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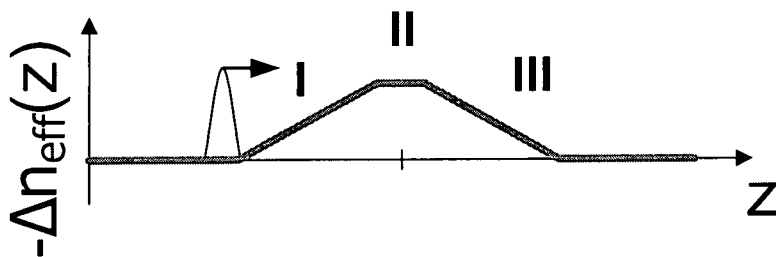
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(54) Title: OPTICAL SENSOR AND METHOD BASED ON THE PROPAGATION OF BRAGG SOLITONS IN NON-UNIFORM ONE-DIMENSIONAL PHOTONIC CRYSTALS

Fig. 1



(57) Abstract: A method for measuring a change in a given environmental parameter, by: (i) implementing a non-uniform one-dimensional photonic crystal comprising: a first region used to obtain Bragg solitons; a second region used to slow down propagating Bragg solitons; and a third region used to de-couple transmitted Bragg solitons outside the one-dimensional photonic crystal; (ii) generating by a laser source pulses train for repetitive launching of Bragg solitons at a sufficiently stable frequency towards said non-uniform one-dimensional photonic crystal; (iii) tuning the laser

light frequency and the one-dimensional photonic crystal's grating pitch to a point of high sensitivity, such that a low magnitude change in the environmental parameter triggers a high magnitude change in the output pulse characteristics; and (iv) detecting the change in the given environmental parameter by measuring the change in the measured output pulse characteristics, and estimating the environmental parameter change magnitude according to a predefined scale.

TITLE OF INVENTION**OPTICAL SENSOR AND METHOD BASED ON THE PROPAGATION OF BRAGG SOLITONS IN NON-UNIFORM ONE-DIMENSIONAL PHOTONIC CRYSTALS****5 FIELD OF INVENTION**

The present invention relates to optical sensors and more particularly to optical environmental sensors and routers based on the propagation of Bragg solitons in a one-dimensional photonic crystal.

BACKGROUND ART

10 A sensor is a device which measures a physical quantity or parameter and converts it into a signal which can be read by an observer or by an instrument. A sensor's sensitivity indicates how much the sensor's output changes when the measured quantity changes. For instance, if the mercury in a thermometer moves 1cm when the temperature changes by 1°, the sensitivity is 1cm/1°. Sensors that
15 measure very small changes must have very high sensitivities.

A router is a device that forwards information along networks A router has at least one input signal terminal and at least two output signal terminals. In addition, the router also has a control signal terminal. According to the control signal through the control terminal the router directs or *routes* the signal at the input terminal to
20 one of the output terminals. Routers are often electronic devices that are common in telephony networks and computer networks, though routers can also be also mechanical or optical devices. Sometimes routers can also be software in a computer.

A photonic crystal is an optical medium that has a periodic or quasi-periodic
25 structure of the refractive index. When the photonic crystal is periodic only in one direction, it is referred to as a one-dimensional photonic crystal. Such one-dimensional (1D) crystal is often referred to as grating. One important family of such gratings is the fiber Bragg gratings (FBG): it is an optical fiber in which the core refractive index is modulated by a periodic function. The FBGs are usually

realized by side illumination of the optical fiber by intense ultra-violet (UV) light. Gratings are characterized by modulation depth of the refractive index, by the periodicity step Λ , and by the average refractive index n_{eff} over one period of the grating. When light enters the grating, the phase and the amplitude of the reflected or transferred light greatly depend on the wavelength of the incident light, λ . The wavelength discrepancy or dispersion of the grating is strongest when $\lambda \approx 2n_{eff}\Lambda = \Lambda_B$. Λ_B is called "Bragg wavelength" and when the wavelength of the incident light is close to the Bragg wavelength, most of the light is reflected from the grating. The high reflectivity region in the wavelength domain is called "photonic bandgap".

Most fiber Bragg gratings are used in single-mode fibers. Telecom applications of FBGs often involve wavelength filtering, e.g. for combining or separating multiple wavelength channels in wavelength division multiplexing systems (optical add-drop multiplexers). Extremely narrow-band filters can be realized e.g. with rather long FBGs (having a length of tens of centimeters) or with combinations of such grating.

FBGs can be used as end mirrors of fiber lasers (distributed Bragg reflector lasers, DBR fiber lasers), then typically restricting the emission to a very narrow spectral range. Even single-frequency operation can be achieved e.g. by having the whole laser resonator formed by a FBG with a phase shift in the middle (distributed feedback lasers). Outside a laser resonator, an FBG can serve as a wavelength reference e.g. for stabilization of the laser wavelength. This method can also be applied for wavelength-stabilized laser diodes.

In some fibers, there can be a significant deviation between the Bragg wavelengths for different polarization directions (i.e., a birefringence). This may be used e.g. for fabricating rocking filters.

Bragg solitons is a general term that refers to intense optical pulses (beams) that propagate inside the photonic crystals, in which the strong dispersion (diffraction) associated with the photonic crystals' bandgap that would in linear

regime broaden the pulses (beams) along their propagation, is compensated by non-linear effects such as Kerr non-linearity resulting in pulses (beams) with constant intensity characteristics that can propagate long distances without broadening [1]. In the scope of this application, the term Bragg soliton specifically refers to strong optical pulses, which central frequency is close to the Bragg wavelength (or the average Bragg wavelength in case of quasi-periodic structures) and may even be located inside the photonic bandgap, which intensity profile is not significantly damaged during the propagation along the photonic crystal, due to the delicate balance between the linear and non-linear effects,, and that at least at some sections along the photonic crystal propagate with group velocity that is much lower than the speed of light.

The central frequency of Bragg or as they are also called "gap" solitons may be located within or close to the grating bandgap. Recently, the propagation of a Bragg soliton with a velocity significantly lower than the speed of light in the fiber was demonstrated using mid-range power pulses [2].

Recently, novel optical logic gates based on the interaction between Bragg solitons were theoretically demonstrated [3]. In these gates the solitons propagation direction is changed due to the two-soliton interaction in non-uniform gratings. It was shown, that the physical effect that causes a soliton to change its propagation is the relatively small shifts in the interacting solitons' frequencies due to the non-linear interaction between them.

The soliton dynamics, as indicated in reference [3] are extremely sensitive to the relative offset between the soliton wavelength and the grating period or pitch. As effective pitch of the grating is a function of the environmental parameters such as temperature and strain, the soliton dynamics in gratings are highly sensitive to the environmental conditions. This sensitivity can be utilized in order to obtain extremely sensitive sensors based on soliton propagation in non-uniform gratings, or in order to route the propagating mid-range power optical pulses by changing the environmental conditions, such as the strain of an FBG.

SUMMARY OF INVENTION

It is an object of the present invention to use propagation properties of Bragg solitons along non-uniform gratings in a one-dimensional photonic crystal in order to obtain a sensor for environmental parameters.

5 It is another object of the present invention to use propagation properties of Bragg solitons along non-uniform gratings in a one-dimensional photonic crystal in order to obtain a sensor for detecting very small changes in an environmental parameter.

10 It is further object of the present invention to perform optical routing of optical pulses by means of environmental changes.

In FBGs, the high frequency selectivity of the grating can be used for utilizing small pitch changes in the grating induced by small environmental changes in order to change the propagation direction of optical pulses.

15 In one aspect the present invention relates to an optical sensor for measuring changes in environmental parameters, comprising:

(i) a non-uniform one-dimensional photonic crystal receiving a plurality of input optical pulses, comprising: a first region used to obtain Bragg solitons; a second region used to slow down propagating Bragg solitons; and a third region used to de-couple the transmitted Bragg soliton outside the one-dimensional photonic crystal's grating;

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(ii) a laser source adapted for repetitive generating of pulses of sufficiently stable frequency for repetitive launching of Bragg solitons towards said one-dimensional photonic crystal;

(iii) a detector for measuring the characteristics of the output pulse of the said one-dimensional photonic crystal; and

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(iv) a predetermined scale to convert the measurements of the output pulse to the corresponding environmental parameter

such that laser light frequency and the one-dimensional photonic crystal's grating pitch are tuned to a point, where the sensitivity of the sensor is at maximum, corresponding to a known environmental parameter according to a predetermined

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scale, and given the change in the measured output pulse characteristics, the change in the environmental parameter is estimated according to said predetermined scale.

Optionally, the laser source can be a pulsed laser source.

The environmental parameters measured include but are not limited to:
5 temperature, barometric pressure, strain, humidity or a concentration of a solvent in a solution in which the sensor is situated.

In one embodiment of the present invention, the one-dimensional photonic crystal is a non-uniform fiber Bragg grating (FBG), Multilayer films, a quasi-periodic structure of the refractive index (i.e. grating) implemented in chalcogenide-based planar waveguides or a quasi-periodic structure of the refractive index (i.e. grating) implemented in Erbium doped fiber.
10

In another embodiment of the present invention, the FBG is a chirped FBG or an appodized FBG.

The measured characteristics of the output pulse are typically intensity and/or energy though other characteristics can also be measured.
15

In another aspect the present invention relates to a method for measuring a change in given an environmental parameter, comprising the steps of:

(i) implementing a non-uniform one-dimensional photonic crystal comprising: a first region used to obtain Bragg solitons; a second region used to slow down propagating Bragg solitons; and a third region used to de-couple transmitted Bragg solitons outside the one-dimensional photonic crystal;
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(ii) generating by a laser light source pulses train for repetitive launching of Bragg solitons at a sufficiently stable frequency towards said non-uniform one-dimensional photonic crystal;

(iii) tuning the laser light frequency and the one-dimensional photonic crystal's grating pitch to a point of high sensitivity, such that a low magnitude change in the environmental parameter triggers a high magnitude change in the output pulse characteristics; and
25

(iv) detecting the change in the given environmental parameter by measuring the change in the measured output pulse characteristics, and estimating the environmental parameter change magnitude according to a predefined scale.

5 In one embodiment of the present invention, the non-uniform one-dimensional photonic crystal comprises a chirped section of a finite length, in which the grating period is monotonically decreasing towards the center the photonic crystal in case of optical material with positive non-linearity, or monotonically increasing towards the center the photonic crystal in case of material with negative non-linearity.

10 In another embodiment of the present invention, the non-uniform one-dimensional photonic crystal comprises a first appodized section, in which the modulation amplitude of the grating is monotonically increasing towards the center the photonic crystal for efficient coupling of light into the grating.

15 In yet another embodiment of the present invention, the non-uniform one-dimensional photonic crystal further comprises a second appodization section for efficient light de-coupling from the grating, in which the modulation amplitude of the grating is decreasing along the fiber.

20 In yet another embodiment of the present invention, the non-uniform one-dimensional photonic crystal further comprises another appodization section for efficient light de-coupling from the grating, in which the modulation amplitude of the grating is decreasing outwards from the center of the photonic crystal.

In a further embodiment of the present invention, the grating is fabricated inside Erbium doped fiber to overcome losses in the grating, in which case the grating is pumped by pumping laser.

25 In yet a further embodiment of the present invention, the stable laser source is a continuous wave (CW) laser followed by optical modulators and Erbium doped optical amplifiers, mode-locked lasers or Q-switched lasers.

30 In yet another embodiment of the present invention, the laser source is followed by a narrow-band filter for further frequency stabilization of the laser source.

In yet another embodiment of the present invention, tuning the grating pitch is performed by building a mechanical arrangement.

In yet another embodiment of the present invention, the mechanical arrangement comprises tuning by temperature control and/or applied mechanical strain through a sensitive piezoelectric element, or an applied transverse direct
5 current (DC) electric field in the proximity of the fiber.

In yet a further embodiment of the present invention, measuring the output pulse characteristics at the output of the grating is performed by a measuring device comprising an optical sensor that translates photons flux into electric current, and an
10 I/O unit that allows one to observe the measured electric current as a function of time or as an averaged electric current.

In yet another embodiment of the present invention, the measuring device is an optical sensor followed by an oscilloscope.

In yet another embodiment of the present invention, a plurality of non-
15 uniform one-dimensional photonic crystals are used simultaneously by splitting the input laser pulse a plurality of gratings and measuring the output of the plurality of grating simultaneously. The plurality of gratings can be tuned differently from each other in order to obtain more accurate (higher resolution) estimations of the environmental parameter at a given time.

20 In yet another aspect the present invention relates to an optical router for mechanical control over the propagation direction of optical pulses, comprising:

(i) a non-uniform one-dimensional photonic crystal receiving a plurality of input optical pulses, comprising: a first region used to obtain Bragg solitons; a second region used to slow down propagating Bragg solitons; and a third region
25 used to de-couple the transmitted Bragg soliton outside the one-dimensional photonic crystal's grating;

(ii) a mechanical controller for controlling the strain of the non-uniform one-dimensional photonic crystal;

such that for strain values below some threshold value the input optical pulses are back-reflected, while above the threshold value the input optical pulses are transmitted.

In one embodiment of the present invention, the mechanical controller is a piezoelectric translator.

The specific parameter of the environmental conditions includes but is not limited to: temperature, barometric pressure, strain, humidity or a concentration of some solvent in a solution in which the non-uniform one-dimensional crystal is situated.

BRIEF DESCRIPTION OF EMBODIMENTS

Fig. 1 show the structure of the chirped FBGs used as a sensor or as an AND gate.

Fig. 2 shows the schematic drawing of the strain-controlled router

Fig. 3 shows the schematic drawing of the novel optical sensor based on soliton propagation.

DESCRIPTION OF THE INVENTION

In Ref. [3] a novel AND gate is presented based on soliton propagation in non-uniform grating. **Fig. 1A** shows the schematic drawing of the non-uniform grating structure that comprises the AND gate. In the specific design, the average index of the grating over one period is not constant along the grating. The average index is given by $n_{eff}(z) = n_{eff}(0) + \Delta n_{eff}(z)$. Along the first section of the grating, the average index is decreased, reaching a minimum value that remains constant along the second, central section, while the average index along the third section is increased, towards its initial value at $z = 0$. The role of the first section is to adiabatically bring the photonic bandgap closer towards the propagating soliton frequency contents. As a result the soliton slows down. In the case of the AND gate,

a single soliton is back reflected before reaching section II. However, if two solitons are launched, during the two-soliton interaction one of the solitons central frequency is up-shifted. As a result, the soliton penetrates section II of the grating, and is accelerated along section III. The frequency gain needed to alter the soliton propagation direction is small, on the order of ~50MHz, in case of the specific structure chosen in Ref. [3].

A similar effect of the grating on the soliton propagating can be obtained if instead of decreasing and increasing the average refractive index $n_{eff}(z)$ along sections I and III respectively, the local grating pitch is decreased in section I and increased in section III. Another option is to keep the average refractive index and the grating pitch constant along the grating, only changing the modulation depth of the grating, increasing it along section I, and decreasing it along section III..

Instead of inducing change in soliton frequency, soliton propagating direction along the grating can be altered by slightly changing the effective Bragg wavelength of the grating. Decreasing Bragg wavelength will bring the created photonic bandgap closer to the propagating soliton, and as a result a soliton that would penetrate the structure before the small increase in the Bragg wavelength, can be back reflected after the small increase.

According to the Bragg condition formula, the decrease in Bragg wavelength can be caused by (a) decrease in the average refractive index or (b) the grating pitch. Grating pitch can be controlled with a sub-picometer resolution using piezo-electric stages. By connecting one of the gating ends to a stationary stage, and the other end to a piezo-electric stage, as shown in **Fig. 2**, the grating pitch can be controlled by the piezo-stage position, accurately increasing or decreasing the strain along the grating. By changing the grating strain using the piezo stage, one can control whether the entering pulse will be transmitted or back-reflected from the grating, obtaining a router that can be controlled by mechanical strain.

The grating pitch change can be induced by various physical changes in the environment of the fiber, such as physical strain, temperature change, humidity change (effectively, through the propagating mode propagation constant) etc.

Accordingly, the described device of the invention can sense extremely small changes in the environment and translate these changes into drastic changes in the transmission intensity. The typical measurement setup to detect such changes is depicted in **Fig. 3**. It includes a grating similar to that introduced above, a (optionally pulsed), stable laser source **10** that generates pulses train for repetitive launching of Bragg solitons at a sufficiently stable frequency and an optical detector **20** on the transmission side of the grating. Optionally, the optical detector **20** can also be connected to a power meter **30** (or any other available measuring device or method) to reflect the change in the measured environmental parameter. The laser frequency and the grating pitch can be tuned one towards the other, both by using laser frequency tuning and the grating strain tuning by the piezo-electric stage. The grating should be put in such way, so that the physical force under the measurement would apply on it. The optical detector **20** would measure the optical intensity at the output of the grating. When the applied physical force becomes lower or higher of some threshold value, the direction of propagating of the Bragg soliton would change. As a result a drastic change in grating transmission would be detected by the sensor.

The sensor relies on propagation of slow Bragg solitons. Since the losses in FBGs are much higher than the losses in untreated fiber, the slowly propagating Bragg solitons can experience a sufficient attenuation while propagating through the grating. Due to the losses the propagating soliton can break and couple to dispersive waves. Accordingly, we propose a method to overcome the attenuation of slow Bragg solitons in the above mentioned sensor and also for other applications not described here. The idea is to write the FBG for Bragg solitons propagation into an Erbium doped fiber, similarly to the distributed feedback (DFB) lasers. Here, however, our interest is not to use the grating as a laser amplifying cavity, but only to achieve a sufficient distributed gain to overcome the losses. As a result we do not restrict ourselves to phase-shifted gratings and to optical frequencies well inside the bandgap.

The sensitivity of the sensor of the invention can be determined as following:

The Bragg condition is:

$$\lambda = 2n_{eff}\Lambda \quad (5)$$

Where λ is the optical wavelength in the vacuum, Λ is the grating pitch and n_{eff} is the effective refractive index of the fiber. For optical fibers and wavelength in the IR (infrared) region, $n_{eff} \approx 1.5$.

As demonstrated for the AND gate, a change of 50MHz in the carrier frequency of the incident pulse causes the soliton to be transmitted or reflected and as a result a peak power detection at the output of the grating changes from 0 to approximately 3 kW. For optical wavelength close to 1550 nm, a deviation of +1nm in the optical wavelength is equivalent to approximately -125 GHz deviation in optical frequency. Hence, a change of 50MHz corresponds to approximately 0.4pm change in the optical wavelength. As a result, the sensitivity of our sensor can be defined as:

$$S_\lambda = \left| \frac{\Delta I}{\Delta \lambda} \right| = \frac{3kW}{0.4pm} \approx 7.5 \frac{kW}{pm} \quad (6)$$

Next, we may use different expansion constants for the silica to determine the temperature and the pressure sensitivity of our device. According to Eq. (5) a connection between the change in the optical wavelength, $\Delta\lambda$, the change in the grating pitch, $\Delta\Lambda$, and the change in the effective refractive index, Δn_{eff} , is given by:

$$\Delta\lambda = 2n_{eff}\Delta\Lambda + 2\Lambda\Delta n_{eff} \quad (7)$$

We base the calculations upon Ref [4].

For a pressure change, ΔP we get:

$$\begin{aligned} \frac{\Delta\Lambda}{\Delta P} &= -\Lambda \frac{1-2\nu}{Y} \approx 5.2 \times 10^{-6} \frac{pm}{Pa} \\ \frac{\Delta n_{eff}}{\Delta P} &= \frac{1-2\nu}{Y} \frac{n_{eff}^3}{2} (p_{11} + 2p_{12}) \approx 6.9 \times 10^{-12} \frac{1}{Pa} \end{aligned} \quad (8)$$

where ν is the Poisson's ratio of silica ($\nu = 0.16$), Y is the Young's modulus ($Y = 6.5 \times 10^{10} \text{ Pa}$), $p_{11} = 0.12$ and $p_{12} = 0.27$. As a result the pressure sensitivity S_p is:

$$S_p = \left| \frac{\Delta I}{\Delta P} \right| = \left| \frac{\Delta I}{\Delta \lambda} \left(\frac{\Delta \lambda}{\Delta \Lambda} \Big|_{\Delta n_{eff}=0} \frac{\Delta \Lambda}{\Delta P} + \frac{\Delta \lambda}{\Delta n_{eff}} \Big|_{\Delta \Lambda=0} \frac{\Delta n_{eff}}{\Delta P} \right) \right| \approx 0.065 \frac{W}{Pa} = 65 \frac{kW}{N/mm^2} \quad (9)$$

5

For the temperature sensitivity, we have:

$$\begin{aligned} \frac{\Delta \Lambda}{\Delta T} &= \Lambda \cdot 5 \times 10^{-7} \frac{1}{^\circ C} = 0.25 \frac{pm}{^\circ C} \\ \frac{\Delta n_{eff}}{\Delta T} &= -10^{-5} \frac{1}{^\circ C} \end{aligned} \quad (10)$$

As a result the temperature sensitivity S_T is:

$$S_T = \left| \frac{\Delta I}{\Delta T} \right| = \left| \frac{\Delta I}{\Delta \lambda} \left(\frac{\Delta \lambda}{\Delta \Lambda} \Big|_{\Delta n_{eff}=0} \frac{\Delta \Lambda}{\Delta T} + \frac{\Delta \lambda}{\Delta n_{eff}} \Big|_{\Delta \Lambda=0} \frac{\Delta n_{eff}}{\Delta T} \right) \right| \approx 64 \frac{kW}{^\circ C} \quad (11)$$

10

Although the invention has been described in detail, nevertheless changes and modifications, which do not depart from the teachings of the present invention, will be evident to those skilled in the art. Such changes and modifications are deemed to come within the purview of the present invention and the appended claims.

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CLAIMS

Claim 1. An optical sensor for measuring changes in an environmental parameter, comprising:

(i) a non-uniform one-dimensional photonic crystal receiving a plurality of input optical pulses, comprising: a first region used to obtain Bragg solitons; a second region used to slow down propagating Bragg solitons; and a third region used to de-couple the transmitted Bragg soliton outside the one-dimensional photonic crystal's grating;

(ii) a laser source adapted for repetitive generation of pulses of sufficiently stable frequency for repetitive launching of Bragg solitons towards said one-dimensional photonic crystal;

(iii) a detector for measuring the characteristics of the output pulse of the said one-dimensional photonic crystal; and

(iv) a predetermined scale to convert the measurements of the output pulse to the corresponding environmental parameter

such that laser light frequency and the one-dimensional photonic crystal's grating pitch are tuned to a point, where the sensitivity of the sensor is at maximum, corresponding to a known environmental parameter according to a predetermined scale, and given the change in the measured output pulse characteristics, the change in the environmental parameter is estimated according to said predetermined scale.

Claim 2. An optical sensor according to claim 1, wherein said environmental parameter comprises: temperature, barometric pressure, strain, humidity or a concentration of a solvent in a solution in which the sensor is situated.

Claim 3. An optical sensor according to claim 1, wherein said one-dimensional photonic crystal is a non-uniform fiber Bragg grating (FBG), Multilayer films, a

quasi-periodic structure of the refractive index implemented in chalcogenide-based planar waveguides or a quasi-periodic structure of the refractive index implemented in Erbium doped fiber.

5 Claim 4. An optical sensor according to claim 3, wherein said FBG is a chirped FBG or an appodized FBG.

Claim 5. An optical sensor according to claim 1, wherein the measured characteristics of the output pulse are intensity or energy or both.

10 Claim 6. An optical sensor according to claim 1, wherein said non-uniform one-dimensional photonic crystal comprises a first appodization section, in which the modulation amplitude of the grating is monotonically increasing towards the center of the photonic crystal for efficient coupling of light into the grating.

15 Claim 7. An optical sensor according to claim 1, wherein said non-uniform one-dimensional photonic crystal comprises a chirped section of a finite length, in which the grating period is monotonically decreasing towards the center of the photonic crystal in case of optical material with positive non-linearity, or monotonically increasing towards the center of the photonic crystal in case of optical material with negative non-linearity.

20 Claim 8. An optical sensor according to claim 1, wherein said non-uniform one-dimensional photonic crystal further comprises another appodization section for efficient light de-coupling from the grating, in which the modulation amplitude of the grating is decreasing along the photonic crystal outwards from the center.

Claim 9. An optical sensor according to claim 1, wherein the grating is fabricated inside Erbium doped fiber to overcome losses in the grating, in which case the grating is pumped by a pumping laser.

Claim 10. An optical sensor according to claim 1, wherein said laser source is a CW laser followed by optical modulators and Erbium doped optical amplifiers, mode-locked lasers or Q-switched lasers.

5 Claim 11. An optical sensor according to claim 10, wherein said laser source is followed by a narrow-band filter for further frequency stabilization of said laser source.

Claim 12. An optical sensor according to claim 1, wherein tuning the grating pitch is performed by building a mechanical arrangement.

10 Claim 13. An optical sensor according to claim 12, wherein said mechanical arrangement comprises grating tuning by temperature control and/or applied mechanical strain through a sensitive piezoelectric element, or by applied DC electrical field.

Claim 14. An optical sensor according to claim 1, wherein measuring the output pulse characteristics at the output of the grating is performed by a measuring device
15 comprising an optical sensor that translates photons flux into electric current, and an I/O unit that allows one to observe the measured electric current as a function of time or as an averaged electric current.

Claim 15. An optical sensor according to claim 14, wherein said measuring device is an optical sensor followed by an oscilloscope.

20 Claim 16. An optical sensor according to claim 1, wherein a plurality of non-uniform one-dimensional photonic crystals are used simultaneously by splitting the input laser pulse between the said plurality of non-uniform one-dimensional photonic crystal and measuring the output of the plurality of non-uniform one-dimensional photonic crystals simultaneously.

25 Claim 17. A method for measuring a change in a given environmental parameter, comprising the steps of:

- 5 (i) implementing a non-uniform one-dimensional photonic crystal comprising: a first region used to obtain Bragg solitons; a second region used to slow down propagating Bragg solitons; and a third region used to de-couple transmitted Bragg solitons outside the one-dimensional photonic crystal;
- (ii) generating by a laser source pulses train for repetitive launching of Bragg solitons at a sufficiently stable frequency towards said non-uniform one-dimensional photonic crystal;
- 10 (iii) tuning the laser light frequency and the one-dimensional photonic crystal's grating pitch to a point of high sensitivity, such that a low magnitude change in the environmental parameter triggers a high magnitude change in the output pulse characteristics; and
- 15 (iv) detecting the change in the given environmental parameter by measuring the change in the measured output pulse characteristics, and estimating the environmental parameter change magnitude according to a predefined scale.

Claim 18. A method according to claim 17, wherein said environmental parameter comprises: temperature, barometric pressure, strain, humidity or a concentration of some solvent in a solution in which the photonic crystal is situated.

20 Claim 19. A method according to claim 17, wherein said one-dimensional photonic crystal is a non-uniform fiber Bragg grating (FBG), Multilayer films, a quasi-periodic structure of the refractive index implemented in chalcogenide-based planar waveguides or a quasi-periodic structure of the refractive index implemented in Erbium doped fiber.

25 Claim 20. A method according to claim 19, wherein said non-uniform photonic crystal is a chirped one or an apodized one.

Claim 21. A method according to claim 17, wherein said non-uniform one-dimensional photonic crystal comprises a first appodization section, in which the modulation amplitude of the grating is monotonically increasing towards the center of the photonic crystal for efficient coupling of light into the grating.

- 5 Claim 22. A method according to claim 17, wherein said non-uniform one-dimensional photonic crystal comprises a chirped section of a finite length, in which the grating period is monotonically decreasing towards the center of the photonic crystal in case of optical material with positive non-linearity, or monotonically increasing towards the center of the photonic crystal in case of optical material with
10 negative non-linearity.

Claim 23. A method according to claim 17, wherein said non-uniform one-dimensional photonic crystal further comprises another appodization section for efficient light de-coupling from the grating, in which the modulation amplitude of the grating is decreasing outwards from the center of the photonic crystal .

- 15 Claim 24. A method according to claim 17, wherein the grating is fabricated inside Erbium doped fiber to overcome losses in the grating, in which case the grating is pumped by a pumping laser.

Claim 25. A method according to claim 17, wherein the said pulsed laser source is a CW laser followed by optical modulators and Erbium doped optical amplifiers,
20 mode-locked lasers or Q-switched lasers.

Claim 26. A method according to claim 25, wherein said laser source is followed by a narrow-band filter for further frequency stabilization of the said laser source.

Claim 27. A method according to claim 17, wherein tuning the grating pitch is performed by building a mechanical arrangement.

- 25 Claim 28. A method according to claim 27, wherein said mechanical arrangement comprises grating tuning by temperature control and/or applied

mechanical strain through a sensitive piezoelectric element, or by applied DC electrical field.

5 Claim 29. A method according to claim 17, wherein measuring the output pulse characteristics at the output of the grating is performed by a measuring device comprising an optical sensor that translates photons flux into electric current, and an I/O unit that allows one to observe the measured electric current as a function of time or as an averaged electric current.

Claim 30. A method according to claim 29, wherein said measuring device is an optical sensor followed by an oscilloscope.

10 Claim 31. A method according to claim 17, wherein a plurality of non-uniform one-dimensional photonic crystals are used simultaneously by splitting the input laser pulse between the said plurality of non-uniform one-dimensional photonic crystal and measuring the output of the plurality of non-uniform one-dimensional photonic crystals simultaneously.

15 Claim 32. An optical router for mechanical control over the propagation direction of optical pulses, comprising:

20 (i) a non-uniform one-dimensional photonic crystal receiving a plurality of input optical pulses, comprising: a first region used to obtain Bragg solitons; a second region used to slow down propagating Bragg solitons; and a third region used to de-couple the transmitted Bragg soliton outside the one-dimensional photonic crystal's grating;

(ii) a mechanical controller for controlling the strain of the non-uniform one-dimensional photonic crystal;

25 such that for strain values below some threshold value the input optical pulses are back-reflected, while above the threshold value the input optical pulses are transmitted.

Claim 33. An optical router according to claim 32, wherein the mechanical controller is a piezoelectric translator.

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Fig. 1

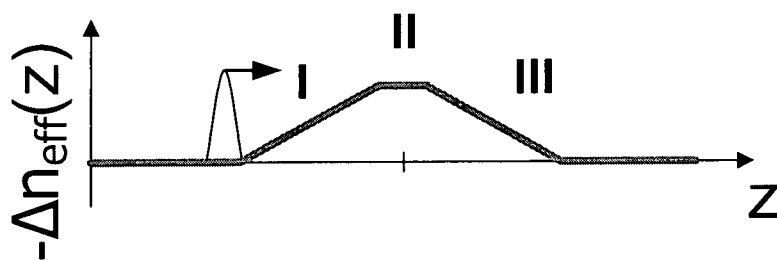


Fig. 2

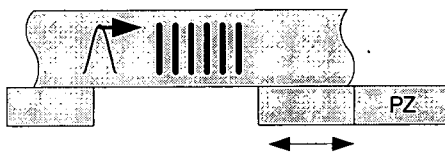
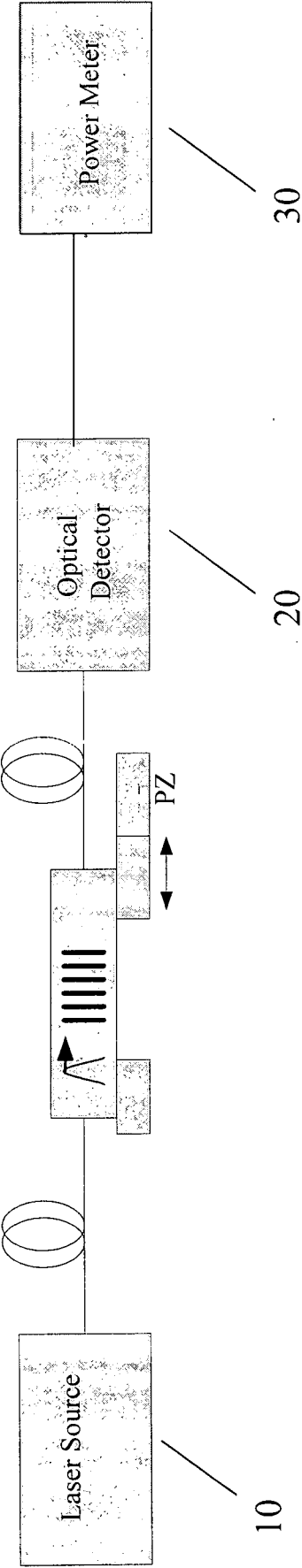


Fig. 3



INTERNATIONAL SEARCH REPORT

International application No
PCT/IL2009/000038

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01B11/16 G01D5/353 G01K11/32 G01L1/24

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)

G01B G01D G01K G01L G02B G01F

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 practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	SHAPIRA Y P ET AL: "OPTICAL AND GATE BASED ON SOLITON INTERACTION IN A FIBER BRAGG GRATING" OPTICS LETTERS, OSA, OPTICAL SOCIETY OF AMERICA, WASHINGTON, DC, US, vol. 32, no. 10, 15 May 2007 (2007-05-15), pages 1211-1213, XP001541124 ISSN: 0146-9592 cited in the application page 1211, left-hand column, line 1 - right-hand column, last line ; figure 1 -----	1-31
A	US 5 844 927 A (KRINGLEBOTN JON THOMAS [NO]) 1 December 1998 (1998-12-01) column 1, line 5 - column 7, line 18; figures 1-5 ----- -/--	1-31

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

☒ 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 document but published on or after the international filing date
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- *O* document referring to an oral disclosure, use, exhibition or other means
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Date of the actual completion of the international search

17 April 2009

Date of mailing of the international search report

15/06/2009

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INTERNATIONAL SEARCH REPORT

International application No

PCT/IL2009/000038

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	W. GORNALL, T. AMAREL: "Applications and techniques for fiber Bragg grating sensor measurements" FIBER BRAGG GRATING SENSORS, no. 1, 2003, XP002524111 EXFO Burleigh Products Group Retrieved from the Internet: URL: http://www.ottawaphotonics.com/mailings/FBG.pdf [retrieved on 2009-04-16] the whole document -----	1-31

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL2009/000038

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers allsearchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search reportcovers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

see annex

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-31

Environmental sensor

2. claims: 32-33

Optical router

Information on patent family members

PCT/IL2009/000038

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