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(54) BEND RESISTANT MULTIMODE OPTICAL FIBER

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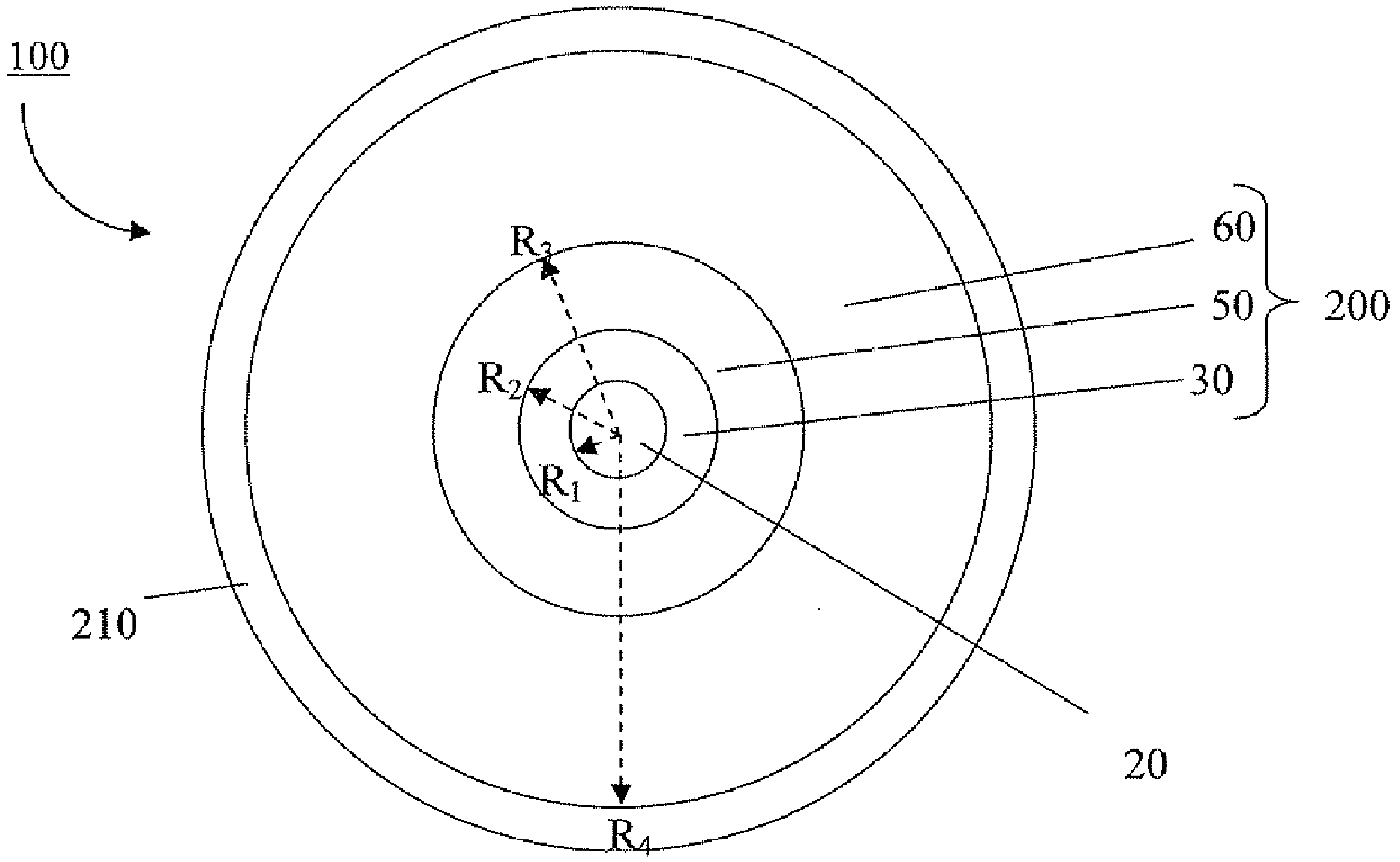
(57) ABSTRACT

Bend resistant multimode optical fibers are disclosed herein. Multimode optical fibers disclosed herein comprise a core region and a cladding region surrounding and directly adjacent to the core region, the cladding region comprising a depressed-index annular portion comprising a depressed relative refractive index which is spaced from the core at least 0.5 microns and less than 4 microns.



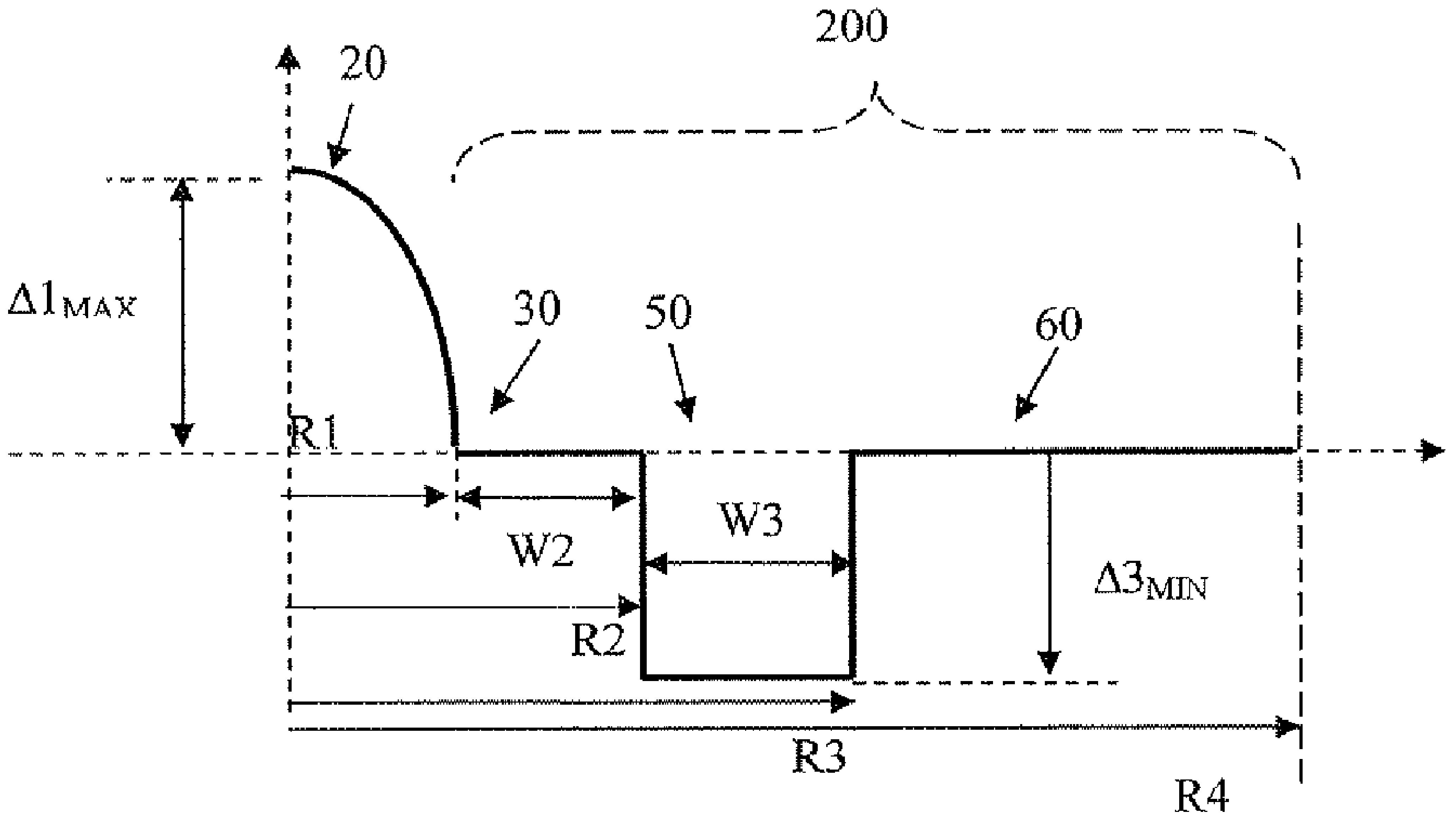

200
20
Δ1MAX
30
50
60
R1
W2
W3
R2
Δ3MIN
R3
R4

FIG. 1

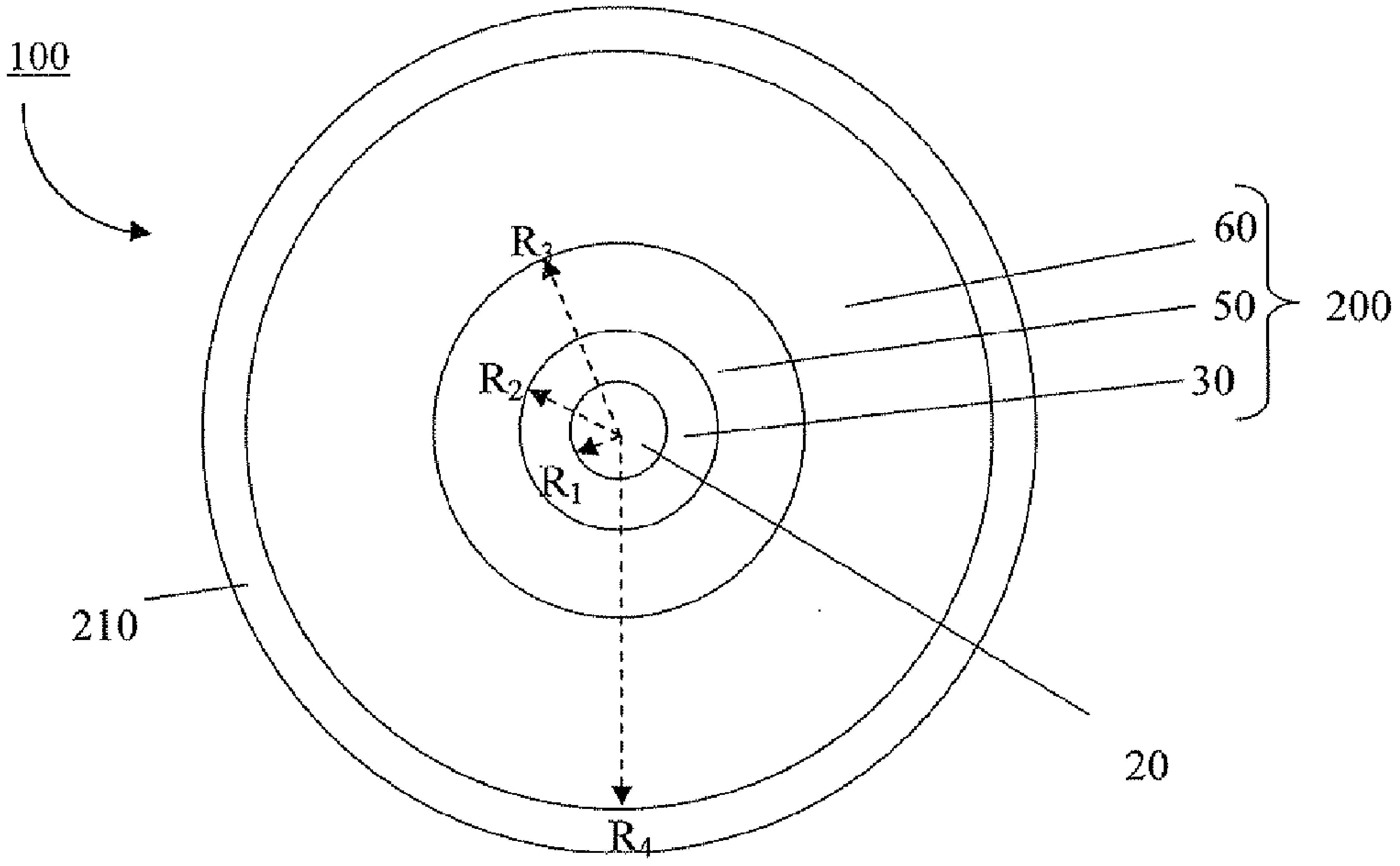

100
R3
R2
R1
60
50
30
200
210
20
R4

FIG. 2

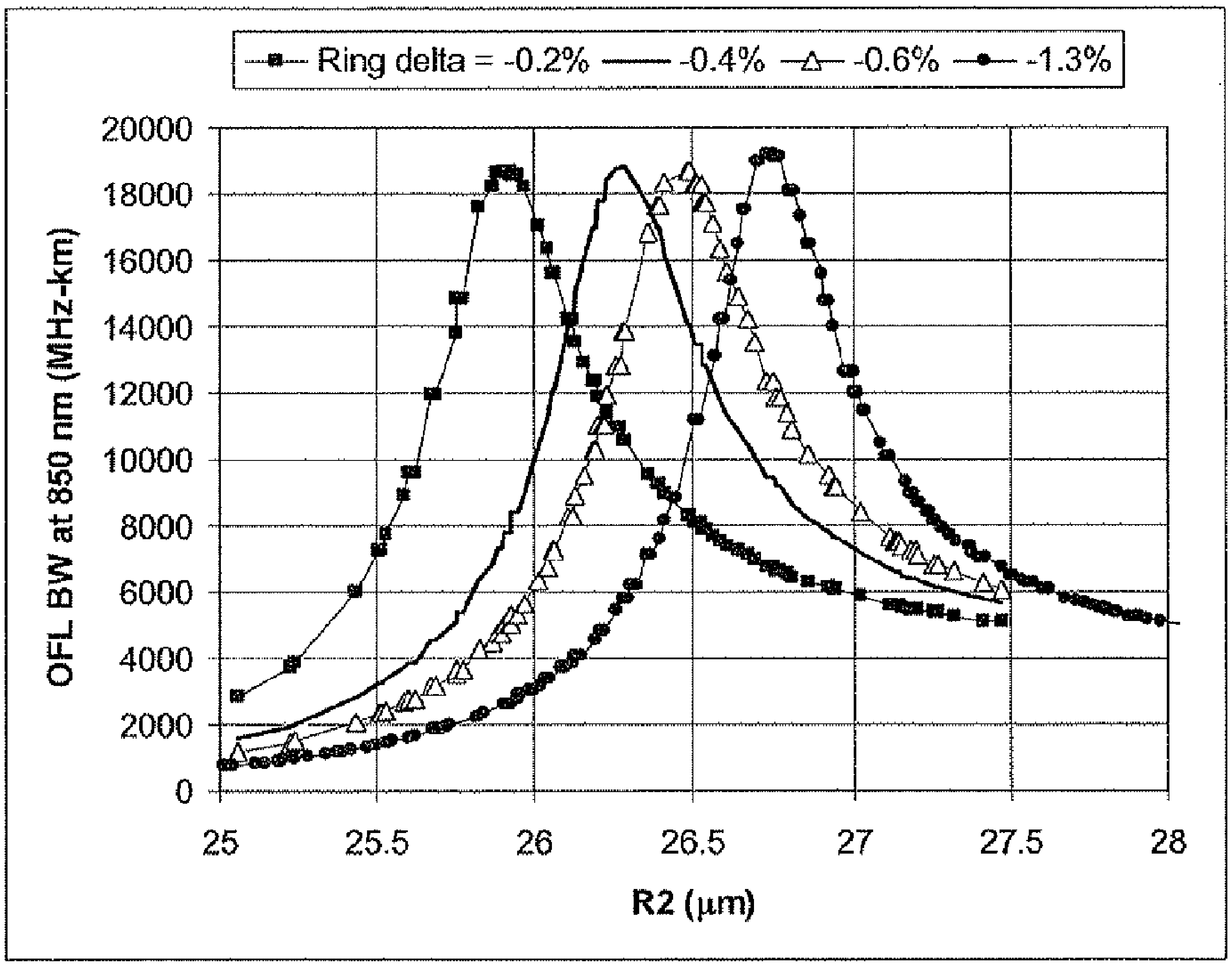

Ring delta = -0.2%
-0.4%
-0.6%
-1.3%
OFL BW at 850 nm (MHz-km)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
25
25.5
26
26.5
27
27.5
28
R2 (μm)

FIG. 3

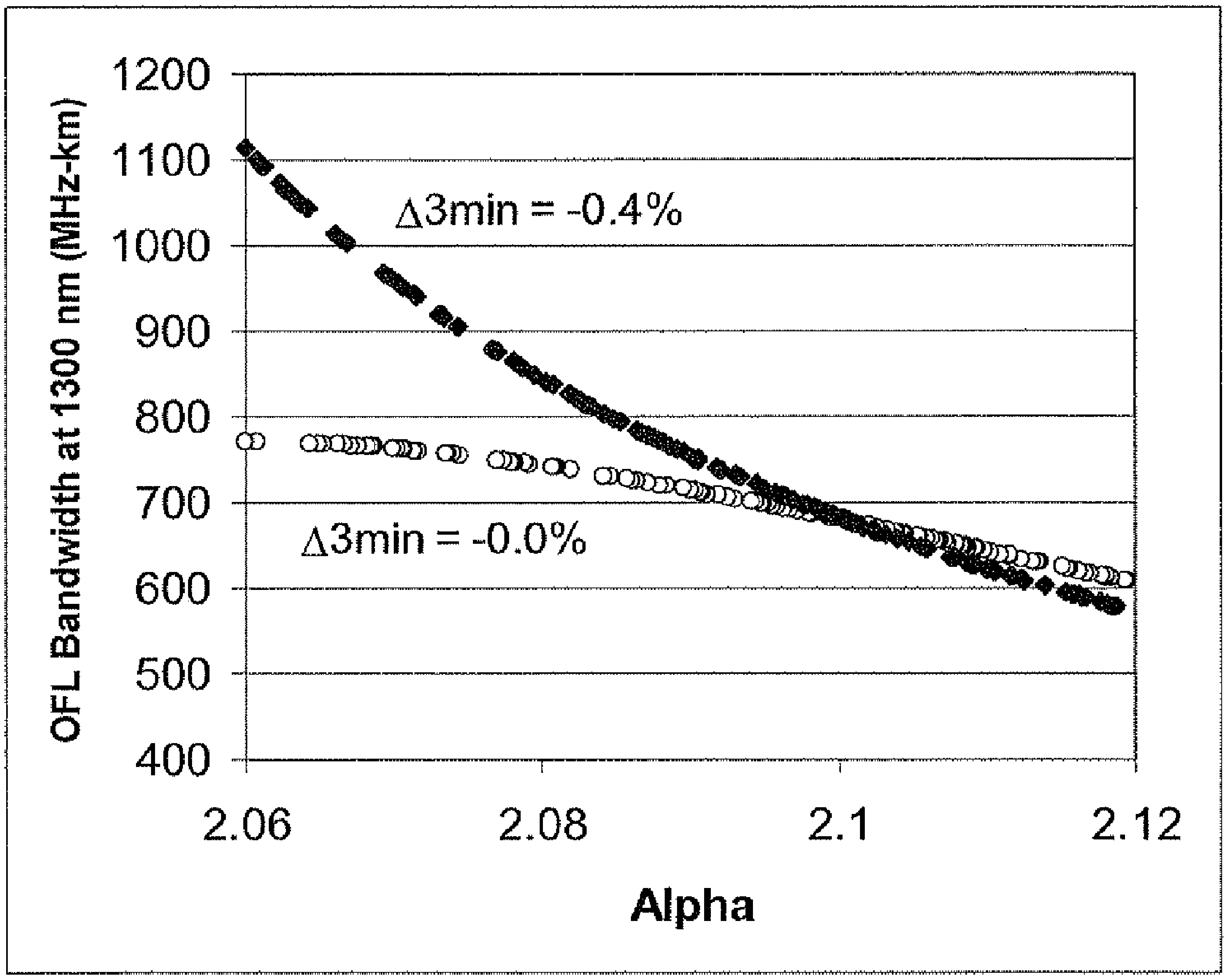

OFL Bandwidth at 1300 nm (MHz-km)
1200
1100
1000
900
800
700
600
500
400
Δ3min = -0.4%
Δ3min = -0.0%
2.06
2.08
2.1
2.12
Alpha

FIG. 4

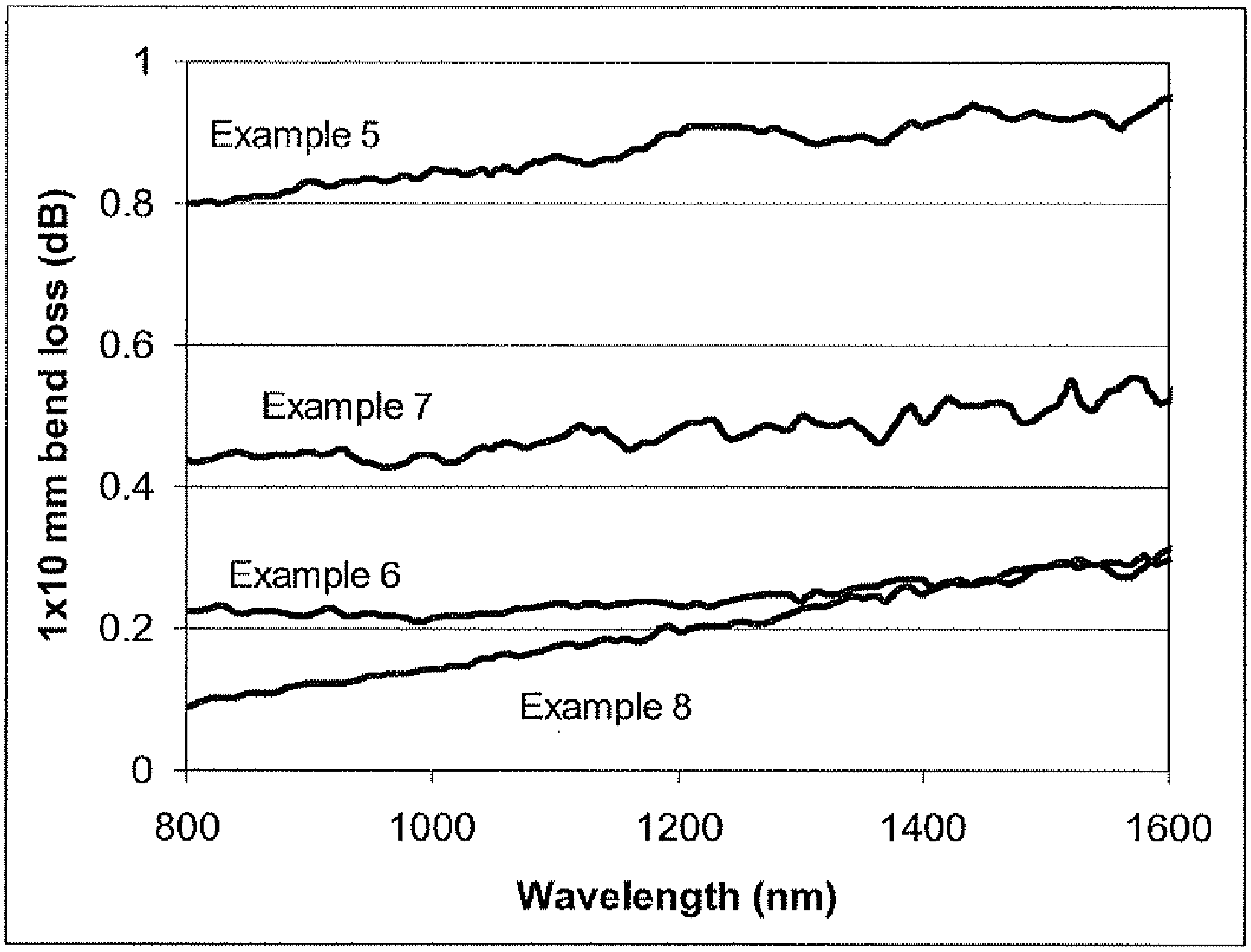

1
0.8
0.6
0.4
0.2
0
1x10 mm bend loss (dB)
Example 5
Example 7
Example 6
Example 8
800
1000
1200
1400
1600
Wavelength (nm)

FIG. 5

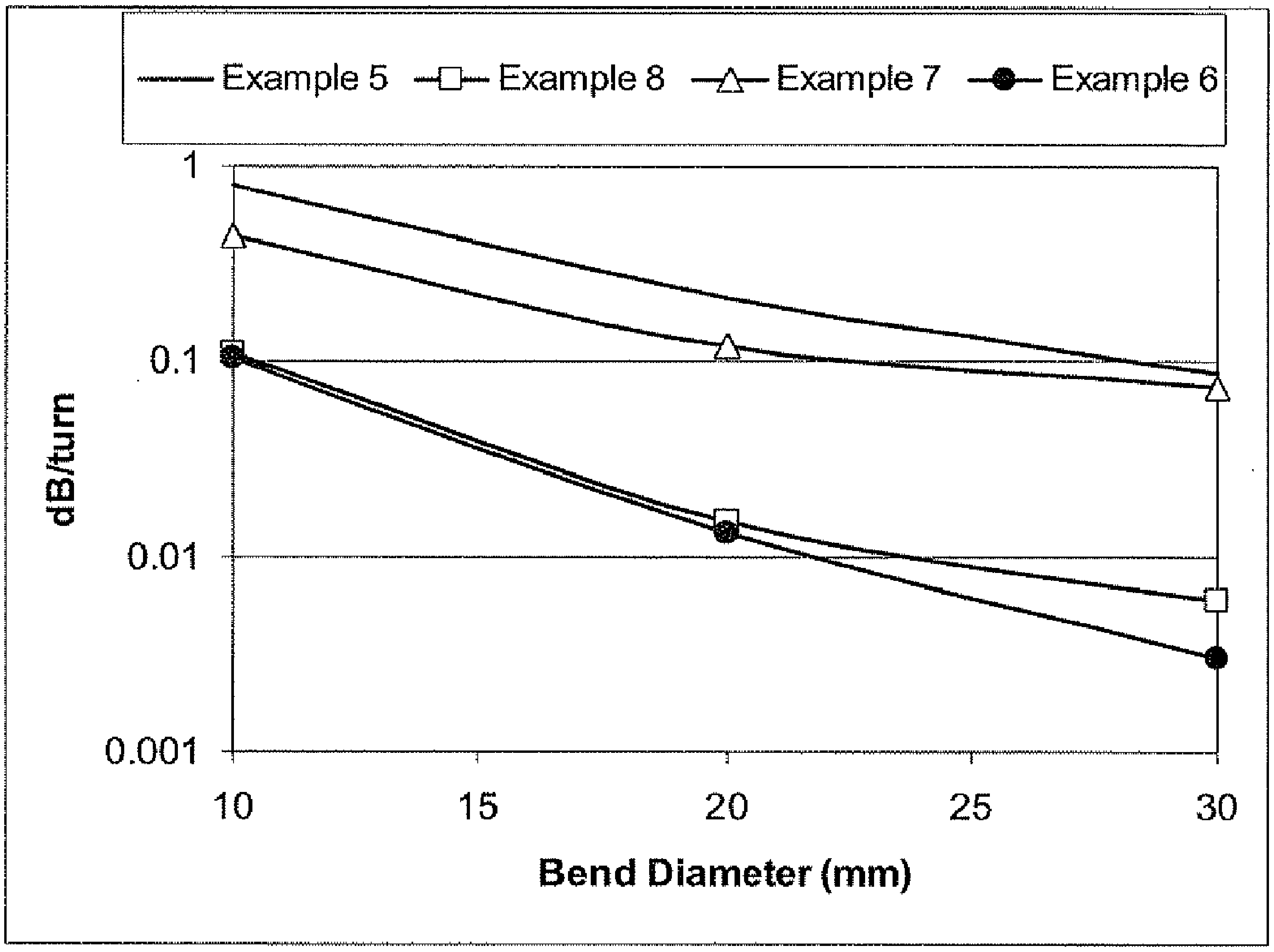

Example 5
Example 8
Example 7
Example 6
1
0.1
0.01
0.001
dB/turn
10
15
20
25
30
Bend Diameter (mm)

FIG. 6

BEND RESISTANT MULTIMODE OPTICAL FIBER

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of, and priority to U.S. Provisional Patent Application No. 61/009,803 filed on Jan. 2, 2008 and U.S. Provisional Patent Application No. 61/133,612 filed on Jul. 1, 2008 entitled, "Bend Resistant Multimode Optical Fiber", the content of which is relied upon and incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The present invention relates generally to optical fibers, and more specifically to multimode optical fibers.

[0004] 2. Technical Background

[0005] Corning Incorporated manufactures and sells InfiniCor® 62.5 μm optical fiber, which is multimode optical fiber having a core with a maximum relative refractive index delta of about 2% and 62.5 μm core diameter, as well as InfiniCor® 50 μm optical fiber, which is multimode optical fiber having a core with a maximum relative refractive index delta of about 1% and 50 μm core diameter.

SUMMARY OF THE INVENTION

[0006] Bend resistant multimode optical fibers are disclosed herein. Multimode optical fibers disclosed herein comprise a graded-index core region and a cladding region surrounding and directly adjacent to the core region, the cladding region comprising a depressed-index annular portion comprising a depressed relative refractive index relative to another portion of the cladding. The depressed-index annular portion of the cladding is preferably spaced apart from the core. Preferably, the refractive index profile of the core has a parabolic or substantially shape. The depressed-index annular portion may, for example, comprise glass comprising a plurality of voids, or glass doped with a downdopant such as fluorine, boron or mixtures thereof, or glass doped with one or more of such downdopants and additionally glass comprising a plurality of voids.

[0007] In some embodiments, the multimode optical fiber comprises a graded index glass core; and a cladding surrounding and in contact with the core, the cladding comprising a depressed-index annular portion surrounding the core, said depressed-index annular portion having a refractive index delta less than about −0.2% and a width of at least 1 micron, said depressed-index annular portion spaced from said core at least 0.5 microns.

[0008] In some embodiments that comprise a cladding with voids, the voids in some preferred embodiments are non-periodically located within the depressed-index annular portion. By "non-periodically located", we mean that when one takes a cross section (such as a cross section perpendicular to the longitudinal axis) of the optical fiber, the non-periodically disposed voids are randomly or non-periodically distributed across a portion of the fiber (e.g. within the depressed-index annular region). Similar cross sections taken at different points along the length of the fiber will reveal different randomly distributed cross-sectional hole patterns, i.e., various cross sections will have different hole patterns, wherein the distributions of voids and sizes of voids do not exactly match. That is, the voids or voids are non-periodic, i.e., they are not periodically disposed within the fiber structure. These voids are stretched (elongated) along the length (i.e. parallel to the longitudinal axis) of the optical fiber, but do not extend the entire length of the entire fiber for typical lengths of transmission fiber. It is believed that the voids extend along the length of the fiber a distance less than 20 meters, more preferably less than 10 meters, even more preferably less than 5 meters, and in some embodiments less than 1 meter.

[0009] The multimode optical fiber disclosed herein exhibits very low bend induced attenuation, in particular very low macrobending induced attenuation. In some embodiments, high bandwidth is provided by low maximum relative refractive index in the core, and low bend losses are also provided. Consequently, the multimode optical fiber may comprise a graded index glass core; and an inner cladding surrounding and in contact with the core, and a second cladding comprising a depressed-index annular portion surrounding the inner cladding, said depressed-index annular portion having a refractive index delta less than about −0.2 % and a width of at least 1 micron, wherein the width of said inner cladding is at least 0.5 microns and the fiber further exhibits a 1 turn 10 mm diameter mandrel wrap attenuation increase, of less than or equal to 0.4 dB/turn at 850 nm, a numerical aperture of greater than 0.14, more preferably greater than 0.17, even more preferably greater than 0.18, and most preferably greater than 0.185, and an overfilled bandwidth greater than 1.5 GHz-km at 850 nm.

[0010] Using the designs disclosed herein, 50 micron diameter core multimode fibers can be made which provide (a) an overfilled (OFL) bandwidth of greater than 1.5 GHz-km, more preferably greater than 2.0 GHz-km, even more preferably greater than 3.0 GHz-km, and most preferably greater than 4.0 GHz-km at a wavelength of 850 nm. These high bandwidths can be achieved while still maintaining a 1 turn 10 mm diameter mandrel wrap attenuation increase at a wavelength of 850 nm, of less than 0.5 dB, more preferably less than 0.3 dB, even more preferably less than 0.2 dB, and most preferably less than 0.15 dB. These high bandwidths can also be achieved while also maintaining a 1 turn 20 mm diameter mandrel wrap attenuation increase at a wavelength of 850 nm, of less than 0.2 dB, more preferably less than 0.1 dB, and most preferably less than 0.05 dB, and a 1 turn 15 mm diameter mandrel wrap attenuation increase at a wavelength of 850 nm, of less than 0.2 dB, preferably less than 0.1 dB, and more preferably less than 0.05 dB. Such fibers are further capable of providing a numerical aperture (NA) greater than 0.17, more preferably greater than 0.18, and most preferably greater than 0.185. Such fibers are further simultaneously capable of exhibiting an OFL bandwidth at 1300 nm which is greater than 500 MHz-km, more preferably greater than 600 MHz-km, even more preferably greater than 700 MHz-km. Such fibers are further simultaneously capable of exhibiting minimum calculated effective modal bandwidth (Min EMBc) bandwidth of greater than about 1.5 MHz-km, more preferably greater than about 1.8 MHz-km and most preferably greater than about 2.0 MHz-km at 850 nm.

[0011] Preferably, the multimode optical fiber disclosed herein exhibits a spectral attenuation of less than 3 dB/km at 850 nm, preferably less than 2.5 dB/km at 850 nm, even more preferably less than 2.4 dB/km at 850 nm and still more preferably less than 2.3 dB/km at 850 nm. Preferably, the multimode optical fiber disclosed herein exhibits a spectral attenuation of less than 1.0 dB/km at 1300 nm, preferably less than 0.8 dB/km at 1300 nm, even more preferably less than

0.6 dB/km at 1300 nm. In some embodiments it may be desirable to spin the multimode fiber, as doing so may in some circumstances further improve the bandwidth for optical fiber having a depressed cladding region. By spinning, we mean applying or imparting a spin to the fiber wherein the spin is imparted while the fiber is being drawn from an optical fiber preform, i.e. while the fiber is still at least somewhat heated and is capable of undergoing non-elastic rotational displacement and is capable of substantially retaining the rotational displacement after the fiber has fully cooled.

[0012] In some embodiments, the numerical aperture (NA) of the optical fiber is preferably less than 0.23 and greater than 0.17, more preferably greater than 0.18, and most preferably less than 0.215 and greater than 0.185.

[0013] In some embodiments, the core extends radially outwardly from the centerline to a radius R**1**, wherein $10 \leqq R1 \leqq 40$ microns, more preferably $20 \leqq R1 \leqq 40$ microns. In some embodiments, $22 \leqq R1 \leqq 34$ microns. In some preferred embodiments, the outer radius of the core is between about 22 to 28 microns. In some other preferred embodiments, the outer radius of the core is between about 28 to 34 microns.

[0014] In some embodiments, the core has a maximum relative refractive index, less than or equal to 1.2% and greater than 0.5%, more preferably greater than 0.8%. In other embodiments, the core has a maximum relative refractive index, less than or equal to 1.1% and greater than 0.9%.

[0015] In some embodiments, the optical fiber exhibits a 1 turn 10 mm diameter mandrel attenuation increase of no more than 1.0 dB, preferably no more than 0.6 dB, more preferably no more than 0.4 dB, even more preferably no more than 0.2 dB, and still more preferably no more than 0.1 dB, at all wavelengths between 800 and 1400 nm.

[0016] In a first aspect, multimode optical fiber is disclosed herein comprising a graded-index glass core, disposed about a longitudinal centerline, and a glass cladding surrounding the core. The cladding comprises an inner annular portion, a depressed-index annular portion, and an outer annular portion. The inner annular portion directly abuts the core, and the depressed-index annular portion directly abuts the inner annular region, and the inner annular portion preferably has a relative refractive index profile having a maximum absolute magnitude, $|\Delta|$, less than 0.05%. In some embodiments, the inner annular portion has a maximum relative refractive index, Δ_{2MAX}, less than 0.05%. All refractive indices are in reference to the outer annular portion as described below.

[0017] 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.

[0018] 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

[0019] FIG. **1** shows a schematic representation (not to scale) of the refractive index profile of a cross-section of the glass portion of an exemplary embodiment of multimode optical fiber disclosed herein wherein the depressed-index annular portion is offset from the core and is surrounded by an outer annular portion.

[0020] FIG. **2** is a schematic representation (not to scale) of a cross-sectional view of the optical waveguide fiber of FIG. **1**.

[0021] FIG. **3** illustrates modeled OFL bandwidth at 850 nm for a variety of fibers made in accordance with some embodiments of the invention.

[0022] FIG. **4** illustrates modeled OFL bandwidth at 1300 nm for a prior art fiber and a fiber made in accordance with some embodiments of the invention.

[0023] FIG. **5** illustrates 1×10 mm bend loss as a function of wavelength for a prior art fiber and fibers made in accordance with some embodiments of the invention.

[0024] FIG. **6** illustrates attenuation loss per turn vs. bend diameter for a prior art fiber and several fibers made in accordance with some embodiments of the invention.

DETAILED DESCRIPTION

[0025] Additional features and advantages of the invention will be set forth in the detailed description which follows and will be apparent to those skilled in the art from the description or recognized by practicing the invention as described in the following description together with the claims and appended drawings.

[0026] The "refractive index profile" is the relationship between refractive index or relative refractive index and waveguide fiber radius.

[0027] The "relative refractive index percent" is defined as $\Delta\% = 100 \times (n_i^2 - n_{REF}^2)/2n_i^2$, where n_i is the maximum refractive index in region i, unless otherwise specified. The relative refractive index percent is measured at 850 nm unless otherwise specified. Unless otherwise specified herein, n_{REF} is the average refractive index of the outer annular portion **60** of the cladding, which can be calculated, for example, by taking "N" index measurements (n_{C1}, n_{C2}, . . . n_{CN}) in the outer annular portion of the cladding, and calculating the average refractive index by:

$$n_C = (1/N)\sum_{i=1}^{i=N} n_{Ci}.$$

[0028] As used herein, the relative refractive index is represented by Δ and its values are given in units of "%", unless otherwise specified. In cases where the refractive index of a region is less than the reference index n_{REF}, the relative index percent is negative and is referred to as having a depressed region or depressed-index, and the minimum relative refractive index is calculated at the point at which the relative index is most negative unless otherwise specified. In cases where the refractive index of a region is greater than the reference index n_{REF}, the relative index percent is positive and the region can be said to be raised or to have a positive index. An "updopant" is herein considered to be a dopant which has a propensity to raise the refractive index relative to pure undoped SiO_2. A "downdopant" is herein considered to be a dopant which has a propensity to lower the refractive index relative to pure undoped SiO_2. An updopant may be present in a region of an optical fiber having a negative relative refractive index when accompanied by one or more other dopants which are not updopants. Likewise, one or more other dopants which are not updopants may be present in a region of an optical fiber having a positive relative refractive index. A downdopant may be present in a region of an optical fiber having a positive relative refractive index when accompanied by one or more other dopants which are not downdopants. Likewise, one or more other dopants which are not downdopants may be present in a region of an optical fiber having a negative relative refractive index.

[0029] Macrobend performance was determined according to FOTP-62 (IEC-60793-1-47) by wrapping 1 turn around either a 6 mm, 10 mm, 20 mm or 30 mm diameter mandrel (e.g. "1×10 mm diameter macrobend loss" or the "1×20 mm diameter macrobend loss") and measuring the increase in attenuation due to the bending using an encircled flux (EF) launch condition. The encircled flux was obtained by launching an overfilled pulse into an input end of a 2 m length of InfiniCor® 50 μm optical fiber which was deployed with a 1×25 mm diameter mandrel near the midpoint. The output end of the InfiniCor® 50 μm optical fiber was spliced to the fiber under test, and the measured bend loss is the ratio of the attenuation under the prescribed bend condition to the attenuation without the bend. The overfilled bandwidth was measured according to FOTP-204 using an overfilled launch. The minimum calculated effective modal bandwidth (Min EMBc) bandwidths were obtained from measured differential mode delay spectra as specified by TIA/EIA-455-220.

[0030] As used herein, numerical aperture of the fiber means numerical aperture as measured using the method set forth in TIA SP3 -2839-URV2 FOTP-177 IEC-60793-1-43 titled "Measurement Methods and Test Procedures-Numerical Aperture".

[0031] The term "α-profile" or "alpha profile" refers to a relative refractive index profile, expressed in terms of Δ(r) which is in units of "%", where r is radius, which follows the equation,

$$\Delta(r)=\Delta(r_o)(1-[|\tau-\tau_0|/(r_1-r_o)]^{\alpha}),$$

where r_o is the point at which Δ(r) is maximum, r_1 is the point at which Δ(r) % is zero, and r is in the range $r_i \leqq r \leqq \tau_f$, 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.

[0032] The depressed-index annular portion has a profile volume, V_3, defined herein as:

$$2\int_{R_{INNER}}^{R_{OUTER}} \Delta_3(r)r\,dr$$

where R_{INNER} is the depressed-index annular portion inner radius and R_{OUTER} is the depressed-index annular portion outer radius as defined below. For the fibers disclosed herein, the absolute magnitude of V_3 is preferably greater than 60%-μm^2, more preferably greater than 80%-μm^2, and even more preferably greater than 100%-μm^2. Preferably the absolute magnitude of V_3 is less than 400%-μm^2, more preferably less than 200%-μm^2, and even more preferably less than 150%-μm^2. In some preferred embodiments, the absolute magnitude of V_3 is greater than 60%-μm^2 and less than 200%-μm^2. In other preferred embodiments, the absolute magnitude of V_3 is greater than 80%-μm^2 and less than 150%-μm^2.

[0033] Multimode optical fiber disclosed herein comprises a core and a cladding surrounding and directly adjacent the core. In some embodiments, the core comprises silica doped with germanium, i.e. germania doped silica. Dopants other than germanium such as Al_2O_3 or P_2O_5, 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 refractive index profile of the optical fiber disclosed herein is non-negative from the centerline to the outer radius of the core. In some embodiments, the optical fiber contains no index-decreasing dopants in the core.

[0034] FIG. **1** shows a schematic representation of the refractive index profile of a cross-section of the glass portion of an embodiment of a multimode optical fiber comprising a glass core **20** and a glass cladding **200**, the cladding comprising an inner annular portion **30**, a depressed-index annular portion **50**, and an outer annular portion **60**. FIG. **2** is a schematic representation (not to scale) of a cross-sectional view of the optical waveguide fiber of FIG. **1**. The core **20** has outer radius R_1 and maximum refractive index delta $\mathbf{\Delta 1}_{MAX}$. The inner annular portion **30** has width W_2 and outer radius R_2. Depressed index annular portion **50** has minimum refractive index delta percent $\mathbf{\Delta 3}_{MIN}$, width W_3 and outer radius R_3. The depressed-index annular portion **50** is shown offset, or spaced away, from the core **20** by the inner annular portion **30**. The annular portion **50** surrounds and contacts the inner annular portion **30**. The outer annular portion **60** surrounds and contacts the annular portion **50**. The inner annular portion **30** has a refractive index profile $\mathbf{\Delta 2}(r)$ with a maximum relative refractive index $\mathbf{\Delta 2}_{MAX}$, and a minimum relative refractive index $\mathbf{\Delta 2}_{MLN}$, where in some embodiments $\mathbf{\Delta 2}_{MAX}=\mathbf{\Delta 2}_{MIN}$. The depressed-index annular portion **50** has a refractive index profile Δ3(r) with a minimum relative refractive index $\mathbf{\Delta 3}_{MIN}$. The outer annular portion **60** has a refractive index profile $\mathbf{\Delta 4}(r)$ with a maximum relative refractive index $\mathbf{\Delta 4}_{MAX}$, and a minimum relative refractive index $\mathbf{\Delta 4}_{MIN}$, where in some embodiments $\mathbf{\Delta 4}_{MAX}=\mathbf{\Delta 4}_{MIN}$. Preferably, $\mathbf{\Delta 1}_{MAX}>\mathbf{\Delta 2}_{MAX}>\mathbf{\Delta 3}_{MIN}$. In some embodiments, the inner annular portion **30** has a substantially constant refractive index profile, as shown in FIG. **1** with a constant $\mathbf{\Delta 2}(r)$; in some of these embodiments, $\mathbf{\Delta 2}(r)=0\%$. In some embodiments, the outer annular portion **60** has a substantially constant refractive index profile, as shown in FIG. **1** with a constant $\mathbf{\Delta 4}(r)$; in some of these embodiments, $\mathbf{\Delta 4}(r)=0\%$. The core **20** has an entirely positive refractive index profile, where $\mathbf{\Delta 1}(r)>0\%$. R_1 is defined as the radius at which the refractive index delta of the core first reaches value of 0.05%, going radially outwardly from the centerline. Preferably, the core contains substantially no fluorine, and preferably the core contains no fluorine. In some embodiments, the inner annular portion **30** preferably has a relative refractive index profile $\mathbf{\Delta 2}(r)$ having a maximum absolute magnitude less than 0.05%, and $\mathbf{\Delta 2}_{MAX}<0.05\%$ and $\mathbf{\Delta 2}_{MIN}>-0.05\%$, and the depressed-index annular portion **50** begins where the relative refractive index of the cladding first reaches a value of less than −0.05%, going radially outwardly from the centerline. In some embodiments, the outer annular portion **60** has a relative refractive index profile $\mathbf{\Delta 4}(r)$ having a maximum absolute magnitude less than 0.05%, and $\mathbf{\Delta 4}_{MAX}<0.05\%$ and $\mathbf{\Delta 4}_{MIN}>-0.05\%$, and the depressed-index annular portion **50** ends where the relative refractive index of the cladding first reaches a value of greater than −0.05%, going radially outwardly from the radius where $\mathbf{\Delta 3}_{MIN}$ is found.

[0035] In the multimode optical fiber disclosed herein, the core is a graded-index core, and preferably, the refractive index profile of the core has a parabolic (or substantially parabolic) shape; for example, in some embodiments, the refractive index profile of the core has an α-shape with an a value preferably between 1.9 and 2.3, more preferably about 2.1, as measured at 850 nm; in some embodiments, the refractive index of the core may have a centerline dip, wherein the maximum refractive index of the core, and the maximum refractive index of the entire optical fiber, is located a small distance away from the centerline, but in other embodiments the refractive index of the core has no centerline dip, and the maximum refractive index of the core, and the maximum refractive index of the entire optical fiber, is located at the centerline. The parabolic shape extends to a radius R_1 and preferably extends from the centerline of the fiber to R_1. As used herein, "parabolic" therefore includes substantially parabolically shaped refractive index profiles which may vary slightly from an a value of about 2.0, for example 1.9, 2.1 or 2.3, at one or more points in the core, as well as profiles with minor variations and/or a centerline dip. Referring to the Figures, the core **20** is defined to end at the radius R_1 where the parabolic shape ends, coinciding with the innennost radius of the cladding **200**.

[0036] One or more portions of the clad layer **200** may be comprised of a cladding material which was deposited, for example during a laydown process, or which was provided in the form of a jacketing, such as a tube in a rod-in-tube optical preform arrangement, or a combination of deposited material and a jacket. The clad layer **200** is surrounded by at least one coating **210**, which may in some embodiments comprise a low modulus primary coating and a high modulus secondary coating.

[0037] Preferably, the optical fiber disclosed herein has a silica-based core and cladding. In some embodiments, the cladding has an outer diameter, 2 times Rmax, of about 125 μm. Preferably, the outer diameter of the cladding has a constant diameter along the length of the optical fiber, wherein any fluctuations have a standard deviation not more than 1.0 μm. In some embodiments, the refractive index of the optical fiber has radial symmetry. Preferably, the outer diameter of the core has a constant diameter along the length of the optical fiber. In some embodiments, one or more coatings surround and are in contact with the cladding. The coating can be a polymer coating such as an acrylate-based polymer. In some embodiments, the coating has a constant diameter, radially and along the length of the fiber.

[0038] In some embodiments, the depressed-index annular portion comprises voids, either non-periodically disposed, or periodically disposed, or both. By "non-periodically disposed" or "non-periodic distribution", we mean that when one takes a cross section (such as a cross section perpendicular to the longitudinal axis) of the optical fiber, the non-periodically disposed voids are randomly or non-periodically distributed across a portion of the fiber. Similar cross sections taken at different points along the length of the fiber will reveal different cross-sectional hole patterns, i.e., various cross sections will have different hole patterns, wherein the distributions of voids and sizes of voids do not match. That is, the voids or voids are non-periodic, i.e., they are not periodically disposed within the fiber structure. These voids are stretched (elongated) along the length (i.e. parallel to the longitudinal axis) of the optical fiber, but do not extend the entire length of the entire fiber for typical lengths of transmission fiber. While not wishing to be bound by theory, it is believed that the voids extend less than a few meters, and in many cases less than 1 meter along the length of the fiber. Optical fiber disclosed herein can be made by methods which utilize preform consolidation conditions which are effective to result in a significant amount of gases being trapped in the consolidated glass blank, thereby causing the formation of voids in the consolidated glass optical fiber preform. Rather than taking steps to remove these voids, the resultant preform is used to form an optical fiber with voids, or voids, therein. As used herein, the diameter of a hole is the longest line segment whose endpoints are disposed on the silica internal surface defining the hole when the optical fiber is viewed in perpendicular cross-section transverse to the longitudinal axis of the fiber.

[0039] In some embodiments, the inner annular portion **30** comprises silica which is substantially undoped with either fluorine or germania. Preferably, the annular portion **30** comprises an inner radius of about 23 microns to 27 microns and an outer radius of less than 28 to 31 microns. Preferably, the annular portion **30** comprises a width of greater than about 0.5 and less than about 4 microns, more preferably greater than about 1.0 and less than about 3.0 microns, most preferably greater than about 1.0 and less than about 2.0 microns. In some embodiments, the outer annular portion **60** comprises substantially undoped silica, although the silica may contain some amount of chlorine, fluorine, germania, or other dopants in concentrations that collectively do not significantly modify the refractive index. In some embodiments, the depressed-index annular portion **50** comprises silica doped with fluorine. In some other embodiments, the depressed-index annular portion **50** comprises silica comprising a plurality of non-periodically disposed voids. The voids can contain one or more gases, such as argon, nitrogen, krypton, CO_2, SO_2, or oxygen, or the voids can contain a vacuum with substantially no gas; regardless of the presence or absence of any gas, the refractive index in the annular portion **50** is lowered due to the presence of the voids. The voids can be randomly or non-periodically disposed in the annular portion **50** of the cladding **200**, and in other embodiments, the voids are disposed periodically in the annular portion **50**. Alternatively, or in addition, the depressed index in annular portion **50** can also be provided by downdoping the annular portion **50** (such as with fluorine) or updoping one or more portions of the cladding and/or the core, wherein the depressed-index annular portion **50** is, for example, silica which is not doped as heavily as the inner annular portion **30**. Preferably, the minimum relative refractive index, or average effective relative refractive index, such as taking into account the presence of any voids, of the depressed-index annular portion **50** is preferably less than −0.1%, more preferably less than about −0.2 percent, even more preferably less than about −0.3 percent, and most preferably less than about −0.4 percent.

[0040] In one set of embodiments, the multimode optical fiber comprises a graded-index, preferably parabolic (substantially parabolic), glass core **20** and glass cladding **200** as depicted in FIG. **1**, wherein the core ends at a radius R_1, which marks the end of the graded index core or parabolic shape. The core **20** is surrounded by and in direct contact with the inner annular portion **30**, which has a substantially constant refractive index profile $\Delta 2(r)$. The inner annular portion **30** is surrounded by and in direct contact with the depressed-index annular portion **50**, and the depressed-index annular portion **50** is surrounded by and in direct contact with the outer annular portion **60**, which has a substantially constant refractive index profile $\Delta 4(r)$. The depressed-index annular portion

50 may comprise a plurality of voids. In some of this set of embodiments, the core **20** comprises germania doped silica, the inner annular portion **30** comprises pure silica, and the outer annular portion **60** comprises pure silica; in some of these embodiments, the depressed-index annular portion **50** comprises hole-free fluorine-doped silica; in others of these embodiments, the depressed-index annular portion **50** comprises a plurality of voids in pure silica; and in yet others of these embodiments, the depressed-index annular portion **50** comprises a plurality of voids in fluorine-doped silica. In embodiments where the inner annular portion **30** comprises pure silica and the depressed-index annular portion **50** comprises pure silica with a plurality of voids, the depressed-index annular portion **50** starts at the innermost radius of the innermost hole. In embodiments where the outer annular portion **60** comprises pure silica, and the depressed-index annular portion **50** comprises pure silica with a plurality of voids, the depressed-index annular portion **50** ends at the outermost radius of the outermost hole.

[0041] The numerical aperture (NA) of the optical fiber is preferably greater than the NA of the optical source directing signals into the fiber; for example, the NA of the optical fiber is preferably greater than the NA of a VCSEL source.

[0042] FIG. **2** is a schematic representation (not to scale) of a cross-sectional view of an optical waveguide fiber **100** as disclosed herein having core **20** and a cladding **200** directly adjacent and surrounding the core **20**, the cladding **200** being comprised of an inner annular portion **30**, a depressed-index annular portion **50**, and an outer annular portion **60**.

[0043] Referring to FIG. **1** as one exemplary depiction of a refractive index profile of a multimode optical fiber disclosed herein, the cladding **200** comprises: an inner annular portion **30** surrounding the core **20** and directly adjacent thereto, and extending radially outwardly to an inner annular portion outer radius, R_2, and having a width W_2 disposed at a midpoint R_{2MID}, the portion **30** having a relative refractive index profile, $\Delta_2(r)$ in %, with a maximum relative refractive index percent, Δ_{2MAX}, in %, a minimum relative refractive index percent, Δ_{2MIN}, in %, and a maximum absolute magnitude relative refractive index percent, $|\Delta_2(r)|_{MAX}$; a depressed-index annular portion (or "ring") **50** surrounding portion **30** and directly adjacent thereto, and extending radially outwardly from R_2 to a depressed-index annular portion radius, R_3, the portion **50** having a width W_3 disposed at a midpoint R_{3MID}, and having a relative refractive index profile, $\Delta_3(r)$ in %, with a minimum relative refractive index percent, Δ_{3MIN}, in %, wherein $\Delta_{1MAX}>0>\Delta_{3MIN}$; and an outer annular portion **60** surrounding the portion **50** and directly adjacent thereto and having a relative refractive index percent, Δ_4 (r) in %. R_1 is defined as the radius at which the refractive index delta of the core first reaches value of 0.05%, going radially outwardly from the centerline. That is, core **20** ends and the annular inner portion **30** starts at a radius R**1**, and portion **30** is defined to end at a radius R**2**. The depressed-index annular portion **50** begins at R_2 and ends at R_3. The width W_3 of the annular portion **50** is R_3-R_2 and its midpoint R_{3MID} is $(R_2+R_3)/2$. In some embodiments, $|\Delta_2(r)|<0.025\%$ for more than 50% of the radial width of the annular inner portion **30**, and in other embodiments $|\Delta_2(r)|<0.01\%$ for more than 50% of the radial width of the annular inner portion **30**. Cladding **200** extends to a radius, R_4, which is also the outermost periphery of the glass part of the optical fiber. In some embodiments, $R_4>40$ μm; in other embodiments, $R_4>50$ μm, and in other embodiments, $R_4>60$ μm, and in some embodiments, 60 μm<R_4<70 μm.

[0044] In some embodiments, W_3 is greater than 0.5 and less than 10 μm, more preferably greater than 1.0 μm and less than 8 μm, even more preferably greater than 2 μm and less than 6 μm.

Set forth below in Table 1 are a variety of modeled examples in accordance with the present invention.

TABLE 1

	Example 1	Example 2	Example 3	Example 4
$\Delta1_{MAX}$ (%)	1.01	1.01	1.01	1.01
R1 (μm)	25	25	25	25
Alpha	2.096	2.096	2.096	2.096
Δ_2 (%)	0	0	0	0
R2 (μm)	25.9	26.3	26.5	26.7
W2 (μm)	0.9	1.3	1.5	1.7
Δ_{3MIN} (%)	−0.2	−0.4	−0.6	−1.3
R3 (μm)	29.25	29.25	29.25	29.25
W3 (μm)	3.35	2.95	2.75	2.55
Δ_4 (%)	0	0	0	0
R4 (μm)	62.5	62.5	62.5	62.5
Peak Bandwidth at 850 nm (MHz-km)	18600	18800	18700	19200

Set forth below in Table 2 are a variety of example optical fibers made in accordance with the present invention, as well as measured properties for each fiber.

TABLE 2

	Example 5	Example 6	Example 7	Example 8
$\Delta1_{MAX}$ (%)	1.1	1.05	1.08	1.1
R1 (μm)	25	25.1	24.25	24
Alpha	2.1	2.12	2.12	2.12
Δ_2 %)	0.008	0	0.012	0
R2 (μm)	n/a	n/a	26.75	26.25
W2 (μm)	0	0	2.5	2.25
Δ_{3MIN} (%)	0	−0.85	−0.85	−0.33
R3 (μm)	n/a	28	29.75	30.25
W2 (μm)	0	3	3	4
Δ_4 (%)	0	0	0	0
R4 (μm)	62.5	62.5	62.5	62.5
OFL Bandwidth at 850 nm (MHz-km)	1170	343	1451	1590
Minimum EMBc Bandwidth at 850 nm (MHz-km)	1087	516	1581	1816
OFL Bandwidth at 1300 nm (MHz-km)	880	158	669	474
1 × 30 mm macrobend (dB)	0.088	0.003	0.073	0.006
1 × 20 mm macrobend (dB)	0.209	0.013	0.121	0.015
1 × 10 mm macrobend (dB)	0.807	0.104	0.445	0.109
1 × 6 mm macrobend (dB)	n/a	n/a	2.26	0.57

EXAMPLE 5—COMPARATIVE

[0045] Corning Incorporated InfiniCor® optical fiber having a core diameter of 50 μm and a 125 micron glass fiber diameter was fabricated comprising a 50 micron diameter core of GeO_2—SiO_2 graded index (1% maximum Δ relative to the pure silica cladding with a parabolic (α=2.1) shape) and a solid silica cladding (with no depressed annular region).

EXAMPLE 6—COMPARATIVE

[0046] 2200 grams of SiO_2 (0.36 g/cc density) soot were flame deposited onto a 1 meter long×24.8 mm diameter solid glass cane of GeO_2—SiO_2 graded index core (1% maximum refractive index relative to pure silica with a parabolic (α=2.1) shape). This assembly was then sintered as follows. The assembly was first dried for 2 hours in an atmosphere consisting of helium and 3 percent chlorine at 1000° C. followed by down driving at 32 min/min through a hot zone set at 1500° C. in an atmosphere comprising 50 percent nitrogen and 50 percent helium, then re-down-driven through the hot zone at 25 mm/min in the same atmosphere, then final sintered in an atmosphere comprising 50 percent nitrogen and 50 percent helium at 6 mm/min, in order to sinter the soot to an "nitrogen-seeded" first overclad preform comprising a void-free GeO_2—SiO_2 graded index core surrounded by a "nitrogen-seeded" cladding layer. The preform was placed for 24 hours in an argon purged holding oven set at 1000° C. The preform was then placed on a lathe where 5910 grams of SiO_2 soot were flame deposited onto the 1 meter long cane. This assembly was then sintered as follows. The assembly was first dried for 2 hours in an atmosphere consisting of helium and 3 percent chlorine at 1000° C. followed by down driving at 6 mm/min through a hot zone set at 1500° C. in a 100 percent helium atmosphere, in order to sinter the soot to an optical preform comprising a void-free GeO_2—SiO_2 graded index core, a "nitrogen-seeded" first cladding layer and a void-free silica outer cladding. The preform was placed for 24 hours in an argon purged holding oven set at 100° C. The preform was drawn to an 8.8 km length of 125 micron diameter fiber at 10 m/s using a draw furnace having a hot zone of about 8 cm length and set at approximately 2000° C. The measured OEL bandwidths of this fiber were 516 and 158 MHz-km at 850 and 1300 nm, respectively. The low bandwidths are due to the absence of an inner annular region between the graded index core and the depressed annular region.

EXAMPLE 7

[0047] 320 grams of SiO_2 (0.36 g/cc density) soot were flame deposited onto a 1 meter long×28 mm diameter solid glass cane with a core/clad (clad=cane diameter) ratio of 0.93 and comprising a GeO_2—SiO_2 graded index core (1% maximum refractive index relative to pure silica with a parabolic (α=2.1) shape) and a silica first cladding layer. This assembly was then sintered as follows. The assembly was first dried for 2 hours in an atmosphere consisting of helium and 3 percent chlorine at 1000° C. followed by down driving at 32 mm/min through a hot zone set at 1500° C. in an atmosphere comprising 50 percent nitrogen and 50 percent helium, then re-down-driven through the hot zone at 25 mm/min in the same atmosphere, then final sintered in an atmosphere comprising 50 percent nitrogen and 50 percent helium at 6 mm/min, in order to sinter the soot to form a "nitrogen-seeded" preform comprising a void-free GeO_2—SiO_2 graded index core, a silica first cladding layer and a "nitrogen-seeded" second cladding layer. The preform was placed for 24 hours in an argon purged holding oven set at 1000° C. The preform was drawn into a 1 meter×24.9 mm diameter cane, which was then placed on a lathe where 3525 grams of SiO_2 soot were flame deposited. This assembly was then sintered as follows. The assembly was first dried for 2 hours in an atmosphere consisting of helium and 3 percent chlorine at 1000° C. followed by down driving at 6 mm/min through a hot zone set at 1500° C. in a 100 percent helium atmosphere, in order to sinter the soot to an optical preform comprising void-free GeO_2—SiO_2 graded index core, a silica first cladding layer, a "nitrogen-seeded" second cladding layer and a void-free silica outer cladding. The preform was placed for 24 hours in an argon purged holding oven set at 1000° C. The preform was drawn to a 8.8 km length of 125 micron diameter fiber at 10 m/s using a draw furnace having a hot zone of about 8 cm length and set at approximately 2000° C. SEM image analysis at 900 and 4000 fold magnification of the end face of these fibers showed an approximate 24.3 micron radius void-free solid silica-germania core **20** surrounded by a approximate 26.8 micron outer radius void-free solid silica containing inner annular portion **30** surrounded by a approximate 29.8 micron outer radius void-containing depressed index annular portion **50** (total ring thickness, W_3, of approximately 3 microns radially) comprising approximately 200 voids in region **50** of approximately 0.2 micron mean diameter with the maximum, minimum and standard deviation of approximately 0.4, 0.03 and 0.07 microns respectively, which is surrounded by a void-free silica outer annular cladding portion **60** having an outer diameter of about 125 microns (all radial dimensions measured from the center of the optical fiber). The overall void containing ring region comprised about 1 percent regional area percent holes (100 percent N_2 by volume). The total fiber void area percent (area of the holes divided by total area of the optical fiber cross-section×100) was about 0.06 percent.

EXAMPLE 8

[0048] 427 grams of SiO_2 (0.36 g/cc density) soot were flame deposited onto a 1 meter long×27.5 mm diameter solid glass cane comprising a GeO_2—SiO_2 graded index core (1% maximum refractive index relative to pure silica with a parabolic (α=2.1) shape) with a silica inner cladding layer and a core/clad (clad=cane diameter) ratio of 0.95. This assembly was then sintered as follows. The assembly was first dried for 2 hours in an atmosphere consisting of helium and 3 percent chlorine at 1125° C. followed by fluorine doping the soot preform in an atmosphere consisting of helium and 20 percent SiF_4 at 1125° C. for 4 hours then down driving at 14 mm/min through a hot zone set at 1480° C. in a 100 percent helium atmosphere in order to sinter the soot to an overclad preform comprising a germania-silica graded index core, a silica inner cladding, and a fluorine-doped second cladding layer. The preform was drawn into a 1 meter×25.0 mm diameter cane, which was then placed on a lathe where 3538 grams of SiO_2 soot were flame deposited. This assembly was then sintered as follows. The assembly was first dried for 2 hours in an atmosphere consisting of helium and 3 percent chlorine at 1000° C. followed by down driving at 6 mm/min through a hot zone set at 1500° C. in a 100 percent helium atmosphere, in order to sinter the soot to a void-free optical preform comprising a GeO_2—SiO_2 graded index core, a silica first cladding layer, a fluorine-doped second cladding layer and a silica outer cladding. The preform was placed for 24 hours in an argon purged holding oven set at 1000° C. The preform was drawn to an 8.8 km length of 125 micron diameter fiber at 10 m/s using a draw furnace having a hot zone of about 8 cm length and set at approximately 2000° C.

[0049] FIG. **3** illustrates modeled OFL bandwidth at 850 nm for a variety of fibers made in accordance with some embodiments of the invention. Each of the fibers illustrated in FIG. **3** correspond to the fibers set forth in Table 1 above. As can be seen in FIG. **3**, a peak OFL bandwidth at 850 nm higher than 6000, more preferably higher than 8000, even more preferably higher than 8000, and even as high as greater than 18000 MHz-km can be achieved using these fiber designs. Furthermore, these examples illustrate that these high bandwidths are achieved when the annular portion **30** comprises a width W_2 greater than about 0.5 and less than about 4 microns, more preferably greater than about 1.0 and less than about 3.0 microns, most preferably greater than about 1.0 and less than about 2.0 microns.

[0050] FIG. **4** illustrates modeled OFL bandwidth at 1300 nm versus core alpha for a prior art fiber and a fiber made in accordance with some embodiments of the invention. The addition of the depressed annular ring results in a higher OFL bandwidth at 1300 nm compared to a comparative fiber without a depressed annular region.

[0051] FIG. **5** illustrates 1×10 mm bend loss as a function of wavelength for a prior art fiber (Example 5) and three fibers set forth in Table 2 which were made in accordance with various embodiments of the invention. As can be seen in FIG. **5**, fibers having a 1×10 mm bend loss less than 0.6 dB, more preferably less than 0.4, and even more preferably less than about 0.3 dB have been achieved across the entire bandwidth region from 800 to 1400 nm. At 850 nm, the attenuation increase with a 1 turn 10 mm diameter mandrel wrap is less than 0.5 dB, more preferably less than 0.3 dB, even more preferably less than 0.2 dB, and most preferably less than 0.15 dB.

[0052] FIG. **6** illustrates attenuation loss at 850 nm per turn vs. bend diameter for a prior art fiber (Example 5) and three fibers set forth in Table 2 which were made in accordance with various embodiments of the invention. As can be seen in FIG. **6**, fibers were made which exhibited a bend loss less than or equal to about 0.1 dB/turn at 10 mm diameter, less than 0.05 dB/turn at 20 mm diameter, and less than 0.01 dB/turn at 30 mm diameter.

EXAMPLE 9 AND 10

[0053] 71.3 grams of SiO_2 (0.36 g/cc density) soot were flame deposited onto a 1 meter long×26.0 mm diameter solid glass core cane comprising a GeO_2—SiO_2 graded index core glass (0.95% maximum refractive index relative to pure silica with a parabolic (α=2.1) shape). This assembly was then sintered as follows. The assembly was first dried for 2 hours in an atmosphere consisting of helium and 3 percent chlorine at 1000° C. followed by down driving at 6 mm/min through a hot zone set at 1500° C. in a 100 percent helium atmosphere, in order to sinter the soot to an optical preform comprising a void-free GeO_2—SiO_2 graded index core and a silica first cladding layer with a core/clad (clad=outer diameter of cane after silica deposition and sintering) ratio of 0.96. This optical preform was drawn into a 1 meter long cane with an outer diameter of 20.1 mm. 246 grams of SiO_2 (0.36 g/cc density) soot were then flame deposited onto the 1 meter long×20.1 mm diameter solid glass cane comprising a GeO_2—SiO_2 graded index core (0.95% maximum refractive index relative to pure silica with a parabolic (α=2.1) shape) with a silica inner cladding layer and a core/clad (clad=cane diameter) ratio of 0.96. This assembly was then sintered as follows. The assembly was first dried for 2 hours in an atmosphere consisting of helium and 3 percent chlorine at 1125° C. followed by fluorine doping the soot preform in an atmosphere consisting of helium and 20 percent SiF_4 at 1125° C. for 4 hours then down driving at 14 mm/min through a hot zone set at 1480° C. in a 100 percent helium atmosphere in order to sinter the soot to an overclad preform comprising a germania-silica graded index core, a silica inner cladding, and a fluorine-doped second cladding layer. The preform was then placed on a lathe where 2892 grains of SiO_2 soot were flame deposited. This assembly was then sintered as follows. The assembly was first dried for 2 hours in an atmosphere consisting of helium and 3 percent chlorine at 1000° C. followed by down driving at 6 mm/min through a hot zone set at 1500° C. in a 100 percent helium atmosphere, in order to sinter the soot to a void-free optical preform comprising GeO_2—SiO_2 graded index core, a silica first cladding layer, a fluorine-doped second cladding layer and a void-free silica outer cladding. The preform was placed for 24 hours in an argon purged holding oven set at 1000° C. The preform was drawn to an 8.8 km length of 125 micron diameter fiber at 10 m/s using a draw furnace having a hot zone of about 8 cm length and set at approximately 2000° C. A near field measurement of the optical fiber verified that the refractive index profile is comprised of a graded index core with a radius **R1**=25.4 μm and a maximum refractive index $\Delta\mathbf{1}_{MAX}$=0.95%, an inner cladding layer with **R2**=26.4 μm, $\Delta\mathbf{2}_{MIN}$>−0.05% and $\Delta\mathbf{2}_{MAX}$<0.05%, a depressed annular region with **R3**=31.6 μm, $\Delta\mathbf{3}_{MIN}$=−0.4% and a volume **V3**=−121%-μm^2, and a silica outer cladding with **R4**=62.5 μm and an average refractive index of 0.0%.

[0054] Table 3 illustrates the actual measured optical properties of the fiber described in Example 9 and an additional fiber (Example 10) made according to the invention. Example 10 was made using a process similar to that disclosed above for Example 9, except where noted. These examples illustrate that high bandwidths and low bend losses can be achieved when the annular portion **30** comprises a width W_2 greater than about 0.5 and less than about 4 microns, more preferably greater than about 1.0 and less than about 3.0 microns, most preferably greater than about 1.0 and less than about 2.0 microns.

TABLE 3

	Example 9	Example 10
Δ1%	0.95	0.94
Δ3MIN %	−0.4	−0.44
R1 (μm)	25.4	25.3
R2 (μm)	26.4	26.5
R3 (μm)	31.6	31.3
W2 (μm)	1.0	1.2
W3 (μm)	5.18	4.77
V3 (%-μm2)	−121.2	−115.8
Attenuation at 850 nm (dB/km)	2.198	2.184
Attenuation 1300 nm (dB/km)	0.437	0.411
Numerical Aperture	0.2026	0.1962
Overfilled Bandwidth at 850 (MHz-km)	2849	2591
Minimum effective modal bandwidth (MHz-km)	3854	2319
Overfilled Bandwidth at 1300 (MHz-km)	765	664
10 mm macrobend at 850 nm (dB/turn)	0.061	0.096
15 mm macrobend at 850 nm (dB/turn)	0.014	0.036
20 mm macrobend at 850 nm (dR/turn)	0.007	0.023

Set forth below in Table 4 are a variety of modelled fiber examples in accordance with the present invention. These examples illustrate that high bandwidths and low bend losses are achieved when the annular portion **30** comprises a width W_2 greater than about 0.5 and less than about 4 microns, more preferably greater than about 1.0 and less than about 3.0

microns. The 1×10 mm macrobend loss is less than 0.6 dB, more preferably less than 0.4, and even more preferably less than about 0.3 dB across the entire bandwidth region from 800 to 1400 nm. At 850 nm, the attenuation increase with a 1 turn 10 mm diameter mandrel wrap is less than 0.5 dB, more preferably less than 0.3 dB, even more preferably less than 0.2 dB, and most preferably less than 0.15 dB. The 1×15 mm macrobend loss is less than 0.2 dB, preferably less than 0.1 dB, and more preferably less than 0.06 dB.

The examples in Table 4 also illustrate that a reduction in the maximum refractive index of the central core enables very high bandwidths at 850 and 1300 nm while maintaining a numerical aperture greater than 0.14, more preferably greater than 0.15, even more preferably greater than 0.16 and most preferably greater than 0.185. In some preferred embodiments, the numerical aperture is greater than 0.185 and less than 0.215. The overfilled bandwidth at 850 nm is greater than 5000 MHz-km, preferably greater than 10000 MHz-km, more preferably greater than 20000 MHz-km and even more preferably greater than 40000 MHz-km. The overfilled bandwidth at 1300 nm is greater than 500 MHz-km, preferably greater than 700 MHz-km, and more preferably greater than 1000 MHz-km.

TABLE 4

	Example 11	Example 12	Example 13	Example 14	Example 15
Δ1%	0.936	0.84	0.75	0.66	0.58
Core Alpha	2.1006	2.1002	2.1015	2.1021	2.1021
Δ3MIN %	−0.4	−0.4	−0.4	−0.45	−0.45
R1 (μm)	25	25	25	25	25
R2 (μm)	26.71	26.75	26.88	27.03	27.14
R3 (μm)	30.6	30.7	31.4	30.94	31.5
W2 (μm)	1.71	1.75	1.88	2.03	2.14
W3 (μm)	3.89	3.95	4.52	3.91	4.36
V3 (%-μm2)	−89	−91	−105	−102	−115
Numerical Aperture	0.201	0.190	0.179	0.168	0.157
Overfilled Bandwidth at 850 (MHz-km)	22634	30081	35796	50386	67469
Overfilled Bandwidth at 1300 (MHz-km)	731	874	1063	1070	1343
10 mm macrobend at 850 nm (dB/turn)	0.103	0.110	0.127	0.133	0.146
15 mm macrobend at 850 nm (dB/turn)	0.040	0.043	0.049	0.052	0.057

[0055] It is to be understood that the foregoing description is exemplary of the invention only and is intended to provide an overview for the understanding of the nature and character of the invention as it is defined by the claims. The accompanying drawings are included to provide a further understanding of the invention and are incorporated and constitute part of this specification. The drawings illustrate various features and embodiments of the invention which, together with their description, serve to explain the principals and operation of the invention. It will become apparent to those skilled in the art that various modifications to the preferred embodiment of the invention as described herein can be made without departing from the spirit or scope of the invention as defined by the appended claims.

What is claimed is:

1. A multimode optical fiber comprising:

a graded index glass core; and

an inner cladding surrounding and in contact with the core, and a second cladding comprising a depressed-index annular portion surrounding the inner cladding, said depressed-index annular portion having a refractive index delta less than about −0.2% and a width of at least 1 micron, wherein the width of said inner cladding is at least 0.5 microns and less than 4 microns.

2. The optical fiber of claim **1**, wherein said inner cladding has a refractive index delta greater than −0.05% and less than 0.05% and comprises an inner radius of about 25 microns and the width of said inner cladding is at least 1 micron.

3. The optical fiber of claim **1**, wherein the width of said inner cladding is less than 3 microns.

4. The fiber of claim **1**, wherein said fiber further exhibits a 1 turn 30 mm diameter mandrel wrap attenuation increase of less than or equal to 0.1 dB/turn at 850 nm.

5. The fiber of claim **1**, wherein said fiber further exhibits a 1 turn 20 mm diameter mandrel wrap attenuation increase, of less than or equal to 0.1 dB/turn at 850 nm.

6. The fiber of claim **1**, wherein said fiber further exhibits a 1 turn 10 mm diameter mandrel wrap attenuation increase, of less than or equal to 0.5 dB/turn at 850 nm.

7. The fiber of claim **2**, wherein said depressed-index annular portion has a width greater than 2 microns.

8. The fiber of claim **7**, wherein said depressed-index annular portion has a width less than 10 microns.

9. The fiber of claim **1**, wherein said fiber further exhibits an overfilled bandwidth greater than 1.5 GHz-km at 850 nm.

10. The fiber of claim **1**, wherein said fiber further exhibits an overfilled bandwidth greater than 2.0 GHz-km at 850 nm.

11. The fiber of claim **1**, wherein said fiber further exhibits an overfilled bandwidth greater than 4.0 GHz-km at 850 nm.

12. The fiber of claim **1**, wherein said fiber further exhibits an overfilled bandwidth greater than 500 MHz-km at 1300 nm.

13. The fiber of claim **1**, wherein said depressed-index annular portion exhibits a refractive index delta less than −0.3 percent.

14. The fiber of claim **1**, wherein said depressed-index annular portion exhibits a refractive index delta less than −0.4 percent.

15. The fiber of claim **1**, wherein said depressed-index annular portion comprises fluorine doped silica.

16. The fiber of claim **1**, wherein said depressed-index annular portion comprises a plurality of non-periodically disposed voids.

17. The fiber of claim **1** wherein the maximum refractive index delta of the graded index glass core is greater than 0.5% and less than 1.2%.

18. The fiber of claim **1** wherein the 1 turn 10 mm diameter attenuation increase is less than 0.6 dB for all wavelengths between 800 and 1400 nm.

19. A multimode optical fiber comprising:

a graded index glass core; and

an inner cladding surrounding and in contact with the core, and a second cladding comprising a depressed-index annular portion surrounding the inner cladding, said depressed-index annular portion having a refractive index delta less than about −0.2% and a width of at least 1 micron, wherein the width of said inner cladding is at least 0.5 microns and said fiber further exhibits a 1 turn 10 mm diameter mandrel wrap attenuation increase, of less than or equal to 0.4 dB/turn at 850 nm, and an overfilled bandwidth greater than 1.5 GHz-km at 850 nm.

20. The multimode fiber of claim **19** further comprising a numerical aperture of greater than 0.18.

21. The multimode fiber of claim **19**, wherein said depressed-index annular portion comprises fluorine.

22. The multimode fiber of claim **19**, wherein said fiber further exhibits an overfilled bandwidth greater than 2.0 GHz-km at 850 nm.

23. The multimode fiber of claim **1** further comprising a numerical aperture of greater than 0.14.

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