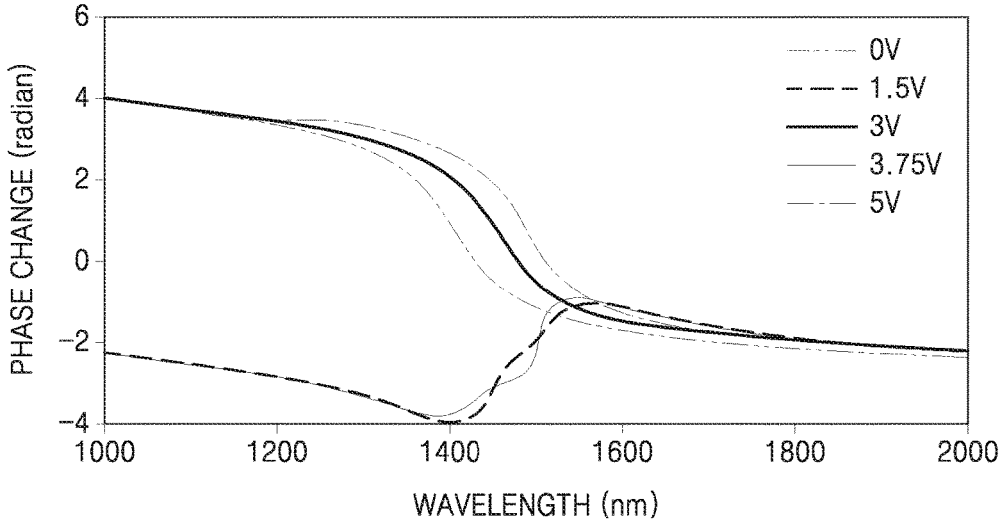

PHASE CHANGE (radian)
6
4
2
0
−2
−4
1000
1200
1400
1600
1800
2000
WAVELENGTH (nm)
0V
1.5V
3V
3.75V
5V

FIG. 6

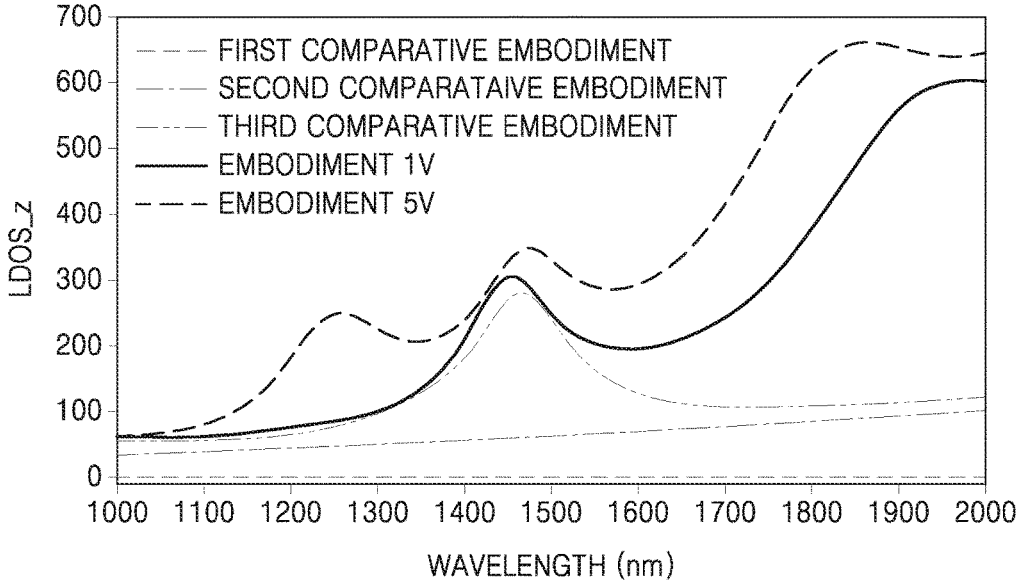

FIRST COMPARATIVE EMBODIMENT
SECOND COMPARATAIVE EMBODIMENT
THIRD COMPARATIVE EMBODIMENT
EMBODIMENT 1V
EMBODIMENT 5V
LDOS_z
WAVELENGTH (nm)
0
100
200
300
400
500
600
700
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000

FIG. 7

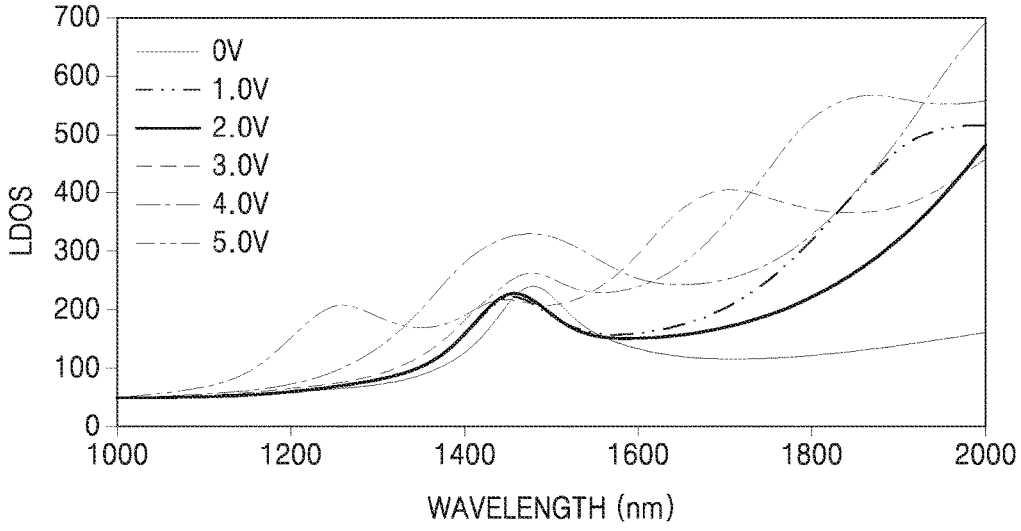

0V
1.0V
2.0V
3.0V
4.0V
5.0V
LDOS
WAVELENGTH (nm)
0
100
200
300
400
500
600
700
1000
1200
1400
1600
1800
2000

FIG. 8

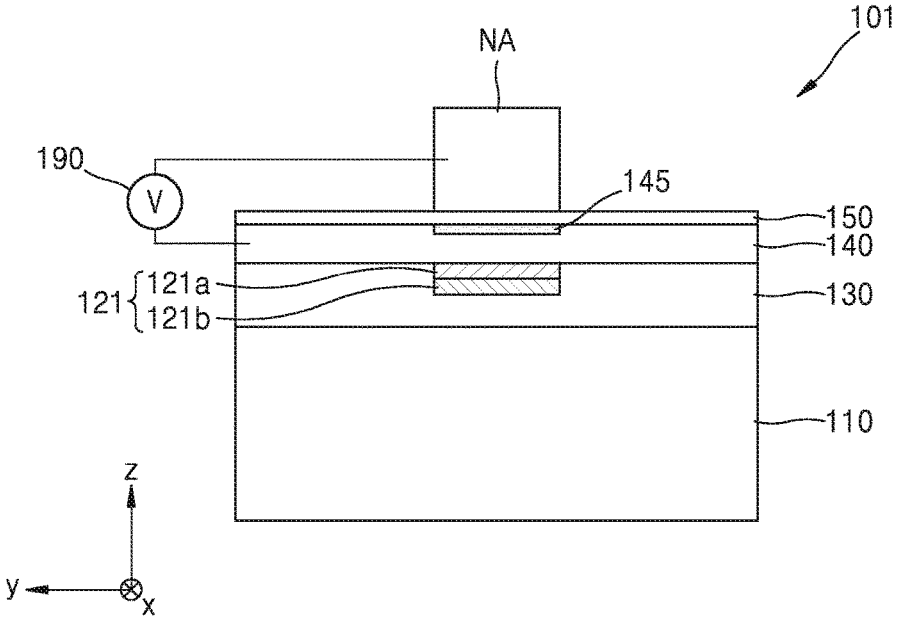

101
NA
190
V
145
150
140
121
121a
121b
130
110
z
y
x

FIG. 9

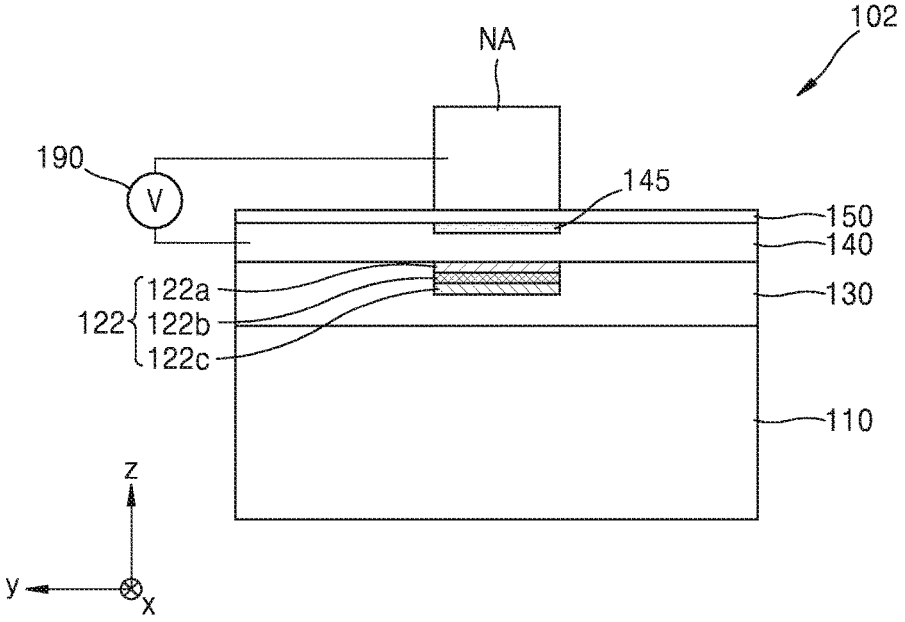

102
NA
190
V
145
150
140
122
122a
122b
122c
130
110
z
y
x

FIG. 10

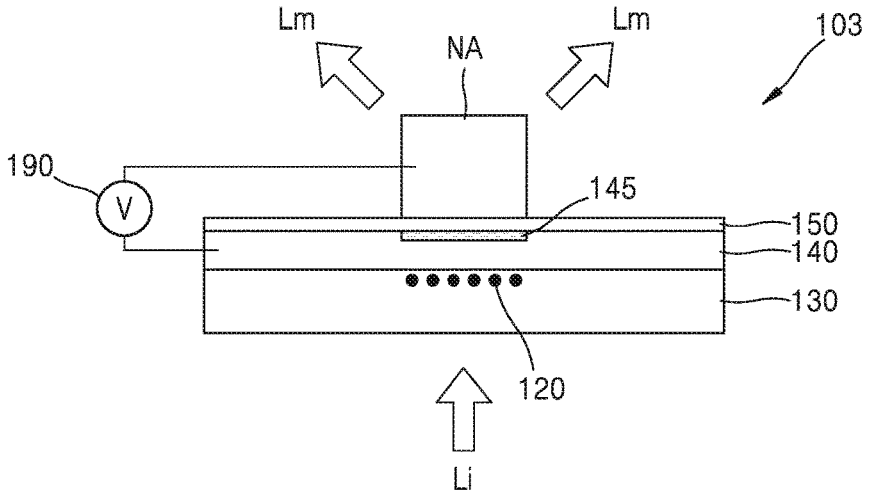

Lm
NA
Lm
103
190
V
145
150
140
130
120
Li

FIG. 11

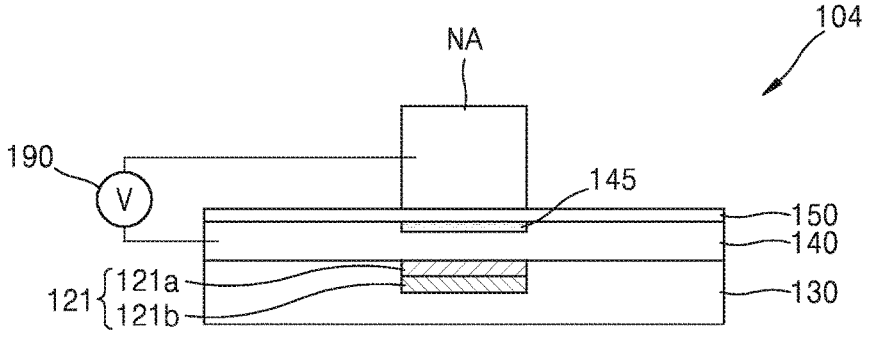

104
NA
190
V
145
150
140
121
121a
121b
130

FIG. 12

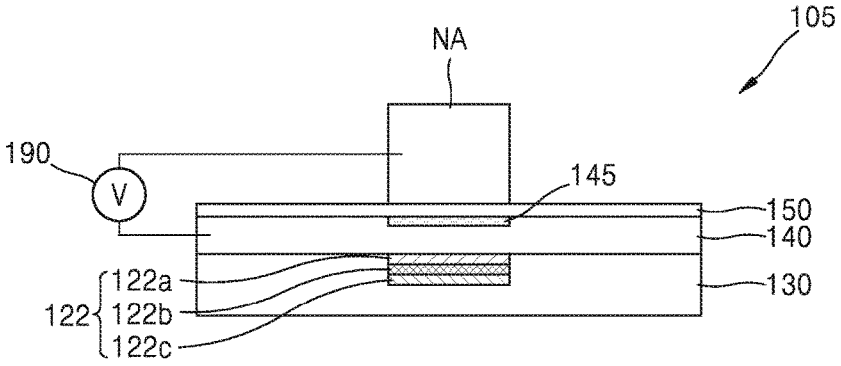

105
NA
190
V
145
150
140
130
122
122a
122b
122c

FIG. 13

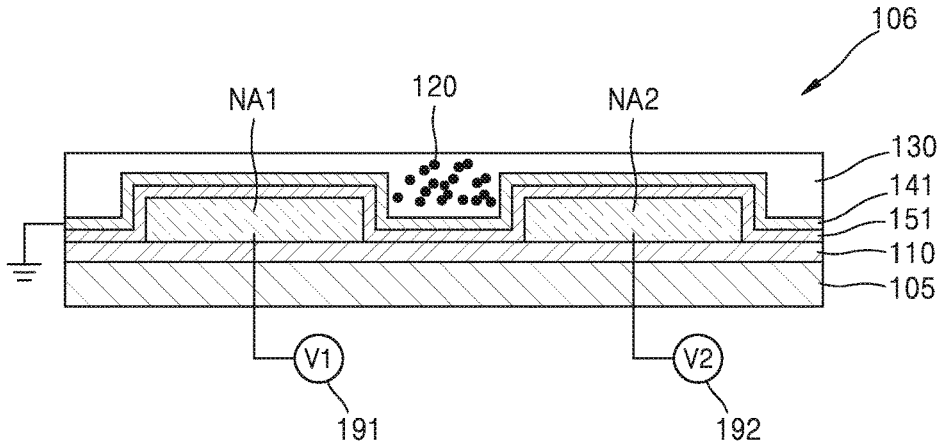

106
NA1
120
NA2
130
141
151
110
105
V1
V2
191
192

FIG. 14

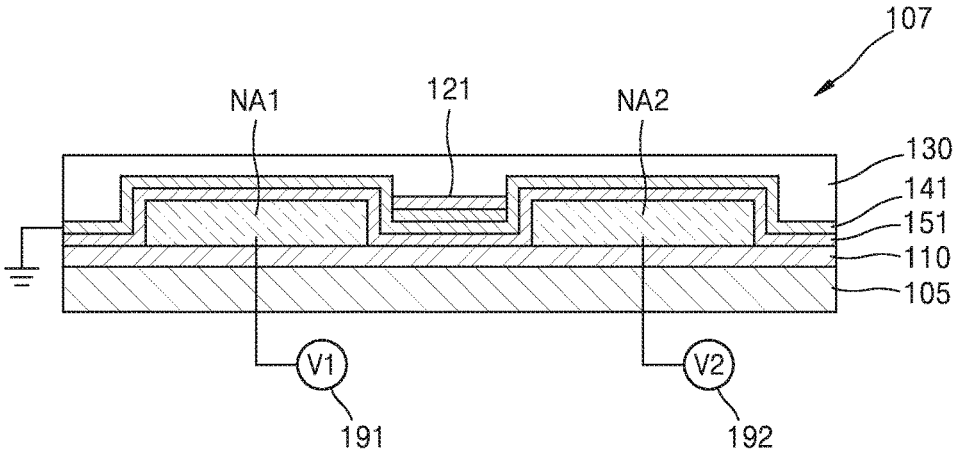

107
NA1
121
NA2
130
141
151
110
105
V1
V2
191
192

FIG. 15

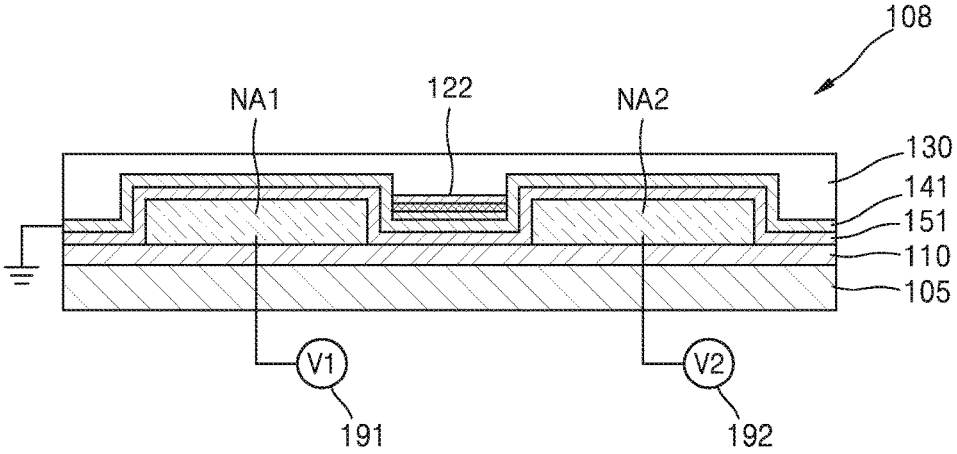
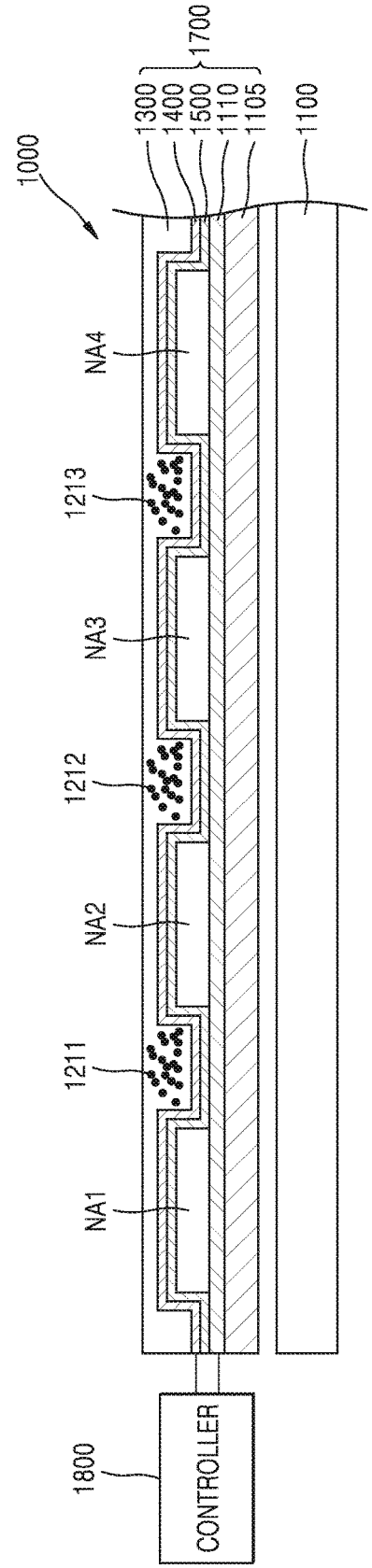

108
NA1
122
NA2
130
141
151
110
105
V1
V2
191
192

FIG. 16


1700
1300
1400
1500
1110
1105
1100
1000
NA4
1213
NA3
1212
NA2
1211
NA1
1800
CONTROLLER

OPTICAL MODULATING DEVICE HAVING GATE STRUCTURE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application No. 62/197,331, filed on Jul. 27, 2015 in the U.S. Patent and Trademark Office, and priority from Korean Patent Application No. 10-2016-0007548, filed on Jan. 21, 2016 in the Korean Intellectual Property Office, the disclosures of which are incorporated herein by reference in their entireties.

BACKGROUND

1. Field

Apparatuses consistent with exemplary embodiments relate to optical devices for modulating light.

2. Description of the Related Art

Optical devices for modulating transmittance/reflection, polarization, phase, intensity, optical path, etc. of incident light are used in various optical apparatuses. Also, optical modulators of various structures are provided to control the properties described above in an optical system in a desired manner.

For example, structures such as liquid crystals having optical anisotropy, a microelectromechanical system (MEMS) using minute mechanical motion of an optical shielding/reflecting element, etc. are widely implemented in general optical modulators. These general optical modulators have a slow operational response rate of several μs, due to characteristics of driving methods thereof.

There have been attempts to implement a nanoantenna using surface plasmon resonance occurring at a boundary between a metal layer and a dielectric layer, in optical devices.

SUMMARY

Exemplary embodiments may address at least the above problems and/or disadvantages and other disadvantages not described above. Also, the exemplary embodiments are not required to overcome the disadvantages described above, and may not overcome any of the problems described above.

Exemplary embodiments provide optical devices for modulating light.

According to an aspect of an exemplary embodiment, there is provided an optical modulating device including a permittivity change layer having a variable permittivity, a dielectric layer disposed on the permittivity change layer, a nanoantenna disposed on the dielectric layer, and a light-emitting structure disposed adjacent to the permittivity change layer.

The light-emitting structure may be configured to emit light having a greater wavelength than light incident on the light-emitting structure in response to the incident light, as an excitation source.

The light-emitting structure may include light-emitting particles.

The optical modulating device may further include an insulating material layer on which the permittivity change layer is disposed, the light-emitting particles being embedded in the insulating material layer.

The light-emitting structure may include a semiconductor quantum well or a semiconductor PN junction.

The optical modulating device may further include a metal layer on which the light-emitting structure, the permittivity change layer, the dielectric layer, and the nanoantenna are sequentially disposed.

The optical modulating device may further include a voltage-applier configured to apply a voltage between the permittivity change layer and the nanoantenna.

The permittivity change layer may include an active area in which a carrier concentration changes based on the applied voltage.

The permittivity change layer may include a transparent conductive oxide.

An optical apparatus may include the optical modulating device.

According to an aspect of another exemplary embodiment, there is provided an optical modulating device including a substrate, nanoantennas disposed on the substrate and spaced apart from one another, a dielectric layer disposed on the nanoantennas, a permittivity change layer disposed on the dielectric layer and having a variable permittivity, and a light-emitting structure disposed on the permittivity change layer and between the nanoantennas.

The light-emitting structure may be configured to emit light having a greater wavelength than light incident on the light-emitting structure in response to the incident light, as an excitation source.

The light-emitting structure may include light-emitting particles.

The optical modulating device may further include an insulating material layer disposed on the permittivity change layer, the light-emitting particles being embedded in the insulating material layer.

The light-emitting structure may include a semiconductor quantum well or a semiconductor PN junction.

The optical modulating device may further include an insulating material layer covering the permittivity change layer and the light-emitting structure.

The optical modulating device may further include voltage-appliers configured to apply respective voltages between the respective nanoantennas and the permittivity change layer.

The permittivity change layer may include a transparent conductive oxide.

An optical apparatus may include the optical modulating device, and a backlight configured to provide light to the optical modulating device.

The optical apparatus may further include a driving circuit disposed on the substrate and configured to control voltages applied to the respective nanoantennas.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and/or other aspects will be more apparent by describing exemplary embodiments with reference to the accompanying drawings, in which:

FIG. **1** is a perspective view of a schematic structure of an optical modulating device according to an exemplary embodiment;

FIG. **2** is a cross-sectional view taken along a line A-A' of the optical modulating device of FIG. **1**;

FIG. **3** is a graph obtained by computer simulation with respect to a change of permittivity in the optical modulating device of FIG. **1**, according to a carrier concentration of a permittivity change layer;

FIG. **4** is a graph obtained by computer simulation with respect to reflectivity in the optical modulating device of

FIG. **1**, according to a voltage applied to a permittivity change layer and wavelengths of incident light;

FIG. **5** is a graph obtained by computer simulation with respect to a phase change in the optical modulating device of FIG. **1**, according to a voltage applied to a permittivity change layer and wavelengths of incident light;

FIG. **6** is a graph obtained by computer simulation with respect to a change of local density of optical states (LDOS) in the optical modulating device of FIG. **1**, according to a voltage applied to a permittivity change layer and wavelengths of incident light, which is shown in comparison with comparative exemplary embodiments;

FIG. **7** is a graph obtained by computer simulation with respect to a change of LDOS in the optical modulating device of FIG. **1**, according to a voltage applied to a permittivity change layer and wavelengths of incident light;

FIG. **8** is a cross-sectional view of a schematic structure of an optical modulating device according to another exemplary embodiment;

FIG. **9** is a cross-sectional view of a schematic structure of an optical modulating device according to another exemplary embodiment;

FIG. **10** is a cross-sectional view of a schematic structure of an optical modulating device according to another exemplary embodiment;

FIG. **11** is a cross-sectional view of a schematic structure of an optical modulating device according to another exemplary embodiment;

FIG. **12** is a cross-sectional view of a schematic structure of an optical modulating device according to another exemplary embodiment;

FIG. **13** is a cross-sectional view of a schematic structure of an optical modulating device according to another exemplary embodiment;

FIG. **14** is a cross-sectional view of a schematic structure of an optical modulating device according to another exemplary embodiment;

FIG. **15** is a cross-sectional view of a schematic structure of an optical modulating device according to another exemplary embodiment; and

FIG. **16** is a cross-sectional view of a schematic structure of an optical apparatus according to an exemplary embodiment.

DETAILED DESCRIPTION

Exemplary embodiments are described in greater detail below with reference to the accompanying drawings.

In the following description, like drawing reference numerals are used for like elements, even in different drawings. The matters defined in the description, such as detailed construction and elements, are provided to assist in a comprehensive understanding of the exemplary embodiments. However, it is apparent that the exemplary embodiments can be practiced without those specifically defined matters. Also, well-known functions or constructions may not be described in detail because they would obscure the description with unnecessary detail.

In addition, the terms such as "unit," "-er (-or)," and "module" described in the specification refer to an element for performing at least one function or operation, and may be implemented in hardware, software, or the combination of hardware and software.

FIG. **1** is a perspective view of a schematic structure of an optical modulating device **100** according to an exemplary embodiment. FIG. **2** is a cross-sectional view taken along a line A-A' of the optical modulating device **100** of FIG. **1**.

Referring to FIGS. **1** and **2**, the optical modulating device **100** includes a permittivity change layer **140** having a variable permittivity, a dielectric layer **150** disposed on the permittivity change layer **140**, a nanoantenna NA disposed on the dielectric layer **150**, and a light-emitting structure **120** disposed adjacent to the permittivity change layer **140**.

The optical modulating device **100** further includes an insulating material layer **130**, and the light-emitting structure **120** is embedded in the insulating material layer **130** and is disposed under the permittivity change layer **140**.

Also, the optical modulating device **100** further includes a metal layer **110** disposed under the permittivity change layer **140**. On the metal layer **110**, the insulating material layer **130** in which the light-emitting structure **120** is embedded, the permittivity change layer **140**, the dielectric layer **150**, and the nanoantenna NA are sequentially disposed.

The permittivity change layer **140** may include a material having an optical property that changes in response to an external signal. The external signal may be an electrical signal. The permittivity change layer **140** may include transparent conductive oxide (TCO), such as indium tin oxide (ITO), indium zinc oxide (IZO), aluminum zinc oxide (AZO), gallium zinc oxide (GZO), aluminum gallium zinc oxide (AGZO), and gallium indium zinc oxide (GIZO). Also, the permittivity change layer **140** may include transition metal nitride, such as TiN, ZrN, HfN, and TaN. In addition, the permittivity change layer **140** may include an electro-optic material, a valid permittivity of which changes when an electrical signal is applied, such as $LiNbO_3$, $LiTaO_3$, potassium tantalate niobate (KTN), and lead zirconate titanate (PZT). Further, the permittivity change layer **140** may include various polymer materials having an electro-optic property.

A voltage applier **190** for applying a voltage between the permittivity change layer **140** and the nanoantenna NA is included in the optical modulating device **100**. Hereinafter, it will be described that the permittivity change layer **140** includes a material, a permittivity of which changes according to an electrical signal. However, the permittivity change layer **140** is not limited thereto. For example, the permittivity change layer **140** may include a material, a permittivity of which changes due to phase transition occurring at a temperature that is equal to or higher than a predetermined temperature when heat is applied thereto. For example, the permittivity change layer **140** may include VO_2, VO_2O_3, EuO, MnO, CoO, CoO_2, $LiCoO_2$, Ca_2RuO_4, or the like.

The nanoantenna NA includes a conductive material, is an artificial structure having a shape with dimension of a sub-wavelength, and intensely gathers light in a predetermined wavelength band. Here, the sub-wavelength denotes a wavelength of a smaller dimension than an operation wavelength of the nanoantenna NA, that is, the predetermined wavelength described above. Any dimension forming a shape of the nanoantenna NA, for example, at least one among a thickness, a width, a height, and a gap between the nanoantennas NAs may correspond to the dimension of the sub-wavelength.

The above-described function of the nanoantenna NA is known to be possible by surface plasmon resonance occurring at a boundary between a metal material and a dielectric material, and a resonance wavelength varies depending on a detailed shape of the nanoantenna NA. Hereinafter, the nanoantenna NA, the dielectric layer **150**, and an interface at which surface plasmon resonance occurs will be called a "metasurface."

It is illustrated that a cross-sectional shape of the nanoantenna NA is cross-shaped. However, it is not limited

thereto. For example, the cross-sectional shape of the nanoantenna NA may be circle-shaped, star-shaped, or polygon-shaped.

The conductive material included in the nanoantenna NA may include a metal material having high conductivity, at which surface plasmon excitation may occur. For example, the conductive material may include at least one selected from Cu, Al, Ni, Fe, Co, Zn, Ti, Ru, Rh, Pd, Pt, Ag, Os, Ir, Pt, and Au, or may include an alloy including any one among Cu, Al, Ni, Fe, Co, Zn, Ti, Ru, Rh, Pd, Pt, Ag, Os, Ir, Pt, and Au. Also, the conductive material may include a two-dimensional material having high conductivity, such as graphene, or conductive oxide.

The dielectric layer **150** may include a material, such as Al_2O_3, HfO_2, MgO, or SiO_2.

The light-emitting structure **120** may include various materials having photoluminescence. For example, the light-emitting structure **120** may include, as light-emitting particles, any one among rare earth ions, quantum dots, plasmonic nanoparticles, dielectric nanoparticles, and semiconductor nanoparticles. For example, the light-emitting particles may include any one among Si-based nanocrystals, groups II-VI based compound semiconductor nanocrystals, groups III-V based compound semiconductor nanocrystals, groups IV-VI based compound semiconductor nanocrystals, and a mixture thereof. The groups II-VI based compound semiconductor nanocrystals may include any one selected from the group consisting of CdS, CdSe, CdTe, ZnS, ZnSe, ZnTe, HgS, HgSe, HgTe, CdSeS, CdSeTe, CdSTe, ZnSeS, ZnSeTe, ZnSTe, HgSeS, HgSeTe, HgSTe, CdZnS, CdZnSe, CdZnTe, CdHgS, CdHgSe, CdHgTe, HgZnS, HgZnSe, HggZnTe, CdZnSeS, CdZnSeTe, CdZnSTe, CdHgSeS, CdHgSeTe, CdHgSTe, HgZnSeS, HgZnSeTe, and HgZnSTe. The groups III-V based compound semiconductor nanocrystals may include any one selected from the group consisting of GaN, GaP, GaAs, AlN, AlP, AlAs, InN, InP, InAs, GaNP, GaNAs, GaPAs, AlNP, AlNAs, AlPAs, InNP, InNAs, InPAs, GaAlNP, GaAlNAs, GaAlPAs, GaInNP, GaInNAs, GaInPAs, InAlNP, InAlNAs, and InAlPAs. The groups IV-VI based compound semiconductor nanocrystals may include SbTe.

FIG. **2** illustrates the light-emitting structure **120** as the light-emitting particles. However, the light-emitting structure **120** is not limited thereto, and may include a PN junction structure or a quantum well structure.

The metal layer **110** may function as a mirror layer for reflecting light. According to the provision of the metal layer **110**, directions of incident light (Li), and modulated light (Lm) are formed, as illustrated in FIG. **2**. The metal layer **110** may include various metal materials capable of performing this function. For example, the metal layer **110** may include at least one selected from Cu, Al, Ni, Fe, Co, Zn, Ti, Ru, Rh, Pd, Pt, Ag, Os, Ir, Pt, and Au.

When the metal layer **110** is provided, a voltage may be applied between the nanoantenna NA and the metal layer **110**, according to necessity.

Referring to FIG. **2**, the permittivity change layer **140** includes an active area **145**, in which a carrier concentration changes according to whether or not a voltage is applied between the permittivity change layer **140** and the nanoantenna NA. The active area **145** is formed in the permittivity change layer **140** to be adjacent to the dielectric layer **150**, and has the carrier concentration that changes according to the applied voltage. According to the carrier concentration formed in the active area **145**, a shape of modulation of light that is incident in the light modulating device **100** may be adjusted. In this respect, the active area **145** may be understood as a gate adjusting and controlling the optical modulation performance of the nanoantenna NA.

A permittivity of the permittivity change layer **140** varies according to a wavelength. Relative permittivity ($\in_r$) to vacuum permittivity ($\in_0$) is called a dielectric constant, and the real part of the dielectric constant of the permittivity change layer **140** is 0 in a wavelength band.

A wavelength band in which the real part of the dielectric constant has a value that is 0 or very adjacent to 0 is called an epsilon near zero (ENZ) wavelength band. A dielectric constant of most of materials is represented as a function of a wavelength, and may be represented as a complex number. A vacuum dielectric constant is 1, and in the case of a general dielectric material, the real part of the dielectric constant is a positive number that is greater than 1. In the case of a metal, the real part of the dielectric constant may be a negative number. In most wavelength bands, the dielectric constant of most of materials has a value that is greater than 1, while in a wavelength band, the real part of the dielectric constant may have a value that is 0.

When the real part of the dielectric constant has a value that is 0 or is very adjacent to 0, it is known that an optical property appears, and the optical modulating device **100** according to an exemplary embodiment may set an operational wavelength band as an area including the ENZ wavelength band of the permittivity change layer **140**. That is, by setting a resonance wavelength band of the nanoantenna NA similar to the ENZ wavelength band of the permittivity change layer **140**, a range within which the optical modulation performance may be adjusted by an applied voltage may be increased.

The ENZ wavelength band of the permittivity change layer **140** varies according to a carrier concentration formed in the active area **145**. To utilize the ENZ wavelength band of the permittivity change layer **140**, a range of a voltage in which the voltage applier **190** applies between the permittivity change layer **140** and the nanoatenna NA may include a voltage value with which a resonance wavelength of a plasmonic nanoantenna layer **170** is consistent with a wavelength in which the permittivity change layer **140** has an ENZ property.

The light-emitting structure **120** may emit, as an excitation source, light having a greater wavelength than incident light, by being excited by the incident light. A dipole emitter formed in the light-emitting structure **120** by excitation light is coupled to a gap plasmon mode in a resonance wavelength band of the metasurface. That is, electromagnetic energy radiated by the dipole emitter is transmitted to a far-field via a resonance mode of the nanoantenna NA, and radiation power is related to local density of optical states (LDOS). The LDOS is related to a decay rate of the dipole emitter, and may be represented as the number of photons emitted per unit time. As the LDOS increases, the radiation power increases. The LDOS may be controlled by a change of permittivity of the permittivity change layer **140**. A complex refractivity change locally occurring in the permittivity change layer **140** contributes to control of the LDOS. That is, it is analyzed that a degree of the coupling of the dipole emitter and the plasmon may be adjusted depending on a degree of accumulation or depletion of charges in the active area **145** formed in the permittivity change layer **140**. The coupling efficiency may be adjusted according to an applied voltage. Also, via this, a relative coupling efficiency of the dipole emitter and the nanoantenna NA may be adjusted. Also, when the nanoantenna NA has directivity, light may be adjusted to be emitted in a desired direction.

As described above, the incident light (Li) to the optical modulating device **100** is emitted as modulated light (Lm), and a wavelength, an intensity, a phase, a direction, etc. of the modulated light (Lm) may be adjusted according to the described elements.

FIG. **3** is a graph obtained by computer simulation with respect to a change of permittivity according to a carrier concentration of the permittivity change layer **140**, in the optical modulating device **100** of FIG. **1**.

In the graph, a horizontal axis indicates a location in the permittivity change layer **140** as a distance from a boundary surface between the permittivity change layer **140** and the dielectric layer **150**. A vertical axis indicates a value of a real number of a permittivity RE.

A unit of the carrier concentration is cm^{-3}, and the graph shows a change in the real part of the permittivity based on three types of carrier concentrations.

FIG. **4** is a graph obtained by computer simulation with respect to reflectivity according to a voltage applied to the permittivity change layer **140** and wavelengths of incident light, in the optical modulating device **100** of FIG. **1**.

A wavelength band in which the reflectivity becomes the smallest is a resonance wavelength band, and it is shown that the reflectivity changes and the resonance wavelength band is adjusted, according to the applied voltage.

FIG. **5** is a graph obtained by computer simulation with respect to a phase change in the optical modulating device **100** of FIG. **1**, according to a voltage applied to the permittivity change layer **140** and wavelengths of incident light

It is shown in the graph that the phase change is adjusted according to adjustment of the applied voltage, and the phase change within a range that is proximate to about 2π is possible.

FIG. **6** is a graph obtained by computer simulation respect to a change of LDOS according to a voltage applied to the permittivity change layer **140** and wavelengths of incident light, in the optical modulating device **100** of FIG. **1**, shown in comparison with comparative exemplary embodiments.

In the graph, an exemplary embodiment 1V is the case in which the applied voltage is 1V, an exemplary embodiment 5V is the case in which the applied voltage is 5V. A first comparative exemplary embodiment has a structure, in which only the nanoantenna NA and the light-emitting structure **120** are provided in the optical modulating device **100** of FIG. **1**, a second comparative exemplary embodiment includes only a lower metal layer **11** and the light-emitting structure **120** in the optical modulating device **100**, and a third comparative exemplary embodiment has a structure in which the permittivity change layer **140** is not provided in the optical modulating device **100**.

In the graph, a vertical axis indicates an LDOS, a subscript z denotes that a dipole direction is computer simulated as a z direction.

Referring to the graph, it is shown that a resonance wavelength band is formed and a level of the LDOS increases, when a metasurface structure is provided. It is also shown that the LDOS may be changed according to adjustment of a complex refractivity by the applied voltage, in exemplary embodiments in which the permittivity change layer **140** is provided.

FIG. **7** is a graph obtained by computer simulation with respect to a change of LDOS according to a voltage applied to the permittivity change layer **140** and wavelengths of incident light, in the optical modulating device **100** of FIG. **1**.

The graph shows that the LDOS may be adjusted by varying the voltage applied to the permittivity change layer **140**.

FIG. **8** is a cross-sectional view of a schematic structure of an optical modulating device **101** according to another exemplary embodiment.

The optical modulating device **101** differs from the optical modulating device **100** of FIG. **1** in that the optical modulating device **101** implements a PN junction structure as a light-emitting structure **121**.

The optical modulating device **101** includes the metal layer **110**, the insulating material layer **130** in which the light-emitting structure **121** is included, the permittivity change layer **140** in which the active area **145** is included, the dielectric layer **150**, and the nanoantenna NA.

The light-emitting structure **121** includes the semiconductor PN junction structure in which a p-type semiconductor layer **121***a* and an n-type semiconductor layer **121***b* are adjoined to each other. An emitter is formed when electrons and holes are combined at an interface of the PN junction by incident optical energy. Coupling of the emitter and a surface plasmon is controlled by a change of complex permittivity of the permittivity change layer **140** and an LDOS is adjusted.

FIG. **9** is a cross-sectional view of a schematic structure of an optical modulating device **102** according to another exemplary embodiment.

The optical modulating device **102** differs from the optical modulating device **100** of FIG. **1** in that the optical modulating device **102** implements a semiconductor quantum well structure as a light-emitting structure **122**.

The optical modulating device **102** includes the metal layer **110**, the insulating material layer **130** in which the light-emitting structure **122** is included, the permittivity change layer **140** in which the active area **145** is included, the dielectric layer **150**, and the nanoantenna NA.

The light-emitting structure **122** may include a plurality of semiconductor layers having different thicknesses and compositions. For example, the light-emitting structure **122** includes a structure in which a well layer **122***b* is interposed between two barrier layers **122***a* and **122***c*. In FIG. **9**, it is illustrated as a single quantum well (SOW) structure in which the well layer **122***b* is interposed between the two barrier layers **122***a* and **122***c*. However, it is only exemplary, and the light-emitting structure **122** is not limited thereto. The light-emitting structure **122** may include a multi-quantum well (MOW) structure in which barrier layers and well layers are repeatedly stacked. The well layer **122***b*, and the barrier layers **122***a* and **122***c* may include group III nitride semiconductor materials. For example, the barrier layers **122***a* and **122***c* may include InGaN or GaN, and the well layer **122***b* may include InGaN. However, it is not limited thereto. The well layer **122***b* includes a material having a less energy band gap than a material of the barrier layers **122***a* and **122***c*. The barrier layers **122***a* and **122***c* may be doped with an n-type or p-type material, and it is also possible that both of the well layer **122***b* and the barrier layers **122***a* and **122***c* are doped.

Electrons and holes are generated when incident optical energy is absorbed in the barrier layers **122***a* and **122***c*. The generated electrons and holes move to the well layer **122***b*, are confined in the well layer **122***b* and combined with each other. The combination of the electrons and holes occurring in the well layer **122***b* serves a as an emitter. Coupling of the emitter and a surface plasmon is controlled by a change of complex permittivity of the permittivity change layer **140** and an LDOS is adjusted. When the LDOS increases, an

amount of light emission increases, and when the LDOS decreases, an amount of light emission decreases.

FIG. **10** is a cross-sectional view of a schematic structure of an optical modulating device **103** according to another exemplary embodiment.

The optical modulating device **103** has a transmittance-type structure. That is, incident light (Li) is transmitted through the optical modulating device **103** and is emitted as modulated light (Lm).

The optical modulating device **103** includes the insulating material layer **130** in which the light-emitting structure **120** is embedded, the permittivity change layer **140** in which the active area **145** is included, the dielectric layer **150**, and the nanoantenna NA. The optical modulating device **103** differs from the optical modulating device **100** of FIG. **1** in that optical modulating device **103** does not include the metal layer **110** of FIG. **1**.

FIG. **11** is a cross-sectional view of a schematic structure of an optical modulating device **104** according to another exemplary embodiment.

The optical modulating device **104** is also the transmittance type as the optical modulating device **103** of FIG. **10**. However, the optical modulating device **104** differs from the optical modulating device **103** of FIG. **10** in that the optical modulating device **104** implements a semiconductor PN junction structure as the light-emitting structure **121**.

FIG. **12** is a cross-sectional view of a schematic structure of an optical modulating device **105** according to another exemplary embodiment.

The optical modulating device **105** is also the transmittance type as the optical modulating device **103** of FIG. **10**. However, the optical modulating device **105** differs from the optical modulating device **103** of FIG. **10** in that the optical modulating device **105** implements a semiconductor quantum well structure as the light-emitting structure **122**.

FIG. **13** is a cross-sectional view of a schematic structure of an optical modulating device **106** according to another exemplary embodiment.

The optical modulating device **106** includes a substrate **105**, a plurality of nanoantennas NA**1** and NA**2** disposed on the substrate **105** to be adjacent to one another, a dielectric layer **151** disposed on the plurality of nanoantennas NA**1** and NA**2**, a permittivity change layer **141** disposed on a dielectric layer **151** and having a variable permittivity, and the light-emitting structure **120** disposed on the permittivity change layer **141** between the plurality of nanoantennas NA**1** and NA**2**.

The light-emitting structure **120** may include light-emitting particles and is embedded in the insulating material layer **130** on the permittivity change layer **140**, as illustrated in FIG. **13**.

The optical modulating device **106** further includes voltage appliers **191** and **192** for separately applying voltages between each of the plurality of nanoantennas NA**1** and NA**2**, and the permittivity change layer **141**. For example, the permittivity change layer **141** may be applied with a ground voltage, and a different voltage may be applied to each of the plurality of nanoantennas NA**1** and NA**2**.

The light-emitting structure **120** disposed between the plurality of nanoantennas NA**1** and NA**2** may be coupled to a surface plasmon, in a respectively different coupling strength, based on the adjacent nanoantennas NA**1** and NA**2**. An LDOS in the location of the light-emitting structure **120** may be determined by the combination of the coupling state.

FIG. **14** is a cross-sectional view of a schematic structure of an optical modulating device **107** according to another exemplary embodiment.

The optical modulating device **107** differs from the optical modulating device **106** of FIG. **13** in that the optical modulating device **107** implements a PN junction structure as the light-emitting structure **121**.

FIG. **15** is a cross-sectional view of a schematic structure of an optical modulating device **108** according to another exemplary embodiment.

The optical modulating device **108** differs from the optical modulating device **106** of FIG. **13** in that the optical modulating device **108** a semiconductor quantum well structure as the light-emitting structure **122**.

FIG. **16** is a cross-sectional view of a schematic structure of an optical apparatus **1000** according to an exemplary embodiment.

The optical apparatus **1000** includes a backlight **1100** and an optical modulating device **1700**.

The optical modulating device **1700** includes a plurality of nanoantennas NA**1**, NA**2**, NA**3**, and NA**4** disposed on a substrate **1105** to be apart from one another. The substrate **1105** may be a transparent substrate. Alternatively, the substrate **1105** may at least have a transparent characteristic with respect to light of a wavelength band provided by the backlight **1100**.

A dielectric layer **1500** and a permittivity change layer **1400** are disposed on the plurality of nanoantennas NA**1**, NA**2**, NA**3**, and NA**4**. The dielectric layer **1500** and the permittivity change layer **1400** are formed along surfaces of the plurality of nanoantennas NA**1**, NA**2**, NA**3**, and NA**4**, and grooved areas may be formed between the plurality of nanoantennas NA**1**, NA**2**, NA**3**, and NA**4**. Light-emitting structures **1211**, **1212**, and **1213** are disposed in these grooved areas. The optical modulating device **1700** further includes an insulating material layer **1300** covering the dielectric change layer **1400**, and the light-emitting structures **1211**, **1212**, and **1213** are embedded in the insulating material layer **1300**. A driving circuit **1110** for controlling voltages applied to the plurality of nanoantennas NA**1**, NA**2**, NA**3**, and NA**4**, respectively, is further disposed on the substrate **1105**.

The backlight **1100** provides light that is to be modulated in the optical modulating device **1700**. The light provided by the backlight **1100** may supply optical energy to the light-emitting structures **1211**, **1212**, and **1213** provided in the optical modulating device **1700**, and may generate an emitter. The backlight **1100** may provide ultraviolet light (UV) or light of a blue color. A light-emitting wavelength in the light-emitting structures **1211**, **1212**, and **1213** is greater than a wavelength of the light provided by the backlight **1100**. Light-emitting power of the emitter generated in each of the light-emitting structures **1211**, **1212**, and **1213** is determined by an LDOS formed according to a change of permittivity of the permittivity change layer **1400** of the optical modulating device **1700**. The change of permittivity may be controlled by an applied voltage.

The optical apparatus **1000** further includes a controller **1800** to separately control voltages applied between each of the plurality of nanoantennas NA**1**, NA**2**, NA**3**, and NA**4** and the permittivity change layer **1400**. Accordingly, the light-emitting structure **1211** between the nanoantennas NA**1** and NA**2**, the light-emitting structure **1212** between the nanoantennas NA**2** and NA**3**, and the light-emitting structure **1213** between the nanoantennas NA**3** and NA**4** may indicate different LDOSs and may serve as separate pixels that are separately controlled.

The optical apparatus **1000** may serve as a display apparatus. To this end, sizes and materials of light-emitting particles of the light-emitting structures **1211**, **1212**, and

1213 may be adjusted such that the light-emitting structures 1211, 1212, and 1213 emit light of different wavelengths. Depending on image information that is to be formed, the controller 1800 may control the voltages between each of the plurality of nanoantennas NA1, NA2, NA3, and NA4 and the permittivity change layer 1400 to control on/off of each of pixels to display the image. The image formed as such may have high color purity, and thus, may represent improved color gamut and high contrast.

The optical apparatus 1000 may be used not only as the display apparatus but also as other apparatuses. For example, the optical apparatus 1000 may be used as a beam deflector or a beam shaper by forming the plurality of nanoantennas NA1, NA2, NA3, and NA4 as shapes having different directionalities, or giving rules to voltages applied thereto.

The light-emitting structures 1211, 1212, and 1213 are illustrated as light-emitting particles. However, the light-emitting structures 1211, 1212, and 1213 are not limited thereto. The semiconductor PN junction structure or the semiconductor quantum well structure illustrated in FIGS. 14 and 15, respectively, may be implemented as the light-emitting structures 1211, 1212, and 1213. In addition, various materials and structures having photoluminescence may be used as the light-emitting structures 1211, 1212, and 1213.

It is illustrated that the optical modulating device 1700 of the optical apparatus 1000 is realized by arraying the structure of FIG. 13. However, it is not limited thereto. For example, the optical modulating device 1700 may be realized by repeatedly arraying the structure of FIG. 1. In this case, the shape of the backlight 1100 may be changed to be more appropriate for providing light to the light-emitting structures 1211, 1212, and 1213.

The optical modulating devices 100 through 108 and 1700 described above include a nanoantenna NA, a permittivity change layer, and a light-emitting structure, and may modulate incident light as various shapes by using an area in the permittivity change layer, in which a carrier concentration changes, as a gate.

Also, energy of the incident light is absorbed in the light-emitting structure of the optical modulating device so that light of different wavelengths may be emitted, and light-emitting energy may be controlled by adjusting a permittivity of the permittivity change layer.

The optical modulating devices 100 through 108 and 1700 may be miniaturized and high speed driving may be possible, and thus, the optical modulating devices 100 through 108 and 1700 may be applied to various optical apparatuses to improve the performance of the optical apparatuses.

The optical modulating devices 100 through 108 and 1700 may realize a display apparatus, together with a backlight, and may provide an image having miniaturized pixels and improved contrast.

The foregoing exemplary embodiments are examples and are not to be construed as limiting. The present teaching can be readily applied to other types of apparatuses. Also, the description of the exemplary embodiments is intended to be illustrative, and not to limit the scope of the claims, and many alternatives, modifications, and variations will be apparent to those skilled in the art.

What is claimed is:

1. An optical modulating device comprising:
- a permittivity change layer having a variable permittivity;
- a dielectric layer disposed on the permittivity change layer;
- a nanoantenna disposed on the dielectric layer; and
- a light-emitting structure disposed adjacent to the permittivity change layer, and configured to emit light having a greater wavelength than light incident on the light-emitting structure in response to the incident light, as an excitation source.

2. The optical modulating device of claim 1, wherein the light-emitting structure comprises light-emitting particles.

3. The optical modulating device of claim 2, further comprising an insulating material layer on which the permittivity change layer is disposed, the light-emitting particles being embedded in the insulating material layer.

4. The optical modulating device of claim 1, wherein the light-emitting structure comprises a semiconductor quantum well or a semiconductor PN junction.

5. The optical modulating device of claim 1, further comprising a metal layer on which the light-emitting structure, the permittivity change layer, the dielectric layer, and the nanoantenna are sequentially disposed.

6. The optical modulating device of claim 1, wherein the permittivity change layer comprises a transparent conductive oxide.

7. An optical apparatus comprising the optical modulating device of claim 1.

8. An optical modulating device comprising:
- a permittivity change layer having a variable permittivity;
- a dielectric layer disposed on the permittivity change layer;
- a nanoantenna disposed on the dielectric layer;
- a light-emitting structure disposed adjacent to the permittivity change layer; and
- a voltage-applier configured to apply a voltage between the permittivity change layer and the nanoantenna.

9. The optical modulating device of claim 8, wherein the permittivity change layer comprises an active area in which a carrier concentration changes based on the applied voltage.

10. An optical modulating device comprising:
- a substrate;
- nanoantennas disposed on the substrate and spaced apart from one another;
- a dielectric layer disposed on the nanoantennas;
- a permittivity change layer disposed on the dielectric layer and having a variable permittivity; and
- a light-emitting structure disposed on the permittivity change layer and between the nanoantennas.

11. The optical modulating device of claim 10, wherein the light-emitting structure is configured to emit light having a greater wavelength than light incident on the light-emitting structure in response to the incident light, as an excitation source.

12. The optical modulating device of claim 10, wherein the light-emitting structure comprises light-emitting particles.

13. The optical modulating device of claim 12, further comprising an insulating material layer disposed on the permittivity change layer, the light-emitting particles being embedded in the insulating material layer.

14. The optical modulating device of claim 10, wherein the light-emitting structure comprises a semiconductor quantum well or a semiconductor PN junction.

15. The optical modulating device of claim 10, further comprising an insulating material layer covering the permittivity change layer and the light-emitting structure.

16. The optical modulating device of claim 10, further comprising voltage-appliers configured to apply respective voltages between the respective nanoantennas and the permittivity change layer.

17. The optical modulating device of claim 10, wherein the permittivity change layer comprises a transparent conductive oxide.

18. An optical apparatus comprising:

the optical modulating device of claim 10; and

a backlight configured to provide light to the optical modulating device.

19. The optical apparatus of claim 18, further comprising a driving circuit disposed on the substrate and configured to control voltages applied to the respective nanoantennas.

20. An optical modulating device comprising:

a permittivity change layer having a variable permittivity;

a dielectric layer disposed on the permittivity change layer;

a light-emitting structure disposed adjacent to the permittivity change layer; and

a nanoantenna disposed on the dielectric layer, the nanoantenna comprising a conductive material and having a shape with a dimension of a sub-wavelength.

21. An optical modulating device comprising:

a permittivity change layer having a variable permittivity, the variable permittivity changing according to an electrical signal;

a dielectric layer disposed on the permittivity change layer;

a nanoantenna disposed on the dielectric layer; and

a light-emitting structure disposed adjacent to the permittivity change layer.

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