(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
8 September 2017 (08.09.2017)

WIPO | PCT

(10) International Publication Number
WO 2017/148937 A1

(51) International Patent Classification:
G02B 6/12 (2006.01) *G02B 6/293* (2006.01)

(21) International Application Number:
PCT/EP2017/054631

(22) International Filing Date:
28 February 2017 (28.02.2017)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
PA 2016 70122 2 March 2016 (02.03.2016) DK

(71) Applicant: UNIVERSITY OF COPENHAGEN [DK/DK]; Nørregade 10, 1165 Copenhagen K (DK).

(72) Inventors: MIDOLO, Leonardo; c/o University of Copenhagen, Nørregade 10, 1165 Copenhagen (DK). STOBBE, Søren; Dannebrogsgade 31, 3rd floor left, 1600 København V (DK). LODAHL, Peter; J.N. Vinthers Vej 11, 3460 Birkerød (DK).

(74) Agent: COPA COPENHAGEN PATENTS; Rosenørns Allé 1, 2nd floor, 1970 Frederiksberg C (DK).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

(54) Title: WAVEGUIDE-INTEGRATED TUNEABLE OPTICAL FILTER

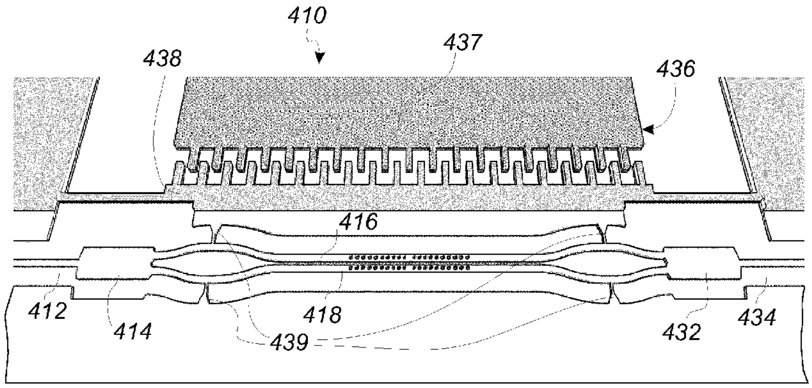

Fig. 5

(57) Abstract: A tuneable optical filter (10, 110, 210, 310, 410) comprising an input waveguide (12, 412), an optical power coupler (14, 414), and two substantially parallel photonic crystal waveguides (16, 416; 18, 418) is disclosed. The optical power coupler (14, 414) is optically coupled between the input waveguide (12, 412) and the two parallel photonic crystal waveguides (16, 416; 18, 418), and the optical power coupler (14, 414) is adapted to split incoming light from the input waveguide (12, 412) into two in-phase light outputs, which are coupled to the two parallel photonic crystal waveguides (16, 416; 18, 418). The tuneable optical filter further comprises an actuator (36, 136, 236, 336, 436), which is arranged and adapted to be able to vary a spacing (d) between the two waveguides (16, 416; 18, 418).

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Waveguide-integrated tuneable optical filter

Field of the Invention

The present invention relates to a tuneable optical filter as well as an optical device comprising such a tuneable optical filter. The invention further relates to a method of optical filtering light.

Background of the Invention

Spectral filtering is a crucial application in hundreds of optics and photonic devices. Spectral filtering is for example used at the core of spectroscopes and spectral analysers, which are commonly used in astronomy and chemistry to identify materials by their absorption.

The miniaturisation of photonic components has recently opened new possibilities to integrate hundreds of devices in a single microchip and to build photonic integrated circuits. These circuits are at the basis of modern electro-optical communications, but are being increasingly employed in many other fields including displays, optical data storage and healthcare. Recently, a large interest has been devoted to realise optical circuits operating at the single-photon level, where the quantum features of light can be harnessed to develop quantum simulators. In this context, the need for ultra-small, low-power, low-loss and scalable devices is crucial to achieve portable, low-carbon footprint and inexpensive products, which make use of light for sensing or information processing.

The essential functionalities of a photonic circuit can be categorised in three aspects: generation (including amplification), manipulation, and detection. Recently the manipulation of light in a chip has gained a lot of attention for the all-optical operation of photonic circuits. The ability to control light in the spectral domain as well as in the time domain is extremely advantageous to perform tasks, such as routing, filtering, and multiplexing.

There exist so-called mini-spectrometers on the market, which are made with millimetre-sized polychromators. These devices are often erroneously considered integrated optical devices, however; they are not integrated on a chip.

Today on-chip spectral filtering may be carried out by arrayed waveguide (AWG) multiplexers or integrated diffraction gratings. However, these devices are not tuneable and provide limited bandwidth and resolving power. They operate in a similar way to prisms and dispersion gratings by funnelling light into different waveguides depending on the wavelength.

Xiongyeu Chew et al.: "Dynamic tuning of an optical resonator through MEMS-driven coupled photonic crystal nanocavities", Optics Letters, Vol. 35, no. 15, pages 2517-2519 (D1) discloses dynamic tuning of optical resonance using MEMS-driven coupled photonic crystal (PhC) cavitivies. The described setup comprises a one-dimensional PhC coupled to an input and an output waveguide and is labeled "cavity A", and a perturbing nanocavity labelled "cavity B". The distance between the two cavities may be varied by use of the MEMS-driven actuator in order to tune the resonance frequency. Both cavities are formed by a Fabry-Perot resonator. Cavity B is identical to Cavity A with the exception that out-tapered holes are replaced with five additional Bragg-stack holes in order to prevent the resonant mode from coupling to the perturbing structure, which in turn prevents unnecessary losses.

Summary of the Invention

It is an object of the invention to obtain a tuneable optical filter and an optical device as well as a method of optical filtering light, which overcome or ameliorate at least one of the disadvantages of the prior art or which provides a useful alternative.

This is according to the invention achieved by a tuneable optical filter comprising an input waveguide, an optical power coupler, and two substantially parallel photonic crystal waveguides, wherein

- the optical power coupler is optically coupled between the input waveguide and the two parallel photonic crystal waveguides, wherein the optical power coupler is adapted to split incoming light from the input waveguide into two in-phase light outputs, which are coupled to the two parallel photonic crystal waveguides, where the tuneable optical filter further comprises:

- an actuator, which is arranged and adapted to be able to vary the distance or spacing between the two substantially parallel photonic crystal waveguides.

Thereby, the invention provides a tuneable optical filter, which truly can be integrated on a single chip. The invention allows the performance of light filtering directly in the chip without having to use free-space elements, such as gratings or prisms. Accordingly, the invention adds a whole new range of functionalities in classic and quantum photonic integrated circuits. Since the light is split up into two in-phase light output, no anti-bonding modes occur, and the light can propagate through the filter with low or no loss, i.e. the efficiency being close to unity. This is in contrast to D1, in which the coupled light will be split up into bonding and anti-bonding stages in the cavity.

The tuneable optical filter provides a continuously tuneable solution with a single-input single-output design. This provides a huge advantage over existing application, such as spectrometers, where many detectors are typically needed on each output arm.

It is clear that the two parallel photonic crystals each comprise a first end and a second end and that the optical power coupler is optically coupled between the input waveguide and first ends of the two parallel photonic crystal waveguides.

The tuneable optical filter has potential applications in a wide range of measurement techniques, such as but not limiting to optical shape sensing, medical imaging, and non-invasive food inspection.

In general, the two parallel photonic crystals have an identical design, i.e. an identical hole design.

According to an advantageous embodiment, the optical power coupler is a 1:2 optical power coupler, such as a 1x2 multi-mode interference coupler. This ensures that the light is split up into two equally powered outputs and maximises the light interaction between the two outputs through the two substantially parallel photonic crystal waveguides and hence the filtering.

According to another advantageous embodiment, the two parallel photonic crystal waveguides are one-dimensional photonic crystal waveguides. The two parallel photonic crystal waveguides may comprise four identical photonic crystal mirrors arranged to form a coupled cavity. Thus, the two substantially parallel photonic crystal waveguides form the coupled cavity. In such a cavity, the optical resonances are split up into bonding and anti-bonding modes due to evanescent coupling between waveguides. The anti-bonding modes are not relevant, since the light in the two waveguides propagate in phase as opposed to D1. The bonding mode is very sensitive to the actual geometry and in particular to the waveguide-to-waveguide distance or spacing. Thus, the coupled cavity provides a stronger tuning capability.

In one embodiment, the input waveguide is a single-mode waveguide.

In another embodiment, the optical filter further comprises an optical combiner and an output waveguide, wherein the optical combiner is arranged between the two parallel photonic crystal waveguides and the output waveguide. The output waveguide may be a single-mode waveguide.

As previously mentioned, the two parallel photonic crystals each comprise a first end and a second end. Accordingly, the optical power combiner is optically coupled between the output waveguide and the second ends of two parallel photonic crystal waveguides.

The two parallel photonic crystal waveguides may each comprise a row of at least 6 holes in a longitudinal direction of the two parallel photonic crystal waveguides. The rows may also comprise at least 8, or at least 10 holes. Further, the two parallel crystal waveguides may each comprise a row comprising at most 100, or at most 75, or at most 50 holes in the longitudinal direction.

The holes are arranged in a background material, where the material of the holes and the material of the background material have different refractive indices. The holes may be air holes or holes made from a different material than the background material.

In yet another embodiment, the photonic crystal mirrors comprise a row of 3-25 holes in the longitudinal direction of the two parallel photonic crystal waveguides.

The holes are preferably arranged in a lattice with a mutual spacing equal to a lattice constant *a*. In one embodiment, the photonic crystal mirrors are formed by displacing or removing one or more holes in each of the two parallel photonic crystal waveguides.

The lattice constant *a* may advantageously lie in the interval 100-500 nm, or 150-400 nm, or 200-300 nm, e.g. around 250 nm.

In one embodiment, a width of each the two parallel photonic crystal waveguides is in the range of 0.5-3 times the lattice constant *a*, advantageously in the range of 0.8-2 times the lattice constant *a*.

In an advantageous embodiment, the actuator is adapted to vary a spacing between the two parallel photonic crystal waveguides in the interval 10-1000 nm, or the interval of 25-800 nm, or the interval of 50-600 nm. The spacing is defined by the distance between sides of the two parallel photonic crystal waveguides.

In another advantageous embodiment, the optical filter is tuneable over a wavelength range of at least 50 nm, advantageously at least 75 nm.

In yet another advantageous embodiment, the optical filter has a Q factor of at least 2500, advantageously at least 4000. This means that the 3dB transmission bandwidth and hence the resolution of the tuneable optical filter is always below 220 pm.

The planar waveguide may advantageously be made from a dielectric material, such as III-V semiconductor material or a silicon-based material, e.g silicon dioxide and/or silicon nitride. The III-V semiconductor material may for instance be made of Gallium Arsenide (GaAs) or Indium Gallium Arsenide (InGaAs). The waveguide may also be made from InP or InGaAsP, which are commonly used in telecom-wavelength photonic integrated circuits.

The optical device may advantageously be provided on a single substrate. The substrate can be manufactured in one or a few steps and thus be mass-produced in manufacturing facilities known per se.

Advantageously, the first nanostructure and/or the second nanostructure comprise air holes. However, in principle the nanostructure may also be made of a different material than the remainder of the planar waveguide material and having a refractive index being different from that of the remainder.

In one embodiment, the planar waveguide is made of a material having a refractive index in the region of 2-5, or 2.5-4.5, e.g. around 3.5, i.e. the material is made of e.g. a high refractive index dielectric. In another embodiment, a difference in refractive index of the planar waveguide material and the first and second nanostructures is in the region of 1-4, or 1.5-3.5, e.g. around 2.5.

In one advantageous embodiment, the actuator is one or more MEMS-based actuators. This provides a simple way of implementing a solution for varying the distance or spacing between the two substantially parallel photonic crystal waveguides on a chip. The MEMS-based actuator may for instance comprise a stator and a shuttle, e.g. based on a comb-design for moving the shuttle relative to the stator. The actuator may be based on one MEMS-based actuator for moving one of the two parallel waveguide relative to the other. The actuator may also be based on two MEMS-based actuators, such that both parallel waveguides may be moved independently of the other. The shuttle may advantageously be movable relative to the stator via electrostatic forces.

In one embodiment, the MEMS-based actuator comprises a highly doped semiconductor layer on top of a slab, e.g. n- or p-doped, such that the layer is able to conduct a current and form electrostatic forces. The MEMS-based actuator may also be made of an electrically conductive metal.

In one advantageous embodiment, at least one of the two parallel photonic crystal waveguides is connected to the MEMS-based actuator via a number of thin tethers. This provides a low optical-loss to connection to the electrostatic MEMS-based actuator.

In another advantageous embodiment, the optical filter comprises a wafer having a substrate, a sacrificial layer on top of the substrate, and a membrane on top of the sacrificial layer.

The membrane is the optical conductive layer and may advantageously have a thickness of between 0.2*a* and 1*a*, or between 0.4*a* and 0.8*a*, or between 0.3*a* and 0.7*a*, e.g. around 0.5*a* or 0.6*a*, where *a* is the distance between holes in the photonic crystal waveguides. Alternatively, the planar waveguide may have a thickness in the range of 50-500 nm, or 75-350 nm, or 100-250 nm, e.g. around 150 nm. Accordingly, it is seen that the optical conductive layer is a slab waveguide having a relative small thickness, or also what in the technical area is called a membrane.

The substrate may for instance be made of GaAs. The sacrificial layer may for instance be made of AlGaAs, e.g. having an Al-contents of 50-85%, e.g. approximately 75%. The membrane may for instance be made of GaAs. The sacrificial layer may for instance have a thickness of 100-2500 nm, e.g. around 1500 nm.

In yet another advantageous embodiment, an etch stop layer is arranged on top of the membrane, and a conductive layer is arranged on top of the etch stop layer. The etch stop layer may for instance be made of p-doped AlGaAs, e.g. having an Al-contents of 50-85%, e.g. approximately 75%. The conductive layer may for instance be made of highly p-doped or n-doped GaAs.

The invention also provides an optical device comprising a tuneable optical filter according to any of the preceding claims.

In a first embodiment, the optical device is a spectrometer or a spectral analyser. In a second embodiment, the optical device is an optical interrogator. The interrogator may for instance be used for optical coherence tomography and optical shape sensing, e.g. in for instance optical frequency-domain reflectometry.

In a third embodiment, the optical device is a single-photon optical device. Accordingly, the optical device is a single-photon source with embedded spectral filtering. The single-photon emitter, such as a quantum dot, may be embedded in the waveguide.

In an advantageous embodiment, the optical device further comprises a photo detector coupled to an output waveguide of the tuneable optical filter. Thus, the detector may directly probe the filtered light.

In one embodiment, the optical device comprises a plurality of tuneable optical filters including at least a first tuneable optical filter and a second tuneable optical filter. The first tuneable optical filter may be tuneable over a first wavelength range, and the second tuneable optical filter may be tuneable over a second wavelength range. By combining a plurality of tuneable optical filters, the overall tuneable range may be expanded and tailored to the specific needs. The first wavelength range and the second wavelength range may be juxtaposed, neighbouring or overlapping.

In one embodiment, the optical device comprises an optical multiplexer so as to split up light into different wavelength ranges, which are sent to different tuneable optical filters. The multiplexer may form partial spectrums according to the aforementioned first wavelength range and second wavelength range.

In a second aspect, the invention provides a method of optical filtering light, the method comprising the following steps:

a) inputting an incoming light into an input waveguide,

b) splitting light up into two in-phase light waves that are input into two substantially parallel photonic crystal waveguides, and

c) tuning a transmission peak wavelength to a desired wavelength by varying the distance or spacing between the two substantially parallel photonic crystal waveguides.

Thereby the invention provides a tuneable optical filter, which truly can be integrated on a single chip. The invention allows the performance of light filtering directly in the chip by simply setting the distance between the two substantially parallel photonic crystal waveguides without having to use free-space elements, such as gratings or prisms.

As previously mentioned, the in-phase light waves are input into a first end of the two substantially parallel photonic crystal waveguides.

In an advantageous embodiment, the method further comprises the step of: d) combining outputs from the two substantially parallel photonic crystal waveguides into an output waveguide. In another advantageous embodiment, the method further comprises the step of: e) detecting light emitted from the output waveguide or the two substantially parallel photonic crystal waveguides. Accordingly, the invention provides a method of continuously filtering, combining, and detecting the filtered light.

As previously mentioned, the light from second ends of the two substantially parallel photonic crystal waveguides are combined and input into the output waveguide.

In yet another advantageous embodiment, step c) comprises the step of sweeping the distance between the two substantially parallel photonic crystal waveguides between a first distance and a second distance. Thereby, it is possible to spectrally analyse the wavelength contents of light input into the input waveguide.

The tuneable optical filter is preferably designed as a planar waveguide structure. Main parts of the planar waveguide, such as the two parallel photonic crystal waveguides, are advantageously designed as a floating structure along at least a substantial part thereof. Such a design minimises the losses by minimising light being coupled out of the plane.

Brief Description of the Figures

The invention is explained in detail below with reference to embodiments shown in the drawings, in which

Fig. 1 shows a schematic view of a tuneable optical filter according to the invention,

Fig. 2 shows a schematic view of a first embodiment of an optical device comprising a tuneable optical filter according to the invention,

Fig. 3 shows a schematic view of a second embodiment of an optical device comprising a tuneable optical filter according to the invention,

Fig. 4 shows a schematic view of a third embodiment of an optical device comprising a tuneable optical filter according to the invention,

Fig. 5 shows a schematic view of an MEMS-based setup used for experimentally verifying the invention,

Fig. 6 shows the intensity of light at the two parallel photonic crystal waveguides,

Fig. 7 shows the transmission spectrum as a function of spacing between the two parallel photonic crystal waveguides,

Fig. 8 shows the epitaxial structure of a wafer for the realisation of the MEMS-based filter in GaAs, and

Fig. 9 shows the steps involved in a method according to invention.

Detailed Description of the Invention

Fig. 1 shows a schematic drawing of a tuneable optical filter 10 according to the invention. The tuneable optical filter 10 comprises an input waveguide 12, an optical power coupler 14, and two substantially parallel photonic crystal waveguides comprising a first photonic crystal waveguides 16 and a second photonic crystal waveguides 18. The two substantially parallel photonic crystal waveguides 16, 18 are coupled to an optical coupler 32, which combines the outputs from the two substantially parallel photonic crystal waveguides 16, 18 and inputs the combined light into an output waveguide 34.

The two substantially parallel photonic crystal waveguides each comprise a first end and a second end. The optical power coupler 14 is coupled to the first ends of the two substantially parallel photonic crystal waveguides, and the optical coupler 32 is coupled to the second ends of two substantially parallel photonic crystal waveguides. The two substantially parallel photonic crystal waveguides may advantageously comprise an identical photonic crystal waveguide design.

The optical power coupler 14 splits incoming light from the input waveguide into two in-phase light outputs, which are coupled to the two parallel photonic crystal waveguides 16, 18. The two parallel photonic crystal waveguides 16, 18 are arranged close to each other, whereby the light in the two parallel photonic crystal waveguides 16, 18 interact with each other. The optical power coupler 14 is advantageously a 1:2 optical power coupler, such as a 1x2 multi-mode interference coupler. This ensures that the light is split up into two equally powered outputs and maximises the light interaction between the two outputs.

The two parallel photonic crystal waveguides 18, 20 are preferably formed as one-dimensional photonic crystal waveguides and comprise a number of holes 20, which are distributed along a longitudinal direction of the waveguides 18, 20. The two waveguides may advantageously comprise four substantially identical mirrors 22, 24, 26, 28 and a coupled cavity 30. In the coupled cavity 30, the optical resonances are split up into bonding and anti-bonding modes due to evanescent coupling between waveguides. The anti-bonding modes are not relevant, since the light in the two waveguides propagate in phase. The bonding mode is very sensitive to the actual geometry and in particular the waveguide-to-waveguide distance or spacing. Thus, the coupled cavity provides a strong tuning capability, which can be carried out by varying the spacing *d* between the two parallel waveguides 16, 18 by use of a (not shown) actuator 36, e.g. a MEMS-based actuator. Accordingly, the light emerging from the output waveguide 34 is filtered from the light input into the input waveguide 12 in dependence of the spacing *d* between the two waveguides 16, 18.

Overall, the invention provides a tuneable optical filter 10, which can be integrated on a single chip, wafer or substrate. The invention allows the performance of light filtering directly in the chip without having to use free-space elements, such as gratings or prisms. Since the light is split up into two in-phase light outputs, no anti-bonding modes occur, and the light can propagate through the filter with low or no loss, i.e. the efficiency being close to unity.

The input waveguide 12 and the output waveguide 34 may advantageously be single-mode waveguides.

The tuneable optical filter 10 is preferably designed as a planar waveguide structure. Main parts of the planar waveguide, such as the two parallel photonic crystal waveguides 16, 18, are advantageously designed as a floating structure along at least a substantial part thereof. Such a design minimises the losses by minimising light being coupled out of the plane. The planar waveguide may advantageously be made from a dielectric material, such as an III-V semiconductor material or a silicon-based material, e.g silicon dioxide and/or silicon nitride. The III-V semiconductor material may for instance be made of Gallium Arsenide (GaAs), Indium Gallium Arsenide (InGaAs), or Aluminium Arsenide (AlAs). The waveguide may also be made from InP or InGaAsP, which are commonly used in telecom-wavelength photonic integrated circuits.

The optical device may advantageously be provided on a single substrate. The substrate can be manufactured in one or a few steps and thus be mass-produced in manufacturing facilities known per se.

Fig. 2 shows a first embodiment of an optical device 100 comprising a tuneable optical filter 110 according to the invention, and where detection or pick-up of filtered light is carried out off-chip. The optical device 100 comprises an input optical fibre 140, which emits light 145, which is coupled into the input waveguide of the tuneable optical filter 110. The distance between the two substantially parallel photonic waveguides may be varied by use of at least a first MEMS-based actuator 136, which comprises a stator 137 and a shuttle 138, and which move the second waveguide relative to the first waveguide. It is also possible to utilise a setup with two MEMS-based actuators, whereby both the first and the second waveguide may be moved independently of the other. The MEMS-based actuator 136 is controlled by use of a controller 160 or control circuit. The filtered output light 155 is coupled into an output optical fibre 150, where it may be detected or utilised for specific purposes. The optical device 100 may for instance be a spectrometer, an optical interrogator, or a single-photon optical device.

Fig. 3 shows a second embodiment of an optical device 200 comprising a tuneable optical filter 210 according to the invention, and where detection of filtered light is carried out on-chip. The optical device 200 comprises an input optical fibre 240, which emits light 245, which is coupled into the input waveguide of the tuneable optical filter 210. The distance between the two substantially parallel photonic waveguides may be varied by use of at least a first MEMS-based actuator 236, which comprises a stator 237 and a shuttle 238, and which move the second waveguide relative to the first waveguide. It is also possible to utilise a setup with two MEMS-based actuators, whereby both the first and the second waveguide may be moved independently of the other. The MEMS-based actuator 236 is controlled by use of a control and data acquisition unit 260. The filtered output light is detected on-chip by e.g. a photodiode or a superconducting nanowire detector 270. The optical device 200 further comprises a photo detector measurement circuit 280, which may also be coupled to the control and data acquisition unit 260, such that the measured light intensity may be plotted against the filter wavelength. The optical device 200 may for instance be a spectrometer, an optical interrogator, or a single-photon optical device.

Fig. 4 shows a third embodiment of an optical device 300 comprising a plurality of tuneable optical filters 310^1-310^N according to the invention, and where detection of filtered light is carried out on-chip. The optical device 300 comprises an input optical fibre 340, which emits light 345, which is coupled into a multiplexing device 390, e.g. in form of a 1 to N switch matrix or an arrayed waveguide grating. The multiplexing device 390 splits the incoming light up into a plurality of wavelength regions λ_1- λ_N, each of which is coupled into a separate tuneable optical filter 310^1-310^N. The wavelength regions λ_1- λ_N may be juxtaposed or slightly overlapping.

The distance between the two substantially parallel photonic waveguides of each of the tuneable optical filters 310^1-310^N may be varied by use of at least a first dedicated MEMS-based actuator 336^1-336^N, which comprises a stator 337^1-337^N and a shuttle 338^1-338^N, and which move the second waveguide relative to the first waveguide. It is also possible to utilise a setup with two dedicated MEMS-based actuators, whereby both the first and the second waveguide may be moved independently of the other. The MEMS-based actuators 336^1-336^N are controlled by use of a control and data acquisition unit 360.

The filtered output light of each of the tuneable optical filters 310^1-310^N is detected on-chip by e.g. a photodiode or a superconducting nanowire detector 370^1-370^N. The optical device 300 further comprises a plurality of photo detector measurement circuits 380^1-380^N, which are also be coupled to the control and data acquisition unit 360, such that the measured light intensity may be plotted against the filter wavelength.

The optical device 300 is highly advantageous for a spectrometer setup, since the incoming light may be split up into a number of different tuneable ranges, whereby the total range of the tuneable optical filters may be expanded.

Fig. 5 shows a schematic view of an MEMS-based setup of a tuneable optical filter 410, which has been used for experimentally verifying the invention, where the tuneable optical filter has been integrated on a single wafer. The tuneable optical filter 410 comprises an input waveguide 412, an optical power coupler 414, and two substantially parallel photonic crystal waveguides comprising a first photonic crystal waveguide 416 and a second photonic crystal waveguide 418. The two substantially parallel photonic crystal waveguides 416, 418 are coupled to an optical combiner 432, which combines the outputs from the two substantially parallel photonic crystal waveguides 416, 418 and inputs the combined light into an output waveguide 434.

The spacing between the two substantially parallel photonic crystal waveguides 416, 418 may be varied by use of a MEMS-based actuator 436, which comprises a stator 437 and a shuttle 438 utilising a comb-structure and electrostatic forces to move the shuttle 438 relative to the stator 437.

The first photonic crystal waveguide 416 and the second photonic crystal waveguide 418 are coupled to the wafer via thin tethers, whereby it is ensured that optical losses are kept low. The wafer is designed such that the first photonic crystal waveguides 416 is coupled to the shuttle part of the MEMS-based actuator 436, whereas the second photonic crystal waveguides 418 is substantially stationary with the stator of the MEMS-based actuator 436.

As previously mentioned, it is also possible to design the wafer such that a first MEMS-based actuator is utilised to move the first photonic crystal waveguide 416, and a second MEMS-based actuator is utilised to move the second photonic crystal waveguides 418.

Fig. 8 shows the epitaxial structure of the wafer for the realisation of the MEMS-based filter in a GaAs-based material. However, other materials, such as silicon-based materials, may also be used for the wafer.

The structure comprises a substrate layer 500, a sacrificial layer 510 on top of the substrate layer 500, a membrane or waveguide layer 520 on top of the substrate layer 510, an etch stop layer 530 on top of the membrane 520, and a conductive layer 540 on top of the etch stop layer, and which is used for the MEMS-based actuator.

The substrate 500 may for instance be made of GaAs. The sacrificial layer 510 may for instance be made of AlGaAs, e.g. having an Al-contents of approximately 75%. The membrane 520 may for instance be made of GaAs and have a thickness of approximately 160 nm. The etch stop layer 530 may for instance be made of a p-doped AlGaAs, e.g. having an Al-contents of approximately 75%. The conductive layer may for instance be made of highly p-doped or n-doped GaAs, alternatively another conductive material, such as a metal, and have a thickness of approximately 300 nm.

For the experimental setup, light was filtered in a range from approximately 880 nm to 930 nm, i.e. approximately 50 nm, by varying the spacing between the two substantially parallel photonic crystal waveguides from 60 nm to 600 nm.

The setup utilised one-dimensional photonic crystal waveguides having a width of 290 nm, a hole size of 89 nm, and a lattice constant 290 nm. The values for the holes and lattice constant are average values, as the holes in practice are slightly displaced and adjusted in size to form to aforementioned cavity.

The results of the simulation experiments based on solving Maxwell's equation using finite elements method are shown in Figs. 6 and 7, where Fig. 6 illustrates an intensity plot showing the resonant mode of the two parallel photonic crystal waveguides, and where Fig. 7 shows transmission spectrums as a function of the spacing between the waveguides. The labels indicate the spacing in nanometres.

It can be seen that the sensitivity of the tuneable is very high, when the two waveguides are close to each other. However, the waveguides may not be too close to each other, as the coupling between waveguides will be too strong causing a field redistribution, which could potentially lead to light leakage and thus reduce the quality factor of the filter. At the other extreme of the variable spacing, it is seen that the sensitivity becomes lower. Accordingly, for the current setup, it is not necessary to expand the variable spacing beyond the shown 600 nm. The different spectrums show very sharp transmission peaks, and the Q factor is more than 4,000 for the entire range, which means that the 3dB transmission bandwidth is always below 220 pm. This means that the tuneable optical filter has a dynamic range of at least 1:227.

As shown in Fig. 4, it is possible to expand the tuneable range and the dynamic range by splitting the incoming light up into separate tuneable optical filters.

Fig. 9 illustrates the steps involved in a method of filtering light according to the invention. In a first step A, incoming light is input into an input waveguide. In a second step B, the light is split up into two in-phase light waves that are input into two substantially parallel photonic crystal waveguides. In a third step C, a transmission peak wavelength is tuned to a desired wavelength by varying the distance between the two substantially parallel photonic crystal waveguides. In a fourth step D, the outputs from the two substantially parallel photonic crystal waveguides are combined into an output waveguide, and in a fifth step E, light is emitted or otherwise processed from the output waveguide. Step C may be carried out by sweeping the spacing between the two substantially parallel photonic crystal waveguides between a first spacing and a second spacing, whereby the incoming light can be analysed for contents between a first wavelength and a second wavelength.

The invention has been described with reference to advantageous embodiments. However, the scope of the invention is not limited to the illustrated embodiments, and alterations and modifications can be carried out without deviating from the scope of the invention, which is defined by the following claims.

List of Reference Numerals

10, 110, 210, 310, 410	Tuneable optical filter
12, 412	Input waveguide
14, 414	Optical power coupler/splitter
16, 416	First waveguide
18, 418	Second waveguide
20	Holes
22, 24, 26, 28	Mirrors
30	Coupled cavity
32, 432	Optical combiner
34, 434	Output waveguide
36, 136, 236, 336, 436	MEMS-based actuator
137, 237, 337, 437	Stator
138, 238, 338, 438	Shuttle
439	Tethers
140, 240	Input optical fibre
145, 245	Input light
150	Output optical fibre
155	Output light
160, 260, 360	Controller
270, 370	Photo detector / superconducting nanowire
280, 380	Photo detector measurement
390	multiplexer
500, 510, 520, 530, 540, 550	Layers of wafer

Claims

1. A tuneable optical filter (10, 110, 210, 310, 410) comprising an input waveguide (12, 412), an optical power coupler (14, 414), and two substantially parallel photonic crystal waveguides (16, 416; 18, 418), wherein

- the optical power coupler (14, 414) is optically coupled between the input waveguide (12, 412) and the two parallel photonic crystal waveguides (16, 416; 18, 418), wherein the optical power coupler (14, 414) is adapted to split incoming light from the input waveguide (12, 412) into two in-phase light outputs, which are coupled to the two parallel photonic crystal waveguides (16, 416; 18, 418), where the tuneable optical filter further comprises:

- an actuator (36, 136, 236, 336, 436), which is arranged and adapted to be able to vary a spacing (*d*) between the two substantially parallel photonic crystal waveguides (16, 416; 18, 418).

2. A tuneable optical filter according to claims 1, wherein the two parallel photonic crystals (16, 416; 18, 418) each comprises a first end and a second end, and wherein the optical power coupler is optically coupled between the input waveguide (12, 412) and first ends of the two parallel photonic crystal waveguides (16, 416; 18, 418).

3. A tuneable optical filter according to claim 1 or 2, wherein the optical power coupler is a 1:2 optical power coupler, such as a 1x2 multi-mode interference coupler.

4. A tuneable optical filter according to any of the preceding claims, wherein the two parallel photonic crystals (16, 416; 18, 418) have substantial identical design.

5. A tuneable optical filter according to any of the preceding claims, wherein the two parallel photonic crystal waveguides are one-dimensional photonic crystal waveguides, e.g. wherein the two parallel photonic crystal waveguides comprise four identical photonic crystal mirrors arranged to form a coupled cavity.

6. A tuneable optical filter according to any of claims 5, wherein the photonic crystal mirrors comprise a row of 3-25 holes in an longitudinal direction of the two parallel photonic crystal waveguides, e.g. wherein the holes are arranged in a lattice with a mutual spacing equal to a lattice constant *a*, and wherein the photonic crystal mirrors

are formed by displacing or removing one or more holes in each of the two parallel photonic crystal waveguides.

7. A tuneable optical filter according to any of the preceding claims, wherein the optical filter further comprises an optical combiner and an output waveguide, and wherein the optical combiner is arranged between the two parallel photonic crystal waveguides and the output waveguide, e.g. wherein the output waveguide is a single-mode waveguide.

8. A tuneable optical filter according to claims 7, wherein the two parallel photonic crystals (16, 416; 18, 418) each comprises a first end and a second end, and wherein the optical power combiner is optically coupled between the output waveguide and the second ends of two parallel photonic crystal waveguides (16, 416; 18, 418).

9. A tuneable optical filter according to any of the preceding claims, wherein the actuator is adapted to vary a spacing between the two parallel photonic crystal waveguides in the interval 10-1000 nm, or the interval of 25-800 nm, or the interval of 50-600 nm, and/or wherein the optical filter is tuneable over a range of at least 50 nm, advantageously at least 75 nm.

10. A tuneable optical filter according to any of the preceding claims, wherein the optical filter has a Q factor of at least 2500, advantageously at least 4000.

11. A tuneable optical filter according to any of the preceding claims, wherein the actuator is one or more MEMS-based actuators, e.g. wherein the the MEMS-based actuator(s) comprise a stator and a shuttle, e.g. based on a comb-design, and where the shuttle may be movable relative to the stator via electrostatic forces, optionally wherein at least one of the two parallel photonic crystal waveguides is connected to the MEMS-based actuator via a number of thin tethers.

12. An optical device comprising a tuneable optical filter according to any of the preceding claims, e.g. wherein the optical device is a spectrometer, an optical interrogator, or a single-photon optical device.

13. An optical device according to claim 12, wherein the optical device further comprises a photo detector coupled to an output waveguide of the tuneable optical filter.

14. An optical device according to any of claims 12-13, wherein the optical device comprises a plurality of tuneable optical filters including at least a first tuneable optical filter and a second tuneable optical filter, e.g. wherein the first tuneable optical filter is tuneable over a first wavelength range, and the second tuneable optical filter is tuneable over a second wavelength range, wherein the first wavelength range and the second wavelength range optionally are juxtaposed, neighbouring or overlapping.

15. An optical device according to any of claims 14, wherein the optical device comprises an optical multiplexer so as to split up light into different wavelength ranges, which are sent to different tuneable optical filters.

16. A method of optical filtering light, the method comprising the following steps:

a) inputting an incoming light into an input waveguide,

b) splitting light up into two in-phase light waves that are input into two substantially parallel photonic crystal waveguides, and

c) tuning a transmission peak wavelength to a desired wavelength by varying the distance between the two substantially parallel photonic crystal waveguides.

17. A method of optical filtering light according to claim 16, wherein the method further comprises the step of:

d) combining outputs from the two substantially parallel photonic crystal waveguides into an output waveguide, and/or

e) detecting light emitted from the output waveguide or the two substantially parallel photonic crystal waveguides.

18. A method of optical filtering light according to any of claims 16-17, wherein step c) comprises the step of sweeping the distance between the two substantially parallel photonic crystal waveguides between a first distance and a second distance.

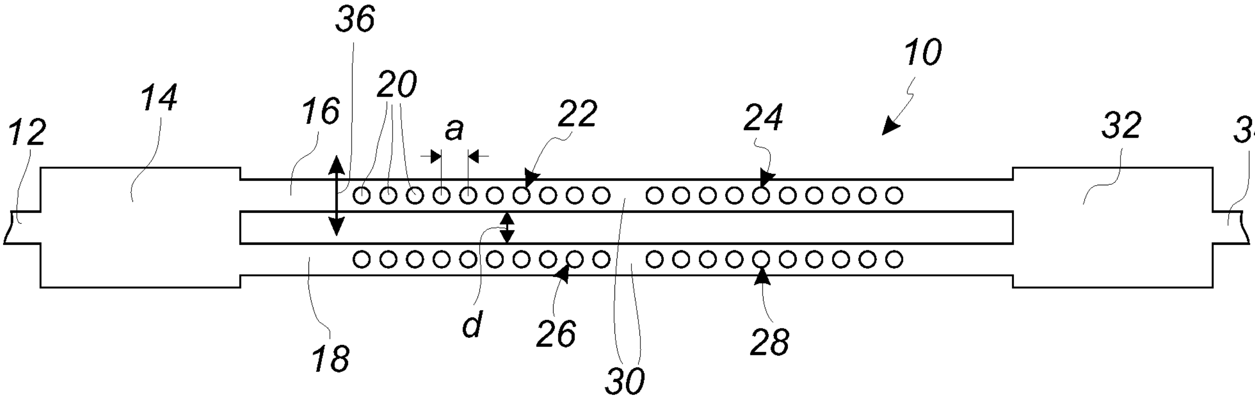


Fig. 1

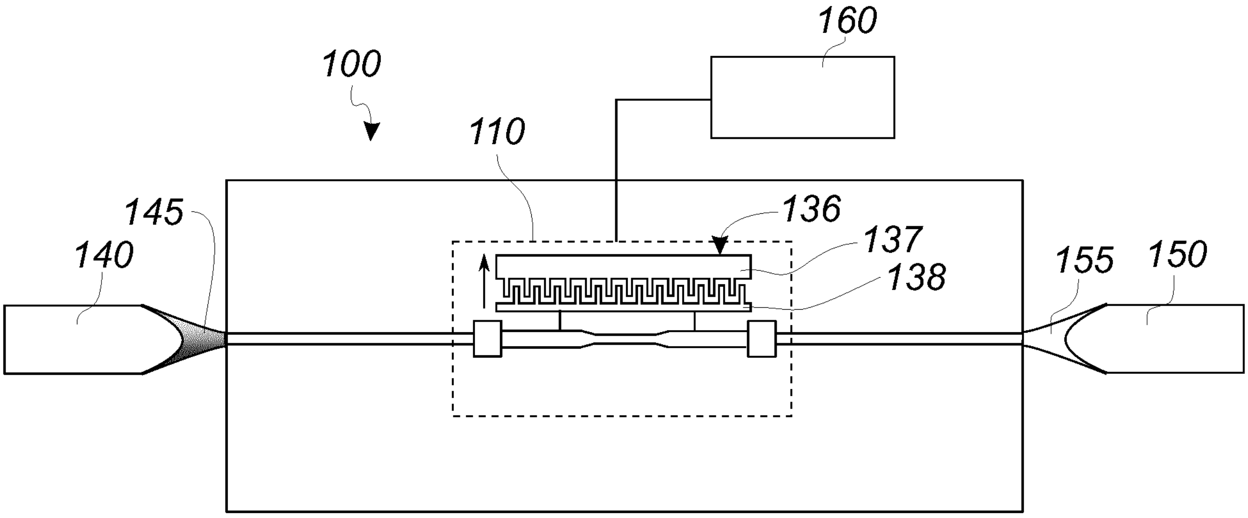


Fig. 2

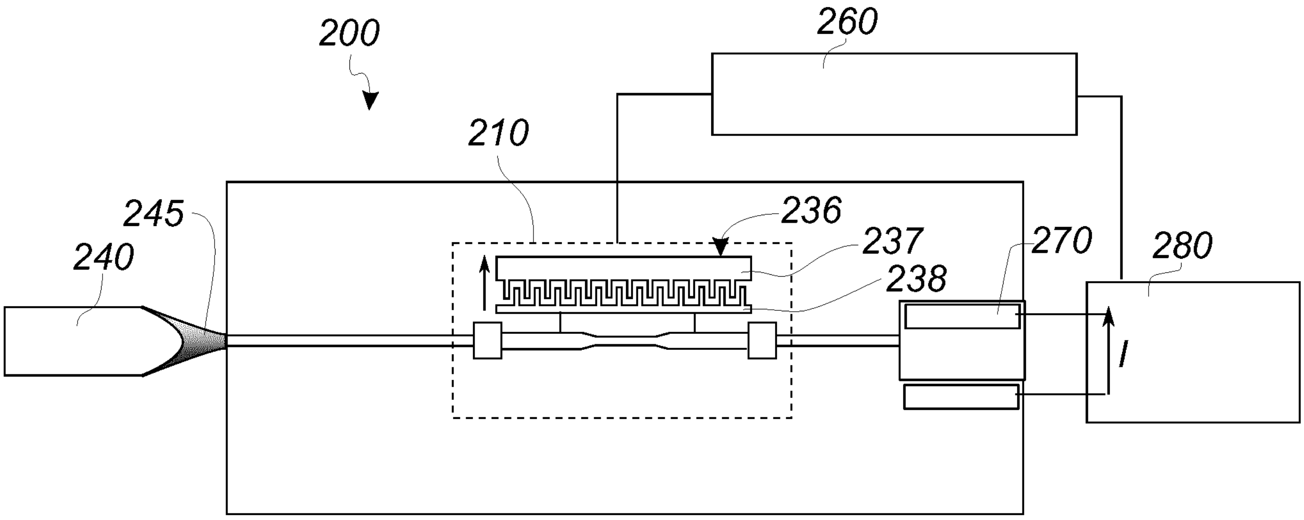
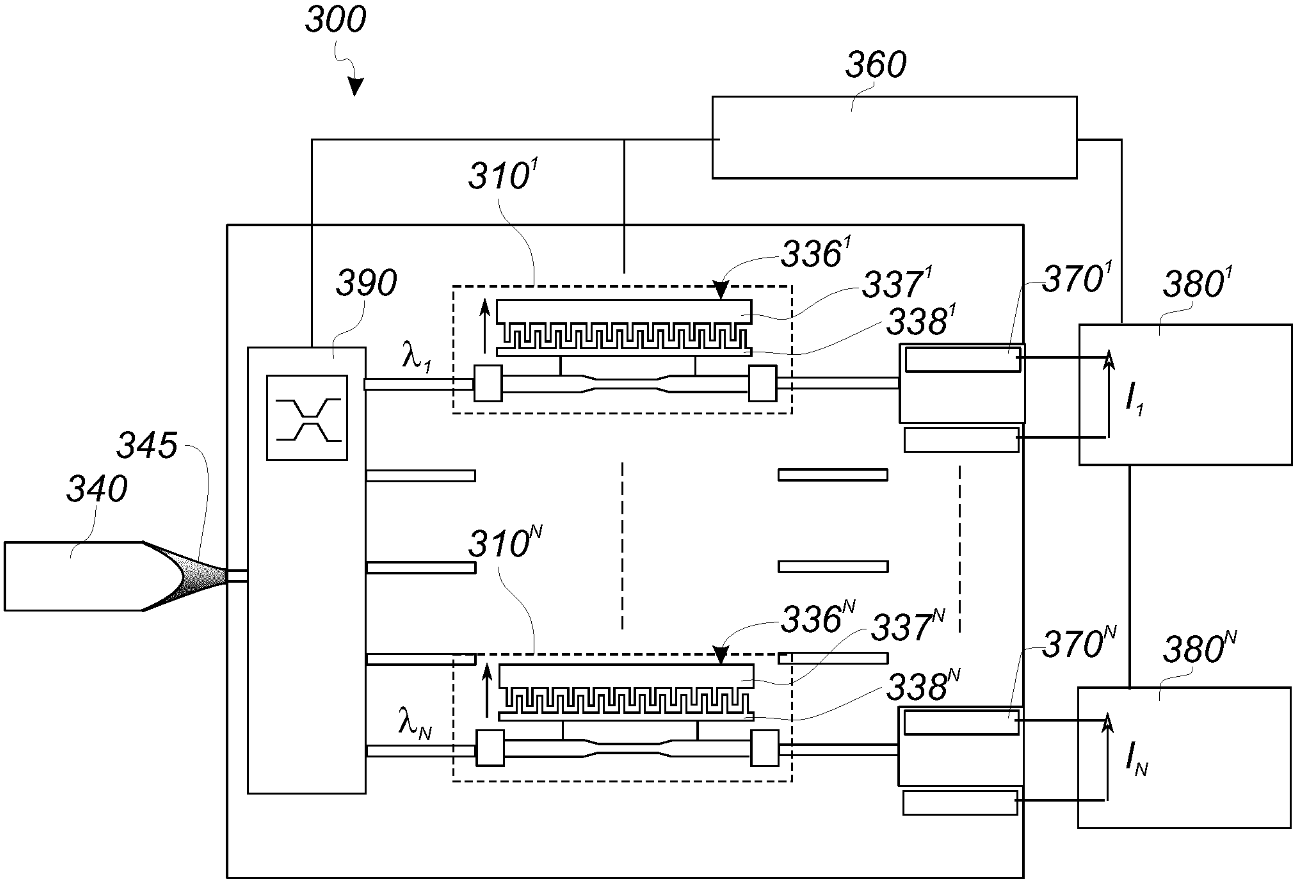


Fig. 3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360
310^1
336^1
337^1
338^1
390
370^1
380^1
λ1
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345
340
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337^N
338^N
370^N
380^N
λN
IN

Fig. 4

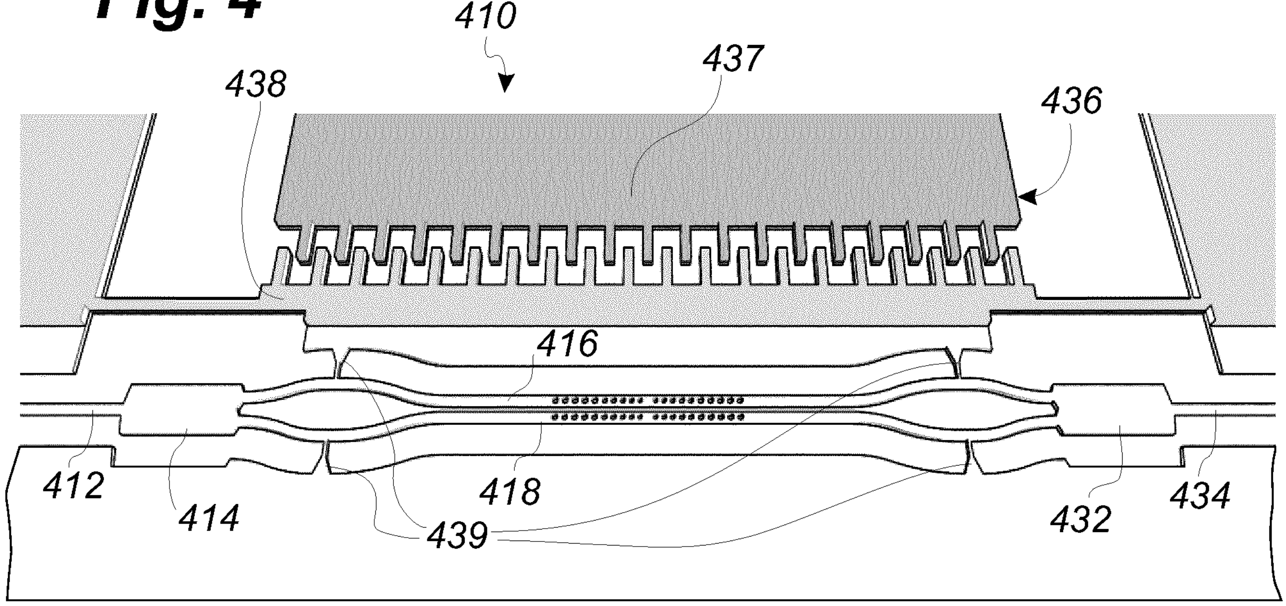
410
437
438
436
416
412
414
418
439
432
434

Fig. 5

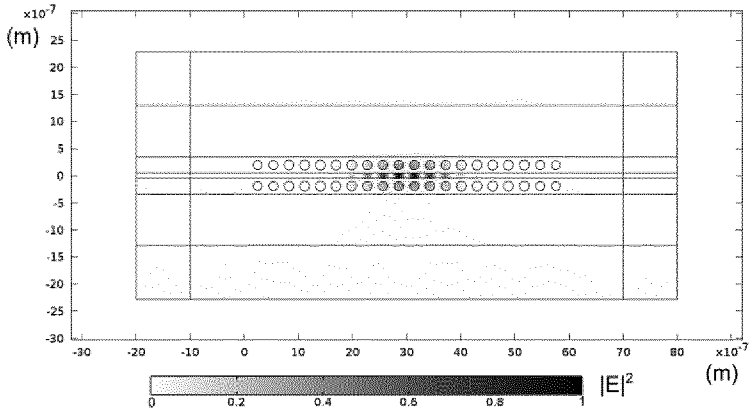

Fig. 6

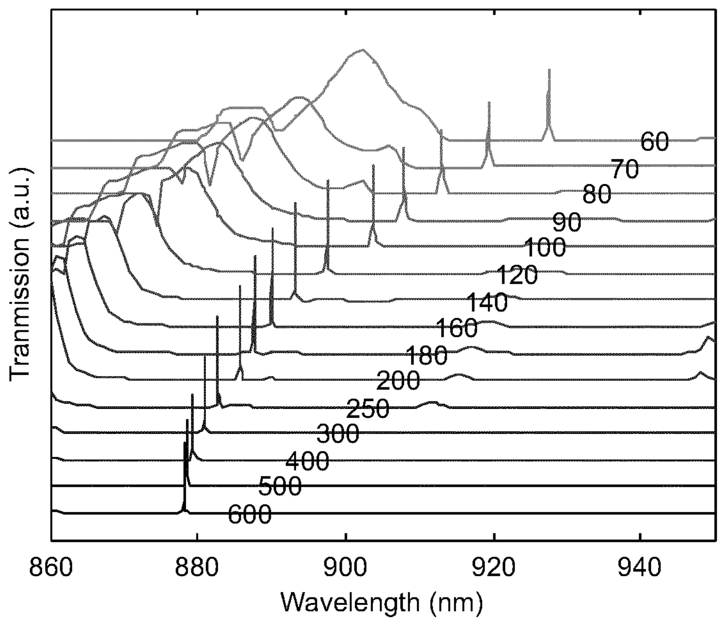

Fig. 7

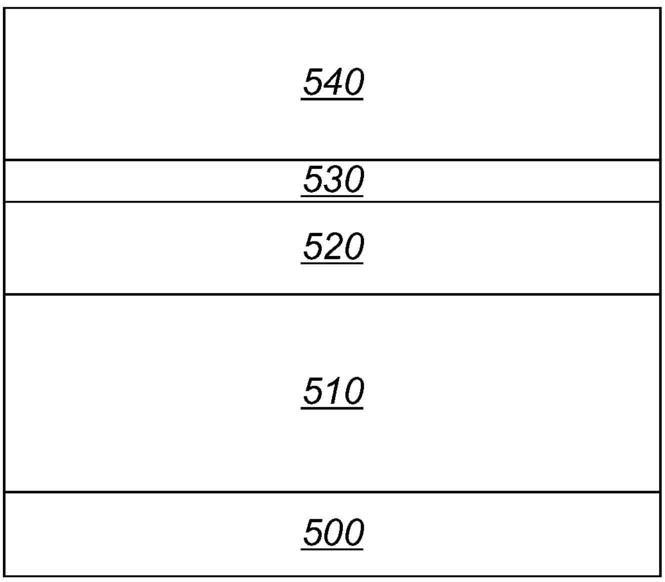

Fig. 8

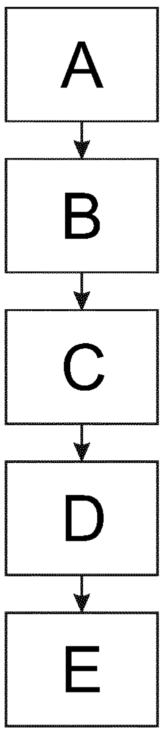

Fig. 9

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/054631

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02B6/12 G02B6/293
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)
G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

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	PARAG B. DEOTARE ET AL: "All optical reconfiguration of optomechanical filters", NATURE COMMUNICATIONS, vol. 3, 846, 22 May 2012 (2012-05-22), XP055370990, DOI: 10.1038/ncomms1830 the whole document -----	1-18
A	XIONGYEU CHEW ET AL.: "Dynamic tuning of an optical resonator through MEMS-driven coupled photonic crystal nanocavities", OPTICS LETTERS, vol. 35, no. 15, 1 August 2010 (2010-08-01), pages 2517-2519, XP001556339, cited in the application the whole document -----	1-18
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[X] 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 application or patent 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

"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
12 May 2017	14/06/2017

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	Kloppenburg, Martin

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	PARAG B DEOTARE ET AL: "Photonic Crystal Nanobeam Cavities for Tunable Filter and Router Applications", IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, vol. 19, no. 2, March 2013 (2013-03), page 3600210, XP011500146, ISSN: 1077-260X, DOI: 10.1109/JSTQE.2012.2225828 the whole document -----	1-18
A	CHUN-CHE CHANG ET AL: "MEMS-actuated waveguide phase modulators", OPTICAL MEMS AND NANOPHOTONICS (OPT MEMS), 2010 INTERNATIONAL CONFERENCE ON, IEEE, 9 August 2010 (2010-08-09), pages 99-100, XP031838407, ISBN: 978-1-4244-8926-8 figure 1 -----	1-18

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