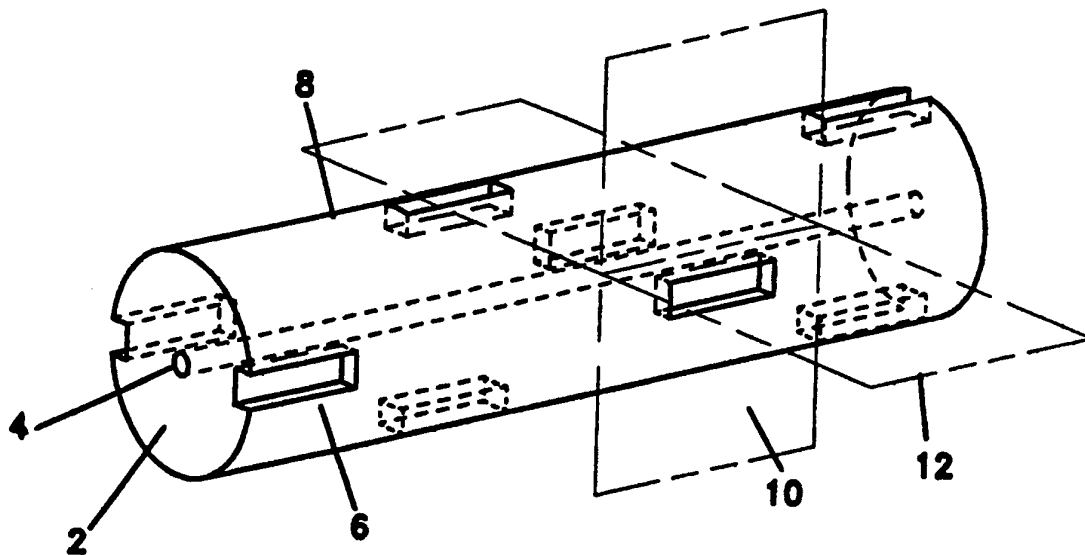




## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

<p>(51) International Patent Classification <sup>6</sup> : G02B 6/00, C03B 37/023</p>	<p>A1</p>	<p>(11) International Publication Number: <b>WO 97/06456</b> (43) International Publication Date: 20 February 1997 (20.02.97)</p>
<p>(21) International Application Number: PCT/US96/16360 (22) International Filing Date: 8 August 1996 (08.08.96) (30) Priority Data: 08/513,260 10 August 1995 (10.08.95) US (71) Applicant: CORNING INCORPORATED [US/US]; 1 Riverfront Plaza, Corning, NY 14831 (US). (72) Inventors: ANTOS, Alfred, J.; 1589 Vanderhoff Road, Elmira, NY 14903 (US). BHAGAVATULA, Venkata, A.; 29 Orchard Drive, Big Flats, NY 14814 (US). CHERVENAK, William, J.; 25 Deerfield Drive, Big Flats, NY 14814 (US). CHOWDHURY, Dipakbin, Q.; 14 Emily Drive, Corning, NY 14830 (US). NOLAN, Daniel, A.; 28 Skyline Drive, Corning, NY 14830 (US). (74) Agent: HERZFELD, Alexander, R.; Corning Incorporated, Patent Dept., SP-FR-02-12, Corning, NY 14831 (US).</p>	<p>(81) Designated States: AU, CA, JP, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).  <b>Published</b> <i>With international search report.</i></p>	

(54) Title: POLARIZATION MODE COUPLED SINGLE MODE WAVEGUIDE



(57) Abstract

A single mode optical waveguide having reduced polarization mode dispersion and a method of making such a waveguide is disclosed. Perturbations (6, 8) are introduced into the waveguide core (4) to couple power between the two polarization modes. A model calculation shows that the perturbation length may be of the order of the correlation length. The inventive waveguide is robust in that polarization mode dispersion is reduced even if perturbations (6, 8) are impressed on the fiber after manufacture.

**FOR THE PURPOSES OF INFORMATION ONLY**

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AM	Armenia	GB	United Kingdom	MW	Malawi
AT	Austria	GE	Georgia	MX	Mexico
AU	Australia	GN	Guinea	NE	Niger
BB	Barbados	GR	Greece	NL	Netherlands
BE	Belgium	HU	Hungary	NO	Norway
BF	Burkina Faso	IE	Ireland	NZ	New Zealand
BG	Bulgaria	IT	Italy	PL	Poland
BJ	Benin	JP	Japan	PT	Portugal
BR	Brazil	KE	Kenya	RO	Romania
BY	Belarus	KG	Kyrgystan	RU	Russian Federation
CA	Canada	KP	Democratic People's Republic of Korea	SD	Sudan
CF	Central African Republic	KR	Republic of Korea	SE	Sweden
CG	Congo	KZ	Kazakhstan	SG	Singapore
CH	Switzerland	LI	Liechtenstein	SI	Slovenia
CI	Côte d'Ivoire	LK	Sri Lanka	SK	Slovakia
CM	Cameroon	LR	Liberia	SN	Senegal
CN	China	LT	Lithuania	SZ	Swaziland
CS	Czechoslovakia	LU	Luxembourg	TD	Chad
CZ	Czech Republic	LV	Latvia	TG	Togo
DE	Germany	MC	Monaco	TJ	Tajikistan
DK	Denmark	MD	Republic of Moldova	TT	Trinidad and Tobago
EE	Estonia	MG	Madagascar	UA	Ukraine
ES	Spain	ML	Mali	UG	Uganda
FI	Finland	MN	Mongolia	US	United States of America
FR	France	MR	Mauritania	UZ	Uzbekistan
GA	Gabon			VN	Viet Nam

## Polarization Mode Coupled Single Mode Waveguide

### Background

5 The invention is directed to an optical waveguide fiber having reduced polarization mode dispersion (PMD), and a method for making such a waveguide fiber.

High performance telecommunications systems, i.e., those having transmission rates above about 5 Gb/s, or long regenerator spacing, with or without optical amplifiers, require waveguide fibers designed to limit all  
10 sources of signal distortion or signal power loss.

In particular, in high data rate transmission systems, essentially all sources of signal dispersion, including PMD, become potential data rate limiting factors, and must be controlled to enable such systems.

PMD may be controlled by controlling the birefringence of the  
15 waveguide fiber which causes the two polarization modes to propagate at different speeds in the waveguide fiber.

There will be no polarization mode dispersion if the waveguide fiber has perfect geometric symmetry and is free of stress which causes random birefringence.

20 However, it is impractical to pursue making a waveguide fiber essentially free of birefringence from the standpoint of cost and process control. Further, given a perfect glass waveguide fiber, birefringence, and thus PMD, can be induced in any of the several additional process steps required to

put the glass waveguide into a usable form. Thus, birefringence can be induced in the coating, buffering, stranding or cabling process.

A practical alternative method for limiting PMD is to introduce birefringence into the waveguide fiber in a controlled way so that the polarization modes are mixed and therefore have travel times in the waveguide which may differ only slightly. An alternative statement is, the two polarization modes experience essentially little or no net birefringence over a pre-selected waveguide fiber length.

One approach to introducing birefringence into a waveguide fiber is discussed in "Applied Optics", Ashkin et al., Vol. 20 (13), page 2299. In that article a particular birefringence is impressed on the fiber by spinning the draw preform during draw. In U.S. Patent No. 5,298,047, Hart et al., a method for impressing a spin on the fiber during draw is disclosed. The number of required spins/meter is stated as being related to the beat length of the waveguide fiber.

It is noteworthy that both cited references teach that the periodicity of the spin must be less than the beat length of the wavelength.

The major drawbacks in a spinning technique during draw are:

- at a reasonable draw speed the spinning rate is very high, thereby introducing perturbations into a drawing process which is already a complex and sensitive step in the waveguide manufacturing process;
- an additional draw control loop is required; and,
- waveguide costs are increased as percent good waveguide length decreases, at a step which occurs after significant investment in raw material and energy has already been made.

### Definitions

- Refractive index profile describes the variation of glass refractive index along a waveguide fiber radius.

- Birefringence is a property of a light propagating material wherein the speed of light in the material is dependent upon the orientation of the electric

field vector of the light in the plane perpendicular to the direction of propagation.

- A birefringence axis of a material is an imaginary line in a plane perpendicular to the direction of light propagation. Light launched with its electric field vector along this axis experiences a particular index of refraction, i.e., has a particular phase velocity. A linear birefringent material has two such axes.

- Beat length of a waveguide fiber is the length required for a particular light polarization to repeat. For example, the first beat occurs at a distance along the fiber where the light polarization is again oriented as it was at launch.

- Correlation length of a waveguide fiber is the length at which the dependence of PMD, expressed as ps/km, transitions from a linear to a square root dependence on length.

### **Summary of the Invention**

The present invention meets the need for an optical waveguide fiber wherein PMD is controlled in a manner which is largely independent of process steps carried out after waveguide production, e.g., buffering or cabling.

Further, the instant invention does not add additional requirements to the drawing step, a process step which is already quite complicated.

A first aspect of the invention is a single mode optical waveguide fiber having a core and a clad, at least a portion of the core refractive index being greater than that of a portion of the clad refractive index. Birefringence is induced in the waveguide fiber by means disposed along the waveguide length. The birefringence means are arranged to have a mirror symmetry, where the mirror plane includes the longitudinal axis of symmetry of the waveguide. Adjacent mirror planes are made to be orthogonal to produce orthogonal axes of birefringence.

To be effective in mixing the orthogonal polarization modes of propagated light, the difference in index of refraction between the two birefringence axes is at least  $1 \times 10^{-6}$ .

5 The birefringence means are arranged along the fiber length so that the net birefringence of the fiber is essentially zero. In this way, the travel time of light in the waveguide fiber will not depend upon the orientation of its electric field vector at launch. One practical way of realizing net zero of birefringence for a waveguide fiber length is to dispose the birefringence means periodically,  
10 i.e., in segments of essentially equal length, along the waveguide.

Birefringence may be induced, for example, by causing variation, along the length of the waveguide, of ellipticity of the core, of the concentricity of the core and the clad, or of the residual stress in the waveguide.

15 A second aspect of the invention is the control of the required length between orthogonal changes in birefringence axes. In contrast to the art cited above, birefringence means, disposed along the waveguide fiber length, having a variation period of less than about three times the correlation length of the waveguide, are effective to produce polarization mode mixing and hence reduction in PMD.

20 If the length of a periodic variation of the birefringence must be close to the beat length of a waveguide, one is essentially constrained to introduce that variation during the drawing step. A typical beat length may be 10 meters or less. A millimeter length of a draw preform which is 50 mm in diameter translates into about 160 meters of waveguide fiber having a nominal diameter  
25 of 125 microns. Because of the very small dimensions which would be involved, modification of the draw preform to induce variable birefringence appears impractical.

30 What has been discovered in the present invention is that PMD reduction benefit can be realized for birefringence variation lengths much greater than the beat length and that the waveguide correlation length is a

good base measurement for determining benefit derived from a particular birefringence variation length.

The relation between wavelength correlation length and birefringence periodic variation is calculated using a model which uses typical waveguide fiber beat length and correlation length. Beat length may vary within the length limits 2 to 40 meters and a typical beat length may be taken as 10 meters. Also, correlation length may vary between the limits 50 to 400 meters with a typical correlation length having a value of 200 meters.

A further aspect of the invention is a method for making a single mode optical waveguide fiber having the birefringence properties identified above. Because birefringence variation lengths may be longer than beat length, the geometric perturbations which cause birefringence may be induced into the core preform or into the draw preform.

A particular embodiment of the method is a core preform having grooves formed in the core preform surface. The grooves have at least one mirror plane of symmetry, which includes the longitudinal axis of the preform, and are spaced apart along the length of the preform.

The preform is overcladded to form a draw blank, which has an essentially uniform cylindrical surface, and drawn into a waveguide fiber having an essentially uniform diameter. The draw preform must have an essentially uniform cylindrical surface when the perturbations are formed in the core portion of the preform so that the perturbations appear in the core after the draw preform is drawn into a waveguide fiber of uniform diameter.

Another method for inducing birefringence includes impressing the birefringence perturbation means into the surface of the draw preform having an essentially cylindrical core preform surface. Then, drawing the preform into a waveguide of uniform diameter effectively transfers the perturbations from the draw preform surface to the core surface of the waveguide.

The conditions which determine the required surface condition of the draw preform are:

- substantially all of the perturbation must be impressed on the core of the waveguide fiber; and,

- the waveguide fiber must be drawn to an essentially uniform diameter.

Characteristic dimensions of the grooves formed in the core or draw preform are a depth in the range of about 3% to 15% of the preform diameter, and a length along the longitudinal axis of the preform no greater than about 4 mm. In order to provide two distinct polarization axes, the circumferential extent of the groove is a length less than half the circumference of the preform and typically of the order of about one fourth the circumference of the preform.

Yet another method of making a waveguide fiber having periodically varying birefringence is contemplated. This method comprises forming a spiral groove in the waveguide core preform or draw preform. The depth and longitudinal extent, i.e., the edge to edge dimension of the spiral channel measured parallel to the preform axis, are chosen as before and the pitch of the spiral is greater than about 0.04 mm. This lower limit on pitch arises from the requirement that the perturbations not produce circular polarization of the launched light (see, Simon and Ulrich, "Applied Optics", 18, pp. 2241-2251, 1979). The upper limit on longitudinal extent of the groove is about 4 mm, as before, a limit which is set by the limits at which the perturbations are effective to mix the polarization modes.

Although the spiral channel is envisioned as being formed over the entire length of the core or draw preform, the spiral need not be formed as a continuous channel. Also the pitch, depth and longitudinal extent of a non-continuous spiral channel may vary along the core or draw preform length. However, the dimensions of the channel which is continuous or non-continuous must have a periodicity which yields an essentially zero net birefringence along each polarization axis as stated above.

An alternative design which does not cause circular polarization but has no lower limit on pitch includes corresponding preform lengths having a spiral groove wherein the pitch of the grooves have respective different directions of

advance. The direction of advance of a spiral is the direction of movement along the pitch when the spiral is traversed in a clockwise direction.

### **Brief Description of the Drawings**

5           **FIG. 1a** shows an example of geometrical perturbations in a draw preform.

**FIGS. 1b** and **1c** illustrate examples of perturbations in a draw preform or a waveguide fiber.

**FIG. 2** is an example of a spiral perturbation in a draw preform.

10           **FIG. 3** is a schematic showing an ideal fiber having adjacent lengths of induced orthogonal birefringence axes.

**FIG. 4** is a schematic showing both random and induced birefringence along the waveguide length.

15           **FIGS. 5a** and **5b** show model calculated results of the improvement in PMD provided by induced birefringence.

### **Detailed Description of the Invention**

20           A major difficulty in dealing with PMD in a single mode waveguide fiber is that birefringence can be induced in a waveguide fiber at essentially any stage of the manufacture, cabling, installation or use of the waveguide. Stress induced in a coating, buffering or cabling step can produce PMD. The same is true for bending stress induced during installation or for stress induced as coating or cabling or installation materials change due to environmental factors or age.

25           Because the glass waveguide itself is quite stable and usually well protected in the cabling process, an attempt to reduce PMD is best directed to building low PMD into the waveguide fiber itself rather than addressing the PMD problem at the coating stage or any subsequent stage of the process.

30           Furthermore, because the bend stress in the glass can change during cabling, installation or use, the method used to eliminate or reduce PMD should be relatively insensitive to downstream process steps and to

environmental factors which can introduce stress and, thus, birefringence into the waveguide fiber.

The uncertainty of what environment a waveguide will have over a normal lifetime, suggests that PMD may best be estimated using statistical methods. A statistical approach serves to average large local effects over a  
5 sufficient waveguide length, of the order of 20 to a few hundred kilometers, to give a more accurate predictor of PMD for an installed link.

The strategy employed in the subject invention is therefore, first, to manufacture a waveguide fiber using techniques which minimize PMD by  
10 mixing the two orthogonal polarization modes propagated in the waveguide. Secondly, for the particular fiber in question, an estimate is made as to how random birefringence affects the total PMD. Such estimates are best done in terms of ratios of performance parameters, in controlled polarization mode mixed waveguides, to standard waveguide fiber.

From experience with the environmental demands of different  
15 installations, such as undersea cable, buried cable, or suspended cable, PMD performance of a waveguide fiber over its lifetime can be made.

**FIG. 1a** shows a draw preform, having a core 4 and a clad 2, which has been prepared with pairs of grooves 6 and 8 formed in the preform surface.  
20 The grooves have a depth, a width, and a length along the waveguide fiber axis. Mirror planes 10 and 12 illustrate that adjacent pairs of grooves are orthogonal. The groove depth lies in the range of about 0.03 to 0.20 of the preform diameter. Shallow grooves are preferred, in the depth range of about 0.03 to 0.10 of the preform diameter, to limit the effect of diameter variations on other waveguide fiber parameters, such as zero dispersion wavelength or  
25 attenuation. The length of the groove is less than about 4 mm. As will be discussed below, a smaller length dimension is preferred. The width of the groove is also of the order of a few millimeters to a few tenths of millimeters. The birefringence is not as sensitive to the width dimension as it is to the  
30 length and depth dimension.

The strategy is to introduce a perturbation sufficient to provide a birefringence index difference of about  $1 \times 10^{-6}$ , but small enough to leave the other operating characteristics, dispersion zero, cutoff wavelength, or attenuation substantially unchanged.

5 When the draw preform of **FIG. 1** is drawn to a uniform diameter, the surface perturbations will appear in the core diameter. The core will be made up of length sections having a particular polarization axis, i.e., a characteristic longer diameter, and adjacent sections will have corresponding polarization axes which are orthogonal. The grooves may be formed in the draw preform surface, as shown, or in the core preform surface. In this latter case the draw preform is made to have a uniform cylindrical shape. Drawing the draw preform to a uniform waveguide fiber diameter again produces perturbations in the core.

10 The grooves may be formed by any of several methods which may be readily implemented by one of ordinary skill in the art. Acceptable methods include, grinding, acid etching, or heating and shaping. It is usually preferred to include a polishing step after grinding or etching to provide a more uniform surface for the next process step.

15 When pairs of groove are formed, as shown in **FIG. 1a**, the drawing step will produce an elliptical core as shown in **FIG. 1b**. Cross sections **14** and **16** show the orthogonally oriented ellipticity of adjacent waveguide fiber sections. Other methods of introducing ellipticity into a waveguide fiber core include, using, in a deposition process, an integral bait rod having orthogonally alternating ellipticity. Methods which include variation of preform density or viscosity are also contemplated.

20 An orthogonally varying offset of the core center relative to the clad center, as illustrated in **FIG. 1c**, can be produced using the preform as shown in **FIG. 1a**, except that single grooves, instead of pairs of grooves, are formed in the core or draw preform. Adjacent grooves have respective mutually orthogonal mirror planes. As an alternative the orthogonally varying core/clad

offset may be produced by using an integral bait rod having an orthogonally alternating centerline offset.

In both cases wherein the perturbations are introduced in the bait rod, i.e. the case having orthogonally alternating ellipticity or that having orthogonally alternating core clad offset, the geometry introduced in the preform step will be preserved through the draw step. Thus **FIGS. 1b** and **1c** may represent either preforms or waveguides having the elliptical or offset perturbation.

Another embodiment is illustrated in **FIG. 2**. In this embodiment, the core perturbations are introduced by means of a spiral pattern **34** formed in the draw preform surface **32** or in the core preform surface (not shown). The limitations on the width and depth of the spiral pattern or groove are determined as discussed above in the case of spaced apart groove shaped perturbations. A lower limit on the pitch of the spiral groove is required to avoid inducing circular polarization in the launched light wave. Thus, a spiral pitch, **36**, greater than about 0.04 mm is required. As before, the benefit of the polarization mode mixing perturbations decreases as the longitudinal extent of the groove increases so that a practical maximum width of the spiral is about 4 mm.

The preform perturbation approach to polarization mode mixing was generally believed to be impractical to manufacture. In a 50 mm diameter draw preform, a segment of the preform having a length of about 6 microns is drawn into an equivalent fiber length of about 1 meter. Thus, if it is required that the polarization mode mixing perturbations have a length of the order of the beat length of the single mode waveguide, i.e., of the order of about 10 meters, the length dimension of the groove formed in the draw or core preform would be in the range of about 60 microns. To form such a narrow groove in a preform surface would add considerable time and thus cost to the waveguide manufacturing process. Further, the extra, exacting, process would be expected to adversely affect the percent yield of waveguide fiber.

However, modelling of the polarization mode mixing using both controlled coupling and controlled plus random coupling models, shows that PMD control benefit can be obtained even when the length of the induced perturbations are an order of magnitude greater than the waveguide fiber beat length. By means of an averaging method, wherein an ensemble of waveguides is considered, one can show that periodic induced perturbations having lengths of the order of a few hundred meters serve to reduce ensemble average PMD.

The idealized case of a single mode waveguide fiber having no random perturbations is shown in **FIG. 3**. The boxes **50** indicate the starting point for a particular orientation of polarization axes in the waveguide. The particular orientation of polarization axes associated with a box **50**, where box **50** is a polarization birefringence inducing perturbation, is under the waveguide fiber length after each box **50**. The orientation persists over the length of waveguide fiber between adjacent boxes, i.e, polarization axis points of change.

Because there are no random perturbations, the two polarization modes of launched light have identical travel time in the waveguide and there is no PMD.

**FIG. 4** is a schematic illustration of a more realistic case, where random coupling as well as controlled coupling, i.e., deliberately induced coupling, between polarization modes occurs at various points along the waveguide. The random mode coupling perturbations are shown as the smaller boxes **52**. Possible orientations of polarization axes of the random coupling is shown as axes **54**.

The model assumptions are:

- beat length  $L_b$  at 1550 nm is 10 meters;
- correlation length of random perturbations  $L_c$  is 200 meters;
- total random inherent birefringence  $B_r$  is 0.5 ps/km; and,
- induced perturbation length  $L_e = n \times L_c$ , where  $n$  is a number less than three.

The model calculation yields:

- ensemble average of PMD for randomly perturbed waveguides,  $P_r$ ;
- ensemble average of PMD for waveguides having random and controlled perturbation,  $P_c$ ;
- total birefringence for waveguides having random and controlled perturbations,  $B_c$ ; and,
- standard deviations  $s_r$  and  $s_c$ , of  $P_r$  and  $P_c$ , respectively.

**FIGS. 5a and 5b** clearly show the superior performance of the inventive waveguide fiber over that of standard single mode optical waveguide fiber.

With reference to the graph, **FIG. 5a**, the vertical axis is the normalized ratio  $P_c/P_r$ , and the horizontal axis is the ratio  $B_c/B_r$ . The group of curves **48** show improvement in ensemble average PMD in the range of about 70% to 80% when the ratio of total birefringence before and after introducing perturbations into the waveguides is less than about three and  $n$  is the range of about 0.25 to 0.50.

Even when the controlled perturbation length is twice the correlation length, i.e.,  $n = 2$ , ensemble average PMD improvement **46** is in the range of about 35% to 40% when the ratio of before and after total birefringence,  $B_c/B_r$ , is less than three.

PMD reduction benefit from introducing birefringence continues up to  $n = 3$ , as is shown in curve **44**.

Controlled perturbations in the core or draw preform which translate into fiber lengths of about 50 meters are within the scope of the methods described herein, which means that performance as illustrated in curves **48** is expected.

An important aspect of curves **48** is the low slope. A factor of three increase in random total birefringence produces only about 7% increase in ensemble average PMD. Thus, the inventive waveguide fiber design is robust, in that birefringence introduced in process steps downstream of the draw produces only small changes in PMD benefit. Note that the waveguide robustness increases as perturbation length becomes a smaller multiple of correlation length.

As PMD variation from fiber to fiber increases, the sensitivity of the fiber to changes in birefringence ratio,  $B_e/B_r$ , also increases, as shown in FIG. 5b. In this chart the horizontal axis is again the birefringence ratio,  $B_e/B_r$ . The vertical axis is the ratio of standard deviations,  $s_e/s_r$ . Curves 42 show that controlled perturbation variations depend weakly upon birefringence ratio when  $n$  is small. Also curve 40 shows that the standard deviation ratio changes only by about 10% when birefringence ratio changes by a factor of three. Curve 38 shows a steeper rise in standard deviation ratio, about 20%, but still shows the good tolerance of the inventive waveguide to downstream perturbations which change the ratio of total birefringence for the inventive waveguide to a standard waveguide.

Thus FIGS. 5a and 5b show that the inventive waveguide provides:

- large improvements in total average PMD;
- improvement even for controlled perturbation lengths as long as three times the correlation length; and,
- relative insensitivity to variation in birefringence which may be caused by steps downstream of the drawing step.

Other means for inducing the core or clad perturbations are available or contemplated such as preferential illumination of the core or draw preform using light of a wavelength which modifies the index profile of the waveguide. For example ultraviolet light could be used.

Also the perturbations may be introduced by means of the waveguide coating, buffering or other techniques employed in the cabling step (although there are obvious disadvantages, i.e., changes due to handling or to environment, of these alternatives). Further, one can envision introducing the perturbations in the installation step for certain applications, e.g., an application in which the cabled fiber is installed in a flexible conduit.

**What is claimed is:**

1. A single mode optical waveguide fiber, which transmits a light wave having two orthogonal polarization modes, comprising:

a core glass region having a refractive index profile;

5 a clad glass layer, surrounding said core glass region and having a refractive index profile, wherein at least a portion of said core glass refractive index profile is greater than at least a portion of said clad glass refractive index profile, said waveguide fiber having a longitudinal axis of symmetry; and,

10 a plurality of birefringence means disposed along the waveguide fiber length to couple power between the two orthogonal polarization modes of light transmitted through the waveguide fiber.

2. The single mode waveguide fiber of claim 1 wherein said birefringence means have at least one mirror plane of symmetry which  
15 includes the longitudinal axis of symmetry so that a first polarization axis is in the mirror plane and a second polarization axis is perpendicular to the mirror plane.

3. The single mode waveguide fiber of claim 2 wherein said  
20 birefringence means which neighbor each other along the waveguide fiber length have their respective mirror symmetries rotated by 90° relative to each other.

4. The single mode waveguide fiber of claim 3 wherein said  
25 birefringence means provides a refractive index difference of at least  $1 \times 10^{-6}$  between the two polarization axes.

5. The single mode waveguide of claim 4 wherein said birefringence  
30 means are disposed substantially periodically along the waveguide fiber length.

6. The single mode waveguide fiber of claim 4 wherein said birefringence means is variation in ellipticity of said core region.

5 7. The single mode waveguide fiber of claim 4 wherein said birefringence means is refractive index difference induced by stress in the waveguide fiber.

10 8. The single mode waveguide fiber of claim 4 wherein said birefringence means is variation in concentricity of said core region and said clad layer.

9. A single mode optical waveguide fiber, which transmits a light wave having two orthogonal polarization modes, comprising:

a core glass region having a refractive index profile;

15 a clad glass layer, surrounding said core glass region and having a refractive index profile, wherein at least a portion of said core glass refractive index profile is greater than at least a portion of said clad glass refractive index profile, said waveguide fiber having a longitudinal axis of symmetry; and,

20 a plurality of birefringence means, each having a length,  $L_e$ , disposed along the waveguide fiber length to couple power between the two orthogonal polarizations modes of light transmitted through the waveguide fiber;

said waveguide fiber having a beat length,  $L_b$ , and a correlation length,  $L_c$ ;

25 wherein  $L_e = n \times L_c$ , and  $n$  is a number no greater than about three.

10. The single mode waveguide fiber of claim 9 wherein the beat length is in the range of about 2 to 40 meters and the correlation length is in the range of 50 to 400 meters.

30 11. A method of making a single mode optical waveguide fiber having low polarization mode dispersion comprising the steps:

fabricating a glass waveguide fiber core preform, having a surface, a diameter, a length, and a longitudinal axis of symmetry;

forming a plurality of geometrical perturbations in said core preform, said geometrical perturbations disposed along the length of said core preform, each said perturbation having at least one plane of mirror symmetry which includes the longitudinal axis of symmetry of the preform, and neighboring perturbations having respective planes of mirror symmetry essentially perpendicular to each other;

applying a clad layer of glass about said core preform to yield a draw preform, said draw preform having a substantially uniform cylindrical shape so that after drawing into a waveguide the geometrical perturbations are impressed on the core; and,

drawing said draw preform into a single mode optical waveguide fiber having a substantially uniform cylindrical cross section.

12. The method of claim 11 wherein said geometrical perturbation is a pattern of grooves formed in the surface of said core preform, the grooves characterized by a depth into the preform, a width oriented substantially perpendicular to the longitudinal axis of symmetry, and a length substantially parallel to the longitudinal axis of symmetry.

13. The method of claim 11 wherein said pattern of grooves is formed using a serial technique selected from the group consisting of, etching and polishing, grinding and polishing, and heating and shaping.

14. The method of claim 11 wherein said pattern of grooves has a depth in the range of about 3% to 15% of the diameter of said preform and a length no greater than about 4 mm.

15. A method of making a single mode optical waveguide fiber having low polarization mode dispersion comprising the steps:

fabricating a glass waveguide fiber draw preform, having a surface, a diameter, a length, and a longitudinal axis of symmetry;

forming a plurality of geometrical perturbations in said draw preform, said geometrical perturbations disposed along the length of said core preform, each said perturbation having a plane of mirror symmetry which includes the longitudinal axis of symmetry of the preform, and neighboring perturbations having respective planes of mirror symmetry essentially perpendicular to each other; and,

drawing said draw preform into a single mode optical waveguide fiber having a substantially uniform cylindrical cross section.

16. A method of making a single mode optical waveguide fiber having low polarization mode dispersion comprising the steps:

fabricating a glass waveguide fiber core preform, having a surface, a diameter, a length, and a longitudinal axis of symmetry;

forming geometrical perturbations in said core preform, said geometrical perturbation made up of at least one spiral groove disposed along the length of said core preform, said spiral groove having a cross section dimension, a pitch, and a depth;

applying a clad layer of glass about said core preform to yield a draw preform, said draw preform having a substantially uniform cylindrical shape; and,

drawing said draw preform into a single mode optical waveguide fiber having a substantially uniform cylindrical cross section.

17. The method of claim 16 wherein said at least one spiral groove has a pitch greater than about 0.04 mm, a cross section dimension no greater than about 4 mm, and a depth in the range of about 3% to 15% of said preform diameter.

18. The method of claim 17 wherein said geometrical perturbations includes at least two spiral grooves and said at least two spiral grooves have respective opposing pitches so that said at least two spiral groove advance along the preform in opposite directions.

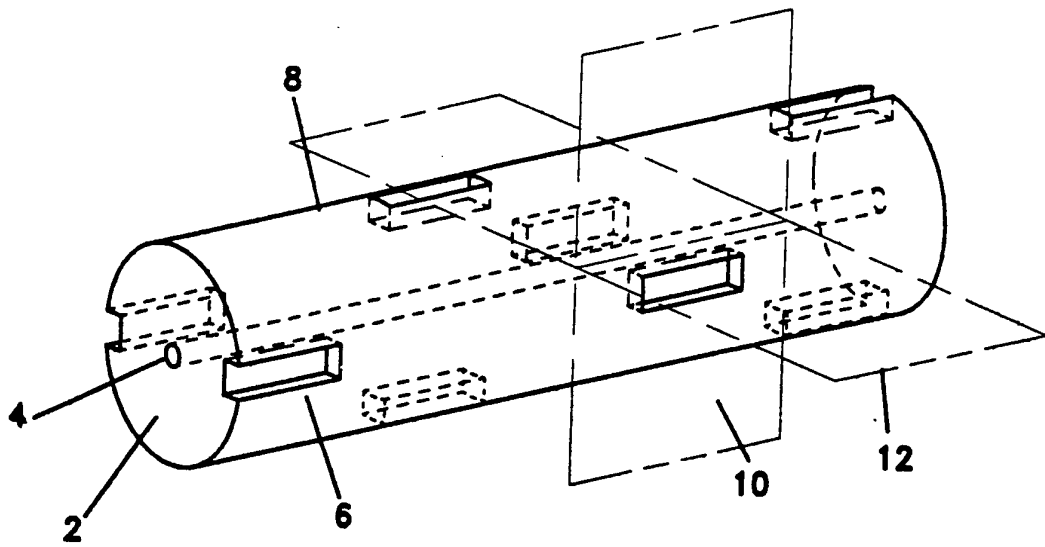


FIG. 1a

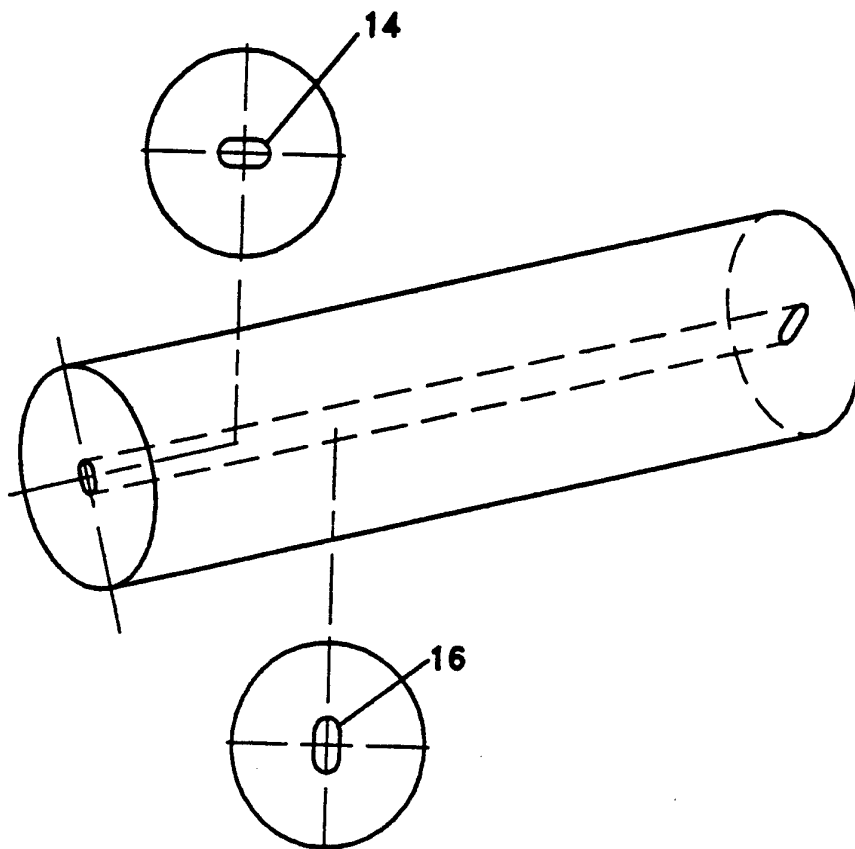


FIG. 1b

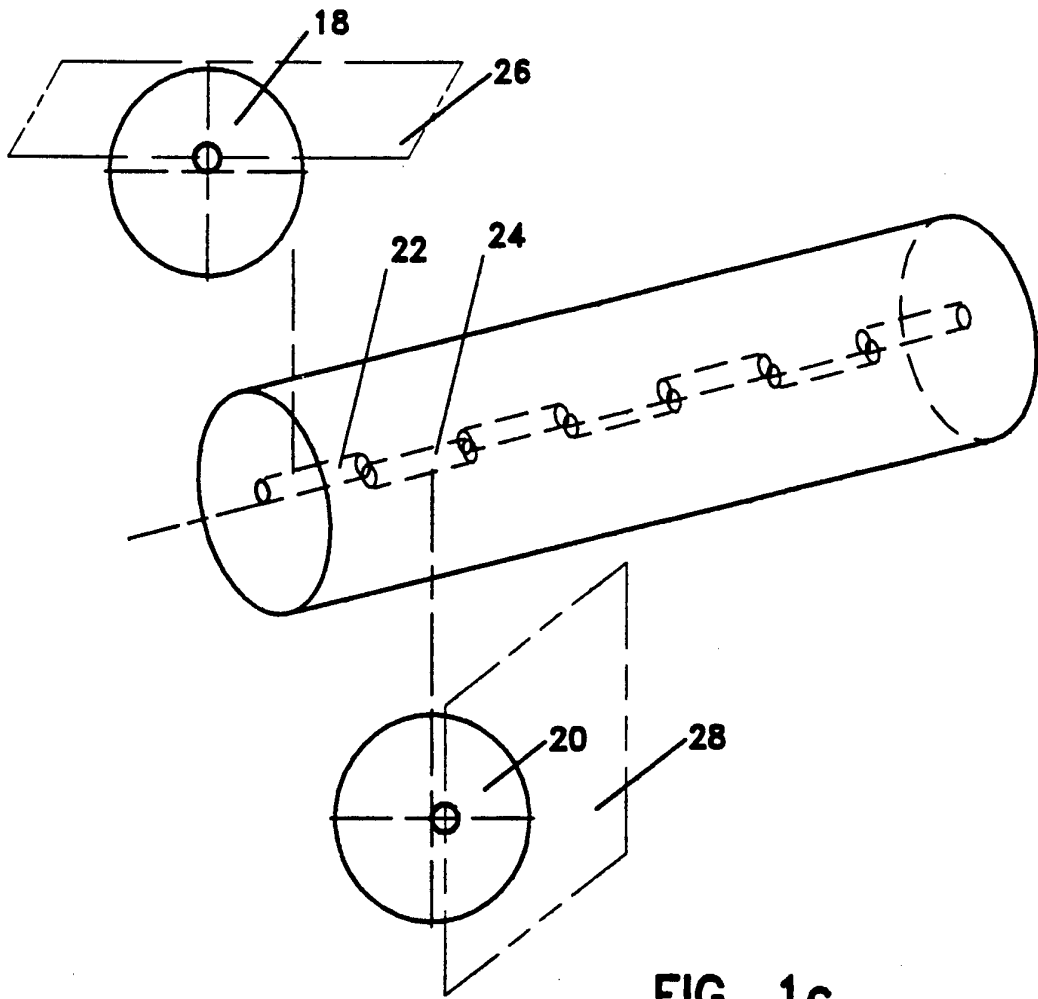


FIG. 1c

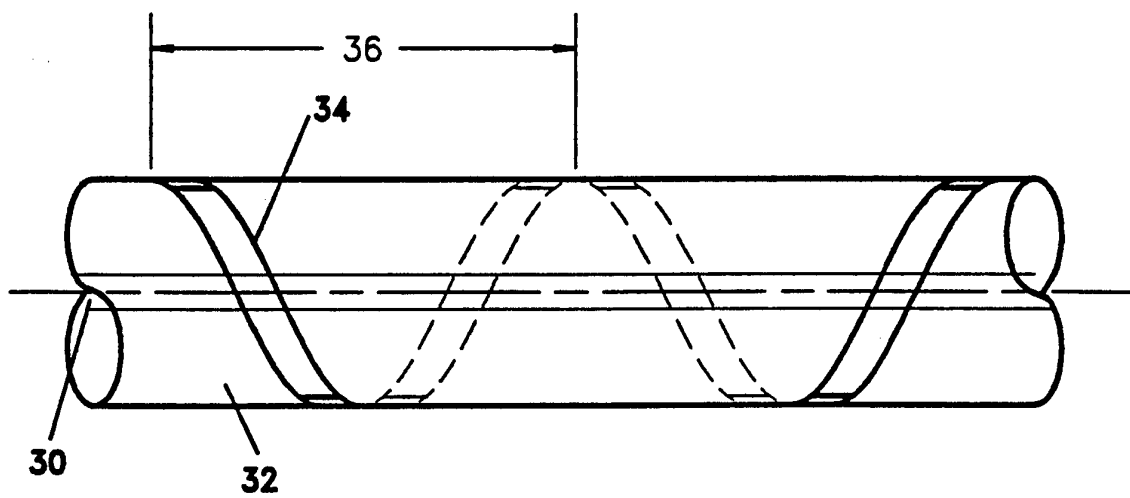


FIG. 2

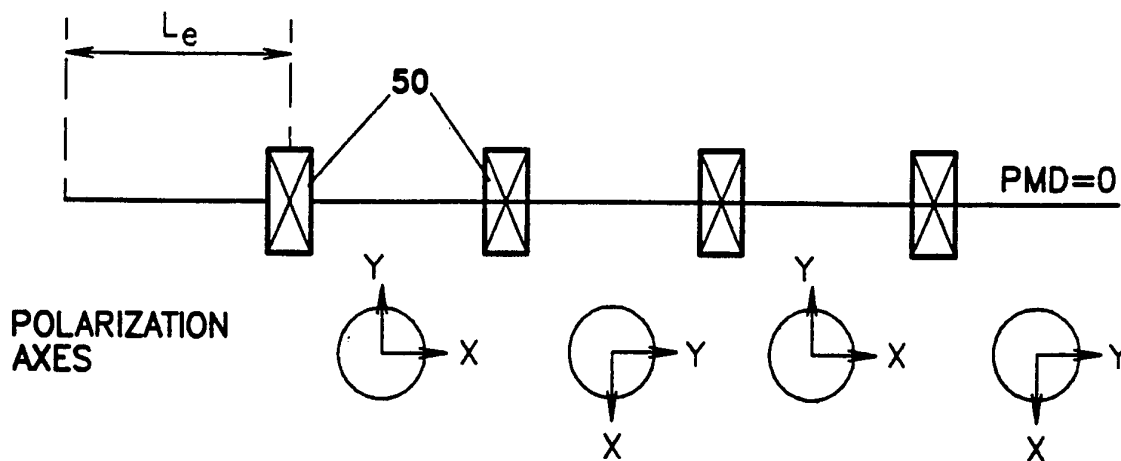


FIG. 3

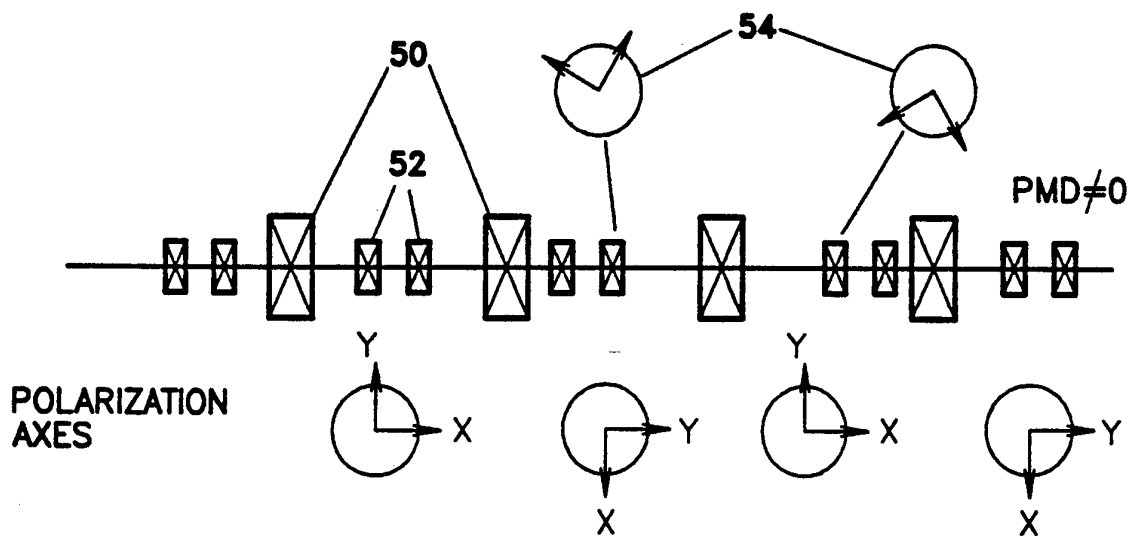


FIG. 4

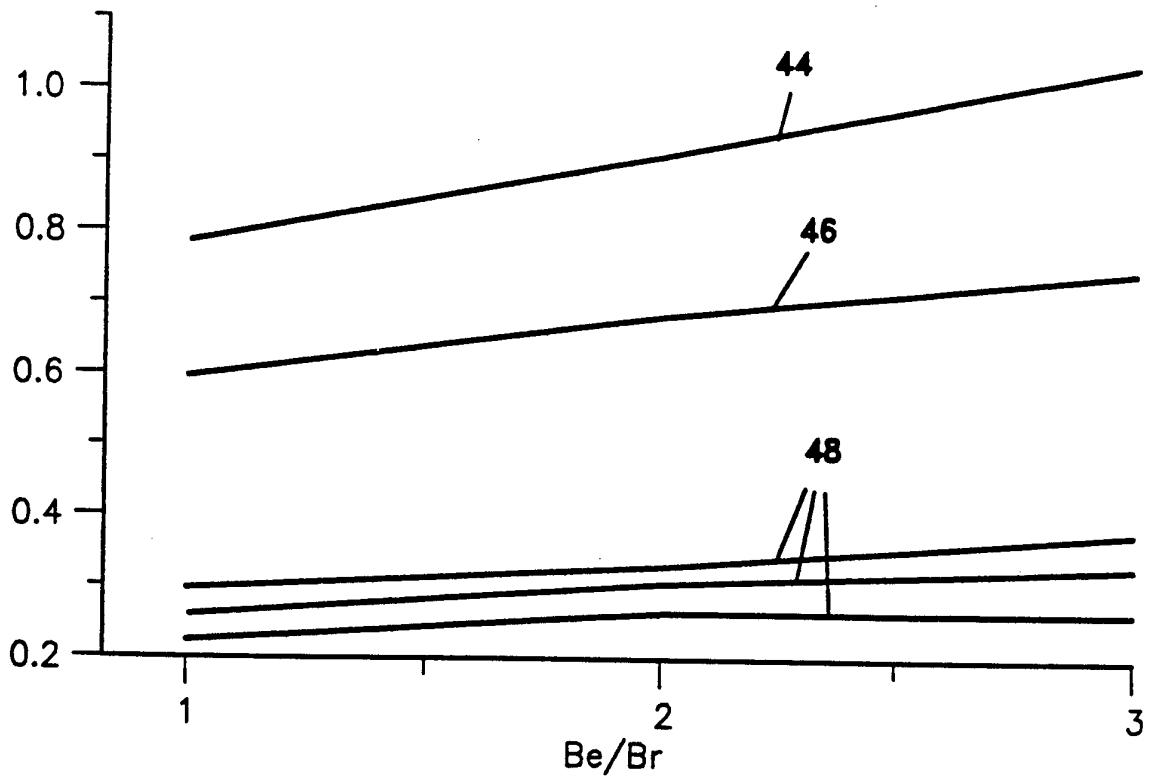


FIG. 5a

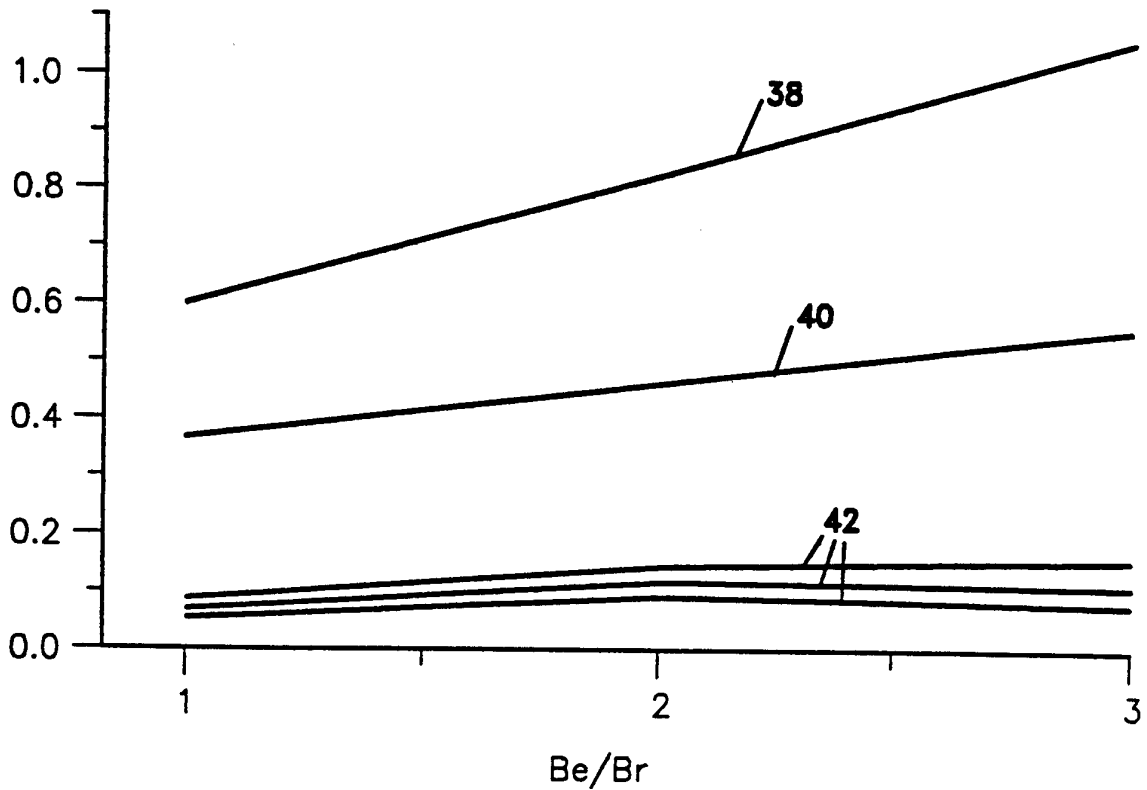


FIG. 5b

# INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US96/16360

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC(6) : GO2B 6/00; CO3B 37/023

US CL : 385/11, 28, 123, 126; 65/402, 403, 412, 415

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)

U.S. : 385/11, 28, 123, 126; 65/402, 403, 412, 415

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)

APS

search terms: fiber# or fibre#, birefringence, grooves or perturbations, preform

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US, 4,988,169 A (WALKER) 29 January 1991, see Abstract, col. 4, lines 24-65, Fig. 3.	1-3
Y	US, 4,480,897 A (OKAMOTO et al) 06 November 1984, see Abstract, Fig. 2	4-8
Y	US 4,684,215 A (SHAW et al) 04 August 1987, columns 5-6	9-10
Y	US 5,152,818 A (BERKEY et al) 06 October 1992, see Abstract, col. 4 lines 60-68, col. 5, lines 1-62.	11-17
A	RAMASWAMY et al, Single polarization optical fibers: Exposed cladding technique, Appl. Phys. Lett., 01 November 1978, pages 814-816, especially page 815.	1-10

Further documents are listed in the continuation of Box C.  See patent family annex.

<p>* Special categories of cited documents:</p> <p>*A* document defining the general state of the art which is not considered to be of particular relevance</p> <p>*E* earlier document published on or after the international filing date</p> <p>*L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>*O* document referring to an oral disclosure, use, exhibition or other means</p> <p>*P* document published prior to the international filing date but later than the priority date claimed</p>	<p>*T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>*X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone</p> <p>*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</p> <p>*G* document member of the same patent family</p>
--	---

Date of the actual completion of the international search  19 NOVEMBER 1996	Date of mailing of the international search report  <b>29 NOV 1996</b>
---	--

Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer <i>Hemang Sanghavi</i> HEMANG SANGHAVI Telephone No. (703) 305-3484
---	---

# INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US96/16360

## Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1.  Claims Nos.:  
because they relate to subject matter not required to be searched by this Authority, namely:
  
2.  Claims Nos.:  
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
  
3.  Claims Nos.:  
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

## Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Please See Extra Sheet.

1.  As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2.  As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3.  As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
  
4.  No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- The additional search fees were accompanied by the applicant's protest.  
 No protest accompanied the payment of additional search fees.

# INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US96/16360

## BOX II. OBSERVATIONS WHERE UNITY OF INVENTION WAS LACKING

This ISA found multiple inventions as follows:

This application contains the following inventions or groups of inventions which are not so linked as to form a single inventive concept under PCT Rule 13.1. In order for all inventions to be searched, the appropriate additional search fees must be paid.

Group I, claims 1-10, drawn to a single mode optical waveguide fiber, classified in Class 385, subclass 11.

Group II, claims 11-18, drawn to a method of making a single mode optical waveguide fiber, classified in Class 65, subclass 415.

The inventions listed as Groups I-II do not relate to a single inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons:

The claims in the different groups do not have in common the same or corresponding "special technical features". In particular the single mode optical waveguide fiber of Group I is completely different from the method of making the single mode fiber of Group II. Also, the single mode optical waveguide fiber of Group I can be made by another and materially different process such as a fusion process, vapor deposition process, coating process, or plasma utilized process, etc.