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- (71) **Applicant: THE REGENTS OF THE UNIVERSITY OF CALIFORNIA** [US/US]; 1111 Franklin Street, 12th Floor, Oakland, California 94607-5200 (US).
- (72) **Inventors: WILLIAMS, Benjamin S.;** c/o UCLA, 10889 Wilshire Blvd., Suite 920, Los Angeles, California 90095-7191 (US). **CURWEN, Christopher;** c/o UCLA, 10889 Wilshire Blvd., Suite 920, Los Angeles, California 90095-7191 (US).
- (74) **Agent: LIU, Cliff Z.** et al.; Foley & Lardner LLP, 3000 K Street, N.W., Suite 600, Washington, District of Columbia 20007-5109 (US).

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(54) **Title:** GRATING-BASED QUANTUM-CASCADE VERTICAL EXTERNAL CAVITY LASERS IN THE TERAHERTZ AND MID-INFRARED

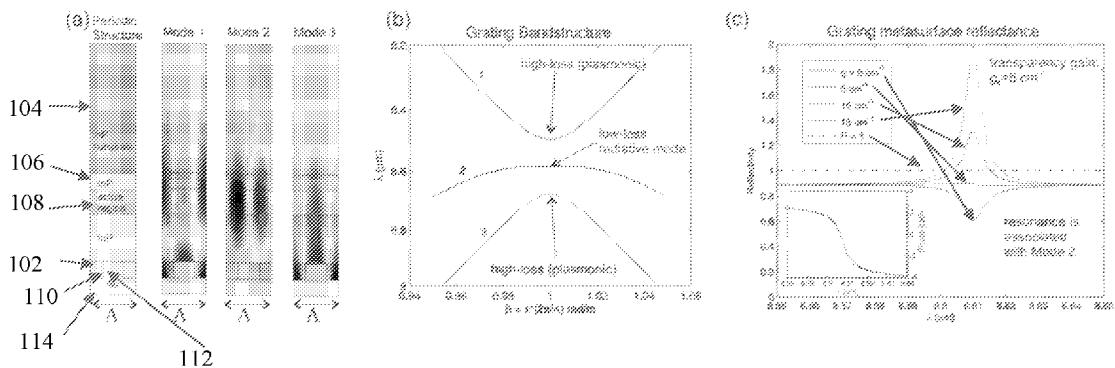


Fig. 1

(57) **Abstract:** A quantum-cascade laser includes a metasurface and an output coupler. The metasurface includes (1) a substrate; (2) a first cladding layer disposed on the substrate; (3) a quantum-cascade laser active layer on the first cladding layer; (4) a second cladding layer disposed on the quantum-cascade laser active layer; and (5) a metallic grating disposed on the second cladding layer. The output coupler is connected to the metasurface and forms a cavity with the metasurface.



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GRATING-BASED QUANTUM-CASCADE VERTICAL EXTERNAL CAVITY LASERS IN THE TERAHERTZ AND MID-INFRARED

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 62/692,192, filed June 29, 2018, the contents of which are incorporated herein by reference in their entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made with government support under grant Number W911NF-17-1-0004, awarded by the U.S. Army, Army Research Office. The government has certain rights in the invention.

TECHNICAL FIELD

[0003] This disclosure generally relates to a vertical external cavity surface-emitting laser including a plasmonic grating.

BACKGROUND

[0004] Quantum-cascade-vertical external cavity surface-emitting lasers (QC-VECSELs) in the Terahertz range can be implemented based on arrays of metallic microcavity resonators with exhibit localized resonance; however, the metallic microcavity resonators impede such implementations from being scaled to shorter wavelengths in the mid-infrared (mid-IR) (e.g., wavelengths below about 15 μm).

[0005] It is against this background that a need arose to develop the embodiments described herein.

SUMMARY

[0006] In some embodiments, a quantum-cascade laser includes a metasurface and an output coupler. The metasurface includes (1) a substrate; (2) a first cladding layer disposed on the substrate; (3) a quantum-cascade laser active layer on the first cladding layer; (4) a second cladding layer disposed on the quantum-cascade laser active layer; and (5) a metallic

grating disposed on the second cladding layer. The output coupler is connected to the metasurface and forms a cavity with the metasurface.

[0007] In additional embodiments, a metasurface for quantum-cascade lasing includes: (1) a substrate; (2) a first cladding layer disposed on the substrate; (3) a quantum-cascade laser active layer on the first cladding layer; (4) a second cladding layer disposed on the quantum-cascade laser active layer; and (5) a metallic grating disposed on the second cladding layer, wherein a period of the metallic grating is in a range of 3 μm to 30 μm .

[0008] Other aspects and embodiments of this disclosure are also contemplated. The foregoing summary and the following detailed description are not meant to restrict this disclosure to any particular embodiment but are merely meant to describe some embodiments of this disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] For a better understanding of the nature and objects of some embodiments of this disclosure, reference should be made to the following detailed description taken in conjunction with the accompanying drawings.

[0010] Fig. 1. Simulated overview of plasmonic grating structure. (a) Schematic for one period of a grating, including plots of vertical electric field intensity for 3 band edge modes. Mode 2 is of interest for VECSEL – it has low absorption, and strong radiative coupling via Bragg scattering. Self-lasing in Mode 1 and Mode 3 is impeded by selective coupling of these modes with the lossy plasmonic grating. (b) Simulation of one-dimensional (1D) photonic bandstructure near Γ point. (c) Simulation of metasurface reflectance and phase with applied QCL gain coefficient.

[0011] Fig. 2. (a) Schematic of a grating-coupled gain chip, where a grating is formed over a larger area than that which receives an electrical bias (e.g., a current injection). (b) Schematic of an external laser cavity. (c) Simulation of finite size bias areas, and the effect on the net reflectivity of an incident Gaussian beam.

[0012] Fig. 3. (a) Simulated reflectance (Comsol) from a grating structure designed for about 4.6 μm for various gain coefficients applied to an active layer. (b) Simulated peak reflectance versus applied gain coefficient for several grating structures with various thicknesses of InP cladding layers in between an active layer and a grating.

[0013] Fig. 4. Simulation parameter sweep of waveguide eigenmode frequencies versus grating tooth width (grating duty cycle) for a fixed cladding thickness of about 1.7 μm .

[0014] Fig. 5. (a) Simulation parameter sweep of modal confinement factor Γ versus grating tooth width. Symmetric mode is relatively insensitive, while antisymmetric modes exhibit changes in confinement through the anti-crossing. (b) Quantity proportional to the modal loss divided by the confinement factor, which is proportional to the gain to bring each mode to threshold. It is desirable for these modes to have large losses so that they don't self-lase. Tracking this quantity establishes the region for design/fabrication tolerance shown by the shaded box.

DETAILED DESCRIPTION

[0015] Embodiments of this disclosure are directed to a quantum-cascade (QC) vertical external cavity surface-emitting laser (VECSEL) in either the Terahertz spectral range (e.g., about 30 μm to about 300 μm) or mid-infrared (mid-IR) spectral range (e.g., about 3 μm to about 30 μm). QC-VECSELs in the Terahertz range can be implemented based on arrays of metallic microcavity resonators with exhibit localized resonance; however, the metallic microcavity resonators impede such implementations from being scaled to shorter wavelengths in the mid-IR (e.g., wavelengths below about 15 μm).

[0016] In some embodiments, a QC-VECSEL includes a dielectric-metallic grating structure that creates surface or substrate emission via a Bragg grating in a strongly-radiating, low-absorption mode. In some embodiments, the structure is based upon an etched Bragg grating coated with gold (Au) (or another metal or combination of metals) in an array of narrow ridge waveguides.

[0017] In some embodiments, referring to Fig. 1(a), a metasurface for a QC laser (QCL) includes a periodic grating etched into an upper cladding layer 102 of indium phosphide (InP) (or another semiconductor material) on top of a narrow ridge QCL waveguide. Specifically, the metasurface includes an InP substrate 104 (or a substrate of another semiconductor material), a lower cladding layer of InP 106 (or another semiconductor material) on the substrate 104, a QCL active layer 108 on the lower cladding layer 106, and the upper cladding layer 102 on the QCL active layer 108. An array of trenches 110 is etched into the upper cladding layer 102, where the trenches are spaced with a period Λ corresponding to a period of the grating. The QCL waveguide is then coated with Au (or another metal or combination of metals) to form a plasmonic metallic grating. In particular, the grating includes an array of metallic strips 112 disposed in the trenches 110 and spaced with the period Λ of the grating, along with a metallic layer 114 extending over

the top cladding layer 102 and interconnecting and integrally formed with the metallic strips 112. The period of the grating is chosen to be about equal to a wavelength of a desired response within the semiconductor material (here, in a range encompassing about $8.2 \mu\text{m}$), so that incident radiation at a surface normal is coupled into the QCL waveguide, and vice versa. Via full-wave electromagnetic (EM) simulation, identification is made that, for certain grating and cladding conditions, the grating creates an one-dimensional (1D) photonic bandstructure with a low-loss surface-emitting band-edge mode – mode 2 in Fig. 1(a,b). This mode is primarily confined to the active layer 108 and cladding layers 102 and 106, and interacts weakly with the metallic strips 112 and the metallic layer 114 of the grating. It does however radiate strongly in the surface normal direction with a coupling constant dictated by a thickness of the cladding layer 102 – this will impede this mode from self-oscillation. Unlike another implementation of metallic gratings to create surface emission in the form of monolithic self-resonant cavities, also referred to as a 2nd order distributed feedback laser, the plasmonic grating here is incorporated in the context of an external cavity and, in particular, a VECSEL.

[0018] Other undesired modes, which do not radiate, are impeded from lasing as these modes are strongly coupled to the grating and experience high loss (Modes 1 and 3 shown in Fig. 1(a,b) have lasing threshold gains greater than about 200 cm^{-1}). A simulated reflectance calculated for an infinite grating shows a low transparency gain – in other words the reflectance is greater than unity for modest values of a QC active material gain (about $5\text{-}10 \text{ cm}^{-1}$ depending upon substrate doping) (Fig. 1c). This grating can be patterned into an array of ridge waveguides, or into a wide area structure without etching to define a ridge.

[0019] Referring to Fig. 2, the metasurface is then mounted top-down on a heat sink 202, so that incident light on the metasurface is coupled through the substrate side. As shown in Fig. 2(a,b), the grating is formed over a larger area than that which receives an electrical bias (e.g., a current injection) from an electrical source 212. In particular, the electrical source 212 is connected to the metasurface to apply an electrical bias to a reference center region of the metasurface, but without applying an electrical bias to a remaining peripheral region of the metasurface outside of the center region. The substrate 104 is a low-doped n-type InP substrate (e.g., about 10^{16} cm^{-3} or smaller) to reduce free carrier losses within the substrate 104. Alternatively an undoped InP substrate may be used provided a contact layer for lateral current injection/extraction is included. Mounting to the heat sink 202 or another carrier can occur via thermocompression metal-metal bonding to a metallized semiconductor carrier, or

top-down die attach soldering with indium solder to a metallized heat sink. This configuration provides several options to configure a VECSEL cavity. In one option, a backside of the high resistivity substrate 104 can be coated with a high reflectivity (HR) coating (e.g., about 90% reflectance or greater) to form a chip-scale monolithic VECSEL source. Alternatively, if more flexible external cavity operation is desired, the substrate 104 can be thinned, an anti-reflective (AR) coating 204 can be coated on the backside of the substrate 104, and an external output coupler 206 (e.g., a mirror or another flat reflector) can be used to define the external cavity, as shown in Fig. 2b. The output coupler 206 is coated with an HR coating 208 on a side facing the metasurface, and is coated with an AR coating 210 on a side facing away from the metasurface.

[0020] As an additional example, an implementation of a VECSEL is presented below at a different wavelength of about 4.6 μm . Modeling is performed using finite-element electromagnetic simulations (Comsol Multiphysics). Extensive parameter sweeps are conducted to establish optimized layer thicknesses, doping levels, and metallization geometry for gratings. Optimization takes place across several key “figures of merit.” For example, these figures of merit include minimizing the transparency gain g_{tr} , and maximizing the radiative loss α_{rad} of a symmetric radiative mode. Maximization of the radiative loss ensures that the symmetric mode does not self-lase, and minimizes a length of a grating interaction, which is proportional to α_{rad}^{-1} . Simultaneously, it is desired that the other two non-radiating anti-symmetric modes to have sufficiently large absorption loss to prevent self-lasing in these undesirable modes.

[0021] Simulated reflectance characteristics are shown in Fig. 3 for an optimized design that is developed, based on an about 1.5 μm thick active layer. For reasonable values of InP upper cladding layer thickness (between the active layer and a grating) of about 1.5 μm to about 2 μm , the transparency gain is predicted to be quite low – $g_{\text{tr}} =$ about 2 cm^{-1} . Of note, this is a factor of about 4 better than predicted at $\lambda =$ about 8 μm . This likely reflects that losses can be dominated by the free-carrier losses in the upper cladding layer, which scale as λ^2 , and thus should be smaller at shorter wavelengths.

[0022] Simulation parameter sweeps are performed of waveguide eigenmode frequencies versus grating tooth width (grating duty cycle – corresponding to a width of etched trenches in a range of about 500 nm to about 1000 nm) for a fixed upper cladding layer thickness of about 1.7 μm (shown in Fig. 4). Three branches are seen, and their evolution and mode profiles are illustrative. The symmetric branch is the “desirable”

symmetric radiative mode; it is relatively spatially separate from the grating and depends little on the grating period. Two anti-symmetric non-radiative modes are formed from hybridizations of waveguide modes and surface plasmon modes. They exhibit an anti-crossing behavior – which represents the design point in which both of these modes couple significantly with the grating and exhibit large absorption losses.

[0023] Simulation parameter sweep is performed of modal confinement factor Γ versus grating tooth width (in a range of about 500 nm to about 1000 nm) as shown in Fig. 5(a). The symmetric mode is relatively insensitive, while the antisymmetric modes exhibit changes in confinement through an anti-crossing. Shown in Fig. 5(b) is a quantity proportional to the modal loss divided by the confinement factor, which is proportional to the gain to bring each mode to threshold. It is desirable for these modes to have large losses so that they don't self-lase. Tracking this quantity establishes the region for design/fabrication tolerance shown by the shaded box.

[0024] Example applications include for use as mid-IR QCLs with high output power and excellent near-diffraction beam patterns desired for remote sensing and IR countermeasures applications. Specifically, for IR countermeasures, lasers in the about 3-5 μm range are desired with high quality beam output power of about tens of Watts (or greater) so that the lasers can be directed at incoming missiles to confuse or blind their IR sensors. The achieving mid-IR grating-coupled VECSEL approach allows scaling of the output power to high levels while maintaining a high quality beam pattern. The surface emission can allow beam combining of multiple laser beams to further boost the output power. Mid-IR QCLs are also desired for gas sensing, since many molecules have vibrational spectral signatures (e.g., fingerprint) between about 2-30 μm .

Example Embodiments

[0025] Some embodiments are directed to a metasurface for quantum-cascade lasing. In some embodiments, the metasurface includes: (1) a substrate; (2) a first cladding layer disposed on the substrate; (3) a quantum-cascade laser active layer on the first cladding layer; (4) a second cladding layer disposed on the quantum-cascade laser active layer; and (5) a metallic grating disposed on the second cladding layer.

[0026] In some embodiments of the metasurface, the metasurface is configured to reflect an incident light of a resonant wavelength with amplification. In some embodiments, the resonant wavelength is in a range of about 30 μm to about 300 μm . In some embodiments,

the resonant wavelength is in a range of about 3 μm to about 30 μm . In some embodiments, a period of the metallic grating is substantially equal to the resonant wavelength.

[0027] In some embodiments of the metasurface, the first cladding layer includes indium phosphide or another semiconductor material, the quantum-cascade laser active layer includes a GaAs/AlGaAs material system, InGaAs/InAlAs material system, or other combination of two or more semiconductor materials, the second cladding layer includes indium phosphide or another semiconductor material, and the metallic grating includes gold, another metal, or an alloy or other combination of two or more metals. In some embodiments, the substrate is an indium phosphide substrate or another semiconductor substrate.

[0028] In some embodiments of the metasurface, the metallic grating includes an array of metallic strips spaced with a period. In some embodiments, the second cladding layer defines an array of trenches spaced with the period, and the array of metallic strips are disposed in respective ones of the array of trenches. In some embodiments, the metallic grating further includes a metallic layer interconnecting the array of metallic strips. In some embodiments, a width of each trench of the array of trenches is in a range of about 100 nm to about 2 μm , about 100 nm to about 1000 nm, or about 500 nm to about 1000 nm.

[0029] In some embodiments of the metasurface, a thickness of the second cladding layer is in a range of about 500 nm to about 10 μm , about 1 μm to about 5 μm , about 1 μm to about 3 μm , or about 1 μm to about 2 μm .

[0030] Additional embodiments are directed to a quantum-cascade laser. In some embodiments, the quantum-cascade laser includes: (1) a metasurface according to any of the foregoing embodiments; and (2) an output coupler connected to the metasurface and which forms a cavity with the metasurface to generate a quantum-cascade laser beam.

[0031] In some embodiments of the quantum-cascade laser, the metasurface is oriented relative to the output coupler, such that the substrate of the metasurface is disposed between the output coupler and the metallic grating of the metasurface.

[0032] In some embodiments of the quantum-cascade laser, the output coupler is a flat or curved reflector, and the quantum-cascade laser beam is reflected between the flat or curved reflector and the metasurface before emitting.

[0033] In some embodiments of the quantum-cascade laser, the quantum-cascade laser further includes a heat sink connected to the metasurface. In some embodiments, the metasurface is oriented relative to the heat sink, such that the substrate of the metasurface is disposed farther away from the heat sink than is the metallic grating of the metasurface.

[0034] In some embodiments of the quantum-cascade laser, the quantum-cascade laser further includes an electrical source connected to the metasurface to apply an electrical bias to a reference center region of the metasurface, but without applying an electrical bias to a remaining peripheral region of the metasurface outside of the center region.

[0035] As used herein, the singular terms “a,” “an,” and “the” may include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to an object may include multiple objects unless the context clearly dictates otherwise.

[0036] As used herein, the term “set” refers to a collection of one or more objects. Thus, for example, a set of objects can include a single object or multiple objects. Objects of a set also can be referred to as members of the set. Objects of a set can be the same or different. In some instances, objects of a set can share one or more common characteristics.

[0037] As used herein, the terms “connect,” “connected,” and “connection” refer to an operational coupling or linking. Connected objects can be directly coupled to one another or can be indirectly coupled to one another, such as via one or more other objects.

[0038] As used herein, the terms “substantially” and “about” are used to describe and account for small variations. When used in conjunction with an event or circumstance, the terms can refer to instances in which the event or circumstance occurs precisely as well as instances in which the event or circumstance occurs to a close approximation. For example, when used in conjunction with a numerical value, the terms can refer to a range of variation of less than or equal to $\pm 10\%$ of that numerical value, such as less than or equal to $\pm 5\%$, less than or equal to $\pm 4\%$, less than or equal to $\pm 3\%$, less than or equal to $\pm 2\%$, less than or equal to $\pm 1\%$, less than or equal to $\pm 0.5\%$, less than or equal to $\pm 0.1\%$, or less than or equal to $\pm 0.05\%$. For example, a first numerical value can be “substantially” or “about” the same as a second numerical value if the first numerical value is within a range of variation of less than or equal to $\pm 10\%$ of the second numerical value, such as less than or equal to $\pm 5\%$, less than or equal to $\pm 4\%$, less than or equal to $\pm 3\%$, less than or equal to $\pm 2\%$, less than or equal to $\pm 1\%$, less than or equal to $\pm 0.5\%$, less than or equal to $\pm 0.1\%$, or less than or equal to $\pm 0.05\%$.

[0039] In the description of some embodiments, a component provided or disposed “on” or “over” another component can encompass cases where the former component is directly on (e.g., in physical or direct contact with) the latter component, as well as cases

where one or more intervening components are located between the former component and the latter component.

[0040] Additionally, concentrations, amounts, ratios, and other numerical values are sometimes presented herein in a range format. It is to be understood that such range format is used for convenience and brevity and should be understood flexibly to include numerical values explicitly specified as limits of a range, but also to include all individual numerical values or sub-ranges encompassed within that range as if each numerical value and sub-range is explicitly specified. For example, a range of about 1 to about 200 should be understood to include the explicitly recited limits of about 1 and about 200, but also to include individual values such as about 2, about 3, and about 4, and sub-ranges such as about 10 to about 50, about 20 to about 100, and so forth.

[0041] While the disclosure has been described with reference to the specific embodiments thereof, it should be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the true spirit and scope of the disclosure as defined by the appended claims. In addition, many modifications may be made to adapt a particular situation, material, composition of matter, method, operation or operations, to the objective, spirit and scope of the disclosure. All such modifications are intended to be within the scope of the claims appended hereto. In particular, while certain methods may have been described with reference to particular operations performed in a particular order, it will be understood that these operations may be combined, sub-divided, or re-ordered to form an equivalent method without departing from the teachings of the disclosure. Accordingly, unless specifically indicated herein, the order and grouping of the operations are not a limitation of the disclosure.

What is claimed is:

1. A quantum-cascade laser comprising:
a metasurface including
 - a substrate;
 - a first cladding layer disposed on the substrate;
 - a quantum-cascade laser active layer on the first cladding layer;
 - a second cladding layer disposed on the quantum-cascade laser active layer;and
 - a metallic grating disposed on the second cladding layer; and
 - an output coupler connected to the metasurface and which forms a cavity with the metasurface.
2. The quantum-cascade laser of claim 1, wherein the metasurface is configured to reflect an incident light of a resonant wavelength with amplification.
3. The quantum-cascade laser of claim 2, wherein the resonant wavelength is in a range of 3 μm to 30 μm .
4. The quantum-cascade laser of claim 2 or claim 3, wherein a period of the metallic grating is substantially equal to the resonant wavelength.
5. The quantum-cascade laser of claim 1, wherein the metallic grating includes an array of metallic strips spaced with a period.
6. The quantum-cascade laser of claim 5, wherein the second cladding layer defines an array of trenches spaced with the period, and the array of metallic strips are disposed in respective ones of the array of trenches.
7. The quantum-cascade laser of claim 6, wherein the metallic grating further includes a metallic layer interconnecting the array of metallic strips.

8. The quantum-cascade laser of claim 1, wherein the metasurface is oriented relative to the output coupler, such that the substrate is disposed between the output coupler and the metallic grating.
9. The quantum-cascade laser of claim 1, wherein the output coupler is a reflector, and a quantum-cascade laser beam is reflected between the reflector and the metasurface before emitting.
10. The quantum-cascade laser of claim 1, further comprising a heat sink connected to the metasurface.
11. The quantum-cascade laser of claim 1, further comprising an electrical source connected to the metasurface to apply an electrical bias to a reference center region of the metasurface, but without applying an electrical bias to a remaining peripheral region of the metasurface outside of the center region.
12. A metasurface for quantum-cascade lasing, comprising:
 - a substrate;
 - a first cladding layer disposed on the substrate;
 - a quantum-cascade laser active layer on the first cladding layer;
 - a second cladding layer disposed on the quantum-cascade laser active layer; and
 - a metallic grating disposed on the second cladding layer, wherein a period of the metallic grating is in a range of 3 μm to 30 μm .
13. The metasurface of claim 12, further comprising an anti-reflective coating disposed on a side of the substrate facing away from the metallic grating.
14. The metasurface of claim 12, wherein the second cladding layer defines an array of trenches spaced with the period, and the metallic grating includes an array of metallic strips disposed in respective ones of the array of trenches.
15. The metasurface of claim 14, wherein the metallic grating further includes a metallic layer interconnecting the array of metallic strips.

16. The metasurface of claim 14, wherein a width of each trench of the array of trenches is in a range of 100 nm to 1000 nm.

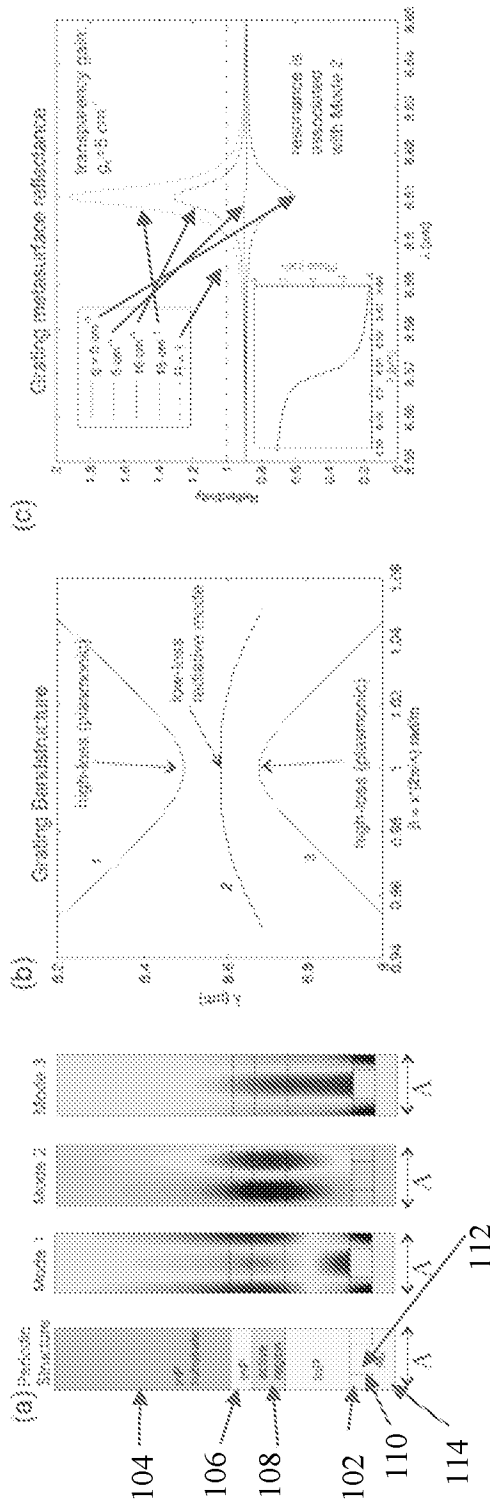


Fig. 1

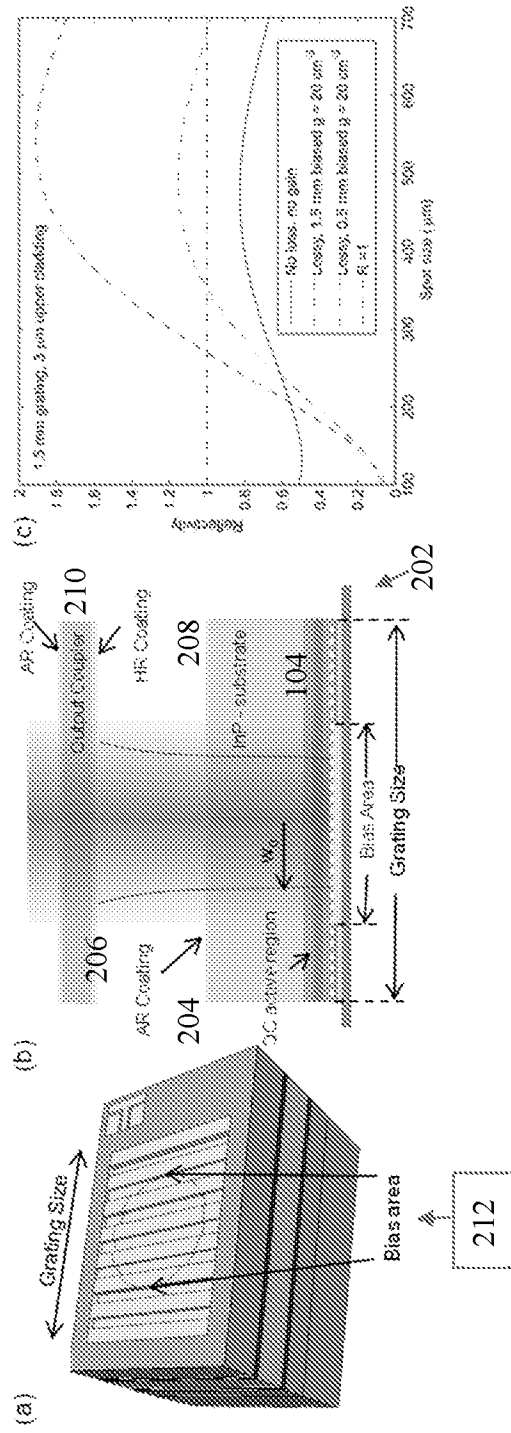
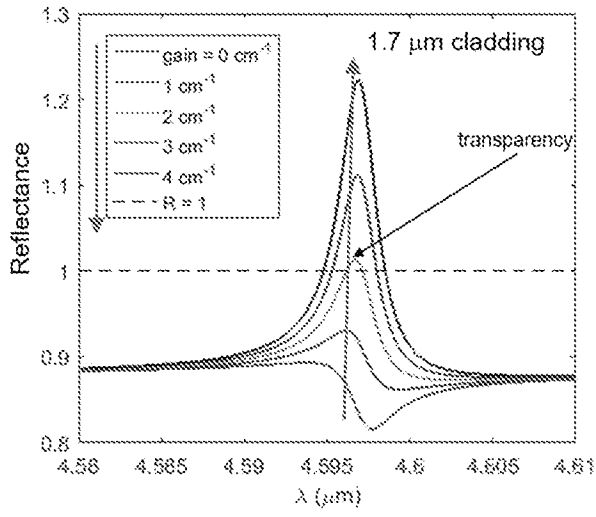
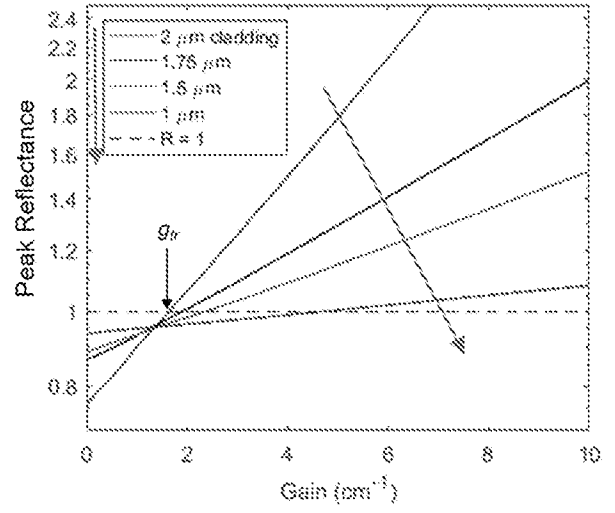


Fig. 2



(a)



(b)

Fig. 3

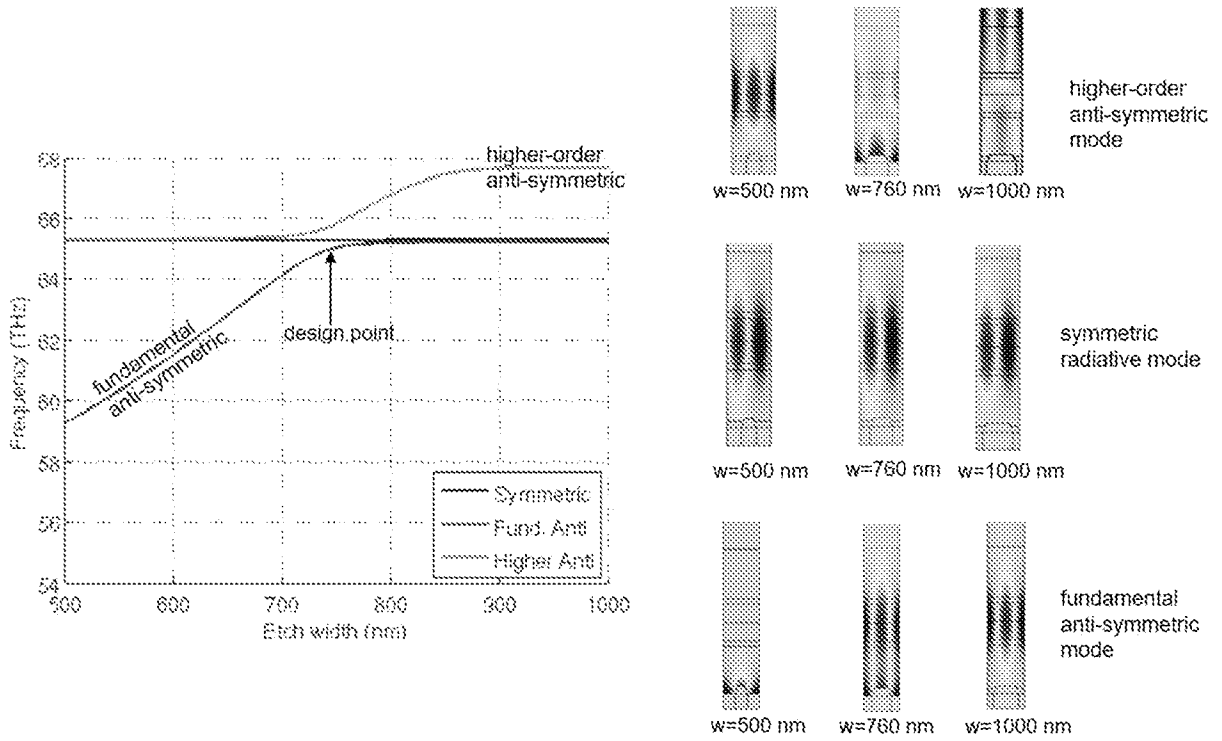


Fig. 4

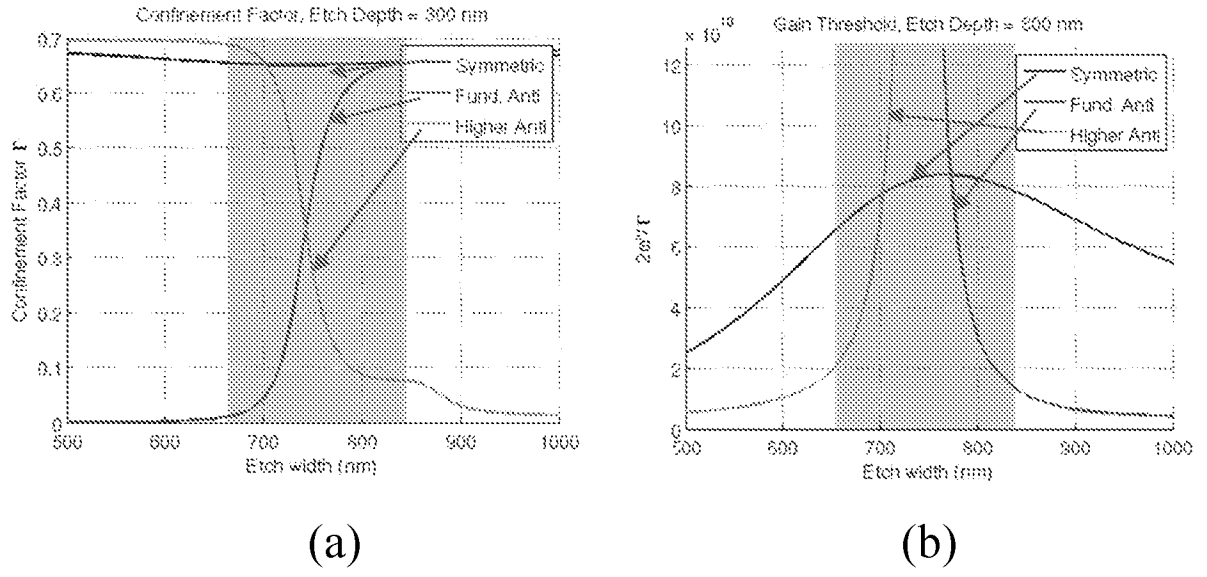


Fig. 5