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(54) Title: PHASE-SHIFTED FIBER BRAGG GRATING SENSOR AND METHOD FOR PRODUCING SAME

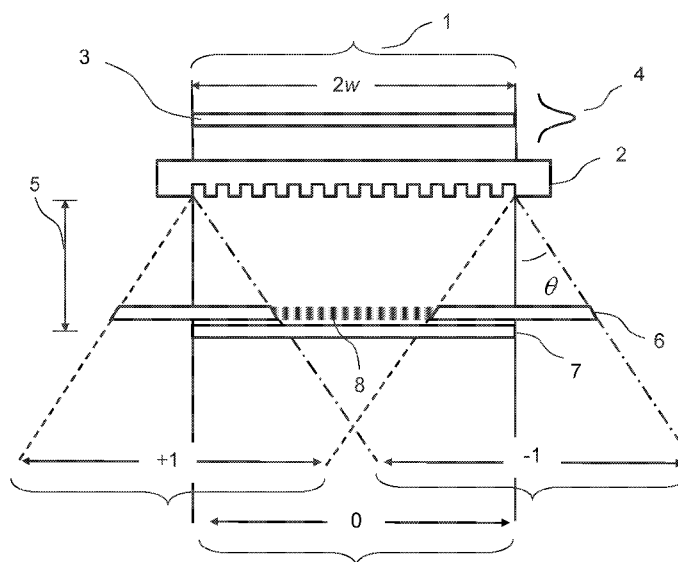
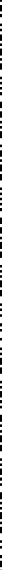


Fig. 1a

(57) **Abstract:** T-phase-shifted fiber Bragg gratings in optical waveguides, and methods of formation thereof. Sensing apparatus comprising such gratings using femtosecond pulse duration lasers and specialized transmission diffraction elements or phase masks.

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Phase-shifted fiber Bragg grating sensor and Method for Producing Same

Field of the Invention

5 The present invention relates to methods for the formation of T-phase-shifted fiber Bragg gratings in optical waveguides and to sensing apparatus comprising such gratings using femtosecond pulse duration lasers and specialized transmission diffraction elements or phase masks. Such sensors can be used for measurement of pressure, strain, temperature, or displacement or index of refraction. Advantageously said sensors, when fabricated in silica
10 based waveguides, can also be made to have high thermal stability, for example up to 1000 °C.

Background of the Invention

Fiber Bragg grating (FBG) sensors are attractive devices for performing quasi-distributed
15 temperature and strain measurements along an optical waveguide (e.g. optical fiber). The grating structure acts as a band-rejection optical filter passing all wavelengths of light not in resonance with it and reflecting those that satisfy the Bragg condition of the core index modulation, namely:

$$A_B = 2n_{\text{eff}}A_G \quad (1)$$

20 where A_B is the FBG Bragg resonance or Bragg wavelength, n_{eff} is the effective refractive index seen by the guided mode of light propagating down the fiber, and A_G is the period of the index modulation that makes up the grating. Variations in the spectral response of the grating result from period changes in the Bragg grating due to strains or temperature variations that are experienced by the optical fiber when placed in a specific environment.
25 These FBG sensors offer important advantages over other sensor technologies because of

their electrically passive operation, electromagnetic interference (EMI) immunity, high sensitivity and multiplexing

capabilities. Fiber Bragg gratings are simple, intrinsic sensing elements which traditionally have been photo-inscribed into photosensitive Ge-doped silica fiber using high power UV

5 laser sources. Each FBG sensor has a characteristic retro-reflective Bragg resonance or Bragg resonance wavelength, which is dependent upon the periodicity of the grating photo-inscribed within the fiber and the effective refractive index n_{eff} , of the fundamental core mode of the optical fiber. The FBG sensors can then easily be multiplexed in a serial fashion along a length of single fiber to produce a quasi-distributed optical fiber sensor array. When
10 embedded into composite materials, optical fibers with an array of FBG sensors allow for distributed measurements of load, strain, temperature and vibration of the material creating what has is commonly referred to as “smart structures” where the health and integrity of the structure is monitored on a real-time basis.

By introducing a T-phase shift (see the Detailed Description of the Invention) in the

15 periodicity of the grating, in the center along the grating length, a very narrow transmission peak can be produced within the spectral stopband of the Bragg resonance which causes the grating to behave like a Fabry-Perot resonator. Due to this special spectral passband feature, phase-shifted FBGs are widely used in distributed-feedback fiber lasers as taught by

Kringlebotn, et al. in US Patent 5,771,251, hereby included as reference. As well phase-shifted

20 FBGs written into passive UV sensitive optical fibers have been used as multiparameter optical sensors as taught by Ronnekleiv et al. in US Patent 6,888,125.

Typically, fiber Bragg gratings are generated by exposing the UV-photosensitive core of a germanium doped silica core optical fiber to a spatially modulated UV laser beam in order

to create permanent refractive index changes in the fiber core. Such a spatially modulated UV beam can be created by using a two-beam interference technique as disclosed in US patent

number 4,807,950 by Glenn et al. or by using a phase mask as disclosed in US patent

5 number 5,367,588 by Hill et al. The techniques taught by Glenn and Hill result in gratings that are typically referred to as Type I gratings.

Formation of a phase shift in the Bragg grating can be performed by inscribing the grating with a specialized transmission diffraction grating called a phase mask that incorporates the phase
10 shift in the mask pattern as demonstrated by Kashyap et al. in Electronics Letters **30** (21), pg. 1977 (1994). The phase shift in the Bragg grating can also be created by performing a post exposure in the center of a uniform FBG as taught by Canning and Sceats in US patent 5,830,622 or by precisely displacing a uniform pitched phase mask with respect to the optical waveguide during FBG inscription as taught by Cole et al. in US Patent 6,072,926. A
15 limitation of the phase shifted phase mask approach taught by Kashyap, is the issue phase shift splitting that occurs in the interference pattern used to generate the Bragg grating. Trembley and Sheng showed in article published in the Journal of the Optical Society of America B **23** (8), 1511 (2005) that the phase shift splitting easily results in spectral asymmetry errors and shifting of the transmission passband of phase shifted Bragg grating that are undesirable from
20 a sensing perspective.

A limitation of the prior-art UV-induced Type I phase-shifted fiber Bragg gratings, especially for high temperature sensor applications, is that operation of the sensor at elevated temperatures results in the removal or annealing of the UV-induced color centers and

densification which are responsible for the induced index change of the grating. In fact, at temperatures approaching the glass transition temperature of the fiber, which for silica is approximately 1300 °C, total removal of the induced index modulation results.

The fabrication of high temperature stable Bragg gratings using infrared ultrafast radiation and a phase mask, as taught by Mihailov et al in US. Pat. No. 6,993,221 results in high temperature stable Bragg gratings with very high index modulations ($\Delta n > 10^{-3}$). Phase-shifted FBGs can be fabricated using infrared (IR) femtosecond (fs) lasers. The primary technique that has been demonstrated is based on point-by-point/line-by-line writing, as shown by G.D. Marshall et al. in Optics Express **18**(19), 19844-19859 (2010). More recently, adaptation of the technique taught by Cole et al. in US Patent 6,072,926 but applied using an infrared femtosecond source to produce a phase-shifted FBG was shown by Bernier et al Optics Letters **40**(1), 81-84 (2015). Similarly adaption of the technique taught by Canning and Sceats in US patent 5,830,622 but applied using an infrared femtosecond source to produce phase-shifted FBGs was demonstrated by He et al. in Optics Letters **40** (9), 2008-2011 (2015). The techniques of point-by-point exposure or precision uniform phase mask translation require precision translation stages with spatial resolutions in the nanometer range that are often expensive. Post exposure introduces an extra processing step. From a manufacturing perspective it is also difficult to reproduce identical structures using these approaches.

Another important advantage of using a femtosecond laser source is that one is not limited to fabricating Bragg gratings in optical fibers or waveguides that are only photosensitive to UV light, which is typically Germanium doped silica glass. The multiphoton nature of the induced index change process, as taught by Mihailov et al in US. Pat. No. 6,993,221, can be applied to

any material that is transmissive to the femtosecond radiation, such as for example pure silica glass, or crystalline sapphire.

Recently Du et al. in IEEE Photonics Technology Letters **29**(24) 143-146 (2017)

demonstrated that a fiber Bragg grating-based Fabry-Perot etalon could be fabricated by

5 blocking the central portion of the fs-laser beam during exposure of a uniform pitched phase mask. Spectrally the Fabry-Perot etalon is similar to that of a phase shifted grating however the bandwidth of the

passband feature of the phase shifted grating is narrower and the centralization of the passband within the stop band defined by the etalon is difficult to achieve. As indicated by Wu et al in
10 Optics Express **20** (27), 28353-28356 (2012), optimization of a phase shifted grating as a sensor, relies on maximizing the amplitude of the transmission of the passband with respect to the transmission of the stopband and on the steepness (bandwidth) of the passband. This occurs when the passband is centralized within the stopband producing a symmetric spectral response.

15 When a single phase-shifted FBG structure is written into an actively doped optical fiber such as an erbium doped optical fiber, a distributed feedback laser (DFB) is formed as first demonstrated by Loh and Laming in Electron. Lett. **31** (17), 1440 (1995). Similarly a dual Bragg grating laser forming a distributed Bragg reflector fiber laser (DBR) is also possible. An advantage of applying the IR femtosecond laser/phase mask inscription method is that DFB fiber
20 lasers are not limited to UV-photosensitive active fibers but can be fabricated in any actively doped waveguide substrate that is transparent to the IR radiation. Recently Bernier et al Optics Letters **40**(1), 81-84 (2015) demonstrated a DFB fiber laser in Holmium doped ZBLAN fluoride glass fibers where the Bragg grating was written by scanning femtosecond IR radiation along a

uniform phase mask that was precision translated half way through the scanned. The method presented here by the inventors could reproducibly fabricate similar DFB fiber lasers without the need of expensive precision translation equipment.

- 5 There still remains in this field of art the need for phase shifted fiber Bragg grating sensors that can be made in non-UV photosensitive fibers, are thermally stable, and can be easily manufactured to have a symmetric spectral response and narrow bandwidth passband.

Summary of the invention

- 10 In one aspect, there is provided a method for inscribing a phase shifted Bragg grating in an optical waveguide, comprising the steps of: providing the optical waveguide; providing electromagnetic radiation from an ultrashort pulse duration laser, wherein the electromagnetic radiation has a pulse duration of less than or equal to 5 picoseconds, and wherein the wavelength of the electromagnetic radiation has a characteristic wavelength in the wavelength
- 15 range from 150 nm to 2.0 microns; providing a diffractive optical element which incorporates a phase shift that when exposed to the ultrashort laser pulse, creates an interference pattern on the optical waveguide which has a phase shift in its pattern , wherein the irradiation step comprises irradiating a surface of the diffractive optical element with the electromagnetic radiation, the electromagnetic radiation incident on the optical waveguide, from the diffractive
- 20 optical element, being sufficiently intense to cause the permanent change in index of refraction in the core of the optical waveguide. In one embodiment, the method further comprises a step of introducing a beam block to remove the effect of phase-shift splitting observed in grating structures written using phase shifted phase masks; irradiating the optical waveguide with the electromagnetic radiation to form a Bragg grating, the electromagnetic radiation incident on

the optical waveguide being sufficiently intense to cause a permanent change in an index of refraction within a core of the optical waveguide when exposed to a succession of laser pulses.

In another aspect, there is provided an optical waveguide with an inscribed Bragg grating prepared according to the method as described herein.

- 5 In still another aspect, there is provided an optical waveguide with an inscribed Bragg grating, wherein: the Bragg grating is stable at a temperature up to the glass transition temperature of the optical waveguide;

In the present application, references to “a permanent change in an index of refraction within a core of the optical waveguide” represents the formation of a grating that is stable at higher
10 temperatures, for example at a temperature up to just below the glass transition temperature of the material forming the optical waveguide being inscribed with the grating. This is also referred to herein and in the art as a type II grating. In one embodiment, where the waveguide is a silica based fiber, a permanent change in an index of refraction within a core of the optical waveguide is one which is stable at temperatures of up to 1000°C. In other embodiments,
15 where the optical waveguide comprises a different material (e.g. crystalline sapphire), the temperature may be higher than 1000°C.

In the present application, references to a “non-permanent grating” refer to gratings that are not stable to high temperatures, and that can be substantially removed by heating the optical waveguide. These are also referred to herein and in this field of art as type I gratings. In one
20 embodiment, a non-permanent grating is one which is substantially removed by heating at temperatures of up to 1000°C. In some embodiments, the non-permanent gratings are substantially erased at temperatures lower than 1000°C, for example 800°C.

Description of the drawings

Fig. 1a depicts the order walk off effect from a uniform phase mask of diffracted femtosecond pulses.

5 Fig. 1b depicts the idealized case of the spatially generated interference pattern produced by the overlap of the +1 and -1 orders of the diffracted femtosecond beams from a uniform pitched phase mask.

Fig. 1c depicts the complex interference field produced by the diffracted beams resulting from a uniform pitched phase mask with a $\lambda/4$ phase shift (i.e., 'T-phase-shifted' phase mask, see
10 the text) introduced in the centre of its periodic structure.

Fig 2 depicts the measured interference field produced by a $1.07\ \mu\text{m}$ pitched phase mask with a $\lambda/4$ phase shift introduced in the centre of its periodic structure.

15 Fig. 3 presents a modeled asymmetric spectrum of a phase shifted Bragg grating written without the inventive correction.

Fig. 4 depicts the complex interference field produced when the phase shift of the mask is blocked.

Fig. 5 depicts the modeled spectral response of the grating written in the geometry of Fig. 4 where the Fabry-Perot cavity comprises two gratings in the fiber of arbitrary interstitial distance but
20 with the second grating periodicity T degrees out of phase with the periodicity of the first grating.

Fig. 6 is the measured spectrum of a fiber Bragg grating written with a T-phase-shifted phase mask.

Fig. 7 is the measured spectrum of a fiber Bragg grating written with a T-phase-shifted phase mask identical to the result in Fig. 6 but with phase-shifted region blocked.

Fig. 8 is the spectral response of a phase shifted grating written using the inventive method where
25 the birefringence is maximized by inscribing the grating with the femtosecond beam polarization

normal to the fiber axis.

Fig. 9 is the spectral response of a phase shifted grating written using the inventive method where the birefringence is minimized by inscribing the grating with the femtosecond beam polarization parallel to the fiber axis.

5 Fig. 10 is an expanded view of the passband peak presented in Fig. 9.

Fig 11a) is the spectral responses of phase shifted grating at room temperature and at 1000 °C written using the inventive method

10 Fig. 11b is the wavelength shift of the central passband within the stopband structure of the grating spectrum as a function of annealing time at 1000 °C.

Fig 12 is a schematic representation of a chemical sensor comprising a T-phase shifted FBG inscribed in a tapered fiber by the described method that is coated with sensing layer that transduces absorption of a chemical analyte into a wavelength shift of the spectral response of the FBG.

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Detailed description of the invention

It is an object of this invention to provide for fabrication of high temperature stable phase shifted FBG sensors. As taught by Mihailov et al. in US patent 7,031,571, femtosecond pulses interact differently with a transmission diffraction grating or phase mask when compared to continuous wave (CW) UV sources. In Fig 1 a), the incident femtosecond beam **1** with a width $2w$, impinges on a uniformly pitched phase mask **2** at normal incidence. The femtosecond beam **1** is composed of a number of femtosecond light pulses **3** which have a spatial dimension or pulse envelope of the electromagnetic radiation **4** which is dependent on the pulse duration. For example a 100 femtosecond pulse has a width of its electromagnetic pulse envelope in the direction of the beam

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propagation that is 30 μm wide. On passing through the phase mask, the femtosecond beam **1** is split into a number of beams that is dependent upon the periodicity A of the corrugation structure of the mask and the wavelength λ of the femtosecond beam such that:

$$\theta = \sin^{-1}\left(\frac{m\lambda}{A}\right) \quad (2)$$

where m is the order number of the diffracted beam. For example, a phase mask that has a nominal periodicity of 1.071 μm when irradiated with 800 nm infrared radiation at normal incidence will produce 3 femtosecond beams related to the diffracted orders of the mask, namely a 0 order that is in line with the incident beam and +1 and -1 orders that diffract with angles $\theta \sim \pm 48^\circ$ with respect to the normal to the mask. By optimizing the depth of the troughs of the corrugation pattern of the mask with respect to the wavelength of the irradiating beam, coupling of the incident beam energy into the ± 1 orders can be maximized. At the phase mask surface, the generated pulses in each of the diffracted orders overlap spatially. The pulses propagate away from the surface at the speed of light along the beam path defined by the diffracted order. At a given distance **5** from the phase mask, the projection of the propagating ± 1 orders **6** on to the normal of the mask no longer overlap with the 0 order **7**. Only the portions of the ± 1 orders that overlap interfere resulting in a sinusoidal interference pattern **8**. This is the order walk-off effect taught by Mihailov in US Patent 7,031,571. For the example of the 1.071 μm pitched phase mask irradiated with 100 femtosecond pulse duration 800 nm infrared radiation, the walk-off distance **5** is $\sim 90 \mu\text{m}$ from the mask surface. Interference patterns produced with fs-pulses and a uniform phase mask are well-studied both theoretically and experimentally. In Fig. 1b) consider an ideal situation when the mask **2** splits the incident light only into +1 and -1 diffraction orders **9** and **10** respectively. A pure two-beam interference pattern is then formed in region **11**, whereas the intensity distribution is fringeless in regions **12** and **13**. It can also be seen that the intensity

distribution at the fiber **14** will be strongly affected by both the effective width $2w$ of the fs-beam at **2** (e.g., the diameter at the $1/e^2$ intensity level for a fs-beam with a Gaussian intensity profile) and the mask-to-fiber distance **15**.

Now we consider a uniform phase mask containing a phase-shift. The introduction of a single phase-shift into a uniform phase mask can be thought of as cutting it into two (equal) sections and then either i) inserting an additional section of length o between the two sections or ii) removing material of length o between the two sections and then stitching them together. A 'T-phase-shifted mask' is defined as a uniform phase mask one half of which is shifted with respect to the other by

$5/4$ of the mask period A_M , i.e., $o = A_M/4$. The 'T-shift' terminology originates from the fact that a phase shift with $o = A_M/4$ in the middle of a uniform phase mask causes a phase-shift of $2\pi\delta/(A_M/2) = \pi$ in the resultant FBG, whose period A_G is $A_M/2$ by definition.

In Fig 1c) a T-phase step **16** is introduced into the corrugation pattern of the mask **2**. The interference pattern produced after the mask becomes more complicated compared with the one presented in Fig. 1(b). The +1 diffraction order of **2** to the right of the phase shift **16** (denoted by dots) and the -1 diffraction order of **2** to the left of the phase shift (denoted by divots) can now generate an additional interference fringe system within region **11** of Fig. 1b), which divides it into three sub-regions **17**, **18**, and **19**. The interference fringes within sub-region **18** are shifted with respect to the fringes in the left and right triangular sub-regions by $T/2$, i.e., by a quarter of the fringe period. The boundaries of the sub-regions are defined by the mask **2** and the diffraction angle δ . When the fiber **14** intercepts all of the three sub-regions **17**, **18** and **19**, the light-imprinted structure inside it will consist of three grating sections with a $T/2$ -shift between the adjacent

sections. The length of the central section overlapping **18** and each of the two side sections overlapping **17** and **19** respectively, can be approximated by $2L\tan(\delta)$ and $w-2L\tan(\delta)$, respectively, provided that the fiber **14** is aligned along the x -axis **20**, where L is the distance between the mask and the fiber core **15**.

5 Figure 2 presents the measured xz -intensity distribution (axes **20** of Fig 1c) of the femtosecond pulses after a T-phase-shifted phase mask with a $1.07\ \mu\text{m}$ pitch. The phase mask surface occurs at $z = 0$. Figure 2 presents the intensity distribution in the vicinity of the T-shift at $x = 0$. To produce the images, the respective xy -intensity distributions with a $1\ \mu\text{m}$ separation along the z -axis were projected onto a CMOS matrix by means of a high numerical aperture (i.e., $\text{NA} = 0.9$)
10 objective lens, recorded and combined into 3D stacks as taught by Hnatovsky et al. in Optics Express **25**

(13), 14247 (2017). The values of points with fixed (x_i, z_i) coordinates were then averaged along the y -axis and the respective mean values projected onto the xz -plane in order to minimize the ~10-times difference in brightness between the intrafocal and out-of-focus regions along the z -axis. The three sub-regions **17**, **18** and **19** denoted in Fig. 1 c) are similarly labeled in Figure 2. The most salient feature of the intensity distribution in Fig. 2 is the pronounced V-shaped region whose apex coincides with the T-shift. The angle at the apex is estimated at $90\text{-}95^\circ$. This value is close to twice the diffraction angle $\theta = \sin^{-1}(\lambda/d)$ corresponding to $\lambda = 800\ \text{nm}$ and $d = 1.07\ \mu\text{m}$, as predicted by Sheng et al. in Optics Express **13** (16), 6111 (2005). The clear Talbot interference
20 pattern observed in Fig. 2, especially at $z < 50\ \mu\text{m}$, is caused by the presence of the 0^{th} diffraction order shown in Fig. 1a, which was neglected in the discussion regarding Fig 1 b), and c). In reality, the 0^{th} order always contains a certain portion of the incident laser power, albeit it can be as low as 1% for state-of-the-art holographic masks. As a consequence, the contrast of the Talbot pattern

generated by a 1st-order mask depends on the ratio of laser powers diffracted into the 1st and 0th order and the longitudinal walk-off of the orders. This power ratio can be varied within a broad range by selecting the mask design, but for a given design it will also be affected by the pulse polarization. The image in Fig. 2 was obtained using the pulse polarization of the ultrafast beam aligned along the x -axis.

The presence of the central section **18** causes an asymmetry in the FBG spectra. The passband features in the spectra are shifted to shorter wavelengths from the center of the stopband. A detailed analysis of why the T-features in the spectra are shifted to shorter wavelengths is provided by Tremblay and Sheng in the J. Opt. Soc. Am. B **23**(8), 1511 (2006).

Using this approach, Figure 3 presents a modeled spectral response for the case depicted in Fig. 1 c) where L (**15**) = 0.5 mm, and the length of sections **17**, **18** and **19** are 2.4 mm, 1.1 mm and 2.4 mm respectively. The mask pitch A_M is 1.07 μm , the effective refractive index of the fiber core n_{eff} is 1.447, the light-induced refractive index modulation in the core Δn is 5×10^{-4} . The passband peak in the spectrum, **31**, is shifted to shorter wavelengths from the center of the stopband. This produces an asymmetric spectral response where the stopband lobes on either side of the passband are unequal in transmissivity, which is undesirable for phase shifted grating sensor.

The inventors have found that for the 3 sub-gratings written by regions **17**, **18** and **19** of Fig. 1 c), the amplitude of the wavelength shift of the passband to shorter wavelengths is dependent upon the length of the central grating created by **18** hence the fiber-phase mask distance **15**. To reduce the passband shift to lower wavelengths, the contribution of the central grating can be minimized. This can be accomplished by making the central grating short relative to the side gratings, which can be achieved, for instance, by expanding the beam along the fiber to increase

$2w$, minimizing L , and using a higher order phase mask (e.g., a 3rd-order mask instead of a 1st-order mask) to decrease θ . However, it is not easy to make L small and avoid the use of a 1st-order mask under certain conditions. For example, to fabricate FBGs through the protective polymer coating of the fiber, it is physically impossible to reduce the distance between the fiber core and phase mask to less than $\sim 100 \mu\text{m}$ (the diameter of standard telecom fibers coated with polyimide and acrylate are

$\sim 150 \mu\text{m}$ and $\sim 250 \mu\text{m}$, respectively). Moreover, in order to protect the mask from a mechanical contact with the fiber it is desirable that the distance between the coated fiber surface and the mask be more than $100 \mu\text{m}$, which would make L greater than $200 \mu\text{m}$. Additionally, 1st-order masks, which have large first order diffraction angles θ_s , are generally preferred in order to produce a pitch consistent with the fundamental Bragg resonance within the fiber.

Figure 4 presents an embodiment of the inventive method where the central sub-grating is removed. The central part of the fs-beam can be obscured by a rectangular stop **21** of width $2s$, as shown in Fig. 4. In this case, the additional interference fringe system due to the sub-region **18** of Fig. 1c) can be moved away from the mask. A phase-shifted Fabry-Pérot interferometer composed of two detached Bragg gratings can then be inscribed into the fiber by choosing a proper mask-to-fiber distance L (**15**). The resulting two Bragg gratings will always be T-shifted with respect to each other because they are produced by interference patterns that are T-shifted by definition (the fringes are 'affixed' to the mask). It can be shown using numerical simulations that such a fiber interferometer will spectrally resemble a standard T-shifted FBG if the separation between the two constituting FBGs, which is given by $2(s+L\tan(\delta))$, remains smaller than their length, which is respectively given by $w-s-2L\tan(\delta)$. Figure 5 presents a simulated spectrum of the phase-shifted Fabry-Pérot interferometer where the mask pitch d is $1.07 \mu\text{m}$, the effective

refractive index of the fiber core n_{eff} is $= 1.447$, the light-induced refractive index modulation in the core Δn is 5×10^{-4} . The passband **51** is centered within the stopband. The mask-to-fiber distance L (**15**) of Fig. 3 is 0.25 mm and $2s = 1$ mm. The beam width **1** used for the simulation in Fig. 3 is 7 mm in width (i.e., $2w$) and is a quasi-flat-top.

Strictly speaking, for the above consideration to be valid, one has to assume that n_{eff} is not affected by the inscription process. In reality, n_{eff} in the laser-irradiated regions and the unexposed portions of the fiber is different, which also causes an asymmetry in the FBG spectrum. If n_{eff} in the irradiated regions is higher/lower than that in the unexposed fiber core, the passband feature moves towards shorter/longer wavelengths within the FBG spectrum.

Figure 6 and Figure 7 present spectral responses of phase shifted FBGs that are made with a T- phase-shifted phase mask without and with the invented method to correct for the asymmetry in the grating spectrum. The mask pitch A_M is $1.07 \mu\text{m}$. The spectrum in Figure 6 is of an FBG written at $L \sim 450 \mu\text{m}$ when the fiber core was exposed to a complex interference pattern consisting of three regions (as given in the description for Fig. 1(c)). The spectrum in Figure 7 is of an FBG written at $L \sim 450 \mu\text{m}$ when the T-shift is blocked by a stop **21** (Fig. 4) with $2s \sim 1$ mm (as given in the description for Fig. 4). The FBG in Figure 7 becomes a T-shifted Fabry-Pérot interferometer composed of two detached uniform Bragg gratings. The laser parameters used to fabricate the gratings for Figure 6 and 7 are the same. The spectra were recorded using a tunable laser source with a 1 pm resolution

We note that, in principle, the above ‘beam-stop technique’ may also be used with standard uniform masks to produce a phase-shifted Fabry-Pérot interferometer if the unexposed region at the fiber core happens to introduce the correct phase shift between the two detached Bragg

gratings. Taking into account that in this case the phase shift critically depends on the length of the unexposed region, the latter has to be somehow adjusted to a fraction of a micrometer to produce a symmetric spectrum.

In another embodiment of the invention, the induced index change of the phase-shifted grating structure can be in the form of the well-known self-organized nanostructures (nanograting) as described by Taylor et al. in US Patent 7,033,519. Hnatovsky et al. demonstrated in Optic Letters 42 (3), 399 (2017) that nanogratings were found in Type II Bragg gratings produced in standard telecommunication germanium-doped silica optical fiber by side-illuminating it with multiple linearly polarized IR fs-laser pulses through a phase mask. Beresna et al. showed in Optical Materials Express 1 (4), 783 (2011) that the planar nanostructures, which are often referred to as nanogratings, are aligned perpendicular to the laser polarization and exhibit strong form birefringence. Form birefringence is observed in a periodically layered medium when the spacing between the layers is small compared with the wavelength of light. In this case the medium behaves as an optically uniaxial crystal whose optical axis is oriented perpendicular to the layers. The refractive index difference between the ordinary and extraordinary rays in fs-laser-induced nanostructures can be as high as 5×10^{-3} .

The spectral characteristics of a phase-shifted Bragg grating whose planes contain nanostructures will therefore depend on how the nanostructures are oriented with respect to the fiber. When the planar nanostructures are at an angle with respect to the axis of the fiber core, the FBG can be thought of as a (multiple-order) wave plate in terms of its birefringent properties. On the other hand, when the planar nanostructures are aligned exactly perpendicular to the axis of the fiber core, the optical axis of the uniaxial crystal associated with them will be aligned parallel to the fiber core and the FBG spectrum is expected to be insensitive to the polarization state of the

light propagating through it, provided that the birefringence of the fiber is caused only by the nanostructures. Thus, in order to avoid or minimize the polarization dependence of the FBG spectrum, the polarization of the fs-laser pulses should be aligned parallel to the fiber axis. Conversely, in order to maximize the birefringence of the phase-shifted Type II FBGs, which is desirable for multi-parameter sensing applications, the fs-laser polarization should be aligned perpendicular to the fiber.

Figure 8 presents spectra of a type II phase shifted Bragg grating written using the disclosed method where the polarization of the fs writing beam is aligned perpendicular to the fiber axis (y- axis). In this case, the polarization-dependent difference in the central wavelength (PD-A) of the passband feature is almost 70 pm. The three traces in Fig. 8 correspond to different states of the probe light polarization (i.e., $\mathbf{p}_s$, $\mathbf{p}_r$ and $\mathbf{p}_{45}$), which were prepared by means of an in-line polarization controller. The dashed and dotted traces represent the situations when the probe light is linearly polarized and the polarization is aligned along the slow axis ($\mathbf{p}_s$; 'large' n_{eff}) and the fast axis ($\mathbf{p}_r$; 'small' n_{eff}) of the FBG, respectively. The solid trace represents the case when the linear polarization is at 45° with respect to the axes (i.e., $\mathbf{p}_{45}$).

On the other hand, the FBG written with the femtosecond beam polarization oriented in the x-direction along the fiber axis, as shown in Figure 9, demonstrates almost an order of magnitude reduction in the PD-A, with all other laser writing conditions being the same in both cases. Stress induced by the Type II modification in the fiber core is the most likely cause of this relatively large PD-A (i.e., 7-8 pm as shown in Figure 10). Importantly, the PD-A of 10-15 dB T- shifted Type I FBGs is found to be much smaller, at the level of 1-2 pm for x-polarization and 3- 5 pm for y-polarization. These results suggest that the observed polarization sensitivity of the Type II FBG spectra (i.e., PD-A) is predominantly caused by the presence of light-induced

planar nanostructures (or nanogratings), which inside dielectrics are aligned perpendicular to the laser polarization and exhibit strong form birefringence.

To test how T-shifted Type II FBGs respond to high-temperature annealing, several devices having different strengths were fabricated (3-30 dB in transmission). For a fixed pulse energy, grating strength increases with the number of pulses deposited into the fiber core. The devices were then temperature-cycled 20 times inside a tube furnace from 20°C to 1000°C in ambient air. During this testing, the FBGs stayed in the furnace at 1000°C for more than 200 hours. We observed that the phase-shift features of all the FBGs tested shifted towards longer wavelength by 150-250 pm. However, this noticeable shift mainly occurred only in the first 30-50 cumulative hours of annealing at 1000°C and almost no shift could be detected during the later stages of the experiment.

As an example, the high-temperature performance of an 8 dB FBG is presented in Fig. 11. Figure 11(a) shows the spectrum (solid line) of this FBG at room temperature (i.e., $T = 20^\circ\text{C}$) right after the inscription together with its spectrum (dashed line) at $T = 1000^\circ\text{C}$ after ~200 cumulative hours of annealing at this temperature. It can be seen that the FBG strength has decreased from ~8 dB to ~7 dB and the FBG spectrum has slightly changed its shape. It is also noted that these transformations took place during the first 25-30 cumulative hours of annealing at 1000°C and after that the FBG remained unchanged. The wavelength shift of the phase shift feature as a function of annealing time at 1000°C is presented in Fig. 11(b). Based on these data, the FBG can be considered 'almost' stable and 'absolutely' stable after respectively ~35 and ~100 hours at 1000°C. Such a behavior is also typical of the other FBGs we used in the experiment.

If the guided mode within the fiber that interacts with the phase shifted grating can also interact evanescently with the surrounding environment, then a sensitive chemical sensor is

possible. A generated evanescent field surrounding an optical fiber can interact with the ambient environment and be used to sense changes of the ambient refractive index n_a of the surrounding medium. Present in-line fiber evanescent field devices that are transmissive in nature are either based on biconical tapered fiber devices as shown by Villatoro et al. in *Electron. Lett.* **40**, 106 (2004), long period gratings as shown by Allsop et al. in *Electron. Lett.* **41**, 471 (2005) and photonic crystal fiber as shown by Hoo et al. in *Appl. Opt.* **42**, 3509 (2003). To operate in a reflection mode, optical fiber based refractometers need to incorporate a reflective element such as a Bragg grating. FBG-based refractometric devices require the guided mode to be converted to an evanescent field that can interact with the surrounding environment. Such evanescent fields have been created either by polishing the fiber down to the core in the grating region as demonstrated by Schroeder et al. *Meas. Sci. Technol.* **12**, 757 (2001) or chemically etching the fiber to small diameter (10–20 μm) as demonstrated by Iadicicco et al. in *IEEE Photon. Technol. Lett.* **16**, 1149 (2004) or using D-shape fiber as demonstrated by Keren and Horowitz in *Opt. Lett.* **28**, 2037 (2003). These structures need to be created in waveguides that were UV-photosensitive. Recently Silva et al demonstrated such a device in *IEEE Photon. Technol. Lett.* **25**, 401 (2013)

where a uniform pitched FBG was fabricated in a 50 μm diameter taper made from standard telecom fiber with a UV femtosecond system and a Talbot interferometer. The device was subsequently coated with palladium making an effective sensor for hydrogen gas.

When tapering silica based fibers, the guided mode becomes cladding-air guided in the tapered region as opposed to core-cladding guided in the untapered single mode fiber when proper conditions are met. For step index single mode fibers, the normalized frequency or V number

is given by: $V = \frac{2\pi r}{\lambda} \sqrt{(n_{co}^2 - n_{cl}^2)}$ (3)

where r is the core radius, A is the wavelength and n_{co} and n_{cl} are the refractive indices of the core and cladding respectively. For single mode operation, $V \lesssim 2.405$. When a fiber is tapered, by using the hydrogen flame brushing technique for example (see Bilodeau et al US Patent 4,895,423 incorporated herein by reference) the ratio of cladding/core radii remains constant however V decreases. As disclosed in Love et al IEE Proceedings Journal **138**, no. 5, p.343-354 (1991), incorporated herein by reference, when single mode optical fiber is tapered down such that the normalized frequency or V number of the taper is $V < 0.84$, the fundamental LP_{01} mode is no longer confined to the core but instead is guided by the cladding-air interface resulting in a mode field with the same diameter as the tapered fiber.

In order to minimize coupling of the fundamental mode into higher modes within the taper, the tapering rate along the length of the fiber must be adiabatic. If z is the distance along the taper and π is the local taper radius then the adiabatic condition can be written as:

$$\left| \frac{d\pi}{dz} \right| > \frac{\pi}{z_b}, \quad z_b = \frac{2\pi}{(\beta_1 - \beta_2)} \quad (4)$$

where z_b is a 'beat length', β_1 is the propagation constant of the fundamental LP_{01} mode and β_2 is the propagation constant for the LP_{02} , which is the closest and most likely mode to which coupling will occur.

Fiber claddings are typically silica which is non-UV-photosensitive. Using the femtosecond laser approach for grating inscription removes the constraint of UV-photosensitivity and makes possible the inscription of grating structures across the entire taper cross section of the non-photosensitive silica fiber tapers. Grobncic et al. showed in IEEE Photon. Technol. Lett. **18**, 160-162 (2006) that volume FBGs written across the entire cross-sections of 50 and 30 μm diameter tapers could be used for refractometric and fluid level measurements.

Figure 12 presents a schematic representation of a phase shifted Bragg grating written into a silica fiber taper. An untapered single mode fiber **1201** has a core region **1202** and a cladding region **1203** such that the fundamental LP_{01} mode **1204** is guided by the boundary between the core and cladding region. Within the adiabatic taper region **1205**, the mode **1204** is no longer core/cladding guided and expands to become a single mode **1206** that fills the cross-section of the taper. This mode is not tightly confined to the taper cross-section but has some evanescent coupling to the surrounding region. A phase-shifted grating **1207** is inscribed across the cross-section of the taper by the disclosed method herein. The phase-shifted FBG/taper region is then surrounded with a sensing layer **1208**, i.e. a material layer that will change either its mechanical or optical properties when exposed to specific environmental conditions or analyte. The effective index n_{eff} of the Bragg resonance of **1207** is then dependent upon the index of the taper which is predominantly that of the fiber cladding n_{cl} and the index of the sensing layer n_{sl} as a result of the evanescent coupling of the expanded LP_{01} mode **1206** into the sensing layer **1208** about the phase shifted grating **1207**. Changes in n_{sl} as the result of say absorption of an analyte will be detected

by a wavelength shift of the fundamental mode **1209** that is reflected by the grating **1207**. The adiabatic nature of the taper ensures that the reflected mode **1209** becomes a single mode **1210** that is core/cladding guided. Incorporation of a phase shift in the grating structure can increase the sensitivity of the device by at least an order of magnitude.

Claims:

1. A method for inscribing a phase shifted Bragg grating in an optical waveguide, comprising the steps of:
 - 5 providing the optical waveguide;
providing a diffractive optical element which incorporates a phase shift that, when exposed to a ultrashort laser pulse, creates an interference pattern on the optical waveguide which has a phase shift in its pattern; and
 - 10 providing electromagnetic radiation from the ultrashort laser pulse, wherein the electromagnetic radiation has a pulse duration of less than or equal to 5 picoseconds, wherein the wavelength of the electromagnetic radiation has a characteristic wavelength in the wavelength range from 150 nm to 2.0 microns, and wherein the electromagnetic radiation step comprises irradiating a surface of the diffractive optical element with the electromagnetic
 - 15 radiation incident on the optical waveguide, from the diffractive optical element, and being sufficiently intense to cause the permanent change in index of refraction in the core of the optical waveguide when exposed to a minimum succession of laser pulses, to form a Bragg grating.
2. The method according to claim 1 further comprising a step of introducing a beam
20 block to remove the effect of phase-shift splitting observed in grating structures written using phase shifted phase masks.
- 3 The method according to any previous claim where the phase shifted Bragg grating is a thermally stable type II phase grating.

4 The method according to claim 3 where the birefringence of the thermally stable type II phase grating is controlled by varying the polarization of the inscription ultrafast laser with respect to the waveguide axis.

5 A device comprising a Bragg grating Fabry-Perot structure in a fiber or waveguide where
5 the first Bragg grating is shifted with respect to the second Bragg grating by $N \cdot A_G + A_G/2$,
where N is an integer number and A_G is the period of the Bragg gratings.

6 The device of claim 5 where the phase shifted grating is written into an optical fiber taper that is coated with a sensing layer.

7 The method of any of claim 1 and claim 2 where the optical waveguide is an
10 actively doped optical fiber.

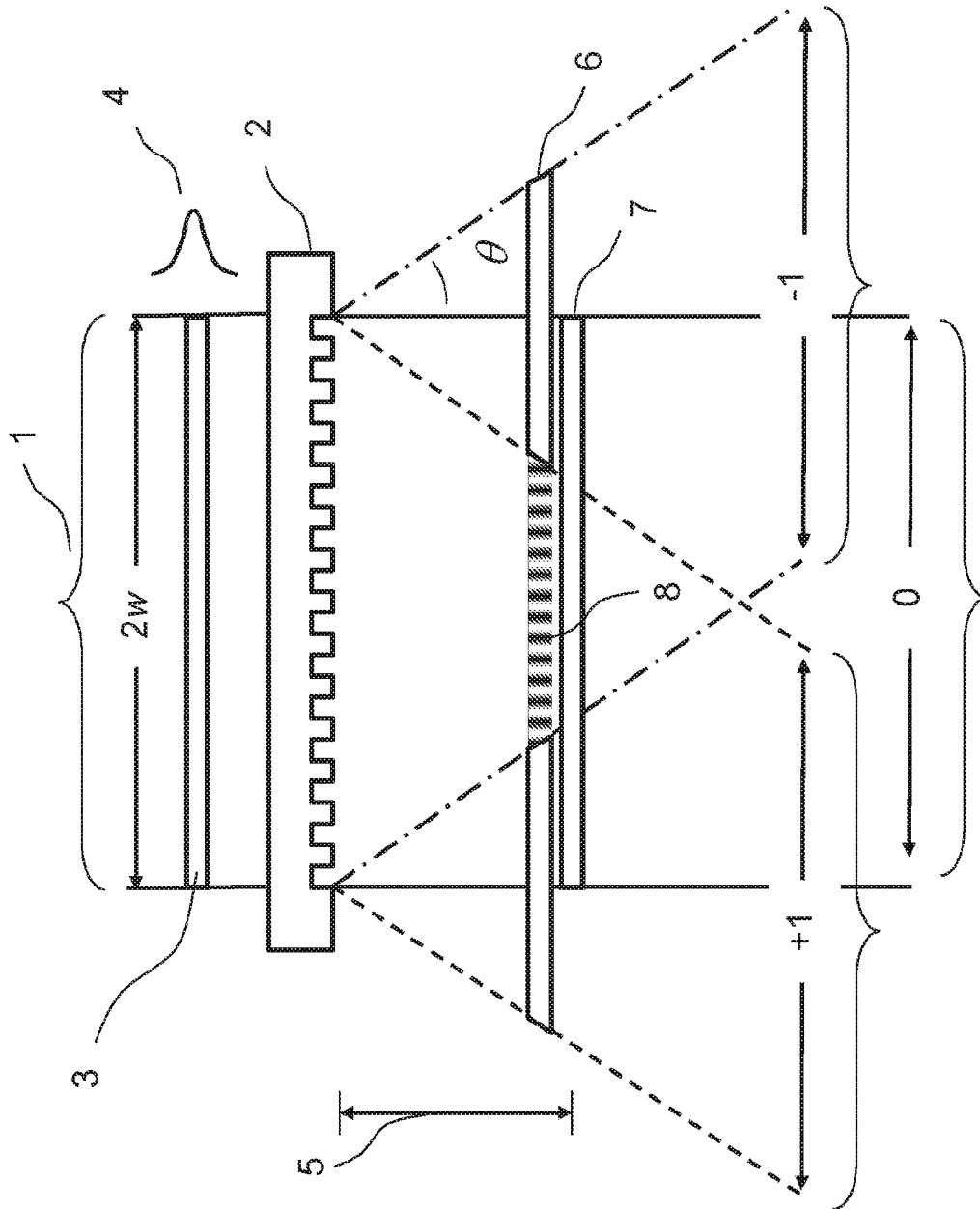


Fig. 1a

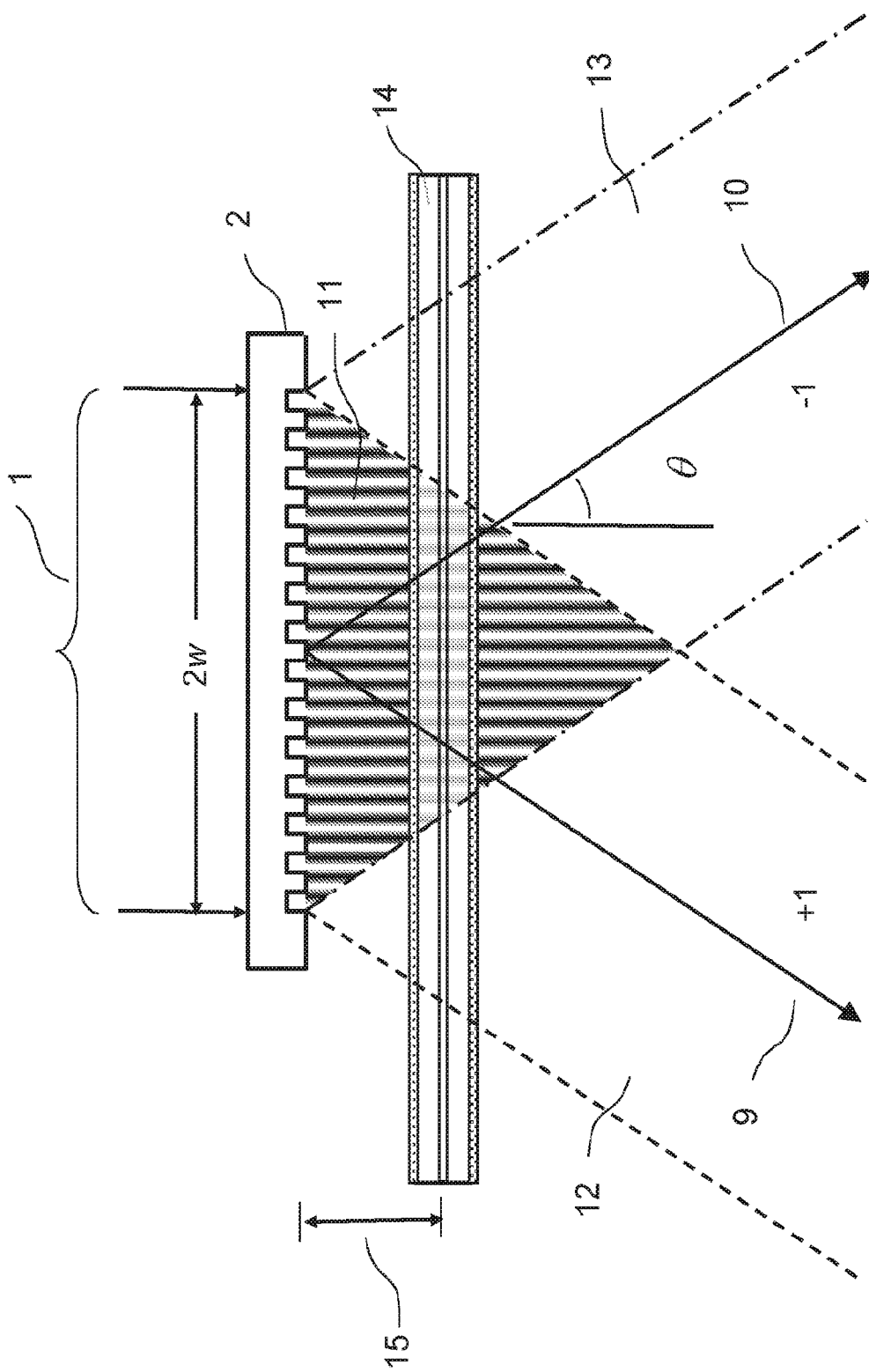


Fig. 1b

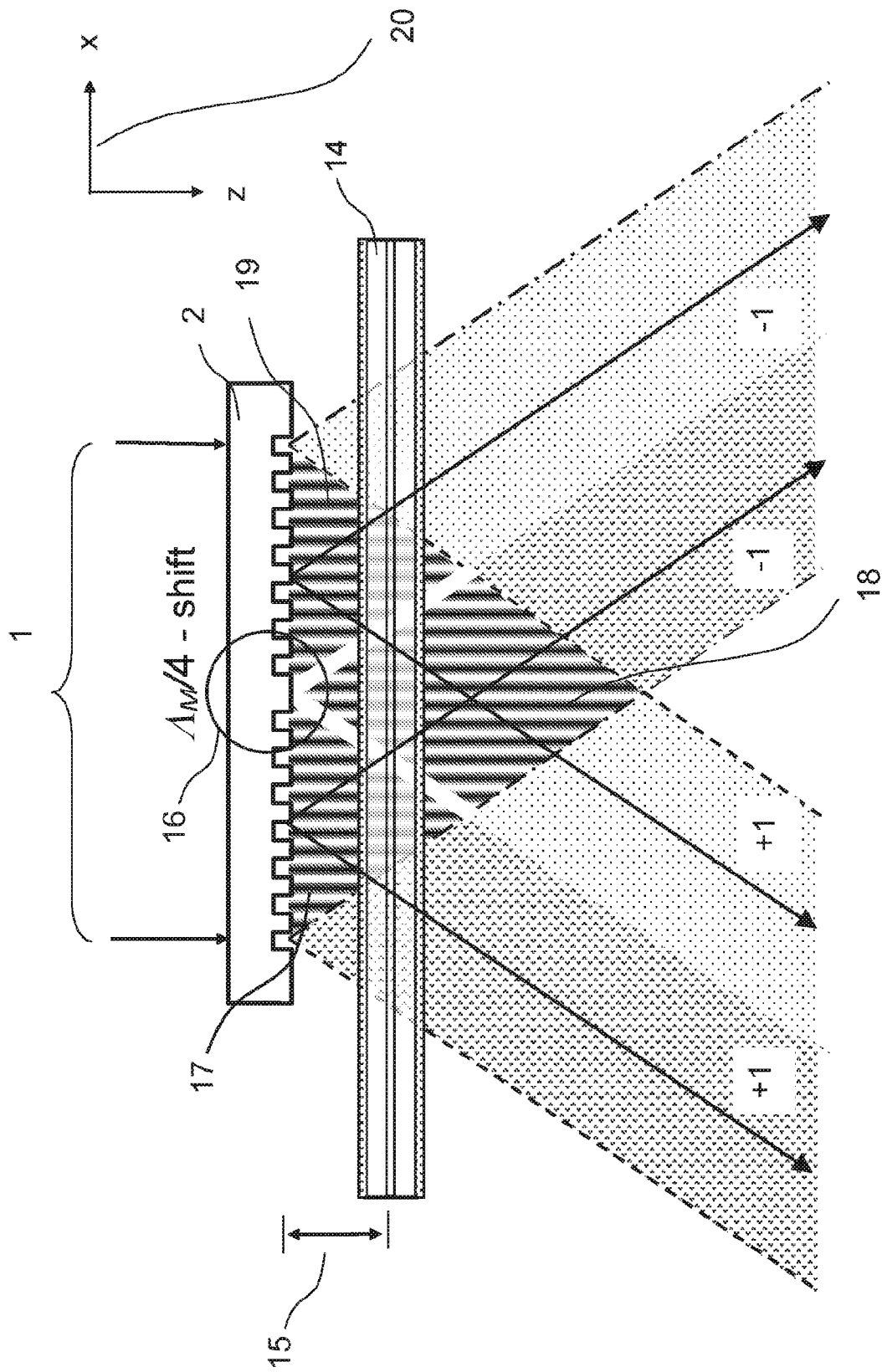


Fig. 1c

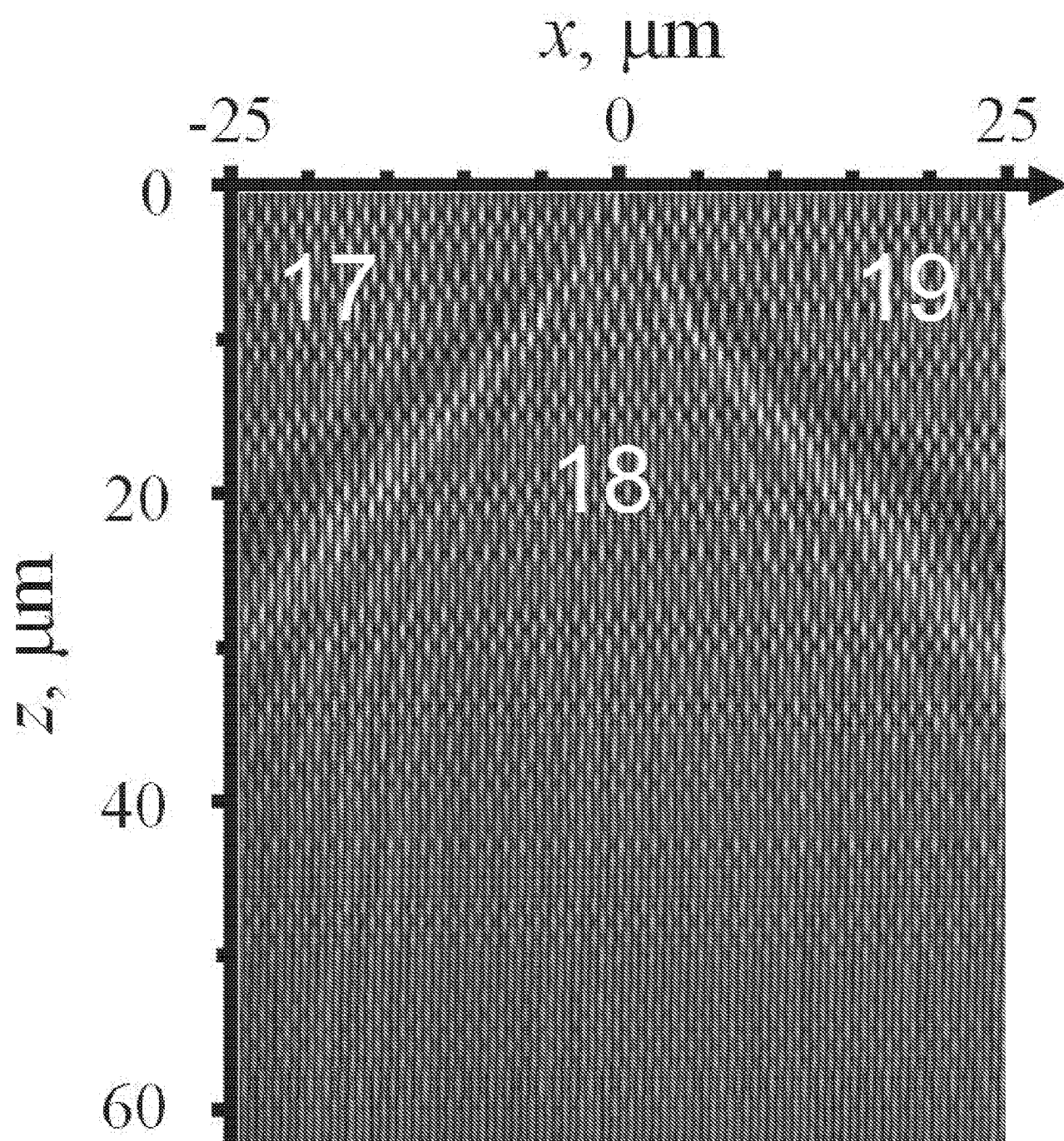


Fig. 2

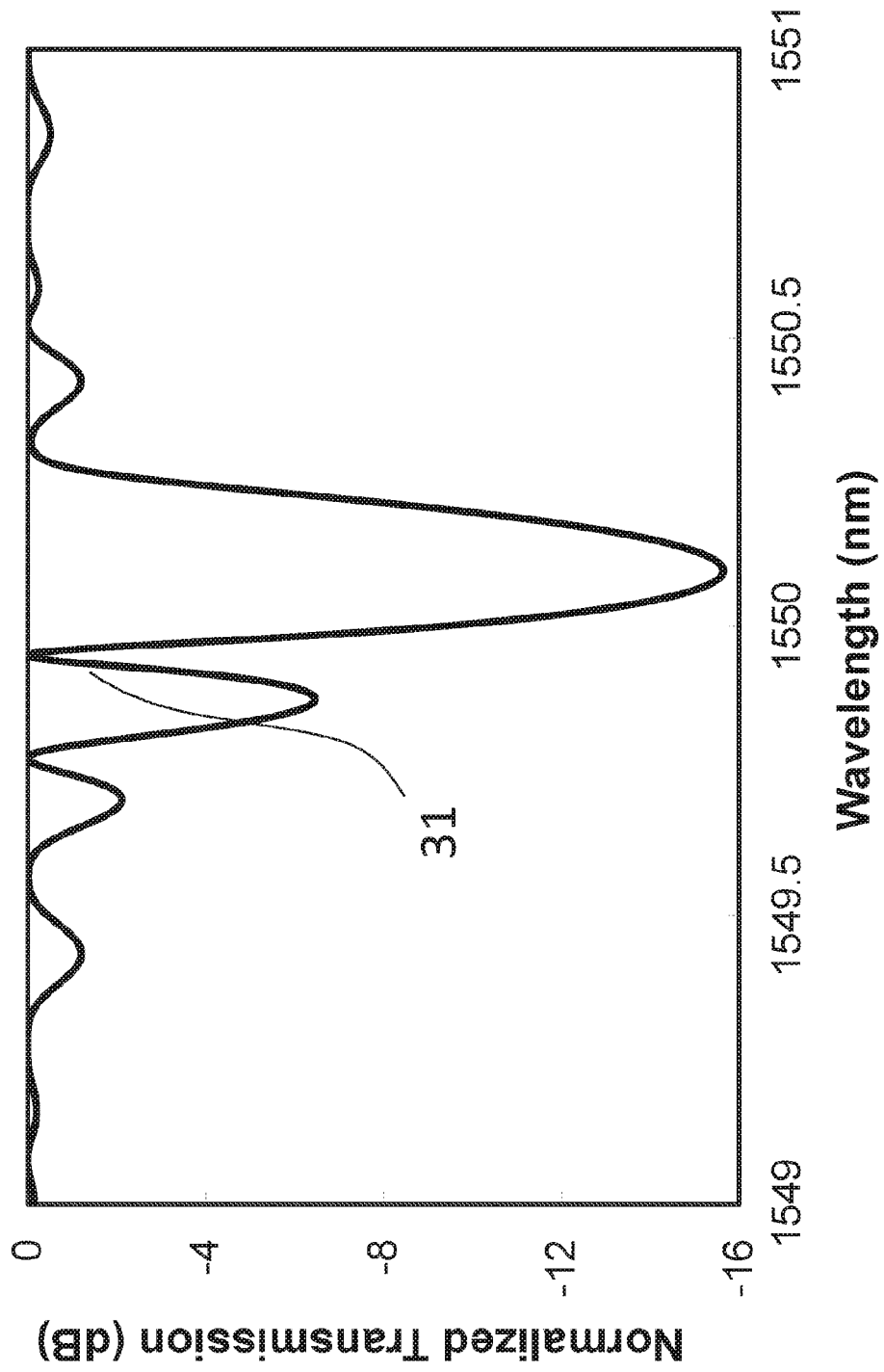


Fig. 3

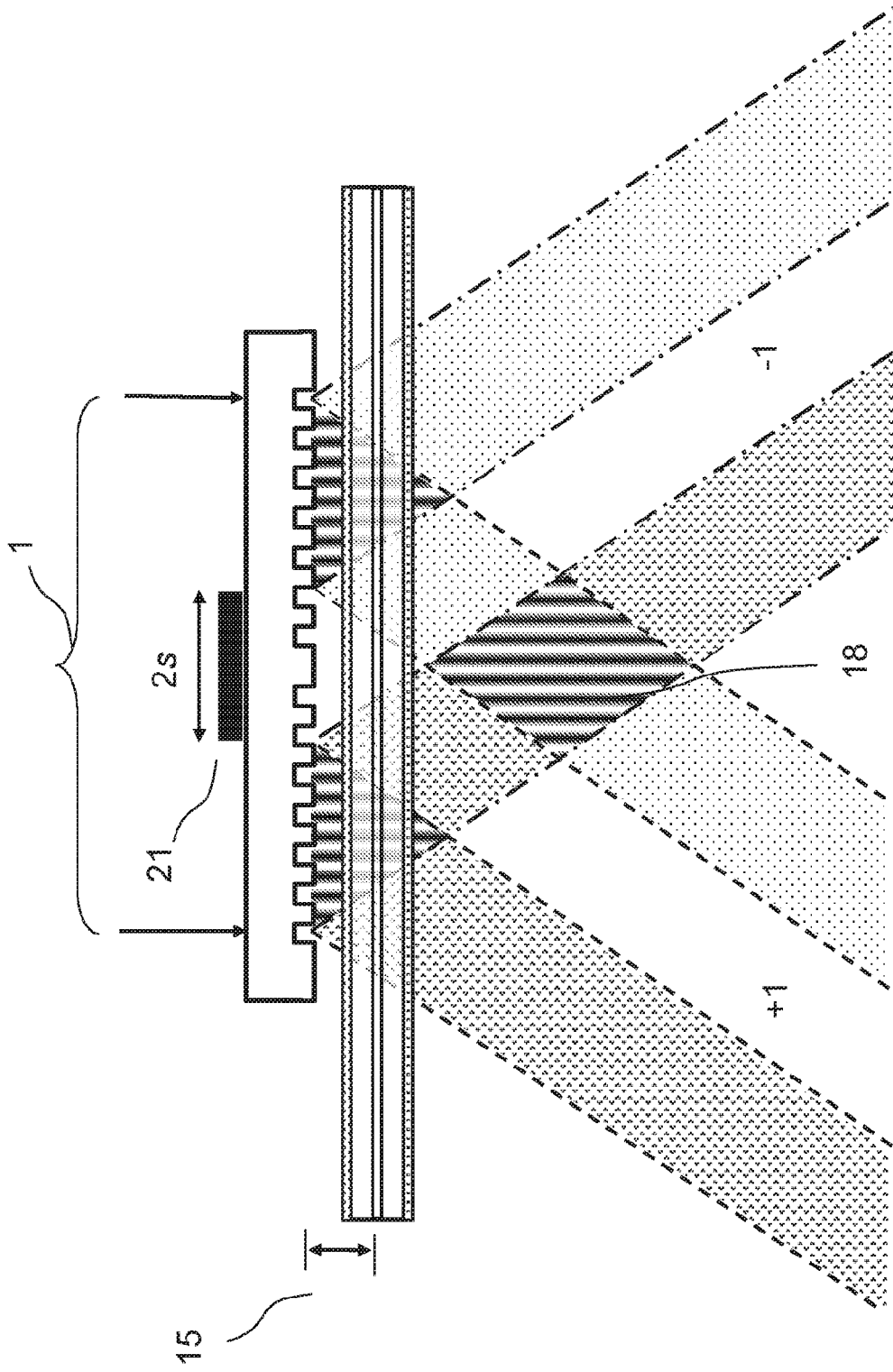


Fig. 4

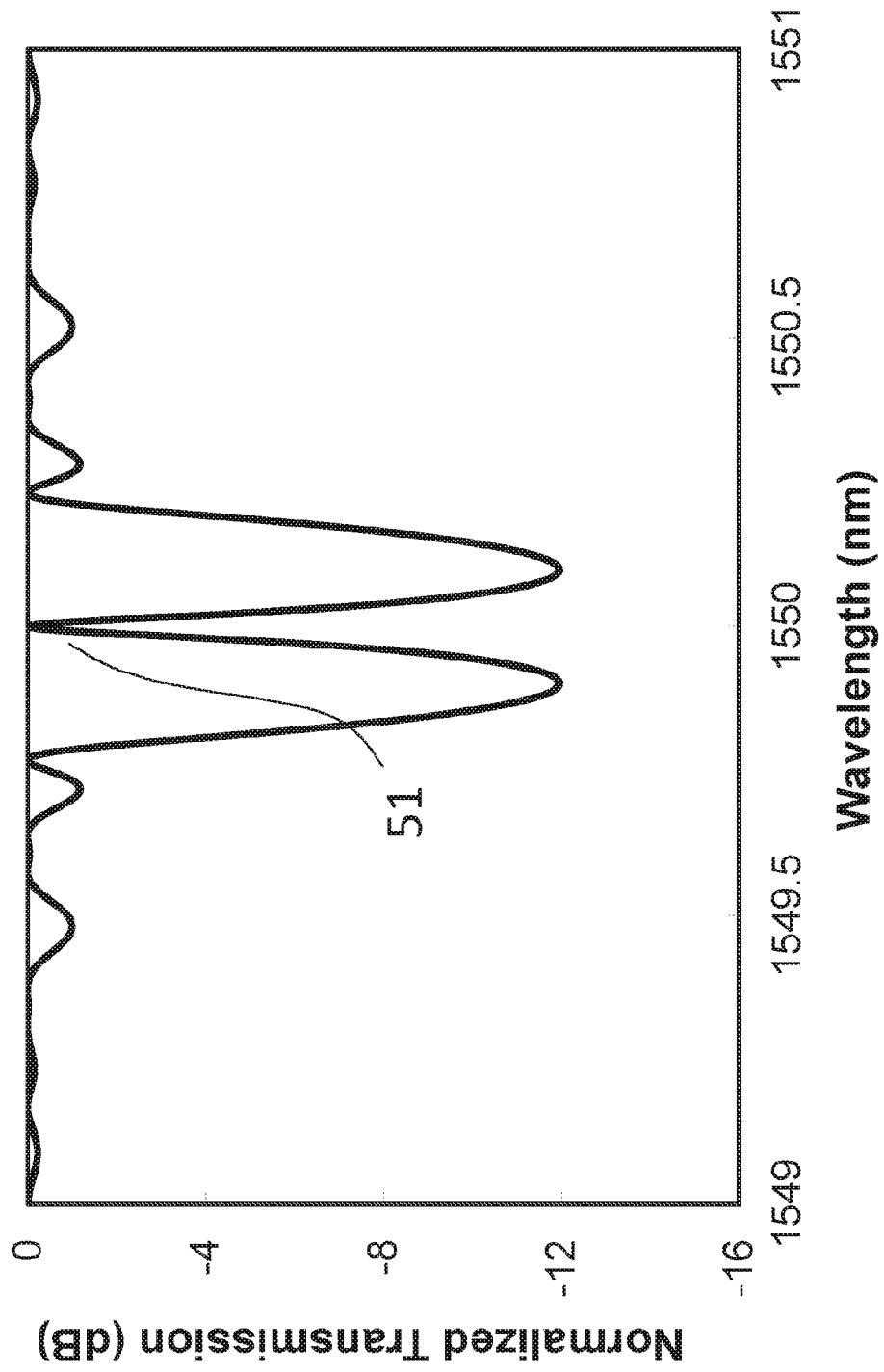


Fig. 5

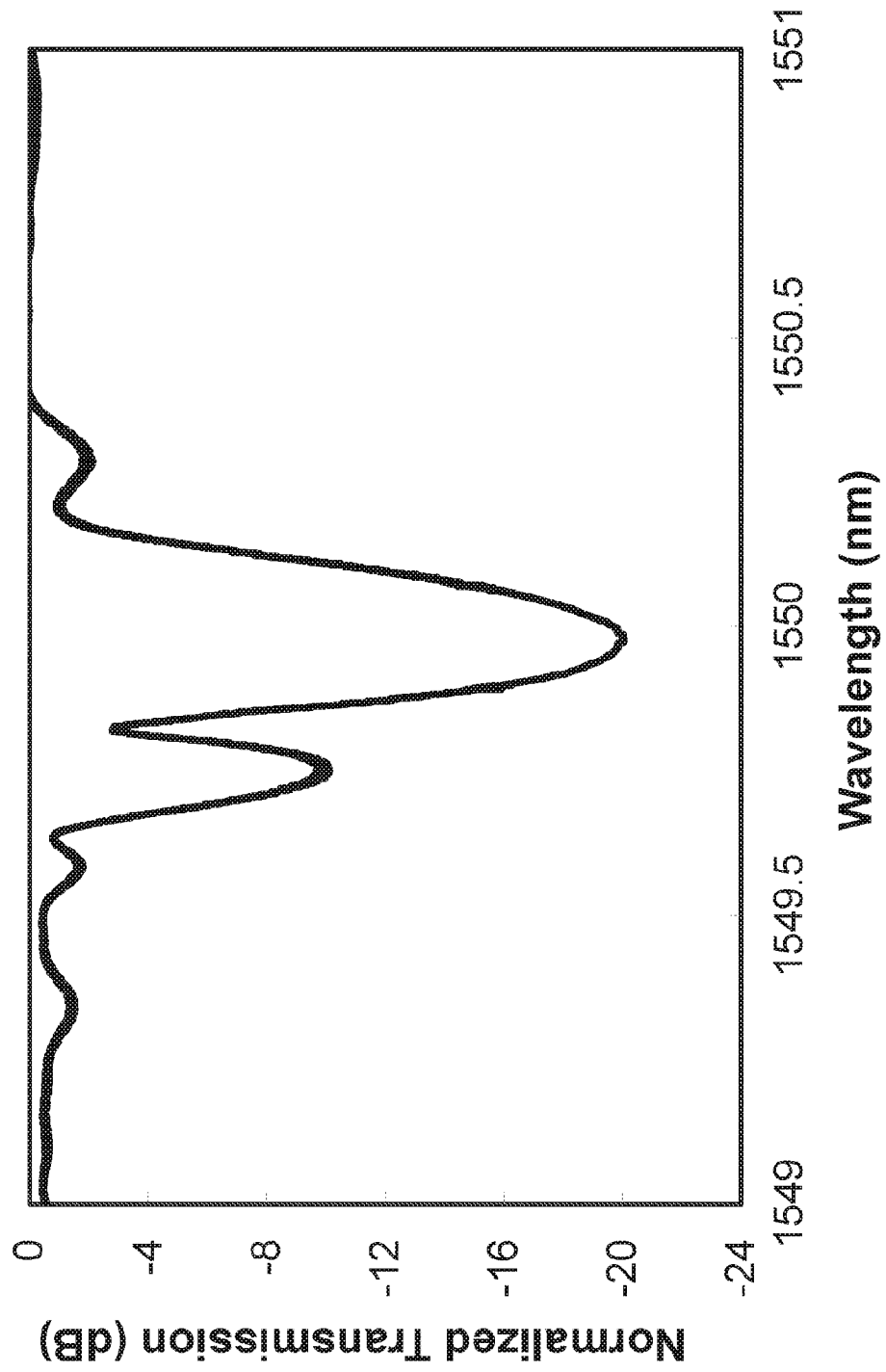


Fig. 6

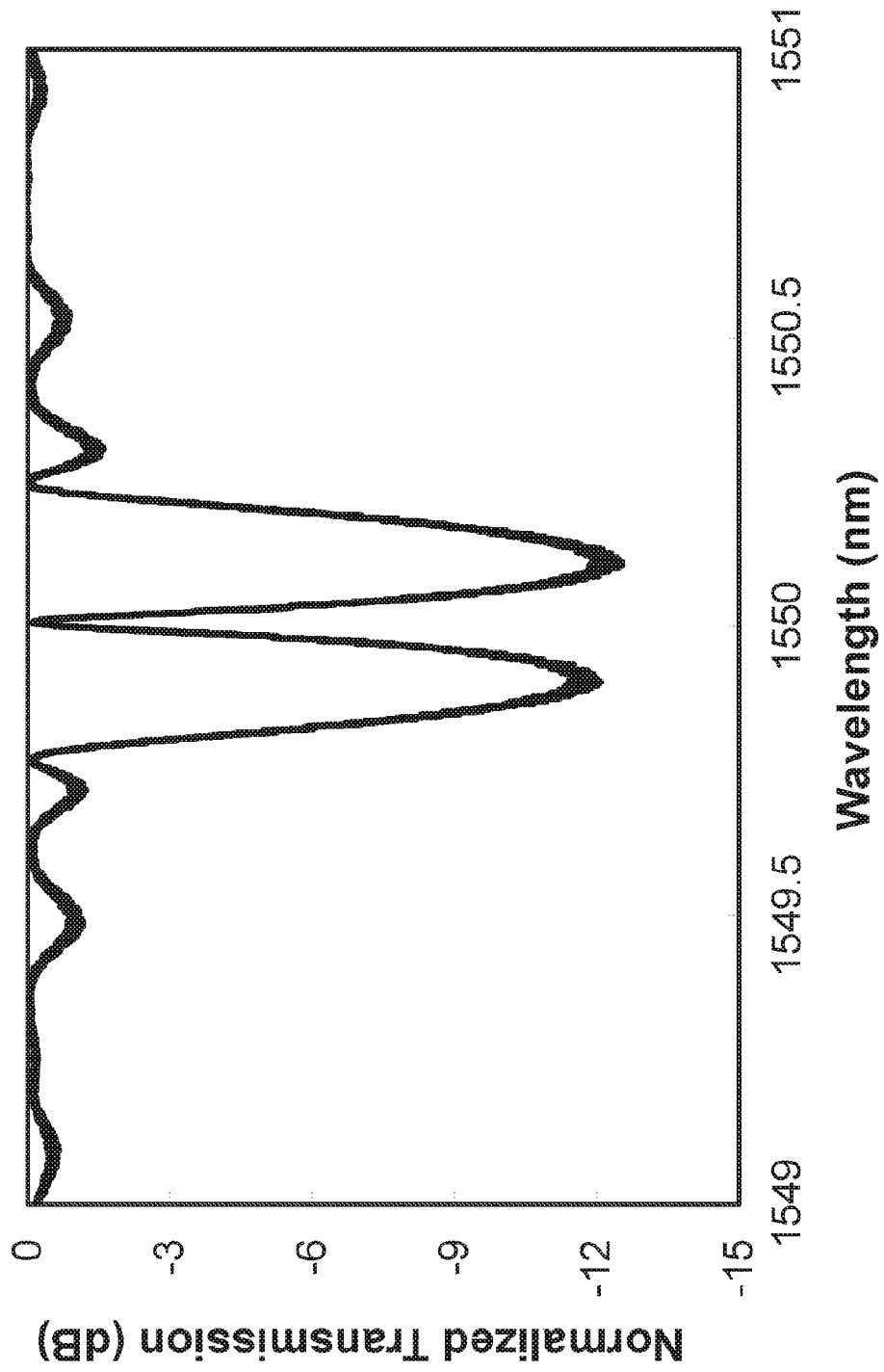


Fig. 7

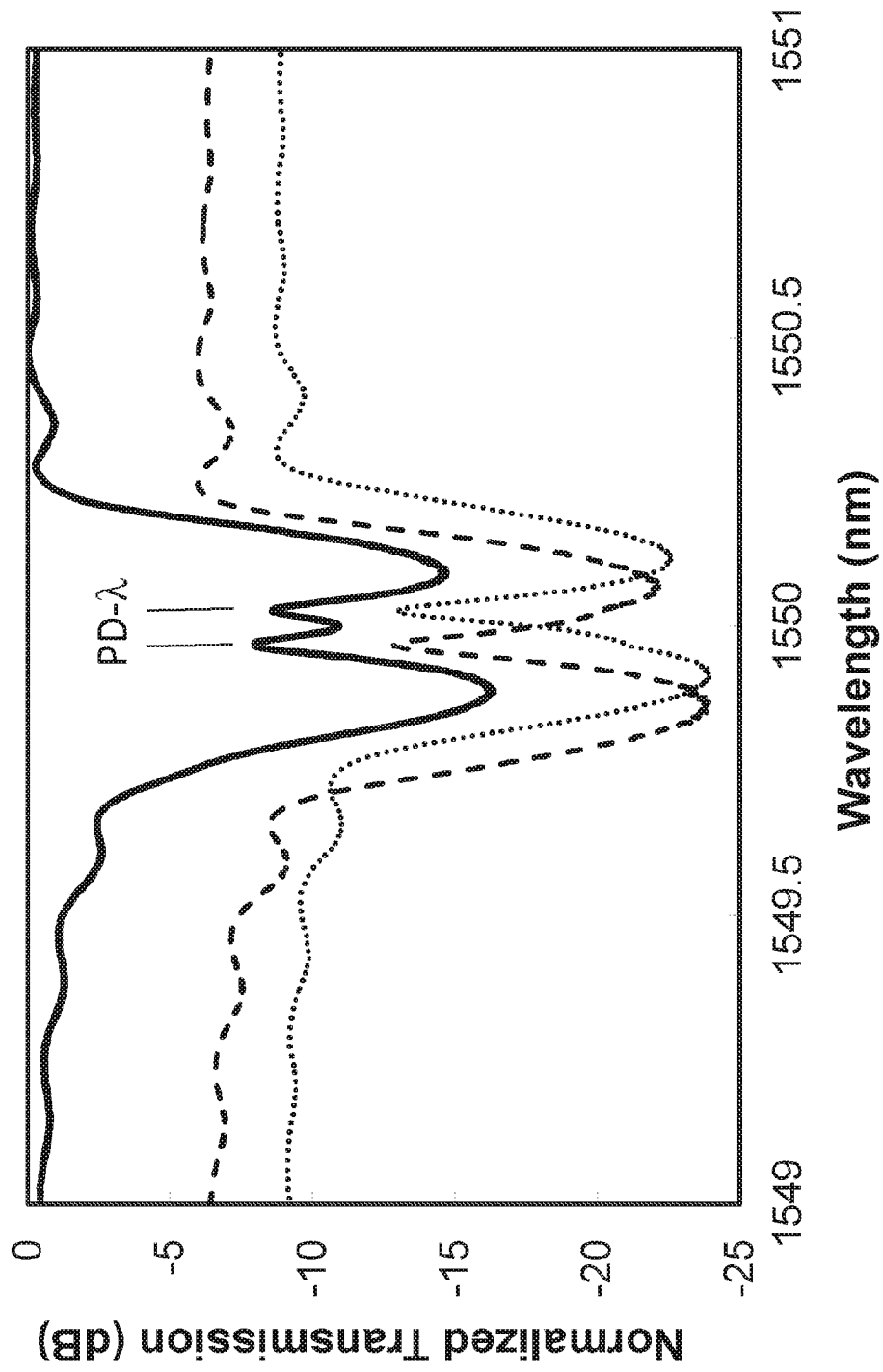


Fig. 8

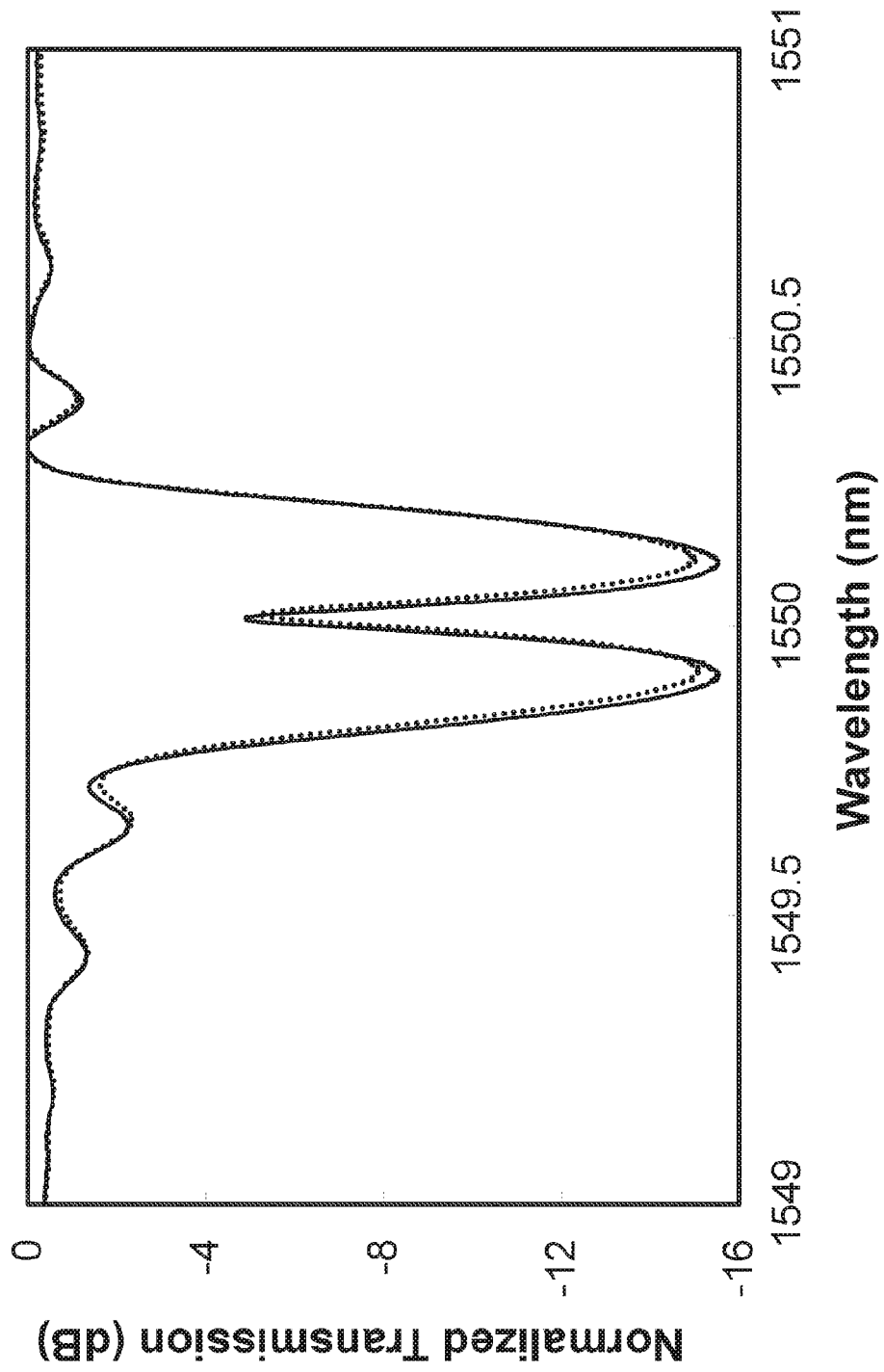


Fig. 9

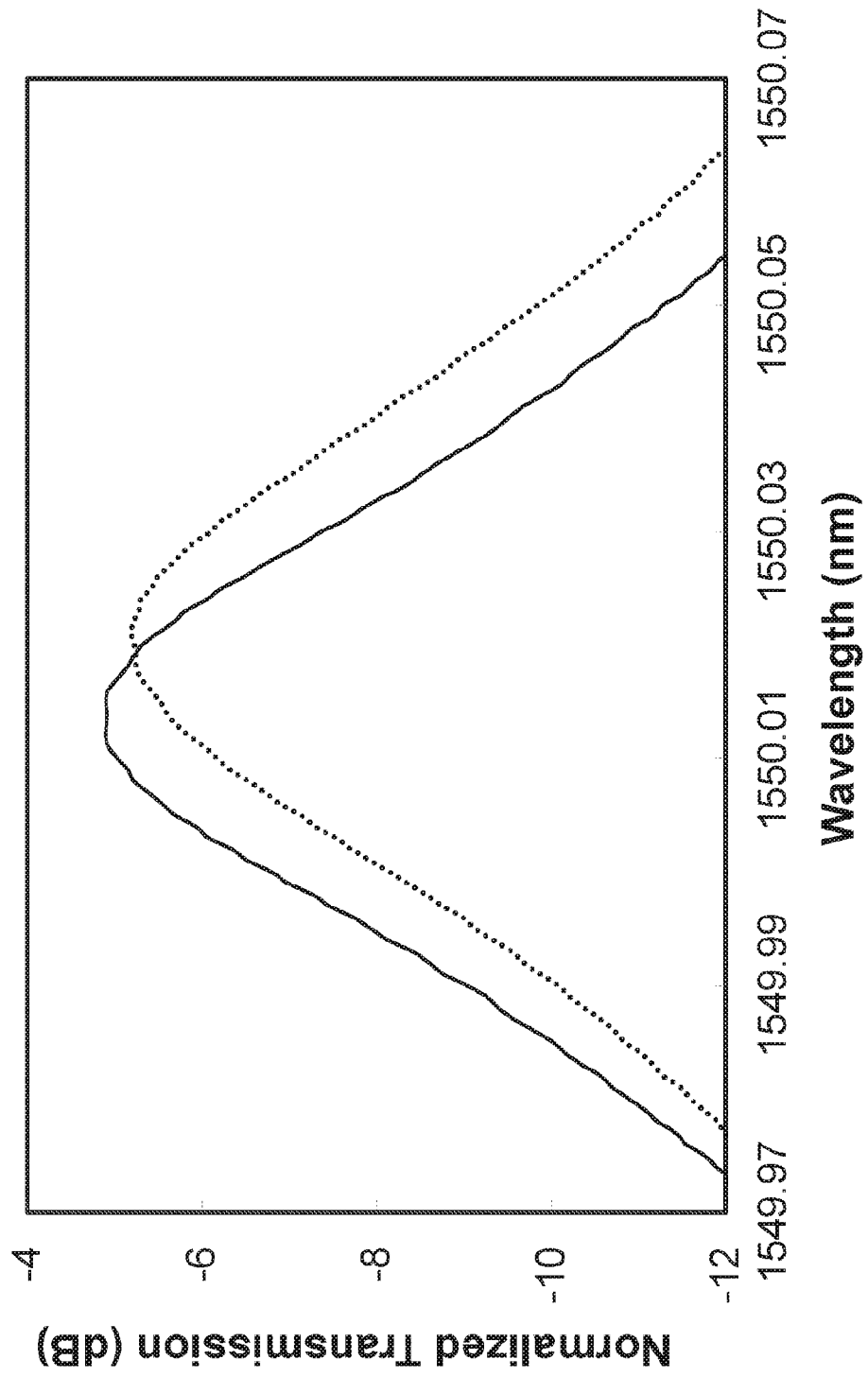


Fig. 10

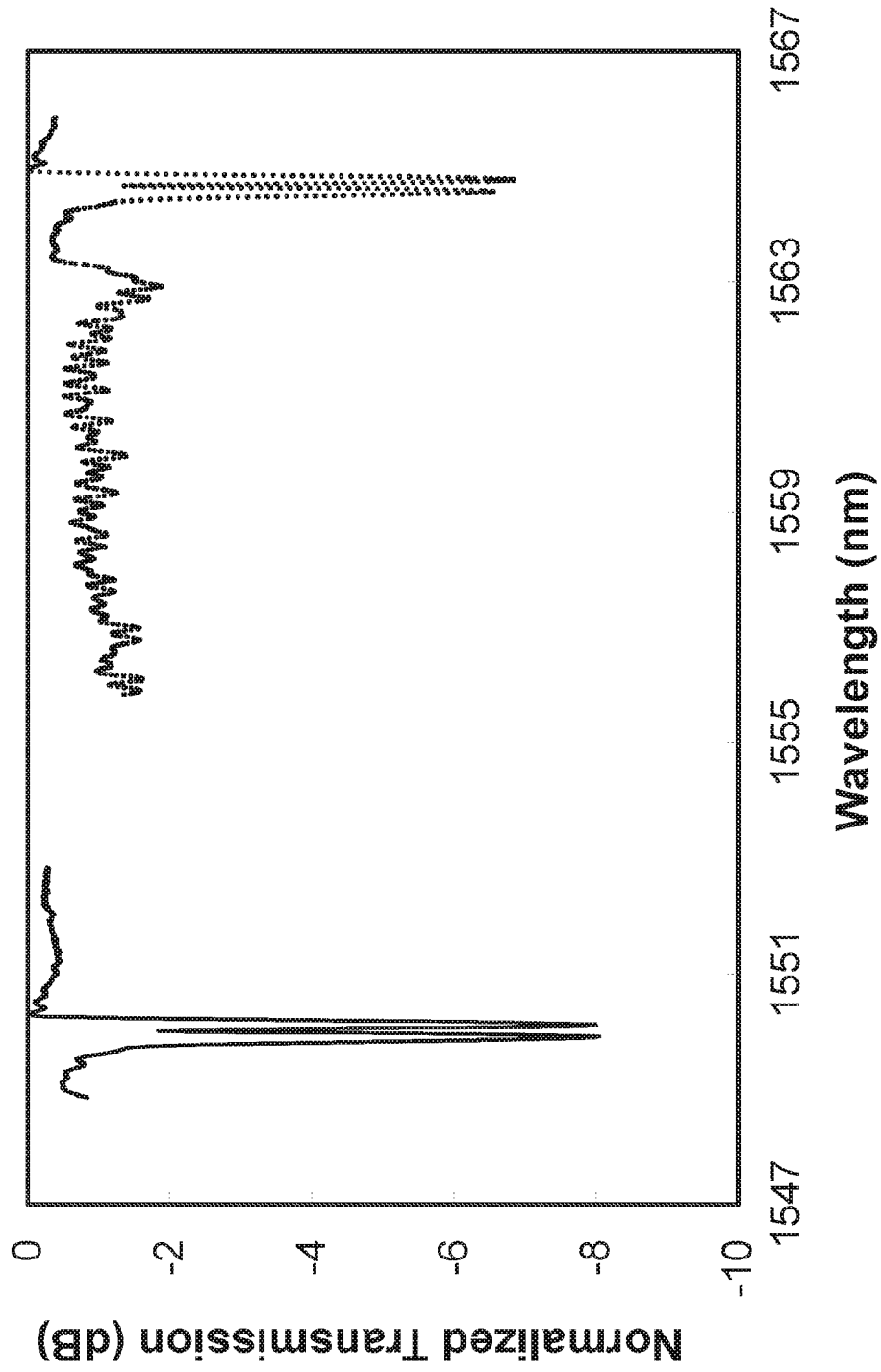


Fig. 11a

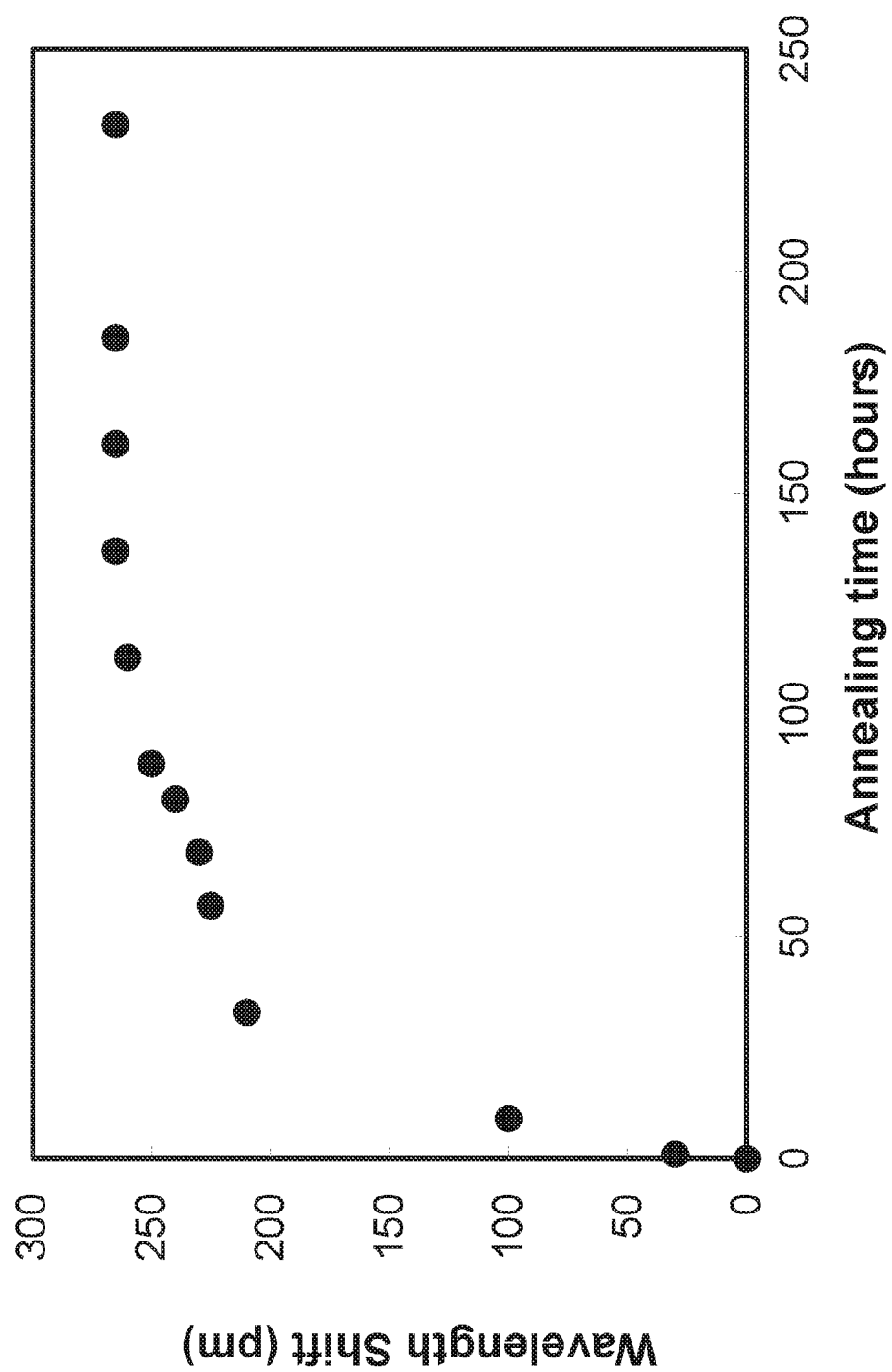


Fig. 11b

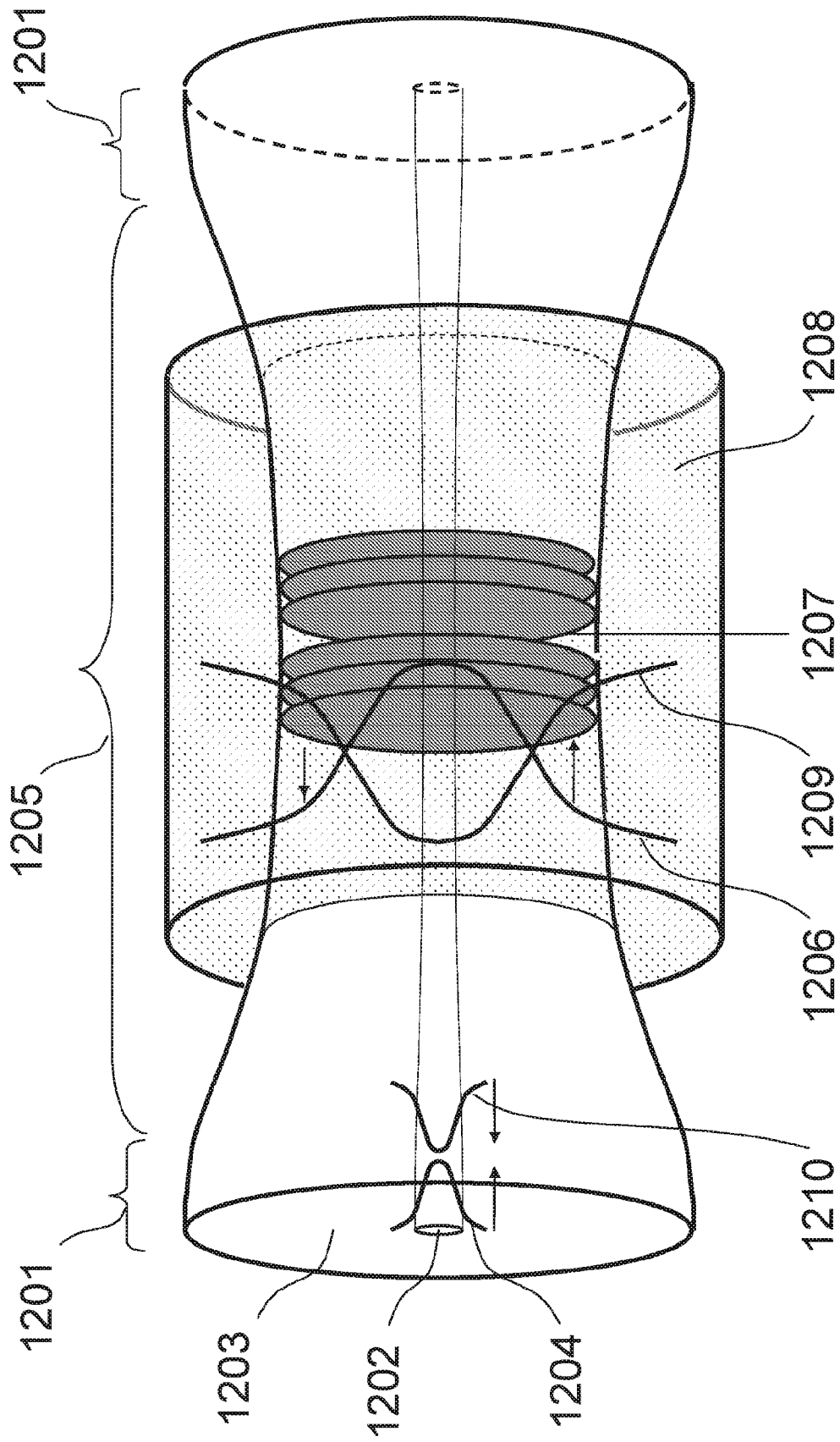


Fig 12

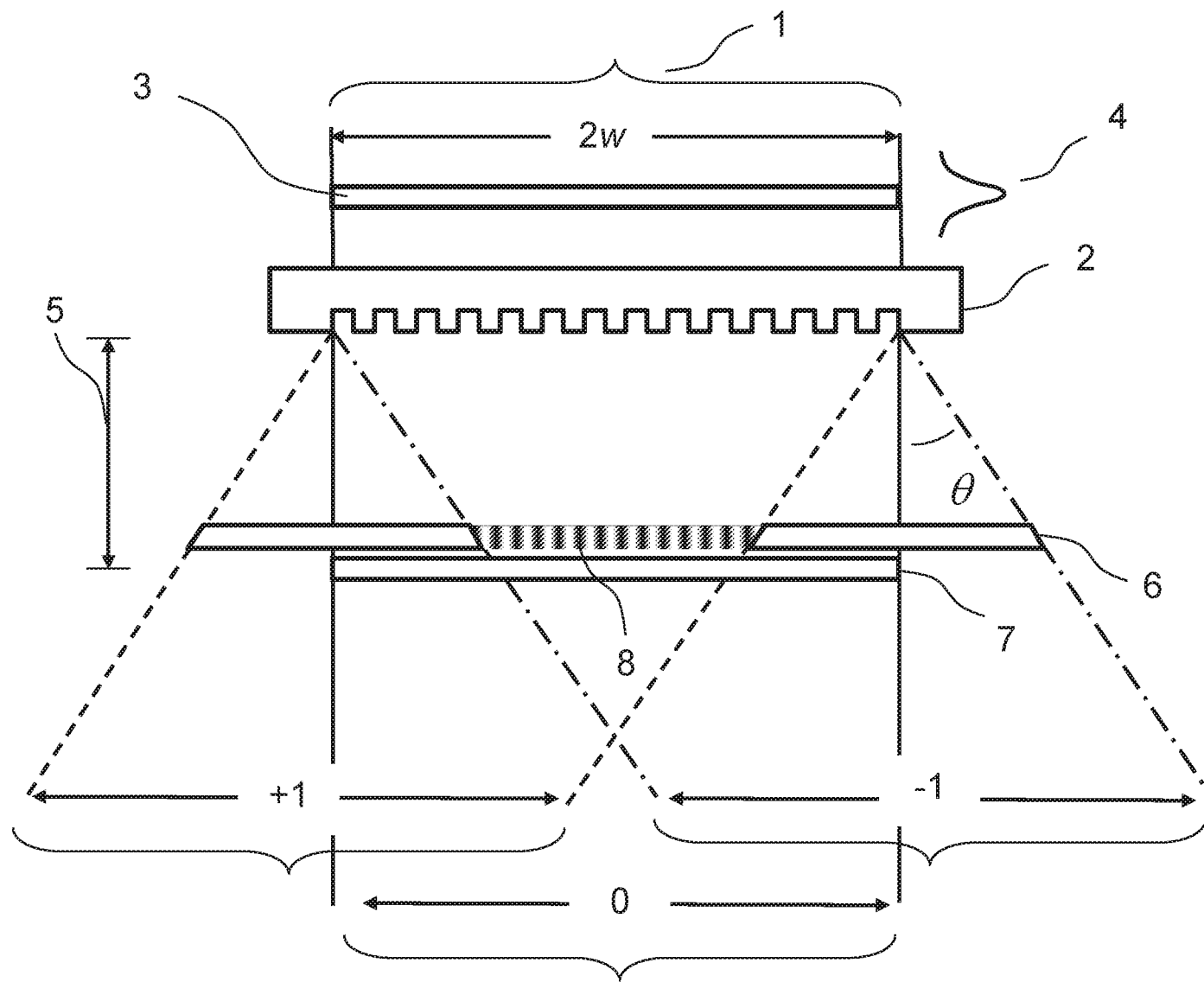


Fig. 1a