

PHOTONIC CRYSTALS AND TAPERED-WAVEGUIDE COUPLERS FOR SPECTROMETERS

5 PATENT APPLICATION SPECIFICATION

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

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CROSS REFERENCE TO RELATED APPLICATION

This application claims priority from U.S. Provisional Application Serial No. 61/676,192, filed July 26, 2012, the disclosure of which is incorporated by reference herein.

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BACKGROUND

The disclosed subject matter relates to systems and methods for spectrometers based on membranes patterned with photonic crystals and tapered-waveguide couplers.

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A spectrometer can be used to measure properties of electromagnetic radiation over portions of the electromagnetic spectrum. For example, certain spectrometers can use a dispersive element such as a prism or diffraction grating to spectrally separate electromagnetic radiation. Electromagnetic radiation, such as light, can be directed into the dispersive element, and the spectrally separated

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electromagnetic radiation can be directed to a detector, such as a photodetector.

Spectrometers can also use photonic crystals patterned in a high-index semiconductor membrane to spectrally separate electromagnetic radiation. However, fabricating photonic crystals in high-index semiconductors can be expensive and time-consuming. Incoming electromagnetic radiation can be coupled into the

30 photonic crystal, e.g., by using end-to-end coupling or vertical coupling via a diffraction grating. Such coupling techniques can be inefficient and can involve alignment that can be time-consuming. Spectrally separated electromagnetic radiation from the photonic crystal can be directed to an in-plane detector, such as an in-plane

photodetector. Such in-plane detectors can be incorporated into the high-index semiconductor membrane, which can be time-consuming and expensive.

There is a need for an improved technique for spectrometers based on membranes patterned with photonic crystals.

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SUMMARY

Systems and methods for spectrometers based on membranes patterned with photonic crystals and tapered-waveguide couplers are disclosed herein.

In one aspect of the disclosed subject matter, devices for detecting
10 electromagnetic radiation are disclosed. A device for detecting electromagnetic radiation can include an optical fiber for transmitting the electromagnetic radiation. The optical fiber can have a main region and a distal region. The distal region can allow at least a portion of the electromagnetic radiation to exist outside of the distal region of the optical fiber. A membrane can include a coupling region and a patterned
15 region. The coupling region can be disposed proximate to the distal region of the optical fiber. The coupling region can couple at least part of the portion of the electromagnetic radiation existing outside of the optical fiber into the membrane. The patterned region can have a plurality of holes defining at least one photonic crystal element therein. The at least one photonic crystal element can spectrally separate the
20 electromagnetic radiation in the membrane and couple the spectrally separated electromagnetic radiation out of the membrane. At least one photodetector can be disposed proximate to the patterned region of the membrane. The at least one photodetector can detect the spectrally separated electromagnetic radiation.

In some embodiments, the optical fiber can be a silica fiber, a polymer
25 fiber, a fluoride glass fiber, a heavy metal fluoride glass (HMFG) fiber, or a chalcogenide glass fiber. Additionally or alternatively, the main region of the optical fiber can have a diameter large enough so that no part of the electromagnetic radiation exists outside of the main region of the optical fiber. The distal region can be tapered from a first end proximate to the main region and having a diameter equal to the
30 diameter of the main region to a second end opposite from the main region and having a diameter less than the diameter of the main region. The second end of the distal region can have a diameter of at least one wavelength of the electromagnetic

radiation. In some embodiments, the distal region can have an adiabatic tapering angle. Additionally or alternatively, the optical fiber can be one-sided or a two-sided.

In some embodiments, a bonding agent can connect the optical fiber to the membrane. The bonding agent can be a transparent adhesive having a refractive index matched to a refractive index of the optical fiber.

In some embodiments, the membrane can be a semiconductor membrane, a transparent polymer membrane, a glass membrane, or a crystal membrane. For example, the membrane can be a silicon membrane. Additionally or alternatively, the membrane can have a thickness of 0.5 to 2 wavelengths of the electromagnetic radiation inside the material.

In some embodiments, the membrane can include a lens region between the coupling region and the patterned region. For example, the lens region can include a photonic crystal superlens.

In some embodiments, the at least one photonic crystal element can include at least one of a photonic crystal superprism, a photonic crystal cavity array, a photonic crystal waveguide, and a photonic crystal drop-filter cavity. Additionally or alternatively, the at least one photonic crystal element can include a photonic crystal dispersive element proximate to the coupling region and a photonic crystal coupling element opposite the coupling region. The photonic crystal dispersive element can spectrally separate the electromagnetic radiation in the membrane. The photonic crystal coupling element can filter the spectrally separated electromagnetic radiation and couple the spectrally separated electromagnetic radiation out of the membrane.

In some embodiments, the at least one photodetector can detect the spectrally separated electromagnetic radiation by producing a current and/or a voltage proportional to the intensity of the spectral component of the electromagnetic radiation. Additionally or alternatively, the at least one photodetector can include at least one of a charge-coupled device (CCD) photodetector, a complementary metal-oxide-semiconductor (CMOS) photodetector, a pyrometer, a bolometer, or a mercury cadmium telluride (MCT) semiconductor. Additionally or alternatively, the at least one photodetector can be a one-dimensional array of photodetectors or a two-dimensional array of photodetectors.

In some embodiments, at least one support structure can connect the membrane to the at least one photodetector. For example, the at least one support structure can include a plurality of spacer beads, a plurality of protrusions from the at

least one photodetector extending towards the membrane, or a plurality of protrusions from the membrane extending towards the at least one photodetector.

In another aspect of the disclosed subject matter, methods for detecting electromagnetic radiation are disclosed. A method for detecting electromagnetic radiation can include coupling the electromagnetic radiation into a membrane. The electromagnetic radiation can be spectrally separated by at least one photonic crystal element defined in the membrane. The spectrally separated electromagnetic radiation can be coupled out of the membrane. The spectrally separated electromagnetic radiation can be detected.

In some embodiments, the electromagnetic radiation can be focused before being spectrally separated. Additionally or alternatively, the spectrally separated electromagnetic radiation can be filtered before being coupled out of the membrane.

In some embodiments, the electromagnetic radiation can be detected by producing a current and/or a voltage proportional to the intensity of the spectral component of the electromagnetic radiation.

In another aspect of the disclosed subject matter, methods for making a device for detecting electromagnetic radiation are disclosed. A method for making a device for detecting electromagnetic radiation can include tapering a distal region of an optical fiber. The distal region of the optical fiber can be bonded to a coupling region of a membrane. A plurality of holes can be created in the membrane to define at least one photonic crystal element in the membrane proximate to the coupling region. The membrane can be supported on at least one photodetector.

In some embodiments, tapering the distal region of the optical fiber can include heating the optical fiber and pulling the distal region of the heated optical fiber. Additionally or alternatively, the tapering can include selectively coating sections of the optical fiber in a cladding and chemically removing uncoated sections of the optical fiber to thereby form a taper in the distal region of the optical fiber.

In some embodiments, bonding the distal region of the optical fiber to the coupling region of a membrane can include connecting the distal region of the optical fiber to the coupling region of the membrane with a transparent adhesive.

In some embodiments, the plurality of holes can be created by lithography, nano-imprinting, or nano-embossing. Additionally or alternatively, the plurality of holes can define at least one of a photonic crystal superprism, a photonic

crystal cavity array, a photonic crystal waveguide, or a photonic crystal drop-filter cavity.

In some embodiments, the membrane can be supported on at least one of a plurality of spacer beads, a plurality of protrusions from the photodetector
5 extending towards the membrane, or a plurality of protrusions from the membrane extending towards the photodetector.

The accompanying drawings, which are incorporated and constitute part of this disclosure, illustrate certain embodiments of the disclosed subject matter and serve to explain the principles of the disclosed subject matter.

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BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross-sectional diagram of an exemplary device for detecting electromagnetic radiation, in accordance with some embodiments of the disclosed subject matter.

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FIG. 2 is a diagram showing an exemplary device for detecting electromagnetic radiation using a photonic crystal (PC) superprism, in accordance with some embodiments of the disclosed subject matter.

FIG. 3 is a diagram showing an exemplary device for detecting electromagnetic radiation using a PC waveguide and drop-filter cavities, in
20 accordance with some embodiments of the disclosed subject matter.

FIG. 4 is a diagram showing an exemplary device for detecting electromagnetic radiation using a PC cavity array, in accordance with some embodiments of the disclosed subject matter.

FIG. 5 is a cross-sectional diagram of an exemplary device for
25 detecting electromagnetic radiation, in accordance with some embodiments of the disclosed subject matter.

FIG. 6 is a flow chart of an exemplary method for detecting electromagnetic radiation, in accordance with some embodiments of the disclosed subject matter.

FIG. 7 is a flow chart of an exemplary method for making a device for
30 detecting electromagnetic radiation, in accordance with some embodiments of the disclosed subject matter.

Throughout the drawings, similar reference numerals and characters, unless otherwise stated, are used to denote like features, elements, components or portions of the illustrated embodiments. Moreover, while the present disclosed subject matter will now be described in detail with reference to the FIGS., it is done
5 so in connection with the illustrative embodiments.

DETAILED DESCRIPTION

Techniques for providing spectrometers based on membranes patterned with photonic crystals and tapered-waveguide couplers are presented. As further
10 discussed below in connection with the illustrative embodiments, a tapered optical fiber can be used to efficiently couple electromagnetic radiation into a membrane, which can be made of various materials including a transparent polymer. The electromagnetic radiation can be spectrally separated by photonic crystal dispersive elements defined in the membrane. The spectrally separated electromagnetic
15 radiation can be coupled out of the membrane using the same photonic crystal elements or a different set of photonic crystal elements. The spectrally separated electromagnetic radiation can then be detected, for example, by an array of photodetectors, which can be in-plane or out-of-plane.

Referring to FIG. 1, a cross-sectional diagram of an exemplary device
20 for detecting electromagnetic radiation is shown. For example, the electromagnetic radiation can include components of red light 131 and green light 132. The optical fiber 101 can have a main region 102 and a distal region 103. The distal region can have a first end 104 and a second end 105. The distal region 103 can allow at least a portion of the electromagnetic radiation to exist outside of the distal region 103 of the
25 optical fiber 101. This portion of the field outside of the fiber 101 can be referred to as an evanescent tail or evanescent field. The evanescent field becomes strong when the diameter of the fiber 101 shrinks to the order of the wavelength of the electromagnetic radiation of interest, for example the diameter D2 of the second end 105 of the distal region 103 can be at least one wavelength, as further discussed
30 below.

A membrane 111 can include a coupling region 112 and a patterned region 113. The coupling region 112 can be disposed proximate to the distal region 103 of the optical fiber 101. The evanescent fields of the optical fiber 101 and the

membrane 111 can overlap, causing a transfer of power between the resonant modes. This phenomenon can be referred to as evanescent coupling. A device for detecting electromagnetic radiation can include an optical fiber 101 for transmitting the electromagnetic radiation. At least part of the portion of the electromagnetic radiation existing outside of the optical fiber 101 can be coupled into the membrane 111. As further discussed below, the optical fiber 101 and membrane 111 can be configured such that the efficiency of coupling from the optical fiber 101 (a one-dimensional waveguide) into the membrane 111 (a two-dimensional waveguide) can be in excess of 95% for a wide spectral band. The distal region 103 of the optical fiber 101 can be hundreds of wavelengths long, while the membrane 111 can have a thickness T of 0.5-2.0 wavelengths. The patterned region 113 can include a plurality of holes 121 defining at least one photonic crystal element. The holes 121 defining the photonic crystal element can be sub-wavelength in size. The holes 121 can have a pitch (spacing) corresponding to the Bragg condition. Additionally or alternatively, the holes 121 can have a pitch on the order of the wavelength divided by two times the effective refractive index of the membrane 111. The spacing of the holes 121 can be "chirped," or changing with distance, to enable operation across a wide spectral region. The photonic crystal element or elements can be adapted to spectrally separate the electromagnetic radiation in the membrane 111 and couple the spectrally separated electromagnetic radiation out of the membrane 111 and into at least one detector, such as a photodetector, as described below.

The membrane 111 can be made of any suitable transparent material, including semiconductors, transparent polymers, glasses, crystals, or other transparent materials. For purpose of illustration and not limitation, the membrane can be a silicon membrane. In other embodiments, for purpose of illustration and not limitation, the membrane can be a polymer membrane, such as a poly(methyl methacrylate) (PMMA) membrane or a SU-8 photoresist membrane. The membrane 111 can have a thickness T on the order of the wavelength of the electromagnetic radiation of interest. For example, the thickness T can be from 0.5 to 2 wavelengths within the material. For purpose of illustration and not limitation, a thinner membrane 111 can correspond with weaker mode confinement. A thicker membrane 111 can correspond with exciting optical modes with higher-order wave-vectors in the vertical direction (perpendicular to the membrane) in addition to those optical modes which have the fundamental wave-vector in the vertical direction. Excitation of

modes with higher-order wave-vectors in the vertical direction can degrade the performance of a spectrometer because, for example, the spatial separation can be other than a one-to-one mapping with spectrum.

5 The membrane 111 can include at least one photonic crystal dispersive element defined by the holes 121 in the patterned region 113. As discussed below, the photonic crystal dispersive element can be any photonic crystal structure suitable to spectrally separate the electromagnetic radiation, including a photonic crystal superprism, a photonic crystal cavity array, a photonic crystal waveguide, and/or a photonic crystal drop-filter cavity.

10 The optical fiber 101 can be made of any suitable material. For purpose of illustration and not limitation, the optical fiber 101 can be a silica fiber or a polymer fiber. In other embodiments, for purpose of illustration and not limitation, the optical fiber 101 can be a fluoride glass fiber, a heavy metal fluoride glass (HMFG) fiber, or a chalcogenide glass fiber. For example, the HMFG glass can be
15 ZBLAN ($\text{ZrF}_4\text{-BaF}_2\text{-LaF}_3\text{-AlF}_3\text{-NaF}$). For example, the chalcogenide glass could be sulphide glass (As_2S_3) or selenide glass (As_2Se_3).

The main region 102 of the optical fiber 101 can have a diameter D1 large enough so that no part of the electromagnetic radiation exists outside of the main region of the optical fiber. For example, the diameter D1 can be several wavelengths
20 within the material. For purpose of illustration and not limitation, the main portion 102 of the optical fiber 101 can be the standard diameter of 125 microns, which can result in only 0.2 dB/km loss. The distal region 103 can taper from a first end 104 proximate to the main region 102 to a second end 105 opposite from the main region 102. At the first end 104, the optical fiber 101 can have a diameter D1 equal to the
25 diameter D1 of the main region 102. At the second end 105, the optical fiber 101 can have a diameter D2 less than the diameter D1 of the main region 102. The optical fiber 101 can be tapered in thickness down to a wavelength-scale diameter. In some embodiments, for purpose of illustration and not limitation, the tapering angle can be chosen under the adiabatic condition to ensure near-unity coupling from the large
30 diameter D1 at the first end 104 into the tapered region 103. In other words, the distal region 103 can have an adiabatic tapering angle 103. The optical fiber 101 can be tapered by any of the tapering techniques discussed below. For purpose of illustration and not limitation, the diameter D2 of the second end 105 can be at least one

wavelength of the electromagnetic radiation of interest to avoid leakage into the substrate.

While FIG. 1 depicts a one-sided optical fiber, the optical fiber 101 can have any suitable shape, including a one-sided optical fiber or a two-sided optical fiber. For example, FIG. 5 depicts a cross-sectional diagram of an exemplary device for detecting electromagnetic radiation similar to the device in FIG. 1, except the optical fiber 101 in FIG. 5 is a two-sided optical fiber. Referring briefly to FIG. 5, the tapered region 103' tapers from diameter D1 at the first end 104' to the smaller diameter D2 at the midpoint 105'. Then the inverse-tapered region 103'' increases in thickness from D2 at the midpoint 105' to a third diameter D3 at the second end 104'. The diameter D3 can be greater than the diameter D2. In some embodiments, the diameter D3 can also be the same as the diameter D1.

Referring again to FIG. 1, because the membrane 111 can act as a two-dimensional waveguide, the membrane 111 can support wave-vectors that are both in the longitudinal and transverse directions with respect to the axis of the optical fiber 101. Accordingly, a wide range of frequencies can efficiently couple from the optical fiber 101 into the membrane 111. For purpose of illustration and not limitation, the optical fiber 101 and the membrane 111 can be configured such that the efficiency of coupling from the distal region 103 of the optical fiber 101 (a one-dimensional waveguide) into the coupling region 112 of the membrane 111 (a two-dimensional waveguide) can be in excess of 95% for a wide spectral band. Furthermore, a high-index membrane 111 can cause the input mode of the electromagnetic radiation to have a narrow spreading angle, as given by the conservation of the transverse wave-vector, i.e., by Snell's law.

In some embodiments, surface forces between the optical fiber 101 and the membrane 111 can be sufficient to hold them together and keep each in place with respect to the other. Additionally or alternatively, the optical fiber 101 can be connected onto the membrane 111 using a bonding agent. For example, the bonding agent can be any suitable transparent adhesive. For purpose of illustration and not limitation, the bonding agent can be PMMA or an ultraviolet (UV) curable adhesive. Depending on where the adhesive is attached, the adhesive can change the optical mode of the coupling between the optical fiber 101 and the membrane 111. To control this change and the effect that it will have on the coupling, the refractive

index of the bonding agent can be matched to the refractive index of the optical fiber 101.

Referring to FIG. 2, a diagram an exemplary device for detecting electromagnetic radiation using a photonic crystal superprism is shown. A photonic crystal dispersive element can be a superprism 213a, which can behave similarly to a
5 crystal dispersive element can be a superprism 213a, which can behave similarly to a conventional prism but with greatly enhanced sensitivities with respect to the wavelength and direction of incident light. Similarly to how a conventional prism separates multiple wavelength components of incident electromagnetic radiation, e.g., light, to form a spectrum of color, a superprism can separate the wavelengths over
10 much wider angles, which can result in super-dispersion. For purpose of illustration and not limitation, superprism 213a can spectrally separate the blue component 133, green component 132, and red component 131 of the electromagnetic radiation. Additionally or alternatively, a small change in the incident angle of electromagnetic radiation entering the superprism 213a can result in a much larger change in the
15 propagation direction of the outgoing electromagnetic radiation exiting the superprism 213a. Thus a superprism 213a can magnify the angular range of electromagnetic radiation to direct it over wider angles, which can result in angular magnification.

A material through which electromagnetic radiation is propagating can affect its group velocity and/or phase velocity characteristics. The group velocity can
20 be a vector that indicates the direction of energy propagation. The phase velocity can be a scalar value that indicates the speed of light in the material, or the speed of the electromagnetic phase within a material. A vector k can indicates the direction in which the phase fronts propagate. In uniform isotropic materials, the group velocity and the k -vector can point in the same direction and can depend on orientation and
25 frequency. For example, inside a conventional glass prism, a spectrum of colors can diverge due to the frequency dependence of the phase and group velocities. By creating a periodic pattern of holes 121 in the patterned region 113, and thus creating a periodic variation in the index of refraction in the patterned region 113 of the membrane 111, a photonic crystal element can be formed, such as superprism 213a or
30 photonic crystal coupling element 213b. In the photonic crystal dispersive element, such as superprism 213a, the group velocity and phase velocity characteristics of light can be manipulated for a much stronger dependence on frequency or orientation. In addition, because the group velocity and k -vector in a photonic crystal can point in different directions, the conditions in which the group velocity can be highly sensitive

to orientation and wavelength can differ from the conditions in which phase velocity can be sensitive to orientation and wavelength. In some embodiments, the superprism 213a can be defined by several hundreds of periods or more of holes 121.

For purpose of illustration and not limitation, the dimensions of the
5 holes 121, the photonic crystal element (such as superprism 213a), and the membrane 111 can be chosen based on two-dimensional or three-dimensional finite-difference time-domain (FDTD) simulations. For example, various commercial and open versions of FDTD algorithms and software are available.

At least one detector, such as photodetector array 241, can be disposed
10 proximate to the patterned region 113 of the membrane 111. The photodetector array 241 can detect the spectrally separated electromagnetic radiation. For example, the photodetector array 241 can detect the spectrally separated electromagnetic radiation by producing a current and/or a voltage proportional to the intensity of a spectral component of interest of the electromagnetic radiation. For purpose of illustration
15 and not limitation, the detector can be any suitable detector, including a charge-coupled device (CCD) photodetector, a complementary metal-oxide-semiconductor (CMOS) photodetector, a low bandgap semi-conductor with a tunable bandgap such as mercury cadmium telluride (MCT), a pyrometer, or a bolometer. Additionally or alternatively, the detector can be a one-dimensional array of photodetectors 241 or a
20 two-dimensional array of photodetectors, such as the photodetector array 341 shown in FIGS. 3 and 4 (discussed further below). The photodetector array 241 can be in-plane or out-of-plane. For example, an out-of-plane photodetector array 241 can be any suitable commercially available array of photodetectors, such as silicon (Si) charge coupled devices (CCD), Si CMOS cameras, indium gallium arsenide
25 (InGaAs) photodetector arrays, or Mercury Cadmium Telluride cameras.

In some embodiments, the electromagnetic radiation can be focused or collimated before entering the patterned region 113 of the membrane 111. For purpose of illustration and not limitation, a lens region 114 can be disposed in the membrane 111 between the coupling region 112 and the patterned region 113. The
30 lens region 114 can focus or collimate the light using any suitable lens, including a concave lens, a convex lens, or a photonic crystal superlens. A photonic crystal superlens can be formed in lens region 214 by creating a periodic pattern of holes, as discussed above. The dimensions of the holes and the superlens in lens region 114 can be chosen based on FDTD simulations, as described above. The dimensions and

resulting properties of the superlens 114 can be designed to focus or collimate the electromagnetic radiation of interest before it enters the patterned region 113. For example, the superlens in lens region 114 can have a negative refractive index, which can focus or collimate the electromagnetic radiation of interest.

5 At least one support structure (not pictured) can connect the membrane 111 to the at least one photodetector 241. The support structure can be any suitable support structure, including a plurality of spacer beads, a plurality of protrusions from the at least one photodetector extending towards the membrane, or a plurality of protrusions from the membrane extending towards the at least one photodetector. The
10 spacing S between the membrane 111 and photodetector 241 can be 1-100 wavelengths of the electromagnetic radiation of interest.

 At least one photonic crystal coupling element 213b can be disposed in the patterned region 113 opposite the coupling region 112. The photonic crystal coupling element 213b can filter the spectrally separated electromagnetic radiation
15 and/or couple the spectrally separated electromagnetic radiation out of the membrane 111 into the photodetector array 241. For purpose of illustration and not limitation, the at least one photonic crystal coupling element 213b can be a series of photonic crystal resonators. The photonic crystal resonators can spectrally filter the coarsely spectrally separated electromagnetic radiation from the superprism 213b. The
20 resonators can also couple the electromagnetic radiation vertically (i.e. out of the plane of the membrane 111) towards the photodetector array 241. Additionally or alternatively, the at least one photonic crystal coupling element 213b can include a periodic arrangement of holes in the membrane 111 with a period (i.e. distance) between the holes of 1 wavelength of the electromagnetic radiation of interest,
25 thereby forming a photonic crystal coupling element that can couple the electromagnetic radiation vertically (i.e. out of the plane of the membrane 111) towards the photodetector array 241.

 FIG. 3 is a diagram an exemplary device for detecting electromagnetic radiation using a photonic crystal waveguide and drop-filter cavities, in accordance
30 with some embodiments of the disclosed subject matter. A photonic crystal waveguide 313a can guide electromagnetic radiation through the photonic crystal drop-filter cavities 313b. The photonic crystal waveguide 313a can couple spectral components 131-133 of the electromagnetic radiation to selective photonic crystal drop-filter cavities 313b. The photonic crystal drop-filter cavities 313b can couple the

spectrally separated electromagnetic radiation out of the membrane 111 and into the two-dimensional photodetector array 341. For purpose of illustration and not limitation, the photonic crystal waveguide 313a and photonic crystal drop-filter cavities 313b can be designed as discussed above with respect to other photonic crystal elements.

FIG. 4 is a diagram an exemplary device for detecting electromagnetic radiation using a photonic crystal cavity array, in accordance with some embodiments of the disclosed subject matter. All spectral components of the incident electromagnetic radiation can interact with each photonic crystal cavity of the photonic crystal cavity array 413. Certain wavelengths of electromagnetic radiation can resonate within each photonic crystal cavity of the photonic crystal cavity array 413. As such, the resonant wavelengths of electromagnetic radiation can be coupled out of the photonic crystal cavity array 413 and into the two-dimensional photodetector array 341. For purpose of illustration and not limitation, the photonic crystal cavity array 413 can be designed as discussed above with respect to other photonic crystal elements.

Referring to FIG. 6, a flow chart of an exemplary method for detecting electromagnetic radiation is shown. Referring also to FIG. 2 for convenience, a method for detecting electromagnetic radiation can include coupling the electromagnetic radiation into a membrane 111 (601), e.g. by using a tapered optical fiber 101, as discussed above. The electromagnetic radiation 131-133 can be spectrally separated by at least one photonic crystal element, e.g. superprism 213a, defined in the membrane 111 (603). The spectrally separated electromagnetic radiation 131-133 can be coupled out of the membrane 111 (605). The spectrally separated electromagnetic radiation can be detected (606), e.g. by photodetector array 241.

In some embodiments, the electromagnetic radiation 131-133 can be focused or collimated, e.g. in lens region 114, before being spectrally separated by the photonic crystal element (602). Additionally or alternatively, the spectrally separated electromagnetic radiation 131-133 can be filtered before being coupled out of the membrane 111 (604), e.g. by photonic crystal coupling element 213b. Additionally or alternatively, the spectrally separate electromagnetic radiation 131-133 can be detected (605) by a producing a current or a voltage proportional to the intensity of

the spectral component of the electromagnetic radiation. For example, the photodetector array 241 can produce such a current or voltage.

Referring to FIG. 7, a flow chart of an exemplary method for making a device for detecting electromagnetic radiation is shown. Referring also to FIG. 2 for convenience, a method for making a device for detecting electromagnetic radiation can include tapering a distal region 103 of an optical fiber 101 (701). A plurality of holes 121 can be created in the patterned region 113 of the membrane 111 to define at least one photonic crystal element in the membrane 111 proximate to the coupling region 112 (703). The membrane 111 can be supported on at least one detector, such as photodetector array 241 (704).

For purpose of illustration and not limitation, the plurality of holes 121 can be created by lithography, nano-imprinting, nano-embossing, or any other suitable method. Additionally or alternatively, the plurality of holes 121 can be created in the membrane 111 to define a photonic crystal superprism, a photonic crystal cavity array, a photonic crystal waveguide, and a photonic crystal drop-filter cavity, or other suitable photonic crystal element or elements.

In some embodiments, the distal region 103 of the optical fiber 101 can be bonded to the coupling region 112 of a membrane 111 (702). The bonding can include connecting the distal region 103 of the optical fiber 101 to the coupling region 112 of the membrane 111 using a transparent adhesive, as described above.

For purpose of illustration and not limitation, the optical fiber 101 can be tapered by heating the optical fiber 101 and pulling the distal region 103 of the heated optical fiber 101. Additionally or alternatively, tapering the optical fiber 101 can include selectively coating sections of the optical fiber 101 in a cladding. For example, the cladding can be any suitable cladding such as a polymer cladding or an acrylate cladding. Uncoated sections of the optical fiber 101 can be chemically removed to thereby form a taper in the distal region 103 of the optical fiber 101. For example, the uncoated sections can be removed using an acid that attacks the material of the optical fiber 101.

The membrane 111 can be supported on a plurality of spacer beads, a plurality of protrusions from the photodetector array 214 extending towards the membrane 111, or a plurality of protrusions from the membrane 111 extending towards the photodetector array 214.

The subject matter disclosed herein can enable spectral analysis of incident electromagnetic radiation with resolution that either can correspond to the grating resolution (better than 0.1% of the frequency of the electromagnetic radiation) or can be improved further by combining the superprism 213a with at least one photonic crystal coupling element 213b, such as photonic crystal cavities acting as the vertical out-couplers. For example, the resonance linewidth of such photonic crystal cavities can be as low as the center wavelength divided by the quality factor Q, which can be in excess of 100,000. Moreover, the spectral resolution can be changed across the spectrum to enhance detection of desired spectral signatures by modifying the design of the photonic crystal elements defined in the patterned region 113. The techniques disclosed herein can apply to electromagnetic radiation from the deep-infrared spectral ranges through the visible spectral range, or to the ultraviolet range. Additionally, the membrane 111 can be supported on a commercially available detector array, as discussed above, which can result in a compact and high-resolution spectrometer suitable for a range of applications, including material and chemical analysis.

The techniques disclosed herein can be efficient relative to certain spectrometers. For example, with reference to FIG. 2, input electromagnetic radiation can be dispersed by wavelength in the photonic crystal dispersive element, i.e. superprism 213a, before being directed towards the spectral filters, i.e. photonic crystal coupling element 213b. In some circumstances, dispersion of input electromagnetic radiation prior to the spectral filters can be more desirable than having all spectral components interact with all cavities, as discussed above with respect to FIG. 4. Referring again to FIG. 2, the photonic crystal coupling element 213b can act as resonant filters, as discussed above, that can enable high spectral selectivity down to, for example, 0.001 nm.

The foregoing merely illustrates the principles of the disclosed subject matter. Various modifications and alterations to the described embodiments will be apparent to those skilled in the art in view of the teachings herein. It will thus be appreciated that those skilled in the art will be able to devise numerous techniques which, although not explicitly described herein, embody the principles of the disclosed subject matter and are thus within its spirit and scope.

CLAIMS

What is claimed is:

1. A device for detecting electromagnetic radiation, comprising:
 - 5 an optical fiber for transmitting the electromagnetic radiation and comprising a main region and a distal region, the distal region adapted to allow at least a portion of the electromagnetic radiation to exist outside of the distal region of the optical fiber;
 - a membrane comprising a coupling region and a patterned region, the
10 coupling region disposed proximate to the distal region of the optical fiber and adapted to couple at least part of the portion of the electromagnetic radiation existing outside of the optical fiber into the membrane, the patterned region having a plurality of holes defining at least one photonic crystal element adapted to spectrally separate the electromagnetic radiation in the membrane and couple the spectrally separated
15 electromagnetic radiation out of the membrane; and
 - at least one photodetector disposed proximate to the patterned region of the membrane and adapted to detect the spectrally separated electromagnetic radiation.
2. The device of claim 1, the optical fiber comprising one of a silica fiber,
20 a polymer fiber, a fluoride glass fiber, a heavy metal fluoride glass (HMFG) fiber, or a chalcogenide glass fiber.
3. The device of claim 1, the main region of the optical fiber further comprising a region having a diameter large enough so that no part of the electromagnetic radiation exists outside of the main region of the optical fiber.
- 25 4. The device of claim 3, wherein the distal region further comprises a region tapered from a first end proximate to the main region and having a diameter equal to the diameter of the main region to a second end opposite from the main region and having a diameter less than the diameter of the main region.
5. The device of claim 4, the second end of the distal region comprising a
30 region having a diameter of at least one wavelength of the electromagnetic radiation.
6. The device of claim 4, the distal region further comprising a region having an adiabatic tapering angle.
7. The device of claim 1, the optical fiber comprising one of a one-sided optical fiber or a two-sided optical fiber.

8. The device of claim 1, further comprising a bonding agent connecting the optical fiber to the membrane.

9. The device of claim 8, the bonding agent comprising a transparent adhesive having a refractive index matched to a refractive index of the optical fiber.

5 10. The device of claim 1, the membrane comprising one of a semiconductor membrane, a transparent polymer membrane, a glass membrane, or a crystal membrane.

11. The device of claim 1, the membrane comprising a silicon membrane.

12. The device of claim 1, the membrane having a thickness of 0.5 to 2
10 wavelengths of the electromagnetic radiation.

13. The device of claim 1, the membrane further comprising a lens region between the coupling region and the patterned region.

14. The device of claim 13, the lens region comprising a photonic crystal superlens.

15 15. The device of claim 1, the at least one photonic crystal element comprising at least one of a photonic crystal superprism, a photonic crystal cavity array, a photonic crystal waveguide, and a photonic crystal drop-filter cavity.

16. The device of claim 1, the at least one photonic crystal element comprising a photonic crystal dispersive element proximate to the coupling region
20 and a photonic crystal coupling element opposite the coupling region, the photonic crystal dispersive element adapted to spectrally separate the electromagnetic radiation in the membrane, the photonic crystal coupling element adapted to filter the spectrally separated electromagnetic radiation and couple the spectrally separated electromagnetic radiation out of the membrane.

25 17. The device of claim 1, the at least one photodetector adapted to detect the spectrally separated electromagnetic radiation by producing one of a current proportional to an intensity of a spectral component of the electromagnetic radiation or a voltage proportional to the intensity of the spectral component of the electromagnetic radiation.

30 18. The device of claim 1, the at least one photodetector comprising one of a charge-coupled device (CCD) photodetector, a complementary metal-oxide-semiconductor (CMOS) photodetector, a pyrometer, a polometer, or a mercury cadmium telluride (MCT) semiconductor.

19. The device of claim 1, the at least one photodetector comprising one of a one-dimensional array of photodetectors or a two-dimensional array of photodetectors.

20. The device of claim 1, further comprising at least one support structure
5 connecting the membrane to the at least one photodetector.

21. The device of claim 20, the at least one support structure comprising one of a plurality of spacer beads, a plurality of protrusions from the at least one photodetector extending towards the membrane, or a plurality of protrusions from the membrane extending towards the at least one photodetector.

22. A method for detecting electromagnetic radiation, comprising:
coupling the electromagnetic radiation into a membrane;
spectrally separating the electromagnetic radiation by at least one
photonic crystal element defined in the membrane;
coupling the spectrally separated electromagnetic radiation out of the
15 membrane; and
detecting the spectrally separated electromagnetic radiation.

23. The method of claim 22, further comprising focusing the electromagnetic radiation before the spectrally separating.

24. The method of claim 22, further comprising filtering the spectrally
20 separated electromagnetic radiation before the coupling the spectrally separated electromagnetic radiation out of the membrane.

25. The method of claim 22, the detecting comprising one of producing a current proportional to an intensity of a spectral component of the electromagnetic radiation or producing a voltage proportional to the intensity of the spectral
25 component of the electromagnetic radiation.

26. A method for making a device for detecting electromagnetic radiation, comprising:
tapering a distal region of an optical fiber;
bonding the distal region of the optical fiber to a coupling region of a
30 membrane;
creating a plurality of holes in the membrane to define at least one photonic crystal element in the membrane proximate to the coupling region; and
supporting the membrane on at least one photodetector.

27. The method of claim 26, the tapering comprising:

heating the optical fiber; and
pulling the distal region of the heated optical fiber.

28. The method of claim 26, the tapering comprising:
selectively coating sections of the optical fiber in a cladding; and
5 chemically removing uncoated sections of the optical fiber to thereby
form a taper in the distal region of the optical fiber.

29. The method of claim 26, the bonding comprising connecting the distal
region of the optical fiber to the coupling region of the membrane with a transparent
adhesive.

- 10 30. The method of claim 26, the creating comprising creating a plurality of
holes by one of lithography, nano-imprinting, or nano-embossing.

31. The method of claim 26, the creating comprising creating a plurality of
holes in the membrane to define at least one of a photonic crystal superprism, a
photonic crystal cavity array, a photonic crystal waveguide, and a photonic crystal
15 drop-filter cavity.

32. The method of claim 26, the supporting comprising supporting the
membrane on at least one of plurality of spacer beads between the membrane and the
at least one photodetector, a plurality of protrusions from the at least one
photodetector extending towards the membrane, or a plurality of protrusions from the
20 membrane extending towards the at least one photodetector.

FIG. 3

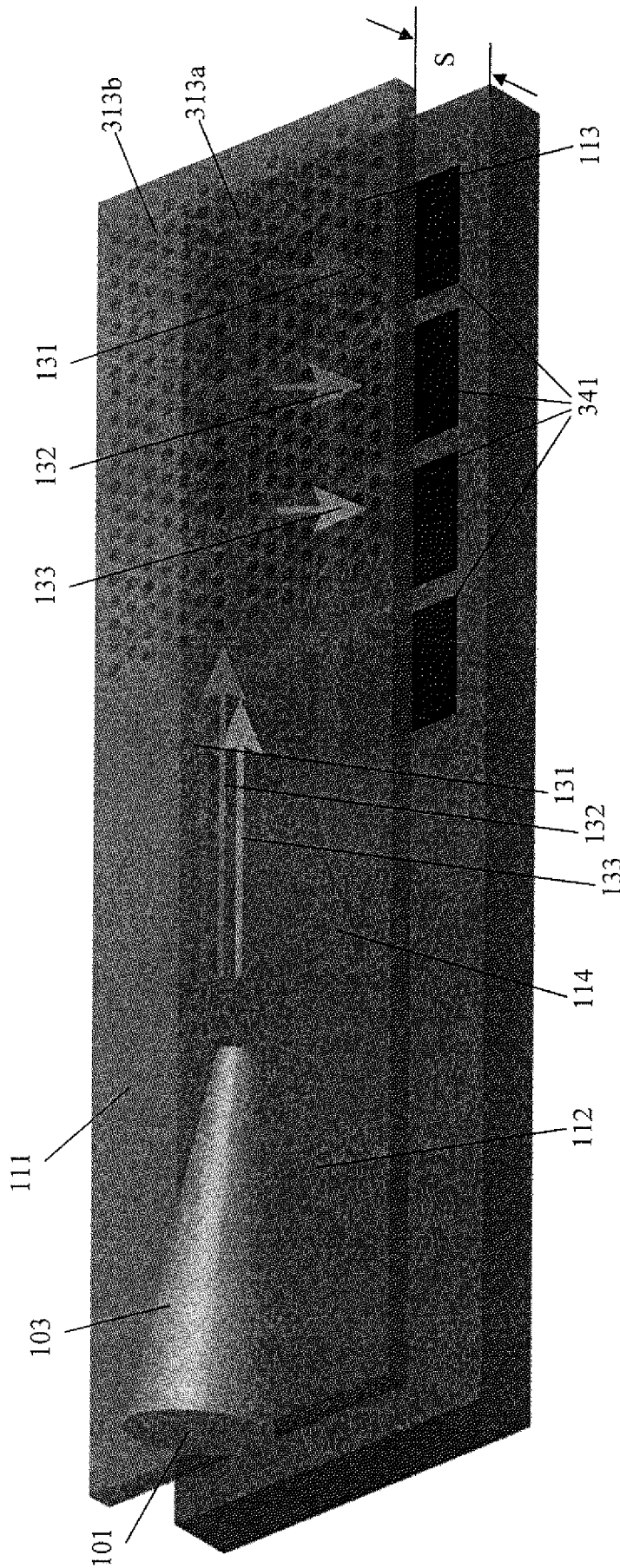


FIG. 4

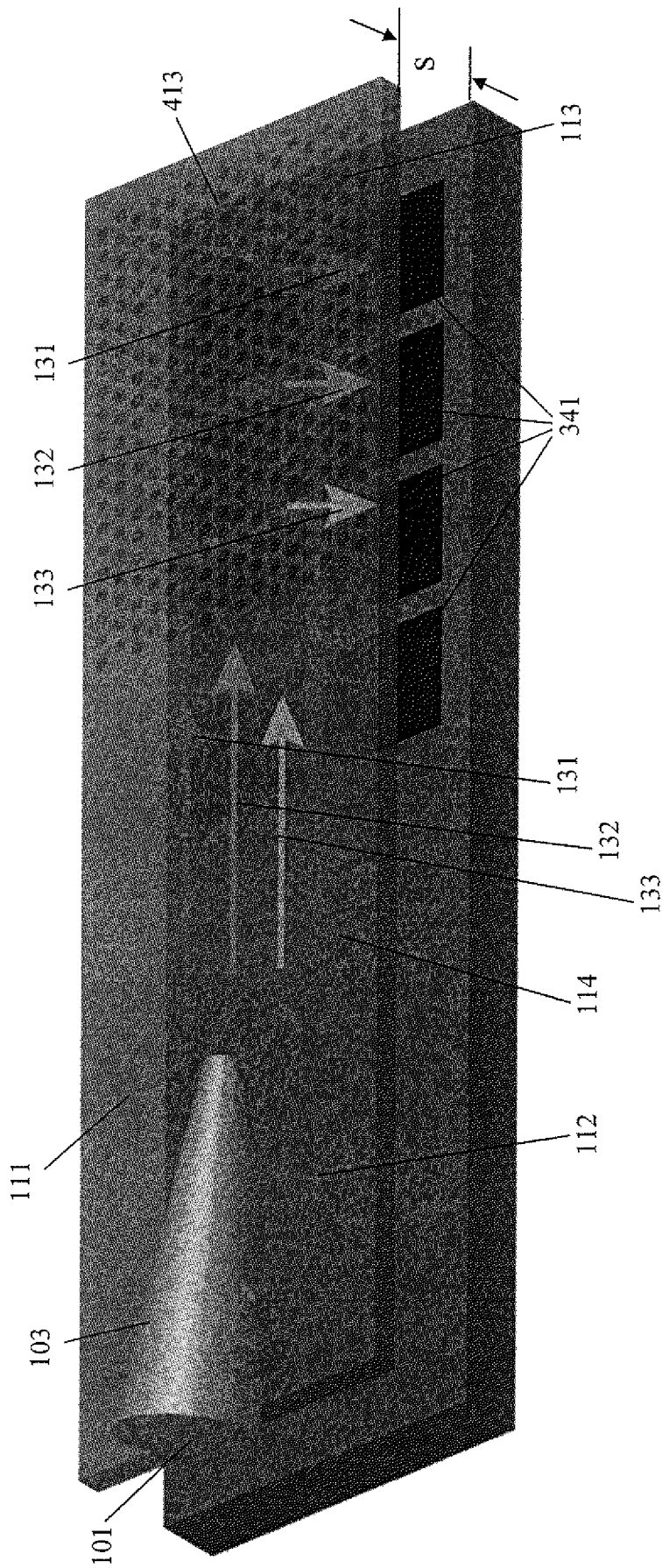


FIG. 5

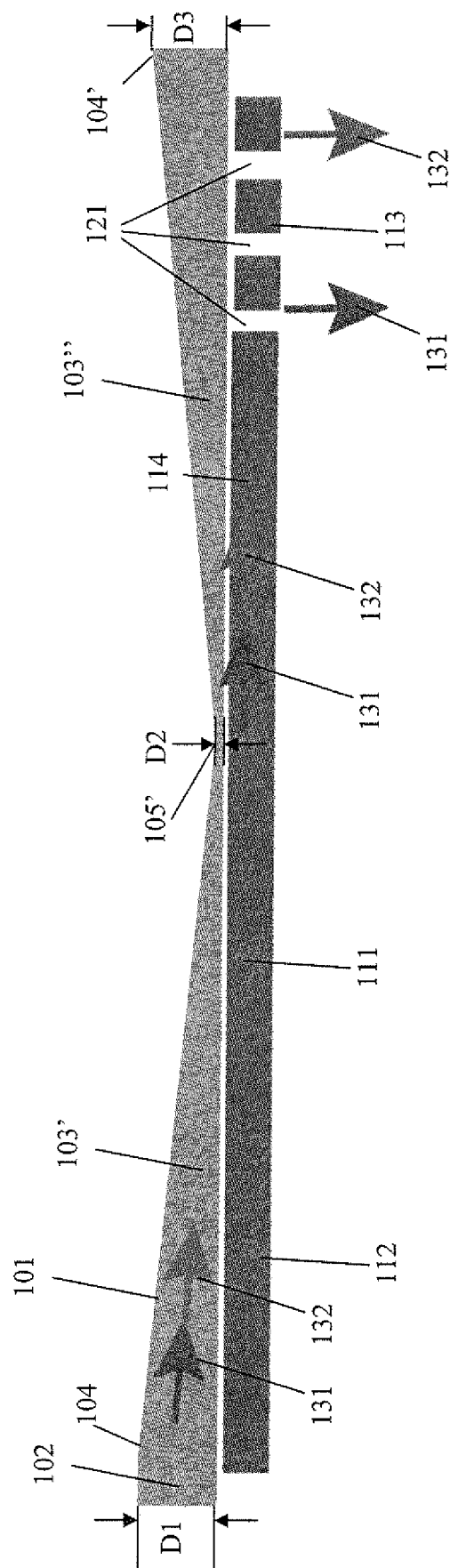


FIG. 6

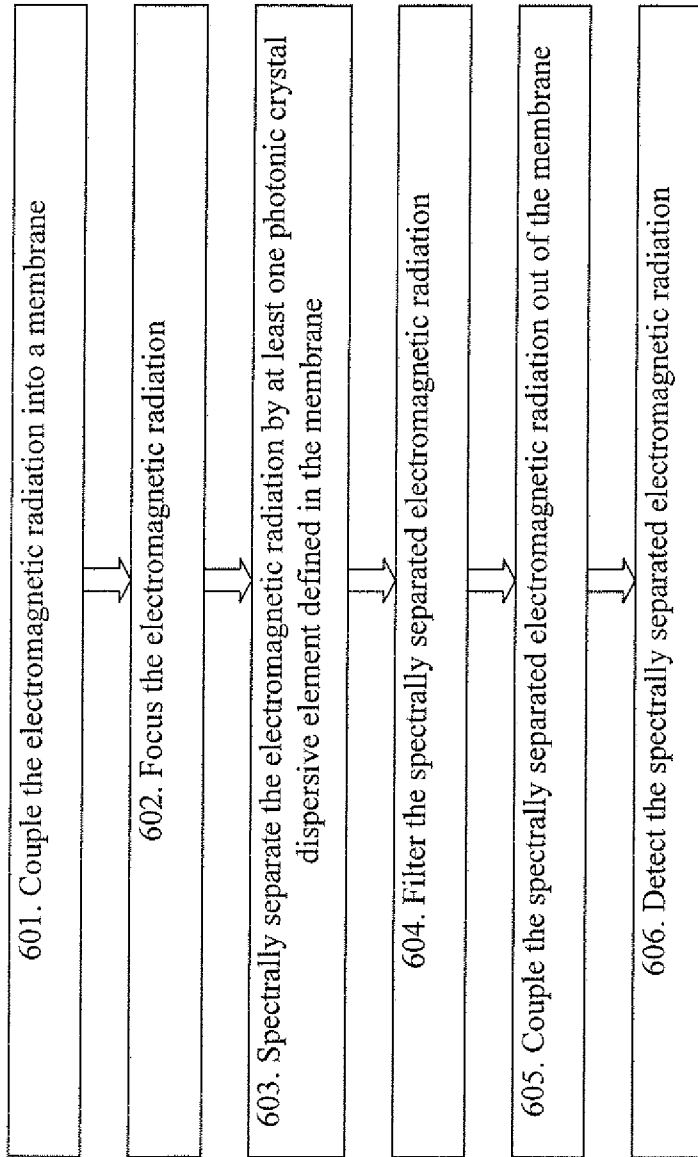
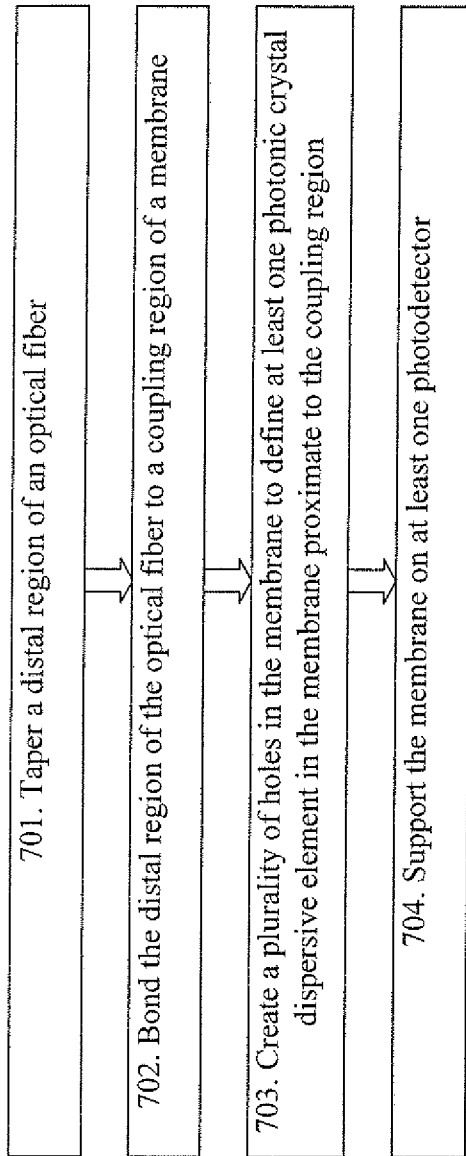


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US13/52020

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - G02F 1/00, 03, 1/035 (2013.01)

USPC - 385/2, 43; 356/480

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)

IPC(8) Classification(s): G02F 1/00, 03, 1/035 (2013.01)

USPC Classification(s): 385/2, 19, 43; 356/300, 480

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)

MicroPatent (US Granted, US Applications, EP-A, EP-B, WO, JP, DE-G, DE-A, DE-T, DE-U, GB-A, FR-A); ProQuest (Derwent, INSPEC, NTIS, PASCAL, Current Contents Search, Dissertation Abstracts Online, Inside Conferences); IP.com; IEEE.com; Google Scholar, Photonic crystal membrane spectrometer tapered fiber superlens adiabatic

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X ---	GAN, X. et al. A High-Resolution Spectrometer based on a compact planar two dimensional photonic crystal cavity array. Applied Physics Letters, Volume 100, Issue 23, id. 231104 1-4 (2012). [retrieved on 2013-11-30]. Retrieved from the Internet: <a abstract.cfm?uri='oe-17-13-10738"' href="http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CCwQFjAA&url=http%3A%2F%2Fqplab.mit.edu%2FQP%2Ffiles%2F2012.APL.Gan.cavity-array-spectrometer.pdf&ei=L-SmUuHgCI_voATp8oD4BQ&usg=AFQjCNG-9CsoW3h0ZSHVAUZI1DAg_Nm7Rw&sig2=H713D2nZmL4sNo3fmy-M3g&bvm=bv.57799294,d.cGU. <DOI: 10.1063/1.4724177 > . Entire document.</td><td>22, 24-25
---</td></tr> <tr> <td>Y</td><td>SARKISSIAN, R. et al. Spectroscopy of a tapered-fiber photonic crystal waveguide coupler. Optics Express, Vol. 17, Issue 13, pp. 10738-10747 (2009) [retrieved on 2013-11-30]. Retrieved from the Internet: <URL: http://www.opticsinfobase.org/oe/abstract.cfm?uri=oe-17-13-10738 > . <DOI: 10.1364/OE.17.010738> . Entire document.	1-21, 23, 26-32
Y	US 7,356,225 B2 (LOEBEL, N.) April 8, 2008. Figures 1-4, column 3, lines 8-64.	1-21, 26-32
Y	ANDRYIEUSKI, A et al. Nanocouplers for infrared and visible light. Advances in OptoElectronics 2012 (2012), June 18, 2012 [retrieved on 2013-11-30]. Retrieved from the Internet: <URL: http://arxiv.org/ftp/arxiv/papers/1206/1206.6601.pdf > . <DOI: 10.1155/2012/839747> . Abstract, figure 1, sections 1, 2.1, and 4.1.	2, 28
Y	US 2012/0045169 A1 (HU, C. et al.) February 23, 2012. Figures 1A1, paragraphs [0077], [0083].	3-6, 12
Y	US 8,213,751 B1 (HO, S. et al.) July 3, 2012. Figures 4-5, 10C-10D, 11D, column 3, lines 7-43; column 5, line 14-21; column 11, line 15- column 12, line 36; column 15, line 39- column 16, line 45; column 19, line 40- column 20, line 4.	8-9, 29
		13-14, 23

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

* Special categories of cited documents:	"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
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"E" earlier application or patent but published on or after the international filing date	"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
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&" document member of the same patent family
"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	

Date of the actual completion of the international search 30 November 2013 (30.11.2013)	Date of mailing of the international search report 20 DEC 2013
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