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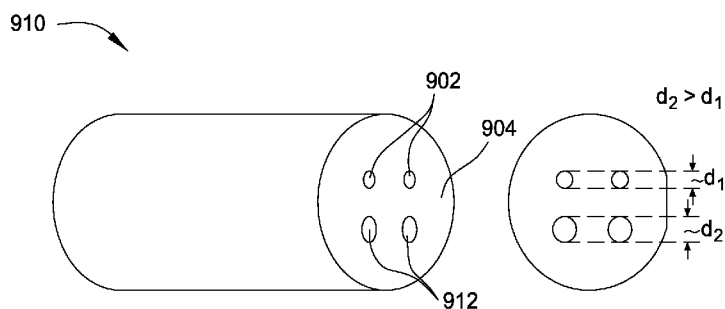


FIG. 9B

(57) **Abstract:** Methods and apparatus are provided for transmitting light along multiple pathways using a multi-core optical device. One example apparatus generally includes a plurality of large diameter optical waveguides, each having a core and a cladding, and a body having a plurality of bores with the optical waveguides disposed therein, wherein at least a portion of the cladding of each of the optical waveguides is fused with the body, such that the apparatus is a monolithic structure. Such an apparatus provides for a cost- and space-efficient technique for feedthrough of multiple optical waveguides. Also, the body may have a large outer diameter which can be shaped into features of interest, such as connection alignment or feedthrough sealing features. For some embodiments, at least some of the cores may have different structural parameters (e.g., size and/or shape).



MULTI-CORE OPTICAL WAVEGUIDE FOR MULTI-PARAMETER SENSING

CROSS-REFERENCE TO RELATED APPLICATIONS

[0100] This application claims benefit of United States patent application serial number 14/081,045, filed November 15, 2013, which is herein incorporated by
5 reference in its entirety.

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] Embodiments of the present invention relate to optical waveguides and, more particularly, to monolithic multi-optical-waveguide feedthroughs and connectors
10 and to multi-core optical waveguides with cores having different structural parameters.

Description of the Related Art

[0002] In many industries and applications, there is a need to have electrical wires or optical waveguides penetrate a wall, bulkhead, or other feedthrough member
15 wherein a relatively high fluid differential pressure exists across the feedthrough member. In addition, one or both sides of the feedthrough member may be subjected to relatively high temperatures and other harsh environmental conditions, such as corrosive or volatile gas, liquids, and other materials.

[0003] Recently, with the introduction of optical sensors, particularly sensors for
20 use in oil and gas exploration and production and for deployment in harsh industrial environments, a need has emerged for a bulkhead feedthrough that can seal an optical fiber at high pressures of 20,000 psi and above, and high temperatures of at least 150°C to 300°C, with a service life of at least 5 to 20 years.

[0004] There are several problems associated with constructing such an optical
25 fiber feedthrough. One of these problems is the susceptibility of the glass fiber to damage and breakage. This is due to the flexibility of the small diameter fiber, the brittle nature of the glass material, and the typical presence of a significant stress concentration at the point where the fiber enters and exits the feedthrough. Attempts to use a sealing glass, such as that used with electrical feedthroughs, have had

problems of this nature due to the high stress concentration at the fiber-to-sealing glass interface.

[0005] Another problem with sealing an optical fiber, as opposed to sealing a conductive metal “pin” in an electrical feedthrough, is that the fused silica material of which the optical fiber is made, has an extremely low thermal expansion rate. Unlike most engineering materials—including metals, sealing glasses, as well as the metal pins typically used in electrical feedthroughs—the coefficient of thermal expansion of the optical fiber is essentially zero. This greatly increases the thermal stress problem at the glass-to-sealing material interface.

[0006] As discussed above, the harsh environments where the sensors are located generally must be isolated by sealed physical barriers from other proximate environments through which the optical fiber communication link of the sensor must pass. It is important to seal the bulkhead around the optical fiber to prevent environments adjacent to the sensor from contaminating the optical fiber communication link. If the optical communication fiber is compromised by contamination from an adjacent harsh environment, the optical fiber and all sensors to which it is connected are likely to become ineffective.

[0007] An exemplary sensing assembly for use in harsh environments is disclosed in U.S. Pub. No. 2007/0003206 to *Dunphy et al.*, entitled “Optical Waveguide Feedthrough Assembly,” which is assigned to the Assignee of the present application and is incorporated herein by reference in its entirety. *Dunphy* discloses the optical waveguide feedthrough assembly of Figure 1. The assembly 100 includes a front housing 10 coupled to a back housing 12. An optical waveguide element 14 passes through a passageway 16 common to both housings 10, 12. The passageway 16 is defined by bores extending across the housings 10, 12. The optical waveguide element 14 includes a glass plug 18 defining a large-diameter, cane-based, optical waveguide preferably having an outer diameter of about 3 millimeters (mm) or greater. The glass plug 18 can have appropriate core and cladding dimensions and ratios to provide the desired outer large-diameter.

[0008] First and second fiber pigtails 19, 20 extend from each end of the glass plug 18. Each of the pigtails 19, 20 includes an optical waveguide such as an optical fiber 26 encased or embedded in a carrier 28 or larger diameter glass structure allowing the fiber 26 to be optically coupled to the glass plug 18. Sealing of the optical waveguide element 14 with respect to the front housing 10 occurs at and/or around the glass plug 18 to enable isolation of fluid pressure in communication with a first end 22 of the passageway 16 from fluid pressure in communication with a second end 24 of the passageway 16. This sealing of the glass plug 18 with respect to the front housing 10 provides the feedthrough capabilities of the feedthrough assembly 100. The glass plug 18 has a cone-shaped tapered surface 50 for seating against a complementary tapered seat 51 of the front housing 10. Engagement between the tapered surface 50 and the complementary tapered seat 51 that is located along the passageway 16 forms a seal that seals off fluid communication through the passageway 16. The glass plug 18 can be machined to provide the cone-shaped tapered surface 50. Additionally, the glass plug 18 is preferably biased against the tapered seat 51 using a mechanical preload.

[0009] A recess 30 formed in one end of the front housing 10 aligns with a corresponding recess 31 in one end of the back housing 12 where the housings 10, 12 are coupled together. Preferably, the front housing 10 is welded to the back housing 12 along mated features thereof. The housings 10, 12 preferably enclose the glass plug 18, a biasing member such as a first stack of Belleville washers 34, and a plunger 32, which are all disposed within the recesses 30, 31.

[0010] The first stack of Belleville washers 34 supply the mechanical preload by pressing the plunger 32 onto an opposite end of the glass plug 18 from the tapered surface 50. Since the plunger 32 is moveable with the glass plug 18, this pressing of the plunger 32 develops a force to bias the glass plug 18 onto the tapered seat 51 of the front housing 10 located along the passageway 16 that passes through the front housing 10. Transfer of force from the plunger 32 to the glass plug 18 can occur directly via an interface 54 between the two, which can include mating conical surfaces. The first stack of Belleville washers 34 compresses between a base shoulder 44 of the recess 31 in the back housing 12 and an outward shoulder 46 of the plunger 32 upon make-up of the front housing 10 to the back housing 12. Once the back housing 12 is welded or otherwise attached to the front housing 10 in order

to keep the front and back housings 10, 12 connected, the first stack of Belleville washers 34 maintains the compression that supplies force acting against the plunger 32.

[0011] The feedthrough assembly 100 further includes a gasket member 52 disposed between the tapered seat 51 and the tapered surface 50 of the glass plug 18. The gasket member 52 comprises an annular gasket. The gasket member 52 may be a gold foil that is shaped to complement the tapered surface 50 and the tapered seat 51. The gasket member 52 deforms sufficiently to accommodate imperfections on the tapered surface 50 and/or the tapered seat 51, thereby completing the seal and reducing stress between contacting surfaces due to any imperfections on the surfaces.

[0012] The housings 10, 12 additionally enclose a cup-shaped backstop sleeve 36, a second stack of Belleville washers 38, a perforated washer 40, and a centering element 42 that are all disposed within the recesses 30, 31. An outward shoulder 56 of the backstop sleeve 36 is trapped by the end of the front housing 10 and an inward shoulder 57 along the recess 31 in the back housing 12. Contact upon sandwiching of the shoulder 56 of the backstop sleeve 36 provides the point at which the housings 10, 12 are fully mated and can be secured together. Clearance is provided such that the end of the back housing 12 does not bottom out prior to the housings 10, 12 being fully mated.

[0013] The centering element 42 includes an elastomeric sealing component disposed between the glass plug 18 and the front housing 10 that can act as a back-up seal in addition to facilitating alignment of the glass plug 18 with respect to the seat 51. The pressure in the recesses 30, 31 entering from the second end 24 of the passageway 16 is higher than the pressure entering from the first end 22 of the passageway 16. This pressure differential advantageously causes the centering element 42 to deform and press against the wall of the recess 30 and the wall of the glass plug 18, thereby creating a pressure-energized seal. One or more holes or annular channels 43 can be formed on the outer surface of the high pressure side of the centering element 42. These holes or channels 43 facilitate the deformation of the centering element 42 and the formation of the seal between the centering element 42 and the walls of the recess 30 and the glass plug 18. Additionally, the perforated

washer 40 enables pressurized fluid to fill the centering element 42 for providing the energized seal.

[0014] Preferably, force transferred through the perforated washer 40 biases the centering element 42 into the recess 30. The second stack of Belleville washers 38 pressed by the backstop sleeve 36 supplies the preloading force to the perforated washer 40. The second stack of Belleville washers 38 allow a maximum pressure force to act on the centering element 42 such that pressure of the centering element 42 against the wall of the glass plug 18 does not override force being put on the glass plug 18 to press the tapered surface 50 against the seat 51.

[0015] The assembly 100 is suited for feedthrough of a single optical waveguide. If feedthrough of multiple waveguides is desired, a separate assembly may be used for each individual waveguide. This means additional costs and additional space requirements on a production tree, for example.

[0016] Accordingly, there is a need for an optical waveguide feedthrough assembly capable of operating in relatively high temperature and high pressure environments in which multiple optical waveguides are fed through.

SUMMARY OF THE INVENTION

[0017] Embodiments of the present invention generally relate to monolithic feedthroughs and connectors supporting multiple optical waveguides and to multi-core optical waveguides with cores having different structural properties for supporting multi-parameter sensing. Such optical waveguides may include optical fibers, large diameter optical waveguides (e.g., cane waveguides), optical sensors, and optical feedthroughs and connectors. Certain advantages (e.g., reduced strain) provided by the monolithic structures may also be applicable to a single (large diameter) optical waveguide fused into a larger capillary.

[0018] One embodiment of the present invention provides an apparatus for transmitting light along multiple pathways. The apparatus generally includes a plurality of large diameter optical waveguides, each having a core and a cladding, wherein the apparatus is a monolithic structure. For some embodiments, the apparatus further includes a body having a plurality of bores with the optical

waveguides disposed therein, wherein at least part of the cladding of each of the optical waveguides is fused with the body to form the monolithic structure.

[0019] Another embodiment of the present invention is a method for forming an apparatus for transmitting light along multiple pathways. The method generally includes positioning a plurality of large diameter optical waveguides, each having a core and a cladding, in a plurality of bores of a body and fusing at least a portion of the cladding of each of the optical waveguides with the body, such that the apparatus resulting therefrom is a monolithic structure.

[0020] Yet another embodiment of the present invention provides an optical waveguide feedthrough assembly. The assembly generally includes a housing, an apparatus for transmitting light along multiple pathways, wherein the apparatus is at least partially disposed in the housing, and one or more annular sealing elements disposed between an inner surface of the housing and an outer surface of the apparatus. The apparatus is a monolithic structure and generally includes a plurality of large diameter optical waveguides, each having a core and a cladding. For some embodiments, the apparatus further includes a body having a plurality of bores with the optical waveguides disposed therein, wherein at least a portion of the cladding of each of the optical waveguides is fused with the body to form the monolithic structure.

[0021] Yet another embodiment of the present invention is a method for forming an apparatus for transmitting light along multiple pathways. The method generally includes positioning a plurality of large diameter optical waveguides, each having a core and a cladding, adjacent one another and fusing at least a portion of the cladding of each of the optical waveguides with the cladding of another one of the optical waveguides, such that the apparatus resulting therefrom is a monolithic structure.

[0022] Yet another embodiment of the present invention is an apparatus for transmitting light along multiple pathways. The apparatus generally includes a plurality of large diameter optical waveguides, each having a core and a cladding, wherein the apparatus is a monolithic structure and wherein the core of a first one of the large diameter optical waveguides has a different structural parameter than the core of a second one of the large diameter optical waveguides.

[0023] Yet another embodiment of the present invention is a method for forming an apparatus for transmitting light along multiple pathways. The method generally includes positioning a plurality of large diameter optical waveguides, each having a core and a cladding, in a plurality of bores of a body, wherein the core of a first one of the large diameter optical waveguides has a different structural parameter than the core of a second one of the large diameter optical waveguides; and fusing at least a portion of the cladding of each of the optical waveguides with the body, such that the apparatus resulting therefrom is a monolithic structure.

[0024] Yet another embodiment of the present invention is an optical waveguide feedthrough assembly. The assembly generally includes a housing; an apparatus for transmitting light along multiple pathways, wherein the apparatus is at least partially disposed in the housing; and one or more annular sealing elements disposed between an inner surface of the housing and an outer surface of the apparatus. The apparatus is a monolithic structure and includes a plurality of large diameter optical waveguides, each having a core and a cladding. The core of a first one of the large diameter optical waveguides has a different structural parameter than the core of a second one of the large diameter optical waveguides.

[0025] Yet another embodiment of the present invention is a method for forming an apparatus for transmitting light along multiple pathways. The method generally includes positioning a plurality of large diameter optical waveguides, each having a core and a cladding, adjacent one another, wherein the core of a first one of the large diameter optical waveguides has a different structural parameter than the core of a second one of the large diameter optical waveguides; and fusing at least a portion of the cladding of each of the optical waveguides with the cladding of another one of the optical waveguides, such that the apparatus resulting therefrom is a monolithic structure.

[0026] Yet another embodiment of the present invention provides an apparatus for transmitting light along multiple pathways. The apparatus generally includes a cladding and a plurality of cores disposed within the cladding, wherein a first one of the cores has a different refractive index property than a second one of the cores.

[0027] Yet another embodiment of the present invention provides an apparatus for transmitting light along multiple pathways. The apparatus generally includes a

cladding and a plurality of cores disposed within the cladding, wherein a first one of the cores has a different microstructure than a second one of the cores.

[0028] Yet another embodiment of the present invention provides an apparatus for transmitting light along multiple pathways. The apparatus generally includes a plurality of large diameter optical waveguides, each having a core and a cladding, wherein the apparatus is a monolithic structure and wherein the cores of the large diameter optical waveguides have the same structural parameters.

BRIEF DESCRIPTION OF THE DRAWINGS

[0029] So that the manner in which the above recited features of the present invention can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only typical embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

[0030] Figure 1 illustrates a cross-sectional view of a prior art optical waveguide feedthrough assembly.

[0031] Figure 2 is a diagram conceptually illustrating a monolithic multi-waveguide structure, according to an embodiment of the present invention.

[0032] Figure 3 is a diagram conceptually illustrating a monolithic multi-waveguide structure with a collapsed region and a larger outer diameter region, according to an embodiment of the present invention.

[0033] Figure 4 is a diagram conceptually illustrating a monolithic multi-waveguide structure disposed in a housing with annulus seals disposed therebetween, according to an embodiment of the present invention.

[0034] Figure 5 is a diagram conceptually illustrating two monolithic multi-waveguide connectors with locating features, according to an embodiment of the present invention.

[0035] Figure 6 is a diagram conceptually illustrating splicing of optical fibers to a monolithic multi-waveguide structure, according to an embodiment of the present invention.

[0036] Figures 7 and 8 are flow diagrams illustrating example operations for forming a monolithic structure for transmitting light along multiple pathways.

[0037] Figure 9A is a diagram conceptually illustrating a multi-core optical waveguide structure with all cores having the same core structure, according to an embodiment of the present invention.

[0038] Figure 9B is a diagram conceptually illustrating a multi-core optical waveguide structure with two different core structures, according to an embodiment of the present invention.

DETAILED DESCRIPTION

[0039] As described above, current approaches to optical waveguide feedthroughs use glass to metal seals constructed from drawn cane. These approaches are limited to around 5 mm outer diameters without specialized equipment and thus are not capable of spreading out stress loads. The approaches are non-monolithic or limited to single waveguides, thus involving multiple duplicates to accommodate multiple waveguides. Similarly, the components are limited to single waveguide connections, or connections built up from single waveguide approaches.

[0040] Accordingly, what is needed are techniques and apparatus to reduce glass stress when sealing multiple fiber optic components against high pressure and to achieve high temperature multi-waveguide fiber optic cable fluid block and connectorization with low loss.

[0041] Embodiments of the present invention provide techniques and apparatus for a robust, reliable, high pressure optical waveguide feedthrough (penetrator) or connector that utilizes a monolithic glass structure. In one embodiment, the apparatus includes a plurality of large diameter optical waveguides, each having a core and a cladding, and a body having a plurality of bores with the optical waveguides disposed therein, wherein at least part of the cladding of each of the optical waveguides is fused with the body, such that the apparatus is a monolithic

structure. In another embodiment, the apparatus includes a plurality of large diameter optical waveguides, each having a core and a cladding, wherein at least part of the cladding of each of the optical waveguides is fused with the cladding of another one of the optical waveguides, such that the apparatus is a monolithic structure.

5 **[0042]** Although the reduced stress and other benefits provided by such monolithic structures are also applicable to a single (large diameter) optical waveguide fused into a larger capillary, only monolithic structures supporting multiple optical waveguides are described in detail below. From this description, the ideas disclosed herein can be adapted to a capillary tube having only a single bore for supporting one optical
10 waveguide.

[0043] As used herein, “optical fiber,” “glass plug,” and the more general term “optical waveguide” refer to any of a number of different devices that are currently known or may later become known for transmitting optical signals along a desired pathway. For example, each of these terms can refer to single mode, multi-mode,
15 birefringent, polarization-maintaining, polarizing, multi-core or multi-cladding optical waveguides, or flat or planar waveguides. The optical waveguides may be made of any glass (e.g., silica, phosphate glass, or other glasses), of glass and plastic, or solely of plastic. For high temperature applications, optical waveguides composed of a glass material are desirable. Furthermore, any of the optical waveguides can be
20 partially or completely coated with a gettering agent and/or a blocking agent (such as gold) to provide a hydrogen barrier that protects the waveguide.

AN EXAMPLE MONOLITHIC MULTI-OPTICAL-WAVEGUIDE PENETRATOR

[0044] Figure 2 conceptually illustrates a monolithic structure 200 with multiple optical waveguides fused with multiple bores of a capillary tube 202. Embodiments of
25 the present invention, such as the monolithic structure 200, may be used in place of the optical waveguide element 14 of Figure 1. As shown, the monolithic structure 200 includes a capillary tube 202 and a plurality of large-diameter optical waveguides 204, each waveguide having a core and a cladding. Before fusing, the capillary tube 202 had a plurality of bores running through the length of the capillary tube 202. Although
30 four bores are shown in Figure 2 as an example, the tube 202 may include more or less than four bores, which may depend on the number of optical waveguides desired for a particular application. The plurality of optical waveguides 204 are inserted into

the bores. As used herein, a large-diameter optical waveguide (also known as a cane waveguide) generally refers to an optical waveguide having an outer diameter (of the cladding) which is greater than or equal to 1 mm (and preferably at least 3 mm). The capillary tube 202 has a larger outer diameter than the outer diameter of the large-diameter optical waveguides 204.

[0045] After insertion of the waveguide 204, the capillary tube 202 is subjected to heat in one or more selected regions to fuse the capillary tube 202 and the optical waveguides 204 (at least within the collapsed region(s)). Typically performed with vacuum assist, this fusing collapses the bores of the capillary tube 202 around the cladding of the optical waveguides 204 to form a single monolithic structure. The monolithic structure 200 is able to conduct light energy through multiple paths and effectively increases the outer diameter of the plurality of optical waveguides 204.

[0046] In some embodiments, the capillary tube 202 and/or the core and cladding of each optical waveguide 204 are composed of silica glass, such as quartz. In some embodiments, the optical waveguides 204 may be 1 mm quartz cane waveguides for 1550 nm light. For some embodiments, the cladding of each optical waveguide 204 and capillary tube 202 have about the same temperature coefficient.

[0047] The capillary tube 202 may be a cylinder or have any of various other suitable shapes. The capillary tube 202 may be made of quartz formed by drawing or drilling (e.g., multibore tubing offered by Friedrich & Dimmock, Inc. of Milleville, NJ). The capillary tube 202 may be shaped by grinding, machining, or other means to form any feature of interest.

[0048] According to one embodiment, the capillary tube 202 may be shaped to form geometries important to sealing and stress reduction. For example, Figure 3 illustrates another monolithic structure 300, similar to the monolithic structure 200 of Figure 2, where the capillary tube 202 includes a collapsed region 306 (wherein fusing of the bores and optical waveguides 204 has occurred) and a shaped sealing region 308. In the embodiment shown in Figure 3, the sealing region 308 has a convex frustoconical shape. The tapered ends of the convex frustoconical shaped sealing region 308 form sealing surfaces that are large compared to the outer diameter of the optical waveguides 204 and the collapsed region 306. In this manner, when the monolithic structure 300 is disposed in a wellhead feedthrough assembly,

for example, downhole pressure may be distributed on the monolithic structure 300 in a desired manner, with a surface reacting force acting on the sealing surface furthest away from the collapsed region.

[0049] In some embodiments, as shown in Figure 4, the monolithic structure 200 may further include one or more annulus seals 410 (e.g., Accuseal, offered by Weatherford International with headquarters in Houston, TX) around the capillary tube 202 in collapsed region 306. The annulus seals 410 may be any of various suitable sealing elements, such as v-ring seals, chevron seals, o-ring seals, gasket seals, etc. The annulus seals 410 see internal pressure within a metal housing 412 corresponding to the outer diameter of the annulus seals 410. The glass, however, sees internal pressure within the metal housing corresponding to the smaller outer diameter of the capillary tube 202 in the collapsed region 306. According to some embodiments the annulus seals 410 seal an annulus around the smaller diameter collapsed region 306, while sealing region 308 has a larger outer diameter and thus reacts to the axial force on the optical waveguide 204 over a much larger area (surface reacting force) which provides reduced stress on the glass.

AN EXAMPLE MONOLITHIC MULTI-OPTICAL-WAVEGUIDE CONNECTOR

[0050] In some embodiments, the capillary tube 202 may be shaped to form geometries important to alignment of two monolithic multi-optical-waveguide connectors. As shown in Figure 5, the capillary tube 202 may be shaped to include at least one locating feature 514. In the embodiment shown in Figure 5, the locating feature 514 is a flat (*i.e.*, a flat surface) along a length of the capillary tube 202. The flat is formed in an outer diameter of the capillary tube 202 and is parallel to an axis of the capillary tube 202. The capillary tube 202 may be divided (e.g., by cutting or dicing) in the collapsed region 306 to form a connector pair. The locating feature 514 allows the optical waveguides 204 to be realigned within the desired submicron alignment. In one embodiment, the parted capillary tube 202 may be realigned by butting the diced ends 512 against one another and using the flat (locating feature 514) to precisely align the outer diameter, thereby also aligning the optical waveguides 204. This is particularly useful for undersea wet connects. In some embodiments, the ends 512 of the cut portion may have a polished face. In some embodiments, rather than having flat faces, the diced ends 512 may be aligned and

connected using male/female connectors, where each end 512 is shaped to mate with the other end 512.

[0051] As shown in Figure 6, in some embodiments, individual optical waveguides 204 may be spliced using a cone or carrier splice at 616, for example, with optical fibers 618. In carrier splicing, for example, all but one of the carriers (which may be the optical waveguides 204) are pulled back, the remaining carrier is spliced, and this process is repeated for each carrier. In another embodiment, the carriers may be spliced using large diameter splicing (LDS) to the ends of the cane waveguides.

EXAMPLE METHODS FOR MAKING A MONOLITHIC MULTI-OPTICAL- WAVEGUIDE PENETRATOR OR CONNECTOR

[0052] Figure 7 is a flow diagram illustrating example operations 700 for forming an apparatus for transmitting light along multiple pathways. The operations 700 begin, at 702, by positioning a plurality of large diameter optical waveguides (*e.g.*, waveguides 204), each having a core and a cladding, in a plurality of bores of a body (*e.g.*, the cylindrical capillary tube 202 of Figure 2). According to some embodiments, the bores may be drilled in the body prior to positioning the optical waveguides in the bores. For other embodiments, the body having the plurality of bores may be drawn from a preform having a plurality of bores.

[0053] At 704, at least a portion of the cladding of each of the optical waveguides is fused with the body, such that the apparatus resulting therefrom is a monolithic structure (*e.g.*, structure 200). For some embodiments, at least one orientation feature may be formed in the body before the fusing at 704 or in the apparatus after the fusing.

[0054] At 706, the apparatus may be diced in the fused portion to form two apparatuses. Each of the two apparatuses may be a monolithic structure (*e.g.*, if the dicing occurs in the collapsed region 306). For some embodiments, an end face of at least one of the two apparatuses may be polished at 707. For some embodiments, at least one orientation feature may be formed in the two apparatuses (*e.g.*, in the end faces 512 of the two apparatuses).

[0055] At 708, the end faces of the two apparatuses may be butted together, such that the optical waveguides in the two apparatuses are aligned. The optical

waveguides may be aligned using at least one orientation feature (e.g., locating feature 514) in at least one of the two apparatuses. In some embodiments, the orientation feature may be at least one flat surface formed in an outer diameter of the body and parallel to an axis of the body.

5 **[0056]** At 710, a plurality of optical fibers (e.g., fibers 618) may be spliced (e.g., at 616) to the plurality of large diameter optical waveguides. The splicing may involve cone splicing or carrier splicing.

10 **[0057]** For some embodiments, a monolithic structure as described above may be formed without using a body (e.g., a capillary tube). For example, Figure 8 is a flow diagram illustrating example operations 800 for forming an apparatus for transmitting light along multiple pathways by fusing the claddings of multiple large diameter optical waveguides together. The operations 800 may begin, at 802, by positioning a plurality of large diameter optical waveguides (e.g., waveguides 204), each having a core and a cladding, adjacent one another (e.g., in a bundle).

15 **[0058]** At 804, at least a portion of the cladding of each of the optical waveguides is fused with the cladding of another one of the optical waveguides, such that the apparatus resulting therefrom is a monolithic structure. This fusing may be performed in the same region on each of the optical waveguides, such that the monolithic structure may be used as an optical feedthrough.

20 **[0059]** Many of the operations 700 of Figure 7 described above may also be performed for the monolithic structure formed according to the operations 800 of Figure 8. For example, the apparatus may be diced in the fused portion to form two apparatuses, which may be polished and later butted together (e.g., using one or more orientation features for alignment).

25 **EXAMPLE MULTI-CORE OPTICAL WAVEGUIDE FOR MULTI-PARAMETER
SENSING**

30 **[0060]** Current solutions for multi-parameter sensing downhole involve employing multiple optical fibers inserted into a fiber-in-metal-tube (FIMT)-style cable. For distributed temperature sensing (DTS), these fibers may be multi-mode or single-mode optical fibers, although multi-mode fibers are typically preferred. Other optical sensing products (for sensing pressure, temperature, seismic properties, or flow, for

example) generally interface with or otherwise use single-mode fibers. However, there may be a limit to the number of individual optical fibers that can fit within the FIMT cable or that can be fed through a wellhead outlet, dry mate connectors, wet mate connectors, and other in-well components.

5 **[0061]** Accordingly, what is needed are methods and apparatus to overcome the space limitations of current optical waveguide structures.

10 **[0062]** Embodiments of the present invention provide multi-core optical waveguides where the cores possess different structural properties. These properties may include any combination of different sizes, transverse shapes, refractive index properties (e.g., different refractive index values and/or graded versus stepped refractive index cores), microstructures (e.g., photonic-crystal fiber (PCF) using hollow cores versus solid cores), and the like.

15 **[0063]** Figure 9A conceptually illustrates an example multi-core optical waveguide structure 900, which may be similar to the monolithic structure 200 in Figure 2. After the plurality of large-diameter optical waveguides 204 are inserted into the multiple bores of the capillary tube 202 and heated, the claddings of the large-diameter waveguides fuse with the collapsed walls of the bores to form the fused cladding region 904 of the structure 900, as described above. Although four cores 902 are shown in Figure 9A as an example, the structure 900 may include more or less than
20 four cores, which may depend on the number of optical pathways desired for a particular application. While the multi-core structure 900 of Figure 9A may be similar to the monolithic structure 200 in Figure 2, the structure 900 may also represent an optical fiber, a cane waveguide, an optical sensor, an optical feedthrough, or an optical connector having multiples cores 902 disposed in a cladding region 904.

25 **[0064]** In Figure 9A, the cores 902 all have the same core structure, meaning that the structural parameters (e.g., size and shape) of the cores are all the same. Here, for example, all four cores 902 are solid cores having a circular transverse shape and the same diameter d_1 . With the same core structural parameters, the cores 902 may function as either all single-mode or all multimode cores.

30 **[0065]** For other embodiments, at least one of the cores of the multi-core optical waveguide may have at least one different structural parameter from another one of

the cores. For example, Figure 9B conceptually illustrates an example multi-core optical waveguide structure 910 with two different core structures, which may also be similar to the monolithic structure 200 in Figure 2 such that the description above applies to Figure 9B, as well. In Figure 9B, cores 902 have the same core structure (e.g., diameter d_1). However, cores 912 have a different core structure, such as the larger diameter d_2 as shown. In this manner, the smaller diameter cores 902 of the multi-core structure 910 may function as single-mode cores, whereas the larger diameter cores 912 may function as multimode cores. The smaller diameter cores 902 may be used for a different application (e.g., Bragg grating sensing or distributed acoustic sensing (DAS)) than the large diameter cores 912 (e.g., distributed temperature sensing (DTS)).

[0066] As an alternative or in addition to different size, the cores of a multi-core optical waveguide may differ with respect to other structural parameters, such as different transverse shapes, different refractive index properties, and/or different microstructures. For example, one core may have a circular cross-section, whereas another core may have an elliptical, rectangular, or annular cross-section. As another example, one core may have a greater refractive index value than another core of the same multi-core optical waveguide structure. For some embodiments, one core may have a stepped refractive index with respect to the cladding (i.e., the core has a single refractive index value throughout, that is distinct from the cladding's refractive index, such that a graph of refractive index versus diameter would form a step between this core and the cladding), while another core may have a graded refractive index (i.e., two or more different refractive index values, whether a piecewise or a continuous function). For some embodiments, one core may be a solid core, whereas another core may be a photonic-crystal fiber (PCF) core, which may guide light through the optical waveguide using the internal structure of the waveguide, rather than only using refractive index differences. For example, one type of PCF known as "holey fiber" uses hollow cores, which may be filled with air.

[0067] Permitting different core structures within the same optical waveguide structure may provide for easier design of feedthroughs, pass-throughs, connectors, cable structures, and the like, especially when it is desirable to include both single-mode and multimode capabilities in a single device (e.g., for space constraints).

[0068] Embodiments of the invention heretofore can be used and have specific utility in applications within the oil and gas industry. Further, it is within the scope of the invention that other commercial embodiments/uses exist with one such universal sealing arrangement shown in the figures and adaptable for use in (by way of
5 example and not limitation) industrial, chemical, energy, nuclear, structural, etc. While the foregoing is directed to preferred embodiments of the invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

CLAIMS

1. An apparatus for transmitting light along multiple pathways, comprising:
a plurality of large diameter optical waveguides, each having a core and a cladding, wherein the apparatus is a monolithic structure and wherein the core of a
5 first one of the large diameter optical waveguides has a different structural parameter than the core of a second one of the large diameter optical waveguides.
2. The apparatus of claim 1, wherein the different structural parameter comprises a diameter, such that the core of the first one of the large diameter optical waveguides has a different diameter than the core of the second one of the large diameter optical
10 waveguides.
3. The apparatus of claim 2, wherein a first diameter of the core of the first one of the large diameter optical waveguides is suitable for single-mode propagation and wherein a second diameter of the core of the second one of the large diameter optical waveguides is suitable for multimode propagation.
- 15 4. The apparatus of claim 1, wherein the different structural parameter comprises a transverse shape, such that the core of the first one of the large diameter optical waveguides has a different transverse shape than the core of the second one of the large diameter optical waveguides.
5. The apparatus of claim 1, wherein the different structural parameter comprises
20 at least one of a different refractive index property or a different microstructure.
6. The apparatus of claim 1, further comprising a body having a plurality of bores with the optical waveguides disposed therein, wherein at least part of the cladding of each of the optical waveguides is fused with the body to form the monolithic structure.
7. The apparatus of claim 6, wherein the body comprises at least one orientation
25 feature.
8. The apparatus of claim 7, wherein the at least one orientation feature comprises at least one flat surface formed in an outer diameter of the body and parallel to an axis of the body.
9. The apparatus of claim 6, wherein the body has at least two different outer

diameters and comprises a sealing surface between the at least two different outer diameters.

10. The apparatus of claim 9, wherein the sealing surface comprises a convex frustoconical section between the at least two different outer diameters.

5 11. The apparatus of claim 1, wherein at least part of the cladding of each of the optical waveguides is fused with the cladding of another one of the optical waveguides to form the monolithic structure.

12. The apparatus of claim 1, wherein an outer diameter of the cladding of the large diameter optical waveguides is at least 1 mm.

10 13. A method for forming an apparatus for transmitting light along multiple pathways, comprising:

positioning a plurality of large diameter optical waveguides, each having a core and a cladding, in a plurality of bores of a body, wherein the core of a first one of the large diameter optical waveguides has a different structural parameter than the core
15 of a second one of the large diameter optical waveguides; and

fusing at least a portion of the cladding of each of the optical waveguides with the body, such that the apparatus resulting therefrom is a monolithic structure.

14. The method of claim 13, wherein the different structural parameter comprises a diameter, such that the core of the first one of the large diameter optical waveguides
20 has a different diameter than the core of the second one of the large diameter optical waveguides.

15. The method of claim 14, wherein a first diameter of the core of the first one of the large diameter optical waveguides is suitable for single-mode propagation and wherein a second diameter of the core of the second one of the large diameter optical
25 waveguides is suitable for multimode propagation.

16. The method of claim 13, wherein the different structural parameter comprises a transverse shape, such that the core of the first one of the large diameter optical waveguides has a different transverse shape than the core of the second one of the large diameter optical waveguides.

30 17. The method of claim 13, wherein the different structural parameter comprises

at least one of a different refractive index property or a different microstructure.

18. The method of claim 13, further comprising drilling the plurality of bores in the body before the positioning.

19. The method of claim 13, further comprising drawing the body having the plurality of bores from a preform before the positioning.

20. The method of claim 13, further comprising forming at least one orientation feature in the body.

21. The method of claim 20, wherein the at least one orientation feature comprises at least one flat surface formed in an outer diameter of the body and parallel to an axis of the body.

22. The method of claim 13, further comprising dicing the apparatus in the fused portion to form two apparatuses.

23. The method of claim 22, further comprising polishing an end face of at least one of the two apparatuses.

24. The method of claim 22, further comprising butting end faces of the two apparatuses together, such that the optical waveguides in the two apparatuses are aligned.

25. The method of claim 24, further comprising using at least one orientation feature in at least one of the two apparatuses to align the optical waveguides.

26. The method of claim 13, further comprising splicing a plurality of optical fibers to the plurality of large diameter optical waveguides.

27. An optical waveguide feedthrough assembly comprising:
a housing;
an apparatus for transmitting light along multiple pathways, wherein the apparatus is at least partially disposed in the housing; and
one or more annular sealing elements disposed between an inner surface of the housing and an outer surface of the apparatus, wherein the apparatus is a monolithic structure and comprises a plurality of large diameter optical waveguides, each having a core and a cladding and wherein the core of a first one of the large

diameter optical waveguides has a different structural parameter than the core of a second one of the large diameter optical waveguides.

28. The assembly of claim 27, wherein the different structural parameter comprises a diameter, such that the core of the first one of the large diameter optical waveguides has a different diameter than the core of the second one of the large diameter optical waveguides.

29. The assembly of claim 28, wherein a first diameter of the core of the first one of the large diameter optical waveguides is suitable for single-mode propagation and wherein a second diameter of the core of the second one of the large diameter optical waveguides is suitable for multimode propagation.

30. The assembly of claim 27, wherein the different structural parameter comprises a transverse shape, such that the core of the first one of the large diameter optical waveguides has a different transverse shape than the core of the second one of the large diameter optical waveguides.

31. The assembly of claim 27, wherein the different structural parameter comprises at least one of a different refractive index property or a different microstructure.

32. The assembly of claim 27, wherein the annular sealing elements comprise at least one of v-ring seals, o-ring seals, or gasket members.

33. The assembly of claim 27, wherein the apparatus further comprises a body having a plurality of bores with the optical waveguides disposed therein and wherein at least a portion of the cladding of each of the optical waveguides is fused with the body to form the monolithic structure.

34. The assembly of claim 33, wherein the housing comprises metal and wherein the body and the core and cladding of each of the optical waveguides comprise silica glass.

35. A method for forming an apparatus for transmitting light along multiple pathways, comprising:

positioning a plurality of large diameter optical waveguides, each having a core and a cladding, adjacent one another, wherein the core of a first one of the large diameter optical waveguides has a different structural parameter than the core of a second one of the large diameter optical waveguides; and

fusing at least a portion of the cladding of each of the optical waveguides with the cladding of another one of the optical waveguides, such that the apparatus resulting therefrom is a monolithic structure.

36. The method of claim 35, wherein the different structural parameter comprises a diameter, such that the core of the first one of the large diameter optical waveguides has a different diameter than the core of the second one of the large diameter optical waveguides.

37. The method of claim 36, wherein a first diameter of the core of the first one of the large diameter optical waveguides is suitable for single-mode propagation and wherein a second diameter of the core of the second one of the large diameter optical waveguides is suitable for multimode propagation.

38. The method of claim 35, wherein the different structural parameter comprises a transverse shape, such that the core of the first one of the large diameter optical waveguides has a different transverse shape than the core of the second one of the large diameter optical waveguides.

39. The method of claim 35, wherein the different structural parameter comprises at least one of a different refractive index property or a different microstructure.

40. An apparatus for transmitting light along multiple pathways, comprising:
a cladding; and

a plurality of cores disposed within the cladding, wherein a first one of the cores has a different refractive index property than a second one of the cores.

41. The apparatus of claim 40, wherein the first one of the cores has a graded refractive index and wherein the second one of the cores has a stepped refractive index with respect to the cladding.

42. The apparatus of claim 40, wherein the first one of the cores has a greater refractive index value than the second one of the cores.

43. The apparatus of claim 40, wherein the first one of the cores has at least one of a different diameter, a different transverse shape, or a different microstructure than the second one of the cores.

44. The apparatus of claim 40, wherein the first one of the cores comprises a photonic-crystal fiber (PCF) core and wherein the second one of the cores comprises a solid core.

45. The apparatus of claim 40, wherein the apparatus comprises at least one of an optical fiber, a large diameter optical waveguide, an optical sensor, or an optical feedthrough.

46. The apparatus of claim 40, wherein a first diameter of the first one of the cores is suitable for single-mode propagation and wherein a second diameter of the second one of the cores is suitable for multimode propagation.

47. The apparatus of claim 40, wherein the apparatus comprises a monolithic structure.

48. An apparatus for transmitting light along multiple pathways, comprising:
a cladding; and
a plurality of cores disposed within the cladding, wherein a first one of the cores has a different microstructure than a second one of the cores.

49. The apparatus of claim 48, wherein the first one of the cores comprises a photonic-crystal fiber (PCF) core and wherein the second one of the cores comprises a solid core.

50. The apparatus of claim 48, wherein the apparatus comprises at least one of an optical fiber, a large diameter optical waveguide, an optical sensor, or an optical feedthrough.

51. An apparatus for transmitting light along multiple pathways, comprising:
a plurality of large diameter optical waveguides, each having a core and a cladding, wherein the apparatus is a monolithic structure and wherein the cores of the

large diameter optical waveguides have the same structural parameters.

52. The apparatus of claim 51, wherein the structural parameters comprise at least one of a size, a transverse shape, a refractive index property, or a microstructure.

53. The apparatus of claim 51, further comprising a body having a plurality of
5 bores with the optical waveguides disposed therein, wherein at least part of the cladding of each of the optical waveguides is fused with the body to form the monolithic structure.

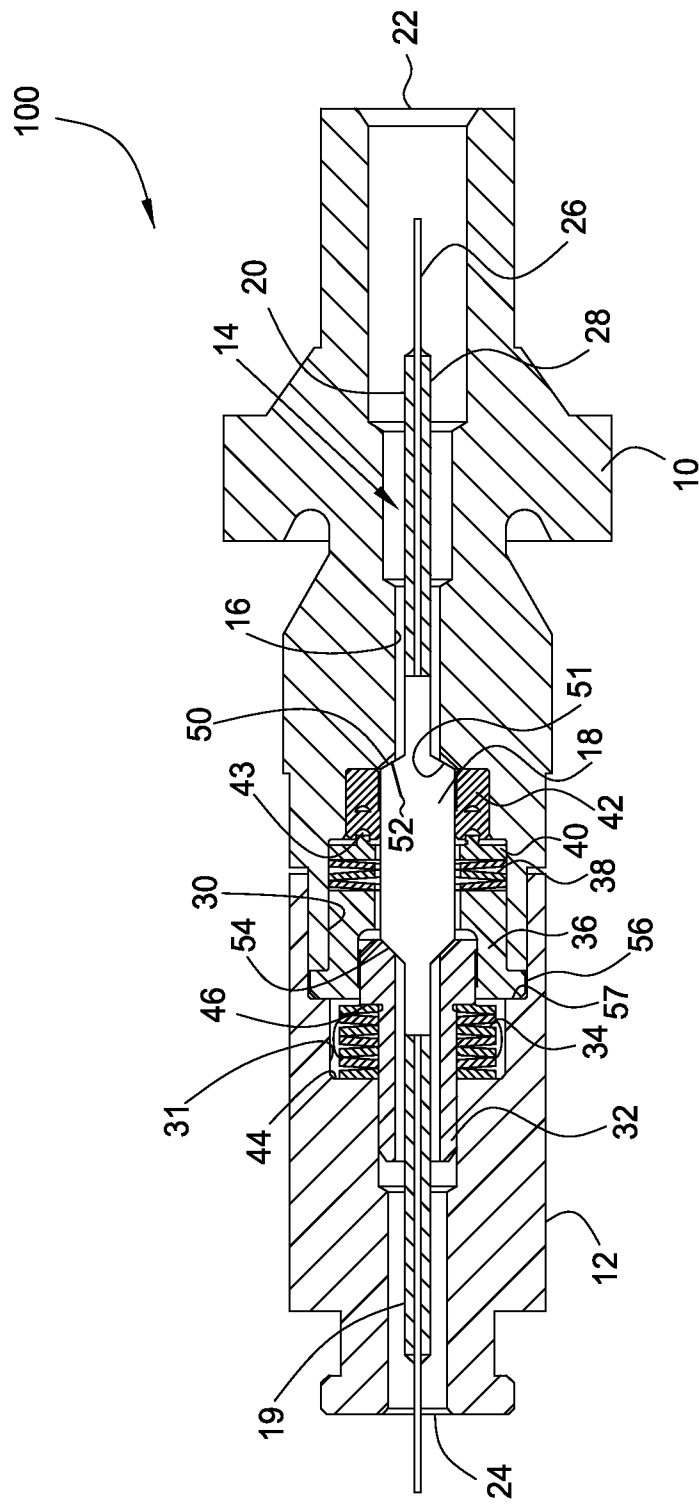


FIG. 1
(PRIOR ART)

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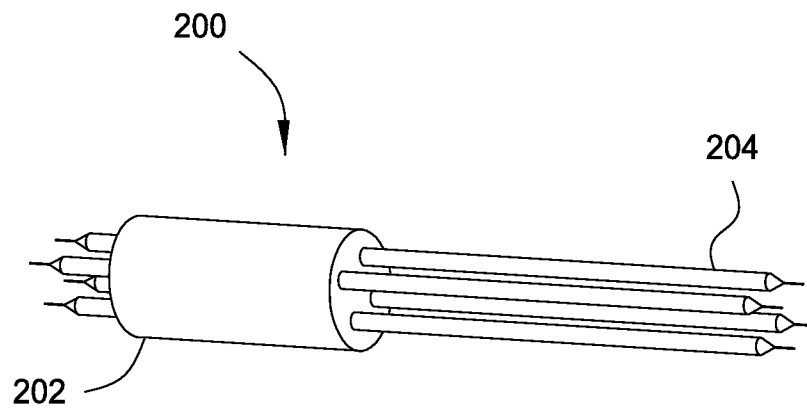


FIG. 2

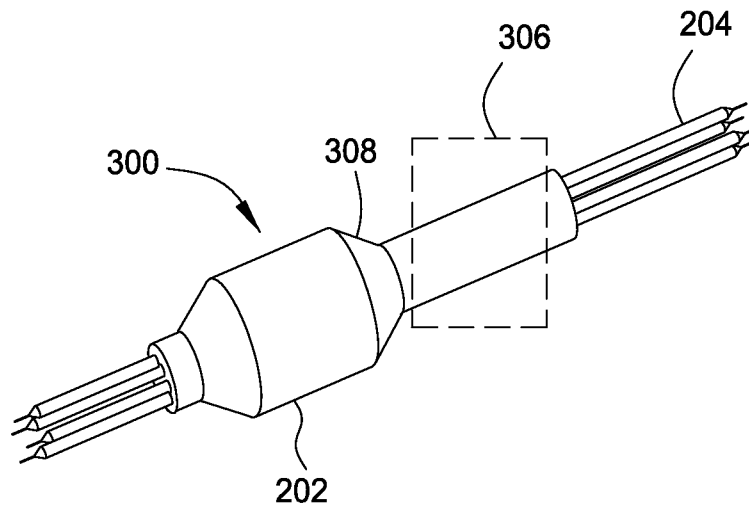


FIG. 3

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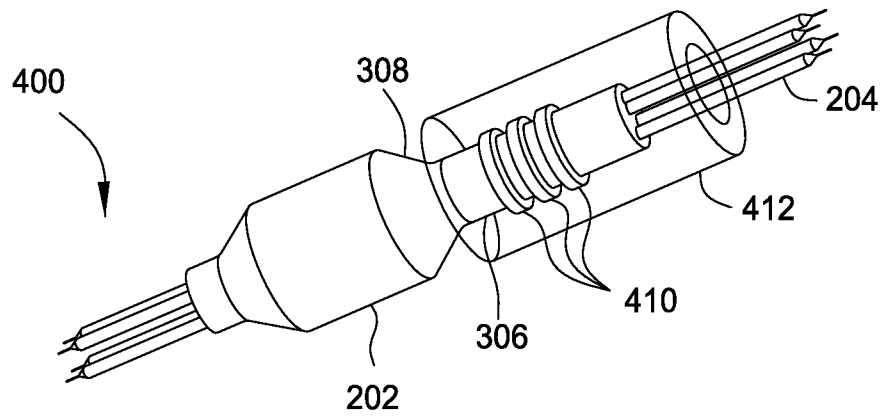


FIG. 4

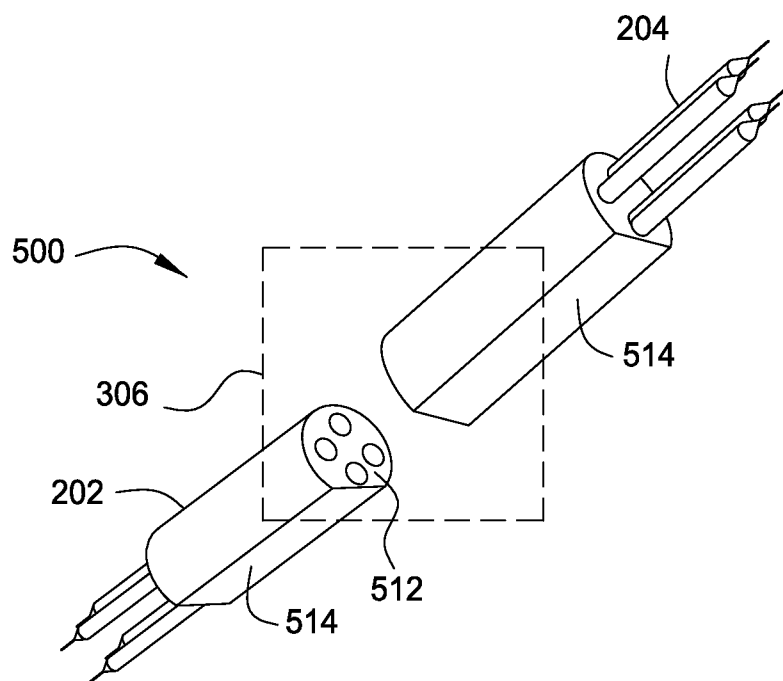


FIG. 5

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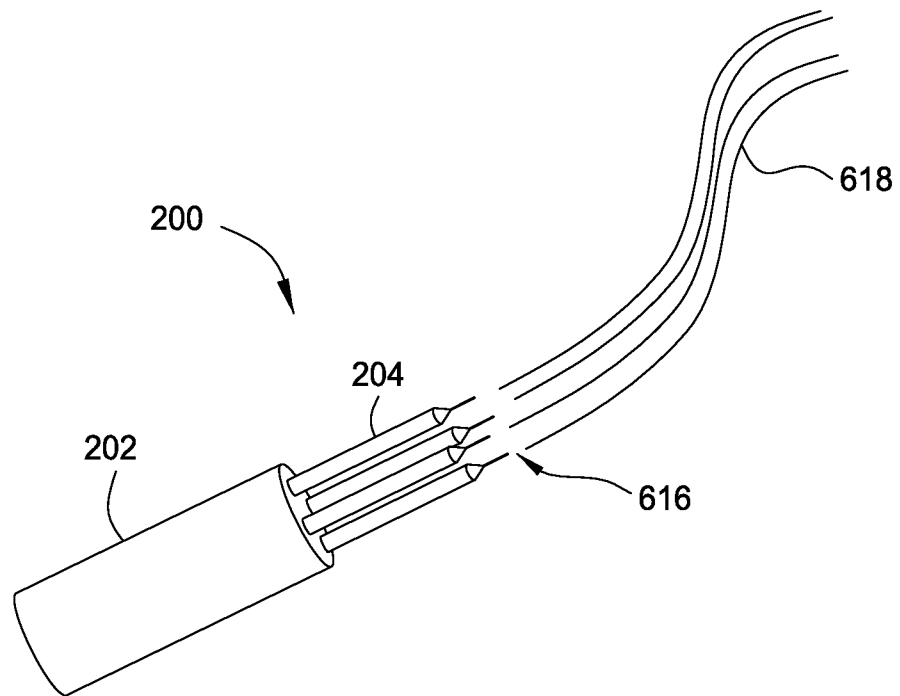


FIG. 6

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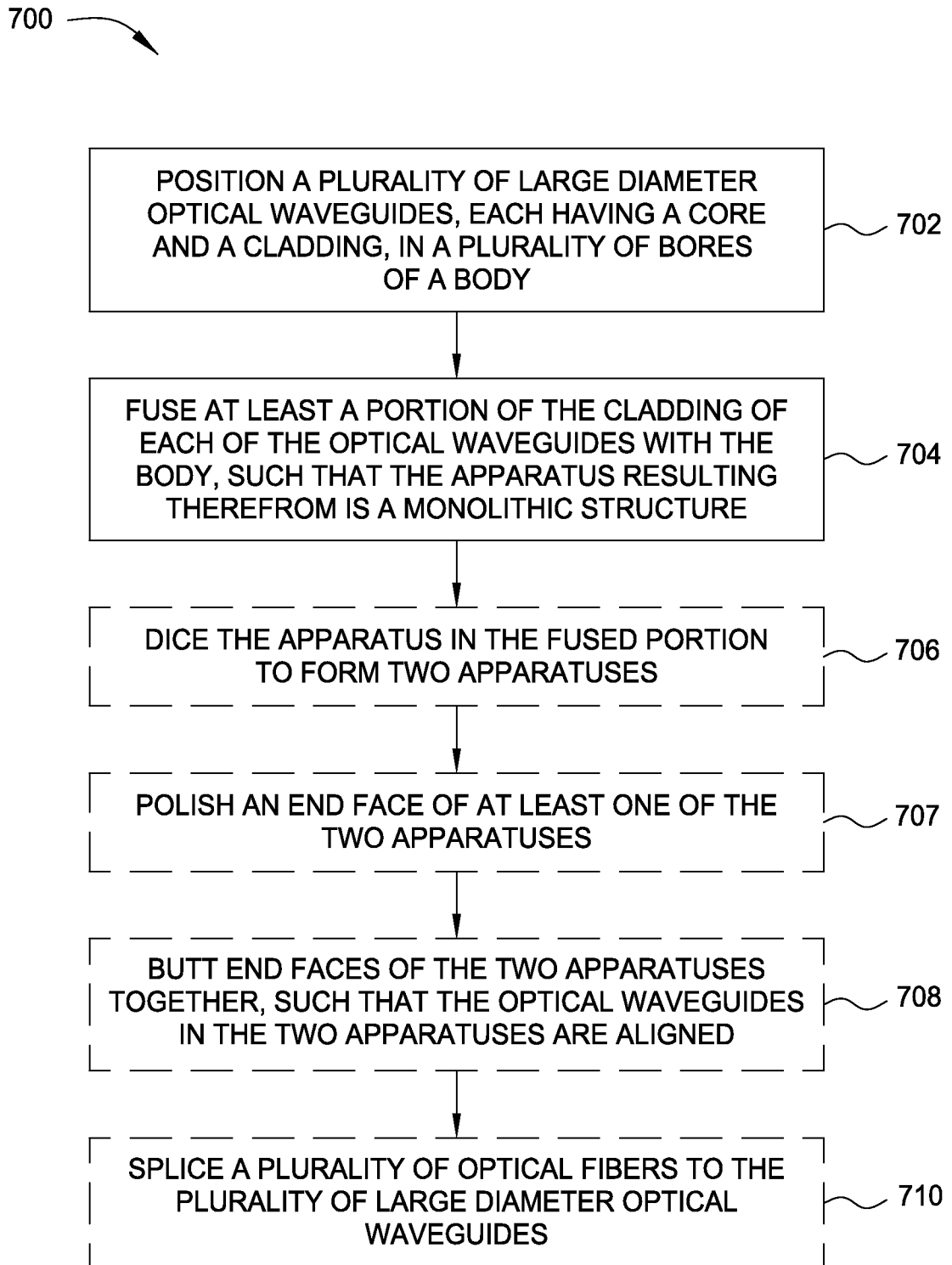


FIG. 7

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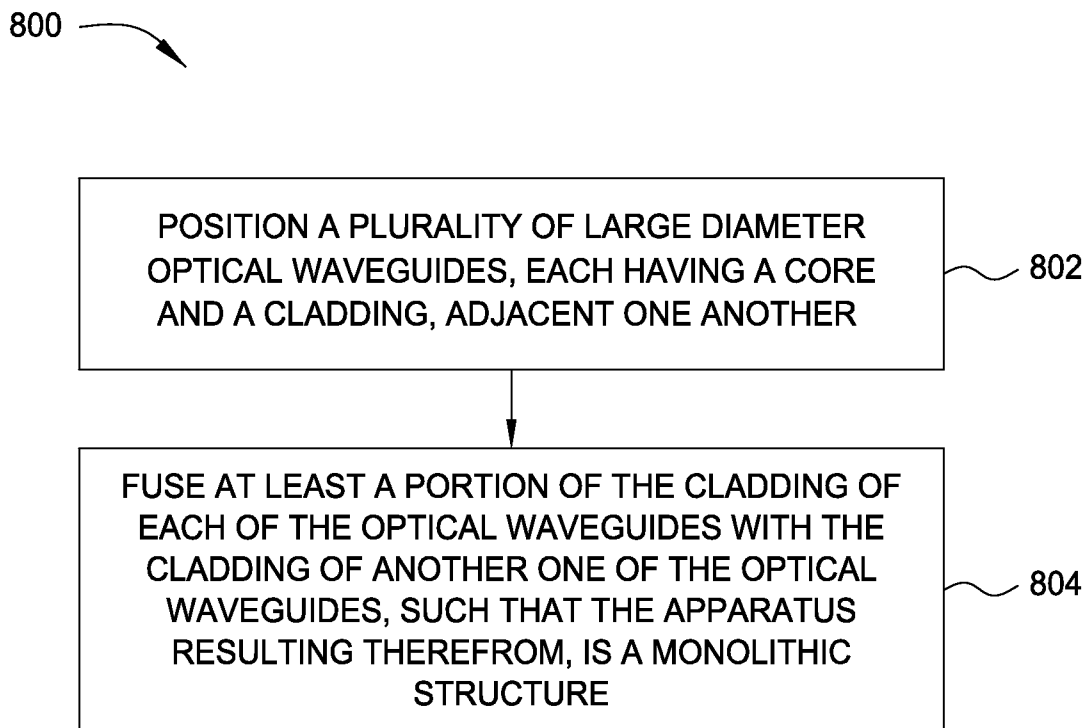


FIG. 8

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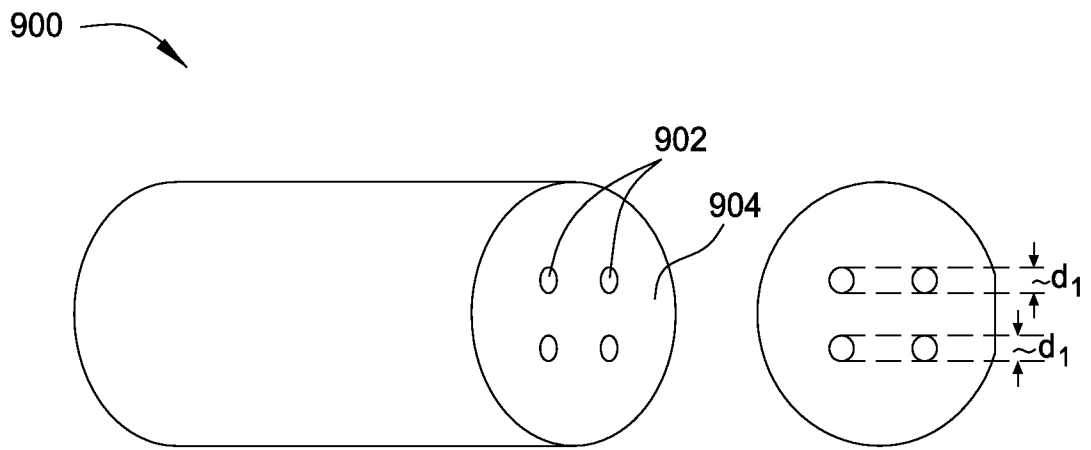


FIG. 9A

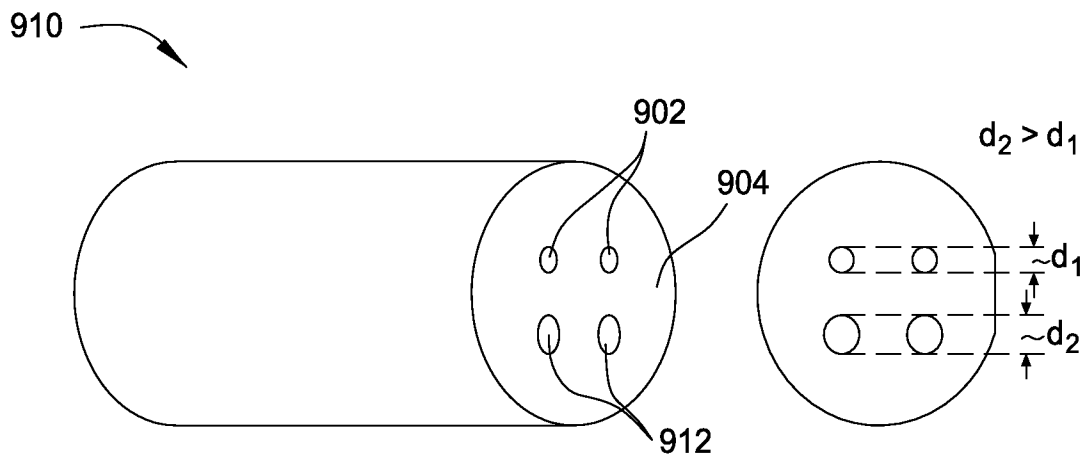


FIG. 9B

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2014/065417

A. CLASSIFICATION OF SUBJECT MATTER

INV. G02B6/38 G02B6/42 G02B6/44
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G02B G01D

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)

EP0-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	GB 2 341 014 A (PIRELLI CABLES SA [FR]) 1 March 2000 (2000-03-01)	1-50
A	page 1, line 3 - page 7, line 21 figures 3, 4	51-53
X	----- US 2008/145015 A1 (DUNPHY JAMES R [US] ET AL) 19 June 2008 (2008-06-19)	51-53
Y	paragraph [0025] - paragraph [0056] figures 5-14	1-50
A	----- EP 0 601 558 A1 (SEIKO GIKEN KK [JP]) 15 June 1994 (1994-06-15) the whole document	1-53



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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"P" document published prior to the international filing date but later than the priority date claimed

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

31 July 2015

Date of mailing of the international search report

11/08/2015

Name and mailing address of the ISA/

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Authorized officer

Szachowicz, Marta

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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