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[Continued on next page]

(54) Title: NANO-ANTENNA AND METHODS FOR ITS PREPARATION AND USE

(57) Abstract: Nano-antennas with a resonant frequency in the optical or near infrared region of the electromagnetic spectrum and methods of making the nano-antennas are described. The nano-antenna includes a porous membrane, a plurality of nanowires disposed in the porous membrane, and a monolayer of nanospheres each having a diameter that is substantially the same as a diameter of the nanowires. The nanospheres are electrically in series with the nanowires.

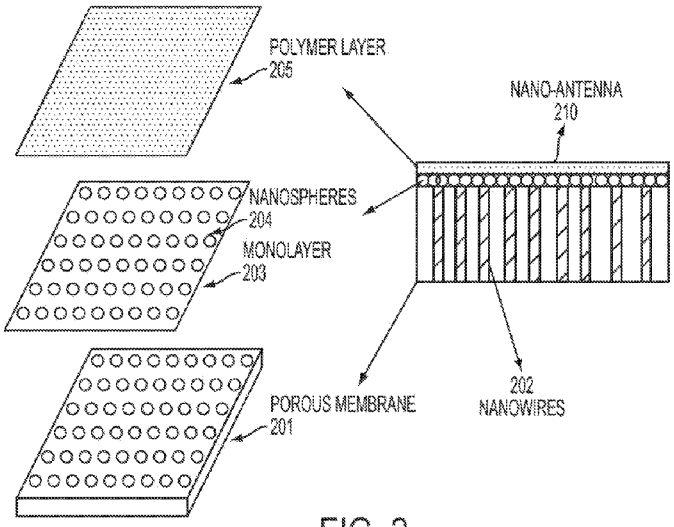


FIG. 2

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NANO-ANTENNA AND METHODS FOR ITS PREPARATION AND USE

BACKGROUND

[0001] An antenna is generally a transducer device that receives or transmits electromagnetic radiation. The frequency of radiation that may be received or transmitted by an antenna is dependent on the size of the antenna, and the speed of light and the distance that electrons can travel (electron mobility) in the material medium of the antenna. Because electromagnetic waves propagate more slowly in a medium than in free space, the same number of waves will span a greater distance in free space than in the transmission medium, hence the transmission medium is said to have an electrical length that is greater than its physical length. Typically, the electrical length of an antenna is expressed in units of the wavelength (in the antenna medium) corresponding to the resonant frequency of the antenna.

[0002] Antennas are typically associated with signals having frequency of about 30 kilohertz (kHz) to about 30 gigahertz (GHz), and may be associated with, for example, longwave AM radio broadcasting, wireless LAN, radars and satellite television broadcasting. In general, the electrical length of an antenna is on the order of the free-space wavelength of the radiation at which the antenna is resonant. For example, a dipole antenna is typically about $1/4^{th}$ the free-space wavelength. Similarly, the physical length of an antenna is on the order of the wavelength in the antenna medium of the radiation at which the antenna is resonant. Given that the wavelength of electromagnetic radiation is shorter in a medium than in free space, the physical length of an antenna is typically shorter than its electrical length.

[0003] The electrical length of an antenna can be modified in order to cause an antenna of a particular physical length to resonate at a required frequency, by adding suitable reactive elements such as capacitors or inductors. For low frequency (long wavelength) transmission or reception, the physical length of an antenna becomes too long to be economically or physically viable. The electrical length of the antenna is, therefore,

lengthened by adding suitable reactive elements to allow a shorter antenna to resonate at lower frequencies. On the other hand transmission or reception of higher frequencies, for example optical frequencies, may necessitate shortening the electrical length of the antenna in order to make the physical length longer.

SUMMARY

[0004] This disclosure is not limited to the particular systems, devices and methods described, as these may vary. The terminology used in the description is for the purpose of describing the particular versions or embodiments only, and is not intended to limit the scope.

[0005] As used in this document, the singular forms "a," "an," and "the" include plural references unless the context clearly dictates otherwise. Unless defined otherwise, all technical and scientific terms used herein have the same meanings as commonly understood by one of ordinary skill in the art. Nothing in this disclosure is to be construed as an admission that the embodiments described in this disclosure are not entitled to antedate such disclosure by virtue of prior invention. As used in this document, the term "comprising" means "including, but not limited to."

[0006] In an embodiment, a method of manufacturing a nano-antenna is described. A plurality of nanowires are disposed in a porous membrane and a monolayer of nanospheres to form the nano-antenna. The nanospheres have a diameter substantially the same as a diameter of the nanowires is placed electrically in series with the nanowires.

[0007] In an embodiment, a nano-antenna comprising a porous membrane, a plurality of nanowires disposed in the porous membrane and a monolayer of nanospheres electrically in series with the nanowires is described. The nanospheres have substantially the same diameter as the nanowires.

[0008] In an embodiment, a method of manufacturing a tunable colorant is described. The method may include providing at least one nano-antenna, and placing at least one reactive element, that may be made from nanospheres, in electrical contact with the nano-antenna.

[0009] In an embodiment, a tunable colorant may include a nano-antenna and a resistive element. The nano-antenna may include a porous membrane, a plurality of nanowires disposed in the porous membrane, and a monolayer of nanospheres electrically in series with the nanowires. The nanospheres have substantially the same diameter as the nanowires.

BRIEF DESCRIPTION OF DRAWINGS

[0010] In the detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. The illustrative embodiments described in the detailed description, drawings, and claims are not meant to be limiting. Other embodiments may be used, and other changes may be made, without departing from the spirit or scope of the subject matter presented herein. It will be readily understood that the aspects of the present disclosure, as generally described herein, and illustrated in the Figures, can be arranged, substituted, combined, separated, and designed in a wide variety of different configurations, all of which are explicitly contemplated herein.

[0011] Figure 1 depicts a flow diagram for an illustrative method of manufacturing a nano-antenna according to an embodiment.

[0012] Figure 2 depicts a schematic of an illustrative nano-antenna according to an embodiment.

[0013] Figure 3 depicts a symbolic diagram of an illustrative tunable colorant according to an embodiment.

DETAILED DESCRIPTION

[0014] Every antenna has a characteristic impedance, which is defined as the ratio of voltage to current at any given point in the antenna. In general, the impedance of an antenna is a complex number dependent on the frequency of the voltage (or current). The real part of the complex impedance is pure resistance and is frequency independent. The complex part (also called reactance) is the frequency dependent part of the impedance and may be either directly proportional to the frequency (inductive reactance) or inversely proportional to the frequency (capacitive reactance). The resonant frequency of an antenna is defined as the frequency at which the capacitive impedance and the inductive impedance of the antenna are equal and opposite to each other, thereby cancelling each other and making the impedance at that frequency purely resistive. The voltage and current at this frequency are in phase with each other.

[0015] The complex impedance of an antenna may be determined by the following formula:

$$Z_a = R_a + iX_a \text{ – (Eq. I)}$$

where R_a is the resistance and X_a is the reactance of the antenna, having a capacitive component and an inductive component according to:

$$X_a = X_C + X_L = (-1/\omega C) + \omega L \text{ – (Eq. II)}$$

where $\omega = 2\pi f$ is the angular frequency and f is the frequency.

[0016] It is evident that by changing one or both of the inductive impedance and the capacitive impedance, the resonant frequency of an antenna can be changed.

[0017] In general, the resonant frequency of an antenna depends on the geometry and the material of the antenna, but may be modulated by adding reactive elements to the antenna circuit. The physical length of an antenna is, in general, roughly inversely proportional to the resonant frequency. Increasing the resonant frequency of an antenna of a

given geometry by adding a capacitive element is referred to as electrically shortening the antenna, thereby allowing resonance at higher frequencies than would otherwise be determined by its physical length. Decreasing the resonant frequency of an antenna of a given geometry by adding an inductive element is referred to as electrically lengthening the antenna, thereby allowing resonance at lower frequencies than would otherwise be determined by its physical length.

[0018] Given that the wavelength for optical and near infrared frequencies (about 12 terahertz (THz) to about 800 THz) is about 1 micrometer (μm) to about 400 nanometer (nm), the required physical length of antennas resonating at optical and near infrared frequencies makes fabricating such antennas a significant challenge. Because optical frequencies are in the range of plasma frequencies of metals, quantum effects apply at these frequencies and classical antenna theory has to be modified. As such, nano-scale fabrication of antennas coupled with electrical shortening using suitable non-classical nano-scale reactive elements may provide a potential solution for creating nano-antennas resonating at optical and near infrared frequencies.

[0019] Figure 1 depicts a flow diagram of an illustrative method of manufacturing a nano-antenna according to an embodiment. The method may include disposing **101** a plurality of nanowires in a porous membrane and placing **102** a monolayer of nanospheres electrically in series with the nanowires to form a nano-antenna. The nanospheres may have substantially the same diameter as the nanowires. In some embodiments, the nano-antenna may have a resonant frequency of about 12 THz to about 800 THz. Specific examples of the resonant frequency can include 12 THz, 25 THz, 50 THz, 100 THz, 200 THz, 300 THz, 400 THz, 500 THz, 600 THz, 700 THz, 800 THz, and ranges between any two of these values.

[0020] In some embodiments, the method may further include placing **103** a polymer layer in electrical contact with the monolayer of nanospheres. In some embodiments,

the polymer layer may be placed **103** over the monolayer of nanospheres, for example, by depositing the polymer layer using a chemical process. In some embodiments, the polymer layer may be placed **103** such that the monolayer of nanospheres and the polymer layer are electrically in series with each other. In other embodiments, the polymer layer may be placed **103** such that the monolayer of nanospheres and the polymer layer are electrically in parallel with each other.

[0021] In some embodiments, the nanowires may be deposited **101** in the porous membrane by physical vapor deposition. In some embodiments, the nanowires may be formed **101** in a thin film by using photolithography followed by etching away the thin film. In some embodiments, the nanowires may be formed by self-assembly.

[0022] In some embodiments, the nanospheres may be deposited **102** in a well adjoining the nanowires to form a monolayer. The well may be formed by etching the porous membrane in an area defined by using photolithography. In some embodiments, the nanospheres may be deposited **102** on the porous membrane to form a monolayer such that the nanospheres are in contact with the nanowires.

[0023] In some embodiments, the polymer layer may be deposited **103** using a chemical vapor deposition process. In some embodiments, the polymer layer may be deposited **103** by placing a thin film of a polymer on top of the monolayer of nanospheres.

[0024] Various embodiments of the nano-antenna are described herein.

[0025] Figure 2 depicts a schematic of an illustrative nano-antenna according to an embodiment. The nano-antenna **210** includes a porous membrane **201**, a plurality of nanowires **202** disposed in the porous membrane **201**, and a monolayer **203** of nanospheres **204** with substantially the same diameter as the nanowires **202** electrically in series with the nanowires. In some embodiments, the nano-antenna **210** has a resonant frequency of about 12 THz to about 800 THz (near infrared to optical).

[0026] In some embodiments, the porous membrane **201** may be made of, for example alumina, silicon, silicon dioxide, polymethyl methacralate, and so forth.

[0027] In some embodiments, the nano-antenna **210** may additionally have a polymer layer **205** in electrical contact with the monolayer of nanospheres. In certain embodiments, the polymer layer **205** may be an insulating layer made from, for example, polydimethyl siloxane (PDMS), polymethyl methacralate (PMMA), polyethylene (PE), polystyrene (PS), polypropylene, polyethylene terephthalate (PET), polycarbonate, polyacrylate, neoprene, nylon, polyvinyl chloride (PVC), polyvinyl butyral (PVB), polyacrylonitrile, silicone, combinations of any two or more, and/or the like. In other embodiments, the polymer layer **205** may be a conductive layer made from, for example, polyacetylene, polypyrrole, polyaniline, poly(p-phylene vinylene), polythiophenes, and/or the like.

[0028] A nano-antenna resonating at optical and infrared frequencies may be used in applications such as conversion of solar energy into electrical energy instead of or in addition to photovoltaic panels. In such applications, it may be desirable for the nano-antenna **210** to be transparent or translucent. In some embodiments, one or more of the porous membrane **201**, the nanowires **202**, the monolayer **203** of nanospheres **204**, and the polymer layer **205** may be transparent. In other embodiments, one or more of the porous membrane **201**, the nanowires **202**, the monolayer **203** of nanospheres **204**, and the polymer layer **205** may be translucent.

[0029] A capacitive reactance has an effect of shortening the electrical length of an antenna, whereas an inductive reactance has an effect of lengthening the electrical length of an antenna. The nanowires **202** may act as a nano-antenna **210** for which the resonant frequency is determined by the physical length of the nanowires **202**. Depending on the specific application, it may be required to lengthen or shorten the electrical length of the

nano-antenna **210** corresponding to its use for a certain frequency. A capacitive reactance may be added by adding a monolayer **203** of dielectric nanospheres **204** electrically in series with nanowires **202**. An inductive reactance may be added by adding a monolayer **203** of conducting nanospheres **204** electrically in series with the nanowires **202**. In some embodiments, the nanospheres **204** may be made of dielectric materials such as, for example, polymers, glasses, silica, carbohydrates, lignins, combinations thereof, and/or the like. In other embodiments, the nanospheres **204** may be made of conductive materials including, without limitation, metals, conductive polymers and/or the like. In certain embodiments, where transparency is desired, the nanospheres **204** may be made of a transparent polymer material.

[0030] The resistance R_a (Eq. I), the capacitive impedance X_C (Eq. II), and the inductive impedance X_L (Eq. II), and thereby the resonant frequency of a nano-antenna **210** are dependent on the dimensions of the nanowires **202** and the nanospheres **204** forming the nano-antenna. In some embodiments, the nanowires **202** may have an aspect ratio of about 3:1 (height to diameter) to provide appropriate impedance to the nano-antenna **210**. In certain embodiments, the nanowires **202** may be made of a metal such as, for example, gold (Au), silver (Ag), iron (Fe), titanium (Ti), platinum (Pt), copper (Cu), zinc (Zn), aluminum (Al), manganese (Mn), cobalt (Co), nickel (Ni), combinations thereof, alloys thereof, and/or the like. In other embodiments, the nanowires **204** may be made of a doped semiconductor such as, for example, boron doped silicon, phosphorous doped silicon, and/or the like. In yet other embodiments, the nanowires **202** may be of a doped metal oxide such as, for example, fluorine doped tin oxide, indium doped tin oxide, and/or the like. A skilled artisan will realize that a nano-antenna **210** may be formed by combining nanowires **202** of any of the appropriate materials listed herein in any combination thereof.

[0031] The reactance offered by the nanospheres **204** is dependent on the size of the nanospheres. Depending on the application, the size of the nanowires **202**, and the required resonant frequency, as determined from the equations listed above the nanospheres **204** may have a diameter of about 5 nm to about 50 nm, about 50 nm to about 100 nm, about 100 nm to about 200 nm, about 200 nm to about 300 nm, about 300 nm to about 400 nm, about 400 nm to about 500 nm, or any combination thereof. Specific examples of diameters include about 5 nm, about 50 nm, about 100 nm, about 200 nm, about 300 nm, about 400 nm, about 500 nm, and ranges between any two of these values.

[0032] In some embodiments, the nanospheres **204** may be made of dielectric materials such as, for example, polymers, glasses, silica, carbohydrates, lignin, combinations thereof, and/or the like. In other embodiments, the nanospheres **204** may be made of conductive materials including, without limitation, metals, conductive polymers and/or the like. In certain embodiments, where transparency is desired, the nanospheres **204** may be of a transparent polymer material.

[0033] A nano-antenna resonating at a specific frequency in the optical range may act as an absorber for the color corresponding to the resonant frequency if the energy received from that color is completely dissipated. Energy received by a nano-antenna may be dissipated as heat, for example, by coupling the nano-antenna with a resistive element. A nano-antenna coupled to a resistive element, when placed on a reflective surface may act as a colorant by removing a specific color from the reflected light. For example, a nano-antenna resonating at a red frequency (about 670 nm to about 750 nm) when coupled with a resistive element would remove red color from the reflected spectrum, resulting in the surface appearing cyan. In some aspects, methods of manufacturing a tunable colorant are described. Figure 3 depicts a symbolic diagram of an illustrative tunable colorant according to an embodiment. A tunable colorant may be manufactured by placing at least one reactive

element **301** in electrical contact with a nano-antenna **302**. Various embodiments of the nano-antenna have been described herein. In some embodiments, the nano-antenna may have a resonant frequency of about 12 THz to about 800 THz.

[0034] In some embodiments, the nano-antenna **302** may have a dipole, a monopole, or a slot configuration. In some embodiments, the nano-antenna **302** may have a specific directivity, or specific polarization. Various embodiments of the nano-antenna are described herein.

[0035] In some embodiments, the at least one reactive element **301** may include nanospheres. In some embodiments, the at least one reactive element **301** may be a capacitive element made of dielectric nanospheres with positive permittivity. In some embodiments, the at least one reactive element **301** may be an inductive element made of conductive nanospheres with negative permittivity. In some embodiments, the at least one reactive element **301** is a resistive element made of an insulating polymer layer. The resistive element may, in some embodiments, be either in an electrically parallel configuration with the nano-antenna **302** or electrically in series with the nano-antenna **302**. Various embodiments of nanospheres that may form the at least one reactive element are described herein.

[0036] In some embodiments the at least one reactive element **301** is configured to allow modulation of the reactance of the reactive element. In certain embodiments, the amount of modulation is determined by a computer-simulation of the nano-antenna **302**.

[0037] In some aspects, a tunable colorant is described. The tunable colorant includes a nano-antenna **302** and a resistive element **301**. The nano-antenna **302** may be configured such that the resonant frequency of the nano-antenna may depend on the resistance of the resistive element **301**. In such a configuration, the color of the colorant changes based on the resistance of the resistive element. In some embodiments, the nano-

antenna **302** has a resonant frequency of about 12 THz to about 800 THz. Various embodiments of the nano-antenna **302** have been described herein.

[0038] In some embodiments, the resistive element is configured such that the resistance of the resistive element is altered by a biological process such as, for example, attachment, absorption, or adsorption of specific molecules, antibodies, antigens, proteins, and the like. In some embodiments, the resistive element is configured to dissipate energy absorbed by the nano-antenna as heat.

EXAMPLES

Example 1: Fabrication of a 50 THz gold nanowire nano-antenna

[0039] Monopole nano-antennas electrically shortened by dielectric nanospheres are constructed. The resonant frequency of the nano-antenna is 50 THz (free-space wavelength of 600 nm) corresponding to an orange color. A 100 nm thick porous alumina membrane **201** (in Figure 2) with a pore size of about 24 nm is used for construction of these nano-antennas. The pores are filled with gold by electro-deposition to form nanowires **201**. A monolayer **203** of 24 nm diameter nanospheres **204** of PMMA is deposited on top of the gold filled alumina membrane, followed by placing a 2 μm thick layer **205** of PDMS on top of the nanospheres to form the nano-antenna **210**.

[0040] The monolayer of the PMMA nanospheres is absorbed to the alumina surface by concentration limited diffusion. A suspension containing PMMA nanospheres is diluted suitably and disposed on the alumina surface.

[0041] The PDMS layer is placed by mixing the PDMS pre-cursors in suitable ratios, degassing the resulting mixture, disposing a suitable amount (calculated based on the area and thickness of the layer required) of the degassed mixture to form a thin layer of PDMS, followed by curing the formed layer for at least about 8 hours at a temperature of about 45 ^{o}C.

Example 2: Fabrication of a cyan colored coating

[0042] Gold nanowires of about 24 nm are fabricated as in example 1. Monopole antennas resonating at a frequency of 50 THz (free-space wavelength of 600 nm) are formed using the gold nanowires by shortening the electrical wavelength of the nanowires by depositing PMMA nanospheres of about 24 nm in diameter. The resonant frequency of 50 THz corresponds to red/orange color in air. A film including monopole nano-antennas constructed in this fashion, when exposed to white light, strongly absorb light at 600 nm (red/orange) resulting in a cyan coloration. The color of such a coating may be changed by changing the diameter of the gold nanowires or the PMMA nanospheres.

Example 3: A biologically tunable colorant.

[0043] The PMMA nanospheres from Example 2 are functionalized by attaching a monoclonal antibody specific to a particular antigen. Nano-antennas having functionalized PMMA nanospheres are incorporated in a film. When this film is exposed to the particular antigen, the antigen specifically attaches to the antibody, thereby changing the capacitance of the PMMA nanospheres. This results in a change in resonant frequency of the nano-antennas, giving an optical signal, wavelength shift, and/or quenching an optical signal that is dependent on the amount of antigen attached to the nanospheres.

[0044] Similar embodiments for biologically tunable colorants can be constructed by using functionalized metal nanospheres. In such a case, the change in inductance of the metal nanospheres is dependent on the amount of antigen attached to the nanospheres.

[0045] The present disclosure is not to be limited in terms of the particular embodiments described in this application, which are intended as illustrations of various aspects. Many modifications and variations can be made without departing from its spirit and scope, as will be apparent to those skilled in the art. Functionally equivalent methods and

apparatuses within the scope of the disclosure, in addition to those enumerated herein, will be apparent to those skilled in the art from the foregoing descriptions. Such modifications and variations are intended to fall within the scope of the appended claims. The present disclosure is to be limited only by the terms of the appended claims, along with the full scope of equivalents to which such claims are entitled. It is to be understood that this disclosure is not limited to particular methods, reagents, compounds, compositions or biological systems, which can, of course, vary. It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments only, and is not intended to be limiting.

[0046] With respect to the use of substantially any plural and/or singular terms herein, those having skill in the art can translate from the plural to the singular and/or from the singular to the plural as is appropriate to the context and/or application. The various singular/plural permutations may be expressly set forth herein for sake of clarity.

[0047] It will be understood by those within the art that, in general, terms used herein, and especially in the appended claims (*e.g.*, bodies of the appended claims) are generally intended as "open" terms (*e.g.*, the term "including" should be interpreted as "including but not limited to," the term "having" should be interpreted as "having at least," the term "includes" should be interpreted as "includes but is not limited to," etc.). It will be further understood by those within the art that if a specific number of an introduced claim recitation is intended, such an intent will be explicitly recited in the claim, and in the absence of such recitation no such intent is present. For example, as an aid to understanding, the following appended claims may contain usage of the introductory phrases "at least one" and "one or more" to introduce claim recitations. However, the use of such phrases should not be construed to imply that the introduction of a claim recitation by the indefinite articles "a" or "an" limits any particular claim containing such introduced claim recitation to embodiments containing only one such recitation, even when the same claim includes the introductory

phrases "one or more" or "at least one" and indefinite articles such as "a" or "an" (*e.g.*, "a" and/or "an" should be interpreted to mean "at least one" or "one or more"); the same holds true for the use of definite articles used to introduce claim recitations. In addition, even if a specific number of an introduced claim recitation is explicitly recited, those skilled in the art will recognize that such recitation should be interpreted to mean at least the recited number (*e.g.*, the bare recitation of "two recitations," without other modifiers, means at least two recitations, or two or more recitations). Furthermore, in those instances where a convention analogous to "at least one of A, B, and C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (*e.g.*, " a system having at least one of A, B, and C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). In those instances where a convention analogous to "at least one of A, B, or C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (*e.g.*, " a system having at least one of A, B, or C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). It will be further understood by those within the art that virtually any disjunctive word and/or phrase presenting two or more alternative terms, whether in the description, claims, or drawings, should be understood to contemplate the possibilities of including one of the terms, either of the terms, or both terms. For example, the phrase "A or B" will be understood to include the possibilities of "A" or "B" or "A and B."

[0048] In addition, where features or aspects of the disclosure are described in terms of Markush groups, those skilled in the art will recognize that the disclosure is also thereby described in terms of any individual member or subgroup of members of the Markush group.

[0049] As will be understood by one skilled in the art, for any and all purposes, such as in terms of providing a written description, all ranges disclosed herein also encompass any and all possible subranges and combinations of subranges thereof. Any listed range can be easily recognized as sufficiently describing and enabling the same range being broken down into at least equal halves, thirds, quarters, fifths, tenths, etc. As a non-limiting example, each range discussed herein can be readily broken down into a lower third, middle third and upper third, etc. As will also be understood by one skilled in the art all language such as "up to," "at least," and the like include the number recited and refer to ranges which can be subsequently broken down into subranges as discussed above. Finally, as will be understood by one skilled in the art, a range includes each individual member. Thus, for example, a group having 1-3 cells refers to groups having 1, 2, or 3 cells. Similarly, a group having 1-5 cells refers to groups having 1, 2, 3, 4, or 5 cells, and so forth.

[0050] Various of the above-disclosed and other features and functions, or alternatives thereof, may be combined into many other different systems or applications. Various presently unforeseen or unanticipated alternatives, modifications, variations or improvements therein may be subsequently made by those skilled in the art, each of which is also intended to be encompassed by the disclosed embodiments.

CLAIMS

What is claimed is:

1. A method of manufacturing a nano-antenna, the method comprising:

disposing a plurality of nanowires in a porous membrane, wherein each nanowire has a diameter; and

placing a monolayer of nanospheres electrically in series with the plurality of nanowires, wherein the nanospheres have substantially the same diameter as the nanowires.

2. The method of claim 1, further comprising placing a polymer layer in electrical contact with the monolayer of nanospheres.

3. The method of claim 2, wherein the polymer layer comprises a conductive layer.

4. The method of claim 2, wherein placing the polymer layer comprises placing the polymer layer over the monolayer of nanospheres.

5. The method of claim 2, wherein placing the polymer layer comprises placing the polymer layer electrically in series with the monolayer of nanospheres.

6. The method of claim 2, wherein each of the porous membrane, the plurality of nanowires, and the polymer layer are visibly transparent.

7. The method of claim 2, wherein each of the porous membrane, the plurality of nanowires, and the polymer layer are visibly translucent.

8. The method of claim 2, wherein the polymer layer comprises an insulating layer comprising one or more of polydimethyl siloxane (PDMS), polymethyl methacralate

(PMMA), polyethylene (PE), polystyrene (PS), polypropylene, polyethylene terephthalate (PET), polycarbonate, polyacrylate, neoprene, nylon, polyvinyl chloride (PVC), polyvinyl butyral (PVB), polyacrylonitrile, silicone, and a combination thereof.

9. The method of claim 1, wherein the nanospheres comprise dielectric nanospheres.

10. The method of claim 1, wherein the nanospheres comprise conductive nanospheres.

11. The method of claim 1, wherein the nanospheres comprise a transparent polymer.

12. The method of claim 1, wherein the nanospheres have a diameter of about 5 nm to about 500 nm.

13. The method of claim 1, wherein the aspect ratio of the nanowires is at least 3:1 (height to diameter).

14. The method of claim 1, wherein the plurality of nanowires comprise gold nanowires.

15. The method of claim 1, wherein the nano-antenna has a resonance frequency of about 12 THz to about 800 THz.

16. A nano-antenna comprising:

a porous membrane;

a plurality of nanowires disposed in the porous membrane, wherein each nanowire has a diameter; and

a monolayer of nanospheres electrically in series with the plurality of nanowires, wherein the nanospheres have substantially the same diameter as the nanowires.

17. The nano-antenna of claim 16, further comprising a polymer layer in electrical contact with the monolayer of nanospheres.

18. The nano-antenna of claim 17, wherein the polymer layer comprises a conductive layer.

19. The nano-antenna of claim 17, wherein the polymer layer is disposed over the monolayer of nanospheres.

20. The nano-antenna of claim 17, wherein the polymer layer is disposed electrically in series with the monolayer of nanospheres.

21. The nano-antenna of claim 17, wherein each of the porous membrane, the plurality of nanowires, and the polymer layer are visibly transparent.

22. The nano-antenna of claim 17, wherein each of the porous membrane, the plurality of nanowires, and the polymer layer are visibly translucent.

23. The nano-antenna of claim 17, wherein the polymer layer comprises an insulating layer comprising one or more of polydimethyl siloxane (PDMS), polymethyl methacralate (PMMA), polyethylene (PE), polystyrene (PS), polypropylene, polyethylene terephthalate (PET), polycarbonate, polyacrylate, neoprene, nylon, polyvinyl chloride (PVC), polyvinyl butyral (PVB), polyacrylonitrile, silicone, and a combination thereof.

24. The nano-antenna of claim 16, wherein the nanospheres comprise dielectric nanospheres.

25. The nano-antenna of claim 24, wherein the nanospheres comprise conductive nanospheres.

26. The nano-antenna of claim 16, wherein the nanospheres comprise a transparent polymer.

27. The nano-antenna of claim 16, wherein the nanospheres have a diameter of about 5 nm to about 500 nm.

28. The nano-antenna of claim 16, wherein the nanowires have a height, a diameter and an aspect ratio at least 3:1 (height to diameter).

29. The nano-antenna of claim 16, wherein the plurality of nanowires comprise gold nanowires.

30. The nano-antenna of claim 16, wherein the nano-antenna has a resonance frequency of about 12 THz to about 800 THz.

31. A method of manufacturing a tunable colorant, the method comprising:

providing at least one nano-antenna; and

placing at least one reactive element comprising nanospheres in electrical contact with the nano-antenna.

32. The method of claim 31, wherein the nano-antenna comprises:

a porous membrane;

a plurality of nanowires disposed in the porous membrane, wherein each nanowire has a diameter; and

a monolayer of nanospheres electrically in series with the plurality of nanowires, wherein the nanospheres have substantially the same diameter as the nanowires.

33. The method of claim 31, wherein the nano-antenna has a resonance frequency of about 12 THz to about 800 THz.

34. The method of claim 31, wherein the reactive elements comprise a capacitor.

35. The method of claim 34, wherein the capacitor comprises a dielectric nanosphere with positive permittivity.

36. The method of claim 34, wherein the reactive elements comprise an inductor.

37. The method of claim 36, wherein the inductor comprises a conductive nanosphere with negative permittivity.

38. The method of claim 31, wherein the reactive elements are configured to allow modulation of a reactance of the reactive elements.

39. The method of claim 38, wherein modulation of the reactance is determined by a computer simulation of the nano-antenna.

40. The method of claim 31, wherein the nano-antenna comprises a dipole antenna.

41. The method of claim 31, wherein the nano-antenna comprises a monopole antenna.

42. The method of claim 31, wherein the nano-antenna comprises a slot antenna.

43. The method of claim 31, further comprising adding a resistive element in series with the nano-antenna.

44. The method of claim 31, further comprising adding a resistive element in parallel with the nano-antenna.

45. A tunable colorant comprising:

a nano-antenna comprising a porous membrane, a plurality of nanowires disposed in the porous membrane, wherein each nanowire has a diameter, and a monolayer of nanospheres electrically in series with the plurality of nanowires, wherein the nanospheres have substantially the same diameter as the nanowires; and

a resistive element,

wherein the colorant is configured to change color based on a resistance of the resistive element.

46. The tunable colorant of claim 45, wherein the resistive element has a resistance configured to be altered by a biological process.

47. The tunable colorant of claim 45, wherein the nano-antenna has a resonance frequency of about 12 THz to about 800 THz.

48. The tunable colorant of claim 45, wherein the nano-antenna has specific directivity or polarization.

49. The tunable colorant of claim 45, wherein the nano-antenna is configured to absorb energy at a resonance frequency.

50. The tunable colorant of claim 45, wherein the resistive element is configured to dissipate energy as heat.

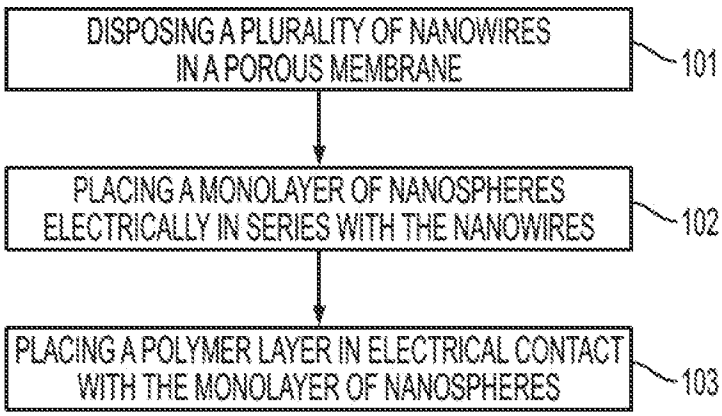

DISPOSING A PLURALITY OF NANOWIRES IN A POROUS MEMBRANE
101
PLACING A MONOLAYER OF NANOSPHERES ELECTRICALLY IN SERIES WITH THE NANOWIRES
102
PLACING A POLYMER LAYER IN ELECTRICAL CONTACT WITH THE MONOLAYER OF NANOSPHERES
103

FIG. 1

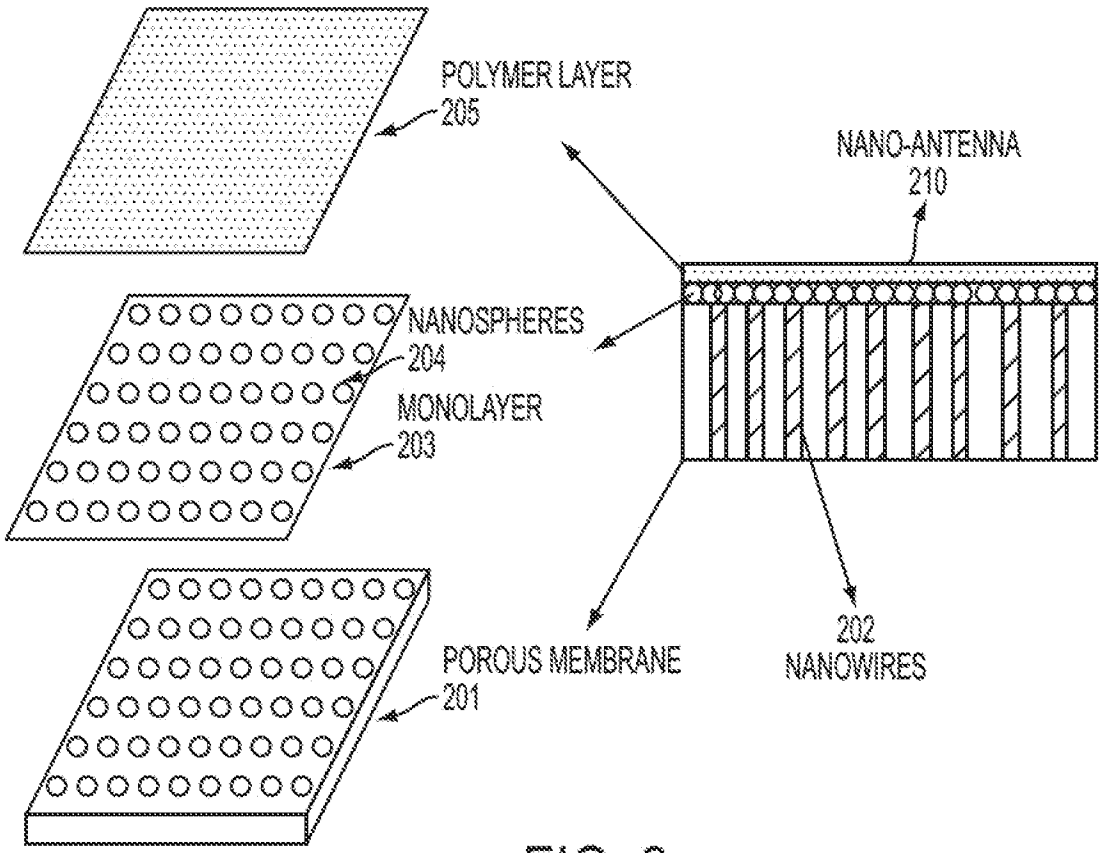

POLYMER LAYER
205
NANO-ANTENNA
210
NANOSPHERES
204
MONOLAYER
203
POROUS MEMBRANE
201
202
NANOWIRES

FIG. 2

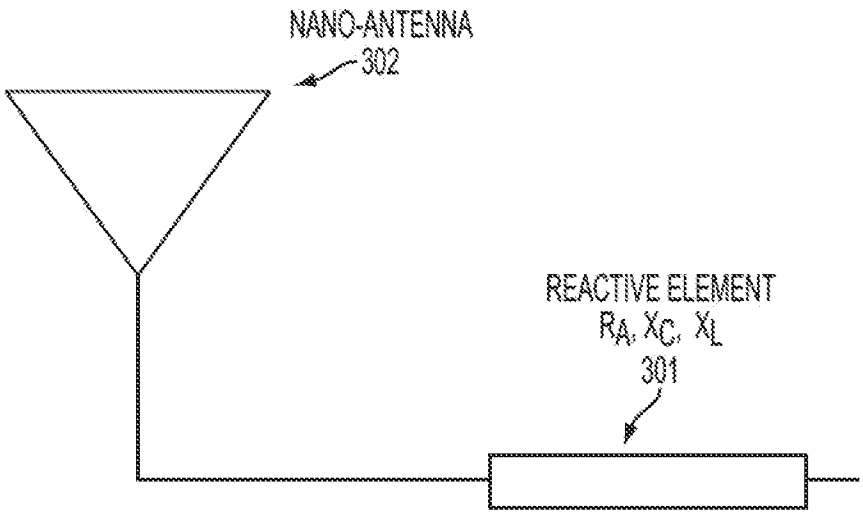


FIG. 3

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2012/051093

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - B82Y 10/00 (2012.01)
USPC - 977/700
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - B32B 15/02; B81B 7/00; B82Y 10/00, 20/00, 30/00, 40/00; H01L 29/12 (2012.01)
USPC - 75/370; 257/43, E29.002; 343/700R, 749; 385/14; 977/700, 754, 755, 774, 762, 773, 778, 840, 896, 932

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)
MicroPatent, Google Patents, Google

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y/A	US 2012/0188540 A1 (BRATKOVSKI et al) 26 July 2012 (26.07.2012) entire document	31, 33-44/32
Y/A	OSGOOD, et al. Nanoantennas with Short-Wavelength Resonance. SPIE Digital Library, Vol. 7032. 2008. [retrieved on 08 October 2012][Retrieved from internet: <URL: http://144.206.159.178/ft/CONF/16418927/16418929.pdf>] entire document	31, 33-44/1-30, 32, 45-50
Y	US 8,071,931 B2 (NOVACK et al) 06 December 2011 (06.12.2011) entire document	33-37
Y	US 2012/0037515 A1 (SOLANSKI) 16 February 2012 (16.02.2012) entire document	35
Y	US 7,843,026 B2 (WANG et al) 30 November 2010 (30.11.2010) entire document	37
Y	US 7,474,823 B2 (WANG et al) 06 January 2009 (06.01.2009) entire document	38, 39
Y/A	ZHAO et al. Effects of Shape and Loading of Optical Nanoantennas on their Sensitivity and Radiation Properties. J. Opt. Soc. Am. B. Vol. 28, No. 5. May 2011.[retrieved on 08 October 2012][Retrieved from internet:<URL:http://www.opticsinfobase.org/josab/abstract.cfm?uri=josab-28-5-1266>] pgs. 1266-1274.	40, 43, 44/1-30, 32, 45-50
Y	MIVELLE, M. et al. Bowtie nano-aperture as interface between near-fields and a single-mode fiber. Optics Express 19 July 2010. Vol. 18, No. 15. [retrieved 08 October 2012]. [Retrieved from internet: <URL: http://www.opticsinfobase.org/oe/abstract.cfm?uri=oe-18-15-15964>] entire document.	41

☒ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
08 October 2012	16 NOV 2012
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (July 2009)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2012/051093

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	ZHANG, et al. Resonant Slot nanoantennas for surface plasmon radiation in optical frequency range. Appl. Phs. Lett. 100, 241115. 15 June 2012. [retrieved on 08 October 2012][Retrieved from internet: <URL:http://apl.aip.org/resource/1/applab/v100/i24/p241115_s1?bypassSSO=1>] entire document	42
A	US 6,730,395 B2 (COVINGTON) 04 May 2004 (04.05.2004) entire document	1-50
A	US 2012/0119117 A1 (FOURKAS et al) 17 May 2012 (17.05.2012) entire document	1-50
A	US 2011/0195201 A1 (ZHU et al) 11 August 2011 (11.08.2011) entire document	1-50
A	US 7,573,045 B2 (GORRELL et al) 11 August 2009 (11.08.2009) entire document	1-50
A	BURKE, P. Quantitative Theory of Nanowire and Nanotube Antenna Performance. arXiv.org. 19 August 2004. [retrieved on 08 October 2012][Retrieved from internet: <URL: http://arxiv.org/pdf/cond-mat/0408418.pdf>]. entire document.	1-50
A	US 7,834,349 B2 (GOLE et al) 16 November 2010 (16.11.2010) entire document	1-50
A	US 2011/0167962 A1 (GHANAVI et al) 14 July 2011 (14.07.2011) entire document	1-50
A	US 2012/0170097 A1 (HAN et al) 05 July 2012 (05.07.2012) entire document	1-50