PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : G02B 6/22

A1

(11) International Publication Number: WO 00/04410

(43) International Publication Date: 27 January 2000 (27.01.00)

(21) International Application Number: PCT/US99/13993

(22) International Filing Date: 21 June 1999 (21.06.99)

(30) Priority Data:
60/092,835 14 July 1998 (14.07.98) US

(71) Applicant *(for all designated States except US)*: CORNING INCORPORATED [US/US]; 1 Riverfront Plaza, Corning, NY 14831 (US).

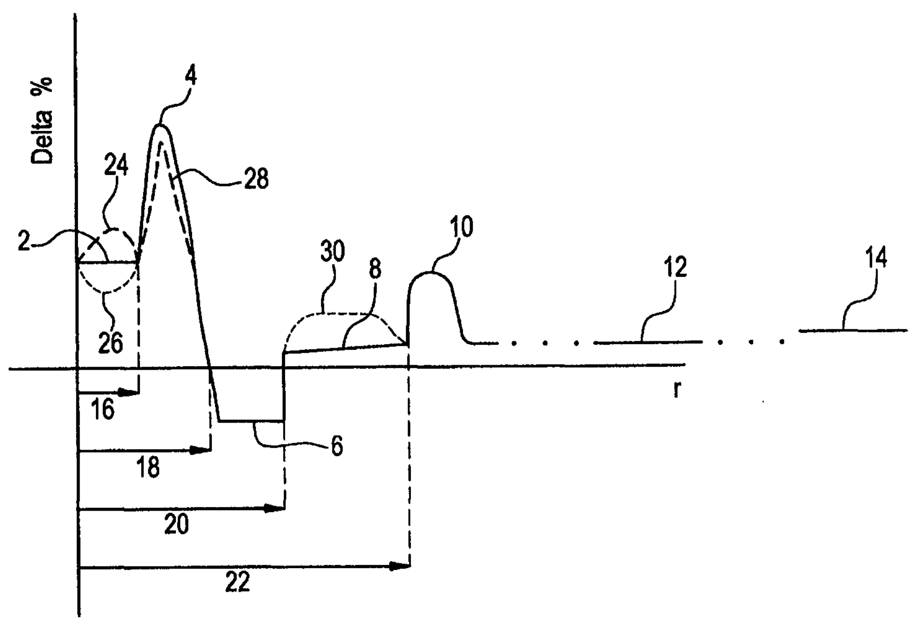
(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: CAIN, Michael, B. [US/US]; 7 Pondview, Painted Post, NY 14870 (US). CHU, Polly, W. [US/US]; 109 Weston Lane, Painted Post, NY 14870 (US). GROCHOCINSKI, James, M. [US/US]; 19 Bower Road, Newfield, NY 14867 (US). LI, Ming–Jun [CA/US]; 10 Ambrose Drive, Horseheads, NY 14845 (US).

(74) Agent: CHERVENAK, William, J.; Patent Department, SP TI 3–1, Corning Incorporated, Corning, NY 14831 (US).

(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, GH, GM, HR, HU, ID, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZW, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.

(54) Title: SINGLE MODE OPTICAL WAVEGUIDE



(57) Abstract

A single mode optical waveguide fiber having a refractive index profile comprising not less than four segments (16, 18, 20, 22) provides waveguide properties well suited to undersea or other long haul telecommunications systems. The novel refractive index profile is characterized by a core segment having a negative relative index, in which, the reference index is that of silica. Another feature of the invention is a cladding layer which contains refractive index increasing dopant at least in the cladding portion adjacent the outermost core segment.

SINGLE MODE OPTICAL WAVEGUIDE

Background of the Invention

The invention is directed to a single mode optical waveguide fiber designed for long repeater spacing, high data rate telecommunication systems. In particular, the single mode waveguide combines excellent bend resistance, low dispersion slope, and large effective area, A_{eff}.

A waveguide having large effective area reduces non-linear optical effects, including self phase modulation, four wave mixing, cross phase modulation, and non-linear scattering processes, all of which can cause degradation of signals in high power systems. In general, a mathematical description of these non-linear effects includes the ratio, P/A_{eff}, where P is optical power. For example, a non-linear optical effect usually follows an equation containing a term, $\exp [P \times L_{eff}/A_{eff}]$, where L_{eff} is effective length. Thus, an increase in A_{eff} produces a decrease in the non-linear contribution to the degradation of a light signal.

The requirement in the telecommunication industry for greater information capacity over long distances, without electronic signal regeneration, has led to a reevaluation of single mode fiber index profile design. The genera of these profile designs, which are called segmented core designs in this application, are disclosed in detail in U. S. patent 4,715,679, Bhagavatula.

The focus of this reevaluation has been to provide optical waveguides which:

- reduce non-linear effects such as those noted above;

- are optimized for the lower attenuation operating wavelength range around 1550 nm;

- are compatible with optical amplifiers; and,

- retain the desirable properties of optical waveguides such as high strength, fatigue resistance, and bend resistance.

The definition of high power and long distance is meaningful only in the context of a particular telecommunication system wherein a bit rate, a bit error rate, a multiplexing scheme, and perhaps optical amplifiers are specified. There are additional factors, known to those skilled in the art, which have impact upon the meaning of high power and long distance. However, for most purposes, high power is an optical power greater than about 10 mw. In some applications, signal power levels of 1 mW or less are still sensitive to non-linear effects, so that A_{eff} is still an important consideration in some lower power systems. A long distance is one in which the distance between electronic regenerators can be in excess of 100 km. The regenerators are to be distinguished from repeaters which make use of optical amplifiers. Repeater spacing, especially in high data density systems, can be less than half the regenerator spacing.

To provide a suitable waveguide for multiplexed transmission, the total dispersion should be low, but not zero, and have a low slope over the window of operating wavelength.

A typical application for such a waveguide fiber is undersea systems that, in order to be economically feasible, must carry high information densities over long distances without regenerators and over an extended window of wavelengths. The present invention describes a novel profile which is singularly suited to meeting the stringent requirements of this kind of use. The detailed requirements of the use system are set forth below.

Definitions

The following definitions are in accord with common usage in the art.

- The radii of the segments of the core are defined in terms of the index of refraction. A particular segment has a first and a last refractive index point.

The radius from the waveguide centerline to the location of this first refractive index point is the inner radius of the core region or segment. Likewise, the radius from the waveguide centerline to the location of the last refractive index point is the outer radius of the core segment.

The segment radius may be conveniently defined in a number of ways, as will be seen in the description of Figs. 1 & 2 below. In the case of Fig. 2, from which Tables 1 & 2 are derived, the radii of the index profile segments are defined as follows, where the reference is to a chart of Δ % vs. waveguide radius:

* the radius of the central core segment, r_1, is measured from the axial centerline of the waveguide to the intersection of the extrapolated central index profile with the x axis, i.e., the Δ % = 0 point;

* the outer radius, r_2, of the first annular segment is measured from the axial centerline of the waveguide to the intersection of the first annular segment profile with the line representing the Δ % of the second annular segment profile;

*the outer radius, r_3, of the second annular segment is measured from the axial centerline of the waveguide to the point at which the relative index is midway between the relative indexes of the second and third annular segments; and,

*the outer radius, r_4, of the third annular segment is measured from the axial centerline of the waveguide to the point at which the relative index is midway between the relative indexes of the third annular segment and the clad layer.

In the more general refractive index profile of Fig. 1, alternative definitions are used. No particular significance is attached to the definition of index profile geometry. Of course, in carrying out a model calculation the definitions must be used consistently as is done herein.

- The effective area is

$A_{eff} = 2\pi (\int E^2 r\, dr)^2/(\int E^4 r\, dr)$, where the integration limits are 0 to ∞, and E is the electric field associated with the propagated light. An effective diameter, D_{eff}, may be defined as,

$$A_{eff} = \pi(D_{eff}/2)^2.$$

- The relative index, Δ%, is defined by the equation,

$\Delta\% = 100 \times (n_1^2 - n_2^2)/2n_1^2$, where n_1 is the maximum refractive index of the index profile segment 1, and n_2 is a reference refractive index which is taken to be, in this application, the refractive index of silica.

- The term refractive index profile or simply index profile is the relation between Δ % or refractive index and radius over a selected portion of the core. The term alpha profile refers to a refractive index profile which follows the equation,

$n(r) = n_0 (1 - \Delta[r/a]^{\alpha})$ where r is core radius, Δ is defined above, a is the last point in the profile, r is chosen to be zero at the first point of the profile, and α is an exponent which defines the profile shape. Other index profiles include a step index, a trapezoidal index and a rounded step index, in which the rounding is typically due to dopant diffusion in regions of rapid refractive index change.

- Total dispersion is defined as the algebraic sum of waveguide dispersion and material dispersion. Total dispersion is sometimes called chromatic dispersion in the art. The units of total dispersion are ps/nm-km.

- The bend resistance of a waveguide fiber is expressed as induced attenuation under prescribed test conditions. Standard test conditions include 100 turns of waveguide fiber around a 75 mm diameter mandrel and 1 turn of waveguide fiber around a 32 mm diameter mandrel. In each test condition the bend induced attenuation, usually in units of dB/(unit length), is measured. In the present application, the bend test used is one turn of the waveguide fiber around a 20 mm diameter mandrel, a more demanding test which is required for the more severe operating environment of the present waveguide fiber.

Summary of the Invention

The novel single mode waveguide fiber of this application meets the high performance telecommunication system requirements set forth herein.

A first aspect of the invention is a single mode optical waveguide fiber having a segmented core surrounded by a cladding glass layer. The core has at least four segments, at least one of which has a negative relative index, -Δ %. The segmented core is defined in terms of the relative index percents, the refractive index profiles and the radii of the segments. The radii are measured from the centerline of the waveguide fiber and extend to a point of the segment defined in terms of the relative refractive indexes as stated in the "Definitions" section and as shown in Figs. 1 & 2. Throughout this application, the core extent, i.e., the outer radius of the core, is defined in terms of the segment geometry. The largest part of the light energy is carried in the core, but it is understood that the portion of the cladding layer adjacent the core does carry a significant amount of light. The portion of the cladding layer adjacent the core in the novel waveguide preferably contains a refractive index increasing dopant.

In one embodiment of the invention, the central segment is made to have a negative relative index, $-\Delta_1$ %.

In another embodiment of the invention, the core region has four segments, all having positive relative indexes except for the central segment which has a negative relative index. For this case, the Δ %'s follow the inequality, $\Delta_2 \% > \Delta_4 \% > \Delta_3 \% > \Delta_1 \%$, in which the numbering of segments is consecutive and begins with 1 at the central segment. In this embodiment the refractive index profiles of the first and third annular segments may be an α-profile, a step index, a trapezoid, or a rounded step or trapezoid. The second annular region may have the form of a step index profile, a term used to identify an index segment consisting of a constant horizontal portion. In addition, the portion of the cladding layer which contains an index increasing dopant, thus providing a cladding layer portion having a refractive index greater than that of silica, may have a step index profile.

Particular ranges of values for Δ_1 %, Δ_2 %, Δ_3 %, Δ_4 %, the relative indexes, and radii, r_1, r_2, r_3, r_4, of a core region having four segments, which provide the set of target properties of the novel waveguide are set forth in the tables below. The appropriate range of the relative index, Δ_5 %, of the preferred doped cladding layer portion is also given in the tables. A radius for the doped cladding layer portion is not required. In effect the doped portion of the clad layer extends to a radius whereat the light intensity carried in the waveguide is negligible. This radius value is typically determined by testing methods known in the art, such as measurement near field intensity.

This aspect of the invention, including its embodiments of profile segment shape and size, is capable of providing a single mode optical waveguide having an effective area $\geq$ 70 μm^2 and a total dispersion slope $\leq$ 0.08 ps/nm^2-km over a pre-selected range operating of operating wavelengths. As is noted above, the window about 1550 nm to 1560 nm is at present preferred because of the low attenuation in this range and its correspondence with the gain curve of erbium doped optical amplifiers. The minimum effective area can be increased and the total dispersion slope can be decreased substantially by tuning the radii, Δ %'s, and shape of one or more profile segment. The effect of such tuning is seen by comparing the data in Table 1 to that in Table 2 below. The ranges of Table 2 provide a waveguide fiber having $A_{eff} \geq 80$ μm^2 and a total dispersion slope $\leq$ 0.07 ps/nm^2-km.

A second aspect of the invention is a waveguide fiber having at least four segments. A portion of the cladding layer adjacent the core contains an index increasing dopant. The Δ 's, radii and profile shapes are chosen to provide the waveguide fiber properties listed in Table 3.

Brief Description of the Drawings

Fig. 1 is a chart of Δ % vs. radius illustrating a refractive index profile in accord with the invention and the definitions of Δ_i and r_i.

Fig. 2 is a chart showing an alternative embodiment of the refractive index profile.

Detailed Description of the Invention

The invention described herein is a family of single mode optical waveguide fibers defined by the parameters of a family of refractive index profiles. The refractive index profiles include at least four core segments, one of which has a negative relative index percent, $-\Delta_i$ %, and a cladding layer which preferably contains a refractive index increasing dopant at least in the cladding portion adjacent the core region.

The refractive index profile of the novel waveguide may be described in terms of the Δ %'s and radii shown in Fig. 1. Thus relative index values, indicated as 2, 4, 6, 8, 10 and 12, in Fig. 1 are the respective relative index values of the central segment, the first, second, third, and nth annular segment of the core. Relative index 14 is that of the cladding layer portion, adjacent the outermost segment of the core, which contains a refractive index increasing dopant. The respective radii, r_i, i=1, 2, 3,...,n are shown as 16, 18, 20, and 22. Radius 16 is measured from the waveguide fiber centerline to the point of intersection of the central segment with the first annular segment. Radius 18 is measured from the centerline to the point of zero relative index, i.e., the intersection of the second annular segment profile with the x-axis.

Dashed lines 24, 26, 28, and 30 show alternative shapes of the index profile of the respective segments. What these dashed lines represent are alternative members of the family of profiles which provide the pre-selected set of waveguide properties set forth in Table 3. These alternatives are regarded as perturbations of the base profile not large enough to appreciably change the energy distribution in the waveguide fiber of the light carried therethrough.

The embodiment of the novel profile illustrated in Fig. 2 is used to calculate the refractive index profile geometry set forth in Tables 1 and 2. A waveguide fiber having a profile as set forth in Tables 1 or 2 can have the waveguide fiber the corresponding performance requirements stated in Table 3. The definitions of r_1, r_2, r_3, and r_4 illustrated in Fig. 2 follow exactly those given in the "Definitions" section above. The relative index percents, Δ_1, Δ_2, Δ_3, Δ_4, and Δ_5 are shown in Fig. 2 as 32, 34, 36, 38, and 40, respectively. It will be understood that small variations of this profile will not appreciably change the waveguide properties. For example, the horizontal profiles of segments 32, 36, or 40 could be slightly concave or convex, or contain a small dip or rise in relative index without having an effect on the calculated waveguide properties.

However, a comparison of the two tables shows that sub-micron changes in certain of the radii, for example the lower limit of radius r_1, can markedly affect the total dispersion slope. Other small changes in certain of the profile variables can impact the waveguide performance.

Table 1

Slope≤ 0.08 A_{eff}>70	Δ_1 %	Δ_2 %	Δ_3 %	Δ_4 %	Δ_5 %	r_1 µm	r_2 µm	r_3 µm	R_4 µm
Low Limit	-0.32	1.24	-0.02	0.40	0.09	1.69	3.72	8.32	9.30
High Limit	-0.24	1.39	0.03	0.52	0.11	1.82	3.87	8.63	9.65

In Table 1, the refractive index profile segments are constrained by the requirement that the total dispersion slope be less than or equal to 0.08 ps/nm^2-km and the effective area be greater than 70 µm^2, over a wavelength range centered about 1550 nm. The effective wavelength range is set by the limit on the total dispersion slope and the total dispersion value at 1555 nm, which in the embodiments of Tables 1 and 2 is taken to be less than about -3 ps/nm-km.

Table 2

Slope≤ 0.07 A_{eff}≥80	Δ_1 %	Δ_2 %	Δ_3 %	Δ_4 %	Δ_5 %	r_1 µm	r_2 µm	r_3 µm	r_4 µm
Low Limit	-0.32	1.26	-0.02	0.41	0.09	1.76	3.72	8.32	9.30
High Limit	-0.25	1.33	0.01	0.52	0.11	1.82	3.82	8.60	9.65

To improve the total dispersion slope to a value less than or equal to 0.07 ps/nm^2-km and the effective area to a value greater than or equal to 80 µm^2, as in Table 2, a comparison of tabulated values show that the overall core radius r_4, and the cladding layer relative index may be held constant, while incremental changes are made in the other profile variables. The values of Δ_2 %, Δ_3 %, and r_1 would seem to be more important than the other variables in reaching target A_{eff} and total dispersion slope. However, the variables interact to provide a profile which satisfies all waveguide performance requirements set forth in Table 3. The overall profile geometry must be considered in each case.

Table 3

	A_{eff} (μm^2)	Disp. Slope (ps/nm^2-km)	Att.1550 (dB/km)	Disp.1560 (ps/nm-km)	λ_c (nm)	Macro-bend (dB/m)
Table 1 fiber	≥ 80	≤ 0.07	≤ 0.25	-2.0	<1500	≤ 10
Table 2 fiber	≥ 70	≤ 0.08	≤ 0.25	-2.0	<1500	≤ 10

For example the low limit of Δ_1, Δ_2, and Δ_3 in Table 1 are set by the requirement that the total dispersion be less negative than -3 ps/nm-km in the operating window about 1555 nm. The edges of the profile family envelope are found by changing a variable or set of variables until the model predicts a performance parameter that is out of specification.

Although particular embodiments of the invention have been herein disclosed and described, the invention is nonetheless limited only by the following claims.

We claim:

1. A single mode optical waveguide fiber comprising:

a core region surrounded by and in contact with a cladding layer,

the core region comprises at least a central segment and a first, second, and third annular segment, each of the segments having a refractive index profile, a relative index percent, Δ_i %, for which the reference refractive index is that of silica, and an associated radius, r_i,

at least one of the at least central, first, second, or third segments having a negative relative index, and wherein at least a portion of the cladding layer, adjacent the outermost annular core segment, has a positive relative index.

2. The single mode waveguide of claim 1 in which the segment having a negative relative index percent, $-\Delta_1$ %, is the central segment.

3. The single mode waveguide of claim 2, having four core segments, in which, the magnitudes of the relative indexes of the respective segments, the segments being numbered consecutively beginning with 1 at the central segment, follow the relationship,

$$\Delta_2 \% > \Delta_4 \% > \Delta_3 \% > \Delta_1 \%.$$

4. The single mode waveguide of claim 2, in which, the first and third annular segments have a refractive index profile selected from the group consisting of an α-profile, a step index profile, a rounded step index profile, and a trapezoidal profile.

5. The single mode waveguide of claim 4, in which, the second annular region is a step index profile.

6. The single mode waveguide of claim 5, in which, the index profile of the cladding layer portion, surrounding and in contact with the third annular region, is a step index profile.

7. The single mode waveguide of claim 1, in which, the core has four segments, the segments being numbered consecutively beginning with 1 at the central segment, and the relative indexes of the segments have respective values, Δ_1 % in the range of about -0.32 to -0.24, Δ_2 % in the range of about 1.24 to 1.39, Δ_3 % in the range of about -0.02 to 0.03, and Δ_4 % in the range of about 0.40 to 0.52 and the radii of the segments have respective values, r_1 in the range of about 1.69 µm to 1.82 µm, r_2 in the range of about 3.72 µm to 3.87 µm, r_3 in the range of about 8.32 µm to 8.63 µm, and r_4 in the range of about 9.3 µm to 9.65 µm.

8. The single mode waveguide of any one of claims 1-7, in which, the cladding layer portion has a relative index, Δ_5 %, in the range of about 0.09 to 0.11.

9. The single mode waveguide of claim 8, in which, the core and clad relative indexes and the core radii are chosen to provide a waveguide fiber having an effective area greater than or equal to 70 μm^2 and a dispersion slope less than or equal to 0.08 ps/nm^2-km.

10. The single mode waveguide of claim 1, in which, the core and clad relative indexes and the core radii are chosen to provide a waveguide fiber having an effective area greater than or equal to 70 μm^2 and a dispersion slope less than or equal to 0.08 ps/nm^2-km.

11. A single mode optical waveguide fiber comprising:

a core region surrounded by and in contact with a cladding layer, in which,

the core region comprises a central segment and a first, second, and third annular segment, each of the segments having a refractive index profile, a relative index percent, Δ_i %, for which the reference refractive index is that of silica, and an associated radius, r_i, where i is an integer greater than or equal to

1, and a cladding layer portion adjacent the outermost core segment containing a refractive index increasing dopant, in which,

the refractive index profile, Δ %, and r of each segment is selected to provide a waveguide having:

- an effective area greater than or equal to 70 μm^2;
- a total dispersion slope less than or equal to 0.08 ps/nm^2-km;
- attenuation at 1550 nm less than or equal to 0.25 dB/km;
- cutoff wavelength measured in the cable less than 1500 nm;
- dispersion at 1560 nm of about -2 ps/nm-km; and,
- macrobend loss for 1 turn about a 20 mm mandrel less than or equal to 10 dB/m.

12. The single mode waveguide of claim 11, having four core segments, in which, the magnitudes of the relative indexes of the respective segments, the segments being numbered consecutively beginning with 1 at the central segment, follow the relationship,

$$\Delta_2 \% > \Delta_4 \% > \Delta_3 \% > \Delta_1 \%.$$

13. The single mode waveguide of claim 12, in which, the core has four segments, the segments being numbered consecutively beginning with 1 at the central segment, and the relative indexes of the segments have respective values, Δ_1 % in the range of about -0.32 to -0.24, Δ_2 % in the range of about 1.24 to 1.39, Δ_3 % in the range of about -0.02 to 0.03, and Δ_4 % in the range of about 0.40 to 0.52 and the radii of the segments have respective values, r_1 in the range of about 1.69 μm to 1.82 μm, r_2 in the range of about 3.72 μm to 3.87 μm, r_3 in the range of about 8.32 μm to 8.63 μm, and r_4 in the range of about 9.3 μm to 9.65 μm.

14. The single mode waveguide of claim 11, in which, the core has four segments, the segments being numbered consecutively beginning with 1 at the

central segment, and the relative indexes of the segments have respective values, Δ_1 % in the range of about -0.32 to -0.24, Δ_2 % in the range of about 1.24 to 1.39, Δ_3 % in the range of about -0.02 to 0.03, and Δ_4 % in the range of about 0.40 to 0.52 and the radii of the segments have respective values, r_1 in the range of about 1.69 μm to 1.82 μm, r_2 in the range of about 3.72 μm to 3.87 μm, r_3 in the range of about 8.32 μm to 8.63 μm, and r_4 in the range of about 9.3 μm to 9.65 μm.

FIG. 1

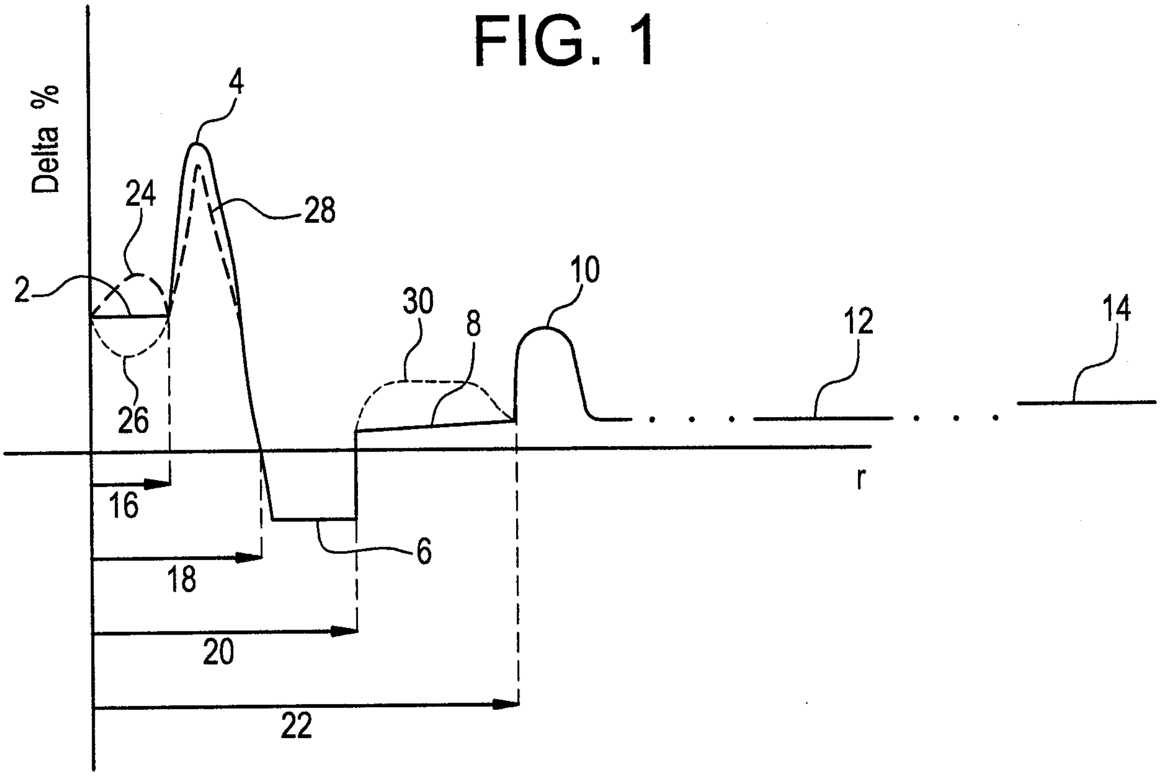
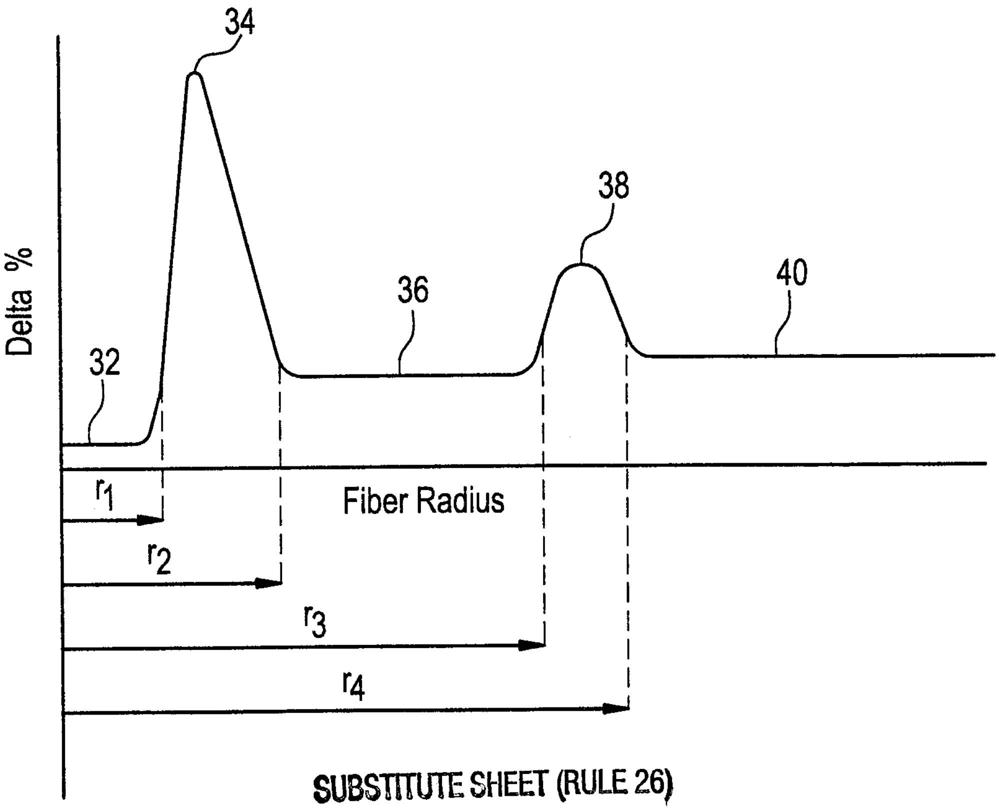

Delta %
4
24
28
2
30
8
10
12
14
26
r
16
6
18
20
22

FIG. 2


34
38
Delta %
36
40
32
r_1
Fiber Radius
r_2
r_3
r_4

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/13993

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G02B 6/22
US CL : 385/123, 124, 126, 127
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. : 385/123, 124, 126, 127

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

U.S. PTO APS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,675,690 A (NOUCHI ET AL) 7 October 1997 (07/10/97), see entire document.	1-14
X	US 5,684,909 A (LIU) 04 November 1997 (04/11/97), see entire document, especially Figuure 1a and column 7 lines 13-39.	1, 2, 4, 5, 6, 10, 11

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

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"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)

"O" document referring to an oral disclosure, use, exhibition or other means

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

"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

"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

"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	Date of mailing of the international search report
24 AUGUST 1999	21 OCT 1999

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	JULIANA K. KANG
Facsimile No. (703) 305-3230	Telephone No. (703) 305-6259

Form PCT/ISA/210 (second sheet)(July 1992)★