

COUPLER EXHIBITING REDUCED POLARIZATION SENSITIVITY

Background of the Invention

The present invention relates to overclad fiber optic couplers that exhibit low polarization dependent insertion loss.

Overclad fiber optic couplers comprise an elongated matrix glass body through which optical waveguide fibers longitudinally extend. The diameter of the central region of the coupler is smaller than that at the ends of the coupler, whereby the fibers are more closely spaced and are of smaller diameter in the central region than they are at the ends of the unit.

Overclad couplers are usually formed by inserting into a glass tube at least a portion of each of a plurality of optical fibers so that the fiber portions occupy the midregion of the tube. The tube is evacuated, and its midregion is heated and collapsed onto fibers. The central portion of the midregion is thereafter drawn down to that diameter and coupling length which is necessary to obtain the desired coupling between the fibers. Couplers having various kinds of coupling characteristics, eg. wavelength division multiplexer (WDM), achromatic, and the like, have been made by this process. See, for example, U.S. patents Nos. 4,931,076 and 5,011,251.

The term "overclad coupler" also includes couplers of the type made in accordance with the teachings of U.S. patent 4,799,949. A coupler preform is initially formed;

it comprises a plurality of spaced glass optical waveguide preforms disposed in a body of matrix glass of refractive index n_3 . Each waveguide preform comprises a core and a cladding of refractive indices n_1 and n_2 , respectively, where $n_1 > n_2 > n_3$. The preform is stretched to form a uniform diameter glass rod in which optical waveguide "fibers" are embedded in the matrix throughout their lengths. The rod is severed into a plurality of units. The central region of each unit is heated and stretched to elongate it and taper it inwardly. Although completely embedded in matrix glass throughout their lengths, the waveguide paths are referred to as fibers since they possess optical fiber dimensions at the ends of the coupler.

Commercially available single-mode optical fibers usually have a value of n_2 that is equal to or near that of silica. If silica is employed as the base glass for the tube, a dopant is added thereto for the purpose of decreasing n_2 to a value lower than n_1 . The dopant B_2O_3 (and optionally fluorine) has been employed to lower the refractive index of silica tubes. They also advantageously decrease the tube viscosity during the tube collapse step to a value lower than that of the coupler fibers, boron having the greater effect on viscosity. This enhances to a certain extent the collapsing of the tube onto the fibers. These dopants also affect the temperature coefficient of expansion (TCE) of the tube, boron increasing the TCE relative to silica, while fluorine reduces the TCE relative to silica when used in concentrations needed for couplers.

When the amount of B_2O_3 (and optionally fluorine) in a silica tube is insufficient to soften the tube glass in 1x2 and 2x2 couplers, the tube glass excessively deforms the fibers during the tube collapse step, thus increasing the excess loss of the coupler. Silica coupler tubes have therefore contained a sufficient concentration of one or more of these dopants to provide an acceptably low value of excess loss. It was found, however, that overclad fiber optic couplers made from tubes containing such relatively

high dopant concentrations exhibit an undesirably high polarization dependent insertion loss (PDL). In a 1x2 3 dB coupler made from a tube of SiO_2 doped with 8 wt. % B_2O_3 , for example, (the dopant concentration being substantially uniform with respect to radius) excess loss is 0.28 dB and PDL is 0.39 dB. The term "substantially uniform" is used herein to mean that the radial concentration of a dopant does not vary from an average value by more than 0.5 wt. percent.

PDL is characterized as follows. Polarized light from a laser is introduced into the coupler input fiber. The insertion loss is measured at one or more of the output fibers as the input source is rotated with respect to the input fiber to cause the polarization of the input power to rotate through 180° . The PDL is the difference between the maximum and the minimum measured insertion loss during this 180° rotation of the input polarization. The PDL results from stress caused by a mismatch between the physical properties, i.e. softening point temperature and TCE, of the fibers and the tube. Cooling rate of a glass body also affects stress.

To more closely match the physical characteristics of the tube to those of the fiber cladding, and thus lower the PDL, the B_2O_3 content throughout the tube can be decreased. In a 1x2 3 dB coupler made from a tube of SiO_2 doped with about 3.5 wt. % B_2O_3 , for example, (the dopant concentration being substantially uniform with respect to radius), the PDL is decreased to 0.19 dB, but excess loss will have increased to 1.14 dB. As B_2O_3 concentration in the tube is increased (while remaining substantially uniform with respect to radius), excess loss decreases, but PDL increases.

Summary of the Invention

It is therefore an object of the present invention to provide overclad fiber optic couplers having both low PDL

and low insertion loss.

Briefly, the present invention relates to overclad fiber optic couplers of the type that include an elongated matrix glass body having first and second opposed ends and a midregion. Extending longitudinally through the body are a plurality of optical fibers, each of which has a core surrounded by a cladding of refractive index greater than that of the body. The fibers are completely surrounded by the midregion of the body. The diameter of the central portion of the midregion and the diameters of the optical fibers in the central portion of the midregion are smaller than the diameters thereof at the ends of the body.

In accordance with the present invention, the body has an inner region adjacent the optical fibers, an outer region having a radius greater than that of the inner region, and a transition region between said inner and outer regions, the softening point temperature of the inner region being greater than that of the outer region. The softening point temperature of the inner region is sufficiently high that stress in the midregion adjacent the fibers is sufficiently low that said coupler exhibits a relatively low value of polarization dependent excess loss. The softening point temperature of the outer region is sufficiently low that the coupler exhibits a relatively low excess loss. In a preferred technique for obtaining the radially concentric regions, each region is provided with a substantially uniform radial composition profile of B_2O_3 . The matrix glass body can also include fluorine to provide characteristics that are useful in certain types of couplers.

The coupler is preferably formed by inserting optical fibers into a glass tube, collapsing the tube midregion onto the fibers and drawing the central portion of the midregion. The tube has an inner region adjacent its bore and an outer region of radius greater than that of the inner region. The softening point temperature of the inner region is greater than that of the outer region.

Brief Description of the Drawings

Fig. 1 is a cross-sectional view illustrating the position of fibers in the bore of a 2x2 coupler tube.

Fig. 2 is a cross-sectional view of a coupler preform connected to apparatus for evacuating the tube.

Fig. 3 is an end view of the preform of Fig. 3.

Fig. 4 is a schematic illustration of coupler forming apparatus.

Fig. 5 is a partial cross-sectional view of a drawn coupler that has been sealed at its ends.

Fig. 6 is a graph of refractive index plotted as a function of tube radius for one type of tube.

Figs. 7 and 8 are schematic diagrams of 2x2 and 1x2 couplers, respectively.

Fig. 9 is a cross-sectional view illustrating the position of fibers in the bore of a 1x2 coupler tube.

Description of the Preferred Embodiments

The drawings are not intended to indicate scale or relative proportions of the elements shown therein.

Fiber optic couplers can be characterized by the number of optical fibers that extend from each end thereof, by the fraction of input power that is coupled to a particular output fiber, and by the wavelength sensitivity of the coupling. In an $M \times N$ coupler, where $M \geq 1$ and $N \geq 2$, M optical fibers extend from one end and N fibers extend from the other end. A 3 dB coupler, for example, is a 1x2 or 2x2 coupler that couples 50% of the power from a first fiber to a second fiber. A tap is a coupler (usually a 1x2 or 2x2 coupler) that couples less than 50% of the input power, usually a small percentage such as 3%, 10% or the like, to one output fiber. A switch is a coupler (usually a 1x2 or 2x2 coupler) that is packaged such that the percentage of power coupled from a first optical fiber to a

second fiber can be changed by changing the angle at which the two fibers are bent in the plane of the two fibers (see U.S. patent 4,763,977). A WDM couples essentially all of the power at a first wavelength from the input fiber to a second fiber while essentially all of the power at a second wavelength remains in the input fiber. The present invention has relevance to all of the above-mentioned coupler types.

Typical of the couplers to which the invention pertains is the 2x2 coupler shown in Figs. 1-5. Funnels 14 and 15 of tube 10 connect longitudinal bore 11 to end surfaces 12 and 13, respectively. While bore 11 is shown as being circularly shaped, it could be non-circular as described in U.S. patent 5,009,692.

In accordance with the present invention, relatively low values of both PDL and excess loss are obtained by employing a coupler tube that is composed of two radially concentric regions, the compositions of which are such that the inner region has a higher softening point temperature than the outer region. In a preferred technique for obtaining the radially concentric regions, each region has a substantially uniform radial composition profile of B_2O_3 . In order to provide the required regions of different softening point temperature, the concentration of B_2O_3 in the inner region is lower than that in the outer region as shown in Fig. 6. The graph of Fig. 6 represents an average tube composition gradient including an inner region (line 6a) between radii r_1 and r_t , a transition region (line 6b), the center of which is located at r_t , and an outer region (line 6c) between radii r_t and r_o . Radii r_1 and r_o represent the inner and outer surfaces of the tube. The concentration of B_2O_3 in the inner region (line 6a) is between 1.5 wt. % and 3.5 wt. %, and the concentration of B_2O_3 in the outer region (line 6c) is between 6.5 wt. % and 11.0 wt. %. The composition of the inner region has a sufficiently high softening point temperature to provide a relatively low PDL. The outer tube region is formed of a

composition the softening point temperature of which is sufficiently low to provide a relatively low insertion loss.

One of the coupler tubes described herein (for a WDM coupler) also contains fluorine for the purpose of adjusting the spacing between the coupled and non-coupled wavelengths. When fluorine is employed, its concentration in the inner region is between 1.8 wt. % and 2.8 wt. %, and its concentration in the outer region is between 1.0 wt. % and 2.0 wt. %.

Tube refractive index was measured on a York Preform Analyzer as a refractive index change relative to silica at 850 nm. The B_2O_3 concentration of a tube comprising SiO_2 doped with only B_2O_3 was determined from the known relationship between B_2O_3 content and refractive index. The average location of the refractive index change on the York plot was taken as the location of the transition region r_t . This point is specified herein as a percentage of the distance from the tube inner surface r_i to the tube outer surface r_o , i.e. the hole is excluded. The transition region r_t is between 20% and 41% of the distance from r_i to r_o . After collapse of the tube onto the fibers, the transition region is located between about 25 % and 50 % of the radius of the outer surface of the device.

Some tube compositions were measured on a microprobe using a 40 μm spot at 10 locations across the radius to determine the wt. % of fluorine, silicon oxide (SiO_2), and boron oxide (B_2O_3). Three measurements were made per blank.

Coated optical fibers 16 and 17 are sufficiently long that connection can easily be made to the fiber "pigtailed" extending from the coupler. Coated fibers 16 and 17 are composed of optical fibers 20 and 21 (each having core and cladding regions) and their protective coatings 18 and 19, respectively. Portions of coatings 18 and 19 are stripped from coated fibers 16 and 17 at locations remote from the fiber ends. Fiber 16 is threaded through bore 11 until its uncoated portion is centered in tube 10. Fiber 17 is then

threaded through bore 11 until its uncoated portion is centered in tube 10. The fiber threading step can be performed either "off-line" (prior to mounting the tube in the stretch apparatus) or "on-line" (after the tube has been mounted in the stretch apparatus). In accordance with either technique, the operator can observe the position of the uncoated fibers and the adjacent coatings through the glass tube in order to properly position the fibers. A fiber insertion station is disclosed in U.S. patent 5,009,692.

As shown in Figs. 2 and 3, small amount 47 of glue is applied to one side of fibers 16 and 17 to attach them to one side of funnel 15 while leaving an opening 48 which permits access to bore 11 between glue 47 and the remainder of the funnel 15. A drop 49 of glue is similarly applied between fibers 16 and 17 and funnel 14, leaving bore access opening 50 between glue 49 and funnel 14. A slight tension is preferably applied to the fibers while they are being glued to the funnels.

Tube midregion 22 is then collapsed onto optical fibers 21 and 22 and thereafter stretched to form the coupling region. These steps can be performed in the draw apparatus of Fig. 4. Preform 51 is inserted through ring burner 60 and is clamped to draw chucks 61 and 62 which were mounted on motor controlled stages 63 and 64. The fibers are threaded through the vacuum attachments 65 and 65', which are then sealed to the ends of preform 51. Referring to Fig. 2, vacuum attachment 65 is slid over the end of tube 10, and collar 66 is tightened to compress O-ring 67 against tube 10. One end of a length of thin rubber tubing 70 is attached to that end of vacuum attachment 65 opposite preform 51; the remaining end of the tubing extending within tube clamping means (not shown). Upper vacuum attachment 65' is similarly associated with line 68', tubing 70' and tube clamping means. The coated portions of the fibers extend from tubing 70 and 70'. When air pressure is directed against tubing 70 and 70' as

indicated by arrows 71, 71', to clamp the tubing against the fibers extending therethrough, bore 11 is evacuated through line 68.

When tube midregion 22 is heated by ring burner 60, it collapses onto optical fibers 20 and 21. Thereafter, burner 60 is reignited to heat the center of the collapsed region, and stages 63 and 64 move to form neckdown region 81 of fiber optic coupler 80 (Fig. 6). Additional glue 82, 83 is applied to funnels 14 and 15 and the uncollapsed bore portions 11a and 11b. This can be done in accordance with the teachings of U.S. patent application S.N. 07/913,622 (G.E. Berkey et al. 26-7) filed July 16, 1992.

Coupler tubes for following examples were produced as follows. A porous preform having the desired radial composition of B_2O_3 -doped SiO_2 particles was formed on an alumina mandrel by a process similar to those disclosed in U.S. Pat. No. 4,165,223 and U.S. patent application S.N. 07/809,697 filed December 16, 1991. The outside diameter of the mandrel tapered from 9.5 mm to 12.6 mm over its 107 cm length. The mandrel was rotated and translated with respect to the burner, which was positioned 17.2 cm from the mandrel. Auxiliary burners directed flames toward the ends of the porous glass preform during deposition. The burner traversed a 70 cm section of the mandrel in 30 seconds. Carbon particles were initially deposited on the mandrel to facilitate removal of the porous preform. Thereafter, the reactants, $SiCl_4$ and BCl_3 , were supplied to a flame hydrolysis burner in accordance with the following programs, and the burner directed a stream of B_2O_3 -doped SiO_2 particles toward the mandrel.

Example A - Making Tubes for Examples 1 and 2

$SiCl_4$ and BCl_3 flowed to the burner at 2.25 slpm and 230 sccm, respectively, as it traversed the preform 100 times to form the inner region. To form the transition region, the flow rate of BCl_3 was linearly ramped to 490 sccm and the flow rate of $SiCl_4$ was linearly ramped to 0.95 slpm from burner pass 101 to pass 110. The flow rates of

the reactants remained constant at those values from pass 110 to pass 350 to form the outer region.

The resultant porous preform was loaded into a scanning consolidation furnace of the type disclosed in U.S. patent 4,741,748 where it was dried, consolidated and etched. During these steps, a muffle gas consisting of 20 slpm helium flowed upwardly from the bottom of the muffle.

During the drying step, a movable induction coil was reciprocated back and forth along the length of the preform at a rate of 1800 mm/minute to isothermally increase its temperature from room temperature to about 1030°C. A drying gas mixture consisting of 1 slpm oxygen, 70 sccm chlorine and 0.7 slpm helium flowed into the axial aperture from which the mandrel had been removed. While the temperature remained at 1030°C, this gas mixture continued to flow for 40 minutes to dry the preform.

While the drying gas mixture continued to flow, the porous preform was consolidated to form a dense glass tube by traversing the coil upwardly along the preform at 12 mm/minute for 83.3 minutes to generate in the preform a sharp 1400°C hot zone.

The inner surface of the resultant tubular blank was then etched by flowing a gas mixture of 0.1 slpm oxygen, 0.3 slpm helium and 75 sccm SF₆ into the top of the axial aperture for the next 71.4 minutes. The coil traversed the preform at 14 mm/minute to generate in the preform a sharp 1365°C hot zone.

Example B - Making the Tube for Example 3

To form the inner region of the tube, 2.25 slpm SiCl₄ and 176 sccm BCl₃ flowed to the burner as it traversed the preform 101 times. To form the transition region, the flow rate of BCl₃ was linearly ramped to 480 sccm and the flow rate of SiCl₄ was linearly ramped to 1.0 slpm from pass 101 to pass 110. The flow rates of the reactants remained constant at those values from pass 111 to pass 380 to form the outer region.

The steps of drying, consolidating and etching were

similar to those described in connection with Example A except that the consolidation temperature was 1413°C and the etch temperature was 1384°C.

Example C - Making the Tube for Example 4

To form the inner region of the tube, 2.25 slpm SiCl_4 and 220 sccm BCl_3 flowed to the burner as it traversed the preform 86 times. To form the transition region, the flow rate of BCl_3 was linearly ramped to 490 sccm and the flow rate of SiCl_4 was linearly ramped to 0.95 slpm from burner pass 86 to pass 95. The flow rates of the reactants remained constant at these values from pass 96 to pass 380 to form the outer region.

The resultant porous preform was then loaded into a scanning consolidation furnace where it was dried, doped, consolidated and etched. The drying step was similar to the drying step of Example A except that its duration was 20 minutes.

The porous preform was doped with fluorine during the next 20 minutes by flowing 200 sccm SiF_4 and 100 sccm BF_3 along with the drying gas mixture into the preform aperture. The temperature remained at 1030°C. The gas mixture remained the same for the consolidation step except that the SiF_4 flow was increased to 1.9 slpm; the consolidation temperature was 1364°C. The fluorine content of the resultant tube decreased radially, the average fluorine content in the inner region being about 2.3 wt. %, and the average fluorine content in the outer region being about 1.5 wt. %.

The etching step was similar to that of Example A.

The consolidated and etched blanks resulting from the methods of Examples A, B and C were drawn to form an elongated tube, the bore diameter of which was the size required for making couplers. The elongated tube was severed into coupler tubes.

The coupler tubes for comparative Examples 1A, 2A, 3A and 4A were made by a method similar to that used to make the tube of Example C except that the flow rates of SiCl_4

and BCl₃, during the deposition of particles on the mandrel were such that the B₂O₃ content of the resultant tube was substantially uniform.

Example 1

A 2x2 3 dB fiber optic coupler was made as follows. A glass capillary tube 10 having a 3.2 cm length, 2.65 mm outside diameter, and 380 μ m bore diameter was employed. The length of bore 11 was approximately 27 mm. The inner region of tube 10 was composed of SiO₂ doped with about 3.0 wt. % B₂O₃. The outer region was composed of SiO₂ doped with about 10 wt. % B₂O₃. The transition region r_t occurred at 35% of the distance between r_i and r_o . The width of the transition region was 2.6% of the thickness of the tube.

To form funnels 14 and 15, one end of tube 10 was heated while NF₃ was flowed into the other tube end; the gas etched the heated end of tube 10 as it exited.

Two 3 m lengths 16 and 17 of coated optical fiber were severed from a reel of fiber; they comprised 125 μ m diameter single-mode optical fibers 20 and 21 having 250 μ m diameter urethane acrylate coatings 18 and 19, respectively. Each of these fibers was a dispersion shifted fiber of the type taught in US patent 4,715,679. A 29 mm long portion of coating 18 was stripped from coated fiber 16 which was then wiped with an ethyl alcohol containing cloth. A first end of fiber 16 was threaded through bore 11, the bore being lubricated by squirting ethyl alcohol into it, as necessary. After the ends of coating 18 were centered in funnels 14 and 15, the first end was secured by a clamp. The second end of fiber 16 was clamped to a 7 g weight. A 23 mm long portion of coating 19 was stripped from coated fiber 17, and the fiber was similarly cleaned and threaded through tube 10 until the ends of coating 19 were centered in bore 11. The first end of fiber 17 was then secured by a clamp, and the second end thereof was clamped to a 7 g weight. Excess alcohol was blown from the tube bore by dry nitrogen.

An operator centered the short stripped section of fiber in the bore by moving the tube. The ends of coating 19 then protruded a distance d of about 2 mm beyond the bottoms (narrow ends) of the funnels into each end of bore 11.

While the fibers extended parallel to one another, being tensioned by the weights, they were tacked to the funnels as described above using UV cure epoxy resin code No. 2728 manufactured by Electrolite Corporation of Danbury, Connecticut. A small amount 47 of the glue was carefully applied to one side of the tube to attach fibers 16 and 17 to funnel 15 and was cured by exposure to UV light. A small amount 49 of the glue was then similarly employed to attach fibers 16 and 17 to funnel 14.

Preform 51 was inserted through the ring burner, clamped to the draw chucks, and vacuum attachments were sealed to its ends. With a vacuum of 50.8 cm of mercury applied to bore 11, burner 60 was ignited. Gas and oxygen were supplied to the burner at rates of 0.33 slpm and 0.67 slpm, respectively. The flame heated tube 10 for about 25 seconds, and midregion 22 collapsed onto fibers 20 and 21.

After the tube cooled, the burner was reignited, the flow rates of the gas and oxygen having been increased to 0.37 slpm and 0.74 slpm, respectively, to heat the center of the collapsed region. After about 12 seconds, the oxygen flow was gradually reduced over a period of about one second to allow the coupler to cool below the glass transition temperature. The gas and oxygen were then turned off. Stages 63 and 64 were moved in opposite directions at a combined rate of 0.60 cm/sec to elongate preform 51 by about 11.0 mm to form neckdown region 81 (Fig. 5). After the resultant fiber optic coupler had cooled, the vacuum lines were removed.

The coupler remained in the chucks during the application of additional glue to funnels 14 and 15 and the uncollapsed bore portions 11a and 11b. One end of an 80 μ m

outside diameter hollow silica microtube was connected to a source of vacuum. The remaining end was inserted through funnel 15 and opening 48 to the bottom of uncollapsed bore portion 11a (Fig. 5). When a drop of Electrolite 2500 epoxy resin made by Electrolite Corporation of Danbury, Connecticut, was placed in funnel 15, it flowed into bore portion 11a where it flowed a short distance into the microtube. This gluing procedure was repeated at uncollapsed bore portion 11b. The glue was cured by exposure to ultraviolet light, the coupler was removed from the chucks, and the protruding hollow filaments were severed.

This process produced more than one hundred 3 dB couplers that operated at 1480 nm. Average excess device loss was about 0.25 dB, and average PDL was 0.07 dB.

Comparative Example 1A

A 2x2 3dB coupler was made by a method similar to that described in Example 1 except that standard single-mode fiber was employed and the tube had a substantially uniform radial composition profile of SiO₂ doped with 2 wt. % B₂O₃, and the fluorine content thereof linearly decreased from 2 wt. % at the inner surface to 1 wt. % at the outer surface. The use of standard single-mode fibers did not affect the PDL of the resultant couplers. Such fibers comprise a 8 μm diameter core of SiO₂ doped with 8.5 wt. % GeO₂ and a 125 μm diameter SiO₂ cladding.

This process produced more than one hundred 3 dB couplers that were designed for operation at 1475 nm. Average excess device loss was about 0.48 dB, and average PDL was 0.19 dB.

Example 2

A 2x2 10 dB tap was made by a method similar to that described in Example 1 except that the preform was elongated by 3.97 mm to form the neckdown region.

This process produced hundreds 2x2 10 dB couplers that

coupled 10 % of the input power at 1558 nm from leg 1 (see Fig. 7) to leg 3. The average insertion loss (legs 1-2) was about 0.65 dB, and the average insertion loss (legs 1-3) was about 10.5 dB. The average PDL (legs 1-3) was 0.14 dB.

Comparative Example 2A

A 2x2 10 dB tap was made by a method similar to that described in Example 2 except that standard single-mode fiber was employed and the tube was as described in Example 1A.

This process produced hundreds of 2x2 10 dB couplers. The average insertion loss (legs 1-2) was about 0.70 dB, and the average insertion loss (legs 1-3) was about 10.5 dB. The coupler legs are shown in Fig. 7. The average PDL (legs 1-3) was 0.96 dB.

Example 3

A 1x2 23.5 dB tap was made by a method similar to that described in Example 1 except for the following differences, reference being made to Fig. 9 wherein elements similar to those of Fig. 1 are represented by primed reference numerals. A tube 10' having a 3.2 cm length, 270 μ m bore diameter, and 2.65 mm outside diameter was inserted into the apparatus of Fig. 9. The inner region of tube 10' was composed of SiO₂ doped with about 2.0 wt. % B₂O₃. The outer region was composed of SiO₂ doped with about 7.5 wt. % B₂O₃. The transition region r_t occurred at 36 % of the distance between r_1 and r_o . The width of the transition region was 2.6 % of the thickness of the tube.

Approximately 27 cm of coating was stripped from the central region of a 3 meter length of fiber 16'. A section of coating 86 about 40 mm long was removed from the end of a 1.5 meter length of coated fiber 85. An antireflection termination was formed on the end of fiber 87 by directing a flame at the center of the stripped region of fiber, while the end of the fiber was pulled and severed to form a

tapered end. The tip of fiber 87 was heated by a burner flame to cause the glass to recede and form a rounded endface, the diameter of which was equal to or slightly smaller than the original uncoated fiber diameter. The resultant stripped end region was about 24 mm long.

Coated fiber 16' was inserted through bore 11' until its uncoated portion was situated below tube end 13'. The uncoated portion of coated fiber 85 was held adjacent the uncoated portion of coated fiber 16', and both were moved together toward tube end 12' until the coating end regions were interior to funnel 15'. The uncoated portion of coated fiber 16' was then disposed intermediate end surfaces 12' and 13'. The end of fiber 87 was located between midregion 22' and end 12' of tube 10'. The tube collapse and stretch steps were similar to those described in Example 1 except that the preform was elongated by about 6.6 mm to form the neckdown region.

This process produced hundreds of 1x2 23.5 dB taps that coupled 0.4 % of the input power at 1558 nm from leg 1 (see Fig. 8) to leg 3. The average insertion loss (legs 1-2) was 0.25 dB, and the average insertion loss (legs 1-3) was 23.5 dB. The average PDL (legs 1-2) was 0.01 dB, and the average PDL (legs 1-3) was 0.21 dB.

Comparative Example 3A

A 1x2 25 dB tap was made by a method similar to that described in Example 3 except that standard single-mode fiber was employed, and the tube was as described in Example 1A. Since this example pertains to 25 dB taps rather than 23.5 dB taps, the stretch distance was about 6.7 mm.

This process produced hundreds 1x2 25 dB taps that coupled 0.3 % of the input power at 1558 nm from leg 1 (Fig. 8) to leg 3. The average insertion loss (legs 1-2) was about 0.21 dB, and the average insertion loss (legs 1-3) was about 24.9 dB. The average PDL (legs 1-2) was 0.01 dB, and the average PDL (legs 1-3) was 2.26 dB.

Example 4

A 1480/1558 nm 1x2 WDM coupler was made by a method similar to that described in Example 3 except for the following differences.

The tube dimensions were the same as Example 3. The inner region of tube 10 was composed of SiO_2 doped with about 2.5 wt. % B_2O_3 and 2.3 wt % fluorine. The outer region was composed of SiO_2 doped with about 7.5 wt. % B_2O_3 and 2.3 wt % fluorine. The transition region r_t occurred at 36 % of the distance between r_1 and r_o . The width of the transition region was 2.6 % of the tube thickness.

The coupler preform, which was formed by a method similar to that described in Example 3, was inserted into the apparatus of Fig. 4. The tube collapse and stretch steps were similar to that described in Example 1 except that the combined stretch rate of both stages was 5.0 cm/sec, and the preform was elongated by 33 mm to form the neckdown region.

This process produced hundreds of 1480/1558 nm 1x2 WDM couplers that coupled 98 % of the input power at 1558 nm from leg 1 (see Fig. 8) to leg 2 and 98 % of the input power at 1480 nm to leg 3. The average insertion loss (legs 1-2) at 1558 nm was 0.4 dB, and the average insertion loss (legs 1-3) at 1480 ± 10 nm was 0.4 dB. The average PDL (legs 1-2) at 1558 nm was 0.05 dB, and the average PDL (legs 1-3) at 1480 nm was 0.4 dB.

Comparative Example 4A

A 1475/1558 nm 1x2 WDM coupler was made by a method similar to that described in Example 4 except that the tube was as described in Example 1A.

This process produced hundreds of 1x2 WDM couplers. The average insertion loss (legs 1-2) at 1558 nm was 0.31 dB, and the average insertion loss (legs 1-3) at 1475 nm was 0.52 dB. The coupler legs are shown in Fig. 8. The average PDL (legs 1-2) at 1558 nm was 0.11 dB, and the average PDL (legs 1-3) at 1475 nm was 0.08 dB.



PATENT CLAIMS:

1. A fiber optic coupler comprising

an elongated body of matrix glass of refractive index n_3 , said body having first and second opposed ends and a midregion,

a plurality of optical fibers extending longitudinally through said body, each of said fibers comprising a core of refractive index n_1 surrounded by a cladding of refractive index n_2 , where $n_1 > n_2 > n_3$,

said fibers being fused to the midregion of said body, the diameter of the central portion of said midregion and the diameters of said optical fibers in said central portion of said midregion being smaller than the diameters thereof at the ends of said body,

said body having an inner region adjacent said optical fibers, an outer region having a radius greater than that of said inner region, and a transition region between said inner and outer regions, the softening point temperature of said inner region being sufficiently high that stress in said midregion adjacent said fibers is sufficiently low that said coupler exhibits a relatively low value of polarization dependent excess loss, the softening point temperature of said outer region being sufficiently low that said coupler exhibits a relatively low excess loss.

2. A fiber optical coupler comprising

an elongated body of matrix glass of refractive index n_3 , said body having first and second opposed ends and a midregion,

a plurality of optical fibers extending longitudinally through said body, each of said fibers comprising a core of refractive index n_1 surrounded by a cladding of refractive index n_2 , wherein $n_1 > n_2 > n_3$,

said fibers being fused to the midregion of said body, the diameter of the central portion of said midregion and



the diameters of said optical fibers in said central portion of said midregion being smaller than the diameters thereof at the ends of said body,

said body having a substantially uniform composition inner region adjacent said optical fibers and a substantially uniform composition outer region having a radius greater than that of said inner region, the softening point temperature of said inner region being greater than that of said outer region, the softening point temperature of said inner region being sufficiently high that stress in said midregion adjacent said fibers is sufficiently low that said coupler exhibits a relatively low values of polarization dependent excess loss, the softening point temperature of said outer region being sufficiently low that said coupler exhibits a relatively low excess loss.

3. A fiber optic coupler in accordance with claim 1 or 2 wherein the outer region of said tube constitutes the major portion of the volume of said tube.

4. A fiber optic coupler in accordance with claim 1 or 2 comprising a transition region between said inner and outer regions, the average radius of said transition region is between about 25 to 50 % of the outer radius of said body.

5. A fiber optic coupler in accordance with claim 1 or 2 wherein the said inner region comprises SiO_2 doped with 1.5 wt. percent to 3.5 wt. percent B_2O_3 , and said outer region comprises SiO_2 doped with 6.5 wt. percent to 11.0 wt. percent B_2O_3 .

6. A fiber optic coupler in accordance with any one of claims 1-5 wherein at least one optical fiber extends from said first end of said body and two optical fibers extend from said second end of said body.



7. A fiber optic coupler in accordance with claim 6 wherein M optical fibers extend from said first end of said body and N optical fibers extend from said second end of said body, wherein $M \geq 1$ and $N \geq 2$.

8. Method of making a fiber coupler comprising providing a glass tube having first and second opposite end portions and a midregion, a longitudinal bore within said tube, said tube having an inner region adjacent said bore and an outer region of radius greater than that of said inner region, and a transition region between said inner and outer regions, the softening point temperature of said inner region being greater than that of said outer region,

disposing within said longitudinal bore at least a portion of each of a plurality of glass glass optical fibers, each of said fibers having a core surrounded by a cladding of refractive index less than that of said core, the refractive index of the claddings of said plurality of optical fibers being greater than the refractive index of said tube, at least that part of each fiber that is located in the tube midregion having no coating thereon, said fibers having a coextensive relationship in said tube midregion, at least a portion of at least one of the fibers in said midregion extending beyond the first end of said tube, at least a portion of at least another of the fibers in said midregion extending beyond the second end of said tube,

collapsing said tube midregion onto said fibers, and drawing the central portion of said midregion to reduce the diameter thereof and form a coupling region in which light propagating in one of said fibers couples to another of said fibers, the softening point temperature of said inner region being sufficiently high that stress in said midregion adjacent said fibers is sufficiently low that said coupler exhibits a relatively low value of polarization dependent excess loss, the softening point



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temperature of said outer region being sufficiently low that said coupler exhibits a relatively low excess loss.

9. Method according to claim 8 wherein the outer region of said tube constitutes the major portion of the volume of said tube, or wherein the average radius of said transition region is between about 20 to 41 % of the outer radius of said tube.

10. Method according to claim 8 or 9 wherein the same inner region comprises SiO_2 doped with 1.5 wt. percent to 3.5 wt. percent B_2O_3 , and said outer region comprises SiO_2 doped with 6.5 wt. percent to 11.0 wt. percent B_2O_3 .