Vertical cavity laser

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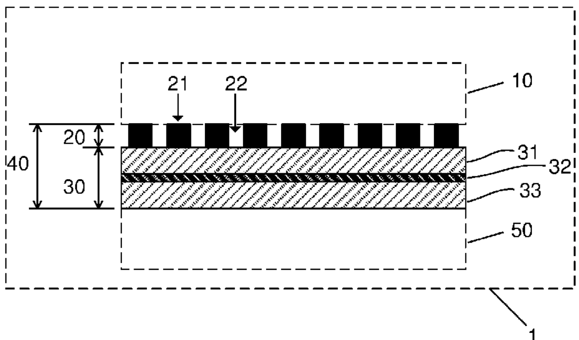

Fig. 1A

(57) **Abstract**: The present invention provides a vertical cavity laser comprising a grating layer comprising an in-plane grating, the grating layer having a first side and having a second side opposite the first side and comprising a contiguous core grating region having a grating structure, wherein an index of refraction of high-index sections of the grating structure is at least 2.5, and wherein an index of refraction of low-index sections of the grating structure is less than 2, the core grating region defining a projection in a direction normal to the grating layer; a cap layer having a first side and having a second side opposite the first side, the first side of the cap layer abutting the second side of the grating layer, and an index of refraction of the cap layer within the projection of the core grating region onto the cap layer is at least 2.5, and within the projection of the core grating region, the second side of the cap layer is abutted by a first low-index layer and/or by air, an index of refraction of the first low-index layer or air being less than 2, and within the projection of the core grating region, the first side of the grating layer is abutted by a second low-index layer and/or by air, an index of refraction of the second low-index layer or air being less than 2; and a thickness of the cap layer and a thickness of the grating layer, and a pitch and a duty cycle of the grating structure are selected to obtain a resonance having a free-space resonance wavelength in the interval 300 nm to 3 microns, the cap layer comprises an active region configured to generate or absorb photons at the free-space

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resonance wavelength by stimulated emission or absorption when a sufficient forward or reverse bias voltage is applied across the active region, a thickness of the first low-index layer is less than 45 % or more than 55 % of the free-space resonance wavelength divided by a highest index of refraction of the first low-index layer within the core grating region, and a thickness of the cap layer is less than 5 microns.

Vertical cavity laser

Technical field

This invention relates to vertical cavity lasers.

Background of the invention

Sub-wavelength high-index-contrast gratings (HCGs) have received lots of attention due to special properties such as broadband high reflection spectrum and ultra-high Q resonance effect. As a reflector, they can be approximately 50 times thinner than a conventional distributed Bragg reflector (DBR), but still offer high reflectivity over a much broader spectral width, and properties that make them useful in a wide application range, including lasers, photodetectors, filters, splitters, couplers, etc. They have been implemented in vertical-cavity surface-emitting lasers (VCSELs) and resonant-cavity-enhanced photodetectors (RCEPDs) in place of conventional DBRs. In addition several unique characteristics of HCGs in VCSEL structures, such as strong single-transverse-mode operation, broad wavelength tunability, and light emission into an in-plane silicon photonics chip have been shown. As a resonator, HCGs can provide an ultrahigh quality factor such as 10^8. Using this property, very compact (small modal volume) lasing devices with ultra-high quality factor have been demonstrated. Different groups have investigated the physics behind HCGs' properties. In all the literature on the HCG reflectors as well as HCG resonators, the grating is required to be surrounded by low index materials. Even if the device substrate is a high-index material, a layer with low-index material is required between the grating layer and the substrate to obtain the HCG properties.

Patent application publication WO 2010/091688 A1 (Inventor: Il-Sug Chung) discloses a hybrid vertical-cavity laser (VCL) structure. It does not disclose for instance a cap layer as defined in the present document. VCLs in accordance with the present invention have an in-plane grating layer which, among other characteristics, is abutted by a layer (called a cap layer) of material consisting of material having an index of refraction of at least 2.5. Such a constitution is not shown in WO 2010/091688 A1.

In the paper "Hybrid grating reflector with high reflectivity and broad bandwidth", Taghizadeh et al. (Optics Express, Vol. 22, No. 18) speculate that a new laser structure may "consist of a passive mirror, a very thin passive cavity, e.g., $\lambda/2$-air cavity, and an active HG [=hybrid grating] reflector." Such a device has some drawbacks. As will become clear in the disclosure of the present invention, such a structure is constructed from a traditional view of how VCSELs work.

Summary of the invention

In a first aspect, the present invention provides a vertical cavity laser (VCL) structure. The VCL structure comprises:

- a grating layer comprising an in-plane grating, the grating layer having a first side and having a second side opposite the first side and comprising a contiguous core grating region having a grating structure, wherein an index of refraction of high-index sections of the grating structure is at least 2.5, and wherein an index of refraction of low-index sections of the grating structure is less than 2, the core grating region defining a projection in a direction normal to the grating layer,
- a cap layer having a first side and having a second side opposite the first side, the first side of the cap layer abutting the second side of the grating layer, and an index of refraction of the cap layer within the projection of the core grating region onto the cap layer is at least 2.5,

and

- within the projection of the core grating region, the second side of the cap layer is abutted by a first low-index layer and/or by air, an index of refraction of the first low-index layer or air being less than 2, and
- within the projection of the core grating region, the first side of the grating layer is abutted by a second low-index layer and/or by air, an index of refraction of the second low-index layer or air being less than 2.

and

- a thickness of the cap layer and a thickness of the grating layer, and a pitch and a duty cycle of the grating structure are selected to obtain a resonance having a free-space resonance wavelength in the interval 300 nm to 3 microns,
- the cap layer comprises an active region configured to generate or absorb photons at the free-space resonance wavelength by stimulated emission or absorption when a sufficient forward or reverse bias voltage is applied across the active region,
- a thickness of the first low-index layer is less than 45 % or more than 55 % of the free-space resonance wavelength divided by a highest index of refraction of the first low-index layer within the projection of the core grating region, and
- a thickness of the cap layer is less than 5 microns.

The present invention provides a vertical cavity laser that is simpler in structure than prior-art-semiconductor lasers and requires fewer semiconductor layers. This makes the task of manufacturing the micro laser significantly easier as well as lowering the fabrication cost. Furthermore, the present invention provides a vertical cavity laser structure with a smaller modal volume than prior art semiconductor lasers.

In contrast to for instance US patent application publication US 2011/0158278 A1 (Brian Koch), the present device can be much thinner, considering that Koch needs high reflectivity mirrors, such as DBRs or a HCG mirror and a DBR, for enablement.

Embodiments of the present invention, surprisingly, do not require that there be two highly reflective mirrors. This means that the device can be much thinner. Furthermore, the design process can be considered to be substantially simpler.

The present invention does not involve design choices regarding for instance the structure of DBRs, since such mirrors with reflectivities of more than for instance 99.8 % cannot be included by virtue of the unconventional limitation on the thickness of what is referred to as the "cap layer" in the present invention. For a given selection of materials of the first and second low-index layers, the cap layer and the high- and low-index sections of the grating, the resonance in embodiments of the present invention are mainly dictated by the pitch and duty cycle of the grating, the thickness of the grating, and in particular the thickness of the cap layer.

In the paper "Hybrid grating reflector with high reflectivity and broad bandwidth", Taghizadeh et al. (Optics Express, Vol. 22, No. 18, P.21175) speculate that a new laser structure may consist of a passive mirror, a very thin passive cavity, e.g., λ /2-air cavity, and an active HG [=hybrid grating] reflector." This suggestion is in line with a conventional thinking concerning VCSELs, namely that a cavity must be positioned between two highly reflective mirrors, and the cavity must have properties very different from the mirrors. In the device suggested in the paper does not have a cap layer, which is a layer that abuts an in-plane grating layer and has a refractive index of at least 2.5.

Furthermore, the present invention relies on a different principle for achieving resonance. Contrary to the conventional understanding referred to above, in which a special cavity and two easily identifiable mirrors are used, the present invention takes a much different approach. It does not include an air cavity surrounded by two mirrors, and there is no *cavity* with a λ/2-condition involved. There is no standalone mirror with high reflectivity close 100 %. Thus, it would not seem that a vertical cavity laser is provided by the present invention, given these properties. This is nevertheless the case. Evidence for the absence of a standalone mirror in a device in accordance with the present invention is that the reflectivity spectrum of this device does not have a high reflectivity value close to 100 %, over a broad wavelength range, e.g. over 100 nm around the resonance wavelength (see Fig. 3A). A reflectivity spectrum of a device in accordance with the conventional approach has high reflectivity values close to 100 % over a broad wavelength range, since there are two broadband high-reflectivity mirrors, as is well known to the person skilled in the art.

The term "resonance" denotes the phenomenon that a photonic structure referred to as "a resonator" or "a cavity" can maintain an optical mode with a certain central wavelength (or wavelengths) in the resonator for some time. The spatial profile and wavelength of the optical mode are determined by, among other things, the geometry of the resonator, i.e. the refractive index profile of the resonator. The energy of an optical mode periodically alternates between the electric field and the magnetic field, which defines a cycle. The "quality factor" or "Q factor" of a resonator represents the resonator's ability to maintain energy in the optical mode in the absence of amplification. The Q factor can therefore be defined as,

Q = 2π (energy stored in the resonator) / (energy dissipated per cycle)

If the optical mode of the resonator can be excited by light incident from outside the resonator, the Q factor can alternatively be defined based on the reflectivity spectrum:

Q = (wavelength of resonance)/(full-width at half-maximum of the reflectivity dip in the reflectivity spectrum)

The reflectivity can be measured for light incident on the second low-index layer and propagating normal to the cap layer in a direction that is from the second low-index layer towards the first low-index layer. Similarly, the reflectivity can be measured for light incident on the first low-index layer and propagating normal to the grating layer in a direction which is from the first low-index layer towards the second low-index layer.

In some embodiments, the thickness of the first low-index layer is less than 40 % or more than 60 % of the free-space resonance wavelength divided by the highest index of refraction of the first low-index layer within the projection of the core grating region.

In some embodiments, the VCL structure has a lateral dimension, L_{cap}, of the cap layer that does not exceed 30 microns.

Some embodiments of the VCL structure comprise a first contact and a second contact for enabling application of the forward and/or reverse bias voltage across the active region.

In some embodiments, the core grating region comprises at least 3 high-index sections.

In some embodiments, one or more of the high-index sections of the core grating region is made of Si, InP-based material, GaAs-based material, or other material with a refractive index higher than 2.5.

In some embodiments, the first low-index and/or second low-index layer comprises SiNx, SiO_2, AlOx, polymer, air, gas or gases, or other material with a refractive index less than 2.

In some embodiments, the first low-index layer within the projection of the core grating region consists of air or other gas or gases. In some embodiments, the VCL is located in a low-pressure environment, or "vacuum", such as below 0.5 atm, such as below 0.1 atm, such as below 0.05 atm, such as below 0.01 atm, or lower. In some embodiments, a specific gas or gases may replace air.

In some embodiments, the Q factor is at least 1000, such as at least 3000, such as at least 5000, such as at least 6000.

Some embodiments of the VCL structure comprise a waveguide formed integrally with the grating layer of the VCL, and the waveguide extends at least 5 microns outside the core grating region, and the waveguide is configured to couple light from the core grating region out of the VCL.

In some embodiments, the cap layer includes a carrier confinement structure, such as an oxide aperture, a tunnel junction, an ion-implanted region, or a diffused region.

A second aspect of the invention provides an optical device comprising a first VCL structure in accordance with one or more embodiments of the first aspect of the invention, and comprising a second VCL structure also in accordance with an embodiment of the first aspect of the invention. In embodiments of the second aspect, the grating layer of the second VCL structure is formed integral with the grating layer of the first VCL structure.

In some embodiment of the optical device, a distance between the core grating region of the first VCL is less than 5 mm from the core grating region of the second VCL.

In some embodiments of the optical device, the free-space resonance wavelength of the first VCL structure is within 5 % of the free-space resonance wavelength of the second VCL structure.

The simplest fabrication of embodiments of an optical device in accordance with the second aspect of the invention involves forming the first and second VCL in the same semiconductor wafer in the same fabrication run. When the grating layer of the first VCL and the grating layer of the second VCL are formed this way, the optical device will be most uniform and have as little undesired light loss as possible. In a preferred embodiment, the grating layer of the first VCL and the grating layer of the second VCL are formed in the same semiconductor wafer layer.

In some embodiments of the optical device of the second aspect of the invention, the first and the second VCLs are optically and/or electrically coupled. This means that the two VCLs can be controlled using the same circuitry, potentially allowing an increased performance of the two VCLs compared to independent operation of the two.

Most of the materials that can be used in the present invention have chromatic dispersion, which is the phenomenon that the phase velocity of light travelling in the material varies with the wavelength of the light. *In the present specification, "refractive index" or "index of refraction" of a material refers, unless otherwise specified, to generally accepted values of the refractive index for that material at a free-space wavelength of 1.5 um.* Table 1 shows values for common high-index materials applicable in the context of the present invention. At high frequencies, the refractive indices for those materials change rapidly with decreasing wavelength, typically increasing at first, and then decreasing to values lower than 2.5. Table 1 also shows the refractive indices at a free-space wavelength of 250 nm to illustrate this.

This definition of refractive index used herein shall not be construed as limiting the scope of the invention. The definition is used because a number of materials that are advantageous in embodiments of aspects of the present invention have refractive indices within certain intervals at various wavelengths. Using the refractive index at a certain wavelength as a reference, the concept of refractive index or index of refraction as these entities pertain to the claims invention becomes unambiguous.

Table 1: Index of refraction for high-index materials

Material	*n* (at 1.5 um)	*n* (at 0.25 um)
Si	3.48206 [1]	1.5808 [2]
InP	3.17085 [1]	2.297 [2]
GaAs	3.39886 [1]	2.5198 [2]

Table 2: Index of refraction for low-index materials

Material	*n* (at 1.5 um)	*n* (at 0.25 um)
Si3N4	1.99038 [3]	2.28189 [4]
SiO2	1.52837 [5]	1.60035 [5]
Al2O3	1.74687 [6]	1.8337 [6]
Air	1.0002733 [7]	1.00030148 [7]

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In many applications, such as optical communication, the pre-specified wavelength interval comprises 850 nm or 1310 nm or 1550 nm.

In some embodiments, the first VCL and the second VCL are substantially identical. In terms of fabrication, this can be obtained by using substantially identical masks and etching/implantation steps. The symmetry provided when the two VCL are at least substantially identical can produce some advantageous effects. In other cases, the two may advantageously be different, even very different. In yet other embodiments, the optical device comprises one or more further VCLs, two or more of which are electrically and/or optically coupled or isolated. In some embodiments, the VCLs are situated with respect to each other in a way that introduces a symmetry among them.

In VCLs in accordance with the first aspect of the invention and in optical devices in accordance with the second aspect of the invention, the grating layer may comprise a first part in which the grating comprises a first periodicity, and comprise a second part in which the grating comprises a second periodicity different from the first periodicity. In this case, widths of all high-index sections may have one value in the first part and another different width in the second part; and similarly for the low-index sections in the first and second parts. The first and/or second parts may each be non-periodic, such as apodized or chirped or almost-periodic or quasi-periodic or consisting of several sections with different grating periods and/or grating width. Such properties are described later in the present specification.

Brief descriptions of the drawings

Figures 1A, 1B, 1C, 1D, 1E, 1F are cross-sectional views of embodiments of or parts of embodiments of VCLs in accordance with an aspect of the present invention.

Figures 2A and 2B are top views of exemplary one-dimensional grating structures for a VCL.

Figure 2C is a top view of an example of a two-dimensional grating structure for a VCL.

Figure 2D is a top view of an example of a circular grating structure for a VCL.

Figure 2E is a top view of an example of a grating structure having a more complex grating structure.

Figures 3A-3L show reflection spectra for various VCL structures.

Figure 4A and 4B show mode profiles for two VCL structures.

Figure 5A and 5B show other VCL structures.

Figure 6A and 6B illustrate embodiments of the VCL having a waveguide for coupling light into or out of the core grating region of the VCL.

Figure 7A, 7B and 7C illustrate embodiments of an optical device in accordance with the second aspect of the invention.

Detailed description of selected embodiments

The invention will now be exemplified by reference to the accompanying drawings. Reference signs in this specification, including the claims, are not to be construed as limiting the scope of the invention. The drawings are not necessarily drawn to scale.

Figures 1A, 1B, 1C, 1D, 1E and 1F illustrate various VCLs in accordance with the present invention. The VCL 1 comprises a section 40 consisting of a grating layer 20 and a "cap layer" 30. The grating layer 20 and cap layer 30 are often made of material from two material systems, for instance group IV semiconductor and III-V semiconductor, respectively and in that case the VCL is referred to as a hybrid VCL. For instance, the grating layer 20 is made of Si and combined with a cap layer 30 made of InP-based materials.

Figure 1A illustrates the components of the VCL: the cap layer 30, the grating layer 20 and the abutting layers 10 and 50. The high-index sections 21 could for instance be Si, which has an index of refraction of about 3.48 (see Table 1) at 1.5-μm (free space) wavelength. The low-index sections 22 can be air (or other mix of gases, or a single gas). Alternatively, depending on the application, materials such as SiNx (Silicon nitride compound), SiO_2, or AlOx (Aluminium oxide compound) can be used, as discussed previously. The same materials can be used for sections 10 and 50. The sections 10 and 50 are indicated with dashed boxes because air is another alternative material, but, not being a solid, the extent of these sections depends on the VCL's surroundings. Sections 10 and 50 need not be made from the same material. In some cases they are, but using different materials provides much more design flexibility. Also, the layers 10 and 50 can be composed of sections having different indices of refraction. The cap layer is typically group-III-V based, for instance InP-based, but other choices are available, as discussed above.

It is important to note that the cap layer in accordance with the invention needs only to consist of a high-index material or materials in a limited region, namely within the core grating region projection defined by the core grating region described previously. In Figure 1C and all other figures showing embodiments of a VCL structure in accordance with the invention, the respective grating layers 20 are in a plane defined by the left and right directions on the respective drawing pages. The up and down directions on those pages are therefore the directions normal to the grating layer. Figure 1C illustrates a structure similar to that in Figure 1B, but with oxide regions 60 for providing current confinement. Figure 1C illustrates a core grating region comprising four high-index sections 21 and three low-index sections 22, within the dashed box 70. The dashed box 70 illustrates those parts of the VCL structure that are inside the projection of the core grating region. The section 70 in Figure 1C is the part that makes up a VCL in accordance with the present invention. In this example, the VCL also has grating sections 21,22 (that are outside the dashed box) with oxide 60 below them, but the structure as a whole (i.e. including the oxide and also contact 35) is nevertheless in accordance with the present invention due to the presence of the core grating region and the characteristics of the layers within the projection of the core grating region (illustrated by box 70).

Within the projection of the core grating region, the core grating region is by definition abutted by material having an index of refraction of at least 2.5. As mentioned, in some embodiments the cap layer includes a carrier confinement structure, such as an oxide aperture, a tunnel junction, an ion-implanted region, or a diffused region, but to the extent that such confinement structures comprise material having a refractive index lower than 2.5, these confinement structures are by definition necessarily not within the projection of the core grating region in a direction normal to the grating layer.

The cap layer 30 is active and typically is a composite layer with sublayers such as an active material layer 32 and two cladding layers 31 and 33. The cladding layers can themselves be composite layers with sublayers. The active material 32 can be a bulk material or contain one or more quantum wells, one or more quantum dot layers, one or more quantum wire layers, one or more quantum dash layers, a buried heterostructure (BH) and so on, or a combination of such materials and material structures. Such an active cap layer can be used for light generation or light absorption or light intensity modulation, depending on the cap layer composition, the wavelength of incident light, use of electrical contacts and so on.

Contacts are illustrated in Figure 1B. Depending on the bias direction, reverse or forward, the active region can either provide absorption or generation of photons.

Figure 1D shows an embodiment in which one of the low-index layers, 50, is an air layer located between a substrate 200 and the VCL, the gap being realized by support elements 51.

Figure 1E shows that the grating pitch can vary across the grating layer, see sections 25 and 26.

Figure 1F shows an embodiment in which one of the low-index layers, 50, is SiO_2 positioned on a substrate 200.

In many embodiments, the high-index sections 21 of the grating layer is group-IV based, typically made of Si. At the same time, the cap layer is typically group-III-V based. In that case, the VCL is referred to as a hybrid grating VCL, indicating this hybridised nature.

A one-dimensional grating could for instance be made of parallel bars of a first material, spaced evenly and being separated by a second material, such as SiO_2 or by air or other gaseous substance. The first material could for instance be Si or InP or GaAs or other high-index material. In some embodiments, the grating is non-periodic, such as apodized or chirped or almost-periodic or quasi-periodic or consisting of several sections with different grating periods and/or grating width. Such options are well known by the person skilled in the art and are applicable as gratings in embodiments of the present invention. The selection of grating depends on the desired properties. Figures 2A and 2B are examples of gratings. Figure 2A shows a periodic grating, and Figure 2B shows a non-periodic grating.

Figure 2C shows a two-dimensional grating with square holes. The holes could also be circular or other shape, and the lattice structure could be a triangular or graphite-like-lattice, with circular holes or material; other shapes of the holes can be used. The same high- and low-index materials as discussed in the one-dimensional case are applicable. Such design options for the grating structure are well known to the person skilled in the art. Figure 2D shows a circular design, which is also a well-known grating pattern.

The grating may also be comprised of more complex unit cells (25) in a grating configuration, either one-dimensional or two-dimensional. Figure 2E shows an example of such gratings. A unit cell (25) of high-index(21a)/low-index(22a)/high-index(21b)/low-index(22b) sections of various widths is repeated to form a super lattice.

Figures 3A-3L illustrate reflection spectra for various dimensions of the grating thickness, cap layer thickness, grating pitch and duty cycle. They also illustrate the shift in resonance wavelength with changes in these parameters. The parameters are:

- duty cycle, DC
- grating period, Λ_g or Lg
- thickness of the cap layer, Tc

- thickness of the grating layer, Tg

These parameters are illustrated in Figures 4A and 4B. Wh, the width of a high-index section, is $DC \cdot \Lambda_g$.

Figure 3A shows the reflectivity spectrum for a structure where the grating period is 646.6 nm, the cap layer thickness Tc is 391.6 nm, the grating layer thickness Tg is 873.3 nm, and the duty cycle DC is 49.8 %. Figure 3B zooms in the spectrum. Figure 3C illustrates the shift in resonance when the grating period is increased or decreased by 10 nm. The resulting Q factors are shown in the graph. Figure 3D illustrates the shift in resonance when the duty cycle DC is increased or decreased by 1% for the same structure. Figure 3E illustrates the shift in resonance when the grating layer thickness is increased or decreased by 10 nm. Figure 3F illustrates the shift in resonance when the cap layer thickness is increased or decreased by 10 nm.

Figure 3G shows the reflectivity spectrum for a structure where the grating period is 853.5 nm, the cap layer thickness Tc is 830.5 nm, grating layer thickness Tg is 742.3 nm, and duty cycle DC is 61.6 %. Figure 3H is a zoom of the spectrum. Figure 3I illustrates the shift in resonance when the grating period is increased or decreased by 10 nm. The resulting Q factors are shown in the graph. Figure 3J illustrates the shift in resonance when the duty cycle DC is increased or decreased by 1% for the same structure. Figure 3K illustrates the shift in resonance when the grating layer thickness is increased or decreased by 10 nm. Figure 3L illustrates the shift in resonance when the cap layer thickness is increased or decreased by 10 nm.

The calculations illustrate designs that provide a high Q factor at different wavelengths. The actual selection depends on the requirements of a specific application.

Figures 4A and 4B illustrate calculated mode profiles for two different structures. Figure 4A corresponds to the reflectivity spectra shown in Figures 3A and 3B, which also show the values of the duty cycle, grating period, and thicknesses of the cap layer and the grating layer. Figure 4B corresponds to the reflectivity spectra shown in Figures 3G and 3H, which also show the values of the duty cycle, grating period, and thicknesses of the cap layer and the grating layer. The modes are calculated using periodic boundary conditions. Each plot illustrates a single grating period, with the high-index section in the middle, and low-index sections in the sides. The total width of the low-index sections is simply $(1 - DC) \cdot \Lambda_g$.

Lasing can in some cases be optimized by placing the active layer in a position where the field intensity is high. Then the active region will provide optimal amplification of light in the resonator, increasing lasing efficiency.
Figure 5A shows another VCL structure. Here, the low-index layer 10 abutting the grating layer is made of SiO_2. Another low-index material will also be viable, as previously mentioned. The low-index layer 10 is supported by substrate layer 220. Figure 5B shows yet another VCL structure. Here, the low-index layer 10 abutting the grating layer is air. Support elements 11 maintain the air gap between the grating layer and the substrate 220. Figure 5B also illustrates a lateral dimension of the cap layer, this lateral dimension being denoted L_{cap}. In some embodiments, including the present example, this dimension does not exceed 30 microns. Embodiments with this technical feature differ substantially from DFB lasers, which are typically hundreds of microns long.

Both Figures 5A and 5B furthermore show contacts for providing a voltage across the active region. For carrier confinement, cladding layers 31 and/or 33 may include a structure such as an oxide aperture, a tunnel junction aperture, or an implanted region.

Figure 6A illustrates an embodiment having a waveguide 610 for coupling light 611 in and/or out of the core grating region of a VCL. An in-plane component of certain modes can couple to propagating modes in the waveguide, and vice-versa.

Figure 6B also illustrates an embodiment having a waveguide 610 for coupling light 611 in and/or out of the core grating region of a VCL. In this embodiment, the grating has a section 725 in which the core grating region has one grating periodicity, and another section 726 in which the core grating region has another grating periodicity. The section 726 can be used to suppress unwanted coupling into the left-hand side.

Figure 7A illustrates an embodiment of an optical device having a first VCL comprising sections 735A and 736A (in this case having different grating periodicities, but this is optional), and a second VCL comprising sections 735B and 736B (in this case having different grating periodicities, but this is optional). The two VCLs are coupled via the grating layer, but they may also be coupled via further material, such as via further wafer layers. There may also (but need not) be an optical interaction 711 (also in Figures 7B and 7C) between the two VCLs.

Figure 7B illustrates further coupling of two VCLs. In this case, more wafer layers remain in the cap layer. Ion implantation of a part of the structure has provided an insulating section 740 between the two VCLs. Although insulation is advantageous in some cases, a stronger interaction may be useful (and obtained for instance simply by not implanting). Figure 7C is similar to Figure 7B, but further includes a waveguide for coupling light into and/or out of the optical device. In Figures 6B and 7A-7C do not show layer 220, but it may or may not be present.

Claims

1. A vertical cavity laser (VCL) structure (1) comprising:
   - a grating layer (20) comprising an in-plane grating, the grating layer having a first side and having a second side opposite the first side and comprising a contiguous core grating region having a grating structure (21, 22), wherein an index of refraction of high-index sections (21) of the grating structure is at least 2.5, and wherein an index of refraction of low-index sections (22) of the grating structure is less than 2, the core grating region defining a projection in a direction normal to the grating layer,
   - a cap layer (30) having a first side and having a second side opposite the first side, the first side of the cap layer abutting the second side of the grating layer, and an index of refraction of the cap layer within the projection of the core grating region onto the cap layer is at least 2.5,

   and

   - within the projection of the core grating region, the second side of the cap layer is abutted by a first low-index layer (50) and/or by air, an index of refraction of the first low-index layer or air being less than 2, and
   - within the projection of the core grating region, the first side of the grating layer is abutted by a second low-index layer (10) and/or by air, an index of refraction of the second low-index layer or air being less than 2.

   and

   - a thickness of the cap layer and a thickness of the grating layer, and a pitch and a duty cycle of the grating structure are selected to obtain a resonance having a free-space resonance wavelength in the interval 300 nm to 3 microns,
   - the cap layer comprises an active region (32) configured to generate or absorb photons at the free-space resonance wavelength by stimulated emission or absorption when a sufficient forward or reverse bias voltage is applied across the active region,
   - a thickness of the first low-index layer is less than 45 % or more than 55 % of the free-space resonance wavelength divided by a highest index of refraction of the first low-index layer within the projection of the core grating region, and
   - a thickness of the cap layer (30) is less than 5 microns.

2. A VCL structure in accordance with claim 1, wherein a lateral dimension of the cap layer, L_{cap}, does not exceed 30 microns.

3. A VCL structure in accordance with claim 1 or 2, further comprising:
    - a first contact (35) and a second contact (36) for enabling application of the forward and/or reverse bias voltage across the active region (32).

4. A VCL structure in accordance with one of the previous claims, wherein the core grating region comprises at least 3 high-index sections (21).

5. A VCL structure in accordance with one of the previous claims, wherein one or more of the high-index regions (21) of the core grating region is made of Si, InP-based material, GaAs-based material, or other material with a refractive index higher than 2.5.

6. A VCL structure in accordance with one of the previous claims, wherein the first low-index and/or second low-index layer comprises SiNx, SiO_2, AlOx, polymer, air, gas or gases, or other material with a refractive index less than 2.

7. A VCL structure in accordance with one of the previous claims, wherein the first low-index layer within the core grating region consists of air or other gas or gases.

8. A VCL structure in accordance with one of the previous claims, wherein the Q factor is at least 1000.

9. A VCL structure in accordance with one of the previous claims, wherein the Q factor is at least 3000.

10. A VCL structure in accordance with one of the previous claims, further comprising a waveguide formed integrally with the grating layer of the VCL, the waveguide extending at least 5 microns outside the core grating region, the waveguide being configured to couple light from the core grating region out of the VCL.

11. A VCL structure in accordance with one of the previous claims, wherein the cap layer includes a carrier confinement structure, such as an oxide aperture, a tunnel junction, an ion-implanted region, or a diffused region.

12. An optical device comprising a first VCL structure in accordance with one of the previous claims and a second VCL structure in accordance with one of the previous claims, the grating layer of the second VCL structure being formed integrally with the grating layer of the first VCL structure.

13. An optical device in accordance with claim 12, wherein a distance between the core grating region of the first VCL is less than 5 mm from the core grating region of the second VCL.

14. An optical device in accordance with claim 12 or 13, wherein the free-space resonance wavelength of the first VCL structure is within 5 % of the free-space resonance wavelength of the second VCL structure.

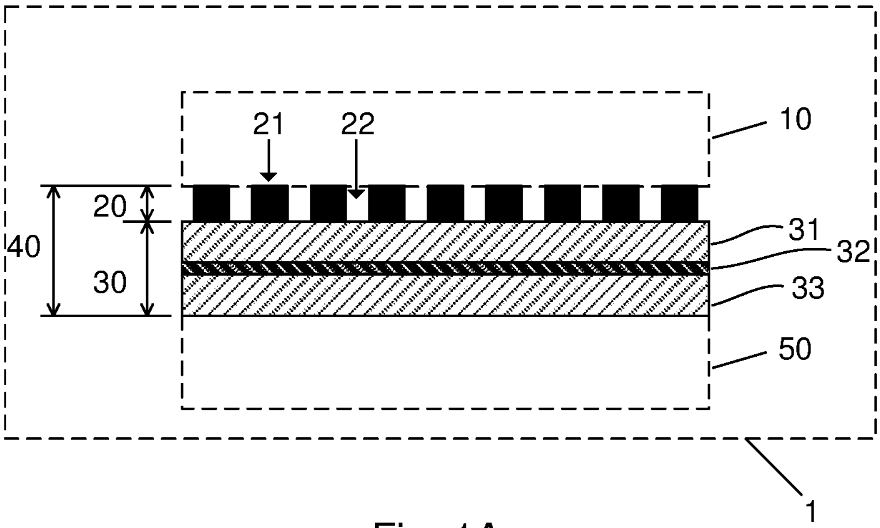


Fig. 1A

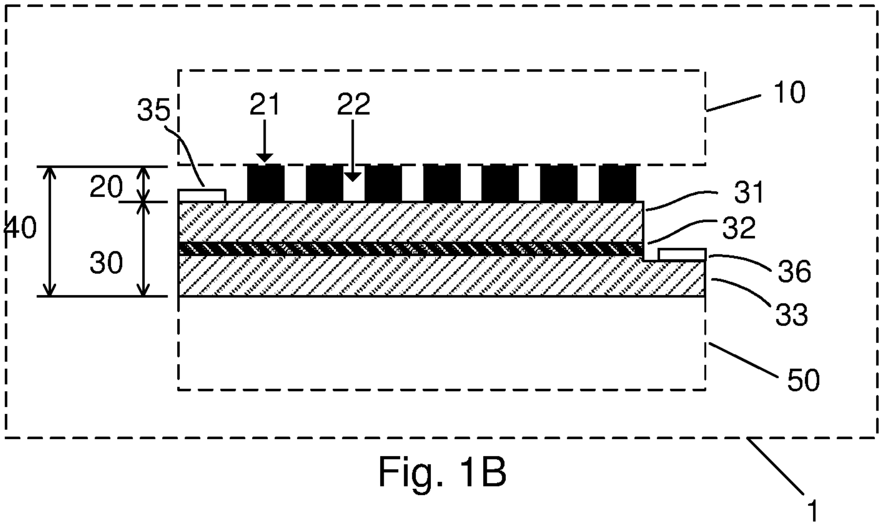

35
21
22
10
20
40
30
31
32
36
33
50
1

Fig. 1B

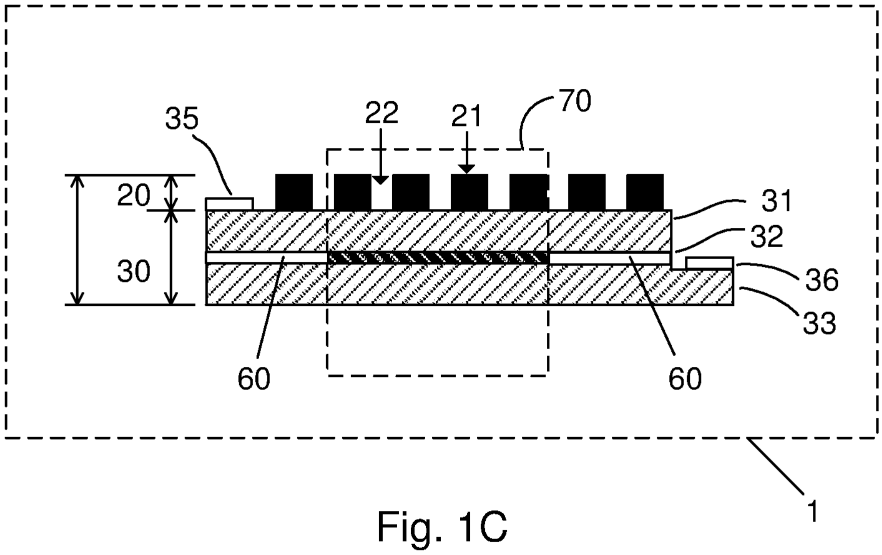

35
22
21
70
20
30
31
32
36
33
60
60
1

Fig. 1C

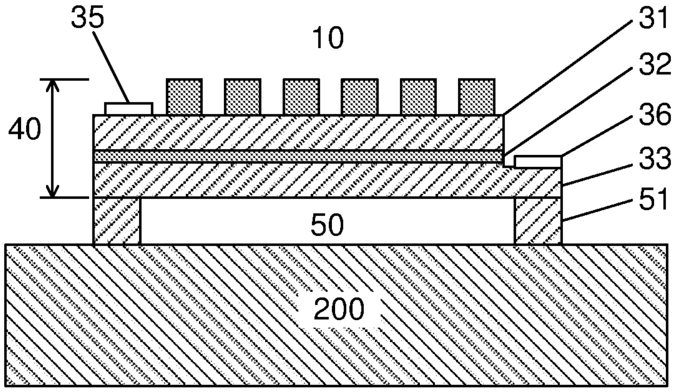


Fig. 1D

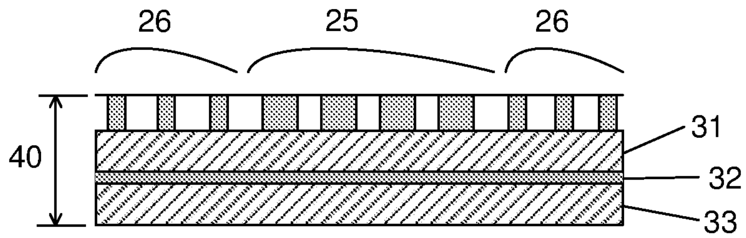


Fig. 1E

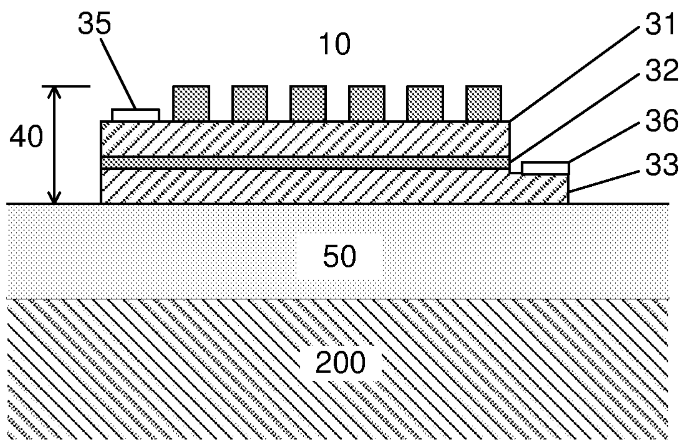


Fig. 1F

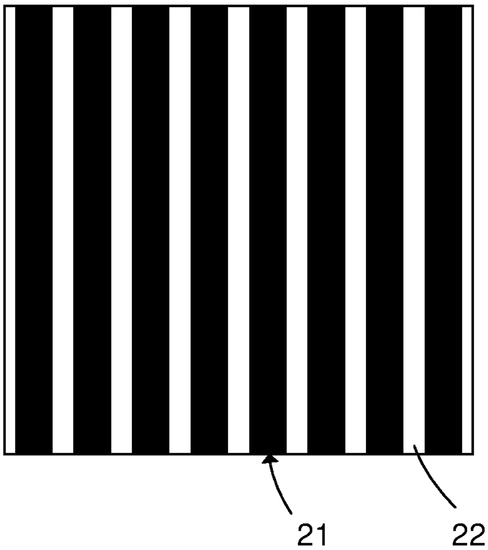


Fig. 2A

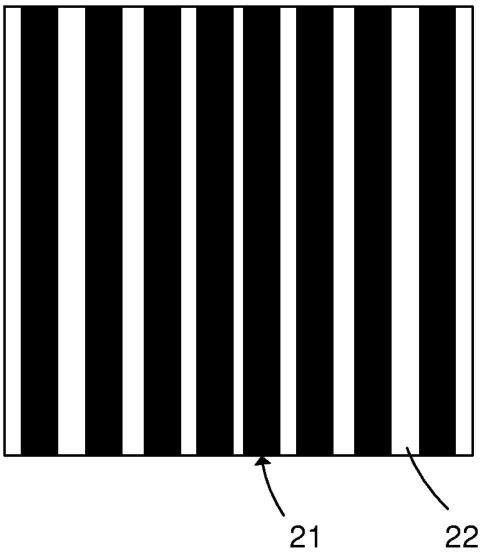


Fig. 2B

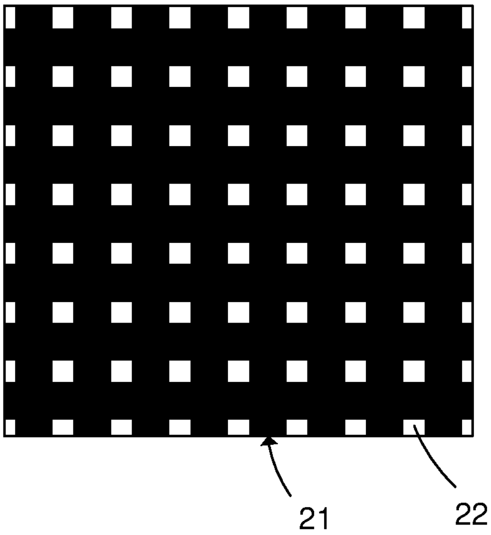
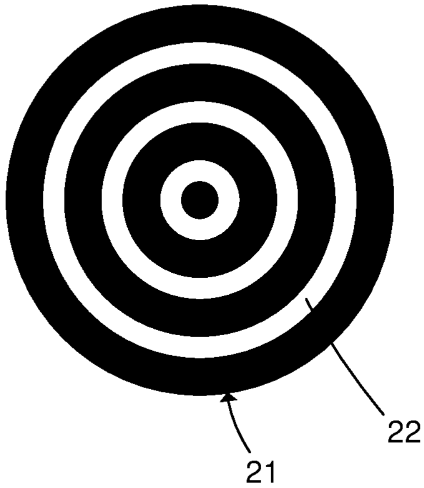


Fig. 2C

Fig. 2D



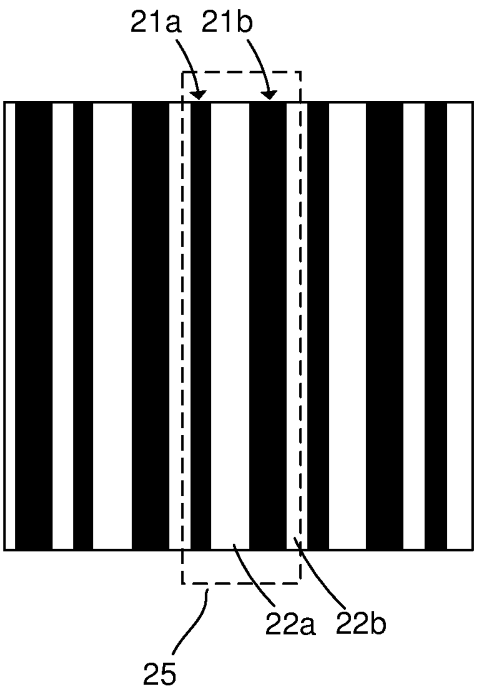
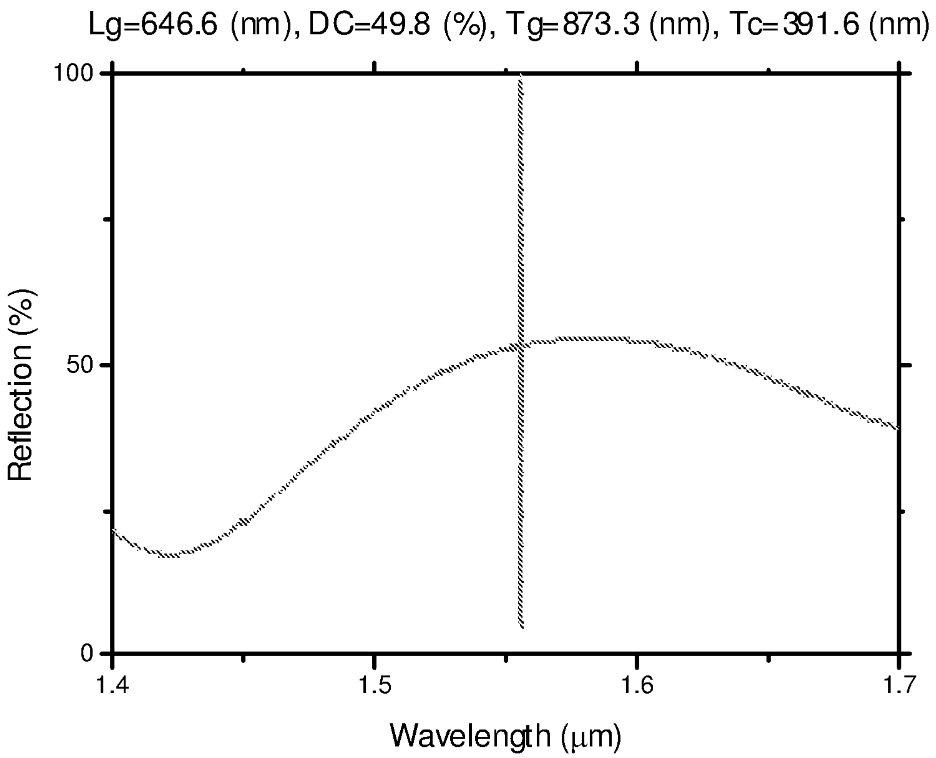


Fig. 2E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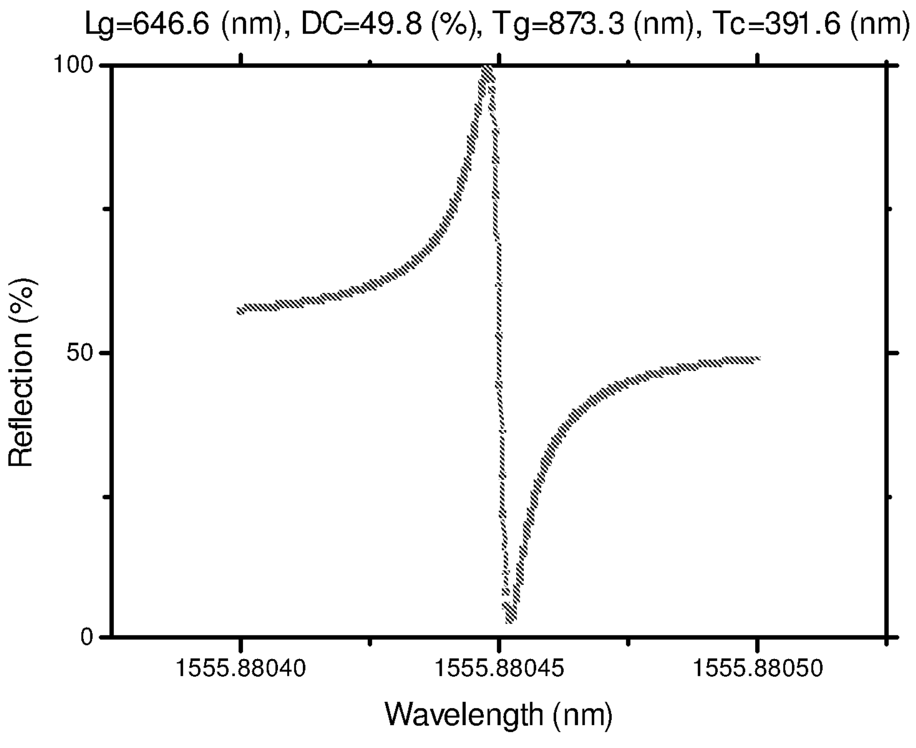
100
50
0
Reflection (%)
1.4
1.5
1.6
1.7
Wavelength (μm)

Fig. 3A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100
50
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Reflection (%)
1555.88040
1555.88045
1555.88050
Wavelength (nm)

Fig. 3B

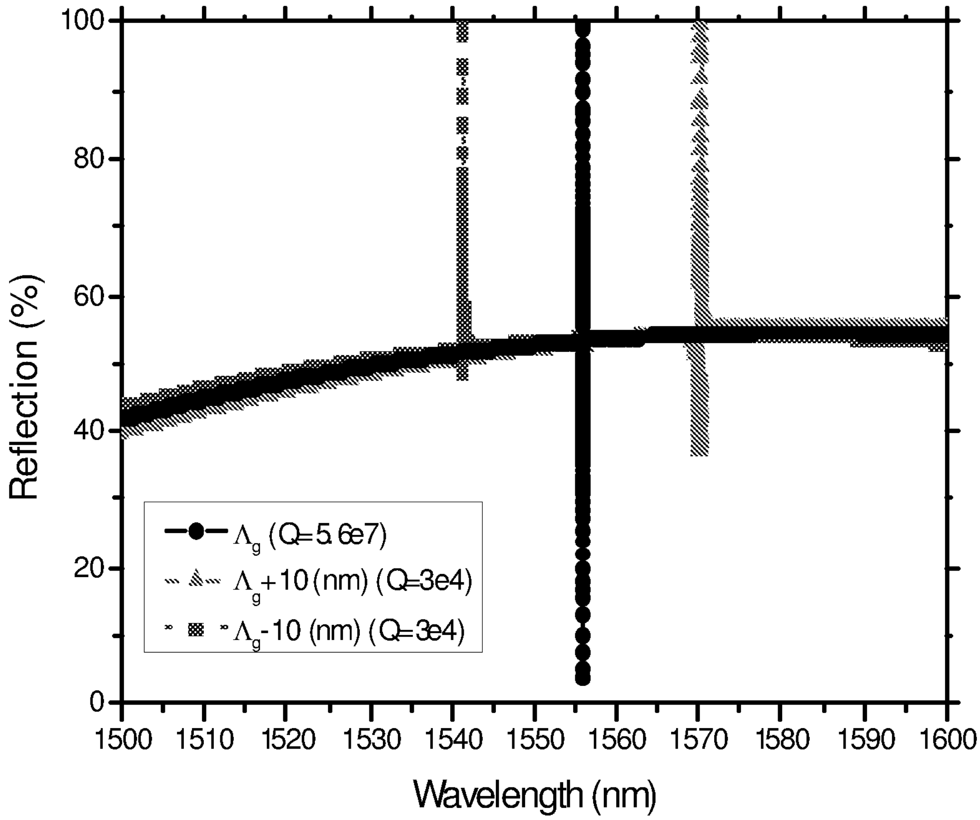

Reflection (%)
Wavelength (nm)
Λ_g (Q=5.6e7)
Λ_g+10 (nm) (Q=3e4)
Λ_g-10 (nm) (Q=3e4)

Fig. 3C

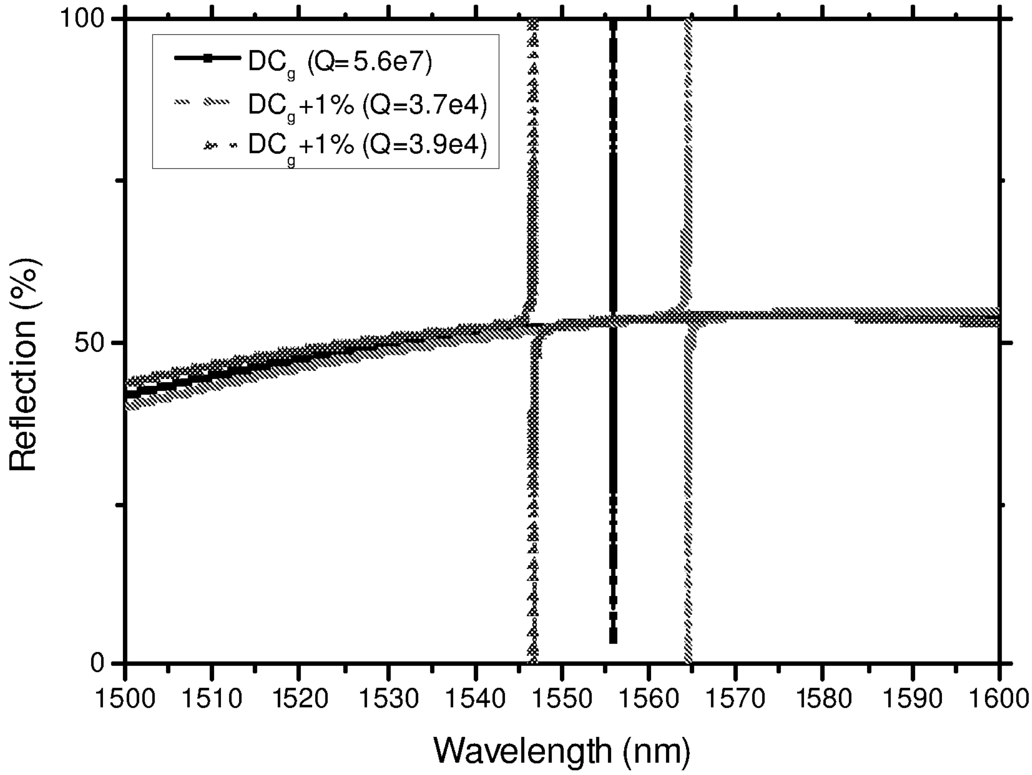
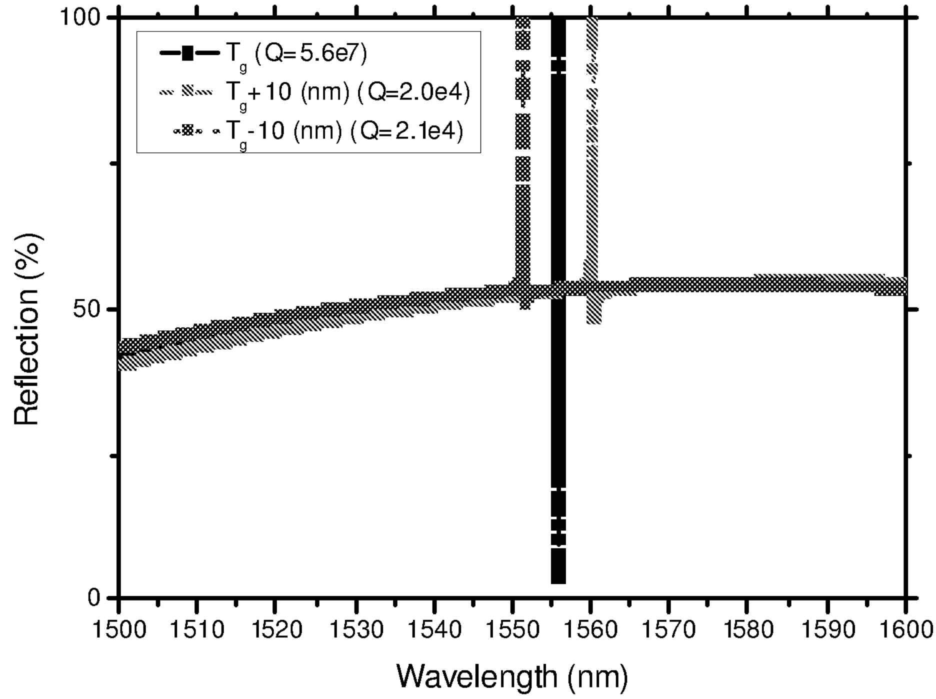
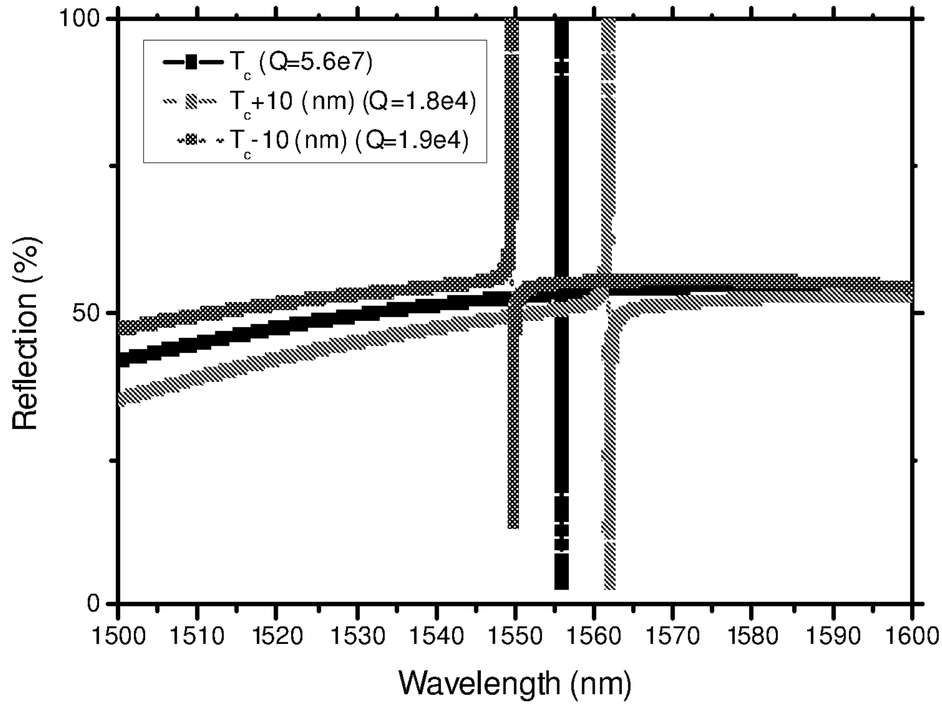

Reflection (%)
Wavelength (nm)
DC_g (Q=5.6e7)
DC_g+1% (Q=3.7e4)
DC_g+1% (Q=3.9e4)

Fig. 3D



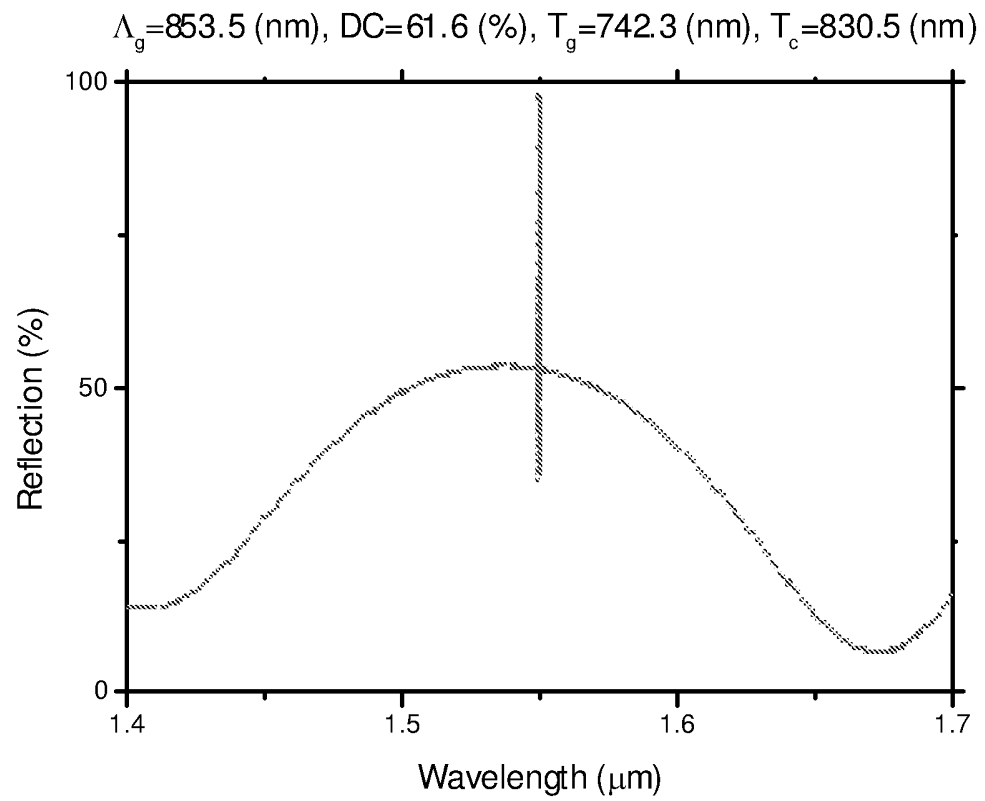
100
50
0
Reflection (%)
1500 1510 1520 1530 1540 1550 1560 1570 1580 1590 1600
Wavelength (nm)
T g (Q=5.6e7)
T g+10 (nm) (Q=2.0e4)
T g-10 (nm) (Q=2.1e4)

Fig. 3E



100
50
0
Reflection (%)
1500 1510 1520 1530 1540 1550 1560 1570 1580 1590 1600
Wavelength (nm)
T c (Q=5.6e7)
T c+10 (nm) (Q=1.8e4)
T c-10 (nm) (Q=1.9e4)

Fig. 3F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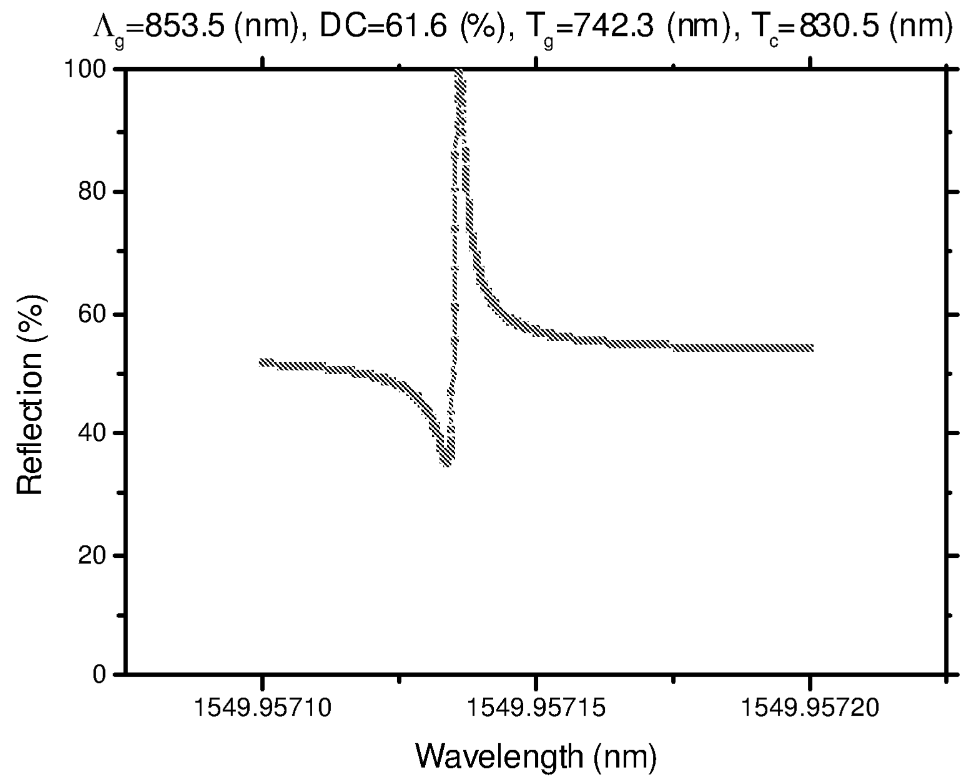
100
50
0
Reflection (%)
1.4
1.5
1.6
1.7
Wavelength (μm)

Fig. 3G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100
80
60
40
20
0
Reflection (%)
1549.95710
1549.95715
1549.95720
Wavelength (nm)

Fig. 3H

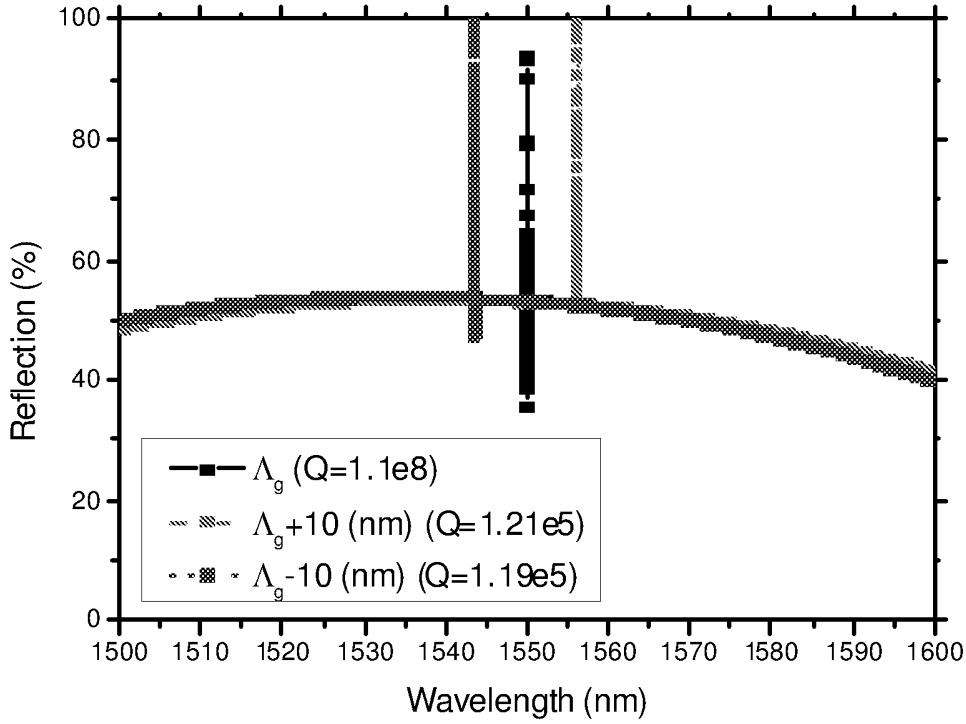

100
80
60
40
20
0
Reflection (%)
1500 1510 1520 1530 1540 1550 1560 1570 1580 1590 1600
Wavelength (nm)
Λg (Q=1.1e8)
Λg+10 (nm) (Q=1.21e5)
Λg-10 (nm) (Q=1.19e5)

Fig. 3I

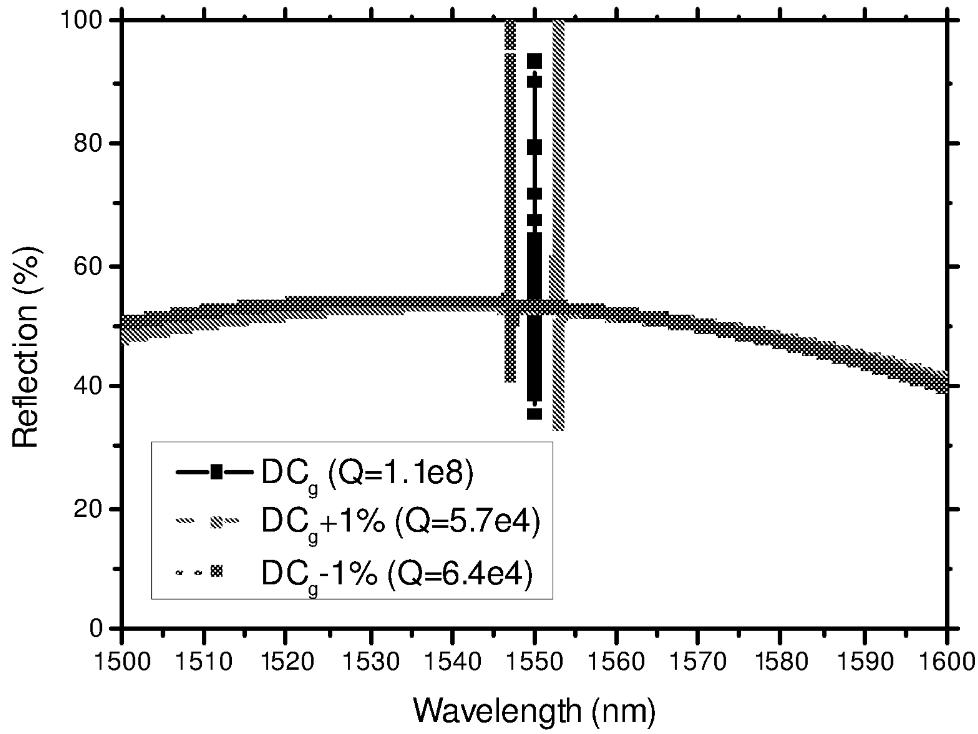

100
80
60
40
20
0
Reflection (%)
1500 1510 1520 1530 1540 1550 1560 1570 1580 1590 1600
Wavelength (nm)
DCg (Q=1.1e8)
DCg+1% (Q=5.7e4)
DCg-1% (Q=6.4e4)

Fig. 3J

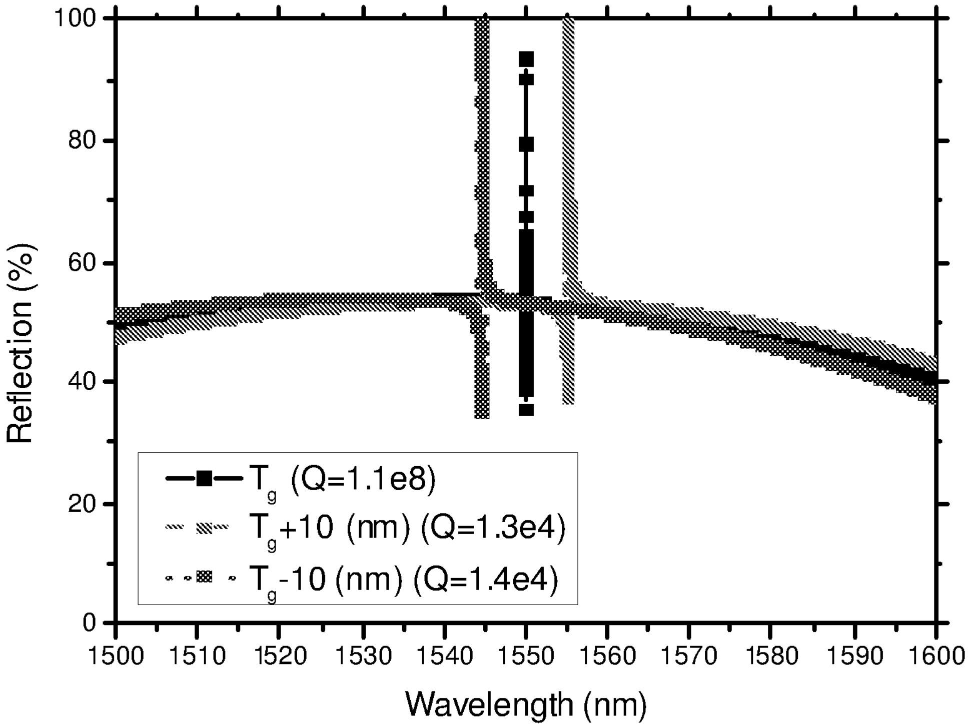

100
80
60
40
20
0
Reflection (%)
1500 1510 1520 1530 1540 1550 1560 1570 1580 1590 1600
Wavelength (nm)
T_g (Q=1.1e8)
T_g+10 (nm) (Q=1.3e4)
T_g-10 (nm) (Q=1.4e4)

Fig. 3K

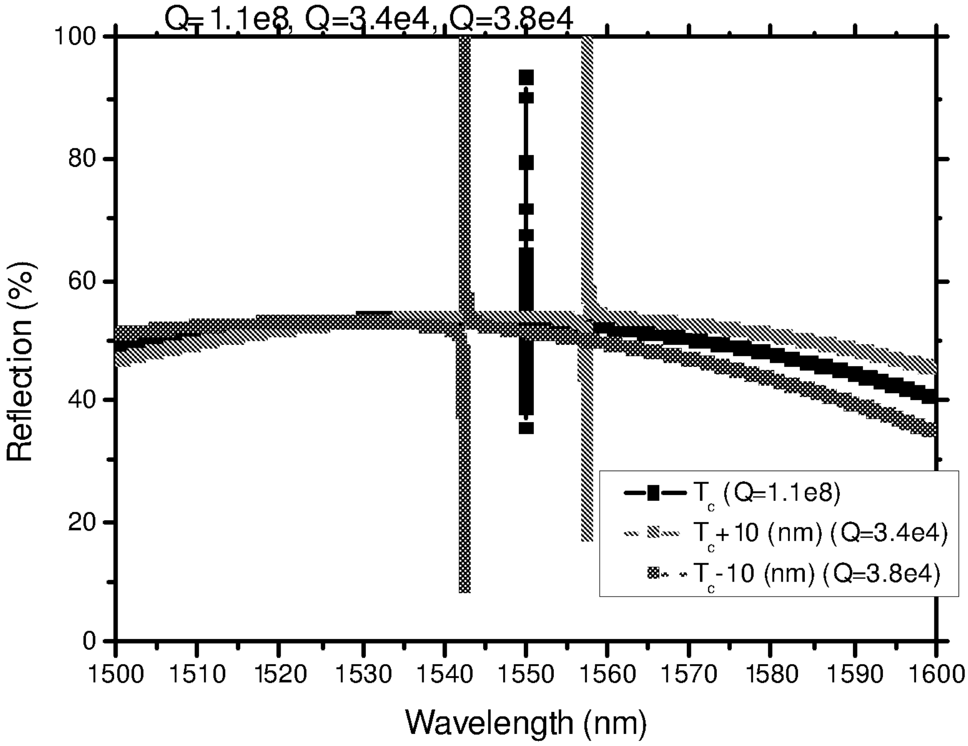

Q=1.1e8, Q=3.4e4, Q=3.8e4
100
80
60
40
20
0
Reflection (%)
1500 1510 1520 1530 1540 1550 1560 1570 1580 1590 1600
Wavelength (nm)
T_c (Q=1.1e8)
T_c+10 (nm) (Q=3.4e4)
T_c-10 (nm) (Q=3.8e4)

Fig. 3L

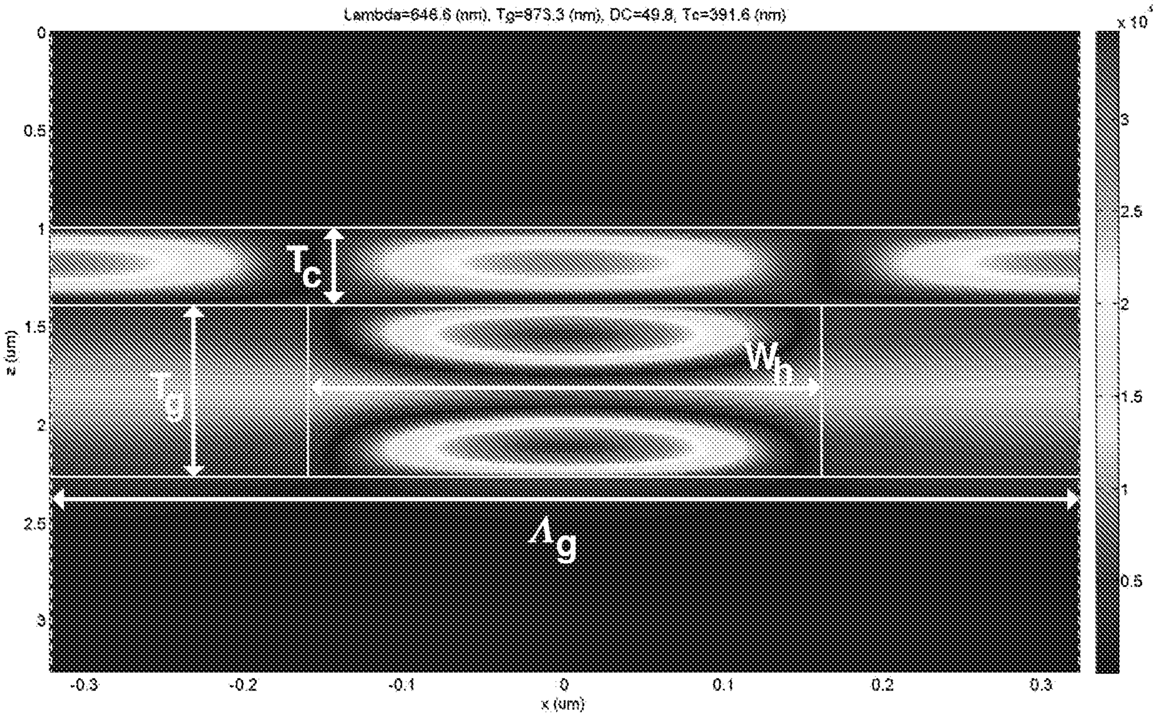

Lambda=646.6 (nm), Tg=873.3 (nm), DC=49.8, Tc=391.6 (nm)
z (um)
x (um)
Tc
Tg
Wh
Λg
x 10

Fig. 4A

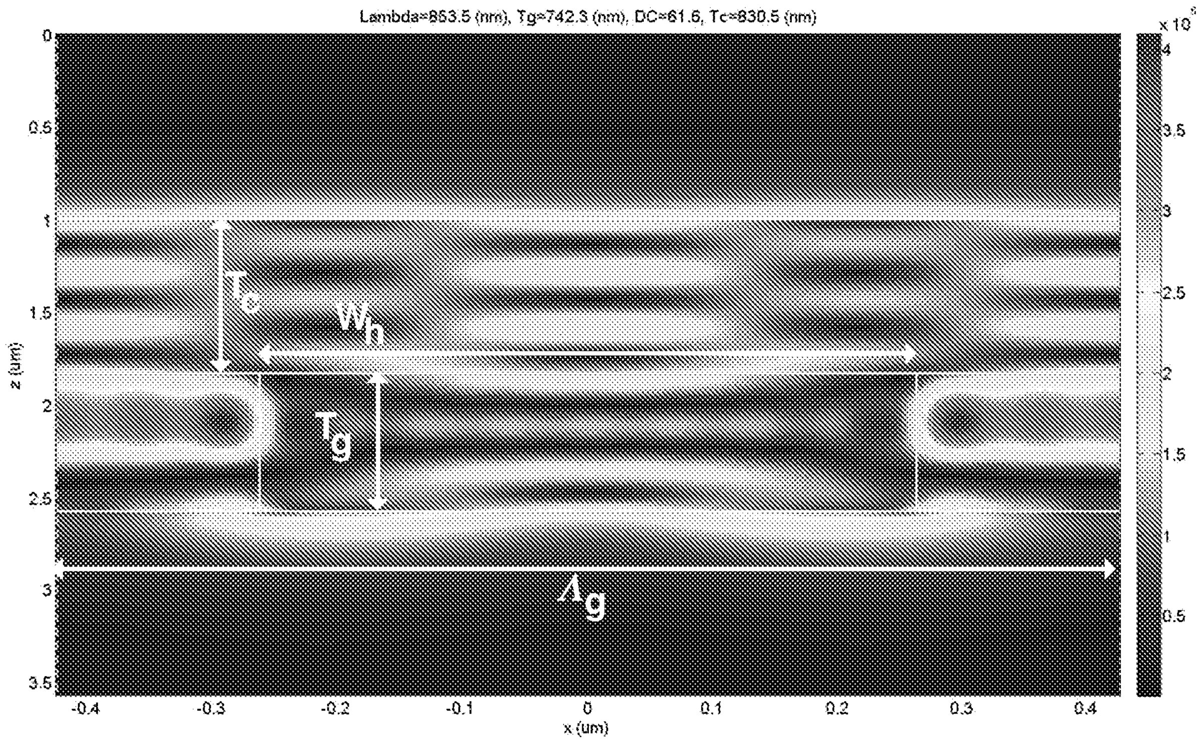

Lambda=853.5 (nm), Tg=742.3 (nm), DC=61.6, Tc=830.5 (nm)
z (um)
x (um)
Tc
Tg
Wh
Λg
x 10

Fig. 4B

Figure 5A

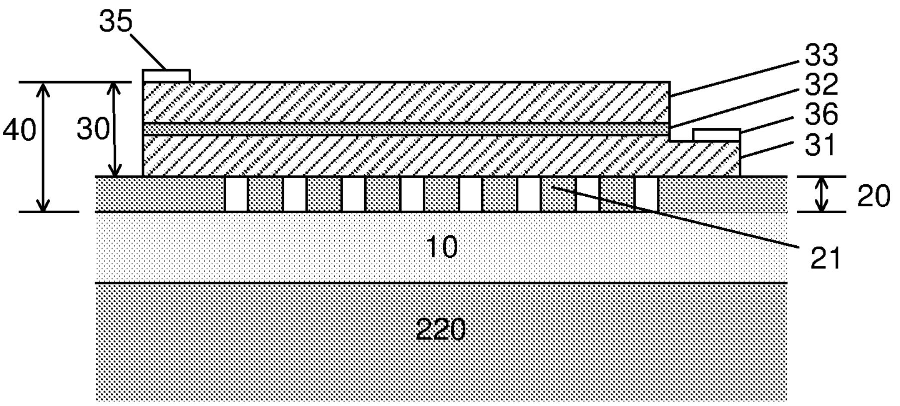
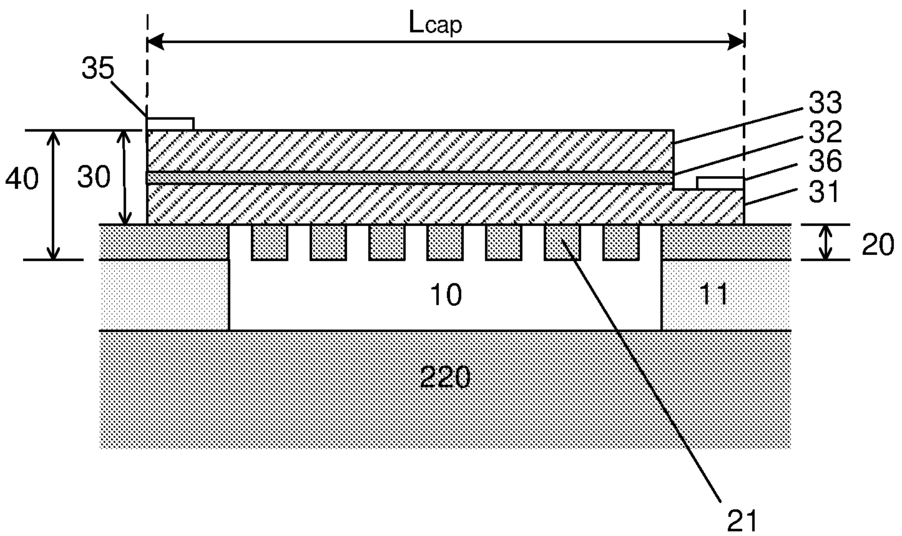


Figure 5B



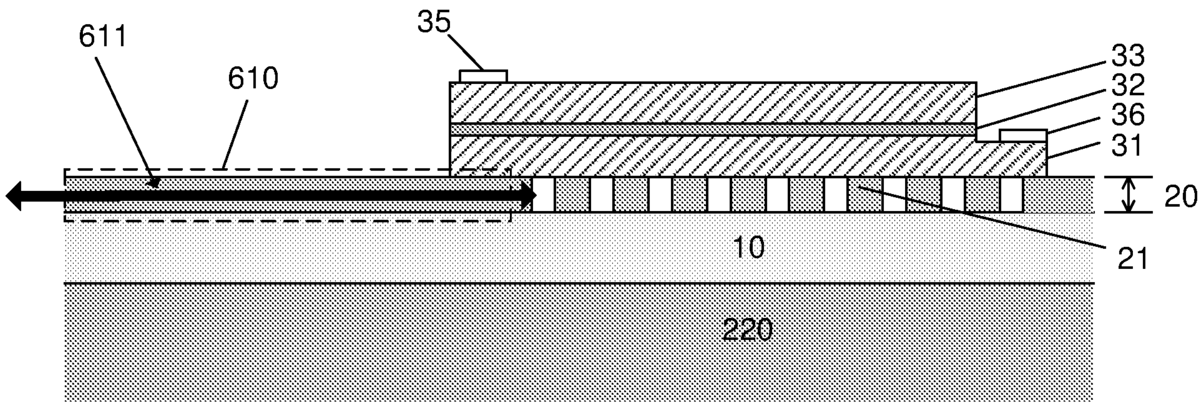


Fig. 6A

Figure 6B

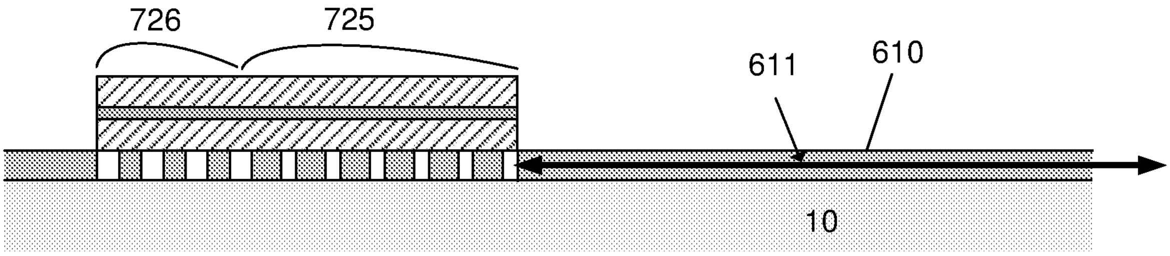


Figure 7A

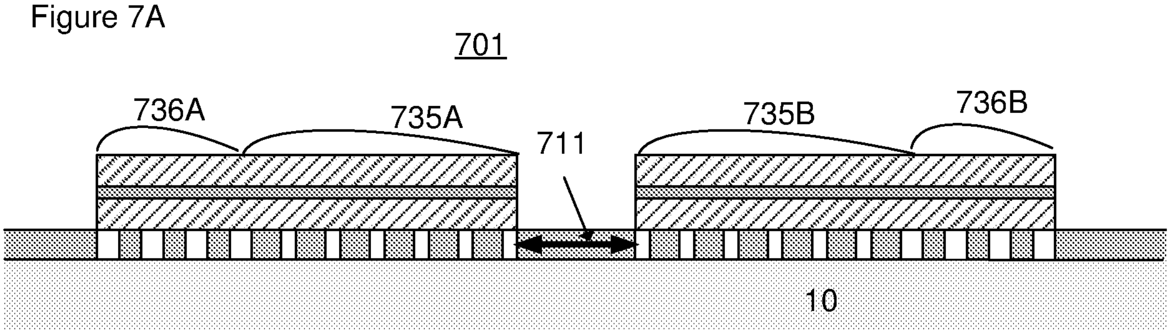


Figure 7B

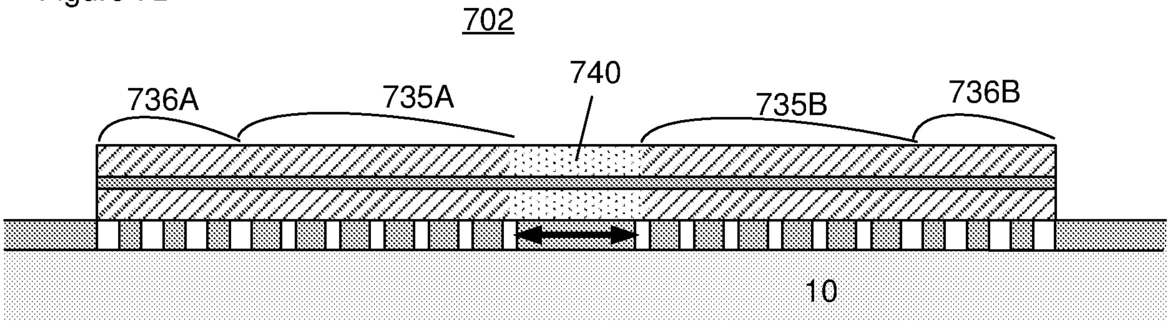
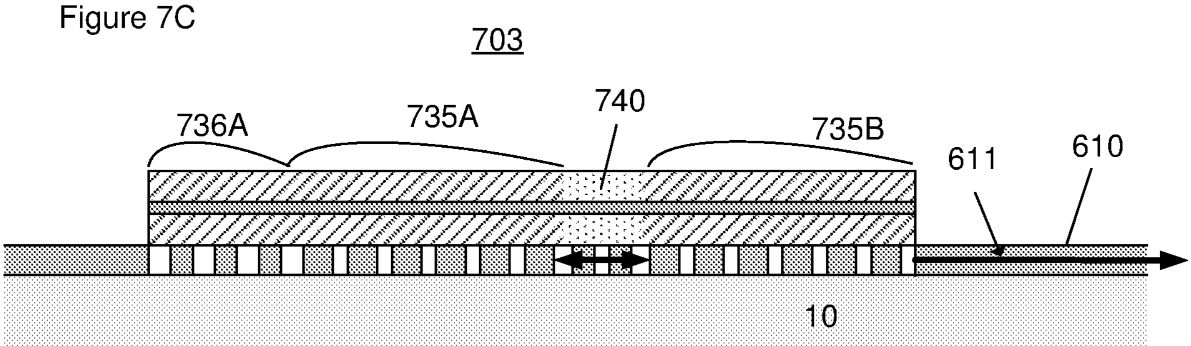


Figure 7C



INTERNATIONAL SEARCH REPORT

International application No
PCT/DK2016/050132

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01S5/042 H01S5/10 H01S5/125 H01S5/20
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01S

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)

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2010/091688 A1 (UNIV DANMARKS TEKNISKE [DK]; CHUNG IL-SUG [DK]) 19 August 2010 (2010-08-19) abstract; figure 8	1-14
A	US 2011/158278 A1 (KOCH BRIAN R [US]) 30 June 2011 (2011-06-30) cited in the application the whole document	1-14

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
5 August 2016	16/08/2016

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Lendroit, Stêphane

1

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	GYEONG CHEOL PARK ET AL: "Hybrid vertical-cavity laser with lateral emission into a silicon waveguide", LASER & PHOTONICS REVIEWS, vol. 9, no. 3, 10 April 2015 (2015-04-10), pages 11-15, XP055223167, DE ISSN: 1863-8880, DOI: 10.1002/lpor.201400418 the whole document -----	1-14
A	VADIM KARAGODSKY ET AL: "Novel inverse-tone High Contrast Grating reflector", CONFERENCE ON LASERS AND ELECTRO-OPTICS (CLEO) AND QUANTUM ELECTRONICS AND LASER SCIENCE CONFERENCE (QELS), 2010 : 16 - 21 MAY 2010, SAN JOSE, CA, USA, IEEE, PISCATAWAY, NJ , USA, 16 May 2010 (2010-05-16), pages 1-2, XP031701185, ISBN: 978-1-55752-890-2 the whole document -----	1-14

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/DK2016/050132

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2010091688 A1	19-08-2010	AU 2010213223 A1	01-09-2011
		CN 102388513 A	21-03-2012
		EP 2396861 A1	21-12-2011
		JP 2012517705 A	02-08-2012
		KR 20110126661 A	23-11-2011
		US 2012008658 A1	12-01-2012
		WO 2010091688 A1	19-08-2010
US 2011158278 A1	30-06-2011	CN 102142656 A	03-08-2011
		TW 201140977 A	16-11-2011
		US 2011158278 A1	30-06-2011
		US 2013208752 A1	15-08-2013
		WO 2011090573 A2	28-07-2011

Form PCT/ISA/210 (patent family annex) (April 2005)