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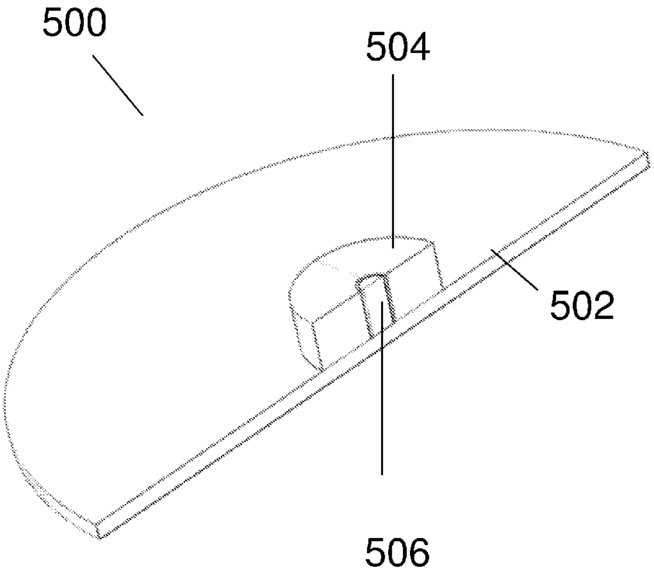
(54) **Title:** ANTENNA, ANTENNA ARRAY, AND METHODS OF FORMING THE SAME

FIG. 5A



(57) **Abstract:** Various embodiments may provide an antenna. The antenna may include a metal substrate having a surface. The antenna may also include a ring on the surface of the metal substrate, the ring including a dielectric or a semiconductor. An inner surface of the ring and a portion of the surface within the ring may define a cavity. The antenna may further include one or more emitters arranged within the cavity, the one or more emitters configured to generate electromagnetic emission upon incidence of incoming electromagnetic waves onto the antenna. The antenna may be configured to resonant at the wavelength of the incoming electromagnetic waves and the wavelength of the electromagnetic emission. The metal substrate may be configured to reflect the electromagnetic emission to direct the electromagnetic emission. The metal substrate may be further configured to generate surface plasmons based on the electromagnetic emission to enhance the electromagnetic emission.

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ANTENNA, ANTENNA ARRAY, AND METHODS OF FORMING THE SAME

TECHNICAL FIELD

[0001] Various aspects of this disclosure relate to an antenna. Various aspects of this disclosure relate to an antenna array. Various aspects of this disclosure relate to a method of forming an antenna. Various aspects of this disclosure relate to a method of forming an antenna array.

BACKGROUND

[0002] Nanoantennas are components that, when coupled to a resonant photon source, may strongly enhance the emission of light from the source into the far field, and conversely, when illuminated by a source of incident light at resonant frequency, may concentrate the field of that light strongly in the near field. The first such devices were implemented in the 1980s in the form of hollow metallic shells for use in near-field optical microscopy. A significant body of work has been built up since then concerning the use of plasmonic structures as nanoantennas. Problems arise, however, due to the presence of non-radiative energy transfers from emitters to surface plasmons in metals, a process known as 'quenching'.

[0003] High-permittivity dielectrics have been proposed as a potential alternative to metals in constructing nanoantennas. By the very nature of dielectric materials, non-radiative energy transfer is greatly suppressed as compared to plasmonic structures. However, as the strength of the field associated with these structures is largely dependent on the refractive index difference between the dielectric and the surrounding medium, the field enhancement produced by such antennas may be considerably weaker than the field produced by plasmonic antennas. This weakness may in turn limit the usefulness of dielectric nanoantennas for applications such as bioassays or deoxyribonucleic acid (DNA) analysis.

SUMMARY

[0004] Various embodiments may provide an antenna. The antenna may include a metal substrate having a surface. The antenna may also include a ring on the surface of the metal substrate, the ring including a dielectric or a semiconductor. An inner surface of the ring and a portion of the surface within the ring may define a cavity. The antenna may further include one or more emitters arranged within the cavity, the one or more emitters configured to generate electromagnetic emission upon incidence of incoming electromagnetic waves onto the antenna. The metal substrate may be configured to reflect the electromagnetic emission to direct the electromagnetic emission. The metal substrate may be further configured to generate surface plasmons based on the electromagnetic emission to enhance the electromagnetic emission.

[0005] Various embodiments may provide a method of forming an antenna. The method may include forming a ring on a surface of a metal substrate, the ring including a dielectric or a semiconductor, an inner surface of the ring and a portion of the surface within the ring defining a cavity. The method may also include arranging one or more emitters within the cavity, the one or more emitters configured to generate electromagnetic emission upon incidence of incoming electromagnetic waves onto the antenna. The metal substrate may be configured to reflect the electromagnetic emission to direct the electromagnetic emission, and may be further configured to generate surface plasmons based on the electromagnetic emission to enhance the electromagnetic emission.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] The invention will be better understood with reference to the detailed description when considered in conjunction with the non-limiting examples and the accompanying drawings, in which:

FIG. 1 is a general illustration of an antenna according to various embodiments.

FIG. 2 is a general illustration of an antenna array according to various embodiments.

FIG. 3 is a general illustration of a method of forming an antenna according to various embodiments.

FIG. 4 is a general illustration of a method of forming an antenna array according to various embodiments.

FIG. 5A shows a cross-sectional perspective view of an antenna according to various embodiments.

FIG. 5B shows a cross-sectional side view of the antenna according to various embodiments.

FIG. 6A is a schematic showing incoming electromagnetic waves, e.g. visible light, incident on the antenna according to various embodiments.

FIG. 6B is a schematic showing electromagnetic emission generated by the one or more emitters under excitation by the resonant electromagnetic field according to various embodiments.

FIG. 6C is a schematic showing the reflection of the electromagnetic emission by the metal substrate according to various embodiments.

FIG. 7A shows a schematic of the modelled antenna according to various embodiments.

FIG. 7B is a plot of emission enhancement as a function of radius (in nanometers or nm) showing the emission enhancement along the normal of the antenna plane for antennas with cylindrical ring resonators of varying radii and a fixed height of 150 nm according to various embodiments.

FIG. 7C is a plot of emission enhancement as a function of height (in nanometers or nm) showing the emission enhancement along the normal of the antenna plane for antennas with cylindrical ring resonators of varying heights and a fixed radius of 250 nm according to various embodiments.

FIG. 7D shows a cross-sectional side view of the resultant nanoantenna according to various embodiments.

FIG. 7E is an emission plot showing the emission profile of emission enhancement of the antenna according to various embodiments.

FIG. 7F is an emission plot showing the emission profile of emission enhancement of the antenna according to various embodiments (cross-sectional schematic shown in bottom left) in comparison with the emission profile of emission enhancement of an antenna including emitters in a silicon (Si) ring in free space (cross-sectional schematic shown in bottom right) as a reference.

FIG. 7G is a plot of emission strength as a function of wavelength (in nanometers or nm) showing the enhancement spectrum of the ring nanoantenna according to various embodiments directly along the normal over a range of wavelengths between 640 nm and 710nm.

FIG. 7H is a plot of field enhancement as a function of wavelength (in nanometers or nm) showing field enhancement of the antenna according to various embodiments may be maximized at 552 nm and 655 nm.

FIG. 7I shows the electric field enhancement inside the cavity of the antenna according to various embodiments at excitation wavelength of 552 nm.

FIG. 7J shows the electric field enhancement inside the cavity of the antenna according to various embodiments at emission wavelength of 655 nm.

FIG. 7K is an emission plot showing the emission profile of fluorescence enhancement of the antenna according to various embodiments.

FIG. 7L is an emission plot showing the emission profile of fluorescence enhancement of the antenna according to various embodiments in comparison with the emission profile of fluorescence enhancement of an antenna including emitters in a silicon (Si) ring in free space as a reference.

FIG. 8 shows a cross-sectional perspective view of an antenna including a metal substrate and an elliptical ring according to various embodiments.

FIG. 9 shows a cross-sectional perspective view of an antenna including a metal substrate and a polygonal ring according to various embodiments.

FIG. 10 shows a top planar view of an antenna array according to various embodiments.

DETAILED DESCRIPTION

[0007] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, and logical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0008] Embodiments described in the context of one of the methods or structures (e.g. antennas or antenna arrays) are analogously valid for the other methods or structures. Similarly, embodiments described in the context of a method are analogously valid for a structure, and vice versa.

[0009] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0010] The word "over" used with regards to a deposited material formed “over” a side or surface, may be used herein to mean that the deposited material may be formed "directly on”, e.g. in direct contact with, the implied side or surface. The word "over" used with regards to a deposited material formed “over” a side or surface, may also be used herein to mean that the deposited material may be formed "indirectly on” the implied side or surface with one or more additional layers being arranged between the implied side or surface and the deposited material. In other words, a first layer “over” a second layer may refer to the first layer directly on the second layer, or that the first layer and the second layer are separated by one or more intervening layers. Further, in the current context, a layer “over” or “on” a side or surface may not necessarily mean that the layer is above a side or surface. A layer “on” a side or surface may mean that the layer is formed in direct contact with the side or surface, and a layer “over” a side or surface may mean that the layer is formed in direct contact with the side or surface or may be separated from the side or surface by one or more intervening layers.

[0011] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0012] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance.

[0013] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0014] Hybrid dielectric-metallic structures have been proposed as a means of overcoming the drawbacks associated with both materials while at the same time making use of their respective advantages, and have been shown to enhance the fluorescence of photon sources stronger than purely dielectric structures and at a comparable level to purely metallic structures, with the potential for improvement to surpass the latter.

[0015] FIG. 1 is a general illustration of an antenna 100 according to various embodiments. The antenna 100 may include a metal substrate 102 having a surface. The antenna 100 may also include a ring 104 on the surface of the metal substrate 102, the ring 104 including a dielectric or a semiconductor. An inner surface of the ring 104 and a portion of the surface within the ring 104 may define a cavity. The antenna 100 may further include one or more emitters 106 arranged within the cavity, the one or more emitters 106 configured to generate electromagnetic emission upon incidence of incoming electromagnetic waves onto the antenna 100. The metal substrate 102 may be configured to reflect the electromagnetic emission to direct the electromagnetic emission. The metal substrate 102 may be further configured to generate surface plasmons based on the electromagnetic emission to enhance the electromagnetic emission.

[0016] In other words, the antenna 100 may include a metal substrate 102 and a ring 104 in contact with the metal substrate 102. The ring 104 may have a hollow core or cavity. The antenna 100 may also include one or more emitters 106 arranged within the hollow core or cavity. The metal substrate 102 may act as a reflector as well as a surface plasmon generator. The metal substrate 102 may together with the ring 104 form a resonant cavity for manipulating the electromagnetic emission of the one or more emitters.

[0017] Various embodiments may relate to a hybrid metal-dielectric antenna 100, e.g. a nanoantenna, including a ring-shaped dielectric or semiconductor structure 104 mounted on a metal surface 102 to form a resonant cavity. By placing light emitters 106 inside the cavity, significant enhancement of the electromagnetic emission may be obtained. The antenna 100 may be used for a range of applications such as single molecule detection, biosensing, food safety, and/or environment monitoring.

[0018] The antenna 100 may be a nanoantenna. Various embodiments may also provide a nanoantenna with both high total emission enhancement and improved directivity of emission in the direction of interest (e.g., perpendicular to the substrate surface).

[0019] Various embodiments may provide strong fluorescence enhancement, while suppressing losses due to surface plasmons. Various embodiments may involve confining the emitters 106 within the mode.

[0020] In various embodiments, the cavity may be a resonant cavity configured to generate a resonant electromagnetic field based on the incoming electromagnetic waves. The one or more emitters may be configured to generate the electromagnetic emission upon excitation by the resonant electromagnetic field.

[0021] In the current context, a ring 104 may be a structure having a hollow core. The ring 104 may include a continuous body of dielectric or semiconductor material defining and surrounding the hollow core. The outer surface of the body of dielectric or semiconductor material may define an outer perimeter or an outer circumference of the ring 104. The inner surface of the body adjoining the hollow core or cavity may define an inner perimeter of an inner circumference of the ring 104. The ring 104 may lie on a plane over a surface of the substrate 102.

[0022] In various embodiments, the ring 104 may be of any suitable shape. In various embodiments, the ring 104 may be circular, polygonal, or elliptical in shape. In other words, the outer circumference of (a cross-section of) the ring 104 may form a circle, a polygon (e.g. a hexagon or a pentagon), or an eclipse. The ring 104 may be a cylinder (with a hollow core extending along a length of the cylinder) with a circular, polygonal, or elliptical cross-section across the width of the cylinder. The ring 104 may alternatively be referred to as a ring resonator. In various embodiments, the ring 104 may have an inner diameter or dimension of about 150 nm or less, e.g. from about 100 nm to about 150 nm, e.g. about 100 nm (radius of about 50 nm). In various embodiments, the ring 104 may have an outer diameter or dimension of 500 nm or more, e.g. about 500 nm (radius of about 250 nm). The diameters or dimensions may pass through a central point of the ring and may extend from one lateral end of the ring 104 to another opposing lateral end. The inner diameter or dimension of the ring 104 may be smaller than a wavelength of the incoming electromagnetic wave or light.

[0023] Various embodiments may involve Mie resonance of the ring 104 hybridized with plasmon resonance of the metal substrate 102.

[0024] In various embodiments, the metal substrate 102 may include or consist of a noble metal. The metal substrate may include or consist of any suitable metal such as gold, silver, or aluminium. By placing a metal substrate 102 under the ring 104, the emission downwards towards the substrate 102 may be reflected, restricting the emission to the upwards direction. Furthermore, by combining the metal substrate 102 with the dielectric antenna structure 104, strong electric fields may be produced while avoiding the dissipative energy loss associated with plasmonic structures, further enhancing the emission produced.

[0025] In various embodiments, the semiconductor may be silicon. However, in various other embodiments, the semiconductor may be any suitable semiconductor such as germanium, silicon germanium, or gallium arsenide.

[0026] In various embodiments, the dielectric may be titanium oxide. However, in various other embodiments, the dielectric may be any suitable dielectric such as silicon oxide or aluminium oxide. In various embodiments, the antenna 100 may be an optical antenna. In various embodiments, the incoming electromagnetic waves may be visible light. In various other embodiments, the incoming electromagnetic waves may be, for instance, infrared radiation or ultraviolet waves.

[0028] In various embodiments, the electromagnetic emission may include photons. The electromagnetic emission may be visible light emission. In various other embodiments, the electromagnetic emission may have wavelengths in the other parts of the electromagnetic spectrum, e.g. infrared radiation or ultraviolet waves.

[0029] The antenna 100 may be dimensioned according to the wavelength(s) of the incoming electromagnetic waves, as well as the desired wavelength(s) of the electromagnetic emission.

[0030] Each of the one or more emitters 106 may be a point emitter. Each of the one or more emitters 106 may be a nanoparticle.

[0031] In various embodiments, the electromagnetic emission may be of or may include a predetermined wavelength. The predetermined wavelength of the electromagnetic emission may be resonant with the cavity. The cavity may be dimensioned so that it is resonant with the predetermined wavelength of the electromagnetic emission. The antenna may be configured to resonant at the wavelength of the incoming electromagnetic waves and the wavelength of the electromagnetic emission.

[0032] The outgoing electromagnetic emission may have a wavelength longer compared to a wavelength of the incoming electromagnetic waves, due to the intrinsic "Stokes shift" of the one or more emitters. When the incoming electromagnetic waves are incident onto the one or more emitters 106, the one or more emitters 106 may absorb a portion of the energy, and emit a remaining portion of the energy as lower energy photons making up the electromagnetic emission. Various embodiments may take into account the intrinsic "Stokes shift" characteristics of the one or more emitters during design of the antenna 100.

[0033] In various embodiments, the metal substrate 102 may be configured to reflect the electromagnetic emission to direct the electromagnetic emission into a single direction, thereby improving a directivity of the electromagnetic emission.

[0034] In the current context, the directivity of the antenna 100 may be a parameter of the antenna which measures the degree to which the electromagnetic emission is concentrated in a single direction, e.g. 90° to the surface of the substrate. When the electromagnetic emission is concentrated in a single direction, a main lobe may be formed centred along the direction.

[0035] In various embodiments, the electromagnetic emission may have a main lobe substantially perpendicular or normal to the surface of the substrate. The main lobe may be centred at about 90° to the surface of the substrate. The main lobe may form a substantial portion of the electromagnetic emission, e.g. more than 60%, more than 70%, more than 80%, or more than 90% of the electromagnetic emission. In addition to the main lobe, the electromagnetic emission may include a plurality of side lobes.

[0036] In various embodiments, the surface plasmons generated may enhance the overall electromagnetic emission. The surface plasmons generated may enhance the overall electromagnetic emission due to the interaction between the generated surface plasmons and the electromagnetic field within the cavity. The interaction between the generated surface plasmons and the electromagnetic field within the cavity may cause greater excitation of the one or more emitters 106, thus enhancing the overall electromagnetic emission. The excitation of the one or more emitters 106 may be due to the formation of a "grating-like" structure on the metal surface.

[0037] In current context, the term "enhance" may mean an increment or an improvement. In various embodiments, the electromagnetic emission of the antenna 100 may be improved compared to the electromagnetic emission of an antenna including a ring but without a metal substrate, or the electromagnetic emission of an antenna without both the ring 104 and the metal substrate 102.

[0038] In various embodiments, an enhancement factor may be calculated as total (integrated) electromagnetic emission emitted by the one or more emitters 106 in the presence of the ring 104 and the metal substrate, divided by the total (integrated) electromagnetic emission emitted by the one or more emitters in the presence of the ring but without the metal substrate, or the total (integrated) electromagnetic emission emitted by the one or more emitters in the absence of both the ring and the metal substrate.

[0039] In various embodiments, the electromagnetic emission may be enhanced along a particular direction, e.g. 90° to the surface of the substrate.

[0040] In various embodiments, the electromagnetic emission at a particular wavelength or range of wavelengths may be enhanced.

[0041] Various embodiments may relate or involve hybridization of modes excited by the ring 104 and modes from the metal substrate 102.

[0042] FIG. 2 is a general illustration of an antenna array 200 according to various embodiments. The antenna array 200 may include a metal substrate 202 having a surface. The antenna array 200 may also include a plurality of rings 204 on the surface of the metal substrate 202 to form a respective antenna of the antenna array 200. Each respective ring of the plurality of rings 204 may include a dielectric or a semiconductor. An inner surface of the respective ring 204 and a portion of the surface within the respective ring 204 may define a respective cavity. The antenna array 200 may also include one or more emitters 206 arranged within the respective cavity, the one or more emitters 206 configured to generate electromagnetic emission upon incidence of incoming electromagnetic waves onto the respective antenna. The metal substrate 202 may be configured to reflect the electromagnetic emission to direct the electromagnetic emission, and further configured to generate surface plasmons based on the electromagnetic emission to enhance the electromagnetic emission.

[0043] In other words, the antenna array 200 may include a metal substrate 202, and a plurality of rings 204 in contact with the surface of the metal substrate 202. The cavity formed by each ring 204 and the metal substrate 202 may include a plurality of emitters 206.

[0044] In various embodiments, the plurality of rings 204 may be in a periodic array. A distance between a particular ring of the plurality of rings 204 and a first neighbouring ring of the plurality of rings may be substantially equal to a distance between the ring and a second neighbouring ring of the plurality of rings.

[0045] In various embodiments, the surface plasmons may also be generated by the incoming electromagnetic waves. The surface plasmons generated at the metal surface 202 may interact with the plurality of rings 204 under the incoming electromagnetic waves. The plurality of rings 204 may help match the momentum of the incoming electromagnetic waves to the momentum of the generated surface plasmonic waves.

[0046] In various embodiments, the plurality of rings 204 may be in a one-dimensional (1D) array. In various other embodiments, the plurality of rings 204 may be in a two-dimensional (2D) array.

[0047] The plurality of rings 204 may be similar or identical to one another. Each ring 204 of the array may include similar or identical emitters 206. The respective cavity defined by the ring 204 and the substrate 202 may contain or include an identical number of emitters. Each ring 204 or element may output photons in the same phase to enhance output through constructive interference.

[0048] In various embodiments, the antenna array 200 may be an optical antenna array.

[0049] FIG. 3 is a general illustration of a method of forming an antenna according to various embodiments. The method may include, in 302, forming a ring on a surface of a metal substrate, the ring including a dielectric or a semiconductor, an inner surface of the ring and a portion of the surface within the ring defining a cavity. The method may also include, in 304, arranging one or more emitters within the cavity, the one or more emitters configured to generate electromagnetic emission upon incidence of incoming electromagnetic waves onto the antenna. The metal substrate may be configured to reflect the electromagnetic emission to direct the electromagnetic emission, and may be further configured to generate surface plasmons based on the electromagnetic emission to enhance the electromagnetic emission.

[0050] In various embodiments, the cavity may be a resonant cavity configured to generate a resonant electromagnetic field based on the incoming electromagnetic waves.

[0051] In various embodiments, the one or more emitters may be configured to generate the electromagnetic emission upon excitation by the resonant electromagnetic field.

[0052] In various embodiments, the ring may be of any suitable shape. In various embodiments, the ring may be circular, polygonal, or elliptical in shape.

[0053] In various embodiments, the metal substrate may include or consist of a noble metal. The metal substrate may include or consist of any suitable metal such as gold, silver, or aluminium.

[0054] In various embodiments, the semiconductor may be silicon. However, in various other embodiments, the semiconductor may be any suitable semiconductor such as germanium, silicon germanium, or gallium arsenide.

[0055] In various embodiments, the dielectric may be titanium oxide. However, in various other embodiments, the dielectric may be any suitable dielectric such as silicon oxide or aluminium oxide.

[0056] In various embodiments, the incoming electromagnetic waves may be visible light. In various other embodiments, the incoming electromagnetic waves may be for instance, infrared radiation or ultraviolet waves.

[0057] In various embodiments, the electromagnetic emission may include photons. The electromagnetic emission may be visible light emission. In various other embodiments, the electromagnetic emission may have wavelengths in the other parts of the electromagnetic spectrum, e.g. infrared radiation or ultraviolet waves.

[0058] Each of the one or more emitters may be a point emitter. Each of the one or more emitters may be a nanoparticle.

[0059] In various embodiments, the electromagnetic emission may be of or may include a predetermined wavelength. The predetermined wavelength of the electromagnetic emission may be resonant with the cavity. The cavity may be dimensioned so that it is resonant with the predetermined wavelength of the electromagnetic emission. The antenna may be configured to resonant at the wavelength of the incoming electromagnetic waves and the wavelength of the electromagnetic emission.

[0060] FIG. 4 is a general illustration of a method of forming an antenna array according to various embodiments. The method may include, in 402, forming a plurality of rings on a surface of a metal substrate to form a respective antenna of the antenna array. Each respective ring of the plurality of rings may include a dielectric or a semiconductor, an inner surface of the respective ring and a portion of the surface within the respective ring defining a respective cavity. The method may also include, in 404, arranging one or more emitters within the respective cavity. The one or more emitters may be configured to generate electromagnetic emission upon incidence of incoming electromagnetic waves onto the respective antenna. The metal substrate may be configured to reflect the electromagnetic emission to direct the electromagnetic emission, and may be further configured to generate surface plasmons based on the electromagnetic emission to enhance the electromagnetic emission.

[0061] In various embodiments, the plurality of rings may be in a periodic array.

[0062] In various embodiments, the plurality of rings may be in a one-dimensional (1D) array. In various other embodiments, the plurality of rings may be in a two-dimensional (2D) array.

[0063] In various embodiments, the surface plasmons may also be generated by the incoming electromagnetic waves.

[0064] Various embodiments may relate to a system including an antenna or antenna array. The system may also include an electromagnetic source configured to emit the incoming electromagnetic waves or a light source configured to emit the incoming light.

FIG. 5A shows a cross-sectional perspective view of an antenna 500 according to various embodiments. FIG. 5B shows a cross-sectional side view of the antenna 500 according to various embodiments.

[0065] A ring-shaped (i.e. cylindrical) dielectric structure 504 may be arranged or placed on a metal substrate, e.g. a thin metal film 502. The cylindrical dielectric structure 504 may form a resonant cavity inside the hole of the ring 504 (together with portion of film 502 within the ring 504). The metal film 502 may reflect light to the cylindrical structure 504 and may generate plasmons to further enhance electromagnetic fields inside the cavity. Light emitters 506 may be placed inside the hole of the ring 504 or cavity. When the antenna 500 is illuminated by incoming electromagnetic waves, e.g. light, at a resonant wavelength of the cavity, strong electromagnetic fields may be generated in the hole or cavity which in turn, may excite the emitters 506 and induce strong fluorescence. The nanoantenna 500 may also be designed with another resonant wavelength matching the electromagnetic emission wavelength of the emitters 506. As a result, the emitters 506 may excite a resonant mode within the hole or cavity that in turn radiates electromagnetic emission, e.g. light, at the same frequency into the far field, greatly amplifying the far field emission. By selecting appropriate dimensions and shapes of the dielectric structure 504, it may be possible not only to set the resonant frequencies of the structure at desired values, but also to determine the direction and the symmetry of the electromagnetic emission into the far field.

[0066] FIGS. 6A – C illustrate the process in which electromagnetic emission is generated according to various embodiments. FIG. 6A is a schematic showing incoming electromagnetic waves, e.g. visible light, incident on the antenna 600 according to various embodiments. The incoming electromagnetic waves may generate a resonant electromagnetic field within the cavity 608. The cavity 608 may be defined or formed by the inner sidewalls of the ring 604 as well as the portion of the surface of the metal substrate 602 within the ring 604. One or more emitters 606 may be within the cavity 608. The one or more emitters 606 may be strongly excited by the resonant electromagnetic field generated within the cavity 608.

[0067] FIG. 6B is a schematic showing electromagnetic emission generated by the one or more emitters 606 under excitation by the resonant electromagnetic field according to various embodiments. The one or more emitters 606 may generate electromagnetic emission under excitation from the resonant electromagnetic field. The electromagnetic emission may include photons. The electromagnetic emission may also be resonant with the cavity 608 of the antenna 600. The electromagnetic emission may be radiated out and directed to the far field.

[0068] FIG. 6C is a schematic showing the reflection of the electromagnetic emission by the metal substrate 602 according to various embodiments. The metal substrate 602 may reflect the electromagnetic emission incident on the metal substrate 602 upwards, thus enhancing the directivity of the electromagnetic emission. In addition, the metal substrate 602 may generate surface plasmons due to the electromagnetic emission. The generated surface plasmons may enhance the electromagnetic emission (due to the interaction between the generated surface plasmons and the electromagnetic field within cavity 608) to the far field. In other words, the metal substrate 602 may enhance the directivity of the electromagnetic emission, as well as enhance the total electromagnetic emission.

[0069] Finite-element modelling (FEM) of the behaviour of a cylindrical ring of silicon placed on an infinite 50nm film of gold has been carried out as proof of concept.

[0070] This model may approximate or represent an actual device in which the gold layer has horizontal dimensions exceeding that of the ring by a factor of more than 10 times. Light sources emitting at 655 nm are placed within the cylindrical hole of the ring, which is held at a constant radius of 50 nm. The thickness of the cylinder wall and the height of the cylinder over the gold film may be chosen to maximize the emission of the nanoantenna into the far field along the normal to the surface.

[0071] In order to simulate the emission enhancement of the light emitters inside the cavity, the field enhancement in the cavity when light is incident to the nanoantenna is first calculated. Once the light emitters are excited, the emission enhancement to the far field from the light emitters may be computed. By multiplying the field enhancement and the emission enhancement, the florescence enhancement of the light emitters may be obtained.

[0072] The simulation has been carried out using the RF module of Comsol Multiphysics. FIG. 7A shows a schematic of the modelled antenna 700 according to various embodiments.

[0073] The antenna 700 may include a cylindrical ring 704 on a gold layer 702. The cylindrical silicon ring 704 may be positioned within a spherical simulation domain of radius 600nm on top of the gold film 702, the boundaries of which were surrounded by the perfectly-matched film 702 of thickness 300nm. Emitters 706 may be arranged within a cavity. The radius of the cylindrical silicon ring 704 is provided by *R,* the diameter of the cavity is provided by *d,* while the height of the cylindrical ring is provided by *h*.

[0074] The field enhancement in the cavity is obtained by simulating the field excited within the cavity by a plane wave at the desired wavelength coming from the desired direction, comparing the field of the same wave passing through a similarly-sized and shaped volume in free space.

[0075] The emission enhancement may be computed using the Lorentz Reciprocity Principle:

$$\iiint E_{\odot}.J_{\infty} d^3r = \iiint E_{\infty}.J_{\odot} d^3r \tag{1}$$

wherein $J_{\odot}$ is the time-harmonic current associated with a first dipole oscillating at a point *r*, $E_{\odot}$ is a first electric field generated by the first dipole. J_{∞} is the time-harmonic current associated with a second dipole oscillating at a point *r*, and E_{∞} is a second electric field generated by the second dipole.

[0076] The emission enhancement may be computed by integrating the electric field within the cavity and dividing the result with the integral of the electric field of the same wave passing through the volume in free space.

[0077] For the proof of concept, the emission at the wavelength of 655nm of the nanoantenna may be maximized directly along the normal. In the interest of simplifying fabrication of the structures, the radius of the hole containing light emitters may be kept equal to 50nm. Calculations of the far field emission in the direction of the normal have been carried out for a series of antennas of varying dimensions. Also, in the interests of simplifying fabrication, the dimensions of the antennas have been each varied at intervals of 10nm.

[0078] First, the height of the ring resonator is held constant at 150nm (the higher, the more difficult to be fabricated) and the strength of emission is calculated for ring resonators with different outer radii. FIG. 7B is a plot of emission enhancement as a function of radius (in nanometers or nm) showing the emission enhancement along the normal of the antenna plane for antennas with cylindrical ring resonators of varying radii and a fixed height of 150 nm according to various embodiments. A maximum of the emission strength is found for a cylindrical ring with a radius of 250nm.

[0079] Next, the radius of the cylinder is held constant and the height of the cylinder is varied. FIG. 7C is a plot of emission enhancement as a function of height (in nanometers or nm) showing the emission enhancement along the normal of the antenna plane for antennas with cylindrical ring resonators of varying heights and a fixed radius of 250 nm according to various embodiments. The radius of 250 nm is obtained based on the plot in FIG. 7B. The maximum of the emission strength is then found for a cylinder with height 140nm.

[0080] The resulting structure is thus considered, within the limitations imposed on these simulations, to be optimized for emission of light at 655nm along the normal. FIG. 7D shows a cross-sectional side view of the resultant nanoantenna according to various embodiments. There are two parameters: h represents the ring height and R represents the ring radius. The resultant structure is obtained based on the abovementioned calculations involving parametric scans with the other parameter held constant. In subsequent subsections, further characterizations of this structure are carried out to demonstrate the emission properties of this structure.

[0081] The resultant antenna obtained above may be characterized by calculating the emission strengths of 655nm light over a 180° arc above the metal surface at the center of the nanoantenna. Calculations of the electric field excited within the hole of the ring resonator are carried out based on plane waves at 655nm wavelength directed from different angles towards the antenna. Using the reciprocity principle, the emission strength of the antenna along the travelling directions of the incident plane waves is calculated.

[0082] FIG. 7E is an emission plot showing the emission profile of emission enhancement of the antenna according to various embodiments. FIG. 7E shows three lobes: a main lobe along the normal to the antenna plane with strongest emission, as well as small side lobes approximately 45° from normal. FIG. 7E shows an emission enhancement of 22.5 times along the normal to the antenna plane. FIG. 7F is an emission plot showing the emission profile of emission enhancement of the antenna according to various embodiments (cross-sectional schematic shown in bottom left) in comparison with the emission profile of emission enhancement of an antenna including emitters in a silicon (Si) ring in free space (cross-sectional schematic shown in bottom right) as a reference.

[0083] The plots in FIGS. 7E-F are plotted based on a constant excitation field within the hole and taking the normal from the surface to be 0°.

[0084] The enhancement provided by the ring nanoantenna has also been calculated over a range of wavelengths surrounding 655nm. FIG. 7G is a plot of emission strength as a function of wavelength (in nanometres or nm) showing the enhancement spectrum of the ring nanoantenna according to various embodiments directly along the normal over a range of wavelengths between 640 nm and 710nm. The target wavelength of 655nm and the full-width half-maximum are marked on the graph. As expected, a strong enhancement peak is present and centred near the emission wavelength due to the optimization described above. The target wavelength may possess a full-width half-maximum of approximately 20nm.

[0085] In order to investigate the cumulative effect of the emitter radiating at a resonant wavelength while being excited by the field at another resonant wavelength, it may be necessary to determine the spectrum of electric field enhancement within the hole of the antenna. Calculations of the electric field excited within the hole by a series of incident plane waves with wavelengths between 450nm and 700nm have been carried out. The volume integral of the electric field within the hole has, in turn, been calculated for each wavelength. A resonance in the electric field strength is found at wavelength 552nm.

[0086] FIG. 7H is a plot of field enhancement as a function of wavelength (in nanometres or nm) showing field enhancement of the antenna according to various embodiments may be maximized at 552 nm and 655 nm. The resonant wavelength at 552nm in FIG. 7H is marked with a vertical dashed line. A second resonant wavelength near the emission wavelength of 655nm has also been produced by the optimization procedure described above. FIG. 7I shows the electric field enhancement inside the cavity of the antenna according to various embodiments at excitation wavelength of 552 nm. FIG. 7J shows the electric field enhancement inside the cavity of the antenna according to various embodiments at emission wavelength of 655 nm.

[0087] Having obtained a resonant wavelength for electric field modes within the cavity of the nanoantenna, it may now be possible to calculate the cumulative enhancement of the excitation field and the emission rate produced by the antenna. This may be done by taking the excitation field within the hole as a multiplier of the reciprocal field from which the emission is calculated using the Lorentz reciprocity theory. The resulting enhanced emission is then calculated and plotted. FIG. 7K is an emission plot showing the emission profile of fluorescence enhancement of the antenna according to various embodiments. FIG. 7L is an emission plot showing the emission profile of fluorescence enhancement of the antenna according to various embodiments in comparison with the emission profile of fluorescence enhancement of an antenna including emitters in a silicon (Si) ring in free space as a reference.

[0088] Due to the strong electric fields created within the cavity by the resonant excitation waves, the enhancement of fluorescence of the emitters in free space may be greatly increased. The cumulative enhancement due to the excitation field as well as the presence of the antenna may be in the order of about 150 times along the normal. This is considerably larger than the florescence enhancement of emitters inside the hole of the Si ring in free space, which is of approximately 50 times, and represents an almost 10-fold improvement over the 17-fold fluorescence enhancement exhibited by other structures in previous reports.

Various embodiments may relate to an antenna including a dielectric or semiconductor ring resonator coupled with a metal film. The dielectric or semiconductor ring resonator may be of any shape, such as elliptical or polygonal. FIG. 8 shows a cross-sectional perspective view of an antenna 800 including a metal substrate 802 and an elliptical ring 804 according to various embodiments. The elliptical ring 804 may include a dielectric or a semiconductor. The antenna 800 may further include one or more emitters 806 within the cavity formed by the ring 804 and the portion of the substrate 802 within the ring 804. FIG. 9 shows a cross-sectional perspective view of an antenna 900 including a metal substrate 902 and a polygonal ring 904 according to various embodiments. The polygonal ring 904 may include a dielectric or a semiconductor. The antenna 900 may further include one or more emitters 906 within the cavity formed by the ring 904 and the portion of the substrate 902 within the ring 904.

[0089] As highlighted above, the material of the ring resonator may be any low loss dielectric or semiconductor with high optical refractive index such as silicon (Si), titanium oxide (TiO_2) and so on. The metal film or substrate may be configured to reflect electromagnetic waves or light and to generate plasmons. The metal film or substrate may include noble metals such as silver, gold or aluminium, but may alternatively include any material which can function as a reflector.

[0090] The antenna may be used alone or as part of an array.

[0091] Various embodiments may relate to an antenna array. The antenna array may include a plurality of antennas. The antenna array may be a one-dimensional (1D) or a two-dimensional array. The array may include a number of individual antennas arranged in lines or regular arrays.

[0092] FIG. 10 shows a top planar view of an antenna array 1000 according to various embodiments. The array 1000 may include a metal substrate 1002, and dielectric or semiconductor rings 1004a-d on the metal substrate. Emitters 1006a-d may be included or arranged in each of the rings 1004a-d.

[0093] Various embodiments may relate to an antenna or nanoantenna including a dielectric or semiconductor ring resonator coupled with a plasmonic metal film.

[0094] A resonant cavity may be formed by the dielectric resonator and the cavity behaviour may be further enhanced by the reflection from the metal film, and plasmons generated by the metal film.

[0095] Light or electromagnetic wave emitters may be located inside the cavity and their emission intensity may be largely amplified and emission direction may be controlled.

[0096] The antenna or nanoantenna may achieve multi-resonant frequencies to match both excitation and emission wavelengths of the light emitters. Strong enhancement of the emission may be obtained due to the cumulative effects of the resonant excitation fields and the resonance of the emitted light with the nanoantenna.

[0097] The dimensions of nanoantenna may be tuned for light emitters with different wavelengths and for emission in the desired direction. The resonances may be tuned by manipulation of dimensional parameters of the antenna.

[0098] Various embodiments may relate to design of a structure or antenna that enhances the florescence of emitters more than existing structures. Various embodiments may 1) enhance the excitation of the emitter(s), and 2) enhance the emission (or radiation) of the emitter(s) by using a cavity or resonator. Since the one or more emitters generally have a shorter (high photon energy) excitation wavelength than emission wavelength, and the excitation wavelength may be of a very wide range, the antenna may be first designed such that one resonant wavelength matches the emission wavelength, in order to generate maximum radiation enhancement. As the resonator is working at subwavelengths, there are generally a number of resonant modes (or wavelengths) that may be present. As such, a resonant wavelength shorter than the emission wavelength may be identified. A light source may then be used to emit the incoming electromagnetic waves or lights with the resonant wavelength to excite the one or emitters.

[0099] Various embodiments may relate to design of a cavity that has strong excitation and radiation at the same time. Various embodiments may possess or leverage the advantages of dielectric antennas and metal antennas. Various embodiments may relate to a hybrid antenna which combines a dielectric or semiconductor ring and a metal substrate. The dielectric or semiconductor ring may generate various modes through Mie resonances that depend on the ring dimensions. The modes for the metal substrate along may be very simple if excited by a plane wave like a simple reflector. However, when a sub-wavelength structure (e.g. silicon ring) is placed on top and excited by one or more point sources (e.g. one or more emitters), the plasmonic modes may be excited and the modes can be very complex. The modes excited from the ring may interact with the plasmon modes generated at the interface between the ring and the metal substrate, thereby forming hybrid modes. As the hybrid antenna is working at sub-wavelength regimes (the feature of structure (~ 100 nm) is less than the wavelength (e.g. 400 nm – 700 nm)), the modes may be very complex and may not be explained via analytical means easily. However, numerical methods may be used to look for the optimal dimensions for particular materials, in order to generate the best mode for emission. Another resonant wavelength, which may be shorter but close to the emission wavelength, may be identified or determined for excitation of the antenna.

[00100] The interaction between the ring and the metal substrate may be easily seen from simulation results. The reference results relate to an optimized bare silicon (Si) ring for an emission wavelength of about 655 nm. The optimized dimensions may include an outside radius of about 210 nm, a height of about 150 nm, a fixed inner-hole diameter of about 100 nm, and the optimal wavelength for excitation may be about 500 nm. The simulation results also include that of the hybrid antenna according to various embodiments, i.e. a Si ring on a gold substrate. The optimized

dimensions of the ring may include an outside radius of about 250 nm, a height of about 140 nm, a fixed inner-hole diameter of about 100 nm, and the optimal wavelength for excitation may be about 550 nm. In other words, various embodiments may consider the interaction between the ring and substrate depending on their materials and/or dimensions.

[00101] It may be envisioned that the strong enhancement of emission enabled by the nanoantenna according to various embodiments may enable more sensitive fluorescent detection of airborne or fluid-borne nanoparticles. This detection technique may have potential for deployment in a variety of applications, including detection of airborne or water-borne pathogens; analysis of contaminants in air, water or food; military detection of chemical or biological agents; and/or analysis of deoxyribonucleic acid (DNA) fragments for genetic testing.

[00102] Various embodiments may be desired by manufacturers of equipment for genetic analysis, pathogen detection, and/or biological assay. Various embodiments may be desired by manufacturers of equipment for detecting chemical agents and/or contaminants in the atmosphere and/or in water.

[00103] Various embodiments may be of interest to companies further down the supply chain of scientific equipment. These include companies offering analytical and monitoring services, or whose core business activity involves making use of such equipment:

[00104] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. An antenna including:

   a metal substrate having a surface; and

   a ring on the surface of the metal substrate, the ring comprising a dielectric or a semiconductor, such that an inner surface of the ring and a portion of the surface within the ring define a cavity;

   one or more emitters arranged within the cavity, the one or more emitters configured to generate electromagnetic emission upon incidence of incoming electromagnetic waves onto the antenna;

   wherein the metal substrate is configured to reflect the electromagnetic emission to direct the electromagnetic emission, and further configured to generate surface plasmons based on the electromagnetic emission to enhance the electromagnetic emission.

2. The antenna according to claim 1,

   wherein the cavity is a resonant cavity configured to generate a resonant electromagnetic field based on the incoming electromagnetic waves.

3. The antenna according to claim 2,

   wherein the one or more emitters are configured to generate the electromagnetic emission upon excitation by the resonant electromagnetic field.

4. The antenna according to claim 1,

   wherein the ring is circular, polygonal, or elliptical in shape.

5. The antenna according to claim 1,

   wherein the metal substrate comprises gold, silver, or aluminum.

6. The antenna according to claim 1,
   wherein the semiconductor is silicon.

7. The antenna according to claim 1,
   wherein the dielectric is titanium oxide.

8. The antenna according to claim 1,
   wherein the incoming electromagnetic waves are visible light.

9. The antenna according to claim 1,
   wherein the electromagnetic emission comprises photons.

10. The antenna according to claim 1,
    wherein each of the one or more emitters is a nanoparticle.

11. The antenna according to claim 1,
    wherein the electromagnetic emission is of a predetermined wavelength; and wherein the predetermined wavelength of the electromagnetic emission is resonant with the cavity.

12. An antenna array comprising:
    a metal substrate having a surface;
    a plurality of rings on the surface of the metal substrate to form a respective antenna of the antenna array, each respective ring of the plurality of rings comprising a dielectric or a semiconductor, such that an inner surface of the respective ring and a portion of the surface within the respective ring define a respective cavity; and
    one or more emitters arranged within the respective cavity, the one or more emitters configured to generate electromagnetic emission upon incidence of incoming electromagnetic waves onto the respective antenna;

wherein the metal substrate is configured to reflect the electromagnetic emission to direct the electromagnetic emission, and further configured to generate surface plasmons based on the electromagnetic emission to enhance the electromagnetic emission.

13. The antenna array according to claim 12,

wherein the surface plasmons are also generated by the incoming electromagnetic waves.

14. The antenna array according to claim 12,

wherein the plurality of rings is in a periodic array.

15. The antenna array according to claim 12,

wherein the plurality of rings is in a one-dimensional (1D) array.

16. The antenna array according to claim 12,

wherein the plurality of rings is in a two-dimensional (2D) array.

17. A method of forming an antenna, the method comprising:

forming a ring on a surface of a metal substrate, the ring comprising a dielectric or a semiconductor, such that an inner surface of the ring and a portion of the surface within the ring define a cavity;

arranging one or more emitters within the cavity, the one or more emitters configured to generate electromagnetic emission upon incidence of incoming electromagnetic waves onto the antenna;

wherein the metal substrate is configured to reflect the electromagnetic emission to direct the electromagnetic emission, and further configured to generate surface plasmons based on the electromagnetic emission to enhance the electromagnetic emission.

18. A method of forming an antenna array, the method comprising:

    forming a plurality of rings on a surface of a metal substrate to form a respective antenna of the antenna array, each respective ring of the plurality of rings comprising a dielectric or a semiconductor, such that an inner surface of the respective ring and a portion of the surface within the respective ring define a respective cavity; and

    arranging one or more emitters within the respective cavity, the one or more emitters configured to generate electromagnetic emission upon incidence of incoming electromagnetic waves onto the respective antenna;

    wherein the metal substrate is configured to reflect the electromagnetic emission to direct the electromagnetic emission, and further configured to generate surface plasmons based on the electromagnetic emission to enhance the electromagnetic emission.

19. The method according to claim 18,

    wherein the plurality of rings is in a one-dimensional (1D) array.

20. The method according to claim 18,

    wherein the plurality of rings is in a two-dimensional (2D) array.

FIG. 1

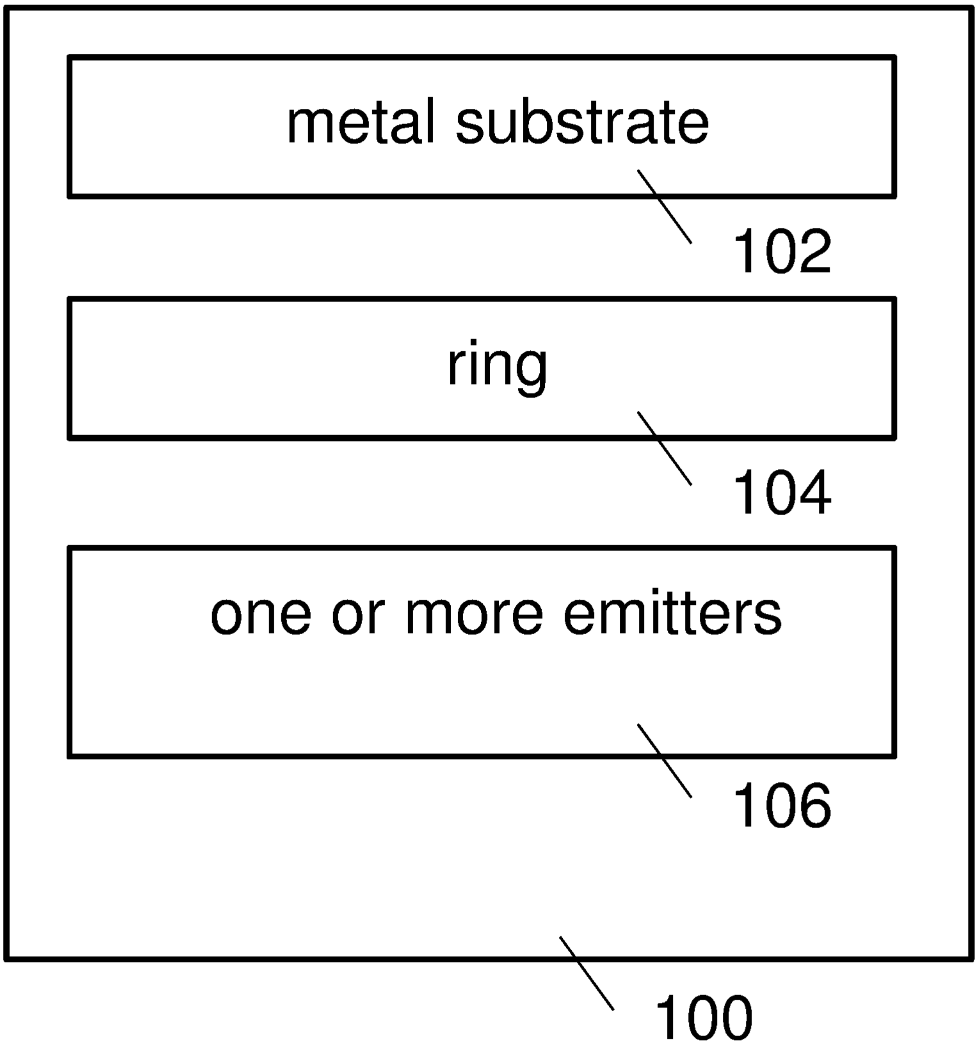


FIG. 2

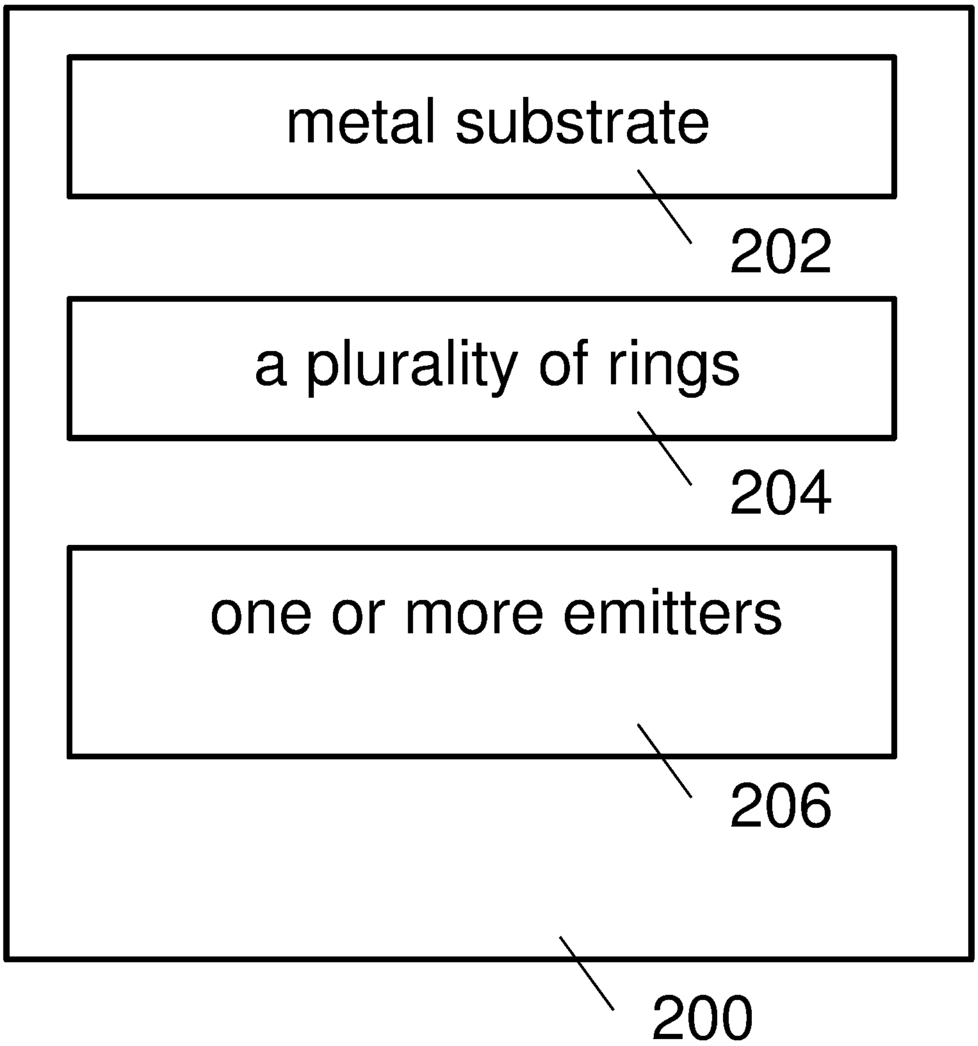

metal substrate
202
a plurality of rings
204
one or more emitters
206
200

FIG. 3

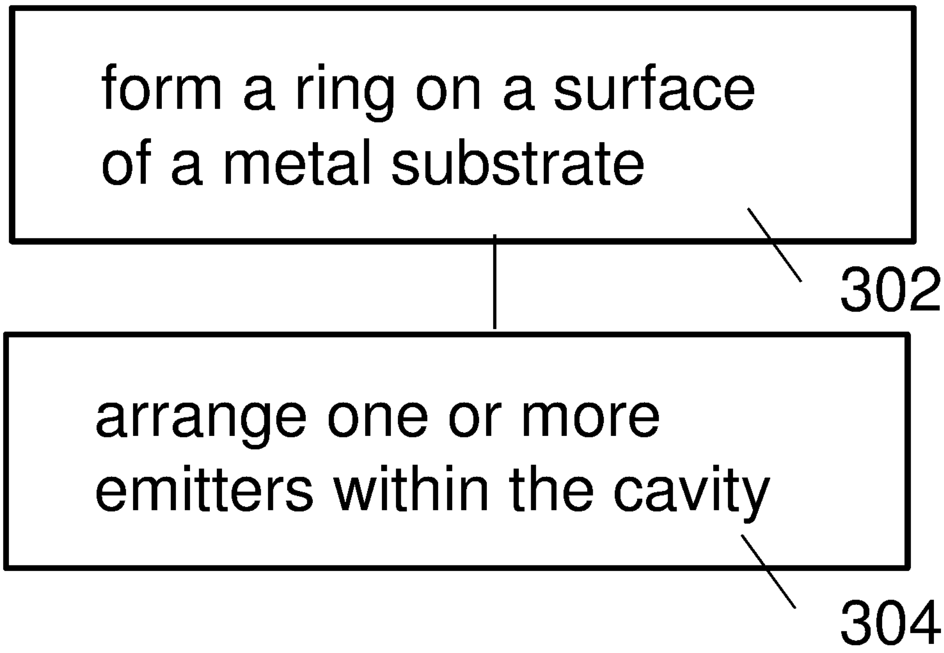

form a ring on a surface
of a metal substrate
302
arrange one or more
emitters within the cavity
304

FIG. 4

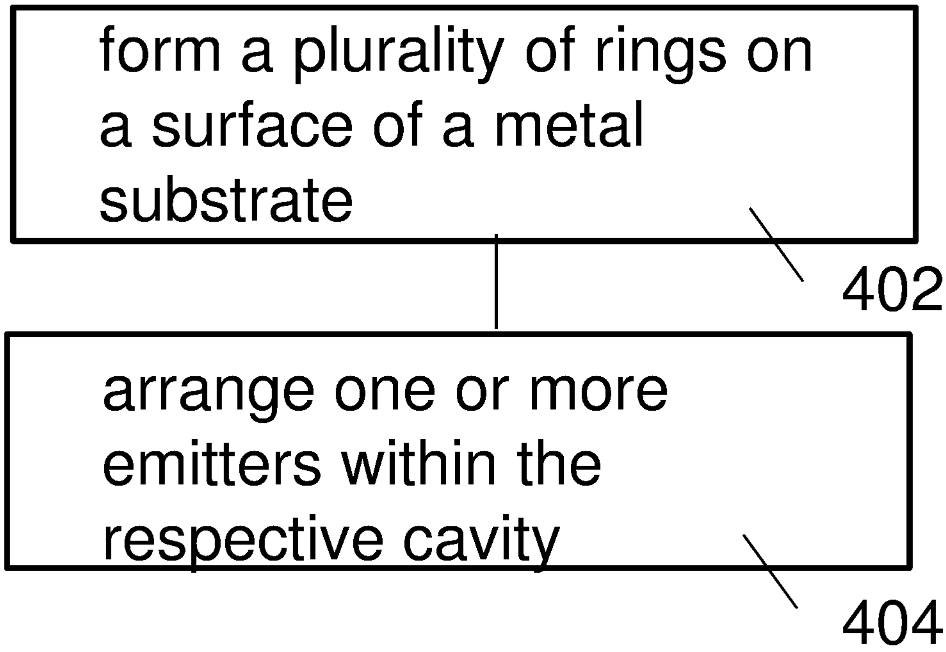

form a plurality of rings on a surface of a metal substrate
402
arrange one or more emitters within the respective cavity
404

FIG. 5A

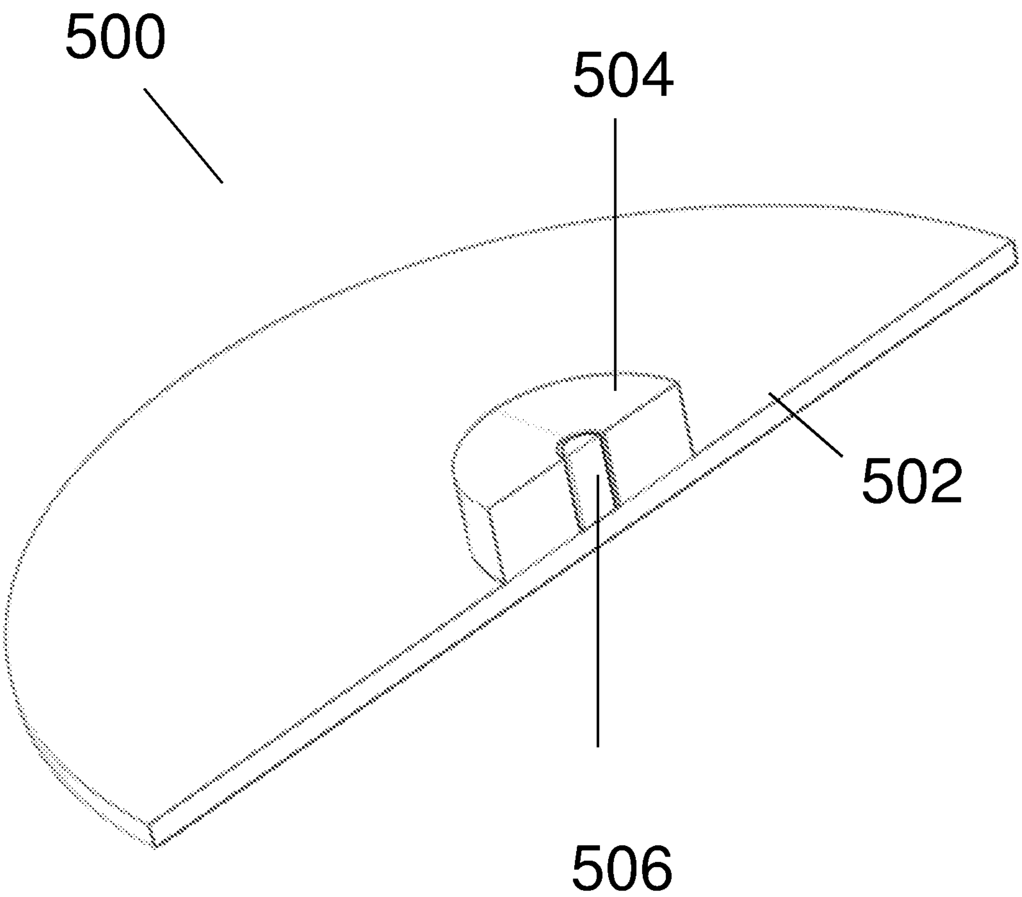


FIG. 5B

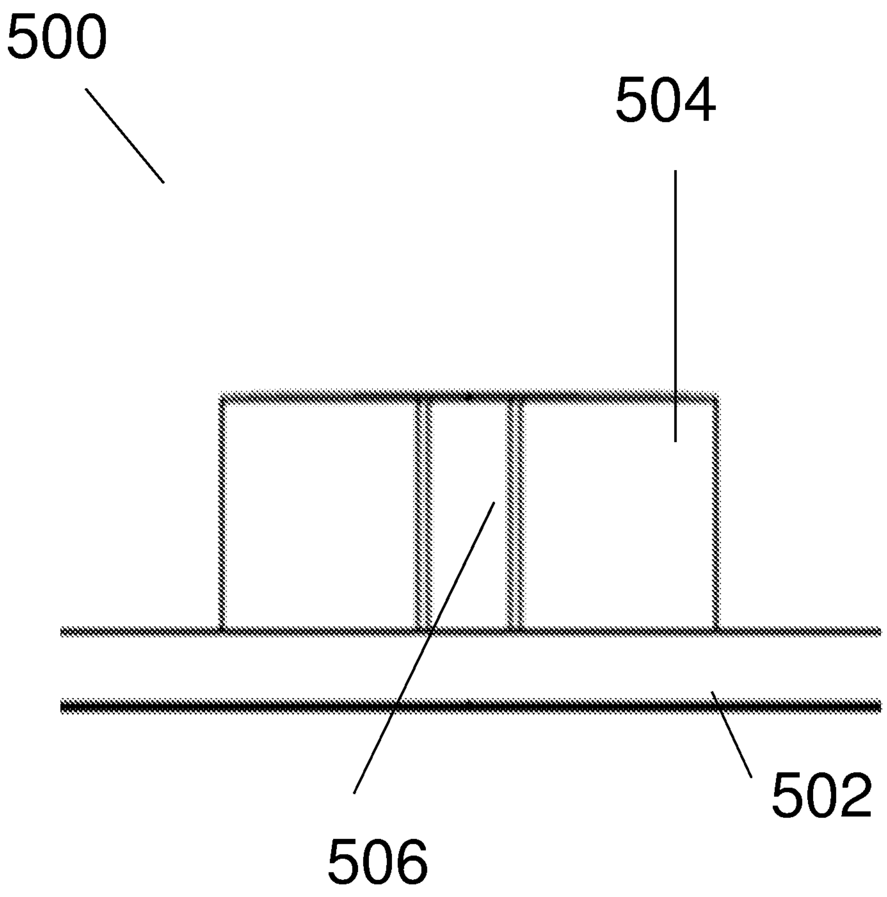


FIG. 6A

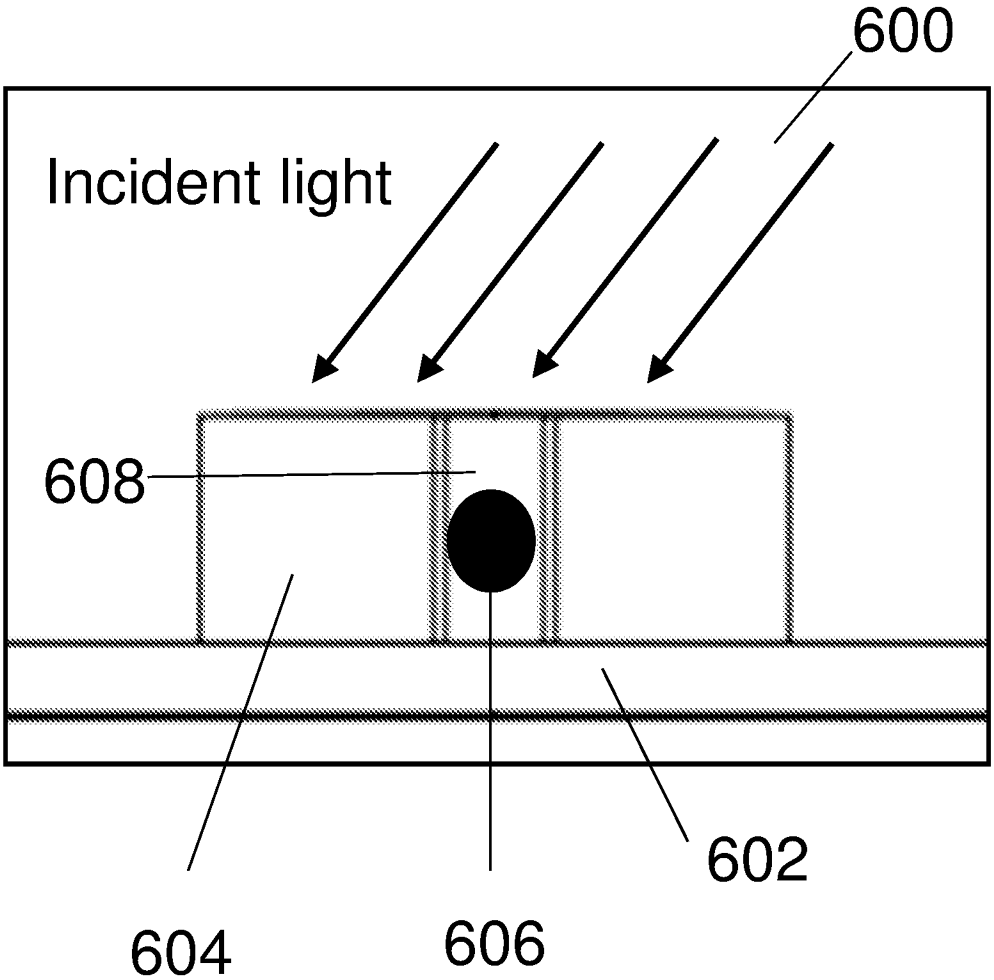


FIG. 6B

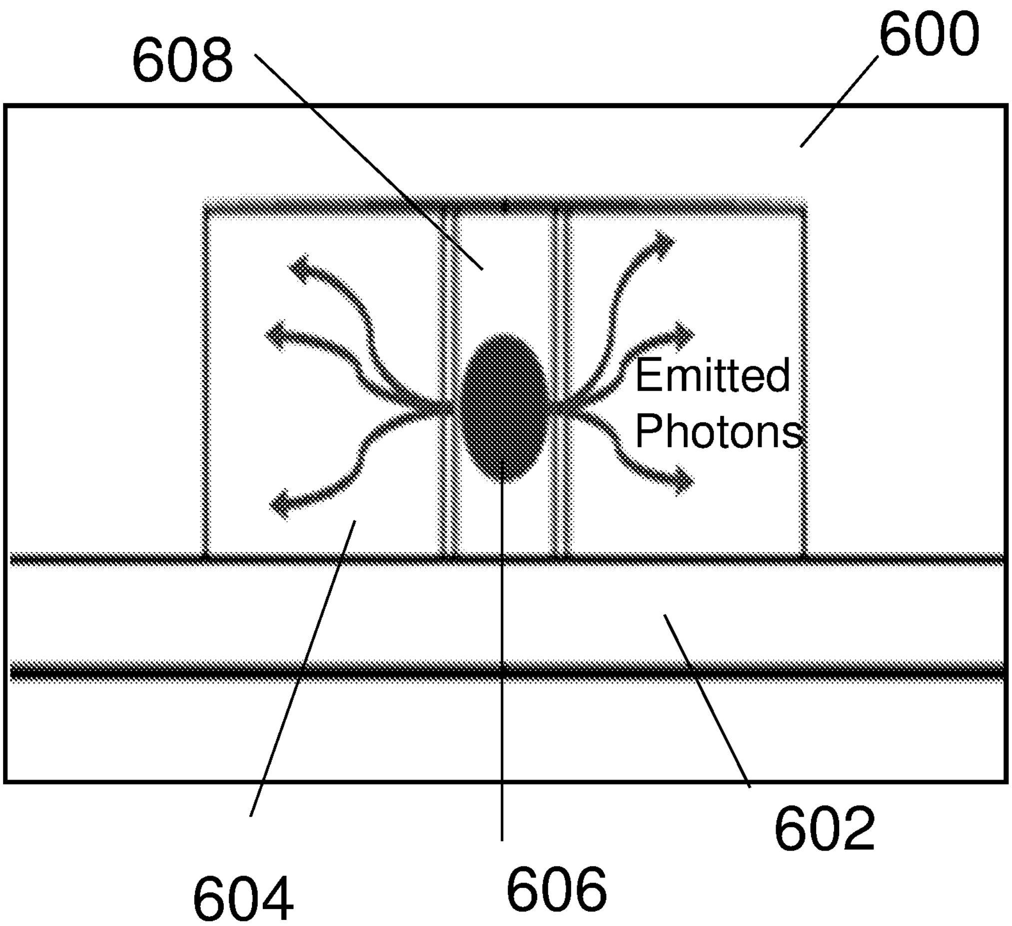
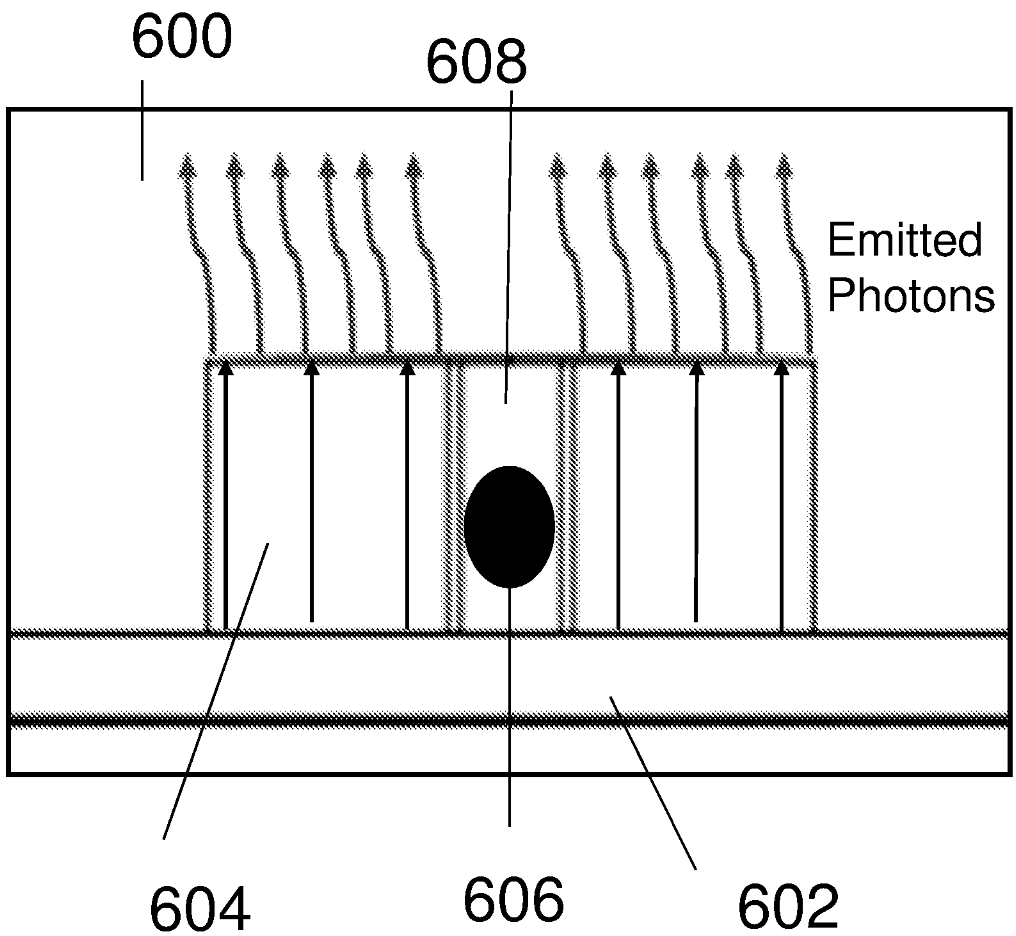


FIG. 6C



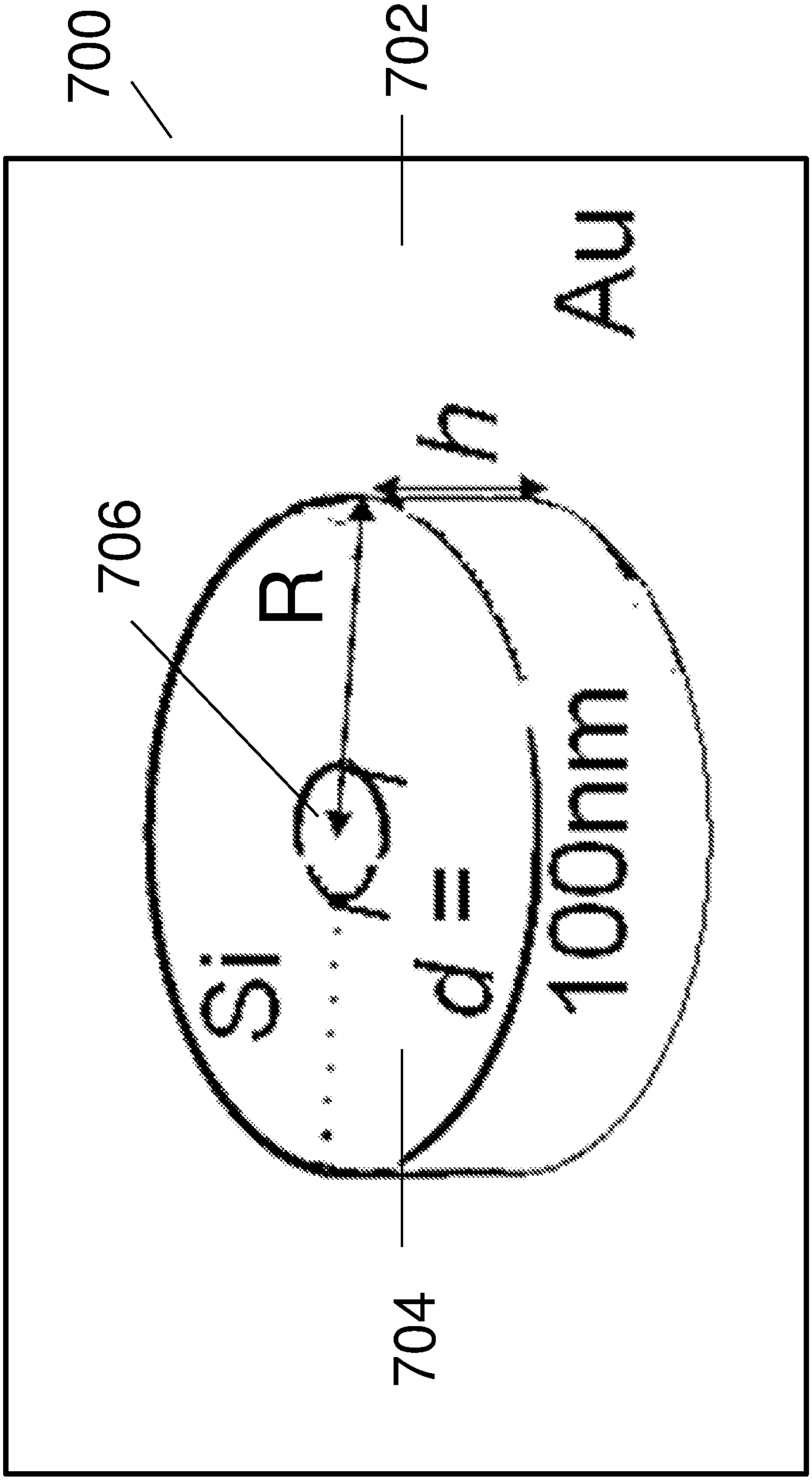


FIG. 7A

FIG. 7B

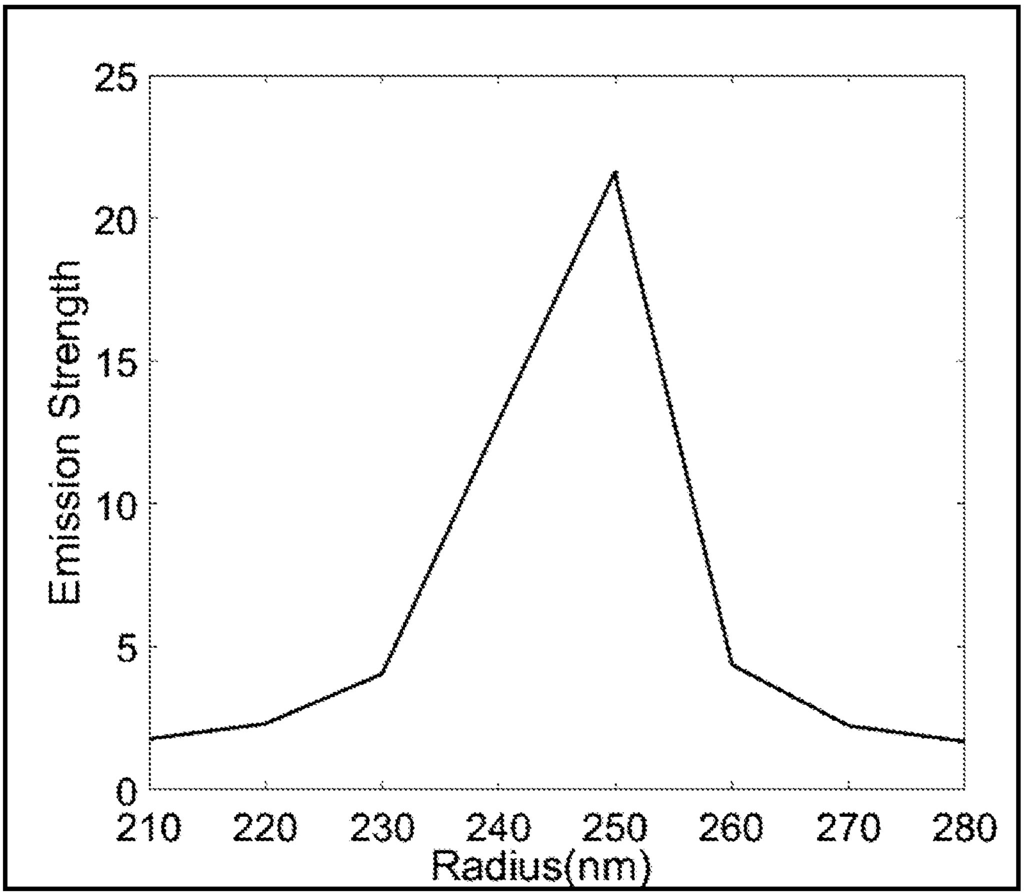

25
20
15
10
5
0
Emission Strength
210
220
230
240
250
260
270
280
Radius(nm)

FIG. 7C

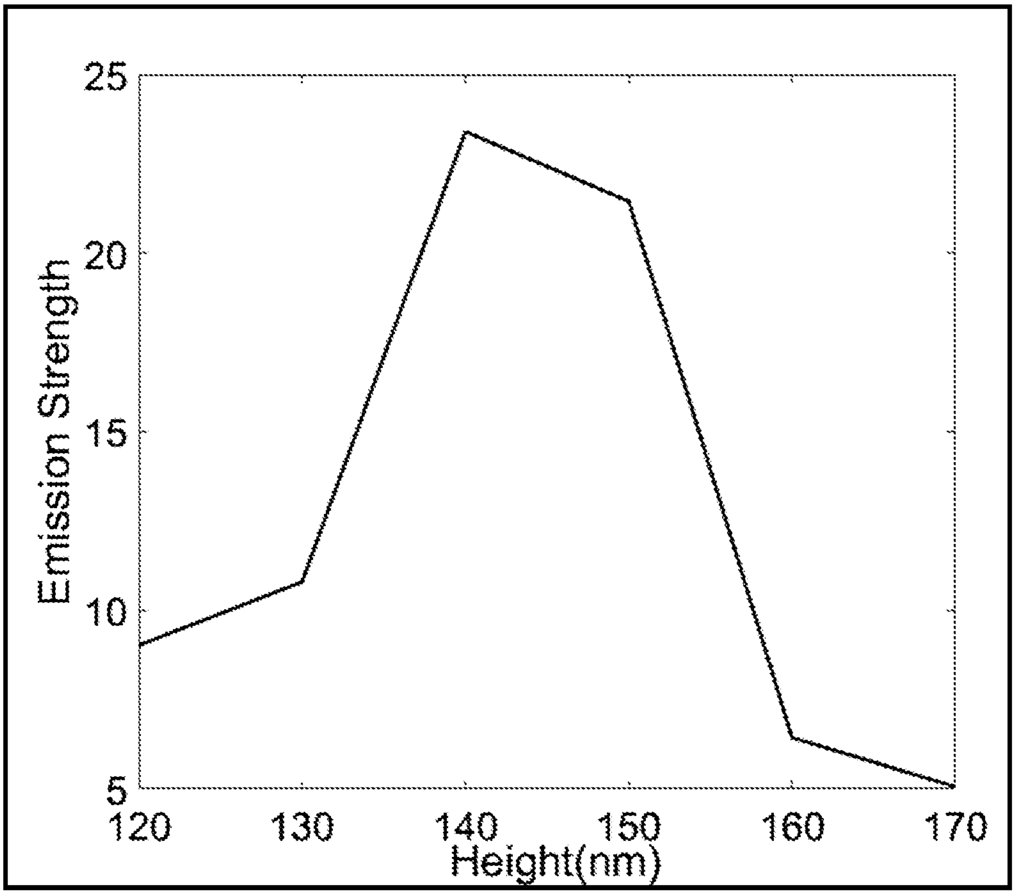

Emission Strength
25
20
15
10
5
120
130
140
150
160
170
Height(nm)

FIG. 7D

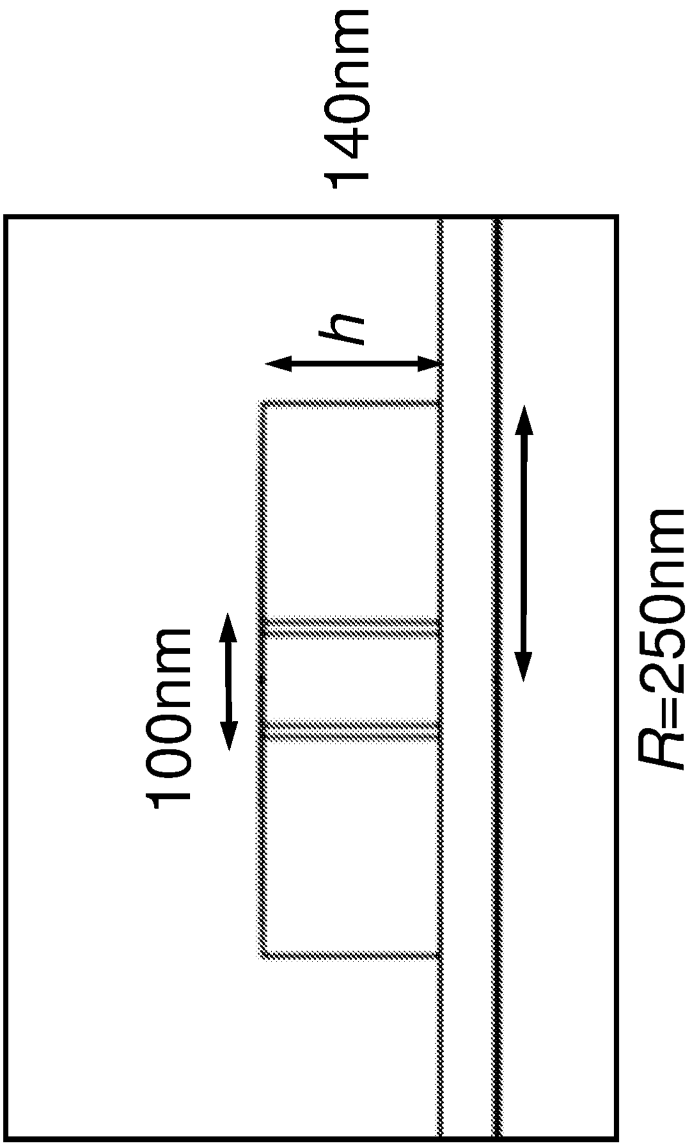


FIG. 7E

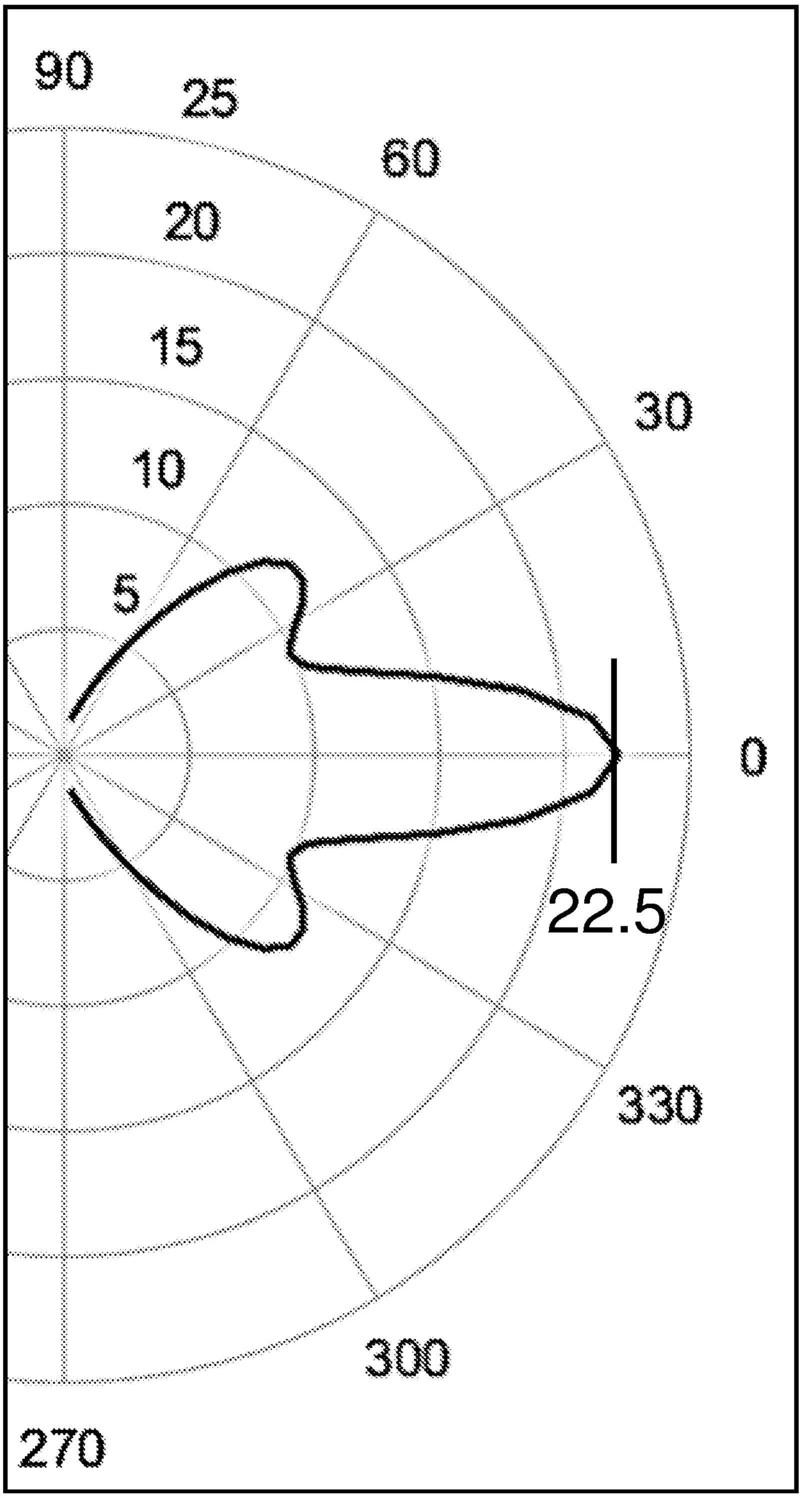
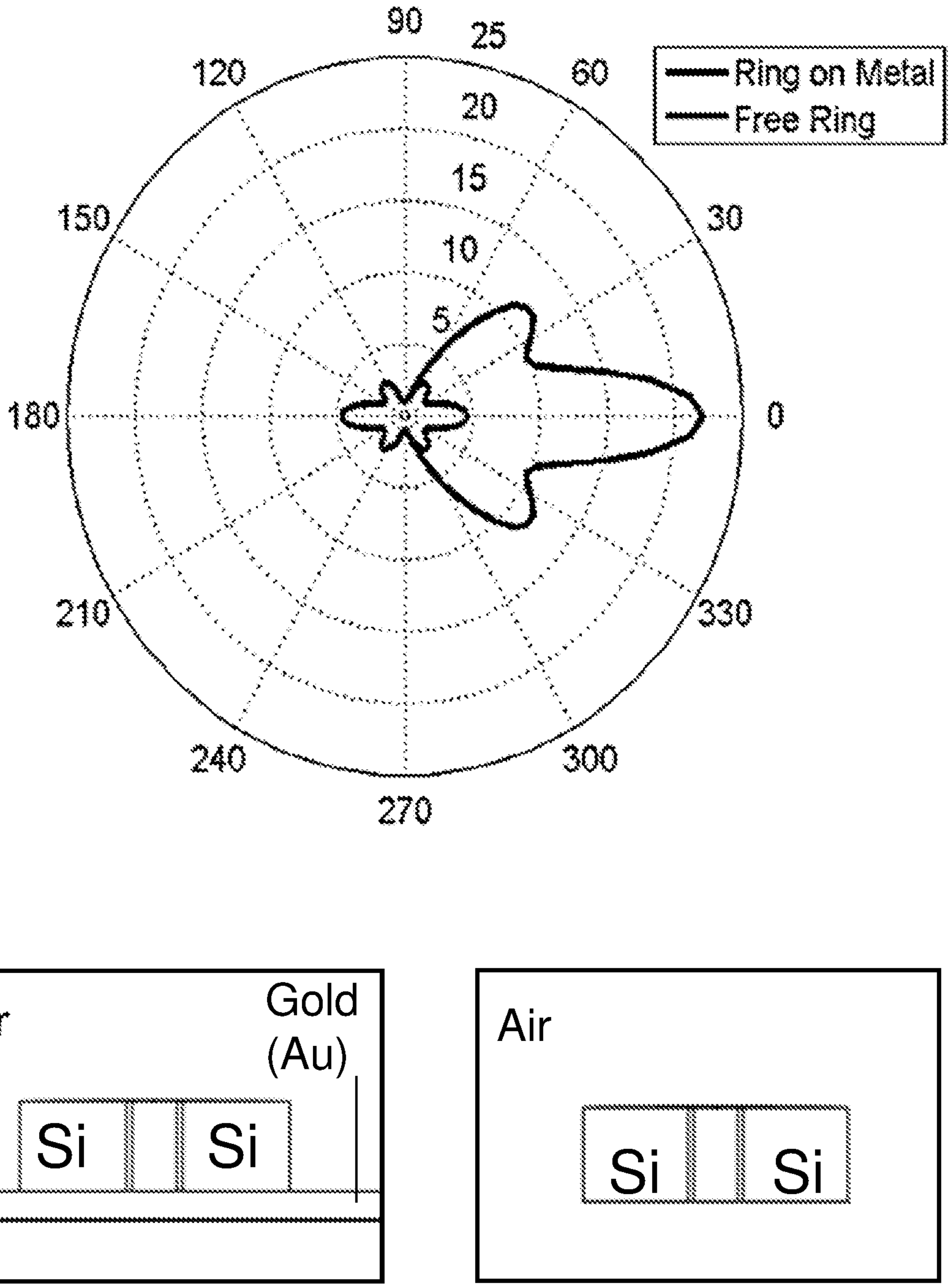


FIG. 7F



Antenna according to various embodiments

Free Si ring antenna

FIG. 7G

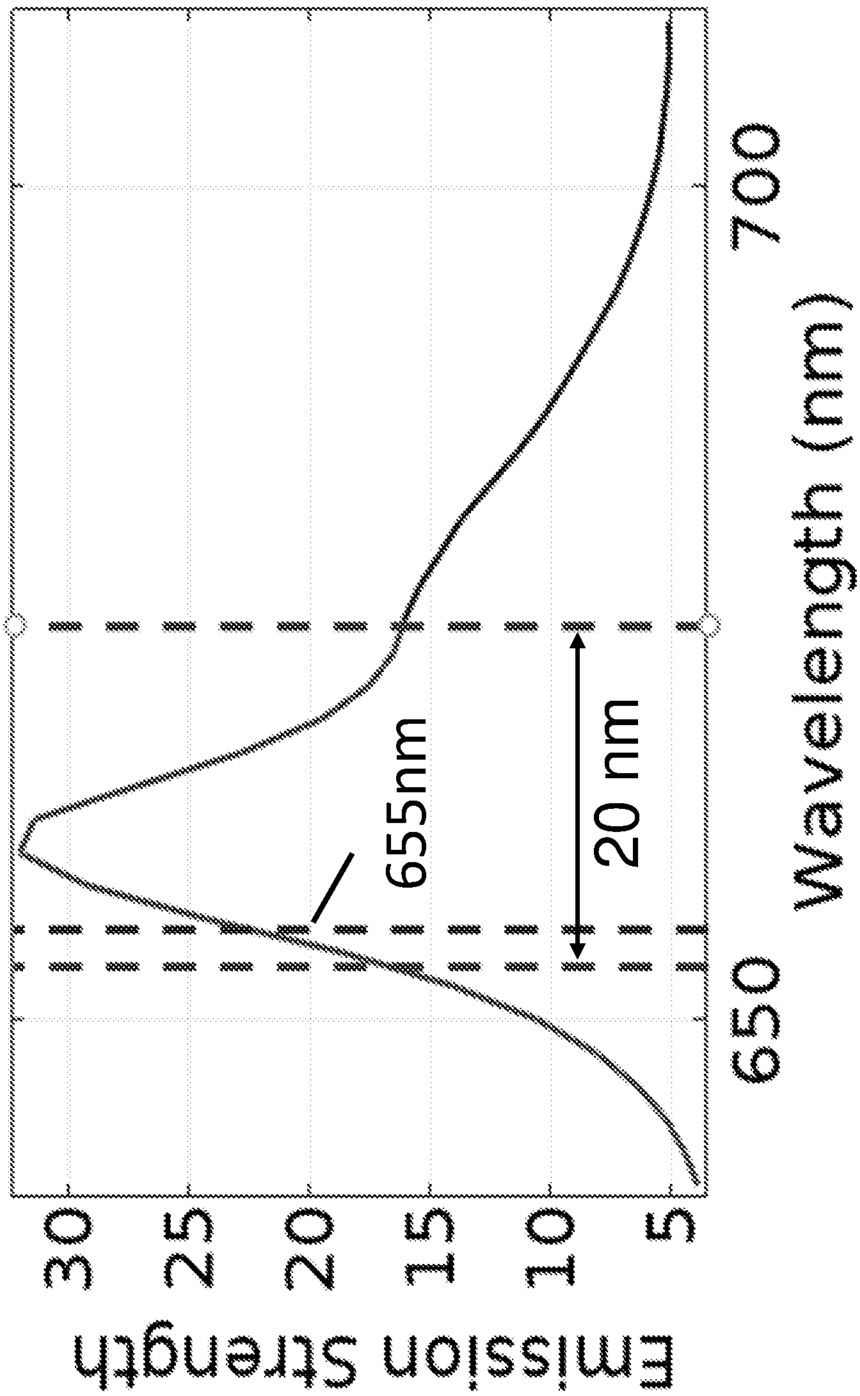

655nm
20 nm
Wavelength (nm)
650
700
Emission Strength
30
25
20
15
10
5

FIG. 7H

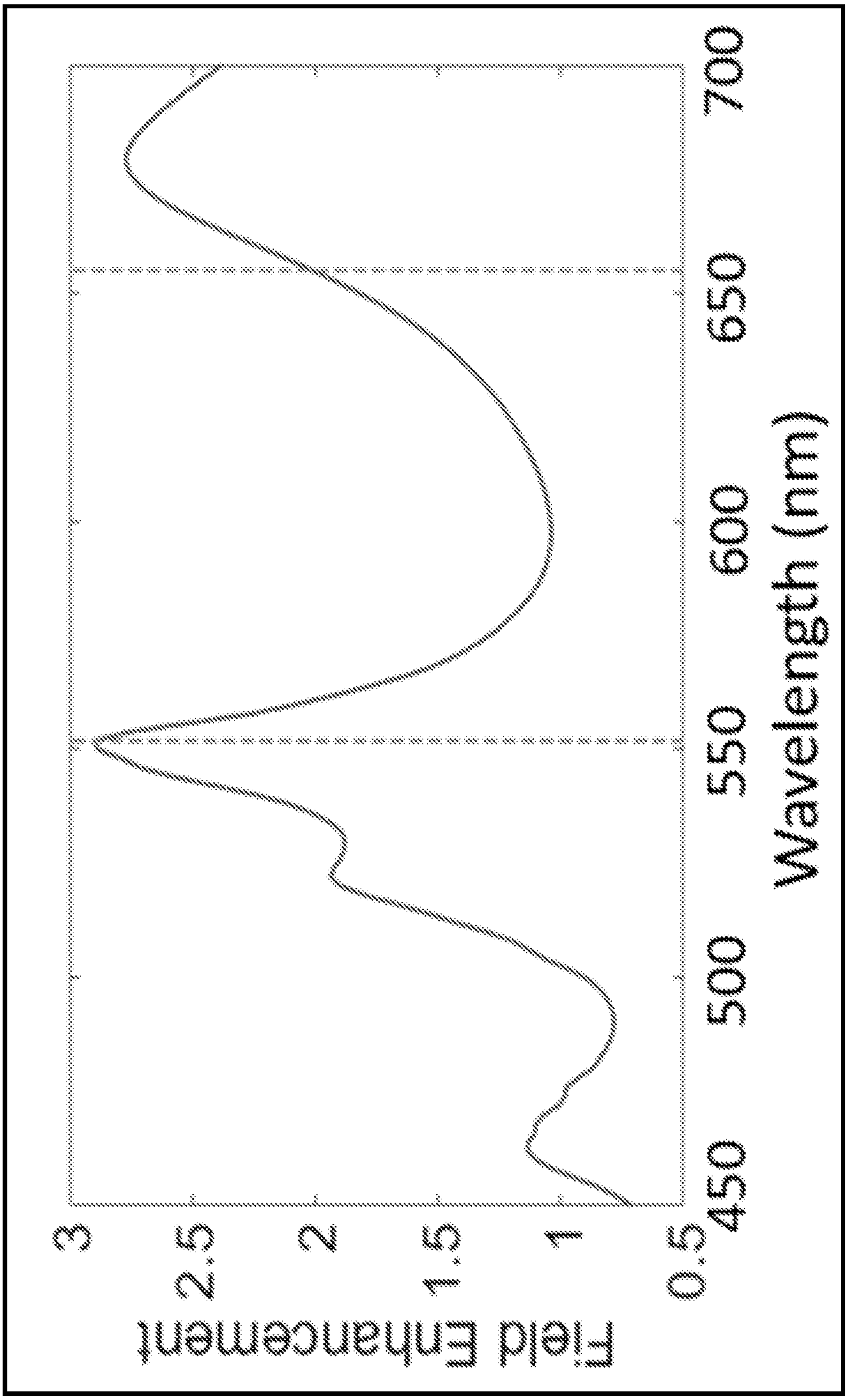

Field Enhancement
3
2.5
2
1.5
1
0.5
450
500
550
600
650
700
Wavelength (nm)

FIG. 7I

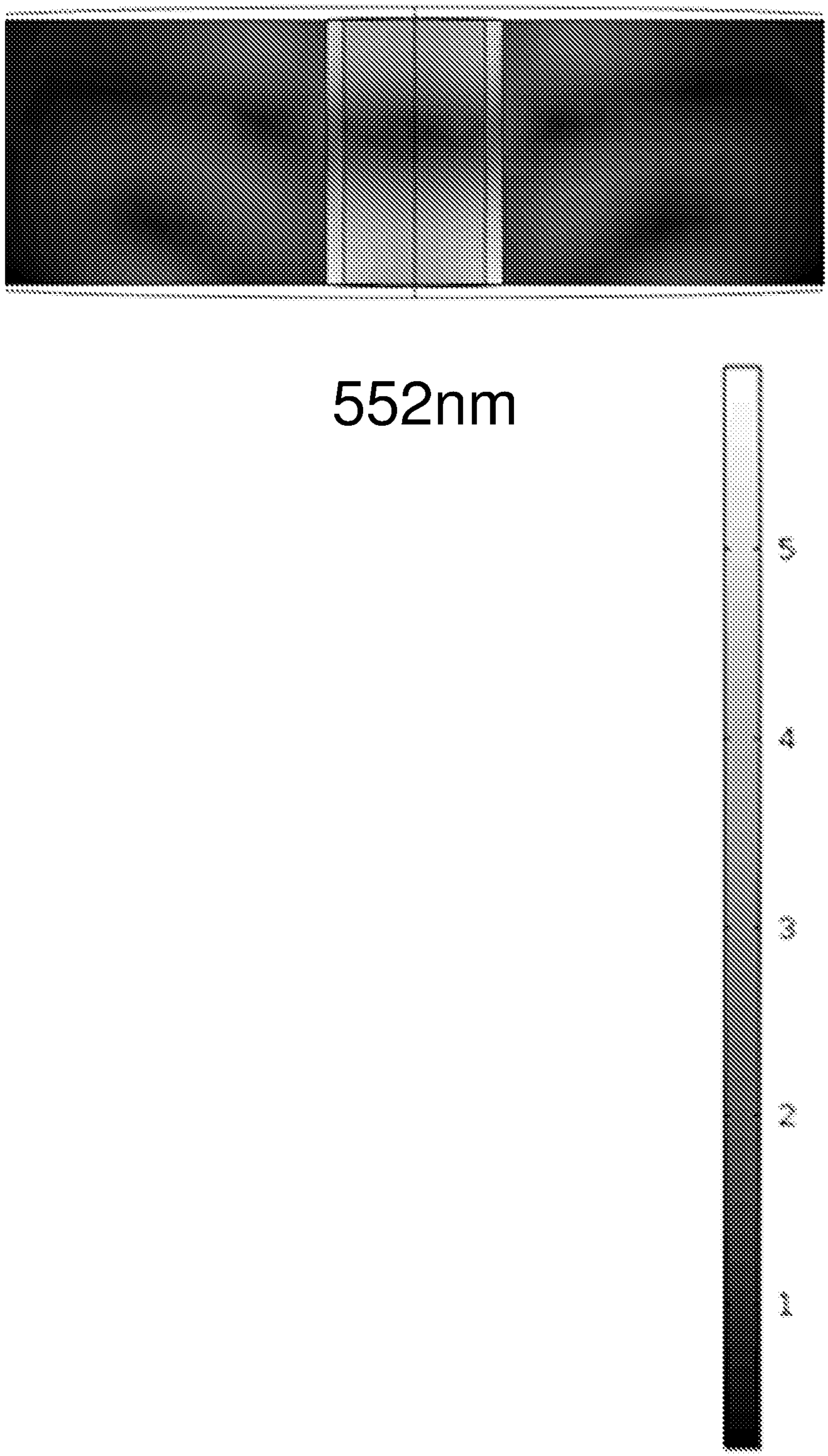


FIG. 7J

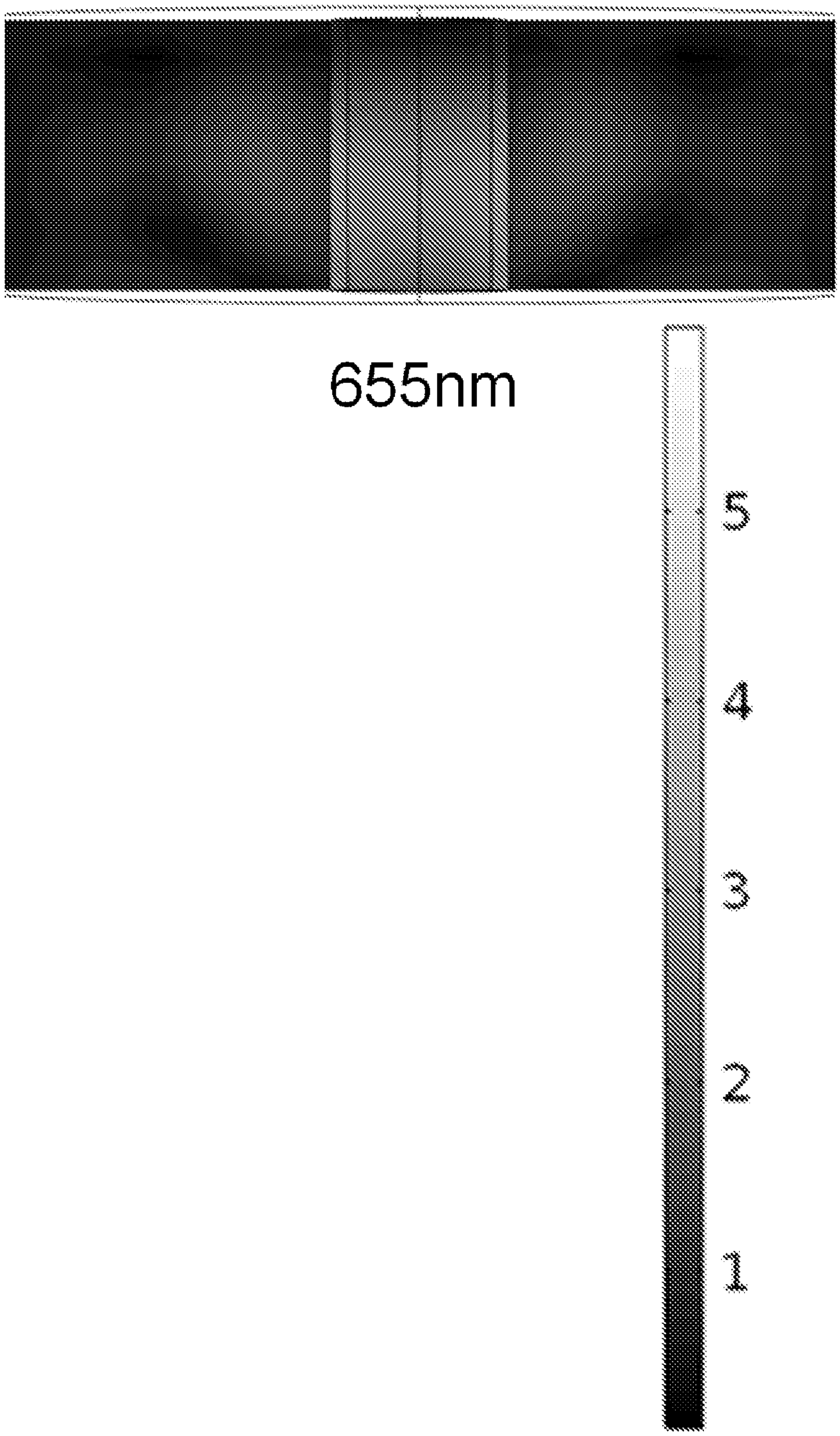


FIG. 7K

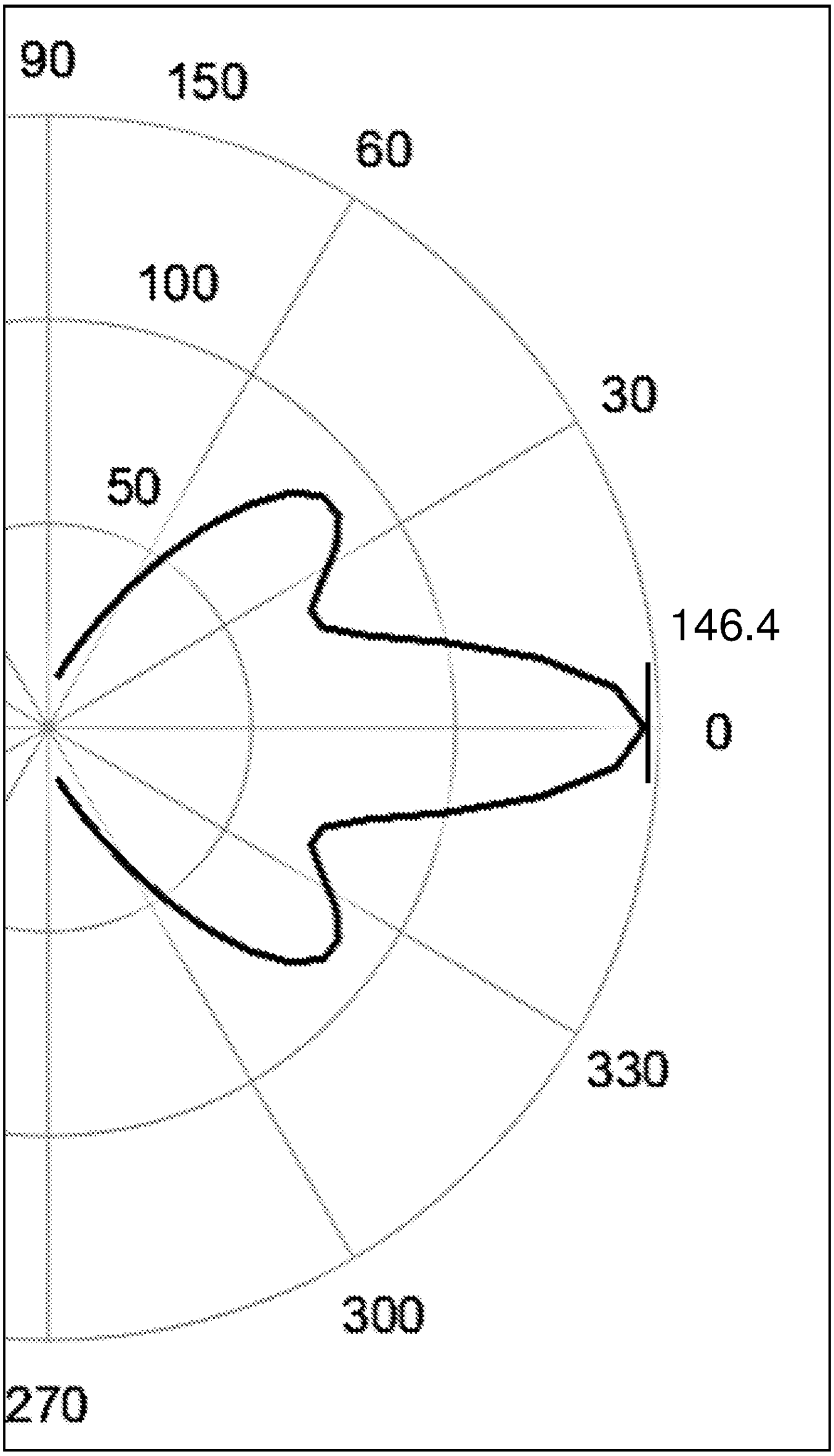
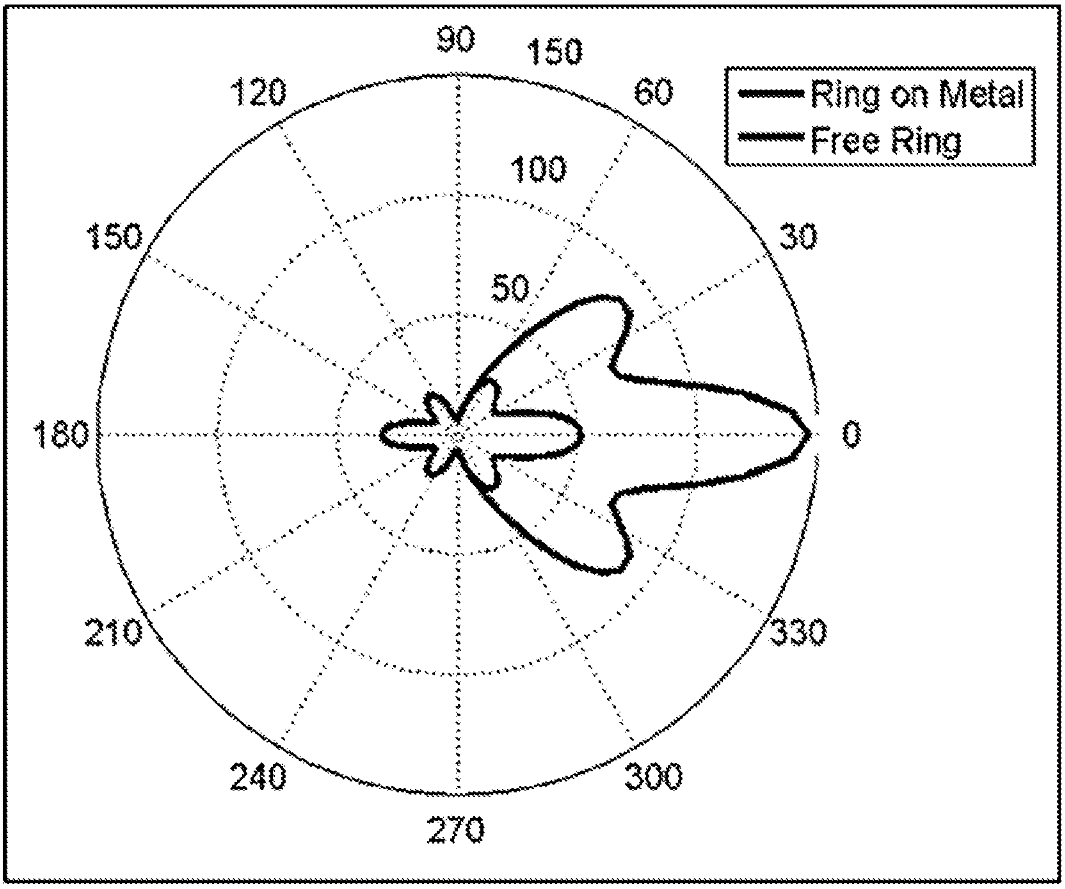


FIG. 7L



90
150
120
60
100
150
30
50
180
0
210
330
240
300
270
Ring on Metal
Free Ring

FIG. 8

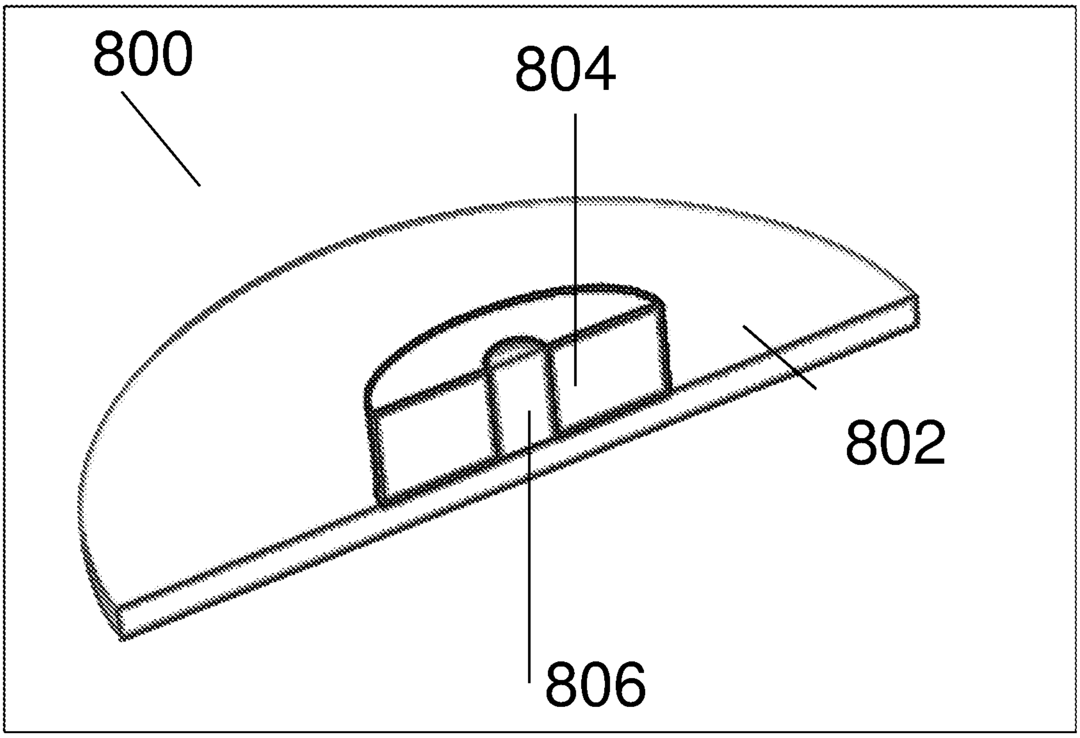


FIG. 9

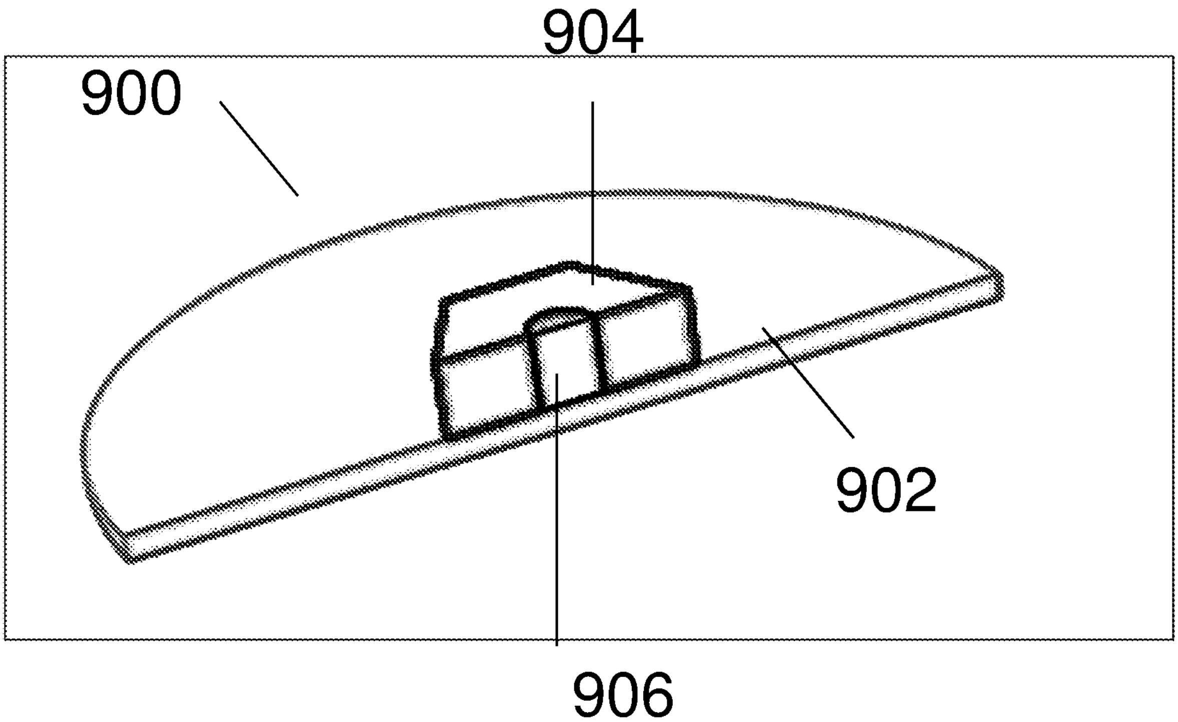
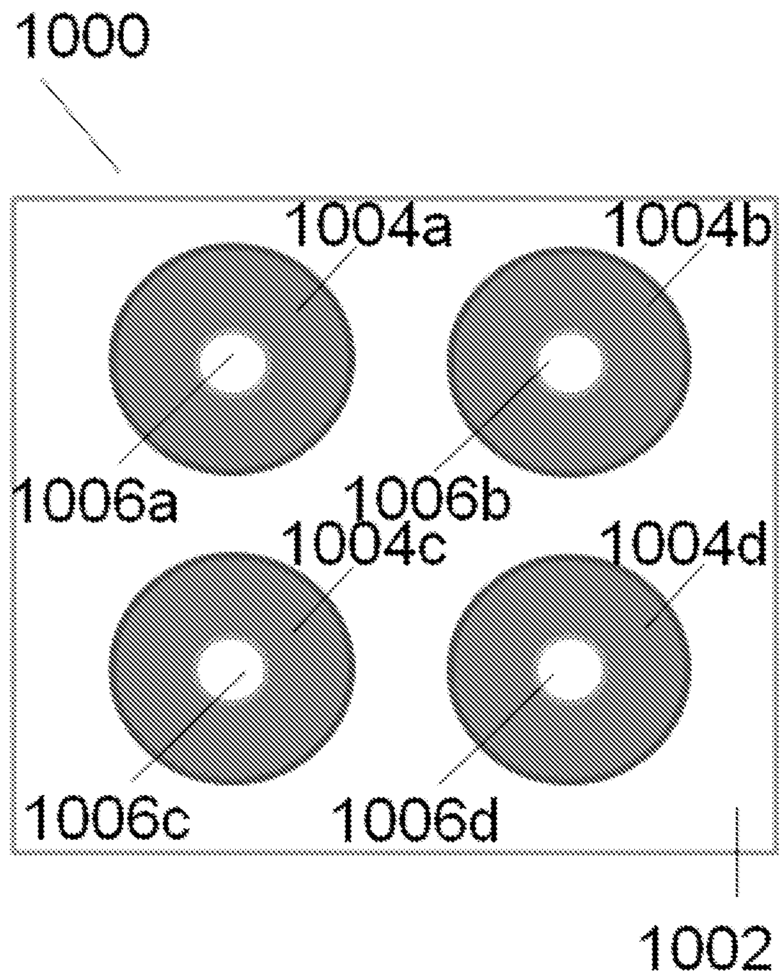


FIG. 10



INTERNATIONAL SEARCH REPORT	International application No. PCT/SG2019/050092

A. CLASSIFICATION OF SUBJECT MATTER

See Supplemental Box

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G02F; G02B; H01Q; B82Y; Y10S

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

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

FAMPAT: dielectric, semiconductor, silicon, oxide, ring, donut, hollow, cylinder, concentric, bullseye, metal layer, gold, silver, enhance output emission, antenna, plasmon, mie, resonant cavity, emitter, source, 纳米天线, 表面等离子, 米氏, 介质, 氧化物, 半导体, 环, 空腔, 共振, 发射, 发光源, 量子点 and related search keywords.
Internet: hybrid nanoantenna, plasmonic, emitter, dielectric ring cavity, mie resonance.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	ANDERSEN S. K. H. ET AL., Hybrid plasmonic bullseye antennas for efficient photon collection. *ACS Photonics*, 7 January 2018, Vol. 5, pages 692-698 [Retrieved on 2019-04-18] <DOI: 10.1021/ACSPHOTONICS.7B01194> Entire document	1-20
A	RAKOVICH A. ET AL., Plasmonic control of radiative properties of semiconductor quantum dots coupled to plasmonic ring cavities. ACS Nano, 20 January 2015, Vol. 9, No. 3, pages 2648-2658 [Retrieved on 2019-04-18] <DOI: 10.1021/NN506433E> Entire document	
A	FENG T. ET AL., Unidirectional emission in an all-dielectric nanoantenna. *J. Phys.: Condens. Matter.*, 27 February 2018, Vol. 30, pages 124002 [Retrieved on 2019-04-18] <DOI: 10.1088/1361-648X/AAAB28> Results and discussion section, figure 1	

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

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G02B 5/00 (2006.01)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SG2019/050092

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2018/048348 A1 (AGENCY FOR SCIENCE, TECHNOLOGY AND RESEARCH) 15 March 2018 Entire document	
A	LEPESHOV S. I. ET AL., Hybrid nanophotonics. *Physics-Uspekhi*, 30 November 2018, Vol. 61, No. 11, pages 1035-1050 [Retrieved on 2019-04-18] <DOI: 10.3367/UFNR.2017.12.038275> Entire document	
A	CN 103066495 B (PEKING UNIVERSITY SHENZHEN GRADUATE SCHOOL) 17 September 2014 Entire document of the original non-English language document (a machine translation is enclosed **only** for your reference)	

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2018/048348 A1	15/03/2018	SG 11201901295U A	28/03/2019
CN 103066495 B	17/09/2014	CN 103066495 A	24/04/2013