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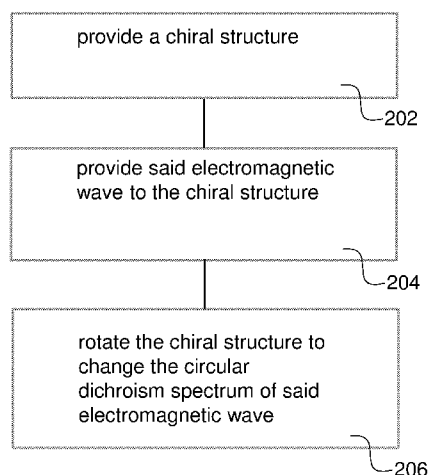
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(54) Title: METHOD OF CHANGING A CIRCULAR DICHROISM SPECTRUM OF AN ELECTROMAGNETIC WAVE

FIG. 2A

200a



(57) Abstract: Various embodiments may provide a method of changing a circular dichroism (CD) spectrum of an electromagnetic wave. The method may include providing a chiral structure. The method may further include providing said electromagnetic wave to the chiral structure. The method may also include rotating the chiral structure to change the circular dichroism spectrum of said electromagnetic wave. The chiral structure may be a planar structure, and may be a nanostructure array comprising a plurality of nanostructure arrangements, wherein each nanostructure arrangement comprises one or more gammotion, spiral, triangular nanostructures, or nanorods and nanodisks in a windmill arrangement.

METHOD OF CHANGING A CIRCULAR DICHROISM SPECTRUM OF AN ELECTROMAGNETIC WAVE

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority of Singapore application No. 10201502544T filed on March 31, 2015 and Singapore application No. 10201502545S filed March 31, 2015, the contents of them being hereby incorporated by reference in their entirety for all purposes.

TECHNICAL FIELD

[0002] Various aspects of this disclosure relate to methods of changing circular dichroism spectra of electromagnetic waves.

BACKGROUND

[0003] Chirality in molecules related to living organisms has fascinated scientists ever since the phenomenon was first observed. FIG. 1A is a schematic showing a chiral molecule 102 with its mirror image 104. A chiral molecule with different handedness is called an enantiomer. The molecules 102, 104 are mirror molecular structures that cannot be superimposed to each other. The enantiomer may greatly influence biological and pharmacological properties of a drug. Even though enantiomers have the same molecular formula, they may have significantly different effects in both pharmacokinetics and pharmacodynamics.

[0004] The importance of enantioselectivity in drugs has been raised since 1980s when it is discovered that half of the drugs concentrations have no effect or have other side effects on patients. Enantioselectivity has been frequently discussed in the pharmaceutical literature. For example, thalidomide, a sedative drug that was prescribed to pregnant women in 1960s and was found to result in horrific birth defects in thousands of children around the world. This is because one of the enantiomer is a sedative, but the other enantiomer may cause phocomelia, which is a congenital disorder involving malformation of the limbs. This tragedy can be avoided if the thalidomide molecules had been tested prior to commercialization. In an effort to achieve more predictable results from chiral drugs, the Food and Drug Administration

(FDA) now requires that these medicines be as pure as possible, which places great demands on drug synthesis, purification, analysis, and testing.

[0005] Nearly two-thirds of the drugs on today's market are chiral drugs. Identifying, reducing and eliminating their negative characteristics are an ongoing and serious challenge for the pharmaceutical industry. Selecting and filtering out single enantiomers of the drugs are important because the chemical production methods used for synthesis of pharmaceuticals often produce racemic mixtures of two enantiomers. The drug industry will continue to improve drug efficacy and to cut the development costs of chiral drug molecules.

[0006] The ability to detect and manipulate chiral molecules has also been a long term goal of biologists and chemists because chirality is implicit in the interactions of macromolecules such as proteins and deoxyribonucleic acids (DNAs).

[0007] After the Thalidomide incident, knowing and changing the chirality of molecules have become essential and crucial. Over the years, a few techniques have been suggested to determine the chirality of molecules.

[0008] Several chiral spectroscopic techniques such as circular dichroism spectroscopy (CD), optical rotator dispersion spectroscopy (ORD), advanced electron microscopy, and Raman optical activity (ROA) have been applied in biomolecular science to discriminate the chirality and detect biomolecules and biopolymers. While spectroscopic techniques such as ORD and advanced electron microscopy have been used to determine the properties of chiral molecules, they often cause damage to the molecules after testing of samples. This would require much more samples and may not be economical for analysis of proteins or DNA samples. ROA often require sophisticated experimental setup.

[0009] Among these techniques, CD is most widely used due to its simplicity and convenience. Currently, it is the most efficient technique amongst the various techniques. Further, CD does not require sophisticated equipment or experimental setup, and does not face as many limitations as other existing methods for detecting and identifying the chirality of biopolymers and biomolecules.

[0010] CD testing may be done using a simple spectroscopy and white light to determine the properties of the chiral molecules. In addition, it may not damage or contaminate the sample. CD methodology is also a quick method to obtain the properties of chiral molecules.

[0011] A major disadvantage is the weak signal obtained due to insufficient time to allow chiral molecules to interact with light. While left- and right-handed

biopolymers/biomolecules interact differently with left (LHC) or right hand circular (RHC) polarized light, the result difference in effect may be very weak. Consequently, CD spectroscopy may have low sensitivity.

[0012] The sensitivity may be improved by enhancing field strength of the light, increasing the interaction with the biopolymers/biomolecules and improving the absorption efficiency by the biopolymers/biomolecules.

[0013] Chemists and drug companies are developing techniques to improve sensitivity. These efforts include attaching fluorophores to the biomolecules and using metallic nanoparticles to support localized field resonance. The method of using silver nanoparticles has previously found to be the most effective and has shown to improve the CD signal by two orders of magnitude in the ultraviolet region. This is extended to the visible light range with sensitivity up to six orders of magnitude using gammadion nanostructures two years later.

[0014] Having overcome the problem of weak detection signal in the earlier stage, a more challenging problem of manipulation of the CD spectrum still remains. The requirement to maintain the high sensitivity of chirality detection while manipulating the CD spectrum is a difficult task.

SUMMARY

[0015] Various aspects of this disclosure provide a method of changing a circular dichroism spectrum of an electromagnetic wave. The method may include providing a chiral structure. The method may further include providing said electromagnetic wave to the chiral structure. The method may also include rotating the chiral structure to change the circular dichroism spectrum of said electromagnetic wave. The chiral structure may be a planar structure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] 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. 1A is a schematic showing a chiral molecule with its mirror image.

FIG. 1B is a table linking various chiral nanostructures to chiral molecules.

FIG. 2A is a schematic illustrating a method of changing a circular dichroism spectrum of an electromagnetic wave according to various embodiments.

FIG. 2B is a schematic illustrating a method of detecting a change in a circular dichroism spectrum of an electromagnetic wave according to various embodiments.

FIG. 3A is a schematic showing the top view of two neighbouring right handed gammadion structures of an array according to various embodiments.

FIG. 3B is a schematic showing the cross-sectional side view of one right handed gammadion structure shown in FIG. 3A according to various embodiments.

FIG. 3C is a schematic illustrating the rotation of the gammadion structure 302 shown in FIG. 3A according to various embodiments.

FIG. 4A is a plot of normalized absorption efficiency (arbitrary units or a.u.) against wavelength (nanometres or nm) showing the absorption spectrum of the unrotated gammadion structures according to various embodiments.

FIG. 4B is a plot of the circular dichroism (CD) spectrum of modes (arbitrary units or a.u.) against wavelength (nanometres or nm) showing the circular dichroism (CD) of the unrotated gammadion structures according to various embodiments.

FIG. 5A is a schematic showing the top view of two neighbouring right handed gammadion structures of an array after being rotated at an angle of about 30° clockwise according to various embodiments.

FIG. 5B is a schematic showing the top view of the two neighbouring right handed gammadion structures of the array after being rotated at an angle of about 60° clockwise according to various embodiments.

FIG. 6 is a plot of the circular dichroism (CD) spectrum of modes (arbitrary units or a.u.) against wavelength (nanometres or nm) showing the different circular dichroism (CD) spectra before rotation and after rotation through different angles of 30, 45, 60 and 75 degrees according to various embodiments.

FIG. 7A is a schematic showing a side view of a substrate according to various embodiments.

FIG. 7B is a schematic showing a side view wherein poly(methyl methacrylate) (PMMA) is deposited onto the substrate to form a dielectric layer according to various embodiments.

FIG. 7C is a schematic showing a side view in which the dielectric layer is being patterned according to various embodiments.

FIG. 7D is a schematic showing a side view of the dielectric layer with cavities on the substrate 704 according to various embodiments.

FIG. 7E is a schematic showing a side view of the substrate with a deposited metal layer according to various embodiments.

FIG. 7F is a schematic showing a side view of the gammadion structure formed on the substrate according to various embodiments.

FIG. 8A is an image of a gammadion array at 0 degree according to various embodiments.

FIG. 8B is an image of a gammadion array at 30 degrees according to various embodiments.

FIG. 8C is an image of a gammadion array at 45 degrees at various embodiments.

FIG. 8D is an image of a gammadion array at 60 degrees at various embodiments.

FIG. 9 is a schematic of an experiment setup for validating the simulation results according to various embodiments.

FIG. 10 is a plot of circular dichroism (CD) spectrum of modes (arbitrary units or a.u.) against wavelength (nanometres or nm) showing the experimental circular dichroism (CD) spectra before rotation and after rotation through different angles of 30, 45, 60 and 75 degrees according to various embodiments.

FIG. 11A is a schematic showing the top view of arrangement of gammadions with two different rotation angles according to various embodiments.

FIG. 11B is a schematic showing the top view of arrangement of gammadions with 4 different rotation angles according to various embodiments.

FIG. 12A shows an asymmetric arrangement of spiral nanostructures according to various embodiments.

FIG. 12B shows an asymmetric arrangement of triangular nanostructures according to various embodiments.

FIG. 12C shows an asymmetric arrangement of nanorods in windmill arrangement according to various embodiments.

FIG. 12D shows an asymmetric arrangement of nanodisk groups in windmill arrangement according to various embodiments.

FIGS. 13A shows a prism with a geometric centre as shown by the intersection of the dotted lines.

FIG. 13B shows the prism being rotated about an axis that passes through the geometrical centre of the prism.

FIG. 13C is a plot of circular dichroism (CD) spectrum of modes (arbitrary units or a.u.) against wavelength (nanometres or nm) showing the circular dichroism (CD) spectra after rotation through different angles of 0, 15, 30, 45, 60, 75 and 90 degrees.

FIG. 13D shows the prism being rotated about an axis that does not pass through the geometrical centre of the prism.

FIG. 13E a plot of circular dichroism (CD) spectrum of modes (arbitrary units or a.u.) against wavelength (nanometres or nm) showing the circular dichroism (CD) spectra after rotation through different angles of 0, 30, 45, 60, 75 and 90 degrees.

FIG. 14A is a schematic showing a perspective view of a structure according to various embodiments.

FIG. 14B is a schematic showing a top view of the structure shown in FIG. 14A according to various embodiments.

FIG. 14C is a schematic showing a cross-sectional side view of the structure shown in FIG. 14A according to various embodiments.

FIG. 14D is a schematic of the structure shown in FIG. 14A when an angle of rotation (θ) between the nanostructure array and further nanostructure array about axis is 15° according to various embodiments.

FIG. 15 is a schematic illustrating simulation performed using frequency solver with Floquet boundaries according to various embodiments.

FIG. 16 is a plot of absorption (arbitrary units or a.u.) against wavelength (nanometers or nm) showing the variation of the absorbance profile when one array is rotated relative to another array for the structure shown in FIG. 15A according to various embodiments.

FIG. 17 is a plot of circular dichroism (CD) spectrum of modes (arbitrary units or a.u.) against wavelength (nanometres or nm) showing the circular dichroism (CD) spectra before rotation and after rotation through different angles of 15, 30, 45, 60, 75 and 90 degrees according to various embodiments.

FIG. 18 is a plot of circular dichroism (CD) (arbitrary units or a.u.) against the relative rotation angle θ between the first nanostructure array and the second nanostructure array (degrees or $^\circ$) according to various embodiments.

FIG. 19 show images showing the tangential field distribution of right-handed circularly polarized (RCP) light (mode 1, mode 2 and mode 3) on the first nanostructure array layer and the second nanostructure array layer according to various embodiments.

FIG. 20A is a schematic showing a setup for determining a structural feature of an entity 2006 according to various embodiments.

FIG. 20B is a diagram illustrating signal enhancement with a structure or arrangement including nanostructures integrated into a detection system according to various embodiments.

FIG. 21 is a schematic illustrating a setup for circular dichroism (CD) spectroscopy according to various embodiments.

FIG. 22A is a schematic of a structure in which nanostructures of the nanostructure array is arranged differently from nanostructures of the further nanostructure array according to various embodiments

FIG. 22B is a schematic of a structure including an array including triangular shaped nanostructures and a further array including triangular shaped nanostructures according to various embodiments.

FIG. 22C is a schematic of a structure including nanorods of the array and nanorods of the further array in an alternate arrangement according to various embodiments.

FIG. 22D is a schematic of a structure in which the nanostructures of the array and the nanostructures of the further array are arranged in five-fold rotational symmetry according to various embodiments.

FIG. 23 is a plot of absorption (arbitrary units or a.u.) against wavelength (nanometres or nm) showing how the circular dichroism (CD) in FIG. 16 is obtained.

DETAILED DESCRIPTION

[0017] 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.

[0018] Various embodiments seek to address or mitigate the problems as described herein. Various embodiments seek to manipulate the CD spectrum while maintaining a reasonable level of sensitivity.

[0019] In recent years, work on rotating the structures of plasmonic structures to manipulate the phase of enhanced light has appeared. Various nanorods are used to change the phase of enhanced light. Each nanorod may be rotated at a specific angle to produce light radiation at different polarization. The resultant polarization of the nanorods cluster may be shifted with respect to the incident polarization and provides phase changing characteristics.

[0020] The nanoengineering strategies that have been developed for chiral nanostructure may be related to concepts that originated in chiral molecules as shown in FIG. 1B. FIG. 1B is a table 100b linking various chiral nanostructures to chiral molecules. Many of the concepts associated with chirality that have initially been developed for molecules are nowadays being transferred to nanostructures.

[0021] (a)-(d) in FIG. 1B show the common structures of chiral molecules that exist in nature while the (e)-(h) is their resemble nanostructures. For example, (a) and (b) are helical chirality molecules with the shape of a propeller and a spiral. Correspondingly, the propeller and spiral shaped nanostructures shows in (e) and (f) also exhibit this form of chirality.

[0022] Chirality is also achieved upon coupling of two or more achiral molecules, as illustrated in (c). Similarly the coupling mechanism occurs in the superposition of achiral crosses, in (g).

[0023] Another well-known chiral type of chirality is supramolecular chirality, represented in (d). In this case, the building blocks themselves are chiral and the chirality is achieved through coupling of these building blocks. Translating this concept to nanostructures, the pattern in Figure (h) shows four 2D spirals that are arranged at different angles. This arrangement may give rise to strong nonlinear CD that may be attributable to chiral coupling of the nanostructures.

[0024] In metal nanostructures with dimensions significant smaller than the wavelength of light, light may be confined, which results in local electromagnetic field enhancements. This confinement of light is called localized surface plasmon resonances (LSPR). The electromagnetic field enhancements may be related to electrons in the conduction band that oscillate upon the incidence on light onto the nanostructures. The oscillations may depend on the size of the nanostructures, their constitution, their geometry, their surroundings and their distance from each other. A strong resonance may be achieved for a given wavelength of light. At resonance, strong absorption and scattering of the light can be observed from nanostructures. When a metal nanostructure is incident with circularly polarized light, the

electron cloud may be driven in spiral form giving rise to electric current on the surface of the nanostructure. If the nanostructure has chiral geometry, the direction of the circular polarized light may be either enhanced or suppressed depending on the surface current of the nanostructure, e.g. the right-handed circular polarized light may cause field enhancement on right-handed nanostructure but not on left-handed nanostructure.

[0025] Various embodiments provide a method of changing a circular dichroism spectrum of an electromagnetic wave. FIG. 2A is a schematic 200a illustrating a method of changing a circular dichroism spectrum of an electromagnetic wave according to various embodiments. The method may include, in 202, providing a chiral structure. The method may further include, in 204, providing an electromagnetic wave to the chiral structure. The method may also include, in 206, rotating said chiral structure to change the circular dichroism spectrum of electromagnetic wave. The chiral structure may be a planar structure.

[0026] In other words, the method may include allowing an electromagnetic wave to incident on a chiral planar structure and rotating the structure to manipulate the CD spectrum of the electromagnetic wave.

[0027] Circular dichroism (CD) is the difference in the absorption of left-handed circularly polarized (LCP) light and right-handed circularly polarized (RCP) light. CD occurs when a medium absorbs one circular polarized light state to a greater extent than the other. CD may occur only at certain specific values or ranges of wavelengths of the electromagnetic spectrum that can be absorbed by the sample. The CD spectrum may include the certain specific values or ranges of wavelengths. Measurements may typically be carried out in the visible, infrared and ultra-violet regions of the electromagnetic spectrum.

[0028] The wordings “light” and “electromagnetic wave” as described herein may be used interchangeably to refer to electromagnetic waves in the infrared -visible-ultraviolet regions, i.e. from about 10 nm to about 1200 nm. In various embodiments, the electromagnetic wave may be visible optical light or ultraviolet light or infrared radiation or any combination thereof. In various embodiments, the electromagnetic wave may refer to visible optical light.

[0029] In various embodiments, the electromagnetic wave may be polarized. The electromagnetic wave may be a left-handed circularly polarized (LCP) light or a right-handed circularly polarized (RCP) light. In various embodiments, the electromagnetic wave may be a linearly polarized light, which is a superposition of a left-handed circularly polarized (LCP) light and a right-handed circularly polarized (RCP) light.

[0030] In various embodiments, the chiral structure may be on a substrate. The substrate may be transparent to the electromagnetic wave.

[0031] In various embodiments, the chiral structure may be or may include a nanostructure. The nanostructure may be of any suitable asymmetric shape, such as a gammadion, or a spiral. The chiral structure may also be or may include a symmetrical nanostructure positioned off the centre of the structure. The nanostructure may be electrically conductive. The nanostructure may be a metal or may include a metal. Unless stated otherwise, symmetry as described herein may refer to reflectional symmetry. A line of symmetry cannot be drawn through an asymmetrical shape that divides the shape into two mirror images of each other.

[0032] A symmetrical nanostructure positioned at the centre of the structure would produce no circular dichroism but there would be circular dichroism by rotating the nanostructure.

[0033] In various other embodiments, the chiral structure may include a plurality of nanostructure arrangements. The nanostructure arrangement may be asymmetric or of any suitable asymmetric shape. Each nanostructure arrangement may be include or consist of one nanostructure, or may include or consist of more than one nanostructure. In other words, each nanostructure arrangement may include or consist of one or more nanostructures. For instance, each nanostructure arrangement may include or consist of one or more gammadion structures. Each nanostructure of the plurality of nanostructures may be spaced from a neighbouring nanostructure by a substantially equal distance. Each nanostructure may be asymmetrical. Each nanostructure may be a metal or may include a metal.

[0034] In various embodiments, the electromagnetic wave may interact with the nanostructure(s) to generate surface plasmons, which enhance the CD effect of the chiral structure. The nanostructure(s) may be planar.

[0035] In various embodiments, the length and width of the chiral structure may contribute to the enhancement of the CD effect. In various embodiments, the thickness of the chiral structure may have a smaller or negligible effect on the CD enhancement.

[0036] The thickness of the chiral structure or nanostructure(s) may be smaller than the length and width. For instance, the length and width of a structure or a nanostructure may each be of 400 nm while the thickness may be of about 110 nm. The electromagnetic wave may be incident on a surface bound by the length and the width.

[0037] In various embodiments, the nanostructure array may be on or over a further nanostructure array to form a bilayer structure. The chiral structure may further include a dielectric layer. In various embodiments, the nanostructure array may be on a first side of the dielectric layer and the further nanostructure array may be on a second side of the dielectric layer opposite the first side. The dielectric layer may be between the nanostructure array and the further nanostructure array.

[0038] In various embodiments, the nanostructure array may be rotated about an axis. Rotating the chiral structure may include rotating the nanostructure array about the axis. The further nanostructure array may be stationary. In various embodiments, the further nanostructure array may be rotated about an axis, and the nanostructure array may be kept stationary. The nanostructure array may be rotated at an angle relative to the further nanostructure array. In various embodiments, the nanostructure array and the further nanostructure array may be rotated relative to each other about an axis. The nanostructure array and/or further nanostructure array may be rotated about an axis which passes through a geometrical centre of the nanostructure array and a geometrical centre of the further nanostructure array.

[0039] In various embodiments, the chiral structure may include a single layer, i.e. a single planar layer.

[0040] In various embodiments, each nanostructure arrangement of the plurality of nanostructure arrangements may be rotated about a respective geometric axis, i.e. an axis that passes through the geometric centre of each nanostructure arrangement. Rotating the chiral structure may include or refer to rotating each nanostructure arrangement about a respective axis.

[0041] In various embodiments, an angle of rotation of one nanostructure arrangement of the plurality nanostructure arrangements may be substantially equal to an angle of rotation of another nanostructure arrangement of the plurality of nanostructure arrangements. In other words, the plurality of nanostructure arrangements may be rotated through the same angles about their respective axes.

[0042] In various other embodiments, each nanostructure arrangement of the plurality of nanostructure arrangements may be rotated about a respective geometric axis. In various embodiments, an angle of rotation of one nanostructure arrangement of the plurality nanostructure arrangements may be substantially different compared to an angle of rotation of

another nanostructure arrangement of the plurality of nanostructure arrangements. In other words, the plurality of nanostructure arrangements may be rotated at different angles about their respective axes.

[0043] Rotating the chiral structure may refer to rotating each nanostructure arrangement of the plurality of nanostructure arrangements included in the chiral structure.

[0044] In various embodiments, the chiral structure or the nanostructure arrangement or the nanostructure array may be rotated in a counter-clockwise direction. In various other embodiments, the chiral structure or the nanostructure arrangement or the nanostructure array may be rotated in a clockwise direction.

[0045] Various embodiments may relate to changing a circular dichroism property of a chiral structure. The method may include providing a chiral structure. The method may further include providing said electromagnetic wave to the chiral structure. The method may also include rotating the chiral structure to change the circular dichroism property of the chiral structure. The chiral structure may be a planar structure.

[0046] A chiral structure may refer to a structure including a chiral nanostructure.

[0047] A chiral structure may alternatively refer to a nanostructure array including a plurality of nanostructure arrangements (which may be referred to as unit cells). The plurality of nanostructure arrangements may each be chiral or may when grouped together imparts the structure chirality. Each nanostructure arrangement or unit cell may include a chiral nanostructure. Each nanostructure arrangement or unit cell may include more than one nanostructure. Each of the more than one nanostructure may be chiral, or the more than one nanostructures may as a whole impart the nanostructure arrangement or unit cell chirality.

[0048] In various embodiments, a method of detecting a change in a circular dichroism spectrum of an electromagnetic wave may be provided. FIG. 2B is a schematic 200b illustrating a method of detecting a change in a circular dichroism spectrum of an electromagnetic wave according to various embodiments. The method may include, in 252, changing the circular dichroism spectrum as described herein. The method may also include, in 254, determining a parameter of a detected electromagnetic wave travelling from the chiral structure for detecting the change in the circular dichroism spectrum. The detected electromagnetic wave may be generated based on the electromagnetic wave provided to the chiral structure.

[0049] In various embodiments, the incident electromagnetic wave may incident on the chiral structure. In various embodiments, the incident electromagnetic wave may be absorbed by the chiral structure. In various embodiments, certain wavelengths or range of wavelengths may be absorbed by the chiral structure.

[0050] Various embodiments may provide determining the absorption of the incident electromagnetic wave by determining the electromagnetic wave or waves that travel from the chiral structure. In other words, the absorption of the incident electromagnetic wave may be determined by detecting or measuring or determining the electromagnetic waves that are scattered by, reflected by and/or transmitted through the chiral structure.

[0051] The detected electromagnetic wave may be an electromagnetic wave scattered by the chiral structure and the parameter of a scattering parameter of the scattered electromagnetic wave. The parameter may be the scattering power.

[0052] The detected electromagnetic wave may be an electromagnetic wave reflected by the chiral structure and the parameter is a reflection parameter of the reflected electromagnetic wave. The parameter may be the reflection power.

[0053] The detected electromagnetic wave may be an electromagnetic wave transmitted by the chiral structure and the parameter is a transmission parameter of the reflected electromagnetic wave. The parameter may be the transmission power.

[0054] The method may further include determining one or more further parameters of one or more further detected electromagnetic waves travelling from the chiral structure. The one or more detected electromagnetic wave may be generated based on the electromagnetic wave provided to the chiral structure. The method may also include determining an absorption parameter of the chiral structure based on the parameter and the one or more further parameters. The absorption parameter may be the absorption power.

[0055] In various embodiments, the method may include determining an absorption parameter of the chiral structure based on a scattering parameter, a reflection parameter and a transmission parameter. In various embodiments, the method may include determining an absorption power of the chiral structure based on scattering power, reflection power and transmission power.

[0056] The determination of the change in the circular dichroism spectrum of the electromagnetic wave or/and the change in circular dichroism property may be based on the absorption parameter.

[0057] Various embodiments may provide a method that demonstrates that the rotation of the chiral structure including gammadion structures may be used to manipulate the CD spectrum, at the same time keeping the sensitivity of CD detection. The whole array of the gammadion structures may be rotated at specific angles and the CD spectrum may be calculated. Various embodiments may apply the principle of using rotated nanostructures to manipulate the resultant phase output and the CD spectrum. FIG. 3A is a schematic showing the top view of two neighbouring right handed gammadion structures 302a, 302b of an array according to various embodiments. Each unit cell may include a single gammadion structure. FIG. 3B is a schematic showing the cross-sectional side view of one right handed gammadion structure 302a shown in FIG. 3A according to various embodiments. The gammadion structure may be made of gold. The gammadion structures 302a, 302b may be on a substrate, such as a glass slide 304. The gammadion structures 302a, 302b may be covered by a liquid such as water 306.

[0058] The length and width are denoted by l and t respectively. The thickness is denoted by t . The electromagnetic wave may be incident on a surface 308 bound by the length (l) and the width (w).

[0059] In various embodiments, a planar structure may refer to a structure in which surface 308 is flat, and the length (l) and width (w) are greater than the thickness (t). A planar chiral structure may refer to a chiral structure including a planar chiral nanostructure or an arrangement including one or more planar chiral nanostructures.

[0060] In various embodiments, the thickness (t) of the nanostructure may be less than 50% or less than 40% of the length or the width.

[0061] Each gammadion structure may be chiral. As shown in FIG. 3A, the width of the chiral gammadion structure may be 80 nm and length of each arm may be 240 nm.

[0062] Each gammadion may consist of 4 arms, rotating in the same direction. The chiral gammadion may have a 4-fold rotational symmetry of 90° and may also not superimpose with its reflection image. Each gammadion structure may be asymmetric (i.e. does not have reflectional symmetry).

[0063] An object has rotational symmetry if there is a center point around which the object is turned (rotated) a certain number of degrees and the object looks the same. The number of positions in which the object looks exactly the same is called the order or folds of the symmetry.

[0064] The gammadion structures 302a, 302b may lie on a glass substrate 304 with refractive index of about 1.45. Glass substrate may be used because does not contaminate biosamples and it is transparent to visible light wavelength. Gold may have good adhesive properties on glass substrate. The surrounding of the gammadion structures 302a, 302b may be water with refractive index of about 1.33.

[0065] Light with LCP or RCP may incident onto the system in air. Upon interacting with the gammadion structure, localized surface plasmon may be excited and hence the field amplitude around may be enhanced. The gammadion structures 302a, 302b may be in an array with period of 800 nm. The gammadion structures 302a, 302b may be made up of gold material. The permittivity may be obtained from standard optical handbook. To ensure consistency and accuracy, the permittivity of the water and glass substrate may be also taken from the optical handbook.

[0066] Simulation of the chirality structure may be performed using finite-different time-domain (FDTD) method with mesh size of 4 nm. To model the system in an array, periodic boundary may be applied to the gammadion in the planar axis while perfectly match layer may be applied to the vertical axis of the array. The unit cell of the gammadion may be a square shape with dimension 800 nm by 800 nm.

[0067] FIG. 3C is a schematic illustrating the rotation of the gammadion structure 302a shown in FIG. 3A according to various embodiments. All the rotations may be carried out in the clockwise direction. Various embodiments may include rotating the gammadion nanostructures. The gammadion nanostructures rotated about a respective centre axis, with different rotating angles shown in FIG. 3C. The centre axis may be set to be on the structure so as to show that the gammadion structure is rotating (the centre axis may coincide with the unit cell centre). The unit cell or gammadion structure may remain in the original position. The details of the simulation for the rotated structures may be as below:

[0068] 1) Rotate the gammadion at selected specific angles. This is for convenience and to facilitate the drawing of the structures for simulation. In addition, the mesh setting for FDTD in these selected angles may be easier to set, without having to use very fine mesh at irregular angles. The selected angles may be set at 0, 30, 45, 60 and 75 degrees.

[0069] 2) Secondly, the whole array may have the same rotation angles. In other words, all the nanostructures in the array may be rotated at substantially equal angles. This may allow the use of the unit cell feature in the simulation algorithm.

[0070] Simulation may be performed for the unrotated gammadion structures. FIG. 4A is a plot 400a of normalized absorption efficiency (arbitrary units or a.u.) against wavelength (nanometres or nm) showing the absorption spectrum of the unrotated gammadion structures according to various embodiments. 402 shows the absorption spectrum for LHC polarized light while 404 shows the absorption spectrum for RHC polarized light. FIG. 4B is a plot 400b of the circular dichroism (CD) spectrum of modes (arbitrary units or a.u.) against wavelength (nanometres or nm) showing the circular dichroism (CD) of the unrotated gammadion structures according to various embodiments. The unrotated gammadion results may be used as a reference for the rotated nanostructures.

[0071] The details for getting the absorption and CD spectrum may be provided as below:

[0072] (1) Monitors were placed to obtain the scattering, reflection and transmission power when incident with LCP and RCP light respectively with the wavelength range of about 400 to about 900 nm.

[0073] (2) Using the conservation of energy, the absorption power may be provided by the equation:

$$A = 1 - T - S - R \quad (1)$$

where A, T, S, R represent the absorption power, transmission power, scattering power and reflected power.

[0074] The absorption power, A_L and A_R , may be obtained for LCP light and RCP light respectively. Then, the CD of the gammadion may be obtained using the equation given as

$$CD = A_L - A_R \quad (2)$$

[0075] Similar steps may be carried out for rotated gammadion in an array for different rotating angles.

[0076] In FIG. 4B, three modes may be identified. These modes may be due to the various physical mechanisms of the array. Modes m2 and m3 may be due to the interaction between the different parts of the gammadion. Mode m1 may be due to the Bloch mode of the gammadion array.

[0077] As the gammadion nanostructures are rotated at different angles, modes m1, m2 and m3 are shifted.

[0078] In the rotation of the gammadion, the three modes change. FIGS. 5A and 5B show the schematic layout for the rotated gammadion. FIG. 5A is a schematic showing the top view of two neighbouring right handed gammadion structures 502a, 502b of an array after

being rotated at an angle of about 30° clockwise according to various embodiments. FIG. 5B is a schematic showing the top view of the two neighbouring right handed gammadion structures 502a, 502b of the array after being rotated at an angle of about 60° clockwise according to various embodiments. The gammadion structures 502a, 502b may correspond to the gammadion structures 302a, 302b shown in FIG. 3A. The period between the gammadion structures 502a, 502b may still remain the same. The gammadion structures 502a, 502b may be rotated about their respective axis. The respective axis may pass through the geometric centre of the unit cell or nanostructure. Each unit cell or nanostructure may be rotated through substantially the equal angles.

[0079] FIG. 6 is a plot 600 of the circular dichroism (CD) spectrum of modes (arbitrary units or a.u.) against wavelength (nanometres or nm) showing the different circular dichroism (CD) spectra before rotation and after rotation through different angles of 30, 45, 60 and 75 degrees according to various embodiments. 602 is the CD plot before rotation; 604 is the CD plot after rotation at 30 degrees; 606 is the CD plot after rotation at 45 degrees; 608 is the CD plot after rotation at 60 degrees; and 610 is the CD plot after rotation at 75 degrees.

[0080] At 30 degree rotating angle, a red shift may be observed in the CD spectrum. This may be due to the change in the orientation of the gammadion with respect to the array. At higher rotation angle, this shift may become smaller but the CD increases at 45 degree rotation angle. Further increasing the rotation angle may result in the significant reduction in CD. Subsequently, at rotation angle of 75 degree, the CD for mode m1, m2 and m3 may flip over to become positive. At rotation angle of 75 degree, the CD may flip because of the change in the rotational symmetry of the array. The 75 degree rotation in the clockwise direction may be analogous to rotating a left handed gammadion by 15 degree in the anti-clockwise direction.

[0081] Various embodiments may provide a method of forming or fabricating a nanostructure, such as a gammadion nanostructure. FIGS. 7A-F show a method of fabricating a gammadion nanostructure according to various embodiments.

[0082] The nano-patterns may be fabricated by electron-beam lithography and lift-off process. The gammadion 702 were formed or provided on a glass substrate 704. FIG. 7A is a schematic showing a side view of a substrate 704 according to various embodiments. The glass substrate may include indium tin oxide (ITO), which may be needed for discharging electrons during electron-beam lithography. The pre-cleaning process may use 70% ethanol.

These cleaning agents may be required in order to ensure that the surface is clean before spinning poly(methyl methacrylate) (PMMA) on the substrate 704 for better cohesion. FIG. 7B is a schematic showing a side view wherein poly(methyl methacrylate) (PMMA) is deposited onto the substrate 704 to form a dielectric layer 710 according to various embodiments. A 170 nm thick PMMA resist may be spin-coated onto quartz substrate. The PMMA resist may be baked at 180 °C for 2 min.

[0083] FIG. 7C is a schematic showing a side view in which the dielectric layer 710 is being patterned according to various embodiments. Patterns may be formed on the layer 710 at a dose of 880 $\mu\text{C}/\text{cm}^2$ by using an electron beam with acceleration voltage of about 100 kV and beam current of about 50 pA. The exposed samples may be developed in methyl isobutyl ketone (MIBK) : isopropyl alcohol (IPA) (1:3) for about 70 s and rinsed in IPA for about 20s. Portions 710' of the dielectric layer 710 may be removed. FIG. 7D is a schematic showing a side view of the dielectric layer 710 with cavities 712 on the substrate 704 according to various embodiments. The dielectric layer 710 may cover a portion of the substrate 704 while exposing another portion through a cavity 712.

[0084] FIG. 7E is a schematic showing a side view of the substrate 704 with a deposited metal layer 714 according to various embodiments. In various embodiments, the metal layer 714 may include more than one sub-layers. For instance, about 3 nm of chromium (Cr) may be deposited followed by 100 nm gold (Au) on top of the patterned substrates by ebeam evaporation (Denton Vacuum, Explorer). The Cr may be added to improve cohesion between the gold sub-layer and glass substrate. The lift-off process may be carried out by soaking in Remover 1165. The samples may then be rinsed with IPA and deionized water and blown dry with nitrogen gas. FIG. 7F is a schematic showing a side view of the gammadion structure 702 formed on the substrate 704 according to various embodiments.

[0085] In various embodiments, rotating the chiral structure may include providing a plurality of the chiral structures with the nanostructure arrangement or nanostructures rotated at different angles.

[0086] FIG. 8A – 8D show fabricated gammadion arrays in different rotation angle according to various embodiments. FIG. 8A is an image 800a of a gammadion array at 0 degree according to various embodiments. FIG. 8B is an image 800b of a gammadion array at 30 degrees according to various embodiments. FIG. 8C is an image 800c of a gammadion

array at 45 degrees at various embodiments. FIG. 8D is an image 800d of a gammadion array at 60 degrees at various embodiments.

[0087] FIG. 9 is a schematic of an experiment setup 900 for validating the simulation results according to various embodiments.

[0088] The details of the setup are given as below. The mask for the gammadion may be rotated at various angles during the pre-ebeam process so that the gammadion are rotated at different angles for different samples.

[0089] The test sample 902 may be immersed in a liquid cell with chiral solution 904. Light from a laser beam 906 may be passed through a polarizer 908 to generate polarized light. The waveplate 910 generates circularly polarized light based on the polarized light. The circularly polarized light is then directed by lens 912 onto the sample 902. The light scattered, reflected and transmitted by the sample 902 may be detected by one or more detectors 914. The information collected by the detector 914 may be transmitted to dark field spectrum analyzer 916.

[0090] In one instance, an Olympus IX 71 inverted optical microscope 914 equipped with standard dark-field (DF) condenser and spectrometer (Acton SP2300) 916 is used for the optical circular dichroism (CD) spectra measurements. Light from a halogen lamp 906 is first made either left- or right-circularly polarized (LCP or RCP) through a combination of a linear polarizer 908 and a quarter-wave plate 910. A dry DF condenser (NA=0.8-0.92) 912 is used to focus the circularly polarized white light onto the sample 902 and a 20× objective lens (NA=0.5) (not shown in FIG. 9) is employed to collect the scattering spectra and DF images through a spectrometer and CCD camera, respectively.

[0091] The transmission and reflection spectra may be obtained from the spectrum analyzer. Using Equation (1), the absorption spectrum for LCP and RCP light may be obtained. The CD spectrum may then be obtained based on Equation (2) for the different gammadion samples. FIG. 10 is a plot 1000 of circular dichroism (CD) spectrum of modes (arbitrary units or a.u.) against wavelength (nanometres or nm) showing the experimental circular dichroism (CD) spectra before rotation and after rotation through different angles of 30, 45, 60 and 75 degrees according to various embodiments. 1002 is the CD plot without rotation; 1004 is the CD plot after rotation at 30 degrees; 1006 is the CD plot after rotation at 45 degrees; 1008 is the CD plot after rotation at 60 degrees; and 1008is the CD plot after rotation at 75 degrees.

[0092] Both the simulation and experimental CD spectra shows excellent match. The wavelength produced by the rotation in simulation results is also clearly observed in the experimental results. The CD modes in the experimental results are broader. The broader modes may not be due to the rotation axis but fabrication imperfection. This may be due to the imperfection of the fabricated samples. Some of the gammadions in the array may have rough edges, which may result in additional scattering and hence, the broadening effect.

[0093] The simulation and experimental CD results show the same phenomenon: the CD of modes m1, m2 and m3 flipped at rotating angles of 75 degree. The CD of mode m1 red shifted at 30 degree and then increase at 45 degree. After this, it reduces and then flipped to the other side at 75 degree.

[0094] A slight difference is the amplitude of CD in the experimental and simulation results. It is observed that the experimental CD amplitude for mode m1 at 75 degree is lower than the simulation CD amplitude. The CD amplitude for mode m2 at 60 degree rotating angle is also lower than the simulated results. It is also observed that the amplitude for mode m2 and m3 is also larger in the experimental results.

[0095] The results shown are for one design as an example. Other types of designs may also be used or introduced to achieve similar phenomenon. Instead of each unit cell or nanostructure arrangement consisting of or including only one nanostructure, each unit cell or nanostructure arrangement may consist or include more than one nanostructures, i.e. each unit cell or nanostructure arrangement may consist of or include a plurality of nanostructures. Other combinations may also be possible for CD manipulation.

[0096] FIGS. 11A and B show schematics of examples of nanostructure arrangement (gammadion group arrangement) in a single unit cell. FIG. 11A is a schematic showing the top view of arrangement of gammadions with two different rotation angles according to various embodiments. The arrangement may consist of two diagonal groups 1102a, 1102b, each group having two gammadion nanostructures with the same rotation angle. Gammadions of different groups have different rotation angles. FIG. 11B is a schematic showing the top view of arrangement of gammadions with 4 different rotation angles according to various embodiments. The arrangement consists of gammadion structures 1104a, 1104b, 1104c and 1104d at different rotations to one another. The group arrangements shown in FIGS. 11A and 11B are asymmetric.

[0097] Besides using gammadion, other kinds of asymmetrical nanostructures may be used to achieve similar results.

[0098] FIGS. 12A-D show schematics of examples of nanostructure arrangement in a single unit cell. FIG. 12A shows an asymmetric arrangement of spiral nanostructures 1202a, 1202b, 1202c, 1202d according to various embodiments. FIG. 12B shows an asymmetric arrangement of triangular nanostructures 1204a, 1204b, 1204c, 1204d according to various embodiments. FIG. 12C shows an asymmetric arrangement of nanorods 1206a, 1206b, 1206c, 1206d in windmill arrangement according to various embodiments. FIG. 12D shows an asymmetric arrangement of nanodisk groups 1208a, 1208b, 1208c, 1208d in windmill arrangement according to various embodiments.

[0099] The proposed shapes/groups shown in FIGS. 12A-D may also manipulate the CD spectrum and may also increase the CD amplitude. These designs may provide much flexibility to explore for observing the phenomenon of CD switching.

[00100] In various embodiments, each unit cell or nanostructure arrangement may include symmetrical nanostructures arranged in an asymmetrical manner so that the arrangement or unit cell is asymmetrical. While each nanostructure may be symmetrical; the nanostructure arrangement including a plurality of nanostructures may be asymmetrical, which imparts chirality. In other words, each nanostructure arrangement may include or may consist of symmetrical nanostructures/groups of nanostructures or asymmetrical nanostructures/groups of nanostructures.

[00101] Various embodiments may including the chiral structure about an off centre axis. In other words, the chiral structure may be rotated about an axis that does not include or pass through the geometric centre of the chiral structure. FIGS. 13A shows a prism 1302 with a geometric centre as shown by the intersection of the dotted lines. FIG. 13B shows the prism 1302 being rotated about an axis that passes through the geometrical centre of the prism. The prism may be about 200nm at all sides. The centre of the prism may be at a third of the height. FIG. 13C is a plot 1300 of circular dichroism (CD) spectrum of modes (arbitrary units or a.u.) against wavelength (nanometres or nm) showing the circular dichroism (CD) spectra after rotation through different angles of 0, 15, 30, 45, 60, 75 and 90 degrees. Line 1304 indicates the spectrum at 0 degree rotation (unrotated); 1306 indicates the spectrum at 15 degree rotation; line 1308 indicates the spectrum at 30 degree rotation; line 1310 indicates the spectrum at 45 degree rotation; line 1312 indicates the spectrum at 60 degree rotation; line

1314 indicates the spectrum at 75 degree rotation; and line 1316 indicates the spectrum at 90 degree rotation. FIG. 13C shows that the sign or polarity of the CD changes at 15, 45, 75 and 90 degrees. There is no significant CD observed at 0, 30 and 60 degrees.

[00102] If the rotation axis does not pass through the geometric centre of a structure, the CD change may occur at different rotation angles. FIG. 13D shows the prism 1302 being rotated about an axis that does not pass through the geometrical centre of the prism. FIG. 13E a plot 1350 of circular dichroism (CD) spectrum of modes (arbitrary units or a.u.) against wavelength (nanometres or nm) showing the circular dichroism (CD) spectra after rotation through different angles of 0, 30, 45, 60, 75 and 90 degrees. Line 1352 indicates the spectrum at 0 degree rotation (unrotated); line 1354 indicates the spectrum at 30 degree rotation; line 1356 indicates the spectrum at 45 degree rotation; line 1358 indicates the spectrum at 60 degree rotation; line 1360 indicates the spectrum at 75 degree rotation; and line 1362 indicates the spectrum at 90 degree rotation. CD is observed at 30 and 60 degrees while no significant CD is observed at 45 and 90 degrees.

[00103] As shown in FIGS. 13A-E, the CD may be lower as the electromagnetic wave or light is not incident in all parts of the nanostructure. Further, CD is observed at a rotation angle of about 60 degree when the structure is rotated at an off-centre axis. Rotating about the off- centre axis may all asymmetric properties to a structure. In various embodiments, the method may include rotating the chiral structure at an axis that does not pass through the geometric centre. Rotation about an off-centre axis may reduce the CD enhancement effect due to unequal absorption of light on the nanostructures or nanostructure arrangements. However, this may be a minor problem. As the rotation about an off centre axis adds an additional asymmetric element, various embodiments may offer increased flexibility to change the CD sign by changing an axis of rotation.

[00104] Various embodiments may relate to plasmonic gammadion structures being rotated to manipulate the CD spectrum. Gammadion nanostructures may be rotated to manipulate the phase of the scatter field. This in turn may change the overall phase and polarization direction of the array. The change in the polarization direction may result in the change in CD of the spectrum.

[00105] Simulation results have shown that the CD spectrum may switch to opposing polarities/signs when at rotated at an angle of about 75 degree. The simulation of the rotated gammadion is first simulated to validate this hypothesis. A set of codes may be used to

generate the structure and rotation axis of the gammadion. The optical properties of the material may then be applied and finite-different time-domain algorithm may be used calculate the effect of electromagnetic field on the nanostructures. The absorption spectrum of the CD may switch polarities or signs at a rotation angle of 75 degree in the clockwise direction.

[00106] There may be good matching between the simulation and fabrication results. As shown in FIG. 6 and FIG. 10, the simulation and experimental CD spectra demonstrate good agreement. Both the results show that the CD switches to the opposite polarity at rotation angle of about 75 degree. Both CD spectra also show that the CD modes of m1, m2 and m3 may red shift when the gammadion is rotated. Smaller red shift is also observed in both spectra at other rotating angles.

[00107] In addition, both the simulation and experimental CD spectra show similar behavior of modes m1, m2 and m3. The CD amplitude of all three modes may be reduced at rotation angle of about 60 degree. The CD amplitude may be seen to be the largest at rotating angle of about 45 degree.

[00108] Simple fabrication method to obtain different gammadion arrays in single layer have also be demonstrated. The fabrication method for the rotated gammadion may be relatively simple and easy. A single layer array may be proposed so that it uses only conventional e-beam machines and lithography method. The proposed nanostructures based on the above examples do not require a precise or delicate fabrication process to fabricate.

[00109] Other types of nanostructures combination may also be used for design flexibility. As shown in FIGS. 11A-B and FIGS. 12A-D, there may be a large number of possible ways to achieve similar CD switching phenomenon with different arrangements, shapes and sizes. Different materials may be used to enhance the CD detection for different biosamples. The advantages may include great flexibility for designs, ability to satisfy wide range of molecular identification needs and/or possibility of further optimization to achieve better results.

[00110] Various embodiments may be compatible for testing of biosamples. Various embodiments may be used for the detection of biosample. With different rotating angles, the CD may be changed, and these properties may be used to change the CD properties of the biosamples. By changing the CD properties of the biosamples, the handedness of the

biosamples may be changed. This advantageously provides a wide range of flexible application for chiral biomolecules development.

[00111] Various embodiments may be suitable for in high-end molecular manipulation and detection enhancement in terms of performance and quality. Various embodiments may have applications in chiral services for drugs, healthcare and cosmetics.

[00112] Various embodiments may relate to manipulating the CD spectrum as well as enhancing the sensitivity via rotation of fourfold rotational symmetry chiral nanostructure. Such chiral nanostructure may enhance the CD response of the chiral molecules and may provide a good platform for biochemical sensing.

[00113] In various embodiments, a chiral subwavelength nanostructure may be provided. The nanostructure may include bilayered fourfold rotationally symmetric nanostrips. The fourfold rotationally symmetric nanostrips may describe the helical chiral phenomenon while the double layers of the structure may represent the coupling chiral effect. The subwavelength feature construct by noble metal nanostrips may result in local electromagnetic field enhancements upon the light incident. The double layer may provide the coupling effect, as well as the ability to manipulate the chiral effect when one layer is rotated with respect to the planar surface of the other layer.

[00114] In various embodiments, the chiral subwavelength nanostructures may be made up of bilayered fourfold rotationally- symmetric nanostrips as shows in FIGS. 14A-D. FIG. 14A is a schematic showing a perspective view of a structure according to various embodiments. FIG. 14B is a schematic showing a top view of the structure shown in FIG. 14A according to various embodiments. FIG. 14C is a schematic showing a cross-sectional side view of the structure shown in FIG. 14A according to various embodiments. The structure may include two layers 1402, 1404. Each individual layer may include or consist of four metal strips 1402a-d, 1404a-d arranged in a chiral windmill arrangement about a common axis 1406. Light with left-handed circular polarized (LCP) or right-handed circular polarized (RCP) may be incident onto the system. Metal strips 1402a-d may form a first nanostructure array and metal strips 1404a-d may form a second nanostructure array. Localized surface plasmon may be excited when light interacts with the structure, enhancing the field amplitude.

[00115] In various embodiments, a structure may be provided. The structure may include a nanostructure array 1402 about an axis. The structure may further include a further nanostructure array 1404 about the axis 1406. The structure may further include a separation

layer, such as a dielectric layer 1408 (e.g. of silicon nitride), between the nanostructure array 1402 and the further nanostructure array 144. The structure may be a chiral structure. The nanostructure array 1402 may be over a further nanostructure array 1404 to form a bilayer structure.

[00116] When the further array 1404 is rotated relative to the first array 1402 about axis 1406, the magnitude of chirality may change from positive to negative, and vice versa. Thus, by manipulating the mutual rotation, the handedness of the structure may switch and this may cause a reversal of the outgoing light.

[00117] The method may include rotating the nanostructure array 1402 is rotated about an axis 1406. The further nanostructure array 1404 may be stationary. In various other embodiments, the further nanostructure array 1404 may be rotated about the axis 1406 while the nanostructure array may be stationary. The nanostructure array 1402 and/or the nanostructure array 1404 may be immersed in a suitable liquid 1410 such as water, or a biological fluid.

[00118] In various embodiments, the structure may include two layers of gold nanostructure arrays 1402, 1404 arranged on top and bottom with a layer of thin silicon nitrate layer 1408 sandwiched in between the layers 1402, 1404.

[00119] The pitch of the unit cell (a) may be about 250nm. The thickness of gold (t_{Au}) layer may be about 20nm and Si_3N_4 (t_{sub}) may be 30nm to about 50nm. Each gold layer may include or consists of 4 nanostrips arranged in windmill arrangement, with the length of each nanostrip (L) to be about 60nm, the separation between nanostrips (d) to be about 30nm, and the width of each nanostrip (w) to be about 30nm.

[00120] In various embodiments, the second layer 1404 may be rotated from $\theta = 0^\circ$ to $\theta = 90^\circ$ relative to the first layer 1402. When $\theta = 0^\circ$ and $\theta = 90^\circ$, the nanostructure array of the second layer 1404 may be exactly identical to the first layer 1402. For the remaining angles (e.g. when θ is between 0° and 90°), the mutual deviation may increase the chiral effect of the whole nanostructure. FIG. 14D is a schematic of the structure shown in FIG. 14A when an angle of rotation (θ) between the nanostructure array and further nanostructure array about axis 1406 is 15° according to various embodiments.

[00121] The silicon nitrate 1408 may be used because of it is high-melting point, relatively chemically inert and thermodynamically stable. It may not contaminate biosamples and may be transparent to visible light wavelength.

[00122] The surrounding of the gold nanostructure may be water with a refractive index of 1.33. The intention of placing the nanostructure in a liquid environment is because one objective is to apply the idea to biosamples.

[00123] Simulation of the chiral structure may be performed using finite-difference time-domain (FDTD) method. FIG. 15 is a schematic illustrating simulation performed using frequency solver with Floquet boundaries according to various embodiments. To model the system in an array 1502, periodic boundary conditions 1504 may be applied in the planar surfaces while perfectly matched layer boundary condition 1506 may be applied to the vertical axis of the array 1502.

[00124] The electromagnetic wave, e.g. circular light may incident on the xy-plane of the system (see FIG. 14A), i.e. on the planar surface of the nanostructure array. The electromagnetic wave may incident substantially parallel to the axis 1406. Gold may be modelled by the free-electron Drude model.

[00125] The interaction of the fourfold rotational symmetry nanostructure with the RCP and LCP light by rotating the mutual angle, θ , has been investigated. The absorption and CD spectrum as well as the field distribution of this nanostructure are also studied.

[00126] The details for getting the absorption and CD spectrum are given as below:

[00127] Monitors are placed to obtain the scattering, reflection and transmission power when incident with LCP and RCP light respectively with the wavelength range of about 400 to about 1200 nm. Using the conservation of energy, the absorption power may be calculated according to equation (1).

[00128] The absorption power, A_L and A_R may be obtained for both LCP and RCP light. Then, the CD of the structure may be obtained using the equation (2).

[00129] From the simulation data, the absorption profile of the nanostructure is extracted from θ to be about 0° to about 90° . FIG. 16 is a plot 1600 of absorption (arbitrary units or a.u.) against wavelength (nanometers or nm) showing the variation of the absorbance profile when one array is rotated relative to another array for the structure shown in FIG. 15A according to various embodiments. The right side of FIG. 16 shows the schematics of the structure in which one array is rotated relative to another array, and each schematic corresponds to the plot shown on the left side. The dotted line 1602 indicates the absorbance profile of RCP light while the solid line 1604 indicates the absorbance profile of LCP light.

[00130] The orientation of the nanostructure may vary from $\theta = 0^\circ$ to 90° . One can clearly observe that a significant reversal of the absorbance on RCP and LCP may happen when $\theta = 15^\circ$ and 75° . This reversal may be due to the changing of the handedness of the structure. From $\theta = 0^\circ$ to $\theta = 30^\circ$ the nanostructure is left-handed and but $\theta = 45^\circ$ to $\theta = 90^\circ$ the nanostructure has changed to right-handed.

[00131] A circular dichroism signal may be positive or negative, depending on whether LCP light is absorbed to a greater extent than RCP light (CD signal positive) or to a lesser extent (CD signal negative).

[00132] FIG. 17 is a plot 1700 of circular dichroism (CD) spectrum of modes (arbitrary units or a.u.) against wavelength (nanometres or nm) showing the circular dichroism (CD) spectra before rotation and after rotation through different angles of 15, 30, 45, 60, 75 and 90 degrees according to various embodiments. Line 1702 shows the spectrum of the unrotated structure; line 1704 shows the spectrum of the structure after rotation of 15 degree; line 1706 shows the spectrum of the structure after rotation of 30 degree; line 1708 shows the spectrum of the structure after rotation of 45 degree; line 1710 shows the spectrum of the structure after rotation of 60 degree; line 1712 shows the spectrum of the structure after rotation of 75 degree; and line 1714 shows the spectrum of the structure after rotation of 90 degree.

[00133] FIG. 17 shows the CD spectra of the structure with multiple CD peaks or and dips, demonstrating how CD varies as a function of wavelength, and that a CD spectrum may exhibit both positive and negative peaks. There are three CD peaks/dips around about 680 nm, about 900nm, and about 980nm. These CD peaks may be allocated as mode 1, mode 2 and mode 3. At mode 1 and mode 3, the CD may be negative for $\theta = 15^\circ$ and $\theta = 30^\circ$, and positive for $\theta = 60^\circ$, $\theta = 75^\circ$. When $\theta = 0^\circ$, 45° , or 90° , the sign of the mode may be undefined. At mode 2, the CD is opposite to that of mode 1 and mode 3. In other words, when mode 1 and mode 3 are positive, mode 2 is negative, vice versa. Mode 2 and mode 3 are of opposite chirality polarities and therefore the CD may receive its bisignate appearance. This is because at such orientation, the structure has gradually changed from left-handed to right-handed. The sign of the CD is flipped, indicating the switching of the handedness of the structure.

[00134] As the angle changes, the chirality polarities may change between positive and negative. At certain specific angles, the structure may act as left-handed structure; while at other specific angles, the structure may act as right-handed structure.

[00135] Upon interaction with a specific handed circular polarized light (for example LCP light), the local electromagnetic field may be enhanced if the structure is left-handed, otherwise the local electromagnetic field may be suppressed.

[00136] FIG. 18 is a plot 1800 of circular dichroism (CD) (arbitrary units or a.u.) against the relative rotation angle θ between the first nanostructure array and the second nanostructure array (degrees or $^{\circ}$) according to various embodiments. 1802 indicates mode 1, 1804 indicates mode 2, and 1806 indicates mode 3. FIG. 18 shows the switching effect of the structure for the three modes upon rotation angle from 0° to 180° . Mode 3 may provide the most significant switching effect amongst the three modes.

[00137] The strong switching effect may be observed in this bilayer fourfold symmetry structure when one of the layers rotates relative to the other layer, thus indicating that the chirality may be manipulated.

[00138] The field distribution of the structure may also be considered when the circular polarized light is normally incident onto the structure.

[00139] FIG. 19 show images showing the tangential field distribution of right-handed circularly polarized (RCP) light (mode 1, mode 2 and mode 3) on the first nanostructure array layer and the second nanostructure array layer according to various embodiments. 1902a shows the first mode on the first nanostructure array, while 1902b shows the first mode on the second nanostructure array. 1904a shows the second mode on the first nanostructure array, while 1904b shows the second mode on the second nanostructure array. 1906a shows the third mode on the first nanostructure array, while 1906b shows the third mode on the second nanostructure array.

[00140] Based on the field distribution shown, it can be concluded that mode 1 is due to Bloch periodicity of the unit cell in the nanostructure, while mode 2 and mode 3 are split between the localized surface plasmonics modes for x- and y-component of RCP light. The subwavelength nanostrips may give rise to interesting optical phenomena such as localized surface plasmon polarities. The resonance coupling between the induced localized surface plasmon modes may enhance the signal field of the nanostructure. Thus, the plasmonic field extension generated from the gold nanostructure may lead to the field enhancement that improves the detection sensitivity. The results have shown that this structure may readily serve as promising amplification labels in surface plasmon resonance (SPR) sensing technology.

[00141] Circular dichroism (CD) spectroscopy is a spectroscopic technique where the CD of molecules is measured over a range of wavelengths. In various embodiments, a method of determining a structural feature of an entity may be provided using a structure or arrangement as described herein. The method may include providing a light source to generate polarized light or electromagnetic wave. The method may further include positioning the structure or arrangement, such as the chiral structure as described herein, in front of the entity so that the polarized light passes through the arrangement or structure before passing through the entity. The method may further include rotating the structure or arrangement. The method may also include providing a detector configured to detect the polarized light that passes through the structure or arrangement, and also passes through the entity; wherein the detector is further configured to generate a circular dichroism signal. The method may additionally include determining the structural feature of the entity based on the circular dichroism signal.

[00142] In various embodiments, a method of determining a structural feature of an entity may be provided. The method may include changing the circular dichroism spectrum as described herein. The method may also include providing the entity so that the polarized light passes through the chiral structure before passing through the entity. The method may further include providing a detector configured to detect the polarized light that passes through the chiral structure and the entity. The detector is further configured to generate a circular dichroism signal. The method may further include determining the structural feature of the entity based on the circular dichroism signal.

[00143] CD may be observed when optically active matter absorbs left and right hand circular polarized light slightly differently.

[00144] FIG. 20A is a schematic showing a setup 2000 for determining a structural feature of an entity 2006 according to various embodiments. A polarized light 2002 may be provided. The polarized light 2002 may pass through a structure or arrangement 2004 including nanostructures as described herein. The light 2002 then passes through the entity 2006, i.e. a chiral sample and is then detected by a detector (not shown in FIG. 20A). The detector detects the light 2002 that passes through the structure or arrangement 2004, and the entity 2006, and generates a signal 2008 including information on absorption or circular dichroism.

[00145] FIG. 20B is a diagram illustrating signal enhancement with a structure or arrangement including nanostructures integrated into a detection system according to various embodiments. 2052 is the absorption spectrum of LCP light, while 2054 is the absorption of

the RCP light. 2056 is a CD signal that results when a structure or arrangement including nanostructures is integrated into the detection system. 2058 is a CD signal when no such structure or arrangement is integrated. FIG. 20B shows that the CD signal may be enhanced when a structure or arrangement including nanostructures is integrated into the detection system. The labels “a” and “b” denote the amplitude and full wave half maximum value of the CD signal respectively.

[00146] The entity 2006 may be a biological entity, such as a biological compound or molecule. The entity 2006 may contain chiral chromophores, which enables one circular polarized light state to be absorbed to a greater extent than the other circular polarized light state. The resulting CD signal 2008 may then be non-zero. CD may be used extensively to study secondary structure of chiral molecules.

[00147] The secondary structure is the general three-dimensional form of local segments of biopolymers such as proteins and nucleic acids (DNA/RNA). However, methods for detecting the secondary structure may not provide information regarding the specific atomic positions in three-dimensional space. Nevertheless, the CD spectra for distinct types of secondary structure present in peptides, proteins and nucleic acids are different from one another. The analysis of CD spectra may therefore yield valuable information about biological macromolecules. In addition, CD may be used to observe how the secondary structure changes with environmental conditions such as temperature or pH, or on interaction with other molecules. Therefore, structural, kinetic and thermodynamic information about macromolecules may be derived from circular dichroism spectroscopy.

[00148] FIG. 21 is a schematic illustrating a setup 2100 for circular dichroism (CD) spectroscopy according to various embodiments. Light from light source 2102a may be passed through linear polarizer 2012b and quarter-wave plate 2012c to generate LCP light or RCP light. The LCP light or RCP light may be passed through a structure or arrangement containing nanostructures 2104 as described herein according to various embodiments, and a sample chamber 2106 containing the entity before being detected by the detector 2018a. The detector 2018a generates a signal containing information on the absorption or circular dichroism of the polarized light. The signal is then passed to signal analyzer 2018b for determination of the structural feature of the entity.

[00149] A structure or arrangement integrated inside the setup 2100 for CD spectroscopy may enhance the sensitivity of the CD signal. The difference in left and right handed

absorbance may be very small, usually in the range of about 0.0001. Usually, the typical concentration of the testing sample such as protein is 0.5 mg/ml. In some situations, protein concentration may be needed to be adjusted to produce the best data. However, changing the concentration may intensely effect on the data. Therefore it may be an essential requirement to increase the sensitivity of the spectroscopy instead of adjusting the concentration of the measured sample. The structure or arrangement including the nanostructures has been proven to exhibit plasmonics effect that enhances the CD signal and consequently increases the sensitivity. The sensitivity may be defined as a ratio of amplitude of signal, b , to its full wave half maximum value, a , as shown in FIG. 20B.

[00150] Usually, conventional CD spectroscopy may be relatively expensive (~\$70k) due to the bulky and expensive high power source as well as its cooling system used in the spectroscopy. As the nanostructure may be adjusted to interact with light within the visible range by tuning the parameter of the unit cell, inexpensive light sources such as light emitting diode or sun light may be used as light sources in the system, leading to decreased source and also increasing the degree of freedom in design of the sensor.

[00151] Various embodiments may include different patterns and designs of nanostructures to achieve the switching effects, as well as for enhancing sensitivity and manipulating the CD properties. The designs and patterns may be altered to tune the switching and sensitivity as well as the CD spectrum properties in order to fit the desired application.

[00152] In various embodiments, the nanostructure array and the further nanostructure array may be of a different structure, size, shape and/or arrangement. The bilayer structure may be hetero-layer. FIG. 22A is a schematic of a structure 2200a in which nanostructures 2202a-d of the nanostructure array is arranged differently from nanostructures 2204a-d of the further nanostructure array according to various embodiments.

[00153] In various embodiments, the nanostructures of the nanostructure array may be of a different material from the nanostructures of the further nanostructure array. For instance, nanostructures may be made of a material selected from a group consisting of gold (Au), silver (Ag), copper (Cu) and aluminum (Al).

[00154] In various embodiments, the nanostructures may be of any suitable shape. FIG. 22B is a schematic of a structure 2200b including an array including triangular shaped nanostructures 2212a-d and a further array including triangular shaped nanostructures 2214a-d according to various embodiments. In various embodiments, the nanostructures of the

nanostructure array may be of a different shape from the nanostructures of the further nanostructure array. For example, nanostructures may be spiral, triangular in shape or may be nanorod.

[00155] In various embodiments, the number of nanostructures in the nanostructure array may be different from the number of nanostructures in the further nanostructure array.

[00156] In various embodiments, the nanostructures of the nanostructure array and the further nanostructure array may be arranged in any suitable arrangement. The nanostructures of the nanostructure array and the further nanostructure array may not be arranged in a windmill arrangement. FIG. 22C is a schematic of a structure 2200c including nanorods 2222a-d of the array and nanorods 2224a-d of the further array in an alternate arrangement according to various embodiments.

[00157] In various embodiments, the structure may have any suitable rotational symmetry. The nanostructures of the array and the nanostructures of the further array may be arranged in any suitable rotational symmetry. The structure may not be limited in the number of folds. FIG. 22D is a schematic of a structure 2200d in which the nanostructures 2232a-e of the array and the nanostructures 2234a-e of the further array are arranged in five-fold rotational symmetry according to various embodiments.

[00158] Various embodiments may involve CD spectrum manipulation using bilayer four-fold symmetry nanostructures. Various embodiments may include a bilayer nanostructure with each layer consisting of unit cells of 4 nanostrips arranged in windmill orientation. The CD spectrum may be manipulated by rotating one of the layers of the structure. In detection of samples containing chiral molecules, this may allow fine tuning of the spectrum to obtain maximum CD and determination of the orientation of the chiral molecule filament.

[00159] Various embodiments may include negative to positive chiral switching when the layers rotate relative to each other. The switching effect due to the mutual angle rotation among layers may change the chiral effect from positive to negative or vice versa depends on the circular polarized states. This switching effect may cause the reversal of the polarization state of out coming light. Various embodiments may be used as a chiral modulator.

[00160] In various embodiments, enantiomers (both left-handed and right-handed molecule) may be detected simultaneously by using only one sensor. The chiral switching properties of the bilayer nanostructure may allow the simultaneously detection of both the

left- and right-handed molecules. This may be an important property which allows the researcher to analyze the concentration of both enantiomers in one drug.

[00161] Various embodiments may relate to the sensitivity enhancement via plasmonic coupling between the nanostructure layers. The subwavelength gold nanostrips in this structure may exhibit plasmonic coupling effect not only in the same layer but also between layers. This may enhance the absorption of the field by exploiting surface plasmon resonance to trap the light. Consequently, the sensitivity of the molecular detection may be enhanced.

[00162] Various embodiments may provide flexibility in design. Various embodiments may include silicon nitride as a substrate in the bilayer structure, which may add flexibility on the sensor design since the substrate is flexible, chemical and thermal stable, enabling use for wide range of biomolecule and chiral drugs detection.

[00163] Various embodiments may find applications in medical imaging instrumentation implementation, drug synthesis and drug purification. In addition, various embodiments may be used in chemical and cosmetics industries for identifying the enantiomers of the molecules.

[00164] Deoxyribonucleic acid (DNA), proteins, amino acids, sugars may all be chiral. Mirror image amino acids are called L- and D-amino acids. Human proteins are exclusively built from L-amino acids. The origin of this fundamental dissymmetry is still mysterious. Molecules may recognize each other during interaction. Mirror image molecules, like mirror image Thalidomides, may have radically different effects on our bodies.

[00165] For instance, aspartame is a sweetening agent that is more than a hundred times sweeter than sucrose. However, the mirror image molecule may be bitter. (S)-carvone may possess the odor perception of caraway while the mirror image molecule (R)-carvone may have a spearmint odor.

[00166] FIG. 23 is a plot 2300 of absorption (arbitrary units or a.u.) against wavelength (nanometres or nm) showing how the absorption spectrum in FIG. 16 is obtained. 2302 denotes s11 and 2304 denotes s12. 2306 denotes the absorption spectrum based on s11 and s12. . The absorption spectrum may be obtained based on the following:

$$\text{Absorption}^2 = 1 - (s11)^2 - (s12)^2 \quad (3)$$

[00167] 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. A method of changing a circular dichroism spectrum of an electromagnetic wave, the method comprising:
 - providing a chiral structure;
 - providing said electromagnetic wave to the chiral structure; and
 - rotating the chiral structure to change the circular dichroism spectrum of said electromagnetic wave;wherein the chiral structure is a planar structure.
2. The method according to claim 1,
 - wherein the chiral structure is on a substrate.
3. The method according to claim 1,
 - wherein the chiral structure is a nanostructure.
4. The method according to claim 1,
 - wherein the chiral structure is a nanostructure array comprising a plurality of nanostructure arrangements.
5. The method according to claim 4,
 - wherein each nanostructure arrangement of the plurality of nanostructure arrangements is rotated about a respective axis that passes through a geometric centre of each nanostructure arrangement.
6. The method according to claim 5,
 - wherein an angle of rotation of one nanostructure arrangement of the plurality nanostructure arrangements is substantially equal to an angle of rotation of another nanostructure arrangement of the plurality of nanostructure arrangements.
7. The method according to claim 4,

wherein the nanostructure array is over a further nanostructure array to form a bilayer structure.

8. The method according to claim 7,
wherein the nanostructure array is rotated about an axis; and
wherein the further nanostructure array is stationary.
9. The method according to claim 4,
wherein each nanostructure of the plurality of nanostructures is spaced from a neighbouring nanostructure by a substantially equal distance.
10. The method according to claim 4,
wherein each nanostructure arrangement is asymmetrical.
11. The method according to claim 4,
wherein each nanostructure arrangement comprises one or more nanostructures.
12. The method according to claim 4,
wherein each nanostructure arrangement comprises one or more gammadion structures.
13. The method of claim 1,
wherein the electromagnetic wave is polarized.
14. A method of detecting a change in a circular dichroism spectrum of an electromagnetic wave, the method comprising:
changing the circular dichroism spectrum according to claim 1; and
determining a parameter of a detected electromagnetic wave travelling from the chiral structure for detecting the change in the circular dichroism spectrum;

wherein the detected electromagnetic wave is generated based on the electromagnetic wave provided to the chiral structure.

15. The method according to claim 14,
wherein the detected electromagnetic wave is an electromagnetic wave scattered by the chiral structure and the parameter is a scattering parameter of the scattered electromagnetic wave.
16. The method according to claim 14,
wherein the detected electromagnetic wave is an electromagnetic wave reflected by the chiral structure and the parameter is a reflection parameter of the reflected electromagnetic wave.
17. The method according to claim 14,
wherein the detected electromagnetic wave is an electromagnetic wave transmitted by the chiral structure and the parameter is a transmission parameter of the reflected electromagnetic wave.
18. The method according to claim 14, further comprising:
determining one or more further parameters of one or more further detected electromagnetic waves travelling from the chiral structure; and
wherein the one or more detected electromagnetic wave are generated based on the electromagnetic wave provided to the chiral structure.
19. The method according to claim 18, further comprising:
determining an absorption parameter of the chiral structure based on the parameter and the one or more further parameters.
20. A method of determining a structural feature of an entity, the method comprising:
changing the circular dichroism spectrum according to claim 1;
providing the entity so that the polarized light passes through the chiral structure before passing through the entity;

providing a detector configured to detect the polarized light that passes through the chiral structure and the entity; the detector further configured to generate a circular dichroism signal; and
determining the structural feature of the entity based on the circular dichroism signal.

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FIG. 1A

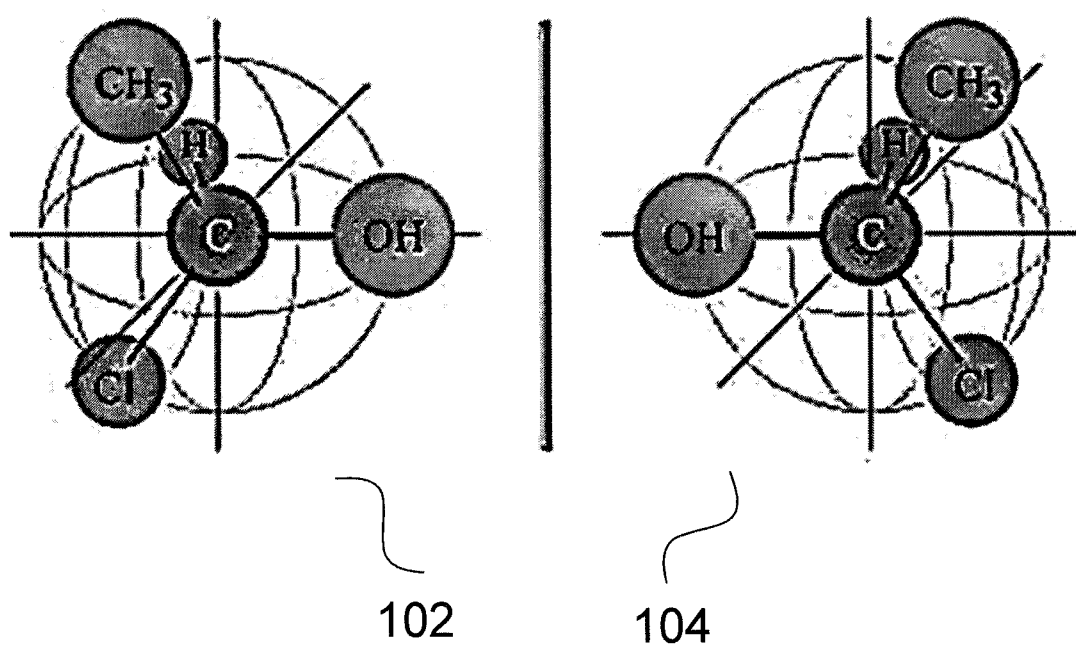
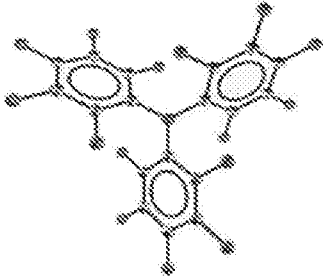
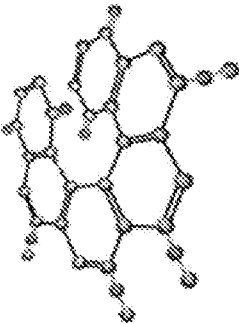
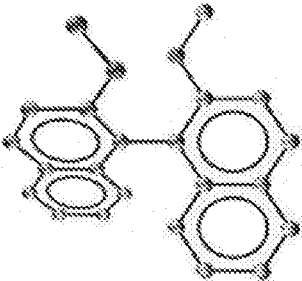
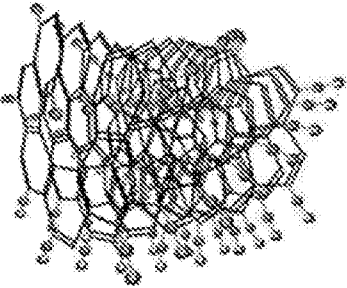
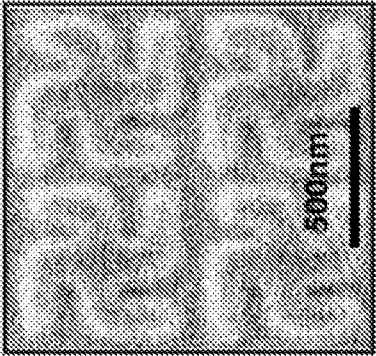
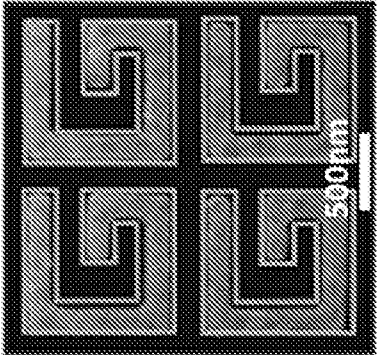
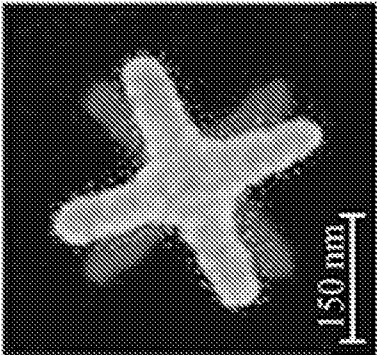
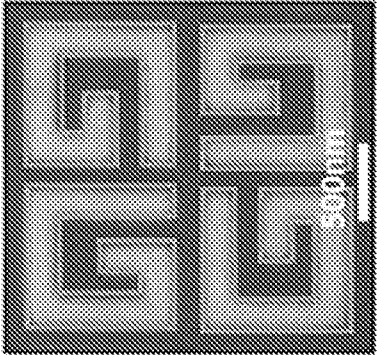


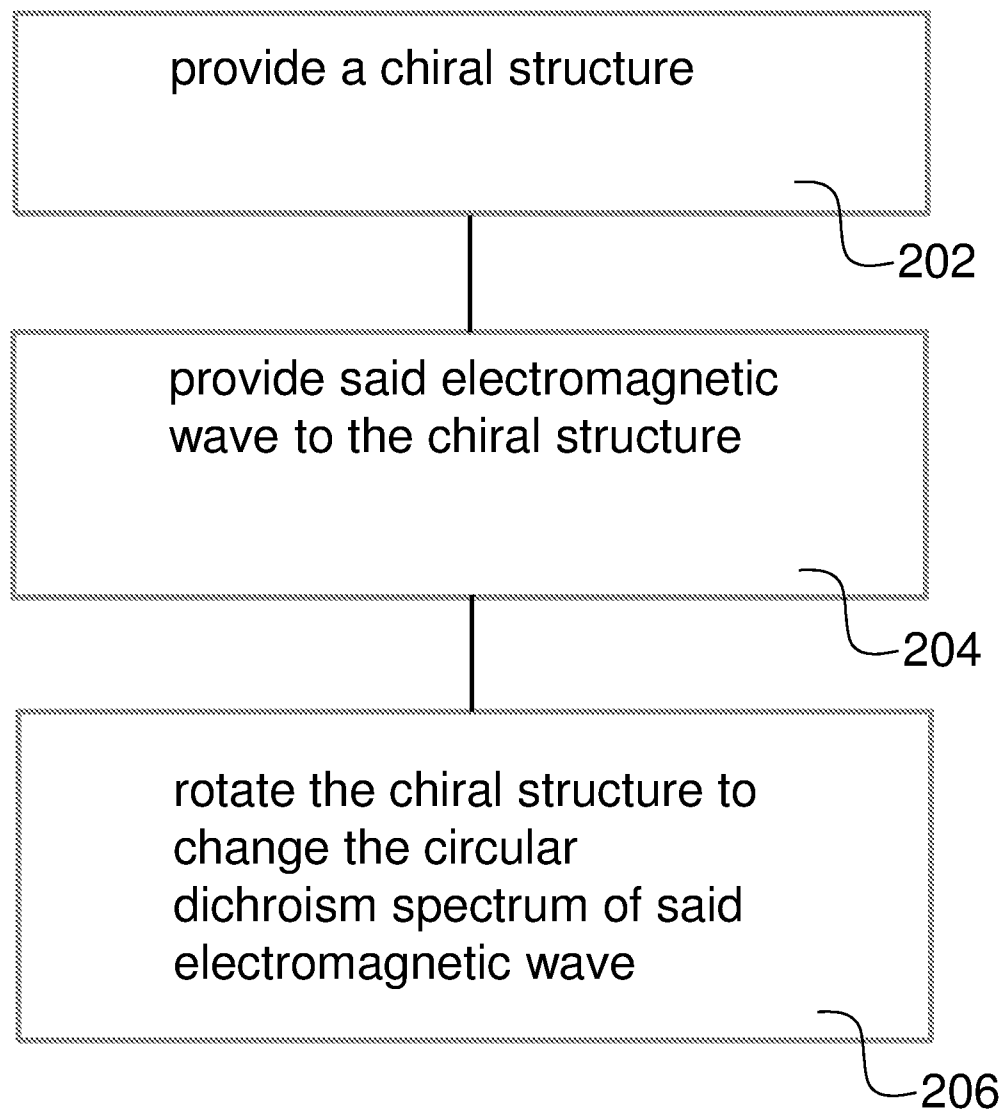
FIG. 1B

150

Propellers	Spirals	Chiral coupling	Supramolecular
 (a)	 (b)	 (c)	 (d)
 (e)	 (f)	 (g)	 (h)

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FIG. 2A

200a

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FIG. 2B

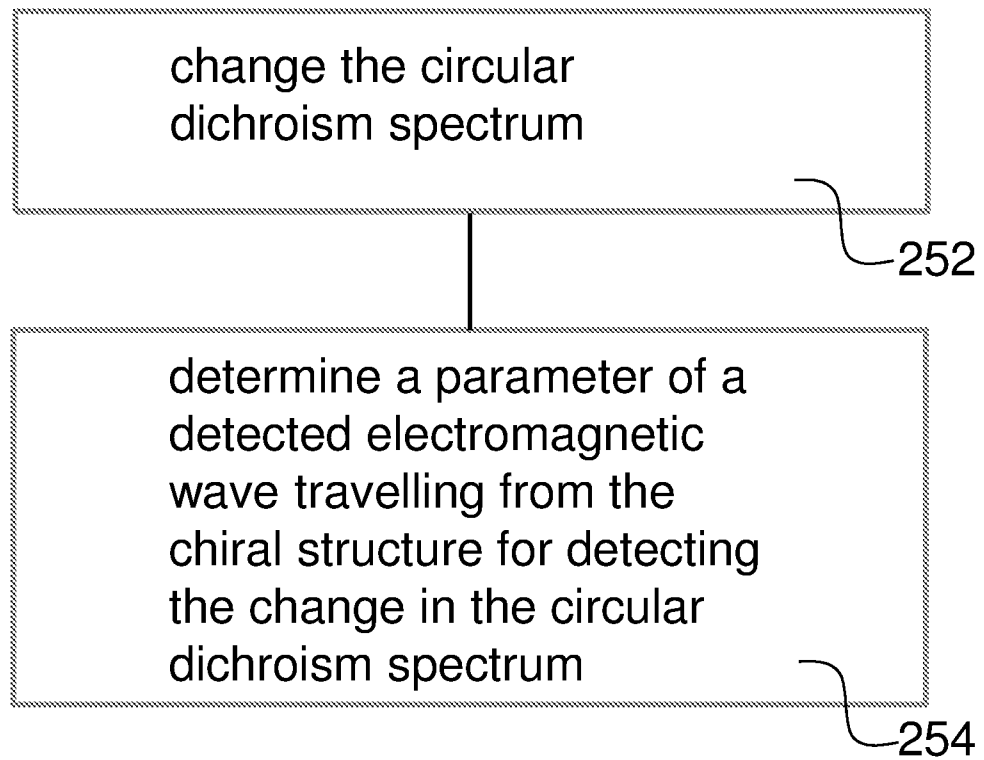
200b

FIG. 3A

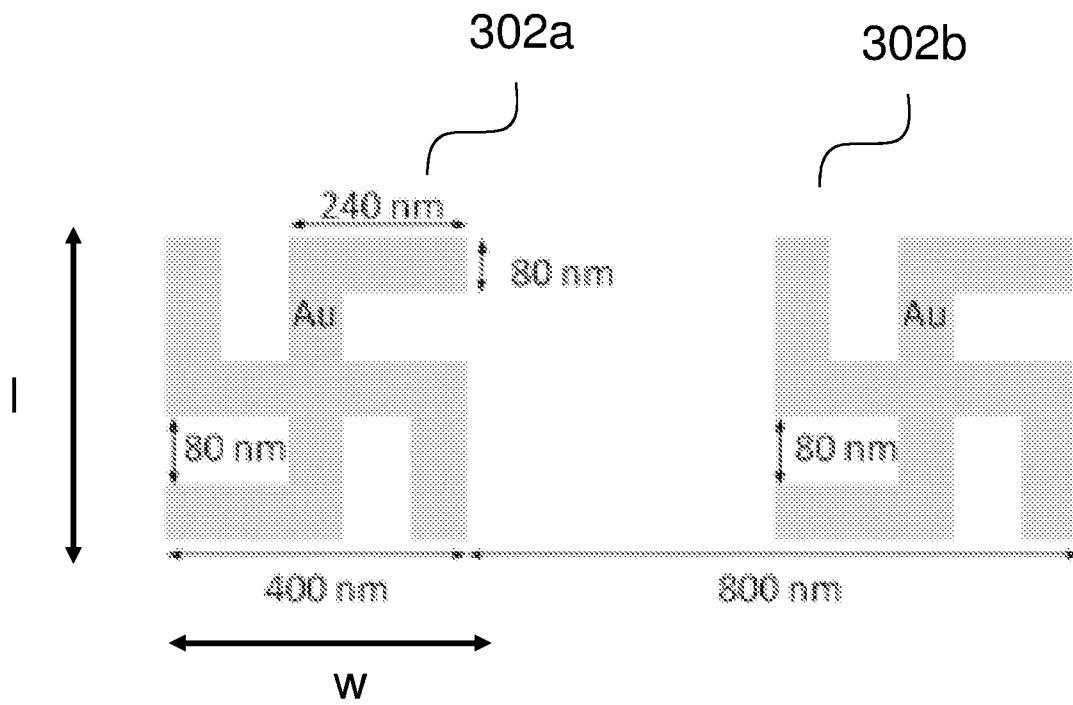
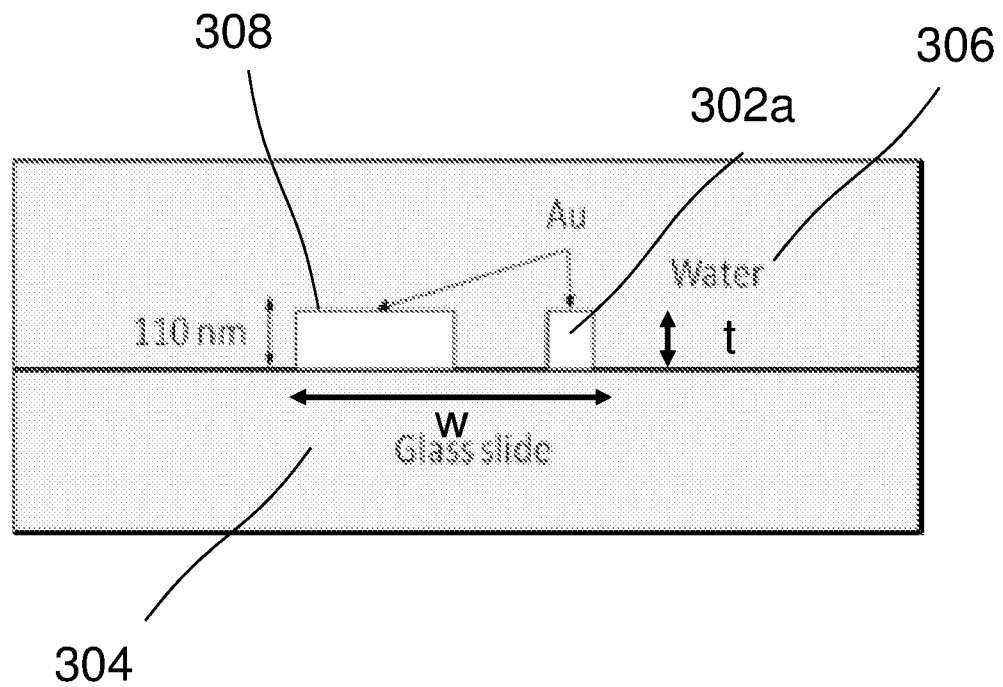
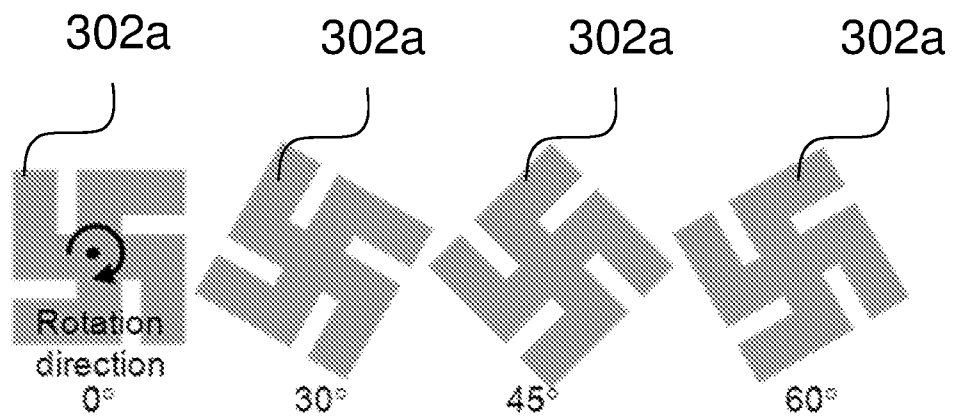


FIG. 3B



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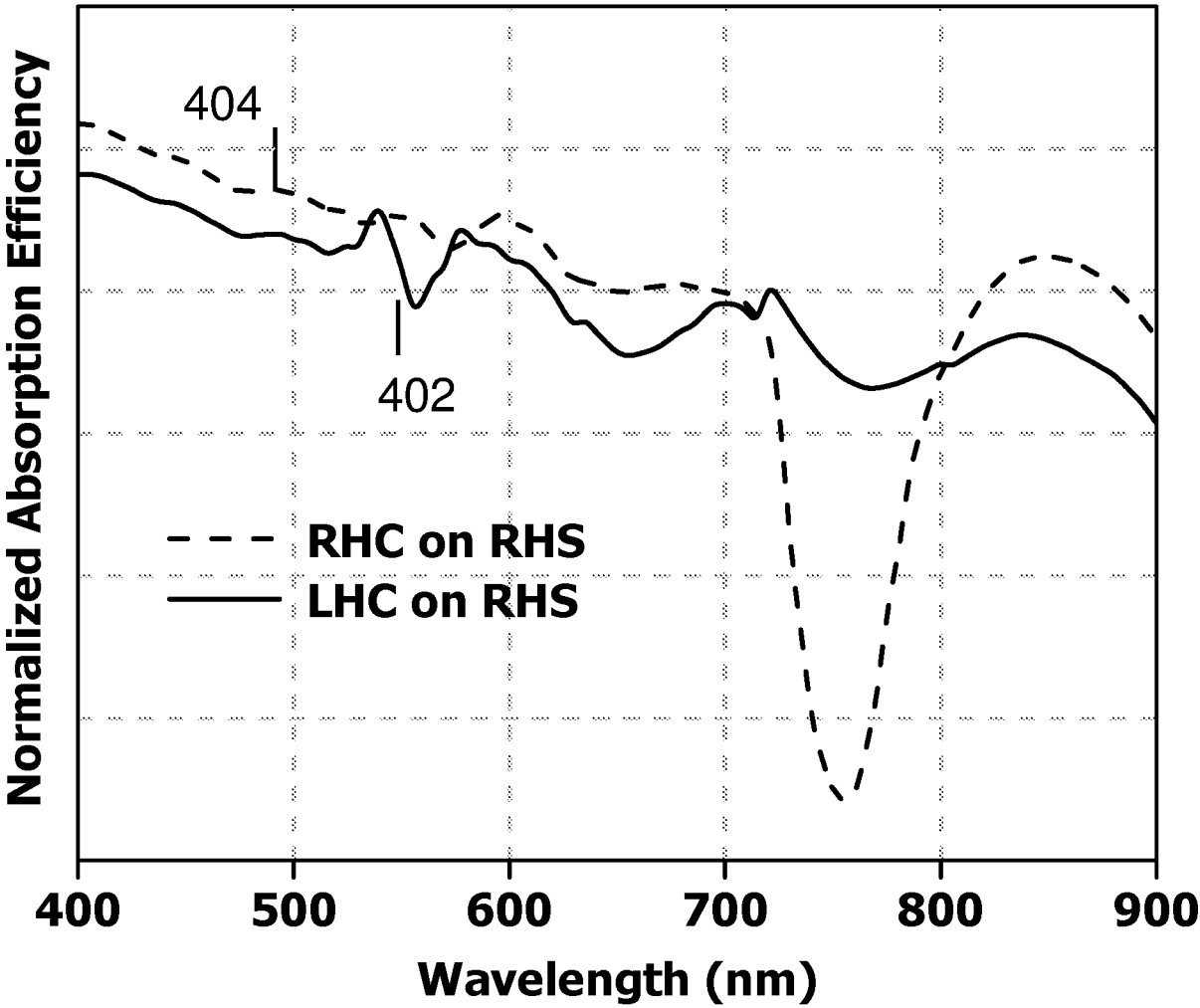
FIG. 3C



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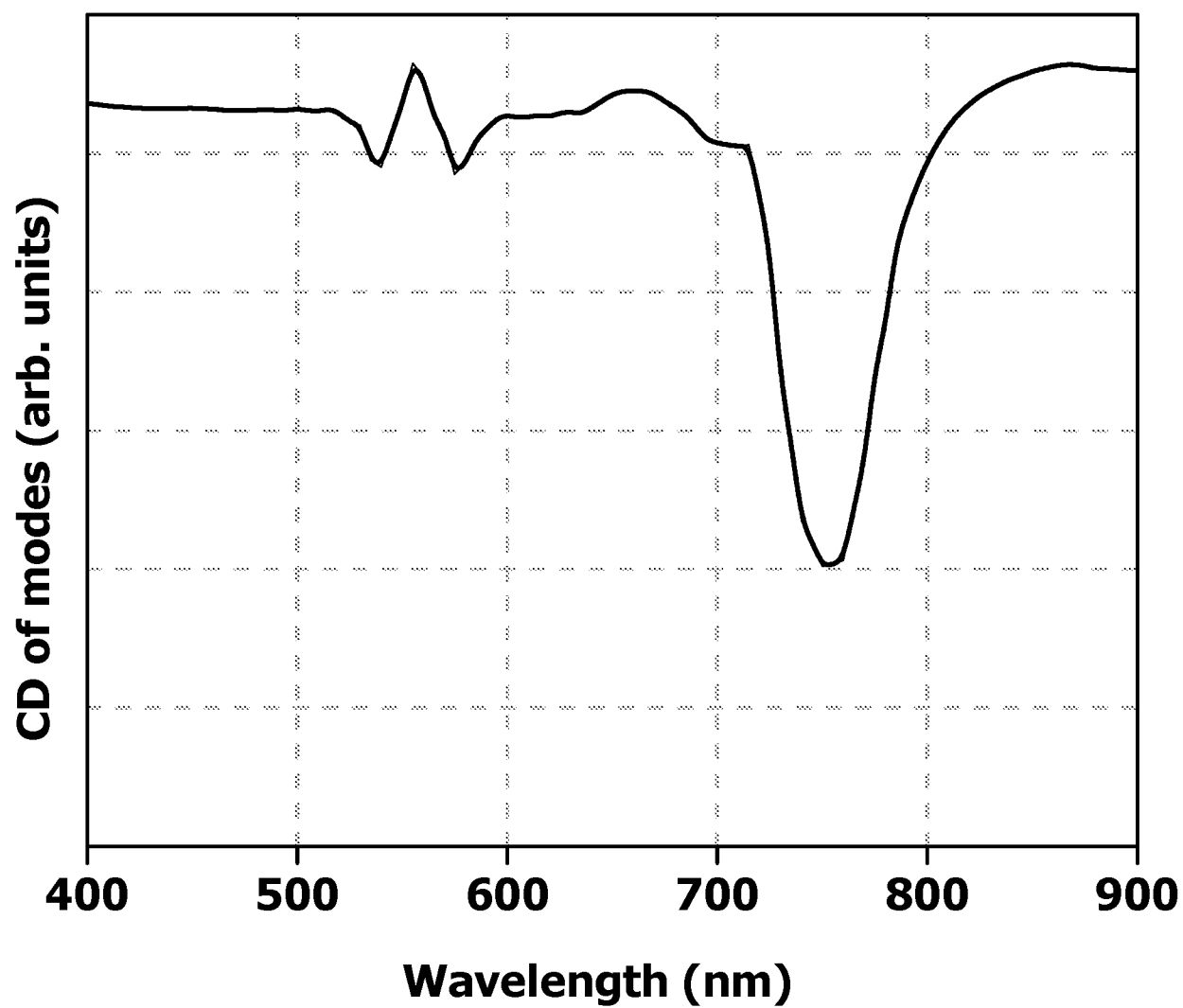
FIG. 4A

400a



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FIG. 4B

400b

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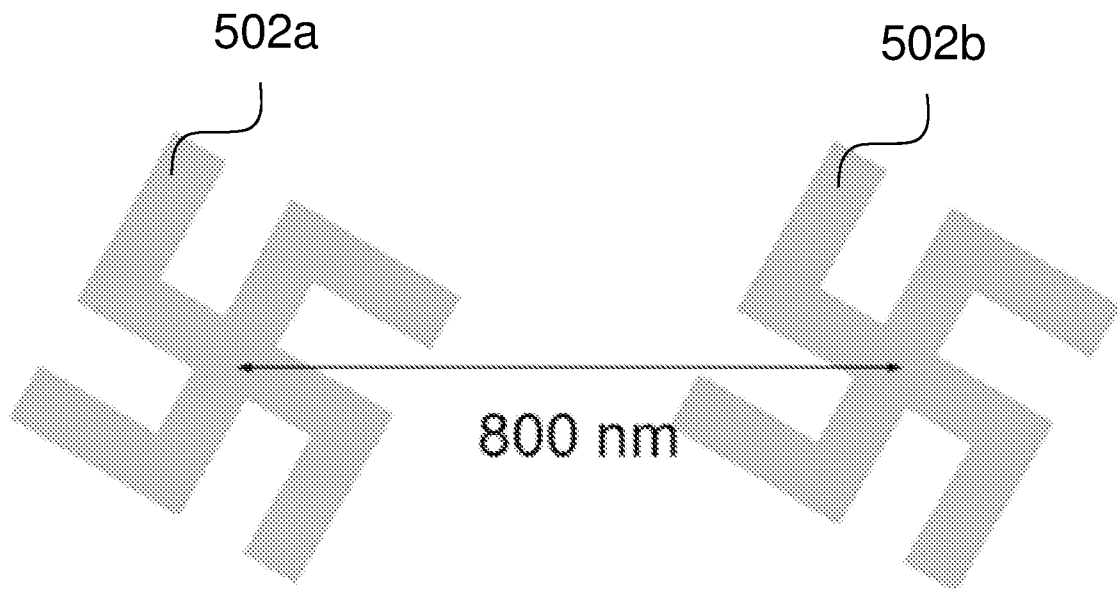
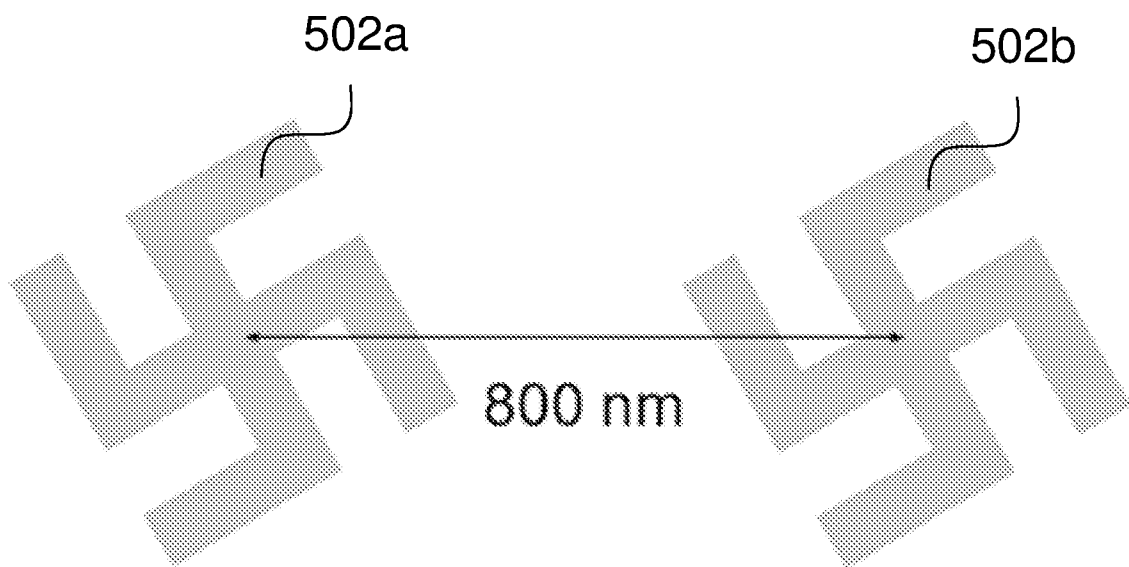
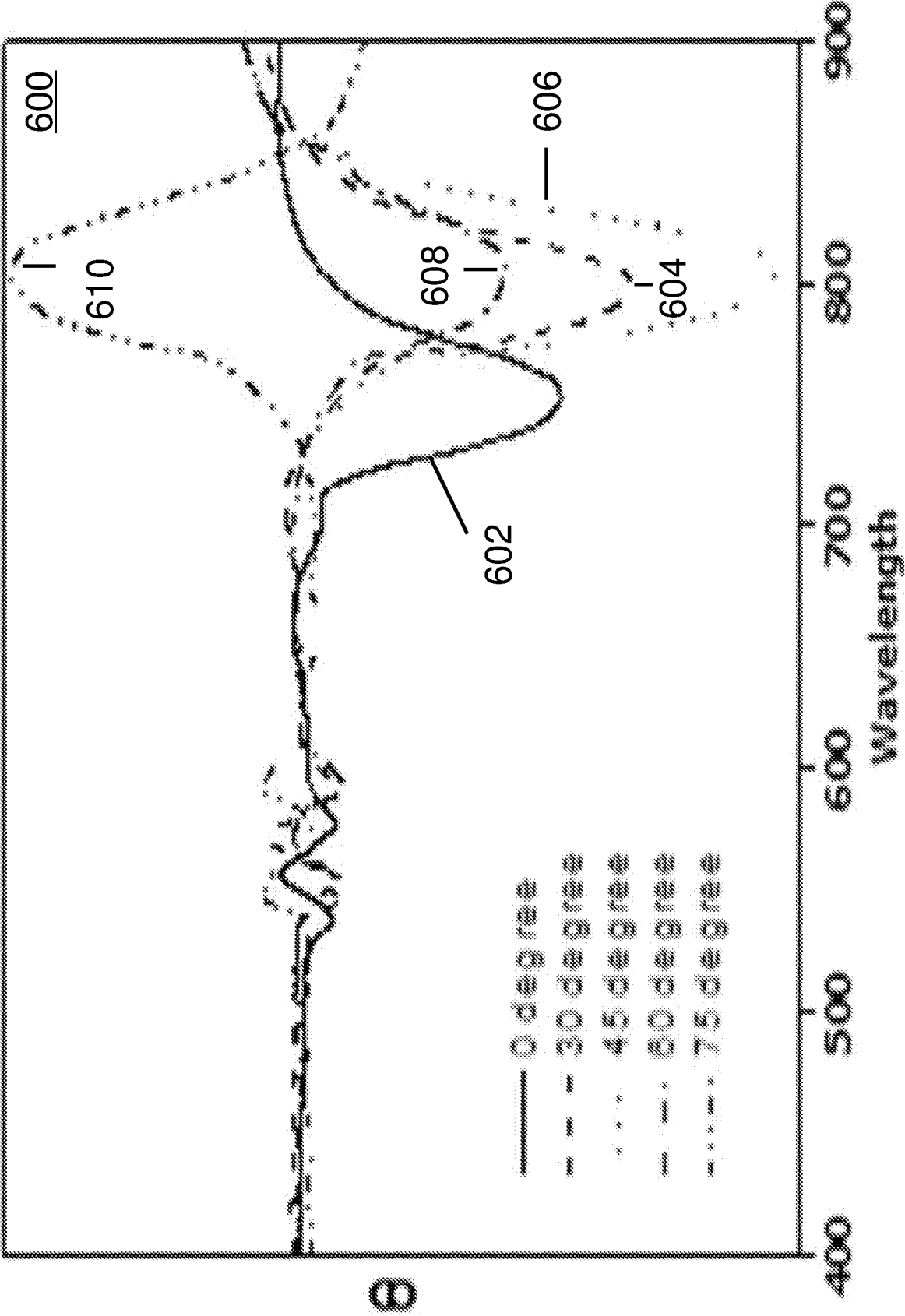
FIG. 5A**FIG. 5B**

FIG. 6



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FIG. 7A



FIG. 7B

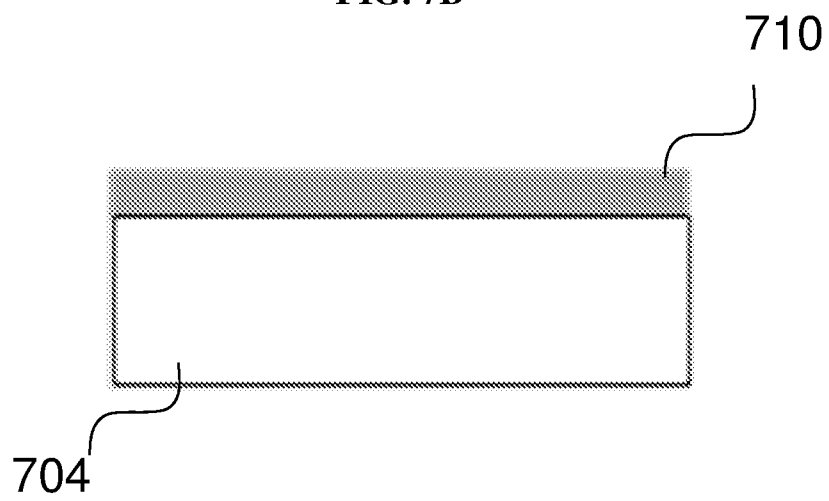


FIG. 7C

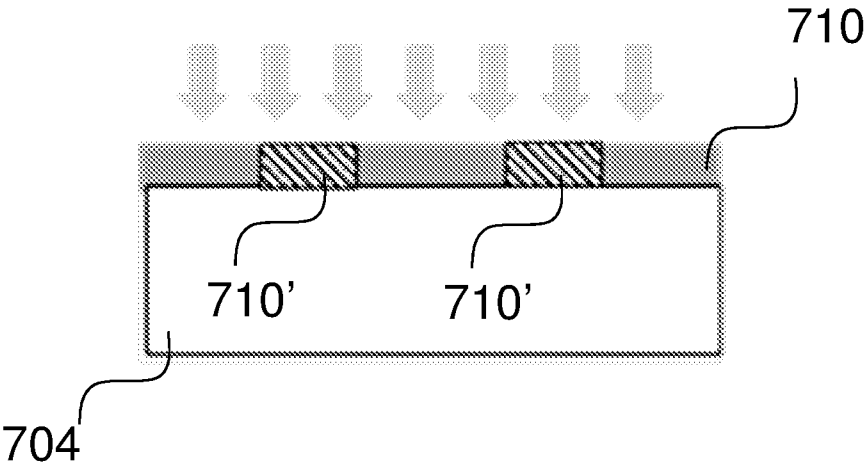
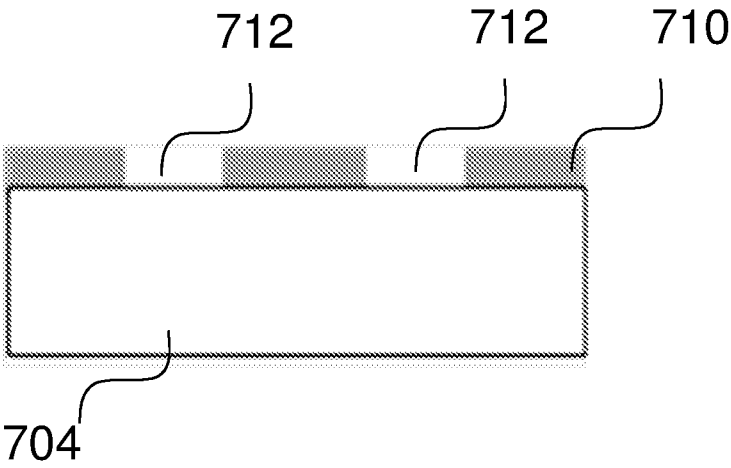


FIG. 7D



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FIG. 7E

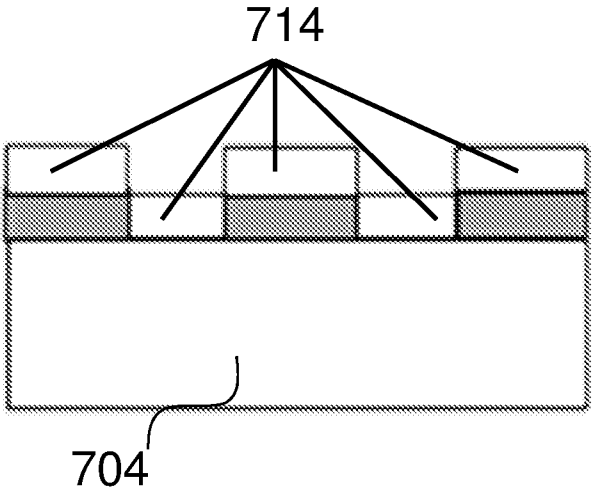
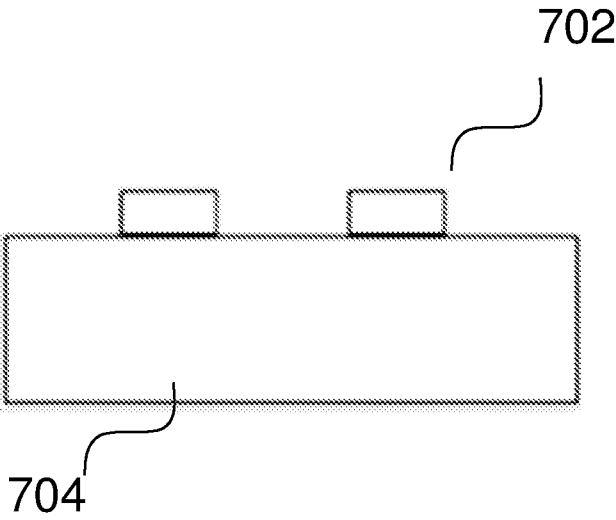


FIG. 7F



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FIG. 8A

800a

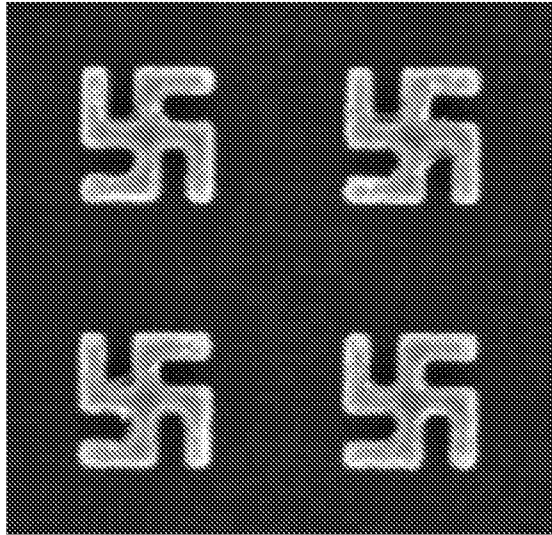
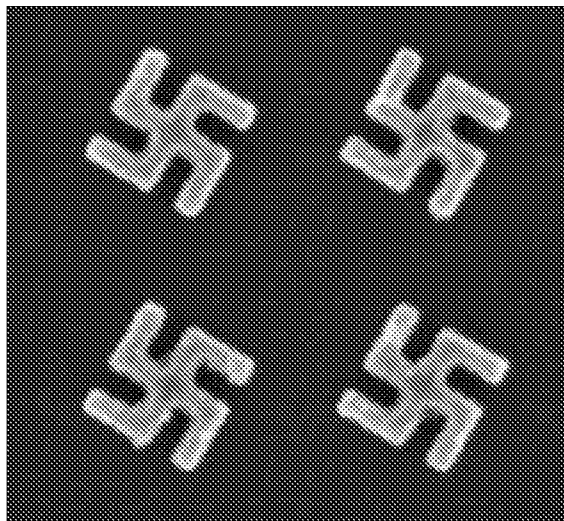


FIG. 8B

800b



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FIG. 8C

800c

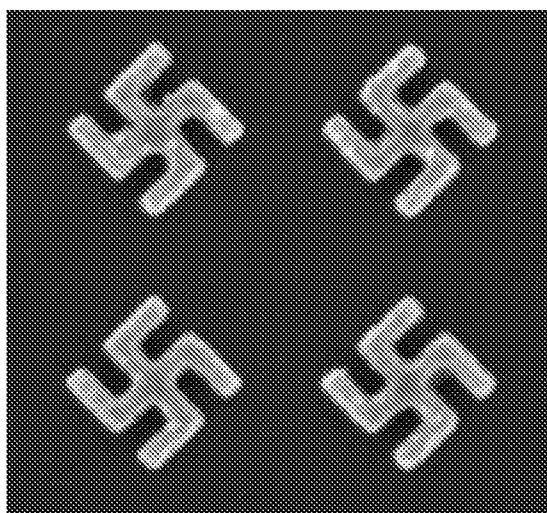


FIG. 8D

800d

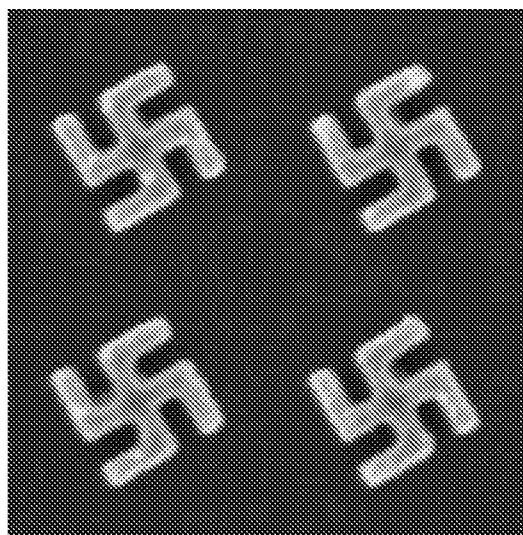


FIG. 9

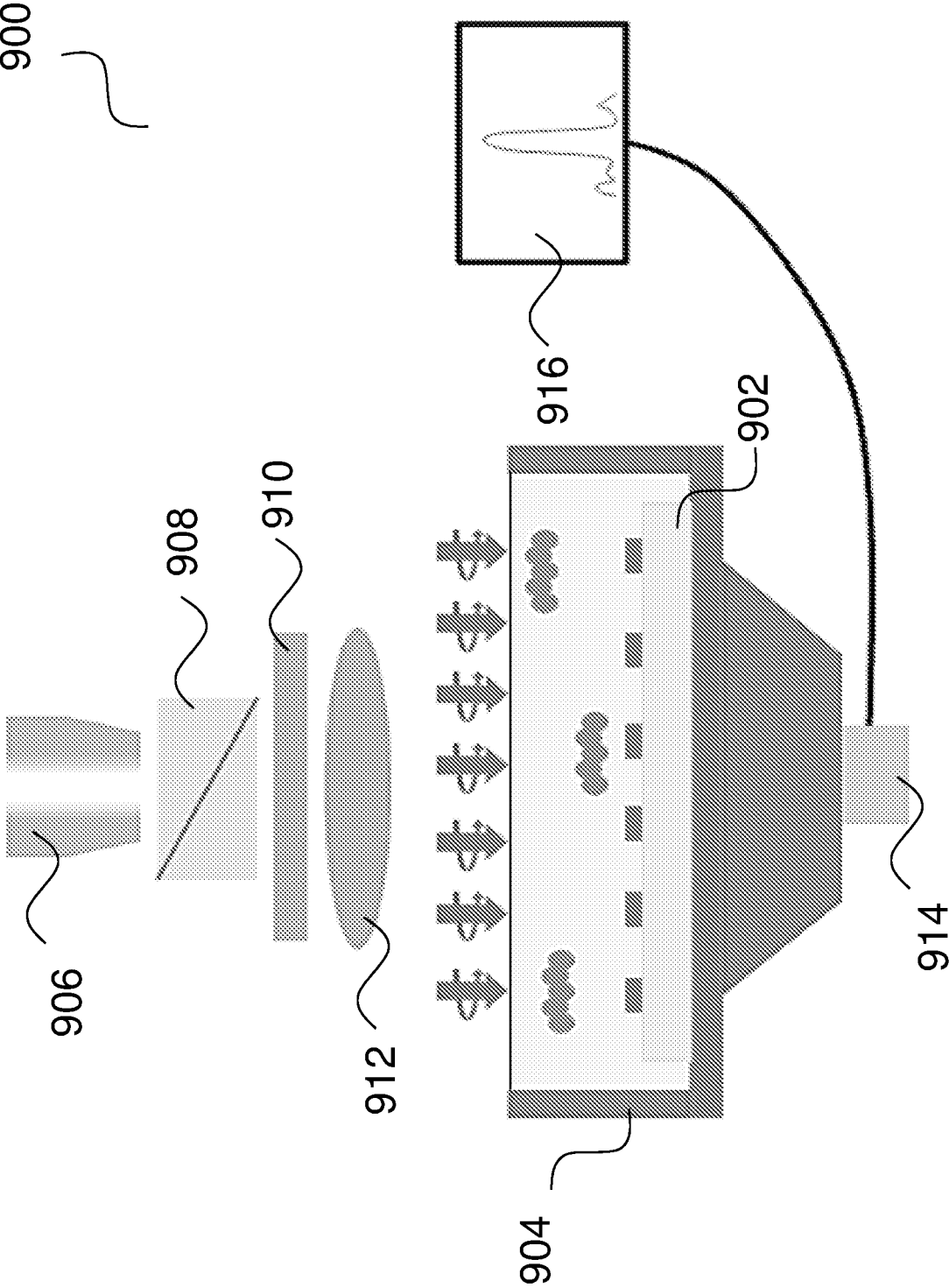
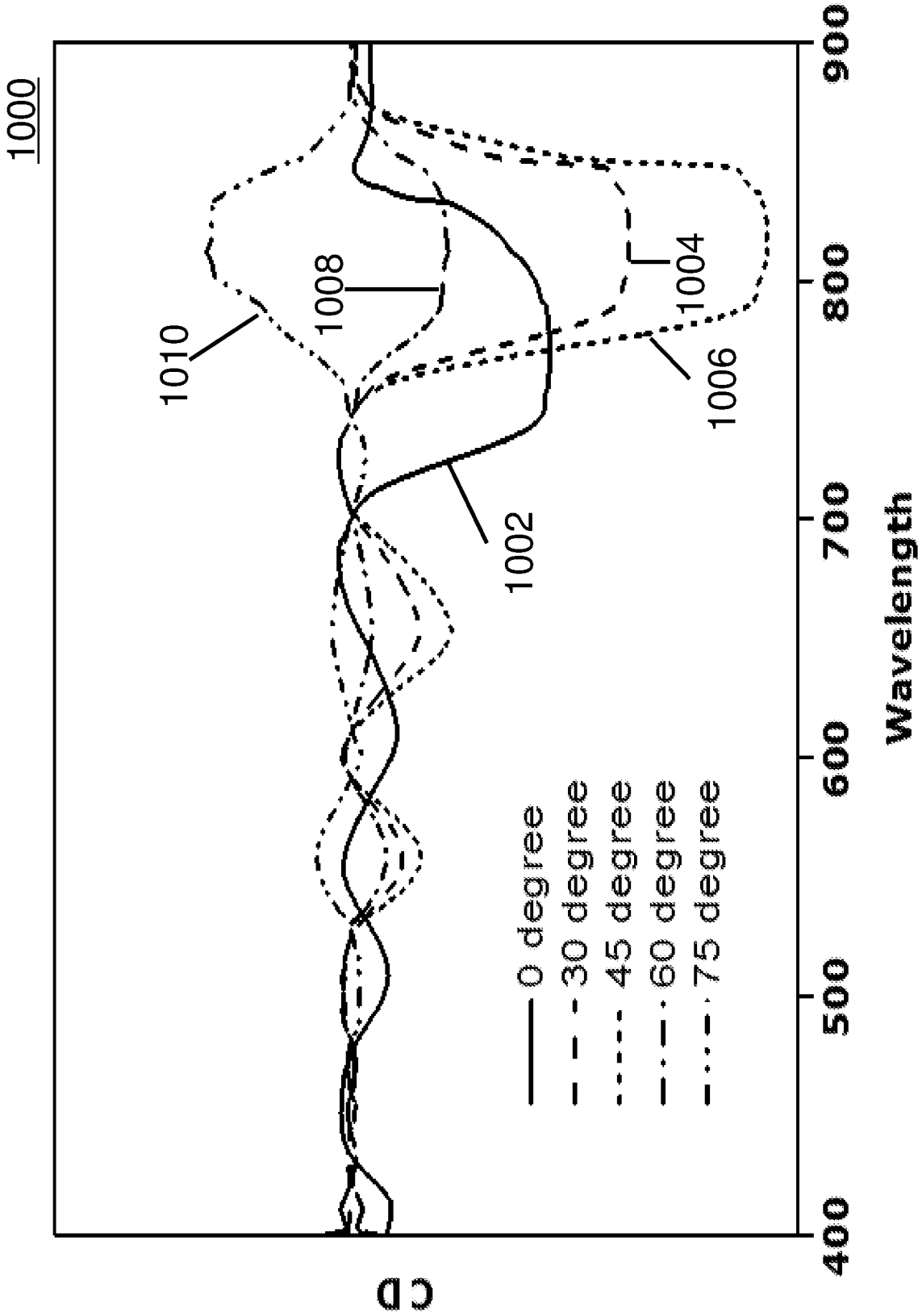


FIG. 10



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FIG. 11A

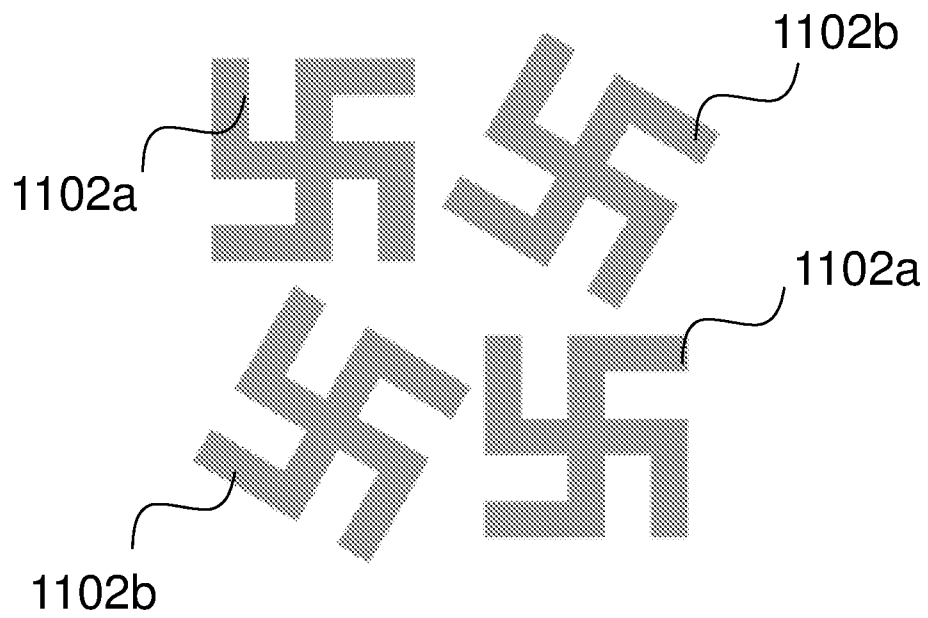
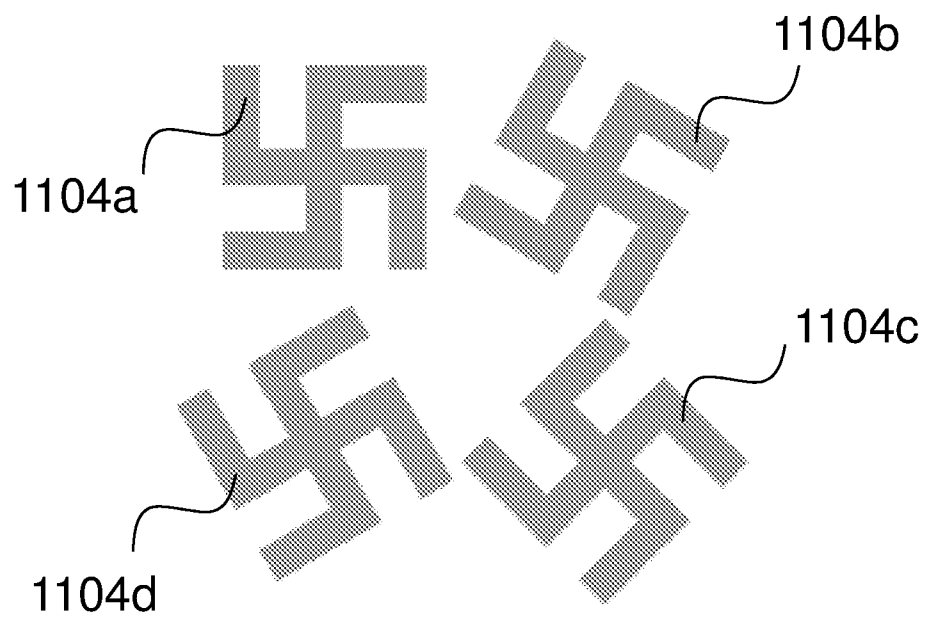


FIG. 11B



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FIG. 12A

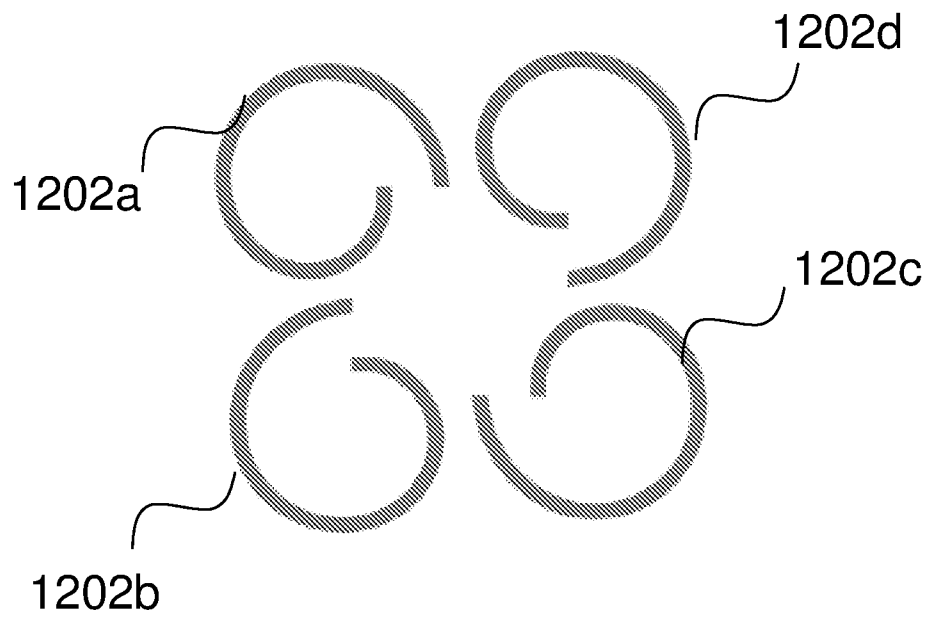
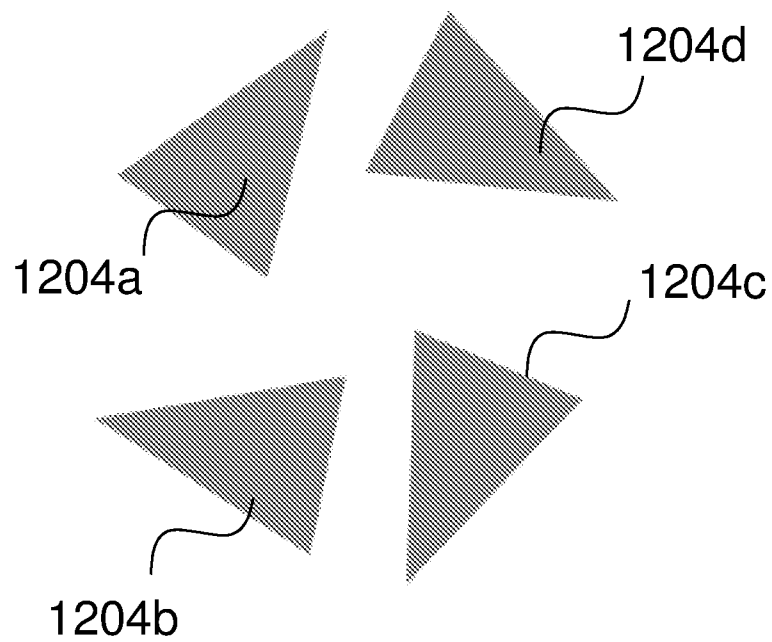


FIG. 12B



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FIG. 12C

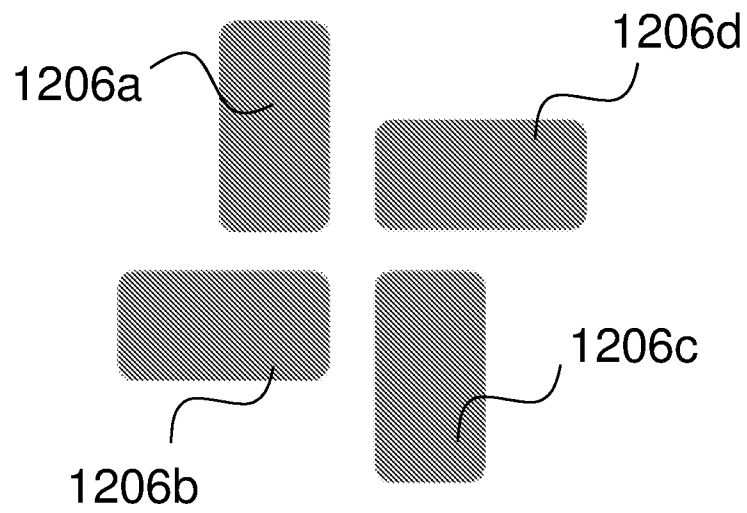
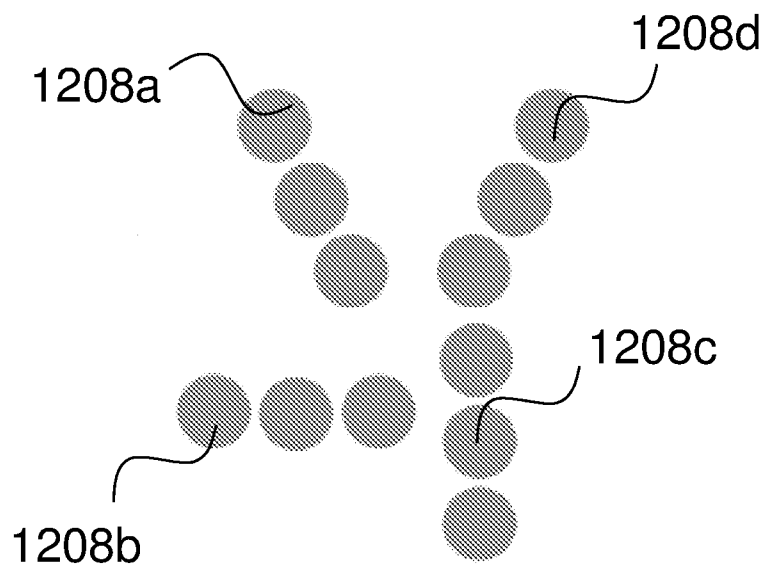


FIG. 12D



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FIG. 13A

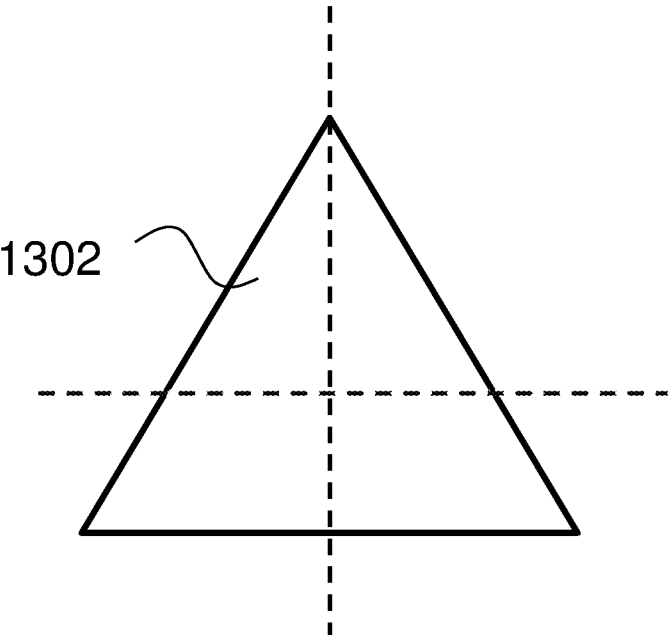


FIG. 13B

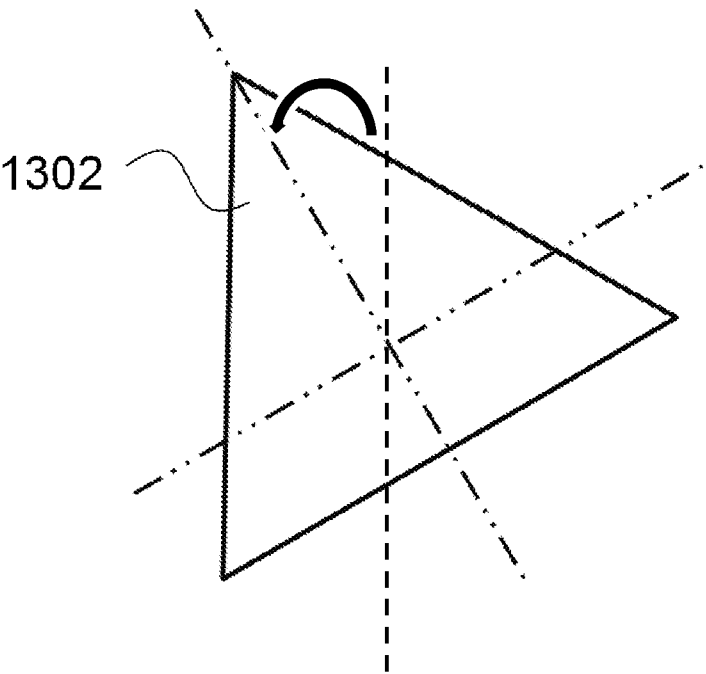


FIG. 13D

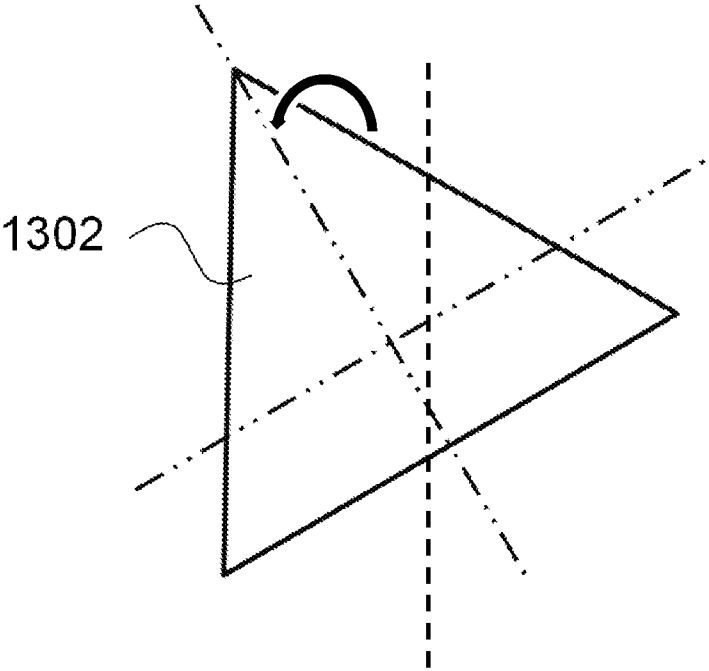
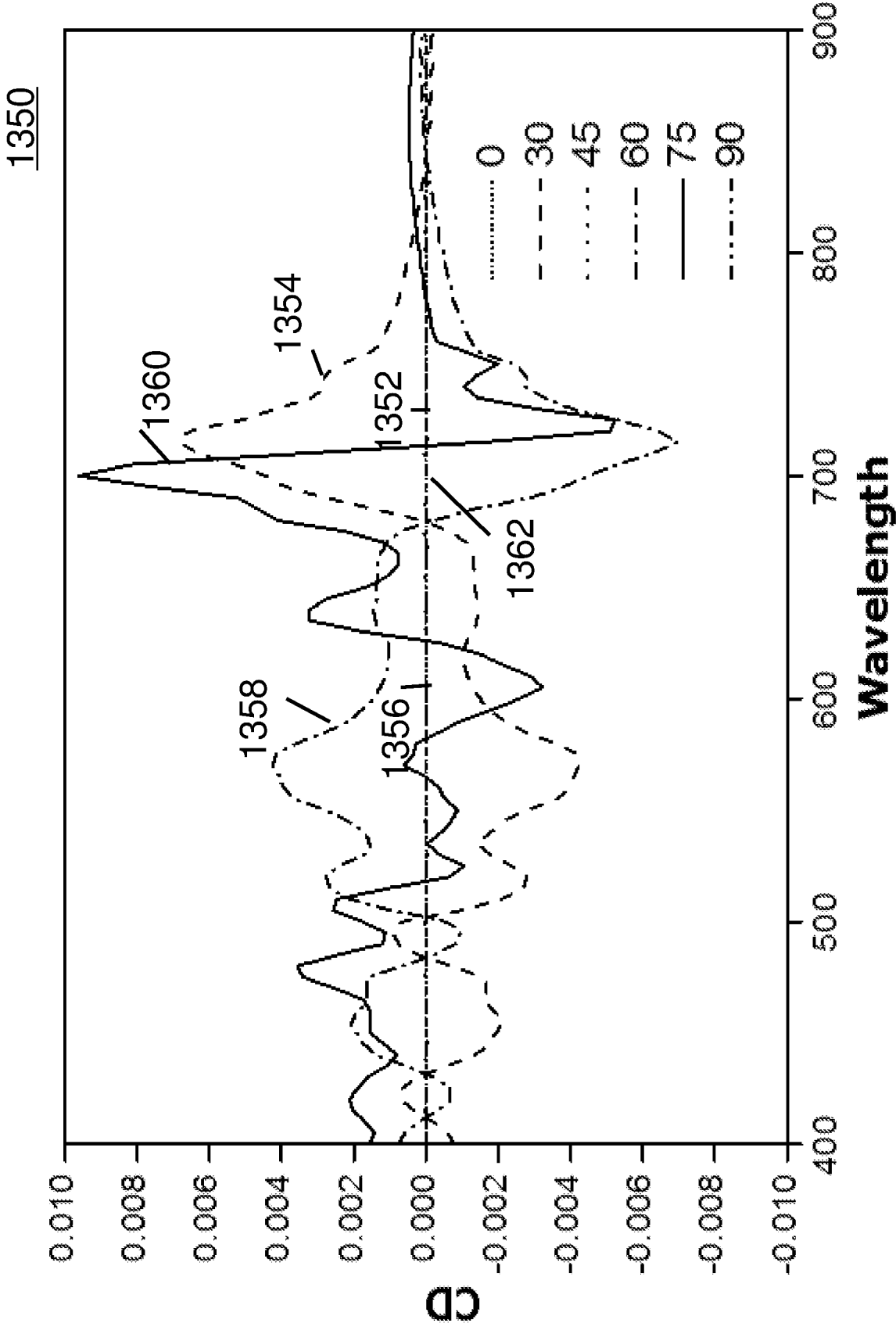


FIG. 13E



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FIG. 14A

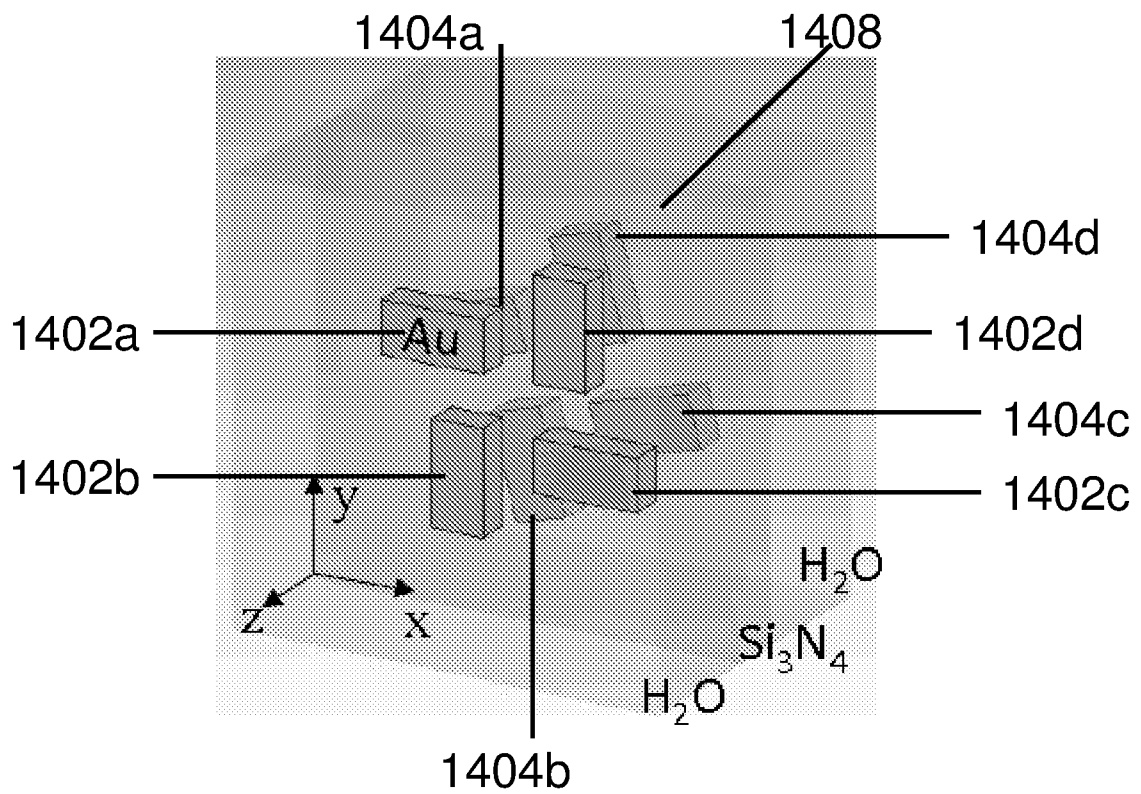
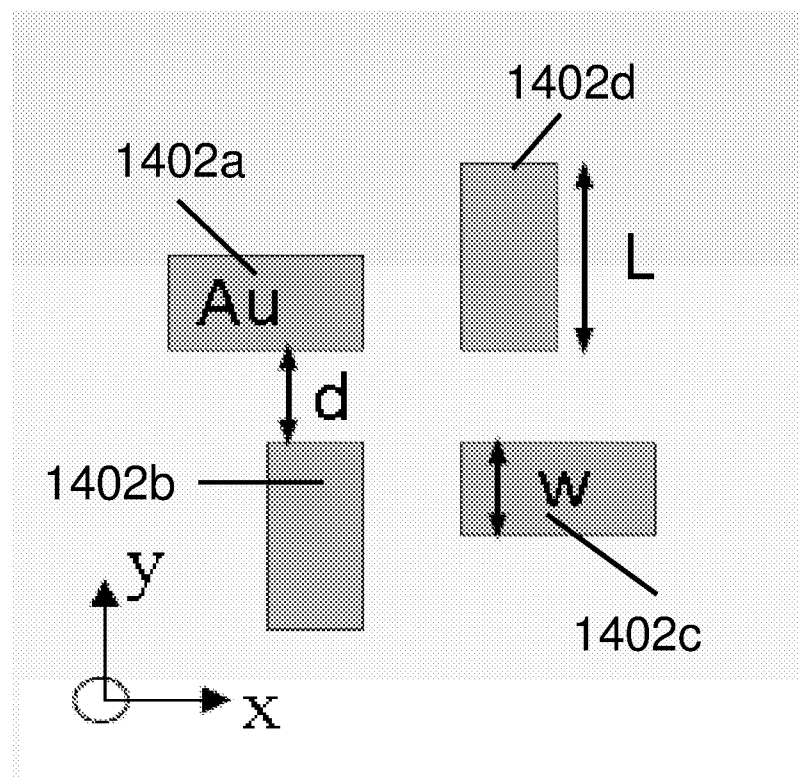


FIG. 14B



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FIG. 14C

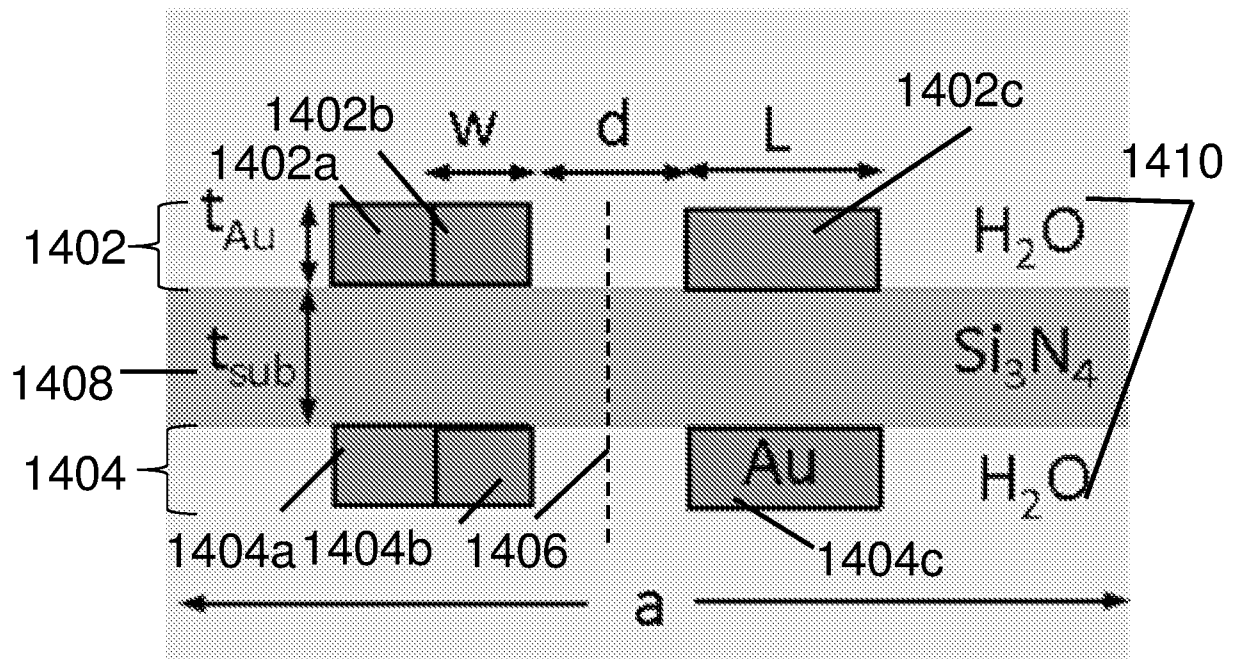
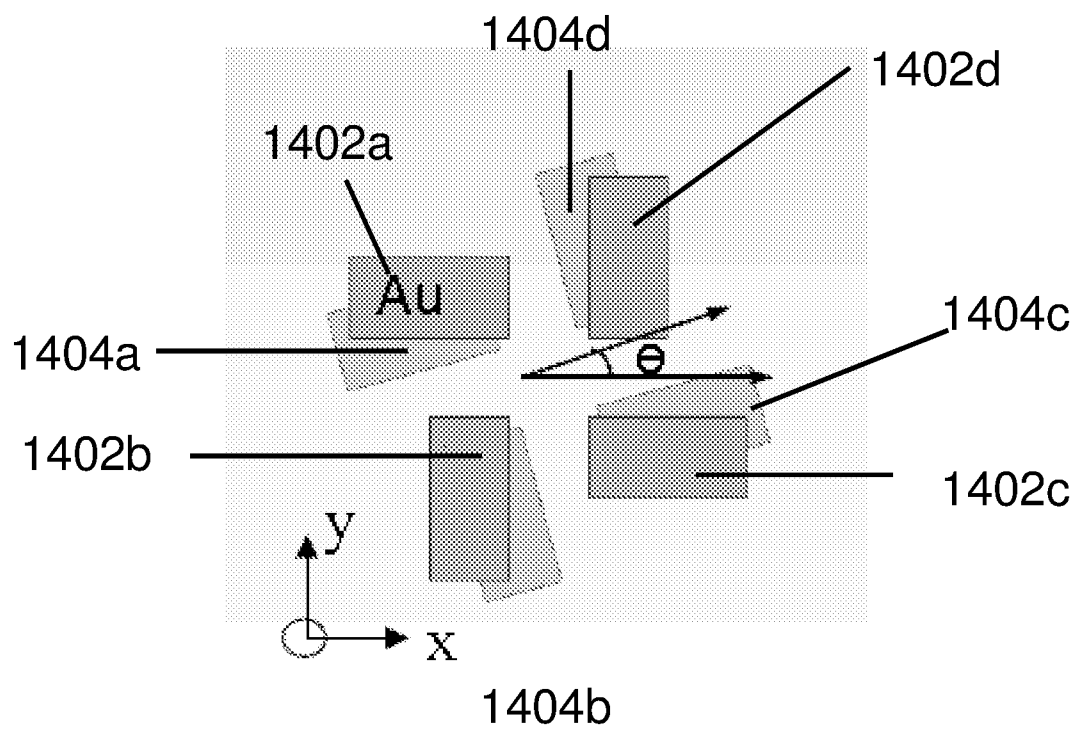
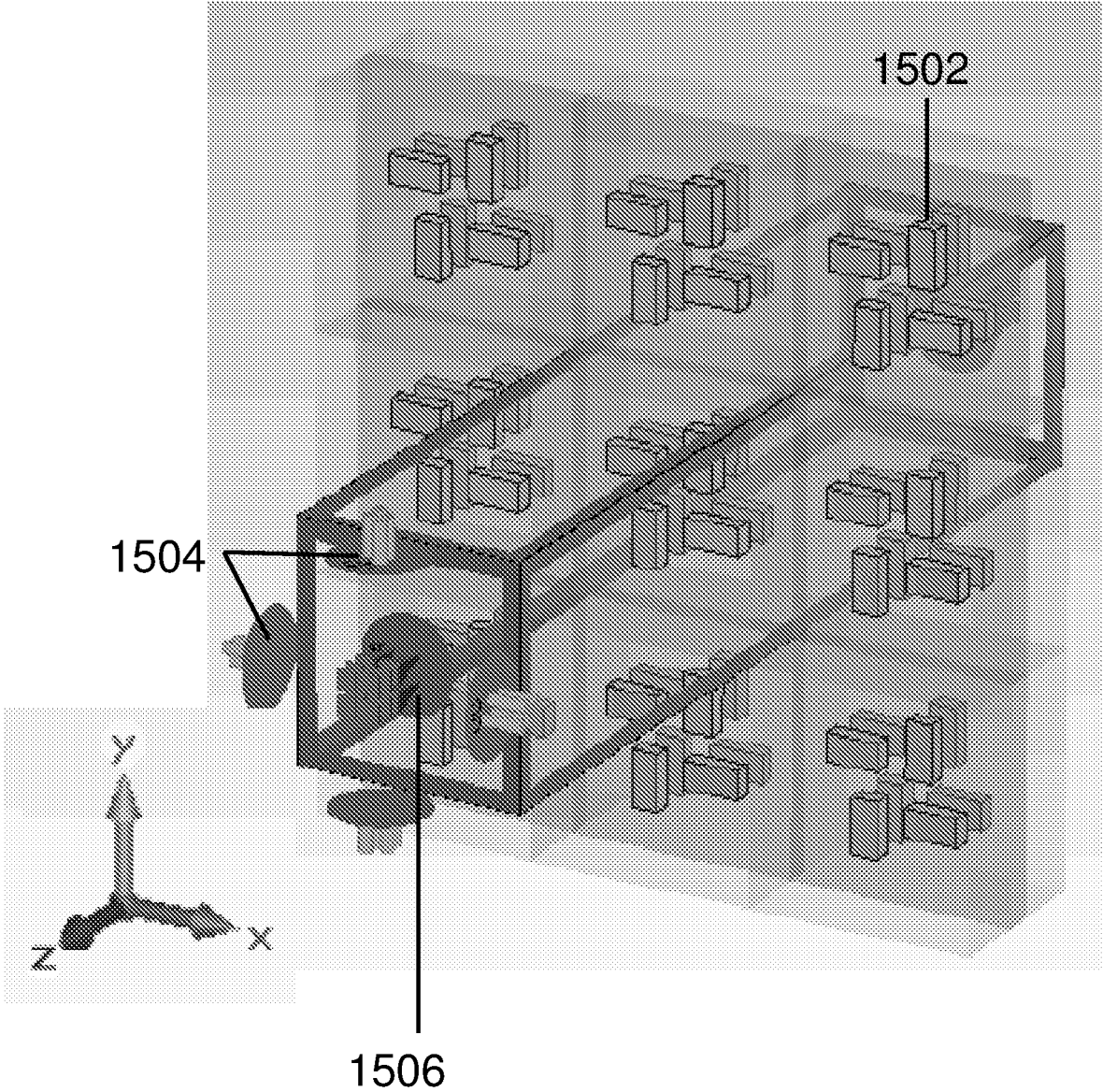


FIG. 14D



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FIG. 15



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FIG. 16

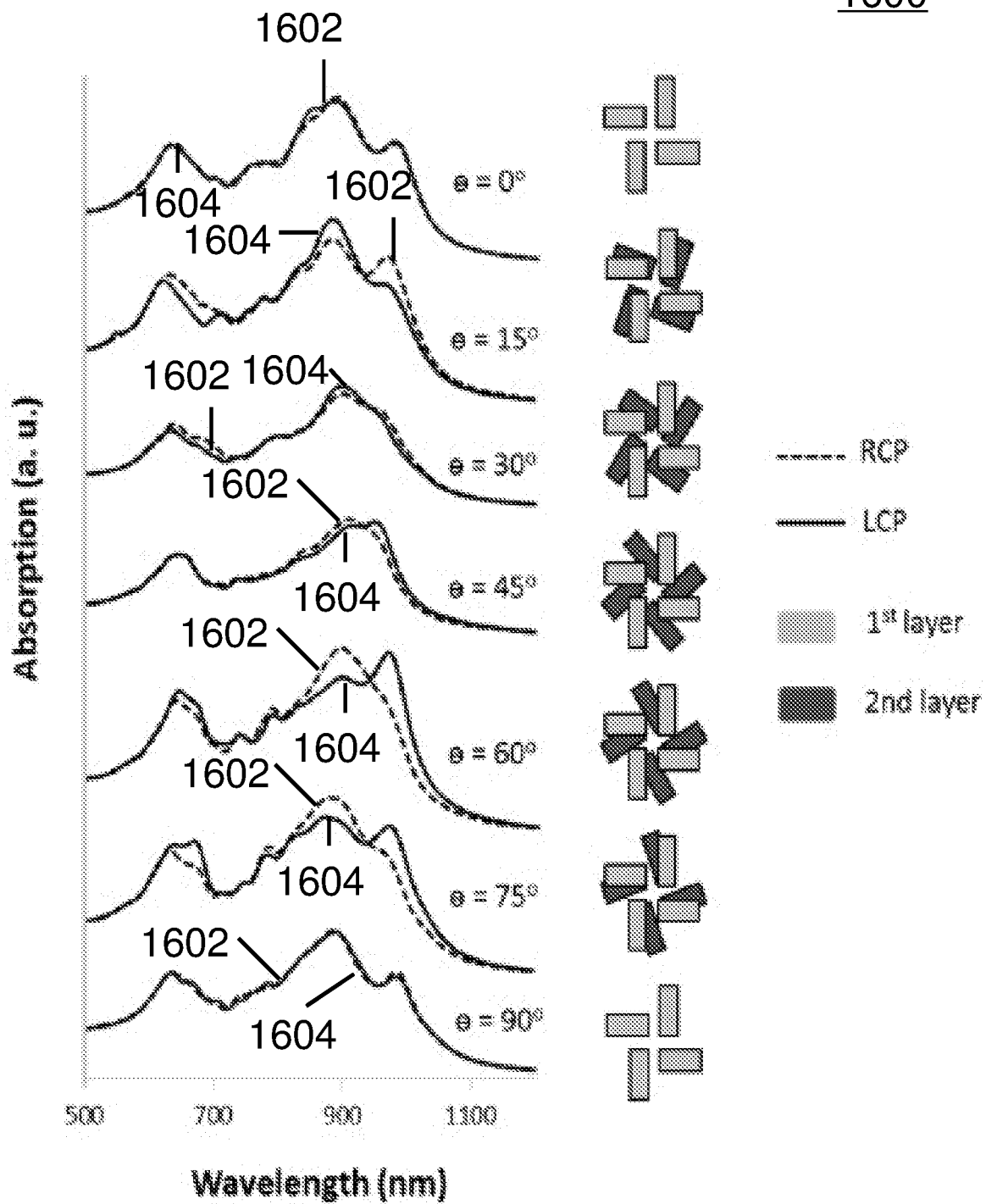
1600

FIG. 17

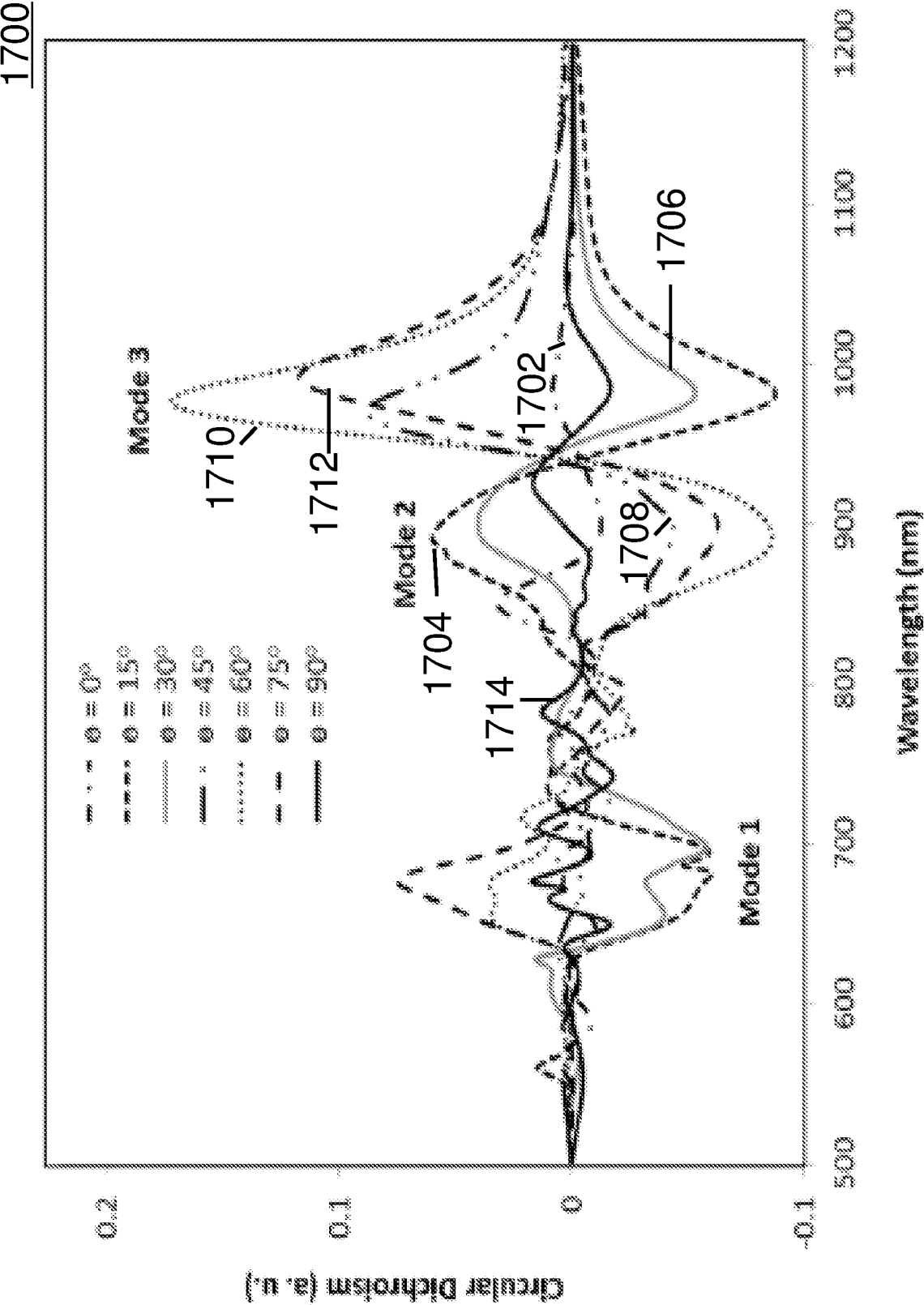
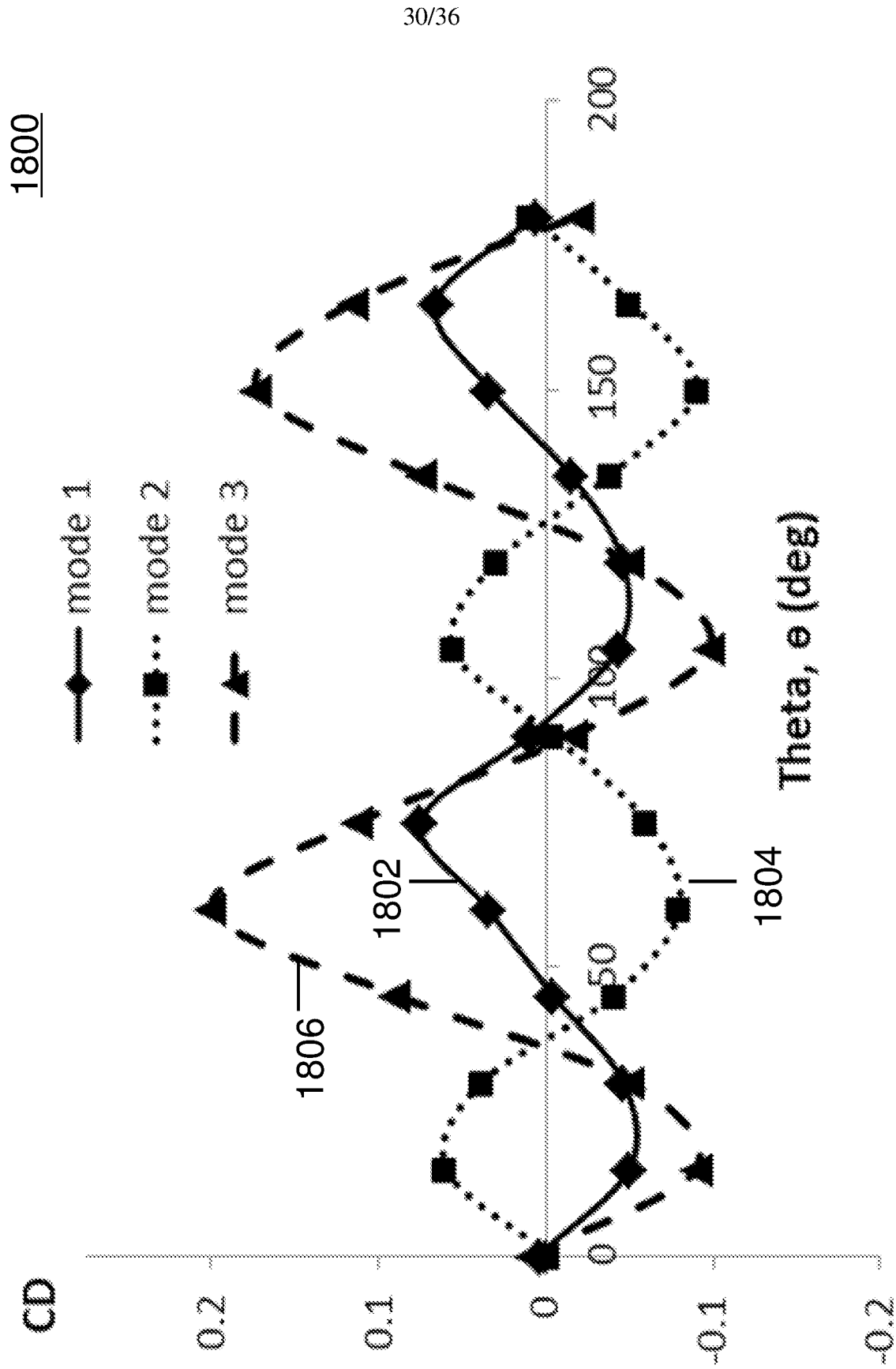
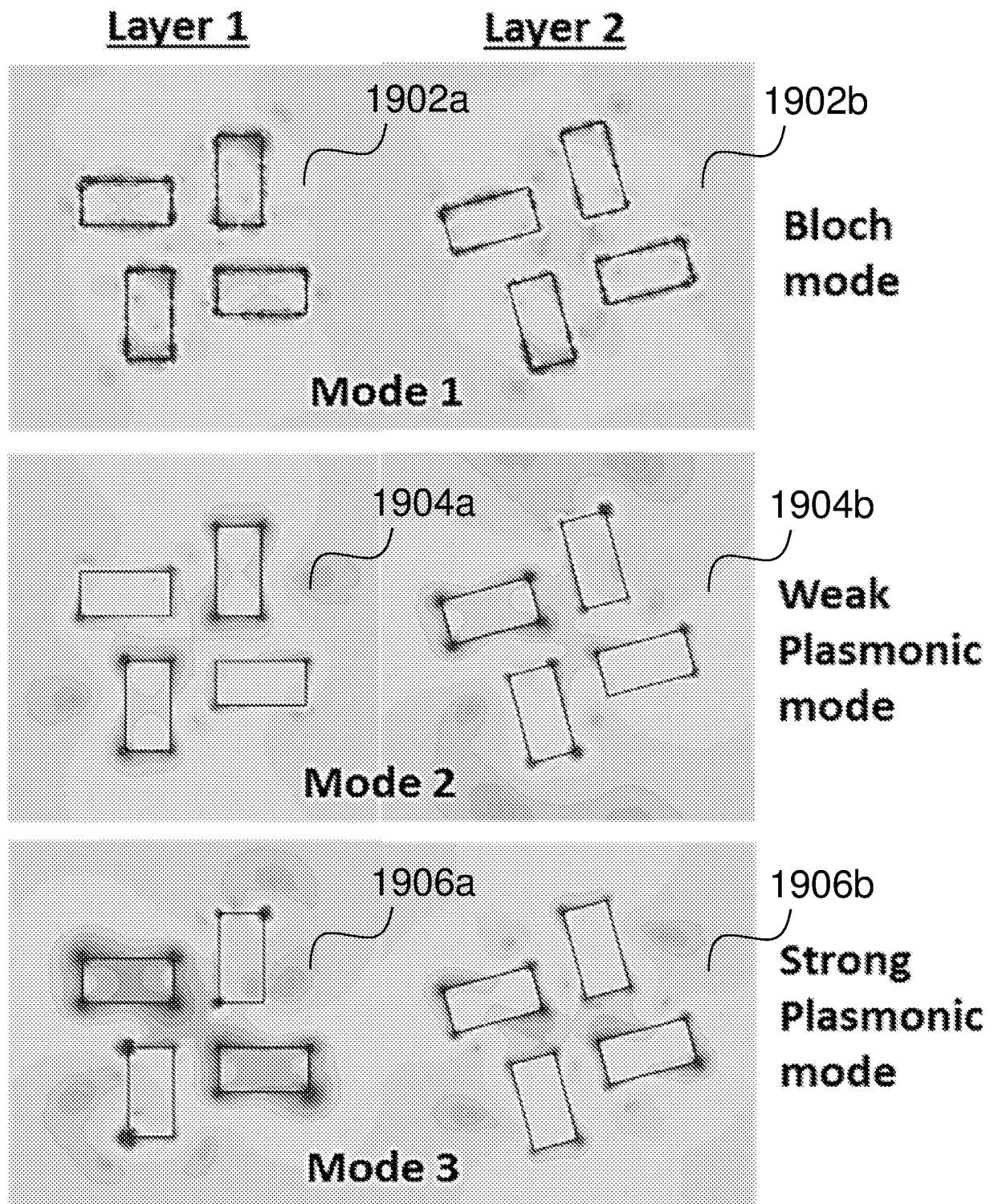


FIG. 18



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FIG. 19



Tangential field distributions

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FIG. 20A

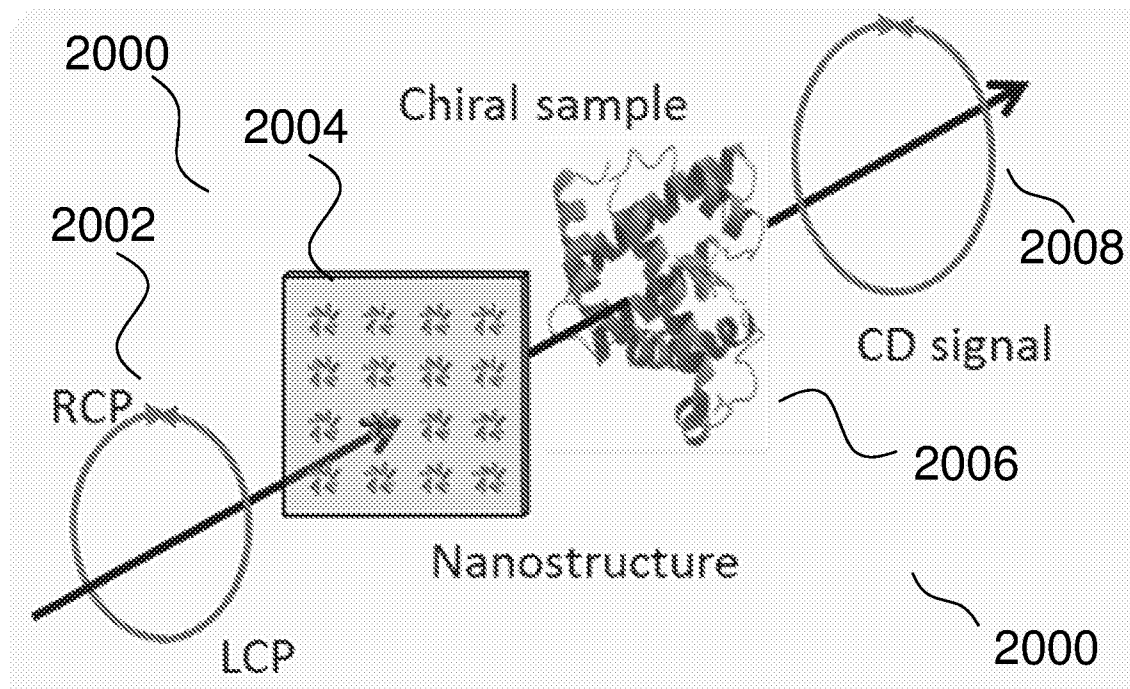


FIG. 20B

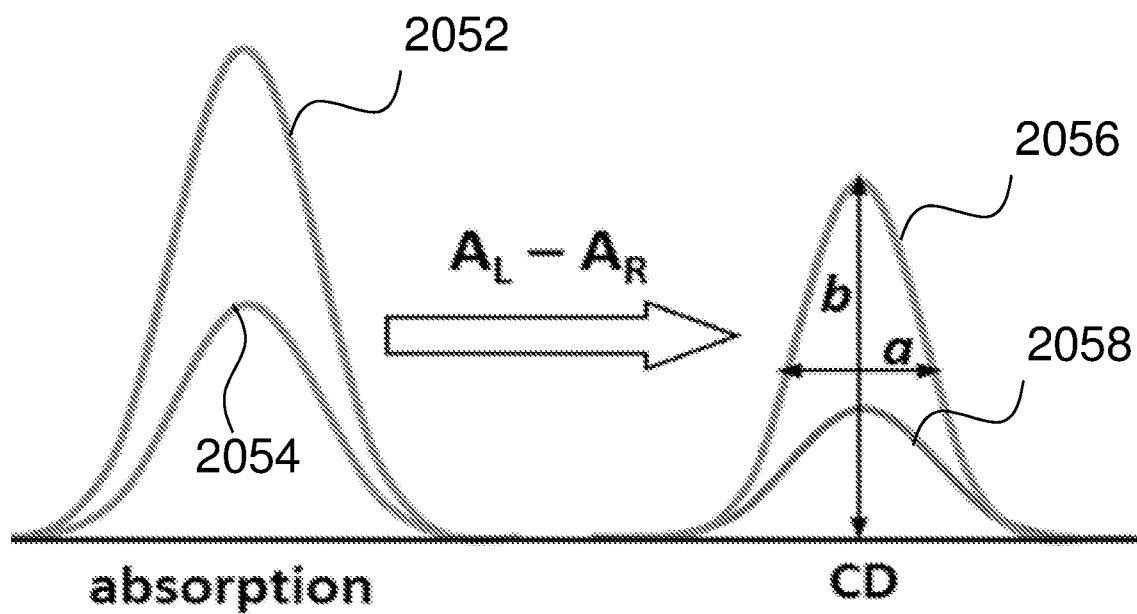
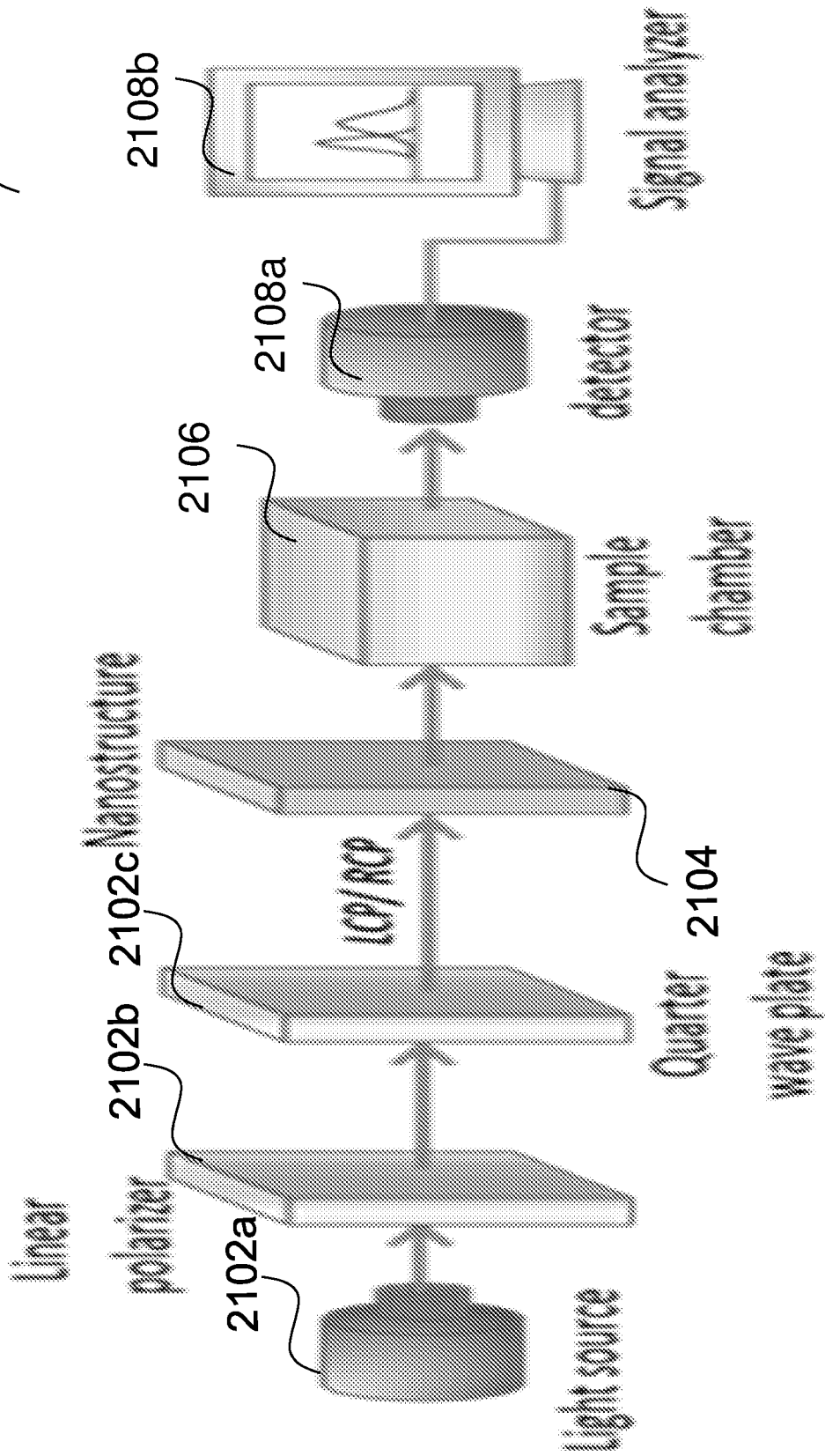


FIG. 21



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FIG. 22A

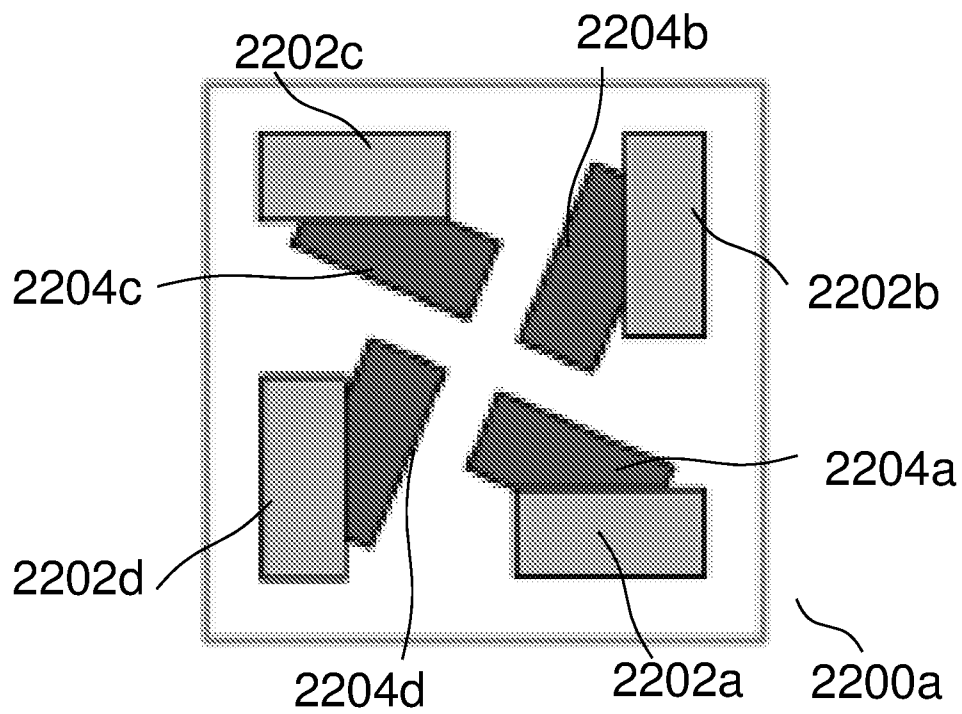
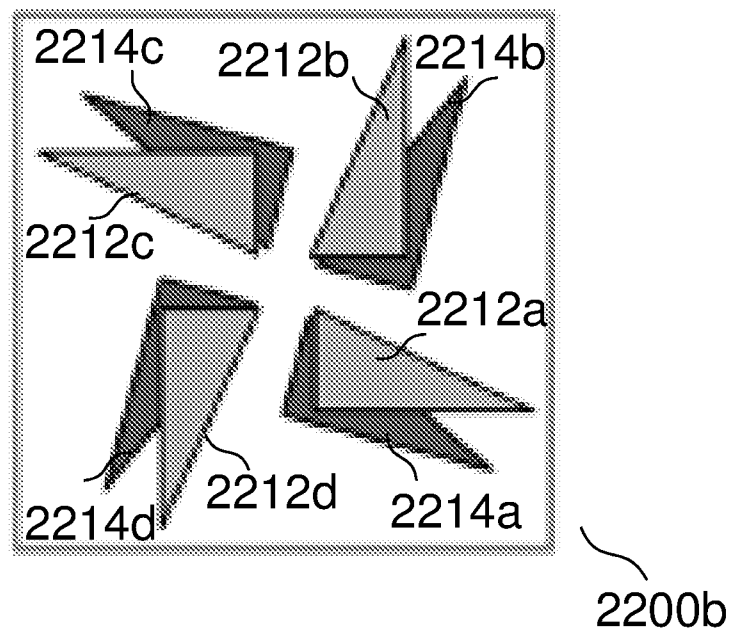


FIG. 22B



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FIG. 22C

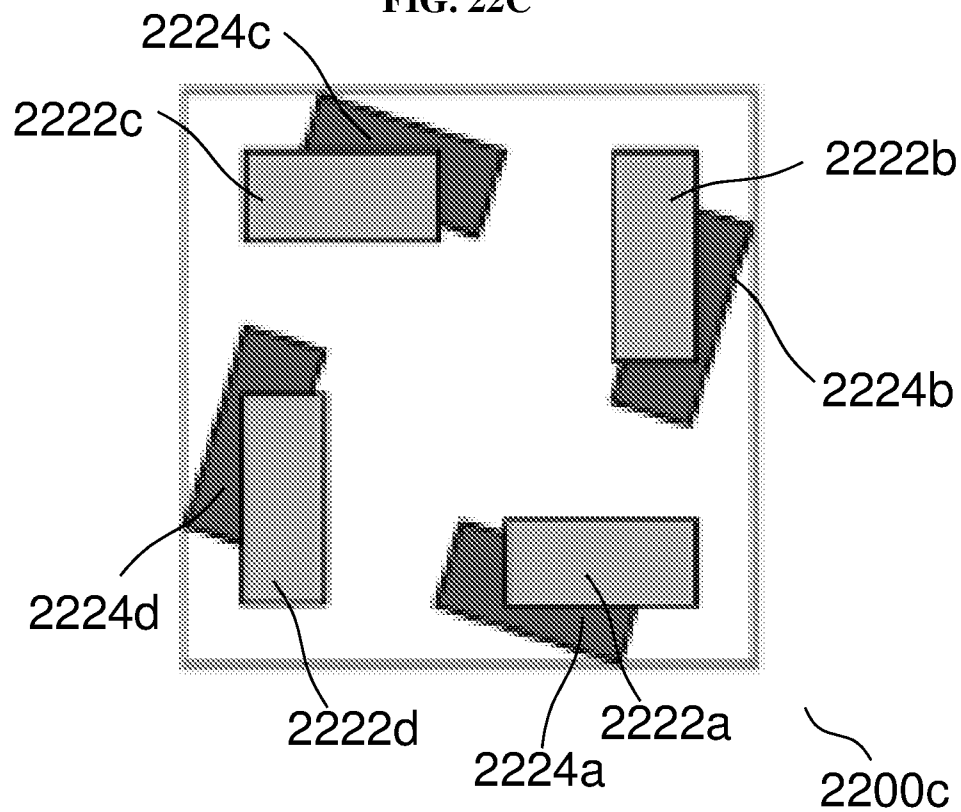
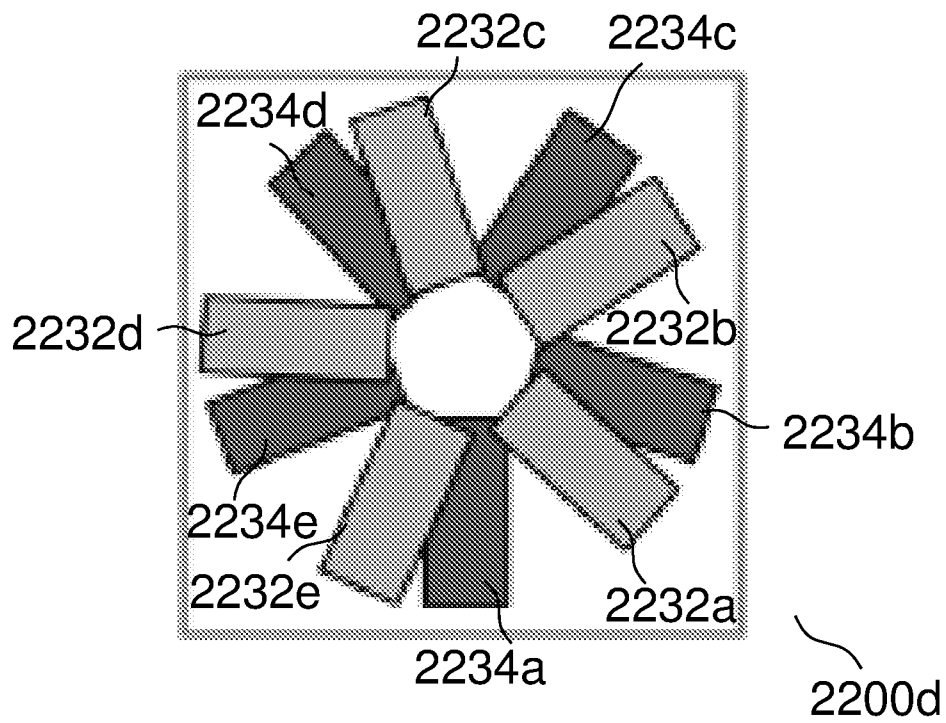
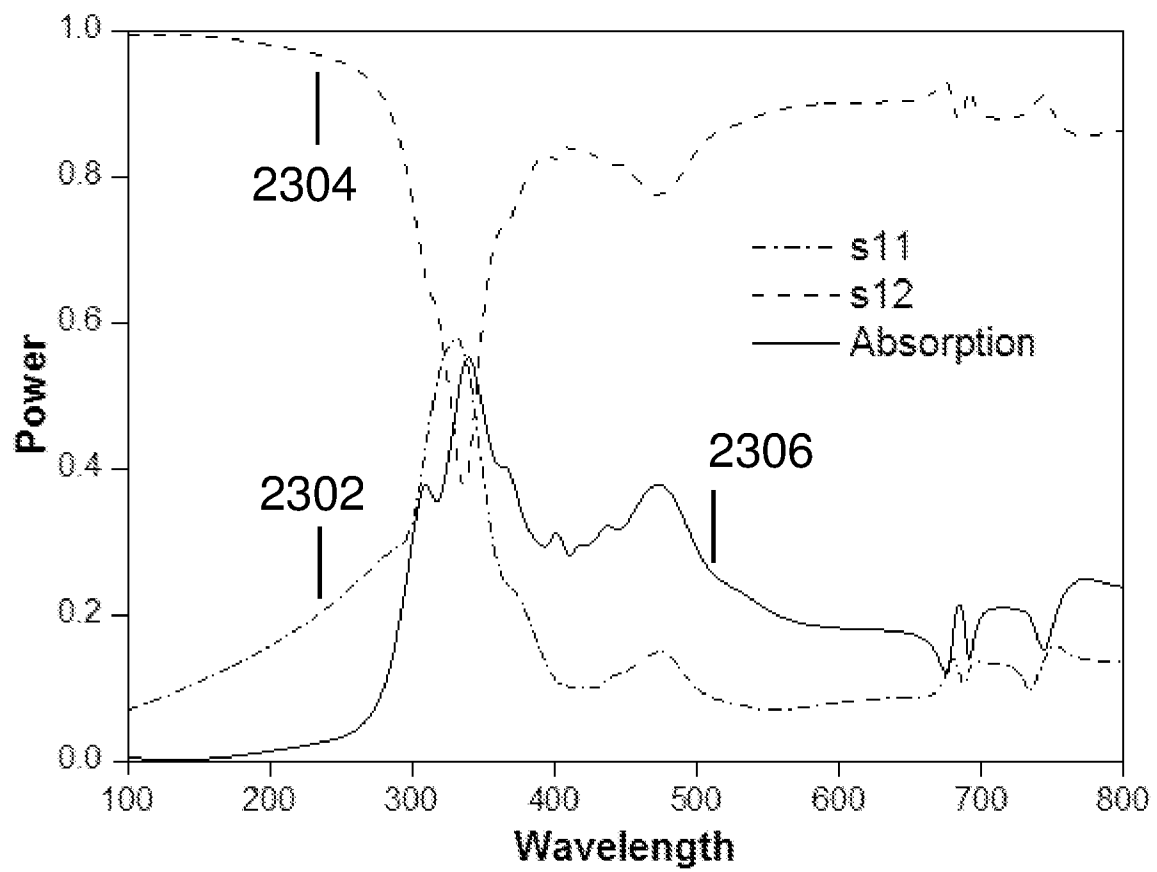


FIG. 22D



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FIG. 232300

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2016/050153

A. CLASSIFICATION OF SUBJECT MATTER

G02F 1/01 (2006.01) G02B 5/30 (2006.01)

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G02F, G02B

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)

EPODOC/ WPI/ CA/ INSPEC: circular dichroism, CD spectrum, nanostructure, chiral, polarize, symmetry, left-handed, right-handed, rotate and like terms.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	HOR, Y. L. ET AL., Effect of Rotational Symmetry on the Optical Rotation of using Asymmetrical Nanostructures. <i>Proc. SPIE</i> , 11 September 2013, Vol. 8806, Metamaterials: Fundamentals and Applications VI, pages 88062F-(1-6) [Retrieved on 2016-06-09] <DOI: 10.1117/12.2022945> See entire document, in particular the abstract, figures and conclusion.	1-20
X	HOR, Y. L. ET AL., Bilayer Four-Fold Rotationally Symmetric Subwavelength Nanostructures for Chirality Switching. <i>Proc. SPIE</i> , 12 September 2014, Vol. 9160, Metamaterials: Fundamentals and Applications 2014, pages 91601Q-(1-7) [Retrieved on 2016-06-09] <DOI: 10.1117/12.2060611> See entire document, in particular the abstract, figures and conclusion.	1-20
A	KHOO, E. H. ET AL., Effect of Layered Composite Meta-Structures on the Optical Activity and Ellipticity of Structural Biomolecules. <i>Proc. SPIE</i> , 12 September 2014, Vol. 9160, Metamaterials: Fundamentals and Applications 2014, pages 91601G-(1-7) [Retrieved on 2016-06-09] <DOI: 10.1117/12.2061492> See abstract.	

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

☐ See patent family annex.

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Date of the actual completion of the international search

09/06/2016

(day/month/year)

Date of mailing of the international search report

13/06/2016

(day/month/year)

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2016/050153

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	LIU, Y. J. ET AL., Effect of Asymmetrical Nanostructures on Detecting the Optical Rotational Properties of Large Biofilaments Structures. <i>Proc. SPIE</i> , 11 September 2013, Vol. 8809, Plasmonics: Metallic Nanostructures and Their Optical Properties XI, pages 88090D-(1-7) [Retrieved on 2016-06-09] <DOI: 10.1117/12.2022947> See abstract.	
A	LIU, M. ET AL., Light-Driven Nanoscale Plasmonic Motors. <i>Nature Nanotechnology</i> , 4 July 2010, Vol. 5, No. 8, pages 570-573 [Retrieved on 2016-06-09] <DOI: 10.1038/NNANO.2010.128> See abstract and figure 3.	
A	KONISHI, K. ET AL., Effect of Surface Plasmon Resonance on the Optical Activity of Chiral Metal Nanogratings. <i>Optics Express</i> , 18 July 2007, Vol. 15, No. 15, pages 9575-9583 [Retrieved on 2016-06-09] <DOI: 10.1364/OE.15.009575> See abstract.	
A	VALEV, V. K. ET AL., Chirality and Chiroptical Effects in Plasmonic Nanostructures: Fundamentals, Recent Progress, and Outlook. <i>Advanced Materials</i> , 2 April 2013, Vol. 25, No. 18, pages 2517-2534 [Retrieved on 2016-06-09] <DOI: 10.1002/ADMA.201205178> See abstract.	