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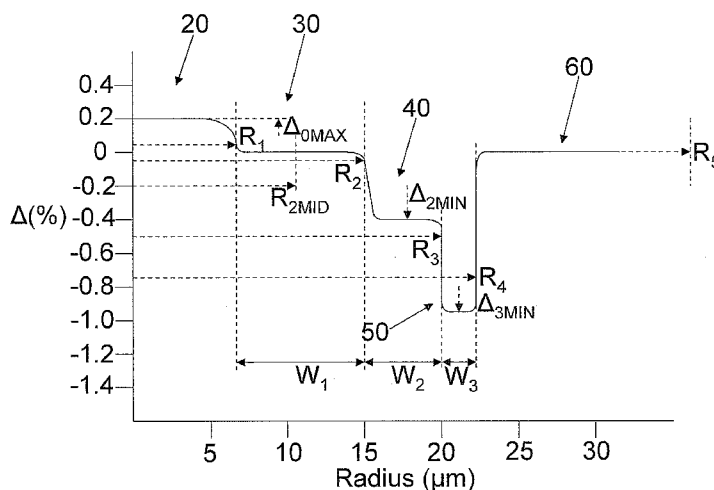
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(54) Title: LARGE EFFECTIVE AREA LOW ATTENUATION OPTICAL FIBER

FIG. 2



(57) Abstract: Optical waveguide fiber that has large effective area and low loss characteristics, such as low attenuation and low bend loss. The optical waveguide fiber includes a dual trench design wherein an annular region closer to the core is preferably doped with at least one dopant such as fluorine, which annular region is surrounded by another annular region that preferably includes closed, randomly dispersed voids.

LARGE EFFECTIVE AREA LOW ATTENUATION OPTICAL FIBER

BACKGROUND OF THE INVENTION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of, and priority to U.S. Provisional Patent Application No. 61/155741 filed on February 26, 2009 entitled, "Large Effective Area Low Attenuation Optical Fiber", the content of which is relied upon and incorporated herein by reference in its entirety.

Field of the Invention

[0002] The present invention relates generally to optical fiber, and particularly to optical fibers that have large effective area and low bend loss at 1550 nm.

Technical Background

[0003] Optical amplifier technology and wavelength division multiplexing techniques are typically required in telecommunication systems that provide high power transmissions for long distances. The definition of high power and long distances 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 impacted upon the definition of high power and long distance. However, for most purposes, high power is an optical power greater than about 10 mW. In some applications, single power levels of 1 mW or less are still sensitive to non-linear effects, so that the effective area is still an important consideration in such lower power systems.

[0004] Generally, an optical waveguide fiber having a large effective area (A_{eff}) 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 powered systems.

[0005] On the other hand, an increase in effective area of an optical waveguide fiber typically results in an increase in macrobending induced losses which attenuate signal transmission through a fiber. The macrobending losses become increasingly significant over long (e.g., 100 km, or more) distances (or spacing between regenerators, amplifiers,

transmitters and/or receivers). Unfortunately, the larger the effective area of a conventional optical fiber is, the higher the macrobend induced losses because the core does not provide sufficient confinement of the optical power.

SUMMARY OF THE INVENTION

[0006] One aspect of the invention is an optical fiber that includes a glass core extending from a centerline to a radius R_1 , wherein R_1 is greater than about 5 μm , and a glass cladding surrounding and in contact with the core. The cladding includes a first annular region extending from the radius R_1 to a radius R_2 , the first annular region having a radial width $W_1 = R_2 - R_1$. The cladding also includes a second annular region extending from the radius R_2 to a radius R_3 , the second annular region having a radial width $W_2 = R_3 - R_2$. In addition, the cladding includes a third annular region extending from the radius R_3 to a radius R_4 , the third annular region having a radial width $W_3 = R_4 - R_3$. The cladding further includes a fourth annular region extending from the radius R_4 to an outermost glass radius R_5 . The core has a maximum relative refractive index, $\Delta_{0\text{MAX}}$. The second annular region has a minimum relative refractive index, $\Delta_{2\text{MIN}}$. The third annular region has a minimum relative refractive index, $\Delta_{3\text{MIN}}$. In addition, $\Delta_{0\text{MAX}} > 0 > \Delta_{2\text{MIN}} > \Delta_{3\text{MIN}}$. Moreover, the core and the cladding provide a fiber with cable cutoff less than 1500 nm and an effective area at 1550 nm of greater than 130 μm^2 .

[0007] In another aspect, the present invention includes an optical fiber that includes a glass core extending from a centerline to a radius R_1 , wherein R_1 is greater than about 5 μm , and a glass cladding surrounding and in contact with the core. The cladding includes a first annular region extending from the radius R_1 to a radius R_2 , the first annular region having a radial width $W_1 = R_2 - R_1$. The cladding also includes a second annular region extending from the radius R_2 to a radius R_3 , the second annular region having a radial width $W_2 = R_3 - R_2$. In addition, the cladding includes a third annular region extending from the radius R_3 to an outermost glass radius R_4 . The core has a maximum relative refractive index, $\Delta_{0\text{MAX}}$. The first annular region has a minimum relative refractive index, $\Delta_{1\text{MIN}}$. The second annular region has a minimum relative refractive index, $\Delta_{2\text{MIN}}$. In addition, $\Delta_{0\text{MAX}} > 0 > \Delta_{1\text{MIN}} > \Delta_{2\text{MIN}}$. Moreover, the core and the cladding provide a fiber with cable cutoff less than 1500 nm, an attenuation at 1550 nm of less than 0.20 dB/km, and an effective area at 1550 nm of greater than 130 μm^2 .

[0008] In yet another aspect, the present invention includes an optical fiber that includes a glass core extending from a centerline to a radius R_1 , wherein R_1 is greater than about 5 μm , and a glass cladding surrounding and in contact with the core. The core and the cladding provide a fiber with cable cutoff less than 1500 nm, an attenuation at 1550 nm of less than 0.20 dB/km, and an effective area at 1550 nm of greater than 150 μm^2 .

[0009] Additional features and advantages of the invention will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the invention as described herein, including the detailed description which follows, the claims, as well as the appended drawings.

[0010] It is to be understood that both the foregoing general description and the following detailed description present embodiments of the invention, and are intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed. The accompanying drawings are included to provide a further understanding of the invention, and are incorporated into and constitute a part of this specification. The drawings illustrate various embodiments of the invention, and together with the description serve to explain the principles and operations of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. 1 is a schematic cross-sectional view of an embodiment of an optical waveguide fiber as disclosed herein;

[0012] FIG. 2 shows a relative refractive index profile of an embodiment of an optical waveguide fiber as disclosed herein;

[0013] FIG. 3 is a schematic cross-sectional view of another embodiment of an optical waveguide fiber as disclosed herein; and

[0014] FIG. 4 shows a relative refractive index profile of another embodiment of an optical waveguide fiber as disclosed herein.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0015] Reference will now be made in detail to the present preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings.

[0016] The “refractive index profile” is the relationship between refractive index or relative refractive index and waveguide fiber radius.

[0017] The “relative refractive index percent” is defined as $\Delta\% = 100 \times (n_i^2 - n_c^2) / 2n_i^2$, where n_i is the maximum refractive index in region i , unless otherwise specified, and n_c is the average refractive index of the outermost region of the cladding. As used herein, the relative refractive index is represented by Δ and its values are given in units of “%”, unless otherwise specified.

[0018] “Chromatic dispersion”, herein referred to as “dispersion” unless otherwise noted, of a waveguide fiber is the sum of the material dispersion, the waveguide dispersion, and the inter-modal dispersion. In the case of single mode waveguide fibers the inter-modal dispersion is zero. Dispersion slope is the rate of change of dispersion with respect to wavelength.

[0019] “Effective area” is defined as:

$$A_{\text{eff}} = 2\pi (\int f^2 r \, dr)^2 / (\int f^4 r \, dr),$$

where the integration limits are 0 to ∞ , and f is the transverse component of the electric field associated with light propagated in the waveguide. As used herein, “effective area” or “ A_{eff} ” refers to optical effective area at a wavelength of 1550 nm unless otherwise noted.

[0020] The term “ α -profile” or “alpha profile” refers to a relative refractive index profile, expressed in terms of $\Delta(r)$ which is in units of “%”, where r is radius, which follows the equation,

$$\Delta(r) = \Delta(r_0)(1 - [r - r_0] / (r_1 - r_0))^\alpha,$$

where r_0 is the point at which $\Delta(r)$ is maximum, r_1 is the point at which $\Delta(r)\%$ is zero, and r is in the range $r_i \leq r \leq r_f$, where Δ is defined above, r_i is the initial point of the α -profile, r_f is the final point of the α -profile, and α is an exponent which is a real number.

[0021] The mode field diameter (MFD) is measured using the Peterman II method wherein, $2w = \text{MFD}$, and $w^2 = (2 \int f^2 r \, dr) / (\int [df/dr]^2 r \, dr)$, the integral limits being 0 to ∞ .

[0022] The bend resistance of a waveguide fiber can be gauged by induced attenuation under prescribed test conditions, for example by deploying or wrapping the fiber around a mandrel of a prescribed diameter.

[0023] The cabled cutoff wavelength, or “cabled cutoff” is approximated by the test described in the EIA-445 Fiber Optic Test Procedures, which are part of the EIA-TIA Fiber Optics Standards, that is, the Electronics Industry Alliance - Telecommunications Industry Association Fiber Optics Standards, more commonly known as FOTP’s. Cabled cutoff measurement is described in EIA-455-170 Cable Cutoff Wavelength of Single-mode Fiber by

Transmitted Power, or “FOTP-170”. By cable cutoff as used herein, we mean the value obtained using the approximated test.

[0024] “Kappa” or κ is total dispersion divided by total dispersion slope, both at 1550 nm.

[0025] Unless otherwise noted herein, optical properties (such as dispersion, dispersion slope, etc.) are reported for the LP01 mode. Unless otherwise noted herein, a wavelength of 1550 nm is the reference wavelength.

[0026] Referring to FIGS. 1-2, in a set of preferred embodiments, optical fiber **10** disclosed herein comprises a core **20** and a cladding layer (or cladding) **200** surrounding and directly adjacent to the core. The core **20** has a refractive index profile $\Delta_{CORE}(r)$. The cladding **200** has a refractive index profile $\Delta_{CLAD}(r)$.

[0027] In some embodiments, the core comprises silica doped with germanium, i.e., germania doped silica. Dopants other than germanium, singly or in combination, may be employed within the core, and particularly at or near the centerline of the optical fiber disclosed herein to obtain the desired refractive index and density. In some embodiments, the optical fiber **10** contains no index-decreasing dopants in the core **20**.

[0028] Referring to FIGS. 1-2, optical waveguide fibers are disclosed herein that include a core **20** extending radially outwardly from the centerline to a radius R_1 and having a relative refractive index profile $\Delta_0(r)$ in %, with a maximum relative refractive index percent, Δ_{0MAX} , and a cladding **200** surrounding and directly adjacent, i.e., in direct contact with, the core **20**. Cladding **200** includes a first annular region **30** extending from the radius R_1 to a radius R_2 , the first annular region having a radial width $W_1 = R_2 - R_1$, a midpoint $R_{2MID} = (R_2 + R_1)/2$, and a relative refractive index profile $\Delta_1(r)$ in %, with a midpoint relative refractive index percent, Δ_{1MID} , at R_{2MID} , maximum relative refractive index percent, Δ_{1MAX} , and a minimum relative refractive index percent Δ_{1MIN} . Cladding **200** also includes a second annular region **40** extending from the radius R_2 to a radius R_3 , the second annular region having a radial width $W_2 = R_3 - R_2$ and a relative refractive index profile $\Delta_2(r)$ in %, with a minimum relative refractive index percent Δ_{2MIN} . Cladding **200** additionally includes a third annular region **50** extending from the radius R_3 to a radius R_4 , the third annular region having a radial width $W_3 = R_4 - R_3$, and a relative refractive index profile $\Delta_3(r)$ in %, with a minimum relative refractive index percent Δ_{3MIN} . Cladding **200** further includes a fourth annular region **60** extending from the radius R_4 to the outermost glass radius R_5 , having a relative refractive index profile $\Delta_4(r)$ in %. Fourth annular region **60** can be optionally surrounded by one or more polymer coatings **65**. R_1 is defined to occur at the radius where $\Delta_0(r)$ first reaches 0.03% going

radially outward from the centerline. That is, core **20** ends and the first annular region **30** begins where the relative refractive index first reaches 0.03% (going radially outward) at a radius R_1 . R_2 is defined to occur at the radius where $\Delta_1(r)$ first reaches -0.05% going radially outward from R_1 . That is, first annular region **30** ends and second annular region **40** begins where the relative refractive index first reaches -0.05% (going radially outward) at a radius R_2 . R_3 is defined to occur at the radius where $\Delta_2(r)$ first reaches -0.5% going radially outward from R_2 . That is, second annular region **40** ends and third annular region **50** begins where the relative refractive index first reaches -0.5% (going radially outward) at a radius R_3 . R_4 is defined to occur at the radius where $\Delta_4(r)$ first reaches -0.05% going radially inward from R_5 . That is, fourth annular region **60** ends and third annular region **50** begins where the relative refractive index first reaches -0.05% (going radially inward) at a radius R_4 . R_1 is greater than about 5 μm . Also, $\Delta_{0\text{MAX}} > 0 > \Delta_{2\text{MIN}} > \Delta_{3\text{MIN}}$. In addition, $\Delta_{0\text{MAX}} > \Delta_{1\text{MAX}} > \Delta_{1\text{MID}} > \Delta_{1\text{MIN}} > \Delta_{2\text{MIN}} > \Delta_{3\text{MIN}}$.

[0029] The second annular region **40** has a profile volume, V_2 , defined herein as:

$$2 \int_{R_2}^{R_3} \Delta(r) r \, dr;$$

[0030] In preferred embodiments, $\Delta_{0\text{MAX}} < 0.3\%$, such as $0.3\% > \Delta_{0\text{MAX}} > 0.1\%$ and $0.25\% > \Delta_{0\text{MAX}} > 0.1\%$, $\Delta_{2\text{MIN}} < -0.1\%$, such as $-0.1\% > \Delta_{2\text{MIN}} > -0.5\%$, and $\Delta_{3\text{MIN}} < -0.5\%$, such as $-0.7\% > \Delta_{3\text{MIN}} > -3\%$ and $-0.7\% > \Delta_{3\text{MIN}} > -2\%$. Preferably, $\Delta_{1\text{MAX}}$ is not greater than 0.03%, $\Delta_{1\text{MIN}}$ is not less than -0.03%, and $0.025\% > \Delta_{1\text{MID}} > -0.025\%$. Preferably, $R_1 > 6 \mu\text{m}$, such as $6 \mu\text{m} < R_1 < 9 \mu\text{m}$, $R_2 > 10 \mu\text{m}$, such as $10 \mu\text{m} < R_2 < 15 \mu\text{m}$, $R_3 > 16 \mu\text{m}$, such as $16 \mu\text{m} < R_3 < 24 \mu\text{m}$, and $R_4 > 20 \mu\text{m}$, such as $20 \mu\text{m} < R_4 < 30 \mu\text{m}$. Preferably, $W_1 > 2 \mu\text{m}$, such as $2 \mu\text{m} < W_1 < 10 \mu\text{m}$, $W_2 > 3 \mu\text{m}$, such as $3 \mu\text{m} < W_2 < 15 \mu\text{m}$, and $W_3 > 1.5 \mu\text{m}$, such as $1.5 \mu\text{m} < W_3 < 4.5 \mu\text{m}$. Preferably, $|V_2|$ is at least 30%- μm^2 , such as $30\text{-}\mu\text{m}^2 < |V_2| < 90\text{-}\mu\text{m}^2$ and further such as $40\text{-}\mu\text{m}^2 < |V_2| < 80\text{-}\mu\text{m}^2$.

[0031] In preferred embodiments, $\Delta_{2\text{MIN}} < -0.25\%$, such as $-0.3\% > \Delta_{2\text{MIN}} > -0.5\%$, and $W_1 > 5 \mu\text{m}$, such as $6 \mu\text{m} < W_1 < 10 \mu\text{m}$. Preferably, $\Delta_{0\text{MAX}} < 0.3\%$, such as $0.3\% > \Delta_{0\text{MAX}} > 0.1\%$, and $\Delta_{3\text{MIN}} < -0.7\%$, such as $-0.7\% > \Delta_{3\text{MIN}} > -3\%$ and $-0.7\% > \Delta_{3\text{MIN}} > -2\%$. Preferably, $\Delta_{1\text{MAX}}$ is not greater than 0.05%, $\Delta_{1\text{MIN}}$ is not less than -0.05%, and $0.025\% > \Delta_{1\text{MID}} > -0.025\%$. Preferably, $R_1 > 6 \mu\text{m}$, such as $6 \mu\text{m} < R_1 < 9 \mu\text{m}$, $R_2 > 12 \mu\text{m}$, such as $12 \mu\text{m} < R_2 < 15 \mu\text{m}$, $R_3 > 16 \mu\text{m}$, such as $16 \mu\text{m} < R_3 < 24 \mu\text{m}$, and $R_4 > 20 \mu\text{m}$, such as $20 \mu\text{m} < R_4 < 30 \mu\text{m}$. Preferably, $W_2 > 3 \mu\text{m}$, such as $3 \mu\text{m} < W_2 < 9 \mu\text{m}$, and $W_3 > 1.5 \mu\text{m}$, such as

$1.5 \mu\text{m} < W_3 < 4.5 \mu\text{m}$. Preferably, $|V_2|$ is at least $30\%-\mu\text{m}^2$, such as $30\%-\mu\text{m}^2 < |V_2| < 90\%-\mu\text{m}^2$ and further such as $40\%-\mu\text{m}^2 < |V_2| < 80\%-\mu\text{m}^2$.

[0032] In preferred embodiments, $\Delta_{2\text{MIN}} > -0.25\%$, such as $-0.1\% > \Delta_{2\text{MIN}} > -0.25\%$, $W_1 < 5 \mu\text{m}$, such as $2 \mu\text{m} < W_1 < 4 \mu\text{m}$, and $W_2 > 5 \mu\text{m}$, such as $6 \mu\text{m} < W_2 < 15 \mu\text{m}$. Preferably, $\Delta_{0\text{MAX}} < 0.3\%$, such as $0.3\% > \Delta_{0\text{MAX}} > 0.1\%$, and $\Delta_{3\text{MIN}} < -0.7\%$, such as $-0.7\% > \Delta_{3\text{MIN}} > -3\%$. Preferably, $\Delta_{1\text{MAX}}$ is not greater than 0.03% , $\Delta_{1\text{MIN}}$ is not less than -0.03% , and $0.025\% > \Delta_{1\text{MID}} > -0.025\%$. Preferably, $R_1 > 6 \mu\text{m}$, such as $6 \mu\text{m} < R_1 < 9 \mu\text{m}$, $R_2 > 10 \mu\text{m}$, such as $10 \mu\text{m} < R_2 < 13 \mu\text{m}$, $R_3 > 16 \mu\text{m}$, such as $16 \mu\text{m} < R_3 < 24 \mu\text{m}$, and $R_4 > 20 \mu\text{m}$, such as $20 \mu\text{m} < R_4 < 30 \mu\text{m}$. Preferably, $W_3 > 1.5 \mu\text{m}$, such as $1.5 \mu\text{m} < W_3 < 4.5 \mu\text{m}$. Preferably, $|V_2|$ is at least $30\%-\mu\text{m}^2$, such as $30\%-\mu\text{m}^2 < |V_2| < 90\%-\mu\text{m}^2$ and further such as $40\%-\mu\text{m}^2 < |V_2| < 80\%-\mu\text{m}^2$.

[0033] In preferred embodiments, second annular region **40** comprises silica glass having at least one dopant selected from the group consisting of germanium, aluminum, phosphorous, titanium, boron, and fluorine. In more preferred embodiments, second annular region **40** consists essentially of silica glass having at least one dopant selected from the group consisting of boron and fluorine. In even more preferred embodiments, second annular region **40** consists essentially of silica glass doped with fluorine. Preferably, second annular region **40** contains no voids (i.e., is void-free).

[0034] Referring specifically to FIG. 1, the third annular region **50** preferably comprises silica based glass (either pure, undoped silica or silica doped with for example, at least one of germanium, aluminum, phosphorous, titanium, boron, and fluorine) containing a plurality of closed randomly dispersed voids **16A**, the voids **16A** being either empty (vacuum) or containing a gas (e.g., argon, air, nitrogen, krypton, or SO_2) filled. Such voids can provide an effective refractive index which is low, e.g., compared to pure silica. The relative percent index of refraction ($\Delta n \%$) in third annular region **50** fluctuates between -28% (index of void filled gas relative to that of silica) and that of the glass surrounding the voids (in this example it is silica, with the relative % index of refraction $\Delta_4(r)$ of about 0%). A typical average relative refractive index percent $\Delta_{3\text{avg}}$ of the third annular region **50** will be between -1% and -3% , relative to pure silica glass, depending on the dopants present in the glass surrounding the voids. That is, the index of third annular region **50** fluctuates, and in the example of FIG. 1 the width of the gas filled voids, and/or the glass filled spacing S_v between the gas filled voids is randomly distributed and/or are not equal to one another. That is, the voids are non-periodic. It is preferable that the mean distance between the voids is less than 5000 nm , more

preferably less than 2000 nm, even more preferably less than 1000 nm, for example less than 750 nm, 500 nm, 400 nm, 300 nm, 200 nm or 100 nm. Preferably, at least 80%, and more preferably at least 90% of the voids have a maximum cross-sectional dimension **Di** of less than 1000 nm, preferably less than 500 nm. Even more preferably, the mean diameter of the voids is less than 500 nm, more preferably less than 300 nm, and even more preferably less than 200 nm. The voids **16A** are closed (surrounded by solid material) and are non-periodic. That is, the voids **16A** may have the same size, or may be of different sizes. The distances between voids may be uniform (i.e., the same), or may be different. Preferably the third annular region **50** when viewed in cross section exhibits at least 50 voids, more preferably at least 100 voids, even more preferably at least 200 voids and most preferably at least 250 voids.

[0035] In some embodiments, a central segment of the core **20** may comprise a relative refractive index profile having a so-called centerline dip which may occur as a result of one or more optical fiber manufacturing techniques. For example, the central segment may have a local minimum in the refractive index profile at radii less than 1 μm , wherein higher values for the relative refractive index (including the maximum relative refractive index for the core segment) occur at radii greater than $r = 0 \mu\text{m}$.

[0036] Referring to FIGS. 3-4, optical waveguide fibers **110** are disclosed herein that include a core **120** extending radially outwardly from the centerline to a radius R_1 and having a relative refractive index profile $\Delta_0(r)$ in %, with a maximum relative refractive index percent, Δ_{0MAX} , and a cladding **300** surrounding and directly adjacent, i.e., in direct contact with, the core **120**. Cladding **300** includes a first annular region **140** extending from the radius R_1 to a radius R_2 , the first annular region having a radial width $W_1 = R_2 - R_1$ and a relative refractive index profile $\Delta_1(r)$ in %, with a minimum relative refractive index percent Δ_{1MIN} . Cladding **300** also includes a second annular region **150** extending from the radius R_2 to a radius R_3 , the second annular region having a radial width $W_2 = R_3 - R_2$, and a relative refractive index profile $\Delta_2(r)$ in %, with a minimum relative refractive index percent Δ_{2MIN} . Cladding **300** additionally includes a third annular region **160** extending from the radius R_3 to the outermost glass radius R_4 , having a relative refractive index profile $\Delta_3(r)$ in %. Third annular region **160** can be optionally surrounded by one or more polymer coatings **165**. R_1 is defined to occur at the radius where $\Delta_0(r)$ first reaches 0% going radially outward from the centerline. That is, core **120** ends and the first annular region **140** begins where the relative refractive index first reaches 0% (going radially outward) at a radius R_1 . R_2 is defined to

occur at the radius where $\Delta_1(r)$ first reaches -0.5% going radially outward from R_1 . That is, first annular region **140** ends and second annular region **150** begins where the relative refractive index first reaches -0.5% (going radially outward) at a radius R_2 . R_3 is defined to occur at the radius where $\Delta_3(r)$ first reaches -0.05% going radially inward from R_4 . That is, third annular region **160** ends and second annular region **150** begins where the relative refractive index first reaches -0.05% (going radially inward) at a radius R_3 . R_1 is greater than about 5 μm . Also, $\Delta_{0\text{MAX}} > 0 > \Delta_{1\text{MIN}} > \Delta_{2\text{MIN}}$.

[0037] The first annular region **140** has a profile volume, V_1 , defined herein as:

$$2 \int_{R_1}^{R_2} \Delta(r)r \, dr;$$

[0038] In preferred embodiments, $\Delta_{0\text{MAX}} < 0.3\%$, such as $0.3\% > \Delta_{0\text{MAX}} > 0.1\%$ and $0.25\% > \Delta_{0\text{MAX}} > 0.1\%$, $\Delta_{1\text{MIN}} < -0.1\%$, such as $-0.1\% > \Delta_{1\text{MIN}} > -0.5\%$, and $\Delta_{2\text{MIN}} < -0.7\%$, such as $-0.7\% > \Delta_{2\text{MIN}} > -3\%$ and $0.7\% > \Delta_{2\text{MIN}} > -2\%$. Preferably, $R_1 > 6 \mu\text{m}$, such as $6 \mu\text{m} < R_1 < 9 \mu\text{m}$, $R_2 > 16 \mu\text{m}$, such as $16 \mu\text{m} < R_2 < 24 \mu\text{m}$, and $R_3 > 20 \mu\text{m}$, such as $20 \mu\text{m} < R_3 < 30 \mu\text{m}$. Preferably, $W_1 > 3 \mu\text{m}$, such as $3 \mu\text{m} < W_1 < 15 \mu\text{m}$, and $W_2 > 1.5 \mu\text{m}$, such as $1.5 \mu\text{m} < W_2 < 4.5 \mu\text{m}$. Preferably, $|V_1|$ is at least $30\%-\mu\text{m}^2$, such as $30\%-\mu\text{m}^2 < |V_1| < 90\%-\mu\text{m}^2$ and further such as $40\%-\mu\text{m}^2 < |V_1| < 80\%-\mu\text{m}^2$.

[0039] In preferred embodiments, first annular region **140** comprises silica glass having at least one dopant selected from the group consisting of germanium, aluminum, phosphorous, titanium, boron, and fluorine. In more preferred embodiments, first annular region **140** consists essentially of silica glass having at least one dopant selected from the group consisting of boron and fluorine. In even more preferred embodiments, first annular region **140** consists essentially of silica glass doped with fluorine. Preferably, first annular region **140** contains no voids (i.e., is void-free).

[0040] Referring specifically to FIG. 3, the second annular region **150** preferably comprises silica based glass (either pure, undoped silica or silica doped with for example, at least one of germanium, aluminum, phosphorous, titanium, boron, and fluorine) containing a plurality of closed randomly dispersed voids **116A**, the voids **116A** being either empty (vacuum) or containing a gas (e.g., argon, air, nitrogen, krypton, or SO_2) filled. Such voids can provide an effective refractive index which is low, e.g., compared to pure silica. The relative percent index of refraction ($\Delta n \%$) in second annular region **150** fluctuates between -28% (index of void filled gas relative to that of silica) and that of the glass surrounding the

voids (in this example it is silica, with the relative % index of refraction $\Delta_4(r)$ of about 0%). A typical average relative refractive index percent $\Delta_{3\text{avg}}$ of the second annular region **150** will be between -1% and -3%, relative to pure silica glass, depending on the dopants present in the glass surrounding the voids. That is, the index second annular region **150** fluctuates, and in the example of FIG. 3 the width of the gas filled voids, and/or the glass filled spacing S_v between the gas filled voids is randomly distributed and/or are not equal to one another. That is, the voids are non-periodic. It is preferable that the mean distance between the voids is less than 5000 nm, more preferably less than 2000 nm, even more preferably less than 1000 nm, for example less than 750 nm, 500 nm, 400 nm, 300 nm, 200 nm or 100 nm. Preferably, at least 80%, and more preferably at least 90% of the voids have a maximum cross-sectional dimension D_i of less than 1000 nm, preferably less than 500 nm. Even more preferably, the mean diameter of the voids is less than 500 nm, more preferably less than 300 nm, and even more preferably less than 200 nm. The voids **116A** are closed (surrounded by solid material) and are non-periodic. That is, the voids **116A** may have the same size, or may be of different sizes. The distances between voids may be uniform (i.e., the same), or may be different. Preferably the second annular region **150** when viewed in cross section exhibits at least 50 voids, more preferably at least 100 voids, even more preferably at least 200 voids and most preferably at least 250 voids.

[0041] In some embodiments, a central segment of the core **120** may comprise a relative refractive index profile having a so-called centerline dip which may occur as a result of one or more optical fiber manufacturing techniques. For example, the central segment may have a local minimum in the refractive index profile at radii less than 1 μm , wherein higher values for the relative refractive index (including the maximum relative refractive index for the core segment) occur at radii greater than $r = 0 \mu\text{m}$.

[0042] The embodiments disclosed herein provide a dual trench design, wherein an annular region closer to the core is preferably doped with at least one downdopant such as fluorine, which annular region is surrounded by another annular region that preferably includes closed, randomly dispersed voids. This dual trench design has been found to provide for an optical fiber having a combination of large effective area and low loss characteristics. In particular, this dual trench design has been found to provide an optical fiber with a cable cutoff of less than 1500 nm and an effective area at 1550 nm of greater than $130 \mu\text{m}^2$, such as an effective area of $130 \mu\text{m}^2$ to $200 \mu\text{m}^2$, wherein the fiber also has low attenuation and low microbend loss.

[0043] Preferably, optical fiber disclosed herein provide a cable cutoff of less than 1450 nm, including a cable cutoff of less than 1400 nm. Preferably, optical fiber disclosed herein provide an effective area at 1550 nm of greater than $140 \mu\text{m}^2$, such as an effective area of $140 \mu\text{m}^2$ to $190 \mu\text{m}^2$. More preferably, optical fiber disclosed herein provide an effective area at 1550 nm of greater than $150 \mu\text{m}^2$, such as an effective area of $150 \mu\text{m}^2$ to $180 \mu\text{m}^2$. Preferably, optical fiber disclosed herein provide an attenuation at 1550 nm of less than 0.21 dB/km, even more preferably less than 0.20 dB/km, and yet even more preferably less than 0.19 dB/km. Preferably, optical fiber disclosed herein provide a bend loss at 1550 nm of less than 1.5 dB/turn around a 20 mm diameter mandrel, even more preferably a bend loss at 1550 nm of less than 1.0 dB/turn around a 20 mm diameter mandrel, and yet even more preferably a bend loss at 1550 nm of less than 0.5 dB/turn around a 20 mm diameter mandrel.

Examples

[0044] Examples 1-5 set forth refractive index profile parameters and optical properties of modeled optical fibers in accordance with embodiments disclosed herein and illustrated, for example, in FIGS. 1-2. Table 1 lists refractive index profile parameters of Examples 1-5 and Table 2 lists modeled optical properties of Examples 1-5.

Table 1: Refractive Index Profile Parameters

Example	1	2	3	4	5
$\Delta_{0\text{MAX}}$ (%)	0.2	0.198	0.198	0.196	0.16
R_1 (μm)	7.17	7.17	7.3	7.3	8.15
$\Delta_{1\text{MID}}$ (%)	0	0	0	0	0
R_2 (μm)	14.5	12.4	11.45	11.1	12.1
W_1 (μm)	7.33	5.23	4.15	3.8	3.95
$\Delta_{2\text{MIN}}$ (%)	-0.4	-0.3	-0.25	-0.18	-0.18
R_3 (μm)	19.5	19.5	19.5	21	22
W_2 (μm)	5	7.1	8.05	9.9	9.9
$\Delta_{3\text{MIN}}$ (%)	-1	-1	-1	-1	-1.3
R_4 (μm)	22	22	22	23	24
W_3 (μm)	2.5	2.5	2.5	2	2
core alpha	8	8	8	8	8
$ V_2 $ (%- μm^2)	68	67.9	62.3	57.2	60.8

Table 2: Modeled Optical Properties

Example	1	2	3	4	5
MFD at 1550 nm (μm)	13.94	13.74	13.67	13.72	15.11
Aeff at 1550 nm (μm^2)	153.0	150.1	150.0	150.9	184.2
Dispersion at 1550 nm (ps/nm/km)	20.92	21.39	21.68	21.56	21.83
Dispersion Slope at 1550 nm (ps/nm ² /km)	0.0643	0.0647	0.0647	0.0643	0.0646
Kappa at 1550 nm (nm)	325.3	330.4	335.3	335.4	337.9
LP11 Cutoff (nm)	1423	1391	1398	1392	1393
Attenuation at 1550 nm (dB/km)	0.1846	0.1845	0.1845	0.1844	0.1831

[0045] Each of the modeled optical fibers of Examples 1-5 is expected to exhibit a bend loss at 1550 nm of less than 1.0 dB/turn around a 20 mm diameter mandrel.

[0046] It will be apparent to those skilled in the art that various modifications and variations can be made to the present invention without departing from the spirit and scope of the invention. Thus it is intended that the present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.

What is claimed is:

1. An optical fiber comprising:

a glass core extending from a centerline to a radius R_1 , wherein R_1 is greater than about $5\text{ }\mu\text{m}$; a glass cladding surrounding and in contact with the core;

wherein the cladding comprises:

a first annular region extending from the radius R_1 to a radius R_2 , the first annular region comprising a radial width $W_1 = R_2 - R_1$;

a second annular region extending from the radius R_2 to a radius R_3 , the second annular region comprising a radial width $W_2 = R_3 - R_2$;

a third annular region extending from the radius R_3 to a radius R_4 , the third annular region comprising a radial width $W_3 = R_4 - R_3$; and

a fourth annular region extending from the radius R_4 to an outermost glass radius R_5 ;

wherein the core comprises a maximum relative refractive index, $\Delta_{0\text{MAX}}$, the second annular region comprises a minimum relative refractive index, $\Delta_{2\text{MIN}}$, and the third annular region comprises a minimum relative refractive index, $\Delta_{3\text{MIN}}$, wherein $\Delta_{0\text{MAX}} > 0 > \Delta_{2\text{MIN}} > \Delta_{3\text{MIN}}$; and

wherein the core and the cladding provide a fiber with cable cutoff less than 1500 nm and an effective area at 1550 nm of greater than $130\text{ }\mu\text{m}^2$.

2. The optical fiber of claim 1, wherein $0.3\% > \Delta_{0\text{MAX}} > 0.1\%$, $-0.1\% > \Delta_{2\text{MIN}} > -0.5\%$, and $\Delta_{3\text{MIN}} < -0.7\%$.
3. The optical fiber of claim 1, wherein $6\text{ }\mu\text{m} < R_1 < 9\text{ }\mu\text{m}$, $10\text{ }\mu\text{m} < R_2 < 15\text{ }\mu\text{m}$, $16\text{ }\mu\text{m} < R_3 < 24\text{ }\mu\text{m}$, and $20\text{ }\mu\text{m} < R_4 < 30\text{ }\mu\text{m}$.
4. The optical fiber of claim 1, wherein $2\text{ }\mu\text{m} < W_1 < 10\text{ }\mu\text{m}$, $3\text{ }\mu\text{m} < W_2 < 15\text{ }\mu\text{m}$, and $1.5\text{ }\mu\text{m} < W_3 < 4.5\text{ }\mu\text{m}$.
5. The optical fiber of claim 1, wherein the second annular region comprises fluorine and is void-free.

6. The optical fiber of claim 1, wherein the third annular region comprises silica based glass with at least 50 closed randomly dispersed voids situated therein, and (i) the mean distance between the voids is less than 5000 nm, and (ii) at least 80% of the voids have a maximum cross-sectional dimension D_i of less than 1000 nm.

7. The optical fiber of claim 1, wherein the second annular region comprises a profile volume V_2 , equal to:

$$2 \int_{R_2}^{R_3} \Delta(r)r \, dr;$$

wherein $|V_2|$ is at least 30%- μm^2 .

8. The optical fiber of claim 1, wherein the core and the cladding provide a fiber having an attenuation at 1550 nm of less than 0.19 dB/km.
9. The optical fiber of claim 1, wherein the core and the cladding provide a fiber with an effective area at 1550 nm of greater than 150 μm^2 .
10. The optical fiber of claim 1, wherein the core and the cladding provide a fiber with a bend loss at 1550 nm of less than 1.0 dB/turn on a 20 mm diameter mandrel.

11. An optical fiber comprising:

a glass core extending from a centerline to a radius R_1 , wherein R_1 is greater than about 5 μm ; a glass cladding surrounding and in contact with the core;

wherein the cladding comprises:

a first annular region extending from the radius R_1 to a radius R_2 , the first annular region comprising a radial width $W_1 = R_2 - R_1$;

a second annular region extending from the radius R_2 to a radius R_3 , the second annular region comprising a radial width $W_2 = R_3 - R_2$;

a third annular region extending from the radius R_3 to an outermost glass radius R_4 ;

wherein the core comprises a maximum relative refractive index, $\Delta_{0\text{MAX}}$, the first annular region comprises a minimum relative refractive index, $\Delta_{1\text{MIN}}$, and the

second annular region comprises a minimum relative refractive index, $\Delta_{2\text{MIN}}$, wherein $\Delta_{0\text{MAX}} > 0 > \Delta_{1\text{MIN}} > \Delta_{2\text{MIN}}$; and

wherein the core and the cladding provide a fiber with cable cutoff less than 1500 nm, an attenuation at 1550 nm of less than 0.20 dB/km, and an effective area at 1550 nm of greater than 130 μm^2 .

12. The optical fiber of claim 11, wherein $0.3\% > \Delta_{0\text{MAX}} > 0.1\%$, $-0.1\% > \Delta_{1\text{MIN}} > -0.5\%$, and $\Delta_{2\text{MIN}} < -0.7\%$.

13. The optical fiber of claim 11, wherein $6 \mu\text{m} < R_1 < 9 \mu\text{m}$, $16 \mu\text{m} < R_2 < 24 \mu\text{m}$, and $20 \mu\text{m} < R_3 < 30 \mu\text{m}$.

14. The optical fiber of claim 11, wherein $3 \mu\text{m} < W_1 < 15 \mu\text{m}$ and $1.5 \mu\text{m} < W_2 < 4.5 \mu\text{m}$.

15. The optical fiber of claim 11, wherein the first annular region comprises fluorine and is void-free.

16. The optical fiber of claim 11, wherein the second annular region comprises silica based glass with at least 50 closed randomly dispersed voids situated therein, and (i) the mean distance between the voids is less than 5000 nm, and (ii) at least 80% of the voids have a maximum cross-sectional dimension D_i of less than 1000 nm.

17. The optical fiber of claim 11, wherein the first annular region comprises a profile volume V_1 , equal to:

$$2 \int_{R_1}^{R_2} \Delta(r)r \, dr;$$

wherein $|V_1|$ is at least 30%- μm^2 .

18. The optical fiber of claim 11, wherein the core and the cladding provide a fiber having an attenuation at 1550 nm of less than 0.19 dB/km.

19. The optical fiber of claim 11, wherein the core and the cladding provide a fiber with an effective area at 1550 nm of greater than $150\ \mu\text{m}^2$.
20. The optical fiber of claim 11, wherein the core and the cladding provide a fiber with a bend loss at 1550 nm of less than 1.0 dB/turn on a 20 mm diameter mandrel.

FIG. 1

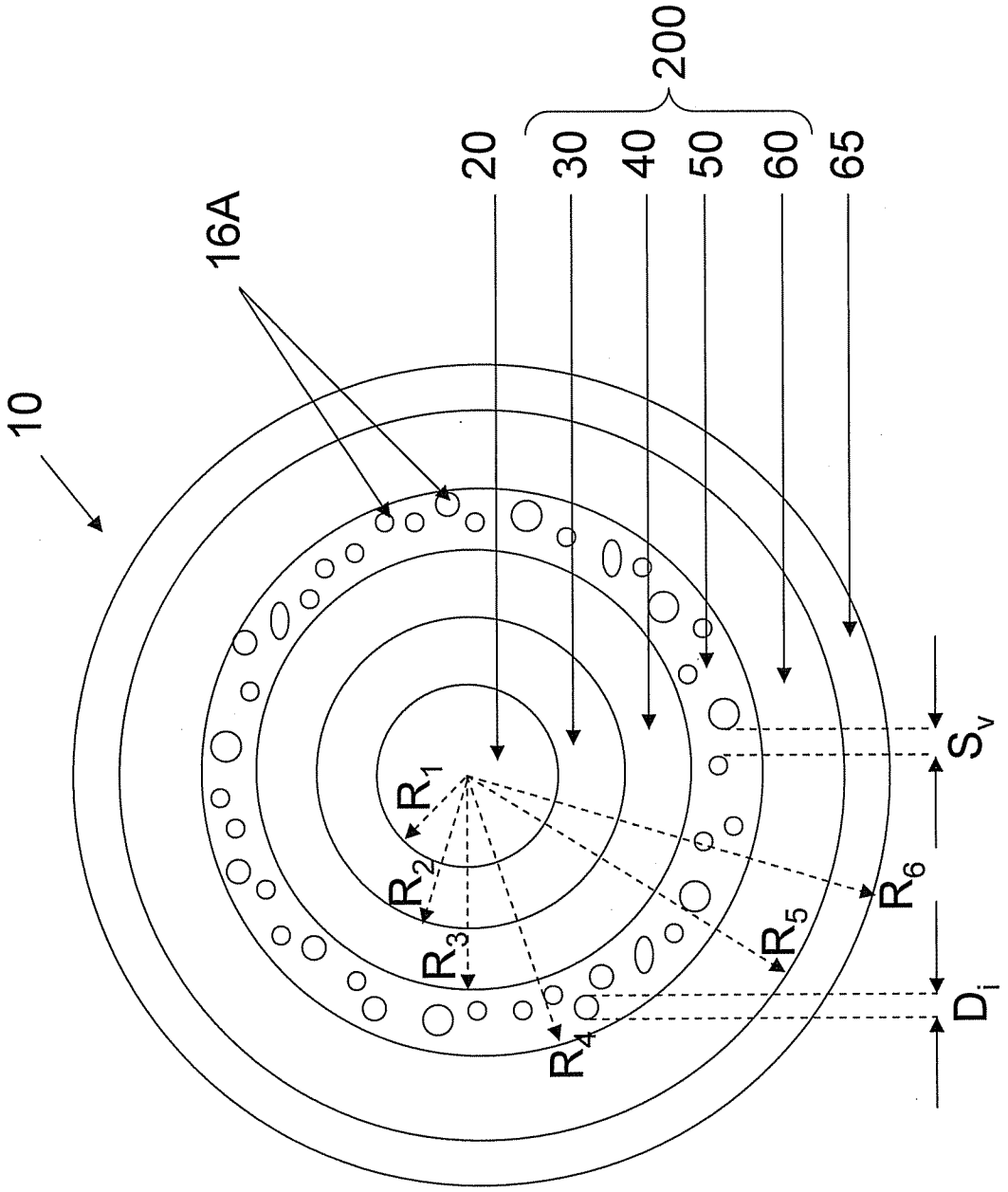
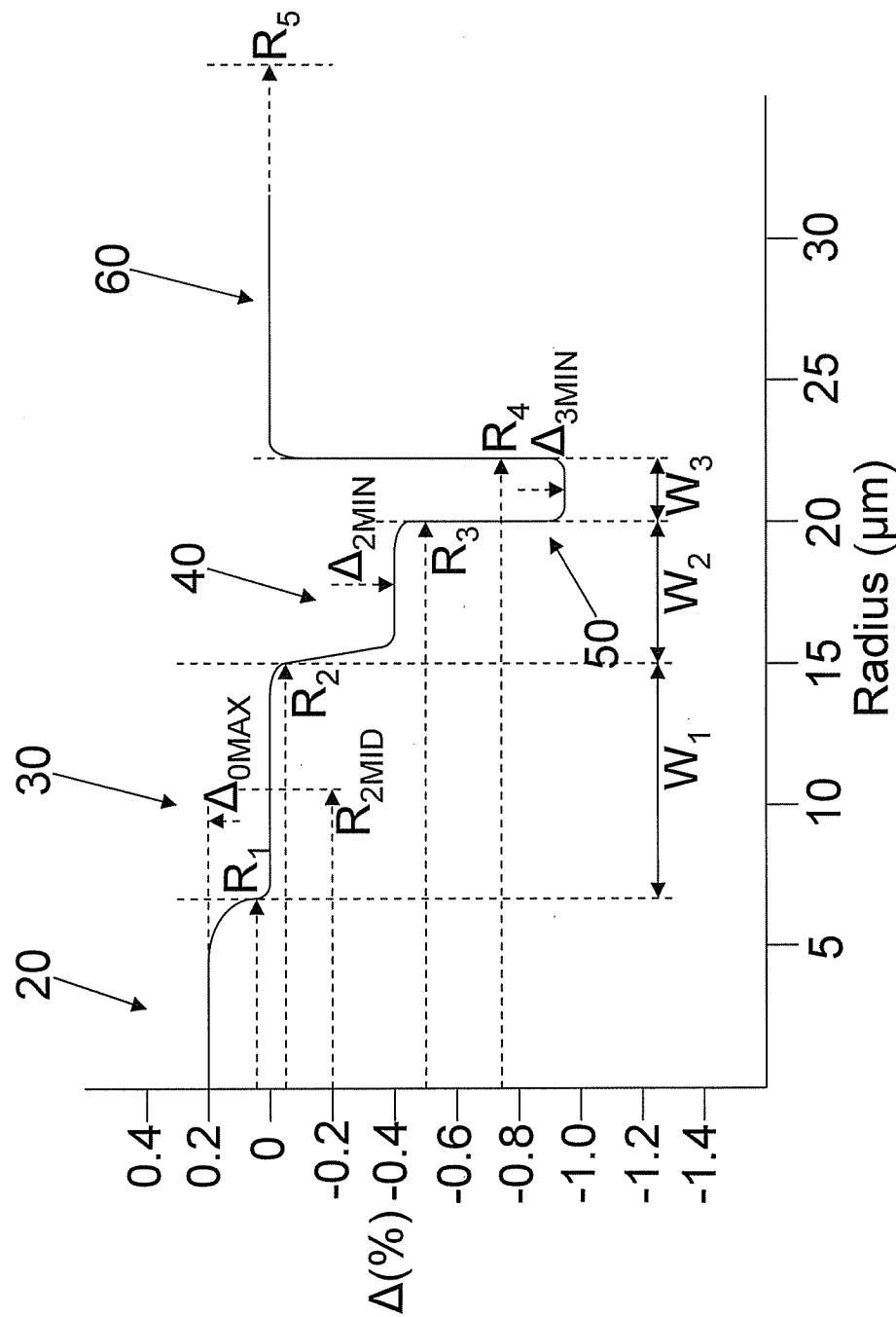


FIG. 2



3/4

FIG. 3

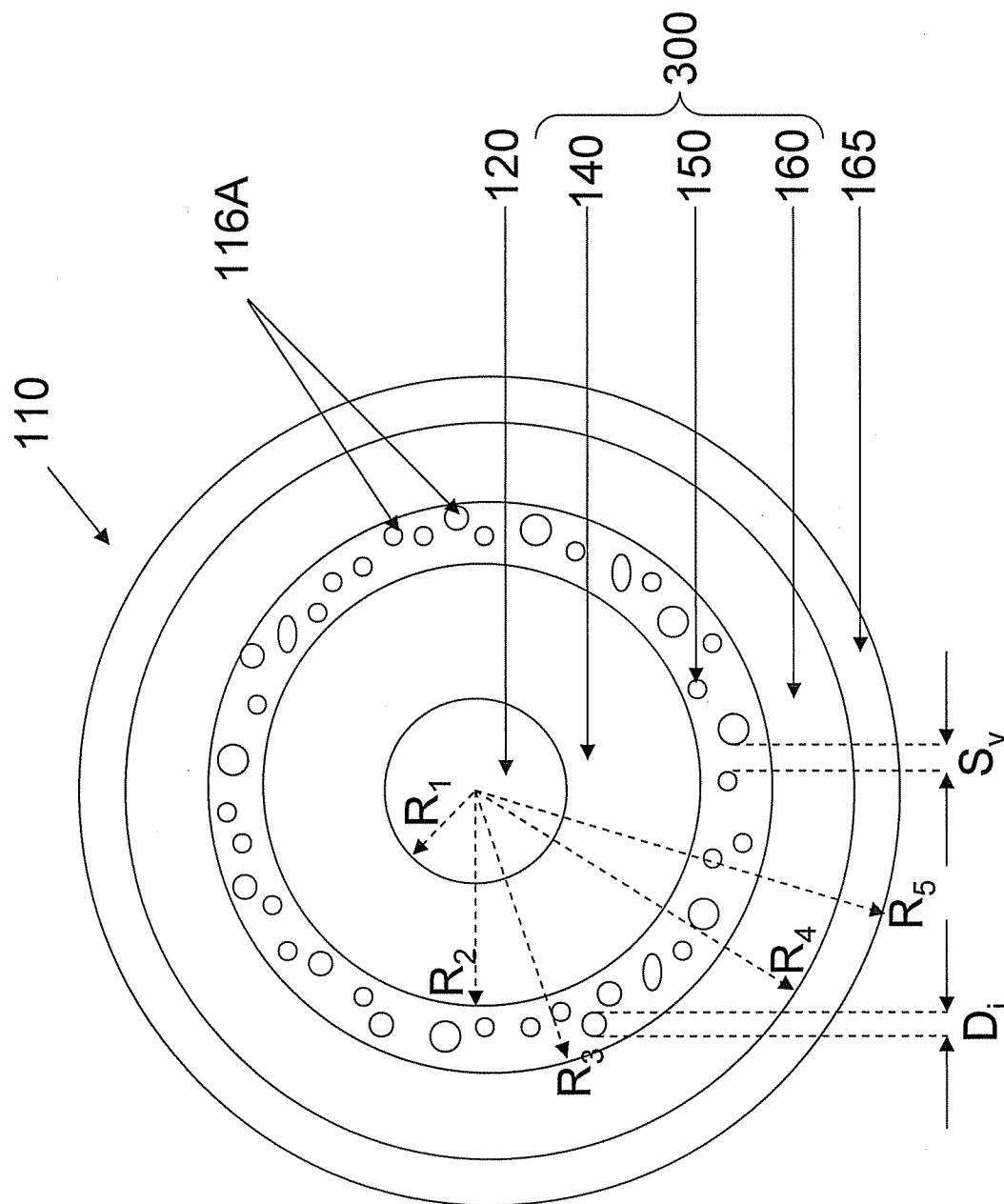
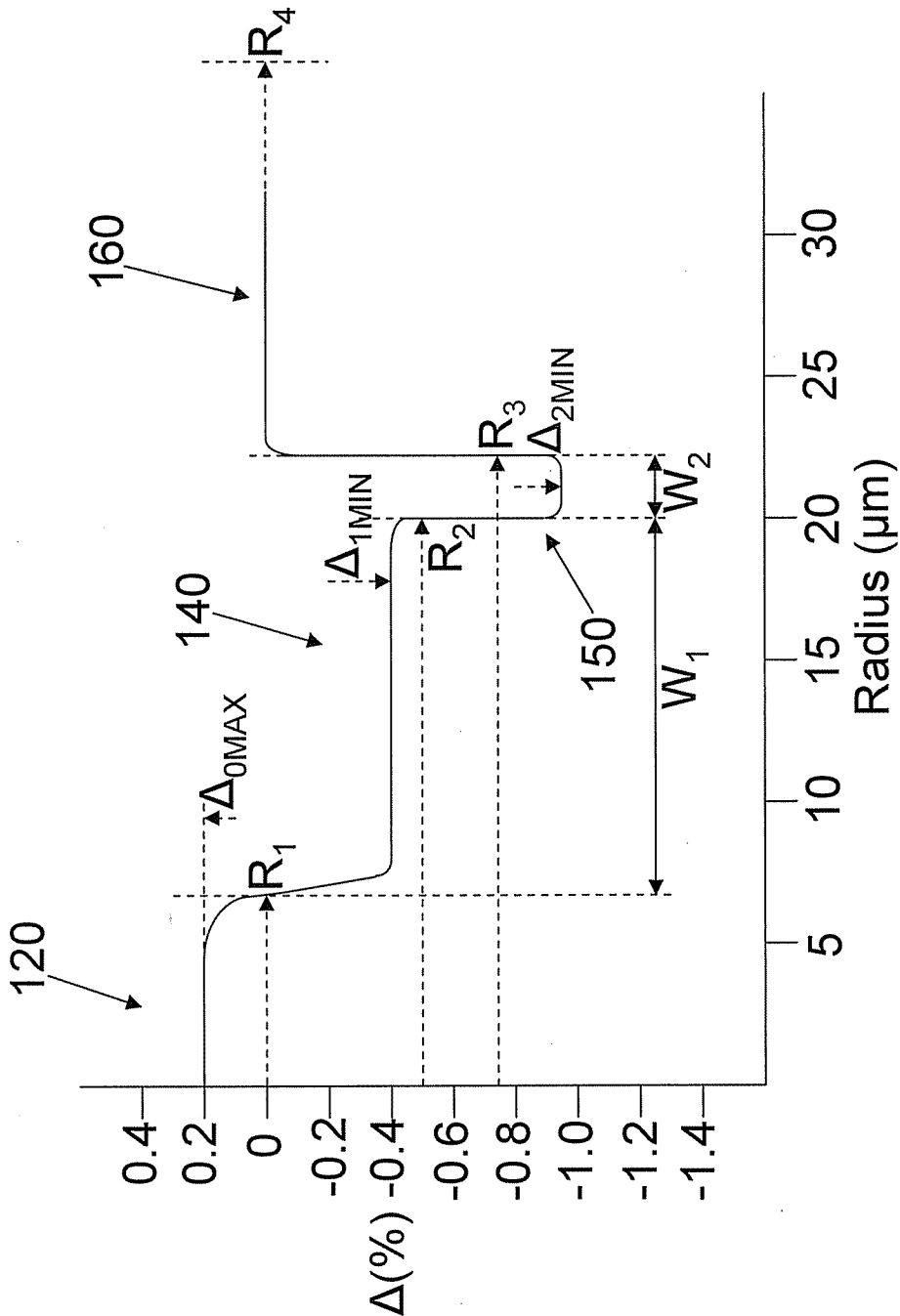


FIG. 4



INTERNATIONAL SEARCH REPORT

International application No
PCT/US2010/024975

A. CLASSIFICATION OF SUBJECT MATTER

INV. G02B6/036

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G02B

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 practical, search terms used)

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	EP 0 260 795 A2 (AMERICAN TELEPHONE & TELEGRAPH [US]) 23 March 1988 (1988-03-23) column 7, line 41 - line 53 column 8, line 12 - line 24 column 11, line 7 - line 21 column 12, line 38 - line 54 column 14, line 16 - line 36; figure 19	1-10
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Y	US 6 301 422 B1 (LI MING-JUN [US]) 9 October 2001 (2001-10-09) column 7, line 11 - line 43; figure 5	1-10
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☒ 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 but 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

25 May 2010

Date of mailing of the international search report

17/08/2010

Name and mailing address of the ISA/

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INTERNATIONAL SEARCH REPORT

International application No
PCT/US2010/024975

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	BIGOT-ASTRUC M ET AL: "trench-Assisted Profiles for Large-Effective-Area Single-Mode Fibers" ECOC2008, ECOC, BRUSSELS, 21-25 SEP 2008, ECOC, BRUSSELS EXPO, BELGIUM, 21 September 2008 (2008-09-21), XP001524535 ISBN: 978-1-4244-2228-9 the whole document	1-10
Y	LOUIS-ANNE DE MONTMORILLON ET AL.: "Bend-Optimized G.652D Compatible Trench-Assisted Single Mode Fibers" INTERNATIONAL WIRE&CABLE SYMPOSIUM, PROCEEDINGS OF THE 55TH IWCS 2006, 5 October 2006 (2006-10-05), pages 342-347, XP002583242 the whole document	1-10
Y	M-J LI ET AL: "Ultra-Low Bending Loss Single-Mode Fiber for FTTH" JOURNAL OF LIGHTWAVE TECHNOLOGY, IEEE SERVICE CENTER, NEW YORK, NY, US, vol. 26, no. 3, 1 February 2009 (2009-02-01), pages 376-382, XP011251719 ISSN: 0733-8724 the whole document	1-10
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A	EP 1 978 383 A1 (DRAKA COMTEQ BV [NL]) 8 October 2008 (2008-10-08) the whole document	1-10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2010/024975

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search 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 No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

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

see additional 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 fees, this Authority did not invite payment of additional fees.
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.:

1-10

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-10

Subject 1 relates to an optical fibre with updoped central core surrounded by three annular regions made of pure silica, down doped second region, and void filled third trench region

2. claims: 11-20

Subject 2 relates to an optical fibre with updoped central core surrounded by two annular regions made of down doped first region, and void filled second trench region

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2010/024975

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