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(54) Title: MULTI-CORE OPTICAL FIBERS

(57) Abstract: One aspect of the disclosure relates to an optical fiber having a cross-sectional profile including a plurality of guiding regions, each guiding region including a core configured to emit radiation having an emitted wavelength when pumped with pump radiation having a pump wavelength, a first cladding surrounding the core, and optionally, one or more additional claddings surrounding the first cladding. The core of each guiding region is configured to guide radiation of the emitted wavelength, and the core and the first cladding of each guiding region are together configured to guide radiation of the pump wavelength. The cross-sectional profile of the optical fiber also includes one or more barrier regions, the barrier regions configured to separate the guiding regions from one another, the barrier regions being configured to prevent radiation of the pump wavelength being guided by the core and the first cladding in each of the guiding regions from substantially coupling into another guiding region.



WO 2014/197052 A2

MULTI-CORE OPTICAL FIBERS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority of U.S. Provisional Patent Application serial no. 61/779,760, filed March 13, 2013, which is hereby incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0002] The present invention relates generally to optical waveguides for the transmission of electromagnetic energy. The present invention relates more particularly to multi-core optical fibers suitable, for example, for use as active optical fibers in fiber lasers and amplifiers, and to devices using them.

2. Technical Background

[0003] Optical fiber lasers and amplifiers are conventional in the art. In such lasers and amplifiers, materials (e.g., rare earth elements, or Raman-active materials) disposed in the core of the active optical fiber of the laser or amplifier receive pump radiation of a predetermined wavelength and, responsive thereto, provide or amplify light of a different wavelength for propagation in the core. For example, the well-known erbium doped fiber amplifier receives pump radiation having a wavelength of 980 or 1480 nm and amplifies an optical signal propagating in the core at a wavelength in the 1550 nm region.

[0004] In such optical fiber lasers and amplifiers, the pump radiation can be introduced directly to the core, which can be difficult due to the small size of the core, or can be introduced to the cladding surrounding the core and absorbed by the core as the rays propagating in the cladding intersect the core. Lasers and amplifiers with the pump radiation introduced to the cladding are known as "cladding-pumped" optical devices, and facilitate the scale-up of lasers and amplifiers to higher power systems. So-called "double-clad" optical fibers, which have an inner cladding surrounding the core that acts to confine radiation of the emitted wavelength substantially in the core of the optical fiber, but itself guides radiation of a pump wavelength, are often used in cladding-pumped systems.

[0005] There remains interest in the use of multi-core double-clad fibers in optical amplifier and laser systems. Conventionally, multi-core double-clad fibers have been problematic to

build and use. One key difficulty has been ensuring that each of the cores is pumped substantially equally, so that the inversion level is known (or at least simply inferred). Substantially equal pumping is desirable to avoid the onset of amplified spontaneous emission resulting from disproportionate pump absorption in one of the cores, and a potentially catastrophic self-lasing effect. A self-lasing event causes the destructive release of the stored energy in the core of the fiber suffering the event. This destruction is permanent and irreversible.

[0006] Accordingly, it is desirable to address one or more of the foregoing disadvantages and drawbacks of the prior art.

SUMMARY OF THE INVENTION

[0007] One aspect of the disclosure relates to an optical fiber having a cross-sectional profile including a plurality of guiding regions, each guiding region including a core configured to emit radiation having an emitted wavelength when pumped with pump radiation having a pump wavelength, a first cladding surrounding the core, and optionally, one or more additional claddings surrounding the first cladding. The core of each guiding region is configured to guide radiation of the emitted wavelength, and the core and the first cladding of each guiding region are together configured to guide radiation of the pump wavelength. The cross-sectional profile of the optical fiber also includes one or more barrier regions, the barrier regions configured to separate the guiding regions from one another, the barrier regions being configured to prevent radiation of the pump wavelength being guided by the core and the first cladding in each of the guiding regions from substantially coupling into another guiding region.

[0008] Another aspect of the invention relates to a method for generating radiation, including introducing pump radiation into the guiding regions of the optical fiber as described herein, the pump radiation having the pump wavelength of the cores of the guiding regions of the optical fiber, such that the cores emit radiation having the emitted wavelength.

[0009] Another aspect of the invention relates to an optical fiber device for use in generating radiation, the optical fiber device including an optical fiber as described herein; and one or more pump sources operatively coupled to the guiding regions of the optical fiber, the pump sources configured to provide pump radiation having the pump wavelength of the cores of the guiding regions of the optical fiber.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The accompanying drawings are not necessarily to scale, and sizes of various elements can be distorted for clarity.

[0011] FIG. 1 is a cross-sectional schematic view of an optical fiber according to one embodiment of the invention;

[0012] FIG. 2 is a cross-sectional schematic view of an optical fiber according to another embodiment of the invention;

[0013] FIG. 3 is a cross-sectional schematic view of an optical fiber according to another embodiment of the invention;

[0014] FIG. 4 is a cross-sectional schematic view of an optical fiber according to another embodiment of the invention;

[0015] FIG. 5 is a cross-sectional schematic view of an optical fiber according to another embodiment of the invention;

[0016] FIG. 6 is a schematic view of an optical fiber device according to another embodiment of the invention; and the invention.

[0017] FIG. 7 is a schematic view of an optical fiber device according to another embodiment of

DETAILED DESCRIPTION OF THE INVENTION

[0018] One embodiment of an optical fiber according to the present invention is shown in cross-sectional view in FIG. 1. Optical fiber 100 has a cross-sectional profile that includes a plurality of guiding regions 105. Each guiding region includes a core 110, and a first cladding 120 surrounding the core. The core 110 of each guiding region 105 is configured to emit radiation having an emitted wavelength when pumped with pump radiation having a pump wavelength. The core of each guiding region is configured to guide radiation of the emitted wavelength (i.e., radiation of the emitted wavelength is substantially confined to the core by the first cladding). The core 110 and the first cladding 120 of each guiding region 105 are together configured to guide radiation of the pump wavelength (i.e., radiation of the

pump wavelength is substantially confined to the core and the first cladding by surrounding materials). While not present in the embodiment of FIG. 1, each guiding region can include one or more additional claddings surrounding the first cladding. In certain such embodiments, the one or more additional claddings can substantially confine radiation of the pump wavelength to the core and the first cladding.

[0019] Notably, the optical fiber of FIG. 1 also includes one or more barrier regions 130, configured to separate the guiding regions from one another. Each barrier region 130 is configured to prevent radiation of the pump wavelength being guided by the core and the first cladding in each of the guiding regions from substantially coupling into another guiding region. For example, in certain embodiments, less than 10%, less than 5%, or even less than 1% of optical power at the pump wavelength guided by each guiding region can couple to another guiding region.

[0020] In other embodiments, the confinement of radiation of the pump wavelength can be determined by calculating overlap integrals. Each guiding region can be multi-mode at the pump wavelength. For each modal pair between two of the guiding regions (e.g., mode m of guiding region 1 and mode n of guiding region 2), the overlap integral can be calculated using the equation:

$$\eta_{m,n} = \frac{\left[\int E_{gr1,m}(x,y) E_{gr2,n}(x,y) dx dy \right]^2}{\left[\int E_{gr1,m}^2(x,y) dx dy \right] \left[\int E_{gr2,n}^2(x,y) dx dy \right]},$$

in which $E_{gr1,m}(x,y)$ and $E_{gr2,n}(x,y)$ are the mode field profiles of the mode m of guiding region 1 and mode n of guiding region 2, respectively. In certain embodiments, the average mode field overlap can be calculated as the arithmetic mean of all mode field combinations between guiding region 1 and guiding region 2:

$$\eta_{avg} = \frac{\sum_{m=1}^{mt1} \left[\sum_{n=1}^{mt2} \eta_{m,n} \right]}{(mt1)(mt2)}$$

in which mt1 is the total number of modes at the pump wavelength for guiding region 1, and mt2 is the total number of modes at the pump wavelength for guiding region 2. In certain embodiments, the average mode field overlap between each pair of guiding regions is less than about 0.1, less than about 0.05, or even less than 0.01.

[0021] In the embodiment of FIG. 1, there are three guiding regions 105; the person of ordinary skill in the art will appreciate that in other embodiments, more or fewer guiding regions can be used. For example, in one embodiment, there are two guiding regions. In other embodiments, there are four, five, six, seven or eight guiding regions. In certain embodiments, the cores and/or the guiding regions are arranged symmetrically in the optical fiber. But as the person of ordinary skill in the art will appreciate, while the optical fibers shown in the figures described herein have symmetrically-disposed cores and guiding regions, in some embodiments, the cores and/or the guiding regions can be arranged asymmetrically in the optical fiber.

[0022] The person of ordinary skill in the art will appreciate that standard optical fiber materials can be used in making the optical fibers of the present invention. For example, the optical fibers can be made from silica-based materials such as substantially undoped silica or silica doped with one or more materials. Suitable dopants can include, for example, phosphorus, germanium, fluorine, boron and aluminum, depending on the application. Doping can be used, for example, to provide desired mechanical or thermal properties to the base glass material, or to provide a desired refractive index to the base glass material. The person of ordinary skill in the art can select appropriate combinations of dopants to give desired refractive indices together with the desired softening points to allow for efficient drawing of the optical fibers with maintenance of the desired cross-sectional profile, as is conventional in the art.

[0023] As described above, the core of each guiding region is configured to emit radiation of an emitted wavelength when pumped with pump radiation having a pump wavelength. In certain embodiments, each core is doped with a rare earth element (e.g., in ionic or oxide form). For example, the core can be silica doped with a rare earth element and optionally one or more additional dopants. The rare earth can be, for example, ytterbium, erbium, thulium, praseodymium or neodymium. In one embodiment, the rare earth is ytterbium, erbium, or a combination of erbium and ytterbium. As is conventional in the art, such materials can provide optical gain, and therefore are useful as active fibers in optical lasers and amplifiers. Base glass material including a rare earth can optionally be doped with one or more other materials, for example, to provide desired mechanical or thermal properties to the base glass material, to provide a desired refractive index to the base glass material, or to provide a desirable environment for the rare earth (e.g., to reduce clustering). In one embodiment, the

rare earth-doped silica is silica doped with rare earth oxide (e.g., erbium (III) oxide) as well as oxides of aluminum, boron and phosphorus. Rare earth doped glass compositions are well known in the art, and such compositions can be used or modified by the person of ordinary skill in the art for use in the optical fibers and optical fiber devices of the present invention. In other embodiments, the core is not doped with a rare earth element, but is configured to provide Raman gain. The person of ordinary skill in the art will select appropriate core materials (e.g., germanium-doped silica) and designs (e.g., relatively small effective mode area, for example, less than about $105\ \mu\text{m}^2$, less than about $95\ \mu\text{m}^2$, or even less than about $85\ \mu\text{m}^2$) for provision of Raman gain as is conventional in the art. As the person of ordinary skill in the art will appreciate, the core can be formed with a variety of refractive indices, e.g., in the range of about 1.4 to about 2.0 at 1550 nm.

[0024] As described above, in each guiding region the first cladding surrounds the core, and substantially confines radiation of the emitted wavelength to the core. Accordingly, the first cladding has a refractive index less than that of the core. In certain embodiments, the first cladding has a refractive index profile that provides for single mode guiding of radiation of the emitted wavelength by the core that it surrounds. The first cladding can be made, for example, from solid material, and can have a uniform refractive index, or a graded refractive index. The first cladding can be made from a single layer or a plurality of layers (i.e., having substantially discontinuous refractive index boundaries between them). Moreover, as described above, in each guiding the first cladding and the core together are configured to guide radiation of the pump wavelength (i.e., radiation of the pump wavelength is substantially confined to the core and the first cladding by surrounding materials). The first cladding region and the core can be configured, for example, to provide multimode guiding of radiation of the pump wavelength. Cladding material glass compositions (for example, pump cladding compositions) are well known in the art, and such compositions can be used or modified by the person of ordinary skill in the art for use in the optical fibers and optical fiber devices of the present invention. As the person of ordinary skill in the art will appreciate, the first cladding can be formed with a variety of refractive indices, e.g., in the range of about 1.4 to about 2.0 at 1550 nm.

[0025] As noted above, in certain embodiments, each guiding region can include one or more additional claddings surrounding the first cladding. One such embodiment is shown in cross-sectional view in FIG. 2. In each guiding region of the optical fiber 200 of FIG. 2, the core

210 is surrounded by a first cladding 220, which in turn is surrounded by an additional cladding 250. In certain such embodiments, the one or more additional claddings can substantially confine radiation of the pump wavelength to the core and the first cladding. Accordingly, in certain such embodiments, the one or more additional claddings have lower refractive indices than the core and the first cladding.

[0026] In certain embodiments of the optical fibers as described herein, the first cladding region has a minimum thickness (i.e., the minimum distance between the core region and the outer boundary of the first cladding region) of at least about 15 μm , at least about 20 μm , at least about 25 μm , at least about 30 μm , or even at least about 35 μm . In certain embodiments, the minimum distance between each core region and each of the barrier regions is at least about 15 μm , at least about 20 μm , at least about 25 μm , at least about 30 μm , or even at least about 35 μm .

[0027] In certain embodiments as described herein, the optical fiber further includes an outer cladding surrounding the guiding regions and the barrier regions. For example optical fiber 100 shown in FIG. 1 includes an outer cladding 140 surrounding the guiding regions 105 and the barrier regions 130. The outer cladding has a lower refractive index than the effective refractive index of each mode guided by the first cladding and the core at the pump wavelength, and thus can serve to confine radiation of the pump wavelength in the first cladding and the core of each guided region. The outer cladding can, for example, have a refractive index that is at least about 0.1 less than, or even at least about 0.2 less than the effective refractive index of each mode guided by the first cladding and the core at the pump wavelength. The outer cladding can be formed from any appropriate material, as would be appreciated by the person of ordinary skill in the art. For example, in certain embodiments, the outer cladding is formed from a polymeric material, as is conventional in double-clad fibers.

[0028] As described above, the barrier regions are configured to separate the guiding regions from one another, each barrier region being configured to prevent radiation of the pump wavelength being guided by the core and the first cladding in each of the guiding regions from substantially coupling into another guiding region. In certain embodiments, and as shown in FIG. 1, each barrier region is a microstructured region. As shown in FIG. 1, each microstructured region 130 includes a solid material 132, and a plurality of features 135

disposed in the solid material. The features have a different refractive index than the solid material. The one or more microstructured regions are configured to prevent radiation of the pump wavelength being guided by the core and the first cladding in one of the guiding regions from substantially coupling into another guiding region, as described above. The solid material can be the same material as the material of the first cladding or an optional additional cladding of each guiding region, or can be different. The person of ordinary skill in the art will select a solid material for the microstructured region to provide the desired confinement of the guiding regions and the desired physical properties.

[0029] In certain embodiments, the one or more microstructured regions prevent radiation of the pump wavelength being guided by the core and the first cladding in each of the guiding regions from substantially coupling into another guiding region through a refractive index confinement effect. The person of ordinary skill in the art will select combinations of features and solid materials of the microstructured regions to provide the desired refractive index confinement effect. For example, in certain embodiments, each microstructured region has an average refractive index of refraction at least about 0.05, at least about 0.1, or even at least about 0.2 less than the effective refractive index of each mode guided by the first cladding and the core at the pump wavelength.

[0030] In certain embodiments, the plurality of features disposed in the solid material of each microstructured region are a plurality of voids. For example, as is conventional in the optical fiber arts, the voids running axially along the fiber can be made by drawing a preform having voids axially formed therein, for example, using the conventional “stack-and-draw” process. As the voids have a refractive index approaching 1.0, they can generally provide high index contrast with the other materials of the optical fiber.

[0031] In other embodiments, the plurality of features disposed in the solid material of each microstructured region are a plurality of solid features. For example, as is conventional in the optical fiber arts, the voids running axially along the fiber can be made by drawing a preform having solid features axially formed therein, for example, using the conventional “stack-and-draw” process. The person of ordinary skill in the art can select materials having a sufficiently low refractive index to provide index confinement in a microstructured configuration.

[0032] In one embodiment, each of the plurality of features disposed in the solid material of each microstructured region has a lower refractive index than the solid material. For example, in certain embodiments, each of the plurality of features disposed in the solid material of each microstructured region has a refractive index at least about 0.05, at least about 0.1, or even at least about 0.2 less than the refractive index of the solid material. In certain embodiments, each of the plurality of features disposed in the solid material of each microstructured region has a refractive index at least about 0.05, at least about 0.1, or even at least about 0.2 less than the effective refractive index of each mode guided by the first cladding and the core at the pump wavelength. In certain embodiments, each of the plurality of features disposed in the solid material of each microstructured region has a refractive index at least about 0.05, at least about 0.1, or even at least about 0.2 less than the effective refractive index of each mode guided by the first cladding and the core at the pump wavelength.

[0033] In certain embodiments, a single row of the refractive index features separates adjacent guiding regions from one another. For example, in the optical fiber 300 of FIG. 3, in the microstructured region 330, a single row of the refractive index features 335 (in this example, voids) separate adjacent guiding regions 305 from one another. In other embodiments, a plurality of rows of the refractive index features separates adjacent guiding regions from one another, for example, as shown in FIGS. 1 and 2. While the refractive index features in FIGS. 1-3 are shown as being in a regular arrangement, the person of ordinary skill in the art will appreciate that the refractive index features can be arranged irregularly.

[0034] In other embodiments, in each microstructured region, the plurality of features taken together has a photonic bandgap which prevents radiation of the pump wavelength being guided by the core and the first cladding in one of the guiding regions from coupling into another guiding region. A photonic bandgap structure can be formed from a periodic arrangement of the features in the solid material of the microstructured region. As the person of ordinary skill in the art will appreciate, when the dielectric constants of the materials are different, the effects of scattering and Bragg diffraction at the lattice interfaces control the propagation of optical signals through the microstructured region. The dielectric constants (and thus the refractive indices) and the size and arrangement of the features can be selected such that radiation of certain frequencies (i.e., falling within the “bandgap”) will not

propagate in the microstructured region. When the frequency corresponding to the pump wavelength falls within the bandgap, radiation of the pump wavelength will not propagate in the microstructured region, thereby preventing radiation of the pump wavelength from coupling from each guiding region to the others. The person of ordinary skill in the art can use conventional methods to select the refractive indices and the sizes and arrangements of the features using conventional techniques to provide a photonic bandgap structure having the desired bandgap.

[0035] In certain embodiments, the features are voids. In other embodiments, the features are formed from solid material. As the person of ordinary skill in the art will appreciate, the features can have a variety of refractive indices as compared to the solid material in which they are disposed. For example, in certain embodiments, the refractive indices of the features are at least about 0.05, or even at least about 0.1 less than the refractive index of the solid material in which they are disposed. In other embodiments, the refractive indices of the features are at least about 0.05, or even at least about 0.1 greater than the refractive index of the solid material in which they are disposed. An example of an optical fiber having photonic bandgap structures as the barrier regions is shown in schematic view in FIG. 4. Optical fiber 400 includes three guiding regions, each including a core 410 and a first cladding 420. Barrier regions 430 separate the guiding regions from one another, as described above. The barrier regions are microstructured, having a plurality of solid features 432 disposed in solid material 435. The solid features in this embodiment have a refractive index higher than that of the solid material in which they are disposed. In this embodiment, the photonic bandgap structure has a triangular lattice structure, but the person of ordinary skill in the art will appreciate that other photonic bandgap structures (e.g., square, hexagonal) can be used.

[0036] Another embodiment is shown in cross-sectional schematic view in FIG. 5. Here, the microstructured barrier region is formed as a set of holes 532, separating nine guiding regions from one another.

[0037] In the microstructured regions of optical fibers as described herein, as the person of ordinary skill in the art will appreciate, the features can be provided with a variety of sizes and spacings. For example, in certain embodiments, the features are less than 5 μm in size, and have center-to-center spacings of less than 5 μm . In other embodiments, the features are less than 2 μm in size, and have center-to-center spacings of less than 2 μm . But the person

of ordinary skill in the art will appreciate that in certain embodiments, e.g., when the barrier regions prevent radiation of the pump wavelength being guided by the core and the first cladding in each of the guiding regions from substantially coupling into another guiding region through a refractive index confinement effect, larger features can be used.

[0038] In certain embodiments, each barrier region is a region of solid material having a refractive index selected such that the barrier regions prevent radiation of the pump wavelength being guided by the core and the first cladding in each of the guiding regions from substantially coupling into another guiding region through a refractive index confinement effect. For example, the region of solid material of each barrier region can have a refractive index at least about 0.05 less, at least about 0.1 less, or even at least about 0.2 less than the effective refractive index of each mode guided by the first cladding and the core at the pump wavelength. The person of ordinary skill in the art will select solid materials of desirably low refractive index, for example, by selecting appropriate glass materials and dopants therefor. Such an embodiment is shown in FIG. 2, in which the barrier regions 230 are formed from solid material having a refractive index lower than the effective refractive index of each mode guided by the first cladding and the core at the pump wavelength.

[0039] In order to provide for the largest cross-sectional area available to accept radiation from a pump fiber, it is desirable that the barrier regions be relatively small. For example, in certain embodiments, the barrier regions have a total area that is no more than about 50% of, no more than about 20% of, or even no more than about 10% of the total area of the guiding regions. In other embodiments, each barrier region has a thickness (e.g., as measured on a core-to-core line traversing the barrier region) that is less than about 50 μm , less than about 25 μm , or even less than about 15 μm .

[0040] In certain embodiments, the barrier regions are continuous in the cross-sectional profile of the optical fiber, for example, as shown in FIGS. 3-5. In other embodiments, the barrier regions are discontinuous, for example, as shown in FIGS. 1 and 2. Even when the barrier regions are discontinuous, the person of ordinary skill in the art can arrange them such that they prevent radiation of the pump wavelength being guided by the core and the first cladding in each of the guiding regions from substantially coupling into another guiding region.

[0041] As the person of ordinary skill in the art will appreciate, the optical fibers of the present invention can be constructed from a number of materials, as described above. “Stack-and-draw” techniques used in making conventional microstructured optical fibers can be used to manufacture the optical fibers according to the present invention. For example, an optical fiber having a cross-sectional profile similar to those of FIGS. 1 and 2 can be made by machining slots into a multicore preform, then placing materials corresponding to the desired barrier region (e.g., hollow capillaries, or solid glass materials in the form of rods, cullet or deposited materials) into the slots. An optical fiber like that of FIGS. 3-5 can be made by making a cylindrical multicore preform, machining it into a number of sections corresponding to the guiding regions of the optical fiber, and stacking them together (e.g., in a jig) with materials corresponding to the desired barrier region (e.g., hollow capillaries, low index glass materials). Optical fiber preforms can also be made by stacking the appropriate combination of solid and hollow capillaries to provide the desired profile. In all cases, after fusion and consolidation to remove any undesired void space, the preform can be drawn into optical fiber and coated with polymer. The person of ordinary skill in the art may use other appropriate methods in the fabrication of the optical fibers described herein, for example, sleeving a bundle of capillaries with a solid tube, redrawing to reduce the preform diameter, and/or etching with SF_6 or aqueous $\text{NH}_4\text{F} \cdot \text{HF}$ to enlarge the size of any holes.

[0042] Another aspect of the invention is a method for generating radiation. The method includes introducing pump radiation into the guiding regions of an optical fiber as described herein. The pump radiation has a pump wavelength of the cores of the guiding regions, such that the cores emit radiation having the emitted wavelength. The methods can be performed, for example, to provide amplification of a signal (e.g., a telecommunications signal), or to provide laser radiation for use in a variety of applications. Accordingly, in certain embodiments, the method further includes receiving a signal having a signal wavelength in the cores of the guiding regions of the optical fiber, the signal wavelength being the same as the emitted wavelength, and wherein the emission of the radiation of the emitted wavelength amplifies the signal.

[0043] The person of ordinary skill in the art will appreciate that methods according to this aspect of the invention can take many forms and include many additional steps as is conventional in the art.

[0044] Another aspect of the invention is an optical fiber device for use in generating radiation. The device includes an optical fiber as described herein, and one or more pump sources operatively coupled to the guiding regions of the optical fiber. The pump sources are configured to provide pump radiation having the pump wavelength of the cores of the guiding regions of the optical fiber. The device can be configured, for example, as an amplifier (e.g., for use in telecommunications applications), or as a laser. The person of ordinary skill in the art will appreciate that optical devices according to this aspect of the invention can take many forms and include many additional components as is conventional in the art. For example, as would be evident to the person of ordinary skill in the art, an optical fiber device of the present invention can be packaged in a suitable enclosure, with appropriate optical and electrical connectors. The optical fiber devices of the present invention can also be used as part of (and packaged together with) a larger optoelectronic system.

[0045] For example, one embodiment of a device is shown in schematic view in FIG. 6. Optical fiber device 670 is configured as a counter-pumped fiber amplifier, and includes an optical fiber 600 as described herein and a pump source 676 operatively coupled to the guiding regions thereof. In this embodiment, the pump source 676 is coupled to the guiding regions of the optical fiber 500 by coupler 674. Isolators 672 are positioned at either end of the device. While the amplifier described above with reference to FIG. 6 is counter-pumped, the person of ordinary skill in the art will recognize that amplifiers according to the present invention can be co-pumped, or pumped with a more complicated pumping scheme.

[0046] In another embodiment, the optical fiber device is configured as a fiber laser, for example, as shown in FIG. 7. Optical fiber device 770 is configured as a fiber laser, and includes a pump source 772 operatively coupled to an optical fiber 700 as described herein. To form a Fabry-Perot cavity 778, a highly reflective (i.e., for the emitted radiation) element 776 (e.g., a fiber Bragg grating) is optically coupled between the pump source 772 and the optical fiber 700; and a partially reflective element 777 (e.g., a fiber Bragg grating) is disposed at the end of the optical fiber 700 to act as an output coupler. Splices 779 are used to interconnect the various optical fibers.

[0047] In certain embodiments of the invention as described herein, the guiding regions of the optical fiber can be configured such that each guiding region is pumped substantially equally. In one embodiment of the invention, the guiding regions of the optical fiber are

configured such that the power of pump radiation guided in each guiding region is within 50%, within 30%, within 20%, or even within 10% of the average power guided by all guiding regions. The person of ordinary skill in the art can use an optical fiber in which the areas of the guiding regions are not all of the same area. Thus, smaller guiding regions can be coupled to areas of larger incoming pump radiation, and larger guiding regions can be coupled to areas of smaller incoming pump radiation.

[0048] Accordingly, in certain embodiments of the optical fibers as described herein, the guiding regions of the optical fibers are not all of the same size. For example, in certain embodiments, one or more of the guiding regions have areas that are at least 10% smaller, at least 20% smaller, at least 35% smaller, or even at least 50% smaller than the other guiding regions of the optical fiber. In certain embodiments, the one or more guiding regions of smaller area are disposed centrally in the cross-sectional profile of the optical fiber, and the one or more guiding regions of larger area are disposed peripherally with respect to the centrally-disposed guiding regions. Such optical fibers can be used with pump radiation having a power profile that is of higher power at a central position thereof, and lower power at peripheral positions thereof. Similarly, in certain embodiments of the methods and devices described herein, in the coupling of the pump radiation to the guiding regions of the fiber, a higher power area of the incoming pump radiation or of the pump source is coupled to a smaller area guiding region of the optical fiber, and a lower power area of the incoming pump radiation or of the pump source is coupled to a larger area guiding region of the optical fiber.

[0049] For example, the optical fiber 500 of FIG. 5 has a centrally-disposed guiding region 505, and peripherally-disposed guiding regions 506. Notably, the centrally-disposed guiding region 505 has a smaller area than the peripherally-disposed guiding regions 506. Such an optical fiber can be useful for coupling to incoming pump radiation having higher power at a central portion thereof.

[0050] In other embodiments, the guiding regions of the optical fibers are roughly similar in size. For example, in certain embodiments, each of the guiding regions has an area that is within 30%, within 20%, or even within 10% of the average area of all guiding regions. Such optical fibers can be especially useful, for example, when the incoming radiation is coupled to the optical fiber such that it has relatively constant power across all guiding regions.

[0051] The person of ordinary skill in the art will appreciate that the optical fibers, devices and methods described herein can be used with a variety of pump wavelengths and emitted wavelengths. For example, in certain embodiments, an optical fiber is designed for use at one or more emitted wavelengths in the range of 800 nm to 2400 nm. For example, in certain embodiments, the optical fiber is designed for use at one or more emitted wavelengths in the range 1000 nm - 1100 nm; 1270 nm - 1330 nm; 1450 nm - 1500 nm; or 1520 nm - 1610 nm. In certain embodiments of the optical fibers, devices, and methods described herein, the pump wavelength is 980 nm or 1480 nm, and the emitted wavelength is in the range of 1520 nm - 1610 nm. Such embodiments can be useful with erbium doping of the cores (e.g., either alone or codoped with ytterbium). In other embodiments of the optical fibers, devices, and methods described herein, the pump wavelength is 940 nm, and the emitted wavelength is in the range of 1000 nm - 1100 nm. Such embodiments can be useful with ytterbium doping of the cores. The person of ordinary skill in the art will select other operating wavelengths for the optical fiber based on the gain medium.

[0052] The optical fibers, devices and methods described herein can provide a number of advantages over conventional optical fibers, devices and methods. For example, in certain embodiments, the optical fibers can be used to ensure that each core is exposed to an approximately equivalent amount of pump energy, such that all cores can be pumped at a relatively high level with a reduced risk of any one core being pumped at too high a level. When incoming pump radiation is coupled to the optical fiber such that it uniformly couples across all guiding regions, guiding regions of roughly equal area can help to ensure that each guiding region has roughly equivalent pump power guided therein (e.g., by tiling the pump radiation ratiometrically along the optical fiber cross-sectional profile). And when incoming pump radiation is coupled to the optical fiber such that the power profile of the pump radiation is not uniform across all guiding regions, guiding regions of different size can be used to reduce the difference in pump power guided by the different guiding regions. Thus, the optical fibers described herein can be pumped at high powers with a reduced risk of amplified spontaneous emission, self-lasing, or other destructive processes (e.g., stimulated Brillouin scattering).

[0053] In the claims as well as in the specification above all transitional phrases such as "comprising", "including", "carrying", "having", "containing", "involving" and the like are

understood to be open-ended. Only the transitional phrases "consisting of" and "consisting essentially of" shall be closed or semi-closed transitional phrases, respectively.

[0054] It is understood that the use of the term "a", "an" or "one" herein, including in the appended claims, is open ended and means "at least one" or "one or more", unless expressly defined otherwise. The occasional use of the terms herein "at least one" or "one or more" to improve clarity and to remind of the open nature of "one" or similar terms shall not be taken to imply that the use of the terms "a", "an" or "one" alone in other instances herein is closed and hence limited to the singular. Similarly, the use of "a part of", "at least a part of" or similar phrases (e.g., "at least a portion of") shall not be taken to mean that the absence of such a phrase elsewhere is somehow limiting.

[0055] Subsequent reference to the phrase "at least one", such as in the phrase "the at least one", to specify, for example, an attribute of the limitation to which "at least one" initially referred is not to be interpreted as requiring that the specification must apply to each and every instance of the limitation, should more than one be under consideration in determining whether the claim reads on an article, composition, machine or process, unless it is specifically recited in the claim that the further specification so applies.

[0056] The use of "or", as in "A or B", shall not be read as an "exclusive or" logical relationship that excludes from its purview the combination of A and B. Rather, "or" is intended to be open, and include all permutations, including, for example A without B; B without A; and A and B together, and as any other open recitation, does not exclude other features in addition to A and B.

[0057] Any of the features described above in conjunction with any one aspect described above can be combined with a practice of the invention according to any other of the aspects described above, as is evident to one of ordinary skill who studies the disclosure herein.

[0058] Those of ordinary skill in the art will recognize or be able to ascertain using no more than routine experimentation many equivalents to the specific embodiments of the invention described herein. It is therefore to be understood that the foregoing embodiments are presented by way of example only and that within the scope of the appended claims and equivalents thereto, the invention may be practiced otherwise than as specifically described. The present invention is directed to each individual feature, system, material and/or method

described herein. In addition, any combination of two or more such features, systems, materials and/or methods, if such features, systems, materials and/or methods are not expressly taught as mutually inconsistent, is included within the scope of the present invention.

What is claimed is:

1. An optical fiber having a cross-sectional profile comprising a plurality of guiding regions, each guiding region comprising a core configured to emit radiation having an emitted wavelength when pumped with pump radiation having a pump wavelength, a first cladding surrounding the core, and optionally, one or more additional claddings surrounding the first cladding, wherein the core of each guiding region is configured to guide radiation of the emitted wavelength, and the core and the first cladding of each guiding region are together configured to guide radiation of the pump wavelength; and one or more barrier regions, the barrier regions configured to separate the guiding regions from one another, the barrier regions being configured to prevent radiation of the pump wavelength being guided by the core and the first cladding in each of the guiding regions from substantially coupling into another guiding region.
2. The optical fiber according to claim 1, wherein less than 10% of optical power at the pump wavelength guided by each guiding region can couple to another guiding region.
3. The optical fiber according to claim 1, wherein less than 5% of optical power at the pump wavelength guided by each guiding region can couple to another guiding region.
4. The optical fiber according to claim 1, wherein less than 1% of optical power at the pump wavelength guided by each guiding region can couple to another guiding region.
5. The optical fiber according to any of claims 1-4, wherein the average mode field overlap between each pair of guiding regions is less than about 0.1.
6. The optical fiber according to any of claims 1-4, wherein the average mode field overlap between each pair of guiding regions is less than about 0.05.
7. The optical fiber according to any of claims 1-4, wherein the average mode field overlap between each pair of guiding regions is less than about 0.01.

8. The optical fiber according to any of claims 1-7, wherein each barrier region is a microstructured region, each microstructured region comprising
- a solid material, and
 - a plurality of features disposed in the solid material, the features having a different refractive index than the solid material,
- wherein the one or more microstructured regions are configured to prevent radiation of the pump wavelength being guided by the core and the first cladding in one of the guiding regions from substantially coupling into another guiding region.
9. The optical fiber according to claim 8 wherein the one or more microstructured regions prevent radiation of the pump wavelength being guided by the core and the first cladding in each of the guiding regions from substantially coupling into another guiding region through a refractive index confinement effect.
10. The optical fiber according to claim 9, wherein each microstructured region has an average refractive index of refraction at least 0.1 less than the effective refractive index of each mode guided by the first cladding and the core at the pump wavelength
11. The optical fiber according to claim 9 or claim 10, wherein each of the plurality of features disposed in the solid material of each microstructured region has a lower refractive index than the solid material.
12. The optical fiber according to claim 11, wherein the refractive indices of the features are at least 0.1 less than the refractive index of the solid material.
13. The optical fiber according to any of claims 9-12, wherein the refractive indices of the features are at least 0.1 less than the effective refractive index of each mode guided by the first cladding and the core at the pump wavelength.

14. The optical fiber according to any of claims 9-12, wherein the refractive indices of the features are at least 0.1 less than the effective refractive index of each mode guided by the core at the emitted wavelength.
15. The optical fiber according to any of claims 9-14, wherein the plurality of features disposed in the solid material of each microstructured region are a plurality of voids.
16. The optical fiber according to any of claims 9-15, wherein in each microstructured region, a single row of the refractive index features separates adjacent guiding regions from one another.
17. The optical fiber according to any of claims 9-15, wherein in each microstructured region, a plurality of rows of the refractive index features separates adjacent guiding regions from one another.
18. The optical fiber according to claim 8, wherein in each microstructured region, the plurality of features taken together has a photonic bandgap which prevents radiation of the pump wavelength being guided by the core and the first cladding in one of the guiding regions from coupling into another guiding region.
19. The optical fiber according to claim 18, wherein the features are voids.
20. The optical fiber according to claim 18, wherein the features are formed from solid material.
21. The optical fiber according to claim 20, wherein the refractive indices of the features are at least about 0.05 less than the refractive index of the solid material.
22. The optical fiber according to claim 21, wherein the refractive indices of the features are at least about 0.1 less than the refractive index of the solid material.
23. The optical fiber according to claim 21, wherein the refractive indices of the features are at least about 0.05 greater than the refractive index of the solid material.

24. The optical fiber according to claim 21, wherein the refractive indices of the features are at least about 0.1 greater than the refractive index of the solid material.
26. The optical fiber according to any of claims 1-7, wherein each barrier region is a region of solid material having a refractive index at least about 0.05 less than the effective refractive index of each mode guided by the first cladding and the core at the pump wavelength, the barrier regions preventing radiation of the pump wavelength being guided by the core and the first cladding in each of the guiding regions from substantially coupling into another guiding region through a refractive index confinement effect.
28. The optical fiber according to claim 26, wherein each barrier region is a region of solid material having a refractive index at least about 0.1 less than the effective refractive index of each mode guided by the first cladding and the core at the pump wavelength.
29. The optical fiber according to claim 26, wherein each barrier region is a region of solid material having a refractive index at least about 0.2 less than the effective refractive index of each mode guided by the first cladding and the core at the pump wavelength.
30. The optical fiber according to any of claims 1-29, wherein the barrier regions are continuous in the cross-sectional profile of the optical fiber.
31. The optical fiber according to any of claims 1-29, wherein the barrier regions are discontinuous in the cross-sectional profile of the optical fiber.
32. The optical fiber according to any of claims 1-31, wherein each core is doped with a rare earth element.
33. The optical fiber according to any of claims 1-31, wherein each core is configured for the provision of Raman gain.
34. The optical fiber according to any of claims 1-33, further comprising an outer cladding surrounding the guiding regions and the barrier regions, the outer cladding having a

lower refractive index than the effective refractive index of each mode guided by the first cladding and the core at the pump wavelength.

35. The optical fiber according to any of claims 1-34, wherein one or more of the guiding regions have areas that are at least 20% smaller than the other guiding regions of the optical fiber.

36. The optical fiber according to claim 35, wherein the one or more guiding regions of smaller area are disposed centrally in the cross-sectional profile of the optical fiber, and the one or more guiding regions of larger area are disposed peripherally with respect to the centrally-disposed guiding regions.

37. A method for generating radiation, comprising introducing pump radiation into the guiding regions of the optical fiber according to any of claims 1-36, the pump radiation having the pump wavelength of the cores of the guiding regions of the optical fiber, such that the cores emit radiation having the emitted wavelength.

38. The method according to claim 37, further comprising receiving a signal having a signal wavelength in the cores of the guiding regions of the optical fiber, the signal wavelength being the same as the emitted wavelength, and wherein the emission of the radiation of the emitted wavelength amplifies the signal.

39. An optical fiber device for use in generating radiation, the optical fiber device comprising
an optical fiber according to any of claims 1-36; and one or more pump sources operatively coupled to the guiding regions of the optical fiber, the pump sources configured to provide pump radiation having the pump wavelength of the cores of the guiding regions of the optical fiber.

40. An optical fiber device according to claim 39, configured to amplify a signal having a signal wavelength that is the same as the emitted wavelength.

41. An optical fiber device according to claim 39, configured as a laser.

42. An optical fiber method or device according to any of claims 37-41, wherein the guiding regions of the optical fiber are configured such that the power of pump radiation guided in each guiding region is within 30% of the average power guided by all guiding regions.

1/5

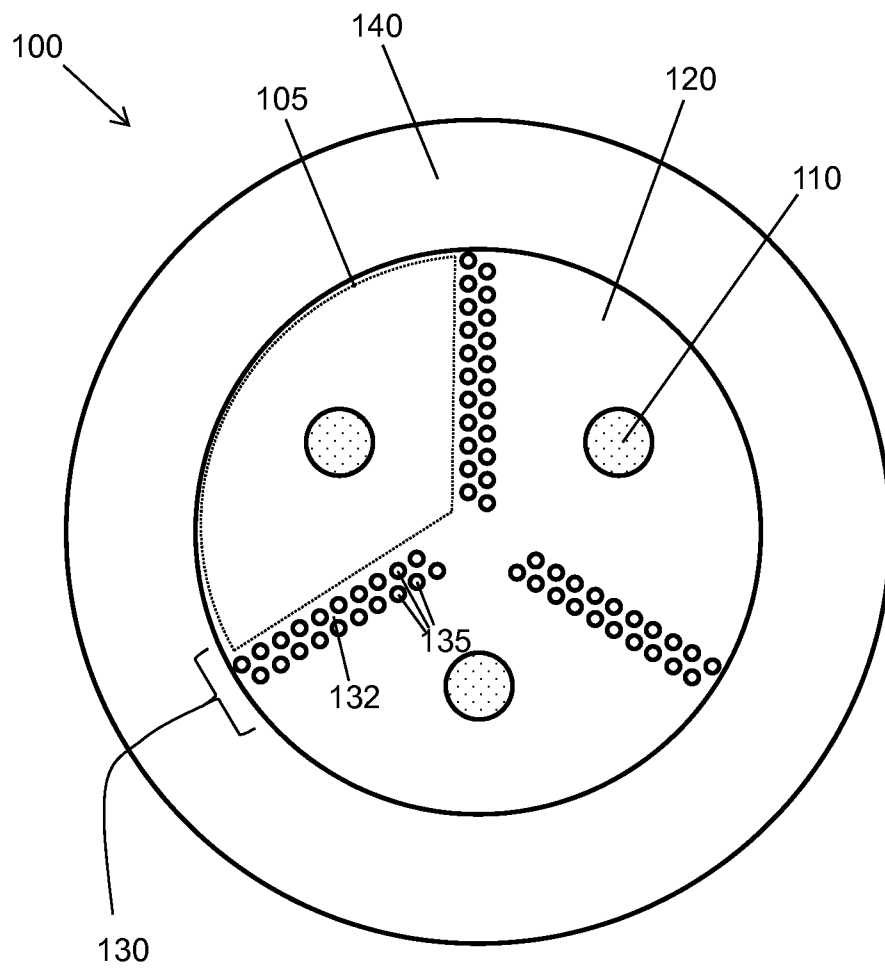


FIG. 1

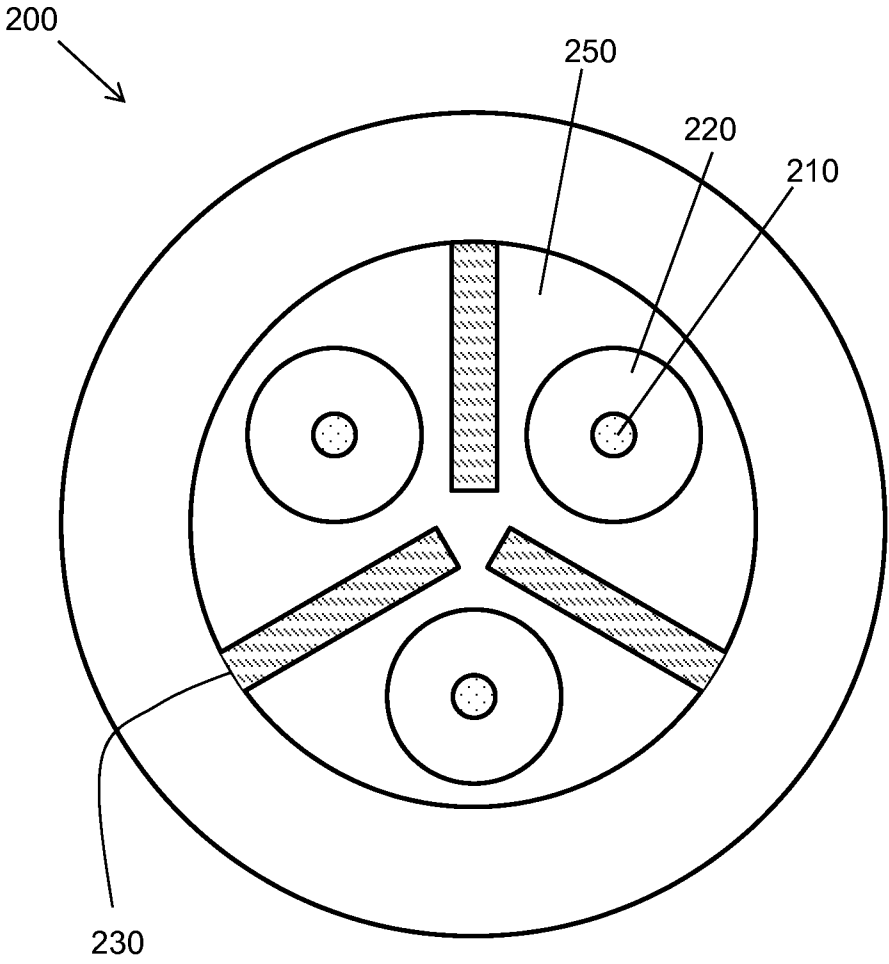


FIG. 2

3/5

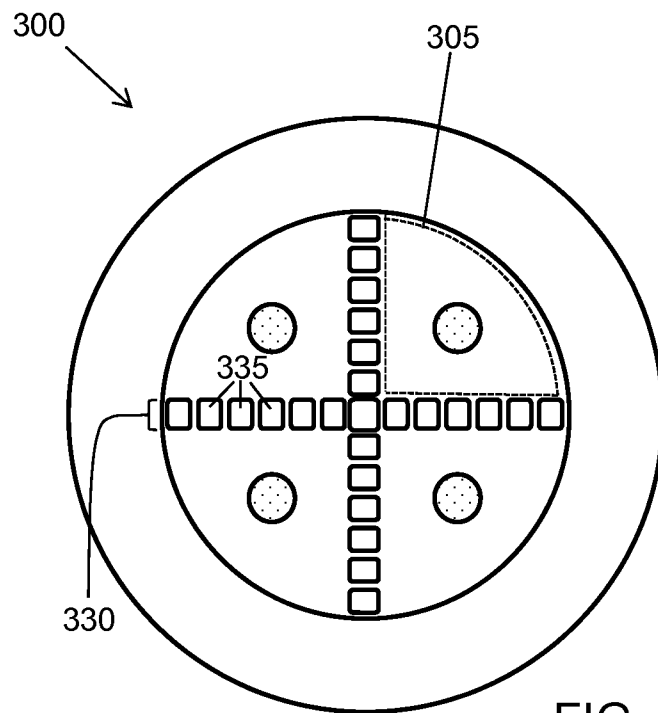


FIG. 3

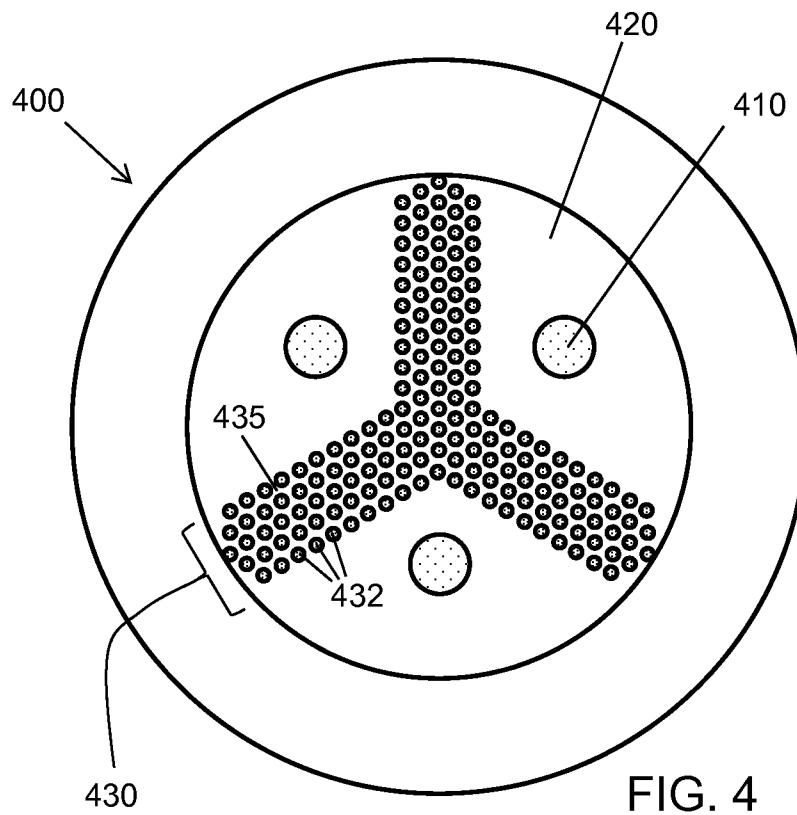


FIG. 4

4/5

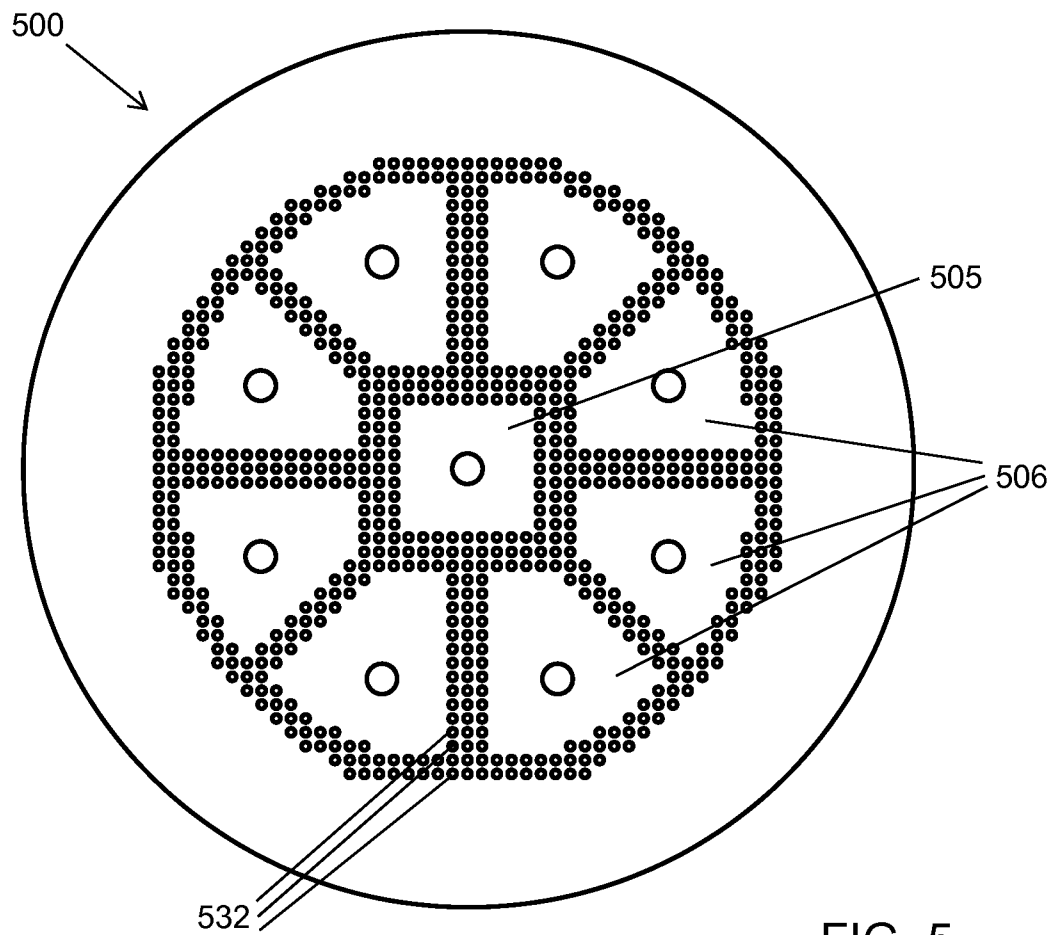


FIG. 5

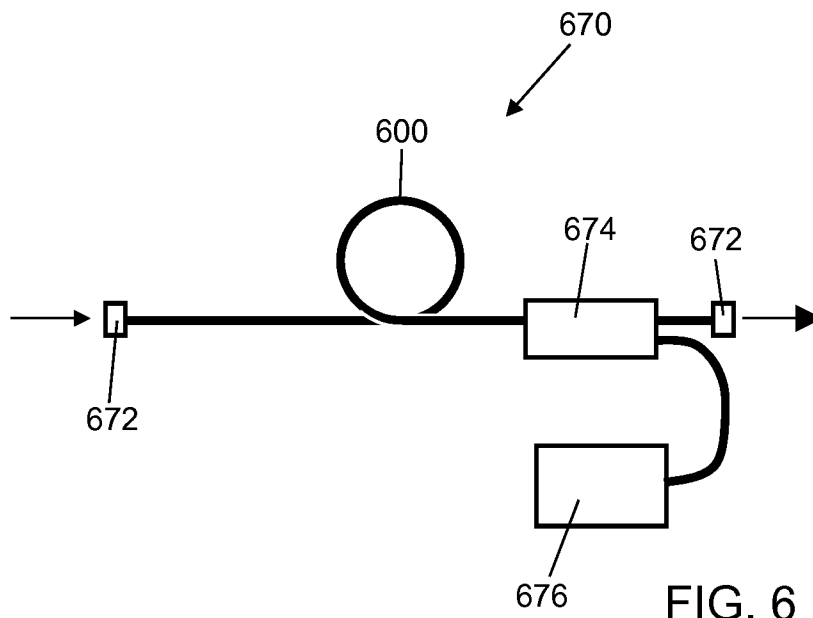


FIG. 6

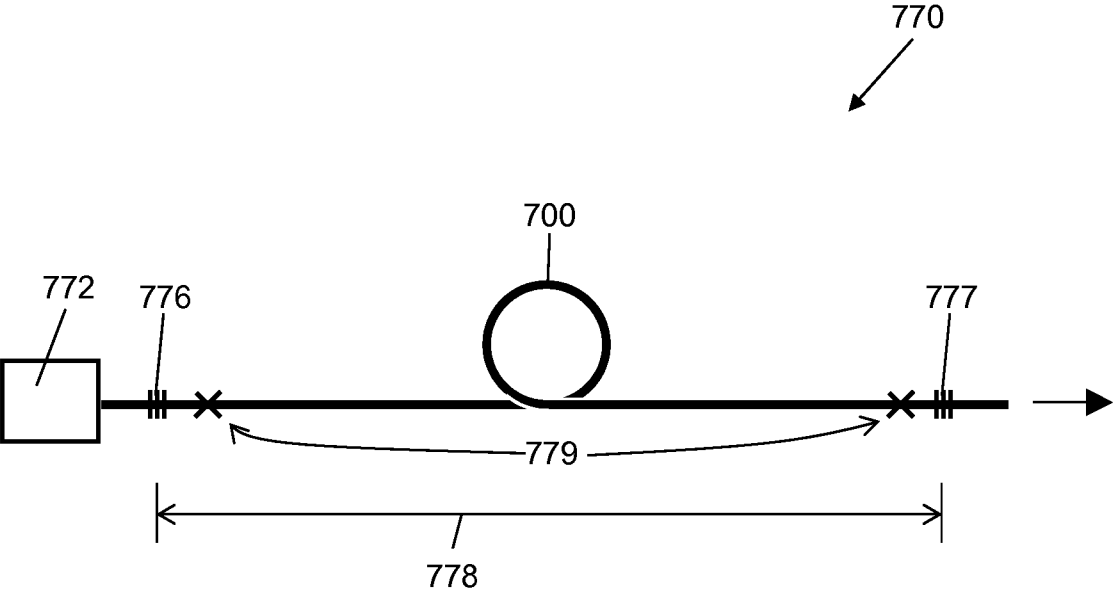


FIG. 7