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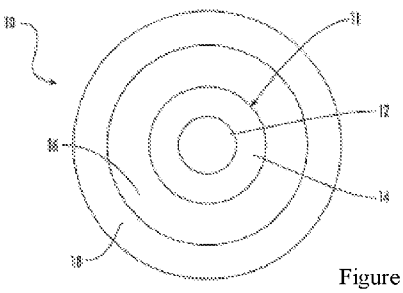


Figure 1

(57) Abstract: An optical fiber is provided that includes a core region, a cladding region having a radius less than about 62.5 microns; a polymer coating comprising a high-modulus layer and a low-modulus layer, wherein a thickness of the low-modulus inner coating layer is in a range of 4 microns to 20 microns, the modulus of the low-modulus inner coating layer is less than or equal to about 0.35 MPa, a thickness of the high-modulus coating layer is in a range of 4 microns to 20 microns, the modulus of the high-modulus inner coating layer is greater than or equal to about 1.6 GPa, and wherein a puncture resistance of the optical fiber is greater than 20 g, and wherein a microbend attenuation penalty of the optical fiber is less than 0.03 dB/km, and wherein an outer diameter of the coated optical fiber is less than or equal to 175 microns.

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SINGLE-MODE OPTICAL FIBER WITH THIN COATING FOR HIGH DENSITY CABLES AND INTERCONNECTS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority under 35 U.S.C. § 119 of U.S. Provisional Application Serial No. 63/054,563 filed on July 21, 2020, the content of which is relied upon and incorporated herein by reference in its entirety.

FIELD OF THE DISCLOSURE

[0002] This disclosure pertains to single-mode optical fibers. More particularly, this disclosure pertains to small diameter single-mode optical fibers. Most particularly, this disclosure pertains to small diameter single-mode optical fibers having a reduced coating thickness without a significant decrease in puncture resistance

BACKGROUND OF THE DISCLOSURE

[0003] Optical fiber technology is penetrating data centers due to cloud computing and internet of things that require high bandwidth, reduced latency, low power consumption, and immunity to EMI/RFI. Future hyper-scale data centers need special features such as 100K servers spreading over half-million square feet, thus generating a need for increased capacity, flexibility, and efficiency in the interconnection schemes within the data center. A large number of interconnects are thus needed within the data center. Ribbon cables allow higher fiber counts; however, these higher fiber counts will require smaller diameter fibers to fit into the ribbon cables. For example, using a 125 μm overall diameter bare fiber ribbon cable instead of a 250 μm overall diameter two-layer acrylate coated fiber ribbon cable results in a volume reduction of at least 75%. However, processing a bare fiber into a ribbon cable can cause the breakage of fiber.

[0004] In addition, submarine fiber optical cables are designed to carry telecommunication signals across stretches of land, ocean and sea. Over the past several years, there has been a dramatic increase in telecommunications signals over submarine cables, with greater than ninety percent of inter-continental communication signals currently being transmitted over these cables. Thus, the demand for the transmission capacity of such submarine cables has increased, driven by the growth of internet traffic among different continents. This growth of capacity has traditionally been driven by increasing the bandwidth capacity of each fiber, for example, but

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increasing the bit rate or using dense-wavelength division multiplexing (DWDM), while keeping the fiber count small – typically between four and eight fiber pairs.

[0005] However, implementing these advanced transmission technologies has driven the electrical power consumption of the optical repeaters in this system beyond the level that can be supplied from the terminals. This power constraint is forcing submarine system designers to utilize higher fiber counts, and these higher fiber counts will require smaller diameter fibers to fit into the limited space inside the optical repeaters. The cladding diameter of these fibers preferably needs to be maintained at 125 microns to facilitate fusion splicing to conventional single-mode fibers, which means that the smaller diameter is achieved by reducing the thickness of the protective coating. This thinner coating needs to have a high modulus combined with a sufficiently large cross-sectional area to ensure high resistance to punctures and abrasions.

[0006] Improvements in the foregoing are desired. Accordingly, the inventors have developed improved thin-coated single-mode optical fibers that have sufficiently high mechanical reliability.

SUMMARY

[0007] According to a first embodiment of the present disclosure, the present description extends to an optical fiber having: a core region; a cladding region surrounding the core region, the cladding region comprising: an inner cladding directly adjacent to the core region, and an outer cladding surrounding the inner cladding, wherein a radius of the cladding region is less than about 62.5 microns; and a polymer coating comprising a high-modulus coating layer surrounding the cladding region and a low-modulus coating layer disposed between the cladding region and the high-modulus coating layer, wherein a thickness of the low-modulus inner coating layer is in a range of 4 microns to 20 microns, the modulus of the low-modulus inner coating layer is less than or equal to about 0.35 MPa, a thickness of the high-modulus coating layer is in a range of 4 microns to 20 microns, the modulus of the high-modulus inner coating layer is greater than or equal to about 1.6 GPa, and wherein a puncture resistance of the optical fiber is greater than 20 g, and wherein a microbend attenuation penalty of the optical fiber is less than 0.03 dB/km, and wherein an outer diameter of the coated optical fiber is less than or equal to 175 microns, wherein the puncture resistance of the optical fiber is calculated by equation $P_R=P_0 + C_1E_sA_s$, wherein A_S is the cross-sectional area of the high-modulus coating, wherein E_S is the elastic moduli of the high-modulus coating, wherein P_0 is a coefficient having a value of 11.3 g and C_1 is a coefficient having a value of 2.1 g/MPa/mm^2, wherein the microbend attenuation penalty of the optical fiber is calculated by equation:

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$MAP = C_0 f_0 \sigma \frac{f_{RIP} f_g(E_g, R_g) f_p(E_p, t_p)}{f_{cs}\left(\frac{E_s}{E_p}, R_s, t_s\right)}$, wherein f_0 is the average lateral pressure of the external surface in contact with the high modulus coating, wherein σ is the standard deviation of the roughness of the external surface in contact with the high modulus coating, wherein $C_0 = 4x10^{35}\left[\left(\frac{\pi}{4}\right)^{2.625}\right]^{-1.}$, and wherein $f_g = \frac{1}{E_g^2 R_g^6}$, and wherein $f_p = \frac{E_p}{t_p^2}$, and wherein $f_{cs} = \left[1 + \frac{E_s}{E_p}\left(\frac{t_p}{R_s}\right)^3\right]^{0.375}\left\{\frac{E_s}{E_p}\left[R_s^4 - (R_s - t_s)^4\right]\right\}^{0.625}$, wherein R_g is the radius of the glass, R_s is the outer radius of the high-modulus outer coating, t_p is the thickness of the inner low-modulus coating, t_s is the thickness of the high-modulus outer coating, E_g is the elastic moduli of the glass, E_p is the elastic moduli of the low-modulus inner coating, and E_S is the elastic moduli of the high-modulus coating.

[0008] According to a second embodiment of the present disclosure, the optical fiber of the first embodiment, wherein the microbend attenuation penalty of the optical fiber is ≤ 0.01 dB/km.

[0009] According to a third embodiment of the present disclosure, the optical fiber of the first embodiment, wherein the microbend attenuation penalty of the optical fiber is ≤ 0.007 dB/km.

[0010] According to a fourth embodiment of the present disclosure, the optical fiber of the first embodiment, wherein the microbend attenuation penalty of the optical fiber is ≤ 0.003 dB/km.

[0011] According to a fifth embodiment of the present disclosure, the optical fiber of the first embodiment, wherein the puncture resistance of the optical fiber is ≥25 g.

[0012] According to a sixth embodiment of the present disclosure, the optical fiber of the first embodiment, wherein the puncture resistance of the optical fiber is ≥30 g.

[0013] According to a seventh embodiment of the present disclosure, the optical fiber of the first embodiment, wherein a radius of the cladding region is less than 52.5 microns and the puncture resistance of the optical fiber is greater than 40 g.

[0014] According to a eighth embodiment of the present disclosure, the optical fiber of the first embodiment, wherein the thickness of the high-modulus coating layer is 9 microns to 18 microns.

[0015] According to a ninth embodiment of the present disclosure, the optical fiber of the first embodiment, wherein an attenuation of the optical fiber is less than 0.20 dB/km.

[0016] According to a tenth embodiment of the present disclosure, the optical fiber of the first embodiment, wherein a mode field diameter of the optical fiber at 1310 nm is ≥ 8.6.

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[0017] According to an eleventh embodiment of the present disclosure the present description extends to an optical fiber having: a core region; a cladding region surrounding the core region, the cladding region comprising: an inner cladding directly adjacent to the core region, and an outer cladding surrounding the inner cladding, wherein a radius of the cladding region is between about 45 microns and 55 microns; and a polymer coating comprising a high-modulus coating layer surrounding the cladding region and a low-modulus coating layer disposed between the cladding region and the high-modulus coating layer, wherein a thickness of the low-modulus inner coating layer is in a range of 6 microns to 20 microns, the modulus of the low-modulus inner coating layer is less than or equal to about 0.35 MPa, a thickness of the high-modulus coating layer is in a range of 12 microns to 18 microns, the modulus of the high-modulus inner coating layer is greater than or equal to about 1.6 GPa, and wherein a puncture resistance of the optical fiber is greater than 30 g, and wherein a microbend attenuation penalty of the optical fiber is less than 0.03 dB/km, and wherein an outer diameter of the coated optical fiber is less than or equal to 175 microns, wherein the puncture resistance of the optical fiber is calculated by equation $P_R=P_0 + C_1E_sA_s$, wherein A_S is the cross-sectional area of the high-modulus coating, wherein E_S is the elastic moduli of the high-modulus coating, wherein P_0 is a coefficient having a value of 11.3 g and C_1 is a coefficient having a value of 2.1 g/MPa/mm^2, wherein the microbend attenuation penalty of the optical fiber is calculated by equation: $MAP = C_0 f_0 \sigma \frac{f_{RIP} f_g(E_g, R_g) f_p(E_p, t_p)}{f_{cs}\left(\frac{E_s}{E_p}, R_s, t_s\right)}$, wherein f_0 is the average lateral pressure of the external surface in contact with the high modulus coating, wherein σ is the standard deviation of the roughness of the external surface in contact with the high modulus coating, wherein $C_0 = 4x10^{25}\left[\left(\frac{\pi}{4}\right)^{2.625}\right]^{-1.}$, and wherein $f_g = \frac{1}{E_g^2 R_g^6}$, and wherein $f_p = \frac{E_p}{t_p^2}$, and wherein $f_{cs} = \left[1 + \frac{E_s}{E_p}\left(\frac{t_s}{R_s}\right)^3\right]^{0.375}\left\{\frac{E_s}{E_p}\left[R_s^4 - (R_s - t_s)^4\right]\right\}^{0.625}$, wherein R_g is the radius of the glass, R_s is the outer radius of the high-modulus outer coating, t_p is the thickness of the inner low-modulus coating, t_s is the thickness of the high-modulus outer coating, E_g is the elastic moduli of the glass, E_p is the elastic moduli of the low-modulus inner coating, and E_S is the elastic moduli of the high-modulus coating.

[0018] According to a twelfth embodiment of the present disclosure, the optical fiber of the eleventh embodiment, wherein the microbend attenuation penalty of the optical fiber is ≤ 0.01 dB/km.

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[0019] According to a thirteenth embodiment of the present disclosure, the optical fiber of the eleventh embodiment, wherein the microbend attenuation penalty of the optical fiber is ≤ 0.007 dB/km.

[0020] According to a fourteenth embodiment of the present disclosure, the optical fiber of the eleventh embodiment, wherein the microbend attenuation penalty of the optical fiber is ≤ 0.003 dB/km.

[0021] According to a fifteenth embodiment of the present disclosure, the optical fiber of the eleventh embodiment, wherein the puncture resistance of the optical fiber is ≥ 25 g.

[0022] According to a sixteenth embodiment of the present disclosure the present description extends to an optical fiber having a core region; a cladding region surrounding the core region, the cladding region comprising: an inner cladding directly adjacent to the core region, and an outer cladding surrounding the inner cladding; and a polymer coating having a thickness of 25 um or less, wherein the polymer coating comprises a high-modulus coating layer surrounding the cladding region, wherein the high-modulus coating layer has a Young's modulus of 1.5 GPa or greater, wherein an outer diameter of the coated optical fiber is less than or equal to 175 microns.

[0023] According to a seventeenth embodiment of the present disclosure, the optical fiber of the sixteenth embodiment, further comprising a low-modulus coating layer surrounding the cladding region, wherein the low-modulus coating layer has a Young's modulus of 0.5 MPa or less and is disposed between the cladding region and the high-modulus coating layer.

[0024] According to a eighteenth embodiment of the present disclosure, the optical fiber of the sixteenth embodiment, wherein a ratio of the thickness of the low-modulus coating layer coating to the thickness of the high-modulus coating layer is in the range of 0.8 to 1.2.

[0025] According to a nineteenth embodiment of the present disclosure the present description extends to a method of coating an optical fiber, comprising: drawing an optical fiber from a draw furnace along a first vertical pathway; routing the optical fiber through a coating system wherein a polymer coating is applied to the optical fiber, wherein the coating system comprises an entrance, a sizing die having a diameter of 129 μm to 203 μm opposite the entrance, and a coating chamber disposed between the entrance and the sizing die, wherein the coating chamber is filled with a coating material in liquid form; and curing the coated optical fiber to form an outer diameter of the coated optical fiber that is less than or equal to 175 microns.

[0026] According to a twentieth embodiment of the present disclosure, the optical fiber of the nineteenth embodiment, wherein the polymer coating has a concentricity of greater than 70%.

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[0027] Additional features and advantages will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from the description or recognized by practicing the embodiments as described in the written description and claims hereof, as well as the appended drawings.

[0028] It is to be understood that both the foregoing general description and the following detailed description are merely exemplary and are intended to provide an overview or framework to understand the nature and character of the claims.

[0029] The accompanying drawings are included to provide a further understanding and are incorporated in and constitute a part of this specification. The drawings are illustrative of selected aspects of the present disclosure, and together with the description serve to explain principles and operation of methods, products, and compositions embraced by the present disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0030] FIG. 1 is a schematic view of a coated optical fiber in accordance with some embodiments of the current disclosure.

[0031] FIG. 2 is a schematic view of a representative optical fiber ribbon in accordance with some embodiments of the current disclosure.

[0032] FIG. 3 is a schematic view of a representative optical fiber cable in accordance with some embodiments of the current disclosure.

[0033] FIG. 4 depicts a cross-section of a single-mode optical fiber in accordance with some embodiments of the current disclosure.

[0034] FIG. 5 depicts a relative refractive index profile of a single-mode optical fiber in accordance with some embodiments of the current disclosure.

[0035] FIG. 6 depicts relative refractive index profiles of optical fibers according to embodiments of the present disclosure.

[0036] FIG. 7 depicts a relative refractive index profile of an optical fiber according to embodiments of the present disclosure.

[0037] FIG. 8 depicts the dependence of the puncture load strength as a function of the cross-sectional area of the high-modulus coating according to the present disclosure.

[0038] FIG. 9 depicts a relative refractive index profile of a single-mode optical fiber in accordance with some embodiments of the current disclosure

[0039] FIG. 10 is a schematic of core and cladding mode distributions for an optical fiber with a thick coating in accordance with some embodiments of the current disclosure.

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[0040] FIG. 11 is a schematic of core and cladding mode distributions for an optical fiber with a thin coating in accordance with some embodiments of the current disclosure.

[0041] FIG. 12 depicts the effects of coating material viscosity and die size on the coating thickness in accordance with some embodiments of the current disclosure.

[0042] FIG. 13 depicts an exemplary parameter window for forming a targeted final coated diameter in accordance with some embodiments of the current disclosure.

[0043] FIG. 14 depicts the coating thickness standard deviation resulting from various coating material viscosity for different die size systems in accordance with some embodiments of the current disclosure.

[0044] FIG. 15 depicts the effect of drawing speed on coating thickness in accordance with some embodiments of the current disclosure.

[0045] FIG. 16 depicts a graph plotting the correlation between lubrication pressure and the die size for a series of coating material viscosity in accordance with some embodiments of the current disclosure.

[0046] FIG. 17 depicts the correlation between lubrication pressure and drawing speed in accordance with some embodiments of the current disclosure.

[0047] FIG. 18 depicts a relative refractive index profile of a single-mode optical fiber in accordance with some embodiments of the current disclosure.

[0048] FIG. 19 depicts the microbend attenuation penalty (MAP) versus the low-modulus coating thickness for fibers with step-index and trench-assisted fiber profiles and a cladding diameter of 100 microns in accordance with some embodiments of the current disclosure.

[0049] FIG. 20 depicts the microbend attenuation penalty (MAP) versus the low-modulus coating thickness for fibers having a trench-assisted fiber profile and a cladding diameter of 100 microns for different moduli of the high-modulus coating in accordance with some embodiments of the current disclosure.

[0050] FIG. 21 depicts the puncture resistance versus the low-modulus coating thickness for fibers having a trench-assisted fiber profile and a cladding diameter of 100 microns for different moduli of the high-modulus coating in accordance with some embodiments of the current disclosure.

[0051] FIG. 22 depicts the microbend attenuation penalty (MAP) versus the low-modulus coating thickness for fibers having a trench-assisted fiber profile and a cladding diameter of 100 microns for different moduli of the low-modulus coating in accordance with some embodiments of the current disclosure.

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DETAILED DESCRIPTION

[0052] The present disclosure is provided as an enabling teaching and can be understood more readily by reference to the following description, drawings, examples, and claims. To this end, those skilled in the relevant art will recognize and appreciate that many changes can be made to the various aspects of the embodiments described herein, while still obtaining the beneficial results. It will also be apparent that some of the desired benefits of the present embodiments can be obtained by selecting some of the features without utilizing other features. Accordingly, those who work in the art will recognize that many modifications and adaptations are possible and can even be desirable in certain circumstances and are a part of the present disclosure. Therefore, it is to be understood that this disclosure is not limited to the specific compositions, articles, devices, and methods disclosed unless otherwise specified. It is also to be understood that the terminology used herein is for the purposes of describing particular aspects only and is not intended to be limiting.

[0053] In this specification, and in the claims, which follow, reference will be made to a number of terms which shall be defined to have the following meanings:

[0054] "Optical fiber" refers to a waveguide having a glass portion surrounded by a coating. The glass portion includes a core and a cladding and is referred to herein as a "glass fiber".

[0055] "Radial position", "radius", or the radial coordinate "r" refers to radial position relative to the centerline (r = 0) of the fiber.

[0056] "Refractive index" refers to the refractive index at a wavelength of 1550 nm, unless otherwise specified.

[0057] The "refractive index profile" is the relationship between refractive index or relative refractive index and radius. For relative refractive index profiles depicted herein as having step boundaries between adjacent core and/or cladding regions, normal variations in processing conditions may preclude obtaining sharp step boundaries at the interface of adjacent regions. It is to be understood that although boundaries of refractive index profiles may be depicted herein as step changes in refractive index, the boundaries in practice may be rounded or otherwise deviate from perfect step function characteristics. It is further understood that the value of the relative refractive index may vary with radial position within the core region and/or any of the cladding regions. When relative refractive index varies with radial position in a particular region of the fiber (e.g. core region and/or any of the cladding regions), it is expressed in terms of its actual or approximate functional dependence, or its value at a particular position within the region, or in terms of an average value applicable to the region as a whole. Unless otherwise

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specified, if the relative refractive index of a region (e.g. core region and/or any of the cladding regions) is expressed as a single value or as a parameter (e.g. Δ or Δ%) applicable to the region as a whole, it is understood that the relative refractive index in the region is constant, or approximately constant, and corresponds to the single value, or that the single value or parameter represents an average value of a non-constant relative refractive index dependence with radial position in the region. For example, if "i" is a region of the glass fiber, the parameter Δ_i refers to the average value of relative refractive index in the region as defined by Eq. (1) below, unless otherwise specified. Whether by design or a consequence of normal manufacturing variability, the dependence of relative refractive index on radial position may be sloped, curved, or otherwise non-constant.

[0058] "Relative refractive index," as used herein, is defined in Eq. (1) as:

$$\Delta_i(r_i)\% = 100\frac{\left(n_i^2 - n_{ref}^2\right)}{2n_i^2} \quad (1)$$

where n_i is the refractive index at radial position r_i in the glass fiber, unless otherwise specified, and n_{ref} is the refractive index of pure silica glass, unless otherwise specified. Accordingly, as used herein, the relative refractive index percent is relative to pure silica glass, which has a value of 1.444 at a wavelength of 1550 nm. As used herein, the relative refractive index is represented by Δ (or "delta") or Δ% (or "delta %) and its values are given in units of "%", unless otherwise specified. Relative refractive index may also be expressed as Δ(r) or Δ(r)%.

[0059] The average relative refractive index (Δ_{ave}) of a region of the fiber is determined from Eq. (2):

$$\Delta_{ave} = \int_{r_{inner}}^{r_{outer}} \frac{\Delta(r)dr}{(r_{outer} - r_{inner})} \quad (2)$$

where r_{inner} is the inner radius of the region, r_{outer} is the outer radius of the region, and Δ(r) is the relative refractive index of the region.

[0060] The refractive index of an optical fiber profile may be measured using commercially available devices, such as the IFA-100 Fiber Index Profiler (Interfiber Analysis LLC, Sharon, MA USA) or the S14 Refractive Index Profiler (Photon Kinetics, Inc., Beaverton, OR USA). These devices measure the refractive index relative to a measurement reference index, $n(r) - n_{meas}$, where the measurement reference index n_{meas} is typically a calibrated index matching oil or pure silica glass. The measurement wavelength may be 632.5 nm, 654 nm, 677.2 nm, 654 nm, 702.3 nm, 729.6 nm, 759.2 nm, 791.3 nm, 826.3 nm, 864.1 nm, 905.2 nm, 949.6 nm, 997.7 nm,

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1050 nm, or any wavelength therebetween. The absolute refractive index n(r) is then used to calculate the relative refractive index as defined by Eq. (1).

[0061] The term "α-profile" or "alpha profile" refers to a relative refractive index profile Δ(r) that has the functional form defined in Eq. (3):

$$\Delta(r) = \Delta(r_0)\left[1 - \left[\frac{|r - r_0|}{(r_z - r_0)}\right]^{\alpha}\right] \quad (3)$$

where r_0 is the radial position at which Δ(r) is maximum, $\Delta(r_0) > 0$, $r_z > r_0$ is the radial position at which Δ(r) decreases to its minimum value, and r is in the range $r_i \leq r \leq r_f$, where r_i is the initial radial position of the α-profile, r_f is the final radial position of the α-profile, and α is a real number. $\Delta(r_0)$ for an α-profile may be referred to herein as Δ_{max} or, when referring to a specific region i of the fiber, as Δ_{imax}. When the relative refractive index profile of the fiber core region is described by an α-profile with r_0 occurring at the centerline (r = 0), r_z corresponding to the outer radius r_1 of the core region, and $\Delta_1(r_1) = 0$, Eq. (3) simplifies to Eq. (4):

$$\Delta_1(r) = \Delta_{1max}\left[1 - \left[\frac{r}{r_1}\right]^{\alpha}\right] \quad (4)$$

[0062] When the core region has an index described by Eq. (4), the outer radius r_1 can be determined from the measured relative refractive index profile by the following procedure. Estimated values of the maximum relative refractive index Δ_{1max}, α, and outer radius r_{1est} are obtained from inspection of the measured relative refractive index profile and used to create a trial function Δ_{trial} between $r = -r_{1est}$ and $r = r_{1est}$. Relative refractive index profiles of representative glass fibers having cores described by an α-profile, in accordance with embodiments of the present disclosure, are shown in FIGS. 5 and 6.

[0063] "Trench volume" is defined as:

$$V_{\text{Trench}} = \left|2\int_{r_{Trench,inner}}^{r_{Trench,outer}} \Delta_{Trench}(r) r dr\right| \quad (5)$$

where $r_{Trench,inner}$ is the inner radius of the trench region of the refractive index profile, $r_{Trench,outer}$ is the outer radius of the trench region of the refractive index profile, $\Delta_{Trench}(r)$ is the relative refractive index of the trench region of the refractive index profile, and r is radial position in the fiber. Trench volume is in absolute value and a positive quantity and will be expressed herein in units of %Δmicron^2, %Δ-micron^2, %Δ-μm^2, or %Δμm^2, whereby these units can be used interchangeably herein. A trench region is also referred to herein as a depressed-index cladding region and trench volume is also referred to herein as V_3.

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[0064] The "mode field diameter" or "MFD" of an optical fiber is defined in Eq. (6) as:

$$MFD = 2w \tag{6}$$

$$w^2 = 2\frac{\int_0^\infty (f(r))^2 r dr}{\int_0^\infty \left(\frac{df(r)}{dr}\right)^2 r dr}$$

where f(r) is the transverse component of the electric field distribution of the guided optical signal and r is radial position in the fiber. "Mode field diameter" or "MFD" depends on the wavelength of the optical signal and is reported herein for wavelengths of 1310 nm, 1550 nm, and 1625 nm. Specific indication of the wavelength will be made when referring to mode field diameter herein. Unless otherwise specified, mode field diameter refers to the LP_{01} mode at the specified wavelength.

[0065] "Effective area" of an optical fiber is defined in Eq. (7) as:

$$A_{eff} = \frac{2\pi \left[\int_0^\infty (f(r))^2 r dr\right]^2}{\int_0^\infty (f(r))^4 r dr} \tag{7}$$

where f(r) is the transverse component of the electric field of the guided optical signal and r is radial position in the fiber. "Effective area" or "A_{eff}" depends on the wavelength of the optical signal and is understood herein to refer to a wavelength of 1550 nm.

[0066] The term "attenuation," as used herein, is the loss of optical power as the signal travels along the optical fiber. Attenuation was measured as specified by the IEC-60793-1-40 standard, "Attenuation measurement methods."

[0067] The bend resistance of an optical fiber, expressed as "bend loss" herein, can be gauged by induced attenuation under prescribed test conditions as specified by the IEC-60793-1-47 standard, "Measurement methods and test procedures - Macrobending loss." For example, the test condition can entail deploying or wrapping the fiber one or more turns around a mandrel of a prescribed diameter, e.g., by wrapping one turn around either a 15 mm, 20 mm, or 30 mm or similar diameter mandrel (e.g. "1×15 mm diameter bend loss" or the "1×20 mm diameter bend loss" or the "1×30 mm diameter bend loss") and measuring the increase in attenuation per turn.

[0068] "Cable cutoff wavelength," or "cable cutoff," as used herein, refers to the 22 m cable cutoff test as specified by the IEC 60793-1-44 standard, "Measurement methods and test procedures – Cut-off wavelength."

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[0069] The optical fibers disclosed herein include a core region, a cladding region surrounding the core region, and a coating surrounding the cladding region. The core region and cladding region are glass. The cladding region includes multiple regions. The multiple cladding regions are preferably concentric regions. The cladding region includes an inner cladding region, a depressed-index cladding region, and an outer cladding region. The inner cladding region surrounds and is directly adjacent to the core region. The depressed-index cladding region surrounds and is directly adjacent to the inner cladding region such that the depressed-index cladding region is disposed between the inner cladding and the outer cladding in a radial direction. The outer cladding region surrounds and is directly adjacent to the depressed-index cladding region. The depressed-index cladding region has a lower relative refractive index than the inner cladding and the outer cladding region. The depressed-index cladding region may also be referred to herein as a trench or trench region. The relative refractive index of the inner cladding region may be less than, equal to, or greater than the relative refractive index of the outer cladding region. The depressed-index cladding region may contribute to a reduction in bending losses and microbending sensitivity. The core region, inner cladding region, depressed-index cladding region, and outer cladding region are also referred to as core, cladding, inner cladding, depressed-index cladding, and outer cladding, respectively.

[0070] Whenever used herein, radial position r_1 and relative refractive index Δ_1 or $\Delta_1(r)$ refer to the core region, radial position r_2 and relative refractive index Δ_2 or $\Delta_2(r)$ refer to the inner cladding region, radial position r_3 and relative refractive index Δ_3 or $\Delta_3(r)$ refer to the depressed-index cladding region, radial position r_4 and relative refractive index Δ_4 or $\Delta_4(r)$ refer to the outer cladding region, radial position r_5 refers to the optional low-modulus inner coating, radial position r_6 refers to the high-modulus coating, and the radial position r_7 refers to the optional pigmented outer coating.

[0071] The relative refractive index $\Delta_1(r)$ has a maximum value Δ_{1max} and a minimum value Δ_{1min}. The relative refractive index $\Delta_2(r)$ has a maximum value Δ_{2max} and a minimum value Δ_{2min}. The relative refractive index $\Delta_3(r)$ has a maximum value Δ_{3max} and a minimum value Δ_{3min}. The relative refractive index $\Delta_4(r)$ has a maximum value Δ_{4max} and a minimum value Δ_{4min}. In embodiments in which the relative refractive index is constant or approximately constant over a region, the maximum and minimum values of the relative refractive index are equal or approximately equal. Unless otherwise specified, if a single value is reported for the relative refractive index of a region, the single value corresponds to an average value for the region.

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[0072] It is understood that the central core region is substantially cylindrical in shape and that the surrounding inner cladding region, depressed-index cladding region, outer cladding region, low-modulus coating, and high-modulus coating are substantially annular in shape. Annular regions are characterized in terms of an inner radius and an outer radius. Radial positions r_1, r_2, r_3, r_4, r_5, r_6 and r_7 refer herein to the outermost radii of the core, inner cladding, depressed-index cladding, outer cladding, optional low-modulus inner coating, high-modulus coating, and optional pigmented outer coating, respectively. The radius r_6 also corresponds to the outer radius of the optical fiber in embodiments without a pigmented outer coating. The pigmented outer coating may have a high modulus. When a pigmented outer coating is present, the radius r_7 corresponds to the outer radius of the optical fiber.

[0073] When two regions are directly adjacent to each other, the outer radius of the inner of the two regions coincides with the inner radius of the outer of the two regions. The optical fiber, for example, includes a depressed-index cladding region surrounded by and directly adjacent to an outer cladding region. The radius r_3 corresponds to the outer radius of the depressed-index cladding region and the inner radius of the outer cladding region. The relative refractive index profile also includes a depressed-index cladding region surrounding and directly adjacent to an inner cladding region. The radial position r_2 corresponds to the outer radius of the inner cladding region and the inner radius of the depressed-index cladding region. Similarly, the radial position r_1 corresponds to the outer radius of the core region and the inner radius of the inner cladding region.

[0074] The difference between radial position r_2 and radial position r_1 is referred to herein as the thickness of the inner cladding region. The difference between radial position r_3 and radial position r_2 is referred to herein as the thickness of the depressed-index cladding region. The difference between radial position r_4 and radial position r_3 is referred to herein as the thickness of the outer cladding region. The difference between radial position r_5 and radial position r_4 is referred to herein as the thickness of the low-modulus coating. The difference between radial position r_6 and radial position r_5 is referred to herein as the thickness of the high-modulus coating.

[0075] As will be described further hereinbelow, the relative refractive indices of the core region, inner cladding region, depressed-index cladding region, and outer cladding region may differ. Each of the regions may be formed from doped or undoped silica glass. Variations in refractive index relative to undoped silica glass are accomplished by incorporating updopants or downdopants at levels designed to provide a targeted refractive index or refractive index profile using techniques known to those of skill in the art. Updopants are dopants that increase the

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refractive index of the glass relative to the undoped glass composition. Downdopants are dopants that decrease the refractive index of the glass relative to the undoped glass composition. In one embodiment, the undoped glass is silica glass. When the undoped glass is silica glass, updopants include Cl, Br, Ge, Al, P, Ti, Zr, Nb, and Ta, and downdopants include Fluorine and Boron. Regions of constant refractive index may be formed by not doping or by doping at a uniform concentration over the thickness of the region. Regions of variable refractive index are formed through non-uniform spatial distributions of dopants over the thickness of a region and/or through incorporation of different dopants in different regions.

[0076] Values of Young's modulus, % elongation, and tear strength refer to values as determined under the measurement conditions by the procedures described herein.

[0077] Reference will now be made in detail to illustrative embodiments of the present description.

[0078] One embodiment relates to an optical fiber. The optical fiber includes a glass fiber surrounded by a coating. An example of an optical fiber is shown in schematic cross-sectional view in FIG. 1. Optical fiber 10 includes glass fiber 11 surrounded by an optional low-modulus inner coating 16 and a high-modulus coating 18. In some embodiments, high-modulus coating 18 may include a pigment. Further description of glass fiber 11, optional low-modulus inner coating 16, and high-modulus coating 18 is provided below. Additionally, one or more pigmented outer coating layers may surround high-modulus coating 18.

[0079] FIG. 2 illustrates an optical fiber ribbon 30, which may include a plurality of optical fibers 20 and a matrix 32 encapsulating the plurality of optical fibers. Optical fibers 20 each include a core region, a cladding region, an optional low-modulus inner coating, and a high-modulus coating as described above. Optical fibers 20 may also include a pigmented outer coating as noted above.

[0080] As shown in FIG. 2, optical fibers 20 are aligned relative to one another in a substantially planar and parallel relationship. The optical fibers in fiber optic ribbon 30 are encapsulated by the ribbon matrix 32 in any of several known configurations (e.g., edge-bonded ribbon, thin-encapsulated ribbon, thick-encapsulated ribbon, or multi-layer ribbon) by conventional methods of making fiber optic ribbons. Fiber optic ribbon 30 in the embodiment of FIG. 2 contains twelve (12) optical fibers 20. However, it is contemplated that any number of optical fibers 20 (e.g., two or more, four more, six or more, 8 or more, 12 or more, or 16 or more) may be employed to form fiber optic ribbon 30 for a particular use. Ribbon matrix 32 has tensile properties similar to the tensile properties of a high-modulus coating and can be formed from the same, similar, or different composition used to prepare a high-modulus coating.

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[0081] FIG. 3 illustrates an optical fiber cable 40 that includes a plurality of optical fibers 20 surrounded by jacket 42. In some embodiments, optical fiber cable 40 is a submarine cable. In some embodiments, optical fiber cable 40 is used in fiber ribbons in interconnection schemes within a data center. Optical fibers 20 may be densely or loosely packed into a conduit enclosed by an inner surface 44 of jacket 42. The number of fibers placed in jacket 42 is referred to as the "fiber count" of optical fiber cable 40. As discussed further below, the optical fibers of the present disclosure have a reduced diameter, thus providing a high "fiber count."

[0082] The jacket 42 is formed from an extruded polymer material and may include multiple concentric layers of polymers or other materials. Optical fiber cable 40 may include one or more strengthening members (not shown) embedded within jacket 42 or placed within the conduit defined by inner surface 44. Strengthening members include fibers or rods that are more rigid than jacket 42. The strengthening member may be made from metal, braided steel, glass-reinforced plastic, fiber glass, or other suitable material. Optical fiber cable 40 may include other layers surrounded by jacket 42 such as, for example, armor layers, moisture barrier layers, rip cords, etc. Furthermore, optical fiber cable 40 may have a stranded, loose tube core or other fiber optic cable construction.

[0083] **Glass Fiber**

[0084] As shown in FIG. 1, glass fiber 11 includes a core region 12 and a cladding region 14, as is known in the art. Core region 12 has a higher refractive index than cladding region 14, and glass fiber 11 functions as a waveguide. In many applications, core region 12 and cladding region 14 have a discernible core-cladding boundary. Alternatively, core region 12 and cladding region 14 can lack a distinct boundary.

[0085] In some embodiments, core region 12 has a refractive index that varies with distance from the center of the glass fiber. For example, core region 12 may have a relative refractive index profile with an α-profile (as defined by Eq. (3) above) with an α value that is greater than or equal to 2 and less than or equal to 100, or for example an α value that is greater than or equal to 2 and less than or equal to 10, or greater than or equal to 2 and less than or equal to 6, or greater than or equal to 2 and less than or equal to 4, or greater than or equal to 4 and less than or equal to 20, or greater than or equal to 6 and less than or equal to 20, or greater than or equal to 8 and less than or equal to 20, or greater than or equal to 10 and less than or equal to 20, or greater than or equal to 10 and less than or equal to 40.

[0086] A schematic cross-sectional depiction of an exemplary optical fiber is shown in FIG. 4. In some embodiments, the optical fiber of FIG. 4 may be used in a submarine cable or to

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optically connect components in a submarine repeater. In some embodiments, the optical fiber of FIG. 4 may be used in data center interconnects. In FIG. 4, optical fiber 46 includes core region 48, cladding region 50, optional low-modulus inner coating 56, and high-modulus coating 58. Cladding region 50 includes inner cladding region 51, depressed-index cladding region 53, and outer cladding region 55. A pigmented outer coating layer (e.g. ink layer) optionally surrounds or is directly adjacent to the high-modulus coating.

[0087] As discussed above, optical fiber 46 may have a reduced coating diameter. Such reduced diameter(s) may increase the fiber density (e.g., "fiber count") of optical fibers 46 when used, for example, in submarine cables or repeaters or data center interconnects. In order to provide low attenuation, large effective area, low bend loss and sufficiently high mechanical reliability with the smaller diameter of optical fiber 46, the properties of the fiber are specifically tailored, as discussed further below.

[0088] A representative relative refractive index profile for a glass fiber, according to embodiments of the present disclosure, is shown in FIG. 5. The profile of optical fiber 60 of FIG. 5 shows a core region (1) with outer radius r_1 and relative refractive index Δ_1 with maximum relative refractive index Δ_{1max}, an inner cladding region (2) extending from radial position r_1 to radial position r_2 and having relative refractive index Δ_2, a depressed-index cladding region (3) extending from radial position r_2 to radial position r_3 and having relative refractive index Δ_3, and an outer cladding region (4) extending from radial position r_3 to radial position r_4 and having relative refractive index Δ_4. In the profile of FIG. 5, the depressed-index cladding region (3) may be referred to herein as a trench and has a constant or average relative refractive index that is less than the relative refractive indices of the inner cladding region (2) and the outer cladding region (4). Core region (1) has the highest average and maximum relative refractive index in the profile. In some embodiments, core region (1) may include a lower index region at or near the centerline (known in the art as a "centerline dip") (not shown). In some embodiments, core region (1) may include a higher index region at or near the centerline (referred to as a "centerline spike") (not shown).

[0089] In the relative refractive index profile of FIG. 5, the core region (1) of the glass fiber has an α-profile with an α value greater than or equal to 2 and less than or equal to 20. The radial position r_0 (corresponding to Δ_{1max}) of the α-profile corresponds to the centerline ($r = 0$) of the fiber and the radial position r_z of the α-profile corresponds to the core radius r_1. In embodiments with a centerline dip, the radial position r_0 may be offset from the centerline of the fiber. In some embodiments, the relative refractive index Δ_1 continuously decreases in the radial

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direction away from the centerline. In other embodiments, relative refractive index Δ_1 varies over some radial positions between the centerline and r_1, and also includes a constant or approximately constant value over other radial positions between the centerline and r_1.

[0090] In FIG. 5, transition region 61 from inner cladding region (2) to depressed-index cladding region (3) and transition region 62 from depressed-index cladding region (3) to outer cladding region (4) are shown as step changes. It is to be understood that a step change is an idealization and that transition region 61 and/or transition region 62 may not be strictly vertical in practice as depicted in FIG. 5. Instead, transition region 61 and/or transition region 62 may have a slope or curvature. When transition region 61 and/or transition region 62 are non-vertical, the inner radius r_2 and outer radius r_3 of depressed-index cladding region (3) correspond to the mid-points of transition regions 61 and 62, respectively. The mid-points correspond to half of the depth 63 of the depressed-index cladding region (3).

[0091] The relative ordering of relative refractive indices Δ_1, Δ_2, Δ_3, and Δ_4 in the relative refractive index profile shown in FIG. 5 satisfy the conditions $\Delta_{1max} > \Delta_4 > \Delta_3$ and $\Delta_{1max} > \Delta_2 > \Delta_3$. The values of Δ_2 and Δ_4 may be equal or either may be greater than the other, but both Δ_2 and Δ_4 are between Δ_{1max} and Δ_3.

[0092] The relative refractive indices Δ_1, Δ_2, Δ_3, and Δ_4 are based on the materials used in the core region, inner cladding region, depressed-index cladding region, and outer cladding region. A description of these material with regard to the relative refractive indices Δ_1, Δ_2, Δ_3, and Δ_4 is provided below.

[0093] While FIG. 5 depicts a schematic cross-sectional depiction of one exemplary optical fiber, other suitable optical fibers may be used with embodiments described herein. For example, FIG. 9 is a schematic cross-sectional depiction of a generic profile design for a single mode fiber that may be used with embodiments described herein. The profile of the optical fiber of FIG. 9 shows a core region with outer radius r_1 and relative refractive index Δ_1, an inner cladding region extending from radial position r_1 to radial position r_2 and having relative refractive index Δ_2, a depressed-index cladding region extending from radial position r_2 to radial position r_3 and having relative refractive index Δ_3, and an outer cladding region extending from radial position r_3 to radial position r_4 and having relative refractive index Δ_4. Table 1 and 2 below depicts various exemplary fiber profile designs that may be used with embodiments described herein and Table 3 depicts various optical properties of various exemplary optical fiber profile designs that may be used with embodiments described herein.

TABLE 1 – Exemplary Optical Fiber Profile Designs

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	Ex. 1	Ex. 2	Ex. 3	Ex. 4	Ex. 5	Ex. 6
Core delta D_1 (%)	0.34	0.29	0.405	0.34	0	0
Alpha	20	20	2.4	20	20	20
Core radius r_1 (microns)	4.5	4.35	5.9	4.05	4.9	5.9
Inner cladding delta D_2 (%)	na	-0.08	0	0	-0.4	-0.3
Inner cladding radius r_2 (microns)	na	12	10	9.8	20	22
Trench delta D_3 (%)	na	na	na	-0.4	na	na
Trench radius r_3 (microns)	na	na	na	16	na	na
Outer cladding delta D_4 (%)	0	0	0.05	0	-0.3	-0.2
Cable cutoff (nm)	1208	1205	1196	1210	1405	1472
MFD at 1310 nm (microns)	9.2	8.8	9.2	8.8	9.1	10.7
Aeff at 1310 nm (micron^2)	66.7	61.9	65.1	60.6	67.6	94.5
Dispersion at 1310 nm (ps/nm.km)	0.33	0.31	-0.10	-0.25	3.17	3.57
Dispersion slope at 1310 nm (ps/nm^2.km)	0.0862	0.0844	0.0884	0.0896	0.0855	0.0878
MFD at 1550 nm (microns)	10.4	10.0	10.5	10.0	10.1	11.8
Aeff at 1550 nm (micron^2)	83.1	77.4	82.6	75.8	80.1	110.8
Dispersion at 1550 nm (ps/nm.km)	17.0	16.3	16.9	17.7	19.8	20.7
Dispersion slope at 1550 nm (ps/nm^2.km)	0.0577	0.0533	0.0579	0.0645	0.0575	0.0597

TABLE 2 - Exemplary Optical Fiber Profile Designs

	Example 1	Example 2	Example 3	Example 4	Example 5
Δ1 (%)	0.399	0.401	0.394	0.391	0.382
r_1 (microns)	4.33	4.38	4.26	4.37	4.29
Alpha	10.07	10.28	11.32	10.85	9.81
Δ2 (%)	0	0	0	0	0
Δ3 (%)	-0.443	-0.394	-0.383	-0.417	-0.292
r_2 (microns)	9.04	9.38	10.47	10.19	10.64
r_3 (microns)	14.71	14.90	15.88	16.28	17.83
Trench Volume (%-microns^2)	59.7	52.8	54.6	67.1	59.8
MFD at 1310 nm (microns)	8.45	8.50	8.52	8.59	8.61
MFD at 1550 nm (microns)	9.43	9.49	9.61	9.65	9.76
Dispersion at 1310 nm (ps/nm/km)	0.56	0.51	-0.18	0.22	-0.47
Slope at 1310 nm (ps/nm^2/km)	0.090	0.090	0.088	0.089	0.088
Zero Dispersion Wavelength (nm)	1304	1304	1312	1307	1315
Theoretical Cutoff (nm)	1245	1269	1248	1264	1224
Fiber Cutoff (nm)	1240	1260	1240	1260	1220
Bend Loss at 1550 nm for 10 mm diam. mandrel (dB/turn)	0.049	0.072	0.082	0.03	0.078

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TABLE 2 CONTINUED

	Example 6	Example 7	Example 8	Example 9	Example 10
Δ1 (%)	0.371	0.382	0.368	0.352	0.334
r_1 (microns)	4.37	4.70	4.51	4.51	4.57
Alpha	10.48	7.74	9.97	10.07	11.00
Δ2 (%)	0	0	0	0	0
Δ3 (%)	-0.375	-0.385	-0.333	-0.360	-0.365
r_2 (microns)	9.61	11.02	9.98	9.93	10.19
r_3 (microns)	14.28	15.13	15.27	14.59	14.62
Moat Volume (%-microns^2)	41.8	41.4	44.5	41.2	40.1
MFD at 1310 nm (microns)	8.71	8.83	8.84	8.96	9.17
MFD at 1550 nm (microns)	9.77	9.91	9.91	10.05	10.29
Dispersion at 1310 nm (ps/nm/km)	0.28	0.46	0.46	0.47	0.59
Slope at 1310 nm (ps/nm^2/km)	0.090	0.089	0.089	0.090	0.090
Zero Dispersion Wavelength (nm)	1307	1305	1305	1305	1303
Theoretical Cutoff (nm)	1224	1305	1254	1228	1219
Fiber Cutoff (nm)	1210	1280	1240	1210	1200
Bend Loss at 1550 nm for 10 mm diam. mandrel (dB/turn)	0.32	0.2	0.234	0.446	0.672

TABLE 3 - Optical Properties of Exemplary Optical Fiber Profile

	Low-Modulus Coating	**High-Modulus Coating**	**Attenuation (dB/km)**		**Cable cutoff (nm)**	**MFD (μm)**	
Glass Diameter (μm)	**Diameter (μm)**	**Diameter (μm)**	**1310 nm**	**1550 nm**		**1310 nm**	**1550 nm**
125	NA	140	0.355	0.215	1240	9.38	10.64
125	133	142	0.324	0.191	1170	9.27	10.97
125	155	175	0.354	0.21	1140	9.41	10.61
115.5	NA	125	0.351	0.223			
125	NA	140	0.339	0.206	1170	9.06	
125	NA	140	0.344	0.221	1210		
125	NA	140	0.336	0.207	1200		
125	NA	140	0.339	0.206	1220	9.28	10.56
125	NA	155	0.333	0.214			
125	NA	132					
125	NA	140					
118	NA	121	0.964	2.01	1140	9.07	10.46
106	NA	125	0.874	4.32	980		
110	NA	126	0.581	1.238	1090	8.71	9.92

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125	NA	132	0.596	0.775			
125	NA	140	0.551	0.747	1190	9.44	
125	NA	140	0.483	0.582		9.2	10.59
125	NA	155	0.439	0.413	1230		
125	NA	175	0.527	0.732	1170	9.46	10.51
125	155	175	0.42	0.284	1150	9.3	10.49

[0094] *Core Region*

[0095] The core region comprises silica glass. The silica glass of the core region may be undoped silica glass, updoped silica glass, and/or downdoped silica glass. Updoped silica glass includes silica glass doped with an alkali metal oxide (e.g. Na_2O, K_2O, Li_2O, Cs_2O, or Rb_2O). Downdoped silica glass includes silica glass doped with F. In one embodiment, the silica glass of the core region may be Ge-free and/or Cl-free; that is the core region comprises silica glass that lacks Ge and/or Cl.

[0096] Additionally, or alternatively, the core region may comprise silica glass doped with at least one alkali metal, such as, lithium (Li), sodium (Na), potassium (K), rubidium (Rb), cesium (Cs) and/or francium (Fr). In some embodiments, the silica glass is doped with a combination of sodium, potassium, and rubidium. The silica glass may have a peak alkali concentration in the range from about 10 ppm to about 500, or in the range from about 20 ppm to about 450 ppm, or in the range from about 50 ppm to about 300 ppm, or in the range from about 10 ppm to about 200 ppm, or in the range from about 10 ppm to about 150 ppm. The alkali metal doping within the disclosed ranges results in lowering of Rayleigh scattering, thereby proving a lower optical fiber attenuation.

[0097] In some embodiments, the core region comprises silica glass doped with an alkali metal and doped with F as a downdopant. The concentration of F in the core of the fiber is in the range from about 0.1 wt% to about 2.5 wt%, or in the range from about 0.25 wt% to about 2.25 wt%, or in the range from about 0.3 wt% to about 2.0 wt%.

[0098] In other embodiments, the core region comprises silica glass doped with Ge and/or Cl. The concentration of GeO_2 in the core of the fiber may be in a range from about 2.0 to about 8.0 wt%, or in a range from about 3.0 to about 7.0 wt%, or in a range from about 4.0 to about 6.5 wt.%. The concentration of Cl in the core of the fiber may be in a range from 1.0 wt% to 6.0 wt%, or in a range from 1.2 wt% to 5.5 wt%, or in a range from 1.5 wt% to 5.0 wt%, or in a range from 2.0 wt% to 4.5 wt%, or greater than or equal to 1.5 wt% (e.g., $\geq$ 2 wt%, $\geq$ 2.5 wt%, $\geq$ 3 wt%, $\geq$ 3.5 wt%, $\geq$ 4 wt%, $\geq$ 4.5 wt%, $\geq$ 5 wt%, etc.).

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[0099] In embodiments where the core is substantially free of Ge or Cl, the relative refractive index Δ_1 or Δ_{1max} of the core region is in the range from about -0.10% to about 0.20%, or in the range from about -0.05% to about 0.15%, or in the range from about 0.0% to about 0.10%. The minimum relative refractive index Δ_{1min} of the core is in the range from about -0.20% to about -0.50%, or in the range from about -0.30% to about -0.40%, or in the range from about -0.32% to about -0.37%. The difference Δ_{1max} to Δ_{1min} is greater than 0.05%, or greater than 0.10%, or greater than 0.15%, or greater than 0.20%, or in the range from 0.05% to 0.40%, or in the range from 0.10% to 0.35%.

[00100] In embodiments where the core is doped with Ge and/or Cl, the relative refractive index Δ_1 or Δ_{1max} of the core region is in the range from about 0.20% to about 0.45%, or in the range from about 0.25% to about 0.40%, or in the range from about 0.30% to about 0.38%. The minimum relative refractive index Δ_{1min} of the core is in the range from about -0.05% to about -0.05%, or in the range from about -0.03% to about 0.03%, or in the range from about -0.02% to about 0.02%. The difference Δ_{1max} to Δ_{1min} is greater than 0.20%, or greater than 0.25%, or greater than 0.30%, or in the range from 0.25% to 0.45%, or in the range from 0.30% to 0.40%.

[00101] The radius r_1 of the core region is in the range from about from about 3.0 microns to about 6.5 microns, or in the range from about 3.5 microns to about 6.0 microns, or in the range from about 4.0 microns to about 6.0 microns, or in the range from about 4.5 microns to about 5.5 microns. In some embodiments, the core region includes a portion with a constant or approximately constant relative refractive index that has a width in the radial direction of at least 1.0 micron, or at least 2.0 microns, or at least 3.0 microns, or in the range from 1.0 microns to 3.0 microns, or in the range from 2.0 microns to 3.0 microns. In some embodiments, the portion of the core region having a constant or approximately constant relative refractive index has a relative refractive index of Δ_{1min}.

[00102] *Inner Cladding Region*

[00103] In embodiments in which the core is substantially free of Ge and Cl, the inner cladding region is comprised of downdoped silica glass that is doped with F. The average concentration of downdopant in the inner cladding region is greater than the average concentration of downdopant in the core region.

[00104] The relative refractive index Δ_2 or Δ_{2max} of the inner cladding region is in the range from about -0.20% to about -0.50%, or in the range from about -0.25% to about -0.45%, or in the range from about -0.30% to about -0.40%, or in the range from about -0.33% to about -0.37%. The relative refractive index Δ_2 is preferably constant or approximately constant. The

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difference Δ_{1max} - Δ_2 (or the difference Δ_{1max} - Δ_{2max}) is greater than about 0.25%, or greater than about 0.30%, or greater than about 0.35%, or in the range from about 0.25% to about 0.45%, or in the range from about 0.30% to about 0.40%.

[00105] The radius r_2 of the inner cladding region is in the range from about 7.0 microns to about 15.0 microns, or in the range from about 7.5 microns to about 13.0 microns, or in the range from about 8.0 microns to about 12.0 microns, or in the range from about 8.5 microns to about 11.5 microns, or in the range from about 9.0 microns to about 11.0 microns, or in the range from about 9.5 microns to about 10.5 microns. The thickness $r_2 - r_1$ of the inner cladding region is in the range from about 3.0 microns to about 10.0 microns, or from about 4.0 microns to about 9.0 microns, or from about 4.5 microns to about 7.0 microns.

[00106] In embodiments in which the core is doped with Ge and/or Cl, the inner cladding region comprises silica that is substantially free of Ge and/or Cl. The relative refractive index Δ_2 or Δ_{2max} of the inner cladding region is in the range from about -0.05% to about -0.05%, or in the range from about -0.03% to about 0.03%, or in the range from about -0.02% to about 0.02%. The relative refractive index Δ_2 is preferably constant or approximately constant. The difference Δ_{1max} - Δ_2 (or the difference Δ_{1max} - Δ_{2max}) is greater than about 0.20%, or greater than about 0.25%, or greater than about 0.30%, or in the range from about 0.25% to about 0.40%, or in the range from about 0.30% to about 0.38%.

[00107] The radius r_2 of the inner cladding region is in the range from about 8.0 microns to about 16.0 microns, or in the range from about 9.0 microns to about 15.0 microns, or in the range from about 10.0 microns to about 14.0 microns, or in the range from about 10.5 microns to about 13.5 microns, or in the range from about 11.0 microns to about 13.0 microns. The thickness $r_2 - r_1$ of the inner cladding region is in the range from about 3.0 microns to about 10.0 microns, or from about 4.0 microns to about 9.0 microns, or from about 5.0 microns to about 8.0 microns.

[00108] *Depressed-Index Cladding Region*

[00109] The depressed-index cladding region comprises downdoped silica glass. As discussed above, the preferred downdopant is fluorine. The concentration of fluorine in the depressed-index cladding region is in the range from about 0.30 wt% to about 2.50 wt%, or in the range from about 0.60 wt% to about 2.25 wt%, or in the range from about 0.90 wt% to about 2.00 wt%.

[00110] The relative refractive index Δ_3 or Δ_{3min} is in the range from about -0.30% to about -0.80%, or in the range from about -0.40% to about -0.70%, or in the range from about -0.50% to

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about -0.65%. The relative refractive index Δ_3 is preferably constant or approximately constant. The difference Δ_{1max} - Δ_3 (or the difference Δ_{1max} - Δ_{3min}, or the difference Δ_1 - Δ_3, or the difference Δ_1 - Δ_{3min}) is greater than about 0.50%, or greater than about 0.55%, or greater than about 0.6%, or in the range from about 0.50% to about 0.80%, or in the range from about 0.55% to about 0.75%. The difference Δ_2 - Δ_3 (or the difference Δ_2 - Δ_{3min}, or the difference Δ_{2max} - Δ_3, or the difference Δ_{2max} - Δ_{3min}) is greater than about 0.10%, or greater than about 0.20%, or greater than about 0.30%, or in the range from about 0.10% to about 0.70%, or in the range from about 0.20% to about 0.65%.

[00111] The inner radius of the depressed-index cladding region is r_2 and has the values specified above. The outer radius r_3 of the depressed-index cladding region is in the range from about 10.0 microns to 20.0 microns, or in the range from about 12.0 microns to about 19.5 microns, or in the range from about 13.0 microns to about 19.0 microns, or in the range from about 13.5 microns to about 18.5 microns, or in the range from about 14.0 microns to about 18.0 microns, or in the range from about 14.5 microns to about 17.5 microns. The thickness $r_3 - r_2$ of the depressed-index cladding region is in the range from 1.0 microns to 12.0 microns, or in the range from about 2.0 microns to about 10.0 microns, or in the range from about 2.5 microns to about 9.0 microns, or in the range from about 3.0 microns to about 8.0 microns.

[00112] The depressed-index cladding region may be an offset trench design with a trench volume of about 30 %Δ-micron^2 or greater, or about 50 %Δ-micron^2 or greater, or about 75 %Δ-micron^2 or less, or about 30 %Δ-micron^2 or greater and about 75 %Δ-micron^2 or less, or about 50 %Δ-micron^2 or greater and about 75 %Δ-micron^2 or less. Trench volumes lower than the disclosed ranges have reduced bending performance, and trench volumes higher than the disclosed ranges no longer operate as single-mode fibers.

[00113] The offset trench designs disclosed herein include an inner cladding region. Furthermore, the offset trench designs disclosed herein provide advantages over traditional trench designs that are adjacent to the core region. More specifically, the offset trench designs disclosed herein reduce confinement of the fundamental mode and provide improved bend loss at large bend diameters (e.g., bend diameters > 25 mm) for target optical fiber mode field diameter and cable cutoff characteristics. Furthermore, the trench designs disclosed herein have a depressed index trench region, which advantageously confines the intensity profile of the fundamental LP01 mode propagating through the optical fiber, thereby reducing the optical fiber mode field diameter.

[00114] *Outer Cladding Region*

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[00115] In embodiments in which the core is substantially free of Ge and Cl, the outer cladding region comprises downdoped silica glass. The preferred downdopant is fluorine. The concentration of fluorine in the outer cladding region is in the range from about 0.30 wt% to about 2.20 wt%, or in the range from about 0.60 wt% to about 2.00 wt%, or in the range from about 0.90 wt% to about 1.80 wt%. The relative refractive index Δ_4 or Δ_{4max} of the outer cladding region is in the range from about -0.20% to about -0.50%, or in the range from about -0.25% to about -0.45%, or in the range from about -0.30% to about -0.40%, or in the range from about -0.33% to about 0.37%. The relative refractive index Δ_4 is preferably constant or approximately constant. As shown in FIG. 5, the relative refractive index Δ_4 may be approximately equal to the relative refractive index Δ_2.

[00116] In an embodiment, the outer cladding is substantially pure silica. Alternatively, the outer cladding may be doped with Cl to a relative refractive index in the range from about 0.01% to about 0.1%, or from about 0.02% to about 0.08%, or from about 0.03% to about 0.06%. The concentration of Cl in the outer cladding may range from about 0.1 wt% to about 1.0 wt%, from about 0.2 wt% to about 0.8 wt%, or from about 0.3 wt% to about 0.6 wt%. Alternatively, the outer cladding may be doped with Titania to strengthen the cladding surface so as to stop defects such as scratches from propagating through the fiber. In some embodiments, the outer cladding may be doped with a Titania concentration of about 5 wt% to about 25 wt%.

[00117] The inner radius of the outer cladding region is r_3 and has the values specified above. In some embodiments, the outer radius r_4 is about 62.5 microns to facilitate splicing to conventional 125 micron cladding diameter fibers using cladding-alignment splicers. The outer radius r_4 of the outer cladding region is in the range from 60.0 microns to 65.0 microns, or in the range from 61.0 microns to 64.0 microns, or in the range from 62.0 microns to 63.0 microns, or in the range from 62.25 microns to 62.75 microns. Thus, for example, the diameter of the cladding region (i.e., outer radius r_4 multiplied by 2) in the range from 120.0 microns to 130.0 microns, or in the range from 122.0 microns to 128.0 microns, or in the range from 124.0 microns to 126.0 microns, or in the range from 124.5 microns to 125.5 microns. The thickness $r_4 - r_3$ of the outer cladding region is in the range from about 20.0 microns to about 60.0 microns, or in the range from about 30.0 microns to about 55.0 microns, or in the range from about 40.0 microns to about 50.0 microns. In some embodiments, the outer radius r_4 is about 50 microns to enable the thickness of the low-modulus and high-modulus coatings to be increased. The outer radius r_4 of the outer cladding region is in the range from 45.0 microns to 55.0 microns, or in the range from 49.0 microns to 51.0 microns, or in the range from 49.5 microns to

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50.5 microns, or in the range from 49.65 microns to 50.35 microns. Thus, for example, the diameter of the cladding region (i.e., outer radius r_4 multiplied by 2) in the range from 90.0 microns to 110.0 microns, or in the range from 98.0 microns to 102.0 microns, or in the range from 99.0 microns to 101.0 microns, or in the range from 99.3 microns to 100.7 microns. The thickness $r_4 - r_3$ of the outer cladding region is in the range from about 20.0 microns to about 50.0 microns, or in the range from about 25.0 microns to about 45.0 microns, or in the range from about 30.0 microns to about 40.0 microns.

[00118] **Optical Fiber Characteristics**

[00119] The optical fibers according to the embodiments of the present disclosure may have a mode field diameter in the range of about 9.0 microns to about 10.0 microns at 1310 nm and in the range of about 10.0 microns to about 11.0 microns at 1550 nm with a cable cutoff of less than about 1520 nm. In some embodiments, the 22-meter cable cutoff wavelength is less than about 1500 nm, or less than about 1450 nm, or less than about 1400 nm, or less than about 1300 nm, or less than about 1260 nm. In some embodiments, the 2-meter fiber cutoff wavelength is less than about 1520 nm, or less than about 1500 nm, or less than about 1450 nm, or less than about 1400 nm, less than about 1300 nm, or less than about 1260 nm.

[00120] Additionally, optical fibers according to the embodiments of the present disclosure may have an effective area at 1550 nm greater than about 75.0 micron^2, greater than about 80 micron^2, or greater than about 85 micron^2, or in the range of about 75 micron^2 to about 95 micron^2, or in the range from about 80 micron^2 to about 90 micron^2, or about 85 micron^2 to about 90 micron^2.

[00121] The attenuation of the optical fibers disclosed herein is less than or equal to 0.36 dB/km at a wavelength of 1310 nm, or less than or equal to 0.30 dB/km, or less than or equal to 0.28 dB/km, or less than or equal to 0.26 dB/km at a wavelength of 1310 nm. The attenuation of the optical fibers disclosed herein is less than or equal to 0.24 dB/km, or less than or equal to 0.22 dB/km, or less than or equal to 0.20 dB/km at a wavelength of 1550 nm.

[00122] As shown in FIG. 5, optical fiber 60 provides an exemplary embodiment of an optical fiber with an alkali doped core, a relative refractive index Δ_1 of the core region (1) between about -0.3% to about -0.42%, and a core radius (r_1) between about 4 microns and about 6.5 microns. Additionally, an inner cladding region thickness of optical fiber 60 is between about 2 microns and about 12 microns. Optical fiber 60 has an off-set trench design with a trench volume of 54.5 %Δ-micron^2. The cladding of optical fiber 60 is fluorine-doped and the

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depressed-index cladding region has a radius (r_3) of about 17.5 microns. The optical properties of optical fiber 60 are shown in Table 4 below.

Table 4 - Optical Properties of Optical Fiber 60

Mode Field Diameter (at 1310 nm)	9.22 microns
Mode Field Diameter (at 1550 nm)	10.27 microns
Mode Field Diameter (at 1625 nm)	10.61 microns
Zero Dispersion Wavelength	1319 nm
Cable Cutoff	1315 nm
Trench Volume	54.5 %Δ-micron^2
15 mm Diameter Bend Loss	0.04 dB/turn
20 mm Diameter Bend Loss	0.009 dB/turn
30 mm Diameter Bend Loss	0.001 dB/turn

[00123] FIG. 6 depicts second and third exemplary embodiments of optical fibers, 64 and 65, with an alkali doped core and a trench volume of greater than about 50 %Δ-micron^2, and wherein the cladding is fluorine doped and the depressed-index cladding region has a radius (r_3) of about 17.5 microns. As shown in Table 5 below, optical fiber 64 results in a mode field diameter of 9.07 microns at 1310 nm, and optical fiber 65 results in a mode field diameter of 9.39 microns at 1310 nm. The optical properties of optical fibers 64 and 65 are shown in Table 2 below.

Table 5 - Optical Properties of Optical Fibers 64 and 65

	Optical Fiber 64	Optical Fiber 65
Mode Field Diameter (at 1310 nm)	9.07 microns	9.39 microns
Mode Field Diameter (at 1550 nm)	10.08 microns	10.48 microns
Mode Field Diameter (at 1625 nm)	10.41 microns	10.83 microns
Zero Dispersion Wavelength	1319 nm	1320 nm
Cable Cutoff	1419 nm	1339 nm
Trench Volume	55 %Δ-micron^2	55 %Δ-micron^2
15 mm Diameter Bend Loss	0.0137 dB/turn	0.042 dB/turn
20 mm Diameter Bend Loss	0.0003 dB/turn	0.009 dB/turn
30 mm Diameter Bend Loss	0.0002 dB/turn	0.001 dB/turn

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[00124] FIG. 7 depicts an embodiment of an optical fiber 66 with a Ge-doped core, a trench volume of greater than 50 %Δ-micron^2, and wherein the inner and cladding regions are substantially pure silica and the depressed-index cladding region has a radius (r_3) of about 16.8 microns. As shown in Table 6 below, optical fiber 64 results in a mode field diameter of 10.6 microns at a wavelength of 1550 nm. The refractive index profile parameters and optical properties of optical fiber 66 are shown in Table 6 below.

Table 6 - Optical Properties of Optical Fiber 66

	Fiber 66
Δ_1 (%)	0.35
r_1 (microns)	5.35
Core alpha	3.0
Δ_2 (%)	0.01
r_2 (microns)	12.0
Δ_3 (%)	-0.46
r_3 (microns)	16.8
V_3 (%-microns^2)	63.6
r_4 (microns)	62.5
r_6 (microns)	80.9
MFD at 1550 nm (microns)	10.6
Aeff at 1550 nm (microns^2)	85.5
Dispersion at 1550 nm (ps/nm/km)	18.3
Dispersion at 1310 nm (ps/nm/km)	0.38
Zero Dispersion Wavelength (nm)	1306
Attenuation at 1550 nm (dB/km)	0.23
22 m Cable Cutoff Wavelength (nm)	1287
2 m Fiber Cutoff Wavelength (nm)	1338
1x10 mm diameter macrobend loss at 1550 nm (dB)	0.6
1x15 mm diameter macrobend loss at 1550 nm (dB)	0.07

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[00125] The off-set trench design of optical fibers 60, 64, 65 and 66 provide improved bend performance for the smaller diameter fibers disclosed herein. More specifically, the off-set trench design disclosed herein provides low attenuation, large effective area, and low bend loss in a compact form, with a cladding diameter of about 125 microns and an outer coating diameter less than 175 microns.

[00126] **Coating Properties**

[00127] The transmissivity of light through an optical fiber is highly dependent on the properties of the coatings applied to the glass fiber. As discussed above (and with reference to FIG. 4), the coatings may include an optional low-modulus inner coating 56 and a high-modulus coating 58, where the high-modulus coating surrounds the optional low-modulus inner coating and the optional low-modulus inner coating contacts the glass fiber (which includes a central core region surrounded by a cladding region). An optional pigmented outer coating layer (e.g. ink layer) surrounds and directly contacts the high-modulus coating.

[00128] High-modulus coating 58 is a harder material (higher Young's modulus) than the optional low-modulus coating 56 and is designed to protect the glass fiber from damage caused by abrasion or external forces that arise during processing, handling, and deployment of the optical fiber. Optional low-modulus inner coating 56 is a softer material (lower Young's modulus) than high-modulus coating 58 and is designed to buffer or dissipates stresses that result from forces applied to the outer surface of the high-modulus coating. The optional low-modulus coating may help dissipate stresses that arise due to the microbends the optical fiber encounters when deployed in a cable but is not essential for short length applications such as optical interconnects. The microbending stresses transmitted to the glass fiber need to be minimized because microbending stresses create local perturbations in the refractive index profile of the glass fiber. The local refractive index perturbations lead to intensity losses for the light transmitted through the glass fiber. By dissipating stresses, the optional low-modulus coating minimizes intensity losses caused by microbending.

[00129] A thinner coating on the optical fiber is considered to increase microbending loss because it provides less protection against external perturbations. These perturbations result in power coupling from the light guided in the core (core mode) to higher-order modes in the cladding (cladding mode). As shown in FIG. 10, the cladding mode can have significant overlap with the coating layer which has high absorption. This process of coupling and absorption by the coating materials result in optical power loss.

[00130] An approach for quantifying the microbending loss of an optical fiber on the properties of the coatings is published in the article entitled "Relationship of Mechanical Characteristics of

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Dual Coated Single Mode Fibers and Microbending Loss," by J. Baldauf, N. Okada and M. Miyamoto, in IEICE Trans. Commun., Vol. E76-B, No. 4, pp. 352-357 (April, 1993). The authors introduced a parameter χ_s, which is an effective spring constant for the force that couples the secondary (high-modulus) coating and the glass fiber. This spring constant parameterization provides qualitative guidance that a thick primary (low-modulus) coating with a low modulus provides better microbending performance, but it does not fully capture the contributions of the glass and the high-modulus coating.

[00131] The combined roles of the glass, low-modulus inner coating, and high-modulus coating result in a microbending attenuation penalty (MAP) of:

$$MAP = C_0 f_0 \sigma \frac{f_{RIP} f_g(E_g, R_g) f_p(E_p, t_p)}{f_{cs}\left(\frac{E_s}{E_p}, R_g, t_s\right)} \qquad (8)$$

where f_0 and σ are the average lateral pressure and standard deviation of the roughness of the external surface in contact with the high-modulus coating, respectively, and

$$C_0 = 4x10^{25}\left[\left(\frac{\pi}{4}\right)^{2.625}\right]^{-1}.$$

f_{RIP} accounts for the role of the refractive index profile and is of order unity. Attenuation data indicates that f_{RIP} is approximately 1.0 for single-mode fiber with a step-index refractive index profile and is about 0.5 for bend-insensitive single-mode fibers with refractive index profiles that include a depressed index trench in the cladding. The other three terms in Eq. 8 are the contributions of the glass, low-modulus inner coating and the system comprising the low-modulus inner coating and high-modulus coating to the microbending response and are given by:

$$f_g = \frac{1}{E_g^2 R_g^6},$$

$$f_p = \frac{E_p}{t_p^2},$$

and $$f_{cs} = \left[1 + \frac{E_s}{E_p}\left(\frac{t_s}{R_s}\right)^3\right]^{0.375}\left\{\frac{E_s}{E_g}\left[R_s^4 - (R_s - t_s)^4\right]\right\}^{0.625},$$

where R_g is the radius of the glass (i.e. the outer radius of the outer cladding region), R_s is the outer radius of the high-modulus outer coating, t_p is the thickness of the inner low-modulus coating, t_s is the thickness of the high-modulus outer coating, and E_g, E_p and E_s are the elastic moduli of the glass, low-modulus inner coating and high-modulus coating, respectively. The

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MAP has units of dB/km when the units for the moduli and radii are GPa and microns, respectively. The low-modulus inner coating coefficient f_p depends on $(1/t_p)^2$, rather than on just $1/t_p$, as predicted by the spring constant parameterization. The f_{cs} coating system coefficient is of interest for fibers with thinner coatings because it is very large when the high-modulus coating is relative thick (t_s is greater than about 20 microns), which corresponds to a low MAP. However, it becomes quite small and yields a MAP value greater than 0.01 dB/km when the high-modulus coating thickness t_s is less than about 10 microns, which is a consequence of a decrease in the rigidity of the outer coating. The fiber attenuation in the absence of any microbending attenuation penalty is assumed to be approximately 0.19 dB.km, so the net attenuation of the coated optical fiber system is 0.19 dB/km plus the microbend attenuation penalty.

[00132] The inventors have found that if the coating is below a certain thickness, as described herein, microbending losses can be reduced. As shown in FIG. 11, when the thickness of the polymer coating is sufficiently reduced, an anti-resonant effect occurs in the coating layer, which makes the light not guided in the coating layer. This anti-resonant effect reduces significantly the absorption by the coating layer, thus decreasing the microbending loss. A conventional coating thickness of greater than 37 microns is too large for the anti-resonant effect. To produce this anti-resonant effect, the total thickness of the polymer coating is less than 25 microns, more preferably less than 20 microns, and even more preferably less than 10 microns. In some embodiments, the total thickness of the polymer coating is about 2 microns to about 25 microns, or about 2 microns to about 20 microns, or about 2 microns to about 15 microns, or about 2 microns to about 10 microns, or about 2 microns to about 5 microns.

[00133] As used herein the term "puncture load" refers to the amount force impinging on the coating of the fiber described herein. As used herein the term "puncture resistance" refers to the force from the fiber coating opposing the puncture load. As described further below, the coating will rupture when the puncture load exceeds the maximum puncture resistance of the coating. With respect to puncture resistance, the analysis by Glaesemann and Clark in the article "Quantifying the Puncture Resistance of Optical Fiber Coatings," Proc. 52nd IWCS, pp. 237-245 (1993) for fibers with one type of coating indicated that the puncture resistance has a linear dependence on the cross-sectional area A_s of the high-modulus coating. The analysis in this paper hypothesized that the puncture resistance was due to hoop stress on the high-modulus coating, which they modeled as a thin cylinder that is subjected to internal pressure from the low-modulus inner coating. However, for most optical fibers, the ratio of the thickness t_s of the high-modulus coating to the outer radius r_6 of is on the order of 10%, so the low-modulus

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coating of the fiber can be approximated as a thick-walled cylinder with pressure P_o acting from the outside and exerting a puncture load. In the limit where the external pressure is much greater than the internal pressure from the low-modulus inner coating, the maximum hoop stress is $\sigma_\theta = \frac{-2R_g^2 P_o}{(R_c^2 - R_g^2)} = \frac{-2\pi R_g^2 P_o}{A_s}$, where A_S is the cross-sectional area of the high-modulus coating. This hoop stress has the observed inverse dependence on A_S, and the puncture resistance is then $P_R = P_0 + C_1 E_s A_s$, where Es is the modulus of the high-modulus coating, and coefficients P_0 and C_1 have values of about 11.3 g and 2.1 g/MPa/mm^2, respectively.

[00134] *Coating Examples – Preparation and Measurement Techniques*

[00135] The properties of the optional low-modulus inner coating and high-modulus coating, as disclosed herein, were determined using the measurement techniques described below:

[00136] Tensile Properties. The curable high-modulus coating compositions were cured and configured in the form of cured rod samples for measurement of Young's modulus, tensile strength at yield, yield strength, and elongation at yield. The cured rods were prepared by injecting the curable high-modulus coating composition into Teflon® tubing having an inner diameter of about 0.025". The rod samples were cured using a Fusion D bulb at a dose of about 2.4 J/cm^2 (measured over a wavelength range of 225-424 nm by a Light Bug model IL390 from International Light). After curing, the Teflon® tubing was stripped away to provide a cured rod sample of the high-modulus coating composition. The cured rods were allowed to condition for 18-24 hours at 23°C and 50% relative humidity before testing. Young's modulus, tensile strength at break, yield strength, and elongation at yield were measured using a Sintech MTS Tensile Tester on defect-free rod samples with a gauge length of 51 mm, and a test speed of 250 mm/min. Tensile properties were measured according to ASTM Standard D882-97. The properties were determined as an average of at least five samples, with defective samples being excluded from the average.

[00137] *In Situ* Glass Transition Temperature. *In situ* T_g measurements were performed on fiber tube-off samples obtained from fibers having a low-modulus inner coating surrounded by a high-modulus coating. The coated fibers included a glass fiber having a diameter of 125 microns, a low-modulus inner coating with thickness 32.5 microns surrounding and in direct contact with the glass fiber, and a high-modulus coating with thickness 26.0 microns surrounding and in direct contact with the glass fiber. The glass fiber and low-modulus inner coating were the same for all samples measured. The low-modulus inner coating was formed from the reference low-modulus inner coating composition described below. Samples with a

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comparative high-modulus coating and a high-modulus coating in accordance with the present disclosure were measured.

[00138] The fiber tube-off samples were obtained using the following procedure: a 0.0055″ Miller stripper was clamped down approximately 1 inch from the end of the coated fiber. The one-inch region of fiber was plunged into a stream of liquid nitrogen and held in the liquid nitrogen for 3 seconds. The coated fiber was then removed from the stream of liquid nitrogen and quickly stripped to remove the coating. The stripped end of the fiber was inspected for residual coating. If residual coating remained on the glass fiber, the sample was discarded, and a new sample was prepared. The result of the stripping process was a clean glass fiber and a hollow tube of stripped coating that includes the intact low-modulus inner coating and the high-modulus coating. The hollow tube is referred to as a "tube-off sample". The diameters of the glass, low-modulus inner coating and high-modulus coating were measured from the end-face of the unstripped fiber.

[00139] *In-situ* Tg of the tube-off samples was run using a Rheometrics DMTA IV test instrument at a sample gauge length of 9 to 10 mm. The width, thickness, and length of the tube-off sample were input to the operating program of the test instrument. The tube-off sample was mounted and then cooled to approximately -85°C. Once stable, the temperature ramp was run using the following parameters:

Frequency: 1 Hz

Strain: 0.3%

Heating Rate: 2°C/min.

Final Temperature: 150°C

Initial Static Force = 20.0 g

Static > Dynamic Force by = 10.0%

[00140] The *in-situ* Tg of a coating is defined as the maximum value of tan δ in a plot of tan δ as a function of temperature, where tan δ is defined as:

$$\tan \delta = E''/E'$$

and E" is the loss modulus, which is proportional to the loss of energy as heat in a cycle of deformation and E' is the storage or elastic modulus, which is proportional to the energy stored in a cycle of deformation.

[00141] The tube-off samples exhibited distinct maxima in the tan δ plot for the low-modulus inner coating and high-modulus coating. The maximum at lower temperature (about –50°C)

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corresponded to the *in-situ* Tg for the low-modulus inner coating and the maximum at higher temperature (above 50°C) corresponded to the *in-situ* Tg for the high-modulus coating.

[00142] *In Situ* Modulus of Low-Modulus Inner Coating. In embodiments that include this optional coating layer, the *in situ* modulus was measured using the following procedure. A six-inch sample of fiber was obtained and a one-inch section from the center of the fiber was window-stripped and wiped with isopropyl alcohol. The window-stripped fiber was mounted on a sample holder/alignment stage equipped with 10 mm x 5 mm rectangular aluminium tabs that were used to affix the fiber. Two tabs were oriented horizontally and positioned so that the short 5 mm sides were facing each other and separated by a 5 mm gap. The window-stripped fiber was laid horizontally on the sample holder across the tabs and over the gap separating the tabs. The coated end of one side of the window-stripped region of the fiber was positioned on one tab and extended halfway into the 5 mm gap between the tabs. The one-inch window-stripped region extended over the remaining half of the gap and across the opposing tab. After alignment, the sample was removed, and a small dot of glue was applied to the half of each tab closest to the 5 mm gap. The fiber was then returned to position and the alignment stage was raised until the glue just touched the fiber. The coated end was then pulled away from the gap and through the glue such that the majority of the 5 mm gap between the tabs was occupied by the window-stripped region of the fiber. The portion of the window-stripped region remaining on the opposing tab was in contact with the glue. The very tip of the coated end was left to extend beyond the tab and into the gap between the tabs. This portion of the coated end was not embedded in the glue and was the object of the *in situ* modulus measurement. The glue was allowed to dry with the fiber sample in this configuration to affix the fiber to the tabs. After drying, the length of fiber fixed to each of the tabs was trimmed to 5 mm. The coated length embedded in glue, the non-embedded coated length (the portion extending into the gap between the tabs), and the primary diameter were measured.

[00143] The *in situ* modulus measurements were performed on a Rheometrics DMTA IV dynamic mechanical testing apparatus at a constant strain of 9e-6 1/s for a time of forty-five minutes at room temperature (21 °C). The gauge length was 15 mm. Force and the change in length were recorded and used to calculate the *in situ* modulus of the low-modulus coating. The tab-mounted fiber samples were prepared by removing any epoxy from the tabs that would interfere with the 15 mm clamping length of the testing apparatus to ensure that there was no contact of the clamps with the fiber and that the sample was secured squarely to the clamps. The instrument force was zeroed out. The tab to which the non-coated end of the fiber was affixed

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was then mounted to the lower clamp (measurement probe) of the testing apparatus and the tab to which the coated end of the fiber was affixed was mounted to the upper (fixed) clamp of the testing apparatus. The test was then executed, and the sample was removed once the analysis was completed.

[00144] *In Situ* Modulus of the High-Modulus Coating. For the high-modulus coating, the *in situ* modulus was measured using fiber tube-off samples prepared from the fiber samples. A 0.0055 inch Miller stripper was clamped down approximately 1 inch from the end of the fiber sample. This one-inch region of fiber sample was immersed into a stream of liquid nitrogen and held for 3 seconds. The fiber sample was then removed and quickly stripped. The stripped end of the fiber sample was then inspected. If coating remained on the glass portion of the fiber sample, the tube-off sample was deemed defective and a new tube-off sample was prepared. A proper tube-off sample is one that stripped clean from the glass and consists of a hollow tube with a low-modulus inner coating and the high-modulus coating. The diameters of the glass, the low-modulus inner coating, and the high-modulus coating were measured from the end-face of the unstripped fiber sample.

[00145] The fiber tube-off samples were run using a Rheometrics DMTA IV instrument at a sample gauge length 11 mm to obtain the *in situ* modulus of the high-modulus coating. The width, thickness, and length were determined and provided as input to the operating software of the instrument. The sample was mounted and run using a time sweep program at ambient temperature (21°C) using the following parameters:

Frequency: 1 Rad/sec

Strain: 0.3%

Total Time = 120 sec.

Time Per Measurement = 1 sec

Initial Static Force = 15.0 g

Static > Dynamic Force by = 10.0%

Once completed, the last five E' (storage modulus) data points were averaged. Each sample was run three times (fresh sample for each run) for a total of fifteen data points. The averaged value of the three runs was reported.

[00146] Puncture Resistance of the High-Modulus Coating. Puncture resistance measurements were made on samples that included a glass fiber, and a low-modulus inner coating surrounded by a high-modulus coating. The glass fiber had a cladding diameter of 125 microns. The low-modulus inner coating was formed from the reference low-modulus inner coating composition listed in Table 1 below. Samples with various high-modulus coatings were prepared as

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described below. The thicknesses of the low-modulus inner coating and high-modulus coating were adjusted to vary the cross-sectional area of the high-modulus coating as described below. The ratio of the thickness of the high-modulus coating to the thickness of the low-modulus inner coating was maintained at about 0.8 for all samples.

[00147] The puncture resistance was measured using the technique described in the article entitled "Quantifying the Puncture Resistance of Optical Fiber Coatings", by G. Scott Glaesemann and Donald A. Clark, published in the Proceedings of the 52nd International Wire & Cable Symposium, pp. 237-245 (2003), which incorporated by reference herein. A summary of the method is provided here. The method is an indentation method. A 4-centimeter length of optical fiber was placed on a 3 mm-thick glass slide. One end of the optical fiber was attached to a device that permitted rotation of the optical fiber in a controlled fashion. The optical fiber was examined in transmission under 100X magnification and rotated until the thickness of the high-modulus coating was equivalent on both sides of the glass fiber in a direction parallel to the glass slide. In this position, the thickness of the high-modulus coating was equal on both sides of the optical fiber in a direction parallel to the glass slide. The thickness of the high-modulus coating in the directions normal to the glass slide and above or below the glass fiber differed from the thickness of the high-modulus coating in the direction parallel to the glass slide. One of the thicknesses in the direction normal to the glass slide was greater and the other of the thicknesses in the direction normal to the glass slide was less than the thickness in the direction parallel to the glass slide. This position of the optical fiber was fixed by taping the optical fiber to the glass slide at both ends and is the position of the optical fiber used for the indentation test.

[00148] Indentation was carried out using a universal testing machine (Instron model 5500R or equivalent). An inverted microscope was placed beneath the crosshead of the testing machine. The objective of the microscope was positioned directly beneath a Vickers diamond wedge indenter, with an included angle of 75°, that was installed in the testing machine. The glass slide with taped fiber was placed on the microscope stage and positioned directly beneath the indenter such that the width of the indenter wedge was orthogonal to the direction of the optical fiber. With the optical fiber in place, the diamond wedge was lowered until it contacted the surface of the high-modulus coating. The diamond wedge was then driven into the high-modulus coating at a rate of 0.1 mm/min and the load on the high-modulus coating was measured. The load on the high-modulus coating increased as the diamond wedge was driven deeper into the high-modulus coating until puncture occurred, at which point a precipitous decrease in load was observed. The indentation load at which puncture was observed was recorded and is reported herein as grams of force (g) and referred to herein as "puncture load". The experiment was

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repeated with the optical fiber in the same orientation to obtain ten measurement points, which were averaged to determine a puncture load for the orientation. A second set of ten measurement points was taken by rotating the orientation of the optical fiber by 180°.

[00149] Macrobending Loss. Macrobending loss was determined using the mandrel wrap test specified in standard IEC 60793-1-47. In the mandrel wrap test, the fiber is wrapped one or more times around a cylindrical mandrel having a specified diameter, and the increase in attenuation at a specified wavelength due to the bending is determined. Attenuation in the mandrel wrap test is expressed in units of dB/turn, where one turn refers to one revolution of the fiber about the the mandrel. Macrobending losses at a wavelength of 1310 nm, 1550 nm and 1625 nm were determined for selected examples described below with the mandrel wrap test using mandrels with diameters of 10 mm, 15 mm and 20 mm.

[00150] *Exemplary Embodiments of Optical Fibers with Low-Modulus Inner Coatings surrounded by High-Modulus Coatings*

[00151] The specific properties of the optional low-modulus inner coating 56 and high-modulus coating 58 may be tailored to provide sufficient robustness and good microbending performance for the smaller diameter fibers disclosed herein. For example, low-modulus inner coating 56 may have a low Young's modulus and/or a low *in situ* modulus. The Young's modulus of the low-modulus inner coating is less than or equal to about 0.7 MPa, or less than or equal to about 0.6 MPa, or less than or equal to 0.5 about MPa, or less than or equal to about 0.4 MPa, or in the range from about 0.1 MPa to about 0.7 MPa, or in the range from about 0.1 MPa to about 0.4 MPa. The *in situ* modulus of the low-modulus inner coating is less than or equal to about 0.50 MPa, or less than or equal to about 0.30 MPa, or less than or equal to about 0.25 MPa, or less than or equal to about 0.20 MPa, or less than or equal to about 0.15 MPa, or less than or equal to about 0.10 MPa, or in the range from about 0.05 MPa to about 0.25 MPa, or in the range from about 0.10 MPa to about 0.20 MPa.

[00152] Low-modulus inner coating 56 preferably has a higher refractive index than cladding region 50 of the glass fiber in order to allow it to strip errant optical signals away from core region 48. Low-modulus inner coating 56 should maintain adequate adhesion to the glass fiber during thermal and hydrolytic aging, yet still be strippable from the glass fiber for splicing purposes.

[00153] To facilitate smaller diameter optical fibers, the low-modulus inner coating may be absent or have a smaller thickness than the low-modulus inner coating used in conventional optical fibers. The high-modulus coating 58 may have a smaller thickness and a smaller cross-

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sectional area compared to conventional optical fibers. However, high-modulus coating 58 must still maintain the required robustness and puncture resistance needed for high reliability in undersea cables and repeaters. As the thickness of the high-modulus coating decreases, its protective function diminishes. Puncture resistance is a measure of the protective function of the cross-sectional area of the outer coatings, which include the high-modulus coating and the optional pigmented outer coating. A high-modulus coating with a higher puncture resistance withstands higher abrasive pressures without failing and provides better protection for the glass fiber.

[00154] In order to provide the required robustness and puncture resistance, high-modulus coating 58 may have an *in situ* modulus greater than about 1500 MPa, or greater than about 1600 MPa, or greater than about 1800 MPa, or greater than about 2200 MPa, or greater than about 2500 MPa, or greater than about 2600 MPa, or greater than about 2700 MPa, or in the range from about 1500 MPa to about 3000 MPa, or in the range from about 1800 MPa to about 2800 MPa, or in the range from about 2000 MPa to about 2800 MPa, or in the range from about 2400 MPa to about 2800 MPa.

[00155] In order to further provide the required robustness and puncture resistance, the product of the cross-sectional area and the *in situ* modulus of the high-modulus coating 58 may be greater than about 10 N, greater than about 12.5 N, greater than about 15 N, greater than about 20 N, greater than about 25 N, greater than about 30 N, or in the range from about 10 N to 30 N, or in the range from about 15 N to about 30 N, or in the range from about 20 N to about 30 N, or in the range from about 25 N to about 30 N.

[00156] In order to provide the required combination of low good microbending performance and puncture resistance, the ratio of the *in situ* modulus of the high-modulus coating 58 to the *in situ* modulus of the low-modulus coating 56 may be greater than about 4000, or greater than about 5000, or greater than about 6000, or greater than about 7000, or greater than about 8000, or greater than about 9000, or greater than about 10,000, or in the range from about 4000 to about 10,000, or in the range from about 4000 to about 10,000, or in the range from about 5000 to about 10,000, or in the range from about 6000 to about 10,000, or in the range from about 7000 to about 10,000, or in the range from about 8000 to about 10,000.

[00157] Low-modulus and high-modulus coatings are typically formed by applying a curable coating composition to the glass fiber as a viscous liquid and curing. The optical fiber may also include a pigmented outer coating that surrounds the high-modulus coating. The pigmented outer coating may include coloring agents to mark the optical fiber for identification purposes

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and typically has a Young's modulus similar to the Young's modulus of the high-modulus coating.

[00158] High-modulus coating 58 may be comprised of a trifunctional monomer. A glass transition temperature (Tg) of high-modulus coating 58 may be greater than about 50°C, or greater than about 60°C, or greater than about 70°C, or greater than about 80°C, or greater than about 90°C, or greater than about 100°C.

[00159] Suitable low-modulus inner coatings 56 and high-modulus coatings 58 may be used so that optical fiber 46 has a puncture resistance greater than or equal to about 28 g, or greater than or equal to about 30 g, or greater than or equal to about 32 g, or greater than or equal to about 34 g, or greater than or equal to about 36 g, or greater than or equal to about 38 g, or greater than or equal to about 40 g, when the cross-sectional area of the high-modulus coating is less than about 10,000 microns^2.

[00160] Suitable low-modulus inner coatings 56 and high-modulus coatings 58 may be used so that optical fiber 46 has a puncture resistance greater than or equal to about 22 g, or greater than or equal to about 24 g, or greater than or equal to about 26 g, or greater than or equal to about 28 g, or greater than or equal to about 30 g, when the cross-sectional area of the high-modulus coating is less than about 8,000 microns^2.

[00161] FIG. 19 depicts the microbend attenuation penalty (MAP) versus the low-modulus inner coating thickness for fibers having step-index and trench-assisted profiles (e.g. as shown in Table 2 above), a cladding diameter of 100 microns, a high-modulus coating having a modulus of 1200 MPa and an outer radius of 82.5 microns, and a low-modulus inner coating having a modulus of 0.5 MPa. As shown in FIG. 19 and Table 7a, a MAP less than 0.1 dB/km can be achieved when the fiber has a trench-assisted profile, a cladding diameter of about 100 microns, and the thickness of the low-modulus inner coating is between about 10 microns and about 26 microns. The calculations were also performed on fibers having step-index and trench-assisted profiles, a cladding diameter of 125 microns, a high-modulus coating having a modulus of 1200 MPa and an outer radius of 82.5 microns, and a low-modulus inner coating having a modulus of 0.5 MPa. As illustrated by Table 7b, a MAP less than 0.1 dB/km can be achieved when the fiber has a trench-assisted profile, a cladding diameter of about 125 microns, and the thickness of the low-modulus inner coating is between about 8 microns and about 17 microns.

TABLE 7a (MAP for fibers having step-index and trench-assisted profiles with a cladding diameter of 100 microns, Ep=0.5 MPa and Es=1200 MPa)

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Glass Radius, R_g (microns)	Low-modulus Inner Coating Thickness, t_p (microns)	Low-modulus Inner Coating Radius, R_p (microns)	High-modulus Coating Radius, R_s (microns)	High-modulus Coating Thickness, t_s (microns)	MAP of Step-index profile (dB/km)	MAP of Trench-assisted profile (dB/km)
50	5	55	82.5	27.5	0.522	0.261
50	6	56	82.5	26.5	0.382	0.191
50	7	57	82.5	25.5	0.297	0.148
50	8	58	82.5	24.5	0.241	0.120
50	9	59	82.5	23.5	0.202	0.101
50	10	60	82.5	22.5	0.174	0.087
50	11	61	82.5	21.5	0.154	0.077
50	12	62	82.5	20.5	0.139	0.069
50	13	63	82.5	19.5	0.128	0.064
50	14	64	82.5	18.5	0.119	0.059
50	15	65	82.5	17.5	0.113	0.056
50	16	66	82.5	16.5	0.108	0.054
50	17	67	82.5	15.5	0.105	0.053
50	18	68	82.5	14.5	0.104	0.052
50	19	69	82.5	13.5	0.104	0.052
50	20	70	82.5	12.5	0.105	0.052
50	21	71	82.5	11.5	0.108	0.054
50	22	72	82.5	10.5	0.112	0.056
50	23	73	82.5	9.5	0.118	0.059
50	24	74	82.5	8.5	0.126	0.063
50	25	75	82.5	7.5	0.137	0.069
50	26	76	82.5	6.5	0.151	0.075
50	27	77	82.5	5.5	0.168	0.084
50	28	78	82.5	4.5	0.189	0.094
50	29	79	82.5	3.5	0.216	0.108
50	30	80	82.5	2.5	0.256	0.128
50	31	81	82.5	1.5	0.333	0.166

TABLE 7b (MAP for fibers having step-index and trench-assisted profiles with cladding diameters of 125 microns, Ep=0.5 MPa and Es=1200 MPa)

Glass Radius, R_g (microns)	Low-modulus Inner Coating Thickness, t_p (microns)	Low-modulus Inner Coating Radius, R_p (microns)	High-modulus Coating Radius, R_s (microns)	High-modulus Coating Thickness, t_s (microns)	MAP of Step-index profile (dB/km)	MAP of Trench-assisted profile (dB/km)
62.5	5	67.5	82.5	15	0.335	0.167

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62.5	6	68.5	82.5	14	0.258	0.129
62.5	7	69.5	82.5	13	0.212	0.106
62.5	8	70.5	82.5	12	0.183	0.091
62.5	9	71.5	82.5	11	0.164	0.082
62.5	10	72.5	82.5	10	0.152	0.076
62.5	11	73.5	82.5	9	0.146	0.073
62.5	12	74.5	82.5	8	0.143	0.072
62.5	13	75.5	82.5	7	0.145	0.072
62.5	14	76.5	82.5	6	0.149	0.075
62.5	15	77.5	82.5	5	0.157	0.078
62.5	16	78.5	82.5	4	0.168	0.084
62.5	17	79.5	82.5	3	0.185	0.092
62.5	18	80.5	82.5	2	0.216	0.108
62.5	19	81.5	82.5	1	0.299	0.149

[00162] FIG. 20 depicts the MAP versus the thickness of the low-modulus inner coating for fibers having trench-assisted fiber profiles (e.g. as shown in Table 2 above), a cladding diameter of 100 microns, a low-modulus inner coating having a modulus of 0.5 MPa and a high-modulus coatings having moduli of 1.2, 1.6 and 2.0 GPa. As shown in FIG. 20 and Table 8a, a MAP less than 0.1 dB/km can be achieved when the high-modulus coating has a modulus of 1.6 GPa and the thickness of the low-modulus inner coating is between about 8 and about 29 microns. A MAP less than 0.05 dB/km can be achieved when the high-modulus coating has a modulus of 1.6 GPa and the thickness of the low-modulus inner coating is between about 13 and about 24 microns. A MAP less than 0.1 dB/km can be achieved when the high-modulus coating has a modulus of 2.0 GPa and the thickness of the low-modulus inner coating is between about 7 and about 30 microns. A MAP less than 0.05 dB/km can be achieved when the high-modulus coating has a modulus of 2.0 GPa and the thickness of the low-modulus inner coating is between about 11 and about 26 microns. The calculations were also performed on fibers having trench-assisted profiles, a cladding diameter of 125 microns, a low-modulus inner coating having a modulus of 0.5 MPa and high-modulus coatings having moduli of 1.2, 1.6 and 2.0 GPa. As shown in Table 8b, a MAP less than 0.1 dB/km can be achieved when the high-modulus coating has a modulus of 1.6 GPa and the thickness of the low-modulus inner coating is between about 6 and about 18 microns. A MAP less than 0.06 dB/km can be achieved when the high-modulus coating has a modulus of 1.6 GPa and the thickness of the low-modulus inner coating is between about 10 and about 14 microns. A MAP less than 0.1 dB/km can be achieved when the high-modulus coating has a modulus of 2.0 GPa and the thickness of the low-modulus inner coating is between about 6 and about 18 microns. A MAP less than 0.05 dB/km can be achieved when the

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high-modulus coating has a modulus of 2.0 GPa and the thickness of the low-modulus inner coating is between about 10 and about 14 microns.

TABLE 8a (MAP for fibers having trench-assisted profiles with a cladding diameter of 100 microns and Ep=0.5 MPa)

Glass Radius, R_g (microns)	Low-modulus Inner Coating Thickness, t_p (microns)	Low-modulus Inner Coating Radius, R_p (microns)	High-modulus Coating Radius, R_s (microns)	High-modulus Coating Thickness, t_s (microns)	MAP for Es=1.2 GPa (dB/km)	MAP for Es=1.6 GPa (dB/km)	MAP for Es=2.0 GPa (dB/km)
50	5	55	82.5	27.5	0.261	0.196	0.157
50	6	56	82.5	26.5	0.191	0.144	0.115
50	7	57	82.5	25.5	0.148	0.111	0.089
50	8	58	82.5	24.5	0.120	0.090	0.072
50	9	59	82.5	23.5	0.101	0.076	0.061
50	10	60	82.5	22.5	0.087	0.066	0.052
50	11	61	82.5	21.5	0.077	0.058	0.046
50	12	62	82.5	20.5	0.069	0.052	0.042
50	13	63	82.5	19.5	0.064	0.048	0.038
50	14	64	82.5	18.5	0.059	0.045	0.036
50	15	65	82.5	17.5	0.056	0.042	0.034
50	16	66	82.5	16.5	0.054	0.041	0.033
50	17	67	82.5	15.5	0.053	0.040	0.032
50	18	68	82.5	14.5	0.052	0.039	0.031
50	19	69	82.5	13.5	0.052	0.039	0.032
50	20	70	82.5	12.5	0.052	0.040	0.032
50	21	71	82.5	11.5	0.054	0.041	0.033
50	22	72	82.5	10.5	0.056	0.043	0.034
50	23	73	82.5	9.5	0.059	0.045	0.037
50	24	74	82.5	8.5	0.063	0.049	0.040
50	25	75	82.5	7.5	0.069	0.053	0.044
50	26	76	82.5	6.5	0.075	0.059	0.049
50	27	77	82.5	5.5	0.084	0.067	0.056
50	28	78	82.5	4.5	0.094	0.076	0.064
50	29	79	82.5	3.5	0.108	0.089	0.076
50	30	80	82.5	2.5	0.128	0.106	0.092
50	31	81	82.5	1.5	0.166	0.139	0.121

TABLE 8b (MAP for fibers having trench-assisted profiles with a cladding diameter of 125 microns and Ep=0.5 MPa)

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Glass Radius, R_g (microns)	Low-modulus Inner Coating Thickness, t_p (microns)	Low-modulus Inner Coating Radius, R_p (microns)	High-modulus Coating Radius, R_s (microns)	High-modulus Coating Thickness, t_s (microns)	MAP for Es=1.2 GPa (dB/km)	MAP for Es=1.6 GPa (dB/km)	MAP for Es=2.0 GPa (dB/km)
62.5	5	67.5	82.5	15	0.167	0.126	0.101
62.5	6	68.5	82.5	14	0.129	0.097	0.078
62.5	7	69.5	82.5	13	0.106	0.080	0.064
62.5	8	70.5	82.5	12	0.091	0.069	0.056
62.5	9	71.5	82.5	11	0.082	0.062	0.050
62.5	10	72.5	82.5	10	0.076	0.058	0.047
62.5	11	73.5	82.5	9	0.073	0.056	0.045
62.5	12	74.5	82.5	8	0.072	0.055	0.045
62.5	13	75.5	82.5	7	0.072	0.056	0.046
62.5	14	76.5	82.5	6	0.075	0.059	0.049
62.5	15	77.5	82.5	5	0.078	0.063	0.053
62.5	16	78.5	82.5	4	0.084	0.068	0.058
62.5	17	79.5	82.5	3	0.092	0.076	0.065
63.5	18	81.5	83.5	2	0.108	0.090	0.078
64.5	19	83.5	84.5	1	0.149	0.125	0.108

[00163] FIG. 21 depicts the puncture resistance versus the thickness of the low-modulus inner coating for fibers having a trench-assisted profile (e.g. as shown in Table 2 above), a cladding diameter of 100 microns, a low-modulus coating having a modulus of 0.5 MPa and a high-modulus coatings having moduli of 1.2, 1.6 and 2.0 GPa. As shown in FIG. 21 and Table 9a, a puncture resistance greater than 30 g can be achieved when the high-modulus coating has a modulus of 1.6 GPa and the thickness of the low-modulus inner coating is less than about 14 microns. A puncture resistance greater than 35 g can be achieved when the high-modulus coating has a modulus of 1.6 GPa and the thickness of the low-modulus inner coating is less than about 8 microns. A puncture resistance greater than 30 g can be achieved when the high-modulus coating has a modulus of 2.0 GPa and the thickness of the low-modulus inner coating is less than about 18 microns. A puncture resistance greater than 35 g can be achieved when the high-modulus coating has a modulus of 2.0 GPa and the thickness of the low-modulus inner coating is less than about 14 microns. A puncture resistance greater than 40 g can be achieved when the high-modulus coating has a modulus of 2.0 GPa and the thickness of the low-modulus inner coating is less than about 9 microns. The calculations were also performed on fibers having a trench-assisted profile, a cladding diameter of 125 microns, a low-modulus inner coating having a modulus of 0.5 MPa and high-modulus coatings having moduli of 1.2, 1.6 and

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2.0 GPa. As shown in Table 9b, a puncture resistance greater than 20 g can be achieved when the high-modulus coating has a modulus of 1.6 GPa and the thickness of the low-modulus inner coating is less than about 12 microns. A puncture resistance greater than 25 g can be achieved when the high-modulus coating has a modulus of 1.6 GPa and the thickness of the low-modulus inner coating is less than about 7 microns. A puncture resistance greater than 20 g can be achieved when the high-modulus coating has a modulus of 2.0 GPa and the thickness of the low-modulus inner coating is less than about 13 microns. A puncture resistance greater than 25 g can be achieved when the high-modulus coating has a modulus of 2.0 GPa and the thickness of the low-modulus inner coating is less than about 9 microns. A puncture resistance greater than 30 g can be achieved when the high-modulus coating has a modulus of 2.0 GPa and the thickness of the low-modulus inner coating is less than or equal to about 6 microns.

TABLE 9a (Puncture resistance for fibers having trench-assisted profiles with a cladding diameter of 100 microns and Ep=0.5 MPa)

Glass Radius, R_g (microns)	Low-modulus Inner Coating Thickness, t_p (microns)	Low-modulus Inner Coating Radius, R_p (microns)	High-modulus Coating Radius, R_s (microns)	High-modulus Coating Thickness, t_s (microns)	Puncture Resistance for Es=1.2 GPa (g)	Puncture Resistance for Es=1.6 GPa (g)	Puncture Resistance for Es=2.0 GPa (g)
50	5	55	82.5	27.5	31.2	37.9	44.5
50	6	56	82.5	26.5	30.6	37.1	43.5
50	7	57	82.5	25.5	30.0	36.3	42.5
50	8	58	82.5	24.5	29.4	35.5	41.5
50	9	59	82.5	23.5	28.8	34.7	40.5
50	10	60	82.5	22.5	28.2	33.8	39.5
50	11	61	82.5	21.5	27.5	33.0	38.4
50	12	62	82.5	20.5	26.9	32.1	37.3
50	13	63	82.5	19.5	26.2	31.2	36.2
50	14	64	82.5	18.5	25.6	30.3	35.1
50	15	65	82.5	17.5	24.9	29.4	34.0
50	16	66	82.5	16.5	24.2	28.5	32.8
50	17	67	82.5	15.5	23.5	27.6	31.6
50	18	68	82.5	14.5	22.8	26.6	30.5
50	19	69	82.5	13.5	22.0	25.6	29.2
50	20	70	82.5	12.5	21.3	24.7	28.0
50	21	71	82.5	11.5	20.6	23.7	26.8
50	22	72	82.5	10.5	19.8	22.7	25.5
50	23	73	82.5	9.5	19.1	21.7	24.2
50	24	74	82.5	8.5	18.3	20.6	23.0

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50	25	75	82.5	7.5	17.5	19.6	21.6
50	26	76	82.5	6.5	16.7	18.5	20.3
50	27	77	82.5	5.5	15.9	17.4	19.0
50	28	78	82.5	4.5	15.1	16.3	17.6
50	29	79	82.5	3.5	14.2	15.2	16.2
50	30	80	82.5	2.5	13.4	14.1	14.8
50	31	81	82.5	1.5	12.5	13.0	13.4

TABLE 9b (Puncture resistance for fibers having trench-assisted profiles with a cladding diameter of 100 microns and Ep=0.5 MPa)

Glass Radius, R_g (microns)	Low-modulus Inner Coating Thickness, t_p (microns)	Low-modulus Inner Coating Radius, R_p (microns)	High-modulus Coating Radius, R_s (microns)	High-modulus Coating Thickness, t_s (microns)	Puncture Resistance for Es=1.2 GPa (g)	Puncture Resistance for Es=1.6 GPa (g)	Puncture Resistance for Es=2.0 GPa (g)
62.5	5	67.5	82.5	15	23.1	27.1	31.0
62.5	6	68.5	82.5	14	22.4	26.1	29.9
62.5	7	69.5	82.5	13	21.7	25.2	28.6
62.5	8	70.5	82.5	12	20.9	24.2	27.4
62.5	9	71.5	82.5	11	20.2	23.2	26.2
62.5	10	72.5	82.5	10	19.4	22.2	24.9
62.5	11	73.5	82.5	9	18.7	21.1	23.6
62.5	12	74.5	82.5	8	17.9	20.1	22.3
62.5	13	75.5	82.5	7	17.1	19.0	21.0
62.5	14	76.5	82.5	6	16.3	18.0	19.6
62.5	15	77.5	82.5	5	15.5	16.9	18.3
62.5	16	78.5	82.5	4	14.7	15.8	16.9
62.5	17	79.5	82.5	3	13.8	14.7	15.5
63.5	18	81.5	83.5	2	13.0	13.5	14.1
64.5	19	83.5	84.5	1	12.1	12.4	12.7

[00164] FIG. 22 depicts the MAP versus the thickness of the low-modulus inner coating for fibers having a trench-assisted fiber profile (e.g. as shown in Table 2 above), a cladding diameter of 100 microns, a high-modulus coating having a modulus of 1.6 GPa and low-modulus inner coatings having moduli of 0.5, 0.35 and 0.2 MPa. As shown in FIG. 22 and Table 10a, a MAP less than 0.05 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.35 MPa and the thickness of the low-modulus inner coating is between about 8 and about 29

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microns. A MAP less than 0.02 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.35 MPa and the thickness of the low-modulus inner coating is between about 16 and about 21 microns. A MAP less than 0.05 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.2 MPa and the thickness of the low-modulus inner coating is between about 4 and about 31 microns. A MAP less than 0.02 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.2 MPa and the thickness of the low-modulus inner coating is between about 7 and about 29 microns. A MAP less than 0.01 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.2 MPa and the thickness of the low-modulus inner coating is between about 11 and about 25 microns. A MAP less than 0.007 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.2 MPa and the thickness of the low-modulus inner coating is between about 16 and about 21 microns. The calculations were also performed on fibers having a trench-assisted fiber profile, a cladding diameter of 125 microns, a high-modulus coating having a modulus of 1.6 GPa and low-modulus inner coatings having moduli of 0.5, 0.35 and 0.2 MPa. As shown in Table 10b, a MAP less than 0.05 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.35 MPa and the thickness of the low-modulus inner coating is between about 6 and about 18 microns. A MAP less than 0.03 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.35 MPa and the thickness of the low-modulus inner coating is between about 10 and about 14 microns. A MAP less than 0.03 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.2 MPa and the thickness of the low-modulus inner coating is between about 4 and about 19 microns. A MAP less than 0.02 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.2 MPa and the thickness of the low-modulus inner coating is between about 6 and about 17 microns. A MAP less than 0.01 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.2 MPa and the thickness of the low-modulus inner coating is between about 10 and about 13 microns.

TABLE 10a (MAP for fibers having trench-assisted profiles with a cladding diameter of 100 microns and Es=1.6 GPa)

Glass Radius, R_g (microns)	Low-modulus Inner Coating Thickness, t_p (microns)	Low-modulus Inner Coating Radius, R_p (microns)	High-modulus Coating Radius, R_s (microns)	High-modulus Coating Thickness, t_s (microns)	MAP for Ep=0.5 MPa (dB/km)	MAP for Ep=0.35 MPa (dB/km)	MAP for Ep=0.2 MPa (dB/km)

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50	5	55	82.5	27.5	0.196	0.096	0.031
50	6	56	82.5	26.5	0.144	0.070	0.023
50	7	57	82.5	25.5	0.111	0.055	0.018
50	8	58	82.5	24.5	0.090	0.044	0.015
50	9	59	82.5	23.5	0.076	0.037	0.012
50	10	60	82.5	22.5	0.066	0.032	0.011
50	11	61	82.5	21.5	0.058	0.028	0.009
50	12	62	82.5	20.5	0.052	0.026	0.008
50	13	63	82.5	19.5	0.048	0.024	0.008
50	14	64	82.5	18.5	0.045	0.022	0.007
50	15	65	82.5	17.5	0.042	0.021	0.007
50	16	66	82.5	16.5	0.041	0.020	0.007
50	17	67	82.5	15.5	0.040	0.020	0.006
50	18	68	82.5	14.5	0.039	0.019	0.006
50	19	69	82.5	13.5	0.039	0.019	0.006
50	20	70	82.5	12.5	0.040	0.020	0.006
50	21	71	82.5	11.5	0.041	0.020	0.007
50	22	72	82.5	10.5	0.043	0.021	0.007
50	23	73	82.5	9.5	0.045	0.023	0.008
50	24	74	82.5	8.5	0.049	0.024	0.008
50	25	75	82.5	7.5	0.053	0.027	0.009
50	26	76	82.5	6.5	0.059	0.030	0.010
50	27	77	82.5	5.5	0.067	0.035	0.012
50	28	78	82.5	4.5	0.076	0.041	0.015
50	29	79	82.5	3.5	0.089	0.048	0.018
50	30	80	82.5	2.5	0.106	0.059	0.023
50	31	81	82.5	1.5	0.139	0.078	0.031

TABLE 10b (MAP for fibers having trench-assisted profiles with a cladding diameter of 125 microns and Es=1.6 GPa)

Glass Radius, R_g (microns)	Low-modulus Inner Coating Thickness, t_p (microns)	Low-modulus Inner Coating Radius, R_p (microns)	High-modulus Coating Radius, R_s (microns)	High-modulus Coating Thickness, t_s (microns)	MAP for Ep=0.5 MPa (dB/km)	MAP for Ep=0.35 MPa (dB/km)	MAP for Ep=0.2 MPa (dB/km)
62.5	5	67.5	82.5	15	0.126	0.062	0.020
62.5	6	68.5	82.5	14	0.097	0.048	0.016
62.5	7	69.5	82.5	13	0.080	0.040	0.013
62.5	8	70.5	82.5	12	0.069	0.034	0.011
62.5	9	71.5	82.5	11	0.062	0.031	0.010
62.5	10	72.5	82.5	10	0.058	0.029	0.010
62.5	11	73.5	82.5	9	0.056	0.028	0.009

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62.5	12	74.5	82.5	8	0.055	0.028	0.009
62.5	13	75.5	82.5	7	0.056	0.029	0.010
62.5	14	76.5	82.5	6	0.059	0.030	0.011
62.5	15	77.5	82.5	5	0.063	0.033	0.012
62.5	16	78.5	82.5	4	0.068	0.037	0.014
62.5	17	79.5	82.5	3	0.076	0.042	0.016
63.5	18	81.5	83.5	2	0.090	0.050	0.020
64.5	19	83.5	84.5	1	0.125	0.070	0.028

[00165] Table 11a depicts the MAP versus the thickness of the low-modulus inner coating for fibers having a trench-assisted fiber profile (e.g. as shown in Table 2 above), a cladding diameter of 100 microns, a high-modulus coating having a modulus of 2.0 GPa and low-modulus inner coatings having moduli of 0.35, 0.2 and 0.1 MPa. As shown in Table 11a, a MAP less than 0.02 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.35 MPa and the thickness of the low-modulus inner coating is between about 6 and about 30 microns. A MAP less than 0.02 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.35 MPa and the thickness of the low-modulus inner coating is between about 13 and about 23 microns. A MAP less than 0.02 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.2 MPa and the thickness of the low-modulus inner coating is between about 6 and about 30 microns. A MAP less than 0.01 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.2 MPa and the thickness of the low-modulus inner coating is between about 9 and about 27 microns. A MAP less than 0.005 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.2 MPa and the thickness of the low-modulus inner coating is between about 14 and about 22 microns. A MAP less than 0.005 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.1 MPa and the thickness of the low-modulus inner coating is between about 6 and about 29 microns. A MAP less than 0.002 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.1 MPa and the thickness of the low-modulus inner coating is between about 13 and about 23 microns. The calculations were also performed on fibers having a trench-assisted fiber profile, a cladding diameter of 125 microns, a high-modulus coating having a modulus of 2.0 GPa and low-modulus inner coatings having moduli of moduli of 0.35, 0.2 and 0.1 MPa. As shown in Table 10b, a MAP less than 0.03 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.35 MPa and the thickness of the low-modulus inner coating is between about 5 and about 12 microns. A MAP less than 0.02 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.2 MPa and the thickness of the low-modulus inner coating is between about 5 and about 18 microns. A MAP less than 0.01 dB/km can be achieved when the

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low-modulus inner coating has a modulus of 0.2 MPa and the thickness of the low-modulus inner coating is between about 8 and about 14 microns. A MAP less than 0.005 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.1 MPa and the thickness of the low-modulus inner coating is between about 5 and about 18 microns. A MAP less than 0.01 dB/km can be achieved when the low-modulus inner coating has a modulus of 0.1 MPa and the thickness of the low-modulus inner coating is between about 8 and about 14 microns.

TABLE 11a (MAP for fibers having trench-assisted profiles with a cladding diameter of 100 microns and Es=2.0 GPa)

Glass Radius, R_g (microns)	Low-modulus Inner Coating Thickness, t_p (microns)	Low-modulus Inner Coating Radius, R_p (microns)	High-modulus Coating Radius, R_s (microns)	High-modulus Coating Thickness, t_s (microns)	MAP for Ep=0.35 MPa (dB/km)	MAP for Ep=0.2 MPa (dB/km)	MAP for Ep=0.1 MPa (dB/km)
50	5	55	82.5	27.5	0.077	0.025	0.006
50	6	56	82.5	26.5	0.056	0.018	0.005
50	7	57	82.5	25.5	0.044	0.014	0.004
50	8	58	82.5	24.5	0.036	0.012	0.003
50	9	59	82.5	23.5	0.030	0.010	0.002
50	10	60	82.5	22.5	0.026	0.008	0.002
50	11	61	82.5	21.5	0.023	0.007	0.002
50	12	62	82.5	20.5	0.021	0.007	0.002
50	13	63	82.5	19.5	0.019	0.006	0.002
50	14	64	82.5	18.5	0.018	0.006	0.001
50	15	65	82.5	17.5	0.017	0.005	0.001
50	16	66	82.5	16.5	0.016	0.005	0.001
50	17	67	82.5	15.5	0.016	0.005	0.001
50	18	68	82.5	14.5	0.015	0.005	0.001
50	19	69	82.5	13.5	0.016	0.005	0.001
50	20	70	82.5	12.5	0.016	0.005	0.001
50	21	71	82.5	11.5	0.016	0.005	0.001
50	22	72	82.5	10.5	0.017	0.006	0.001
50	23	73	82.5	9.5	0.018	0.006	0.002
50	24	74	82.5	8.5	0.020	0.007	0.002
50	25	75	82.5	7.5	0.022	0.007	0.002
50	26	76	82.5	6.5	0.025	0.008	0.002
50	27	77	82.5	5.5	0.029	0.010	0.003
50	28	78	82.5	4.5	0.034	0.012	0.003
50	29	79	82.5	3.5	0.041	0.015	0.004
50	30	80	82.5	2.5	0.051	0.020	0.006

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50	31	81	82.5	1.5	0.067	0.027	0.009

TABLE 11b (MAP for fibers having trench-assisted profiles with a cladding diameter of 125 microns and Es=2.0 GPa)

Glass Radius, R_g (microns)	Low-modulus Inner Coating Thickness, t_p (microns)	Low-modulus Inner Coating Radius, R_p (microns)	High-modulus Coating Radius, R_s (microns)	High-modulus Coating Thickness, t_s (microns)	MAP for Ep=0.35 MPa (dB/km)	MAP for Ep=0.2 MPa (dB/km)	MAP for Ep=0.1 MPa (dB/km)
62.5	5	67.5	82.5	15	0.050	0.016	0.004
62.5	6	68.5	82.5	14	0.039	0.013	0.003
62.5	7	69.5	82.5	13	0.032	0.010	0.003
62.5	8	70.5	82.5	12	0.028	0.009	0.002
62.5	9	71.5	82.5	11	0.025	0.008	0.002
62.5	10	72.5	82.5	10	0.023	0.008	0.002
62.5	11	73.5	82.5	9	0.023	0.008	0.002
62.5	12	74.5	82.5	8	0.023	0.008	0.002
62.5	13	75.5	82.5	7	0.024	0.008	0.002
62.5	14	76.5	82.5	6	0.025	0.009	0.002
62.5	15	77.5	82.5	5	0.028	0.010	0.003
62.5	16	78.5	82.5	4	0.031	0.011	0.003
62.5	17	79.5	82.5	3	0.036	0.014	0.004
63.5	18	81.5	83.5	2	0.043	0.017	0.005
64.5	19	83.5	84.5	1	0.061	0.024	0.008

[00166] The results of the calculated MAP and puncture resistance given in FIGS. 19-23 and Table 7-11 can be merged to provide the minimum thicknesses of the low-modulus inner coating and high-modulus coating that yield a maximum MAP and minimum puncture resistance for input values of the the maximum modulus of low-modulus primary coating (Ep), the minimum modulus of the high-modulus coating (Es), the glass radius (Rg), and the radius of the high-modulus coating (R_S). Table 12a summarize the coating properties for Examples 1-4 with cladding diameters of 100 micron and Es=1.6 GPa. Tables 12b and 12c summarize the the coating properties for Example 5-14 with cladding diameters of 100 micron and Es=2.0 GPa. Tables 12d and 12e summarize the the coating properties for Examples 15-21 with cladding diameters of 100 micron.

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TABLE 12a (Minimum thicknesses of the low-modulus inner coating and high-modulus coating that provide the given values of the maximum MAP and minimum puncture resistance).

	Example 1	Example 2	Example 3	Example 4
Glass Radius, R_g (microns)	50	50	50	50
Maximum Ep (Mpa)	0.5	0.35	0.2	0.2
Minimum Es (Gpa)	1.6	1.6	1.6	1.6
Maximum MAP of Trench-assisted profile (dB/km)	0.05	0.03	0.03	0.01
Minimum Puncture Resistance (g)	30	30	30	30
Minimum Low-modulus Inner Coating Thickness, t_p (microns)	13	11	7	11
Maximum Low-modulus Inner Coating Thickness, t_p (microns)	14	14	14	14
Minimum High-modulus Coating Thickness, t_s (microns)	18.5	18.5	18.5	18.5
Maximum High-modulus Coating Thickness, t_s (microns)	19.5	21.5	25.5	21.5
Minimum High-modulus Coating Radius, R_s (microns)	64	64	64	64
Minimum Cross Sectional Area of Secondary Coating (sq. microns)	17029	17029	17029	17029

TABLE 12b (Minimum thicknesses of the low-modulus inner coating and high-modulus coating that provide the given values of the maximum MAP and minimum puncture resistance).

	Example 5	Example 6	Example 7	Example 8	Example 9
Glass Radius, R_g (microns)	50	50	50	50	50
Maximum Ep (Mpa)	0.5	0.35	0.5	0.35	0.2
Minimum Es (Gpa)	2	2	2	2	2
Maximum MAP of Trench-assisted profile (dB/km)	0.05	0.02	0.05	0.02	0.02
Minimum Puncture Resistance (g)	30	30	35	35	35
Minimum Low-modulus Inner Coating Thickness, t_p (microns)	11	13	11	13	6
Maximum Low-modulus Inner Coating Thickness, t_p (microns)	18	18	14	14	14
Minimum High-modulus Coating Thickness, t_s (microns)	14.5	14.5	18.5	18.5	18.5
Maximum High-modulus Coating Thickness, t_s (microns)	21.5	19.5	21.5	19.5	26.5
Minimum High-modulus Coating Radius, R_s (microns)	68	68	64	64	64

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Minimum Cross Sectional Area of Secondary Coating (sq. microns)	13711	13711	17029	17029	17029

TABLE 12c (Minimum thicknesses of the low-modulus inner coating and high-modulus coating that provide the given values of the maximum MAP and minimum puncture resistance).

	Example 10	Example 11	Example 12	Example 13	Example 14
Glass Radius, R_g (microns)	50	50	50	50	50
Maximum Ep (Mpa)	0.2	0.2	0.1	0.2	0.1
Minimum Es (Gpa)	2	2	2	2	2
Maximum MAP of Trench-assisted profile (dB/km)	0.01	0.007	0.003	0.01	0.007
Minimum Puncture Resistance (g)	35	35	35	40	40
Minimum Low-modulus Inner Coating Thickness, t_p (microns)	9	11	9	9	5
Maximum Low-modulus Inner Coating Thickness, t_p (microns)	14	14	14	9.5	9.5
Minimum High-modulus Coating Thickness, t_s (microns)	18.5	18.5	18.5	23	23
Maximum High-modulus Coating Thickness, t_s (microns)	23.5	21.5	23.5	23.5	27.5
Minimum High-modulus Coating Radius, R_s (microns)	64	64	64	59.5	59.5
Minimum Cross Sectional Area of Secondary Coating (sq. microns)	17029	17029	17029	20521	20521

TABLE 12d (Minimum thicknesses of the low-modulus inner coating and high-modulus coating that provide the given values of the maximum MAP and minimum puncture resistance).

	Example 15	Example 17	Example 18	Example 19
Glass Radius, R_g (microns)	62.5	62.5	62.5	62.5
Maximum Ep (Mpa)	0.35	0.35	0.35	0.2
Minimum Es (Gpa)	1.6	1.6	2	2
Maximum MAP of Trench-assisted profile (dB/km)	0.05	0.03	0.03	0.01
Minimum Puncture Resistance (g)	20	20	25	25
Minimum Low-modulus Inner Coating Thickness, t_p (microns)	6	10	8	7
Maximum Low-modulus Inner Coating Thickness, t_p (microns)	12	12	10	10
Minimum High-modulus Coating Thickness, t_s (microns)	8	8	10	10

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Maximum High-modulus Coating Thickness, t_s (microns)	14	10	12	13
Minimum High-modulus Coating Radius, R_s (microns)	74.5	74.5	72.5	72.5
Minimum Cross Sectional Area of Secondary Coating (sq. microns)	7892	7892	9739	9739

TABLE 12e (Minimum thicknesses of the low-modulus inner coating and high-modulus coating that provide the given values of the maximum MAP and minimum puncture resistance).

	Example 20	Example 21	Example 22
Glass Radius, R_g (microns)	62.5	62.5	62.5
Maximum Ep (Mpa)	0.1	0.1	0.1
Minimum Es (Gpa)	2	2	2
Maximum MAP of Trench-assisted profile (dB/km)	0.007	0.003	0.007
Minimum Puncture Resistance (g)	25	25	30
Minimum Low-modulus Inner Coating Thickness, t_p (microns)	5	7	5
Maximum Low-modulus Inner Coating Thickness, t_p (microns)	10	10	6
Minimum High-modulus Coating Thickness, t_s (microns)	10	10	14
Maximum High-modulus Coating Thickness, t_s (microns)	15	13	15
Minimum High-modulus Coating Radius, R_s (microns)	72.5	72.5	68.5
Minimum Cross Sectional Area of Secondary Coating (sq. microns)	9739	9739	13283

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[00167] **Reduced Diameter Exemplary Embodiments**

[00168] As discussed above, the optical fibers of the embodiments disclosed herein may have a glass diameter of about 125 microns and a reduced coating diameter may have an outer diameter of about 175 microns or less, or about 170 microns or less, or about 165 microns or less, or about 160 microns or less, or about 145 microns or less. It is noted that the outer diameter of cladding region 50 is the glass diameter of optical fiber 46 and that the outer diameter of high-modulus coating 58 may be the outer overall diameter of optical fiber 46 (when an outer pigmented outer coating layer is not applied).

[00169] In some exemplary examples, cladding region 50 has an outer diameter of about 125 microns and high-modulus coating 58 has an outer diameter between about 155 and 175 microns, or cladding region 50 has an outer diameter of about 125 microns and high-modulus coating 58 has an outer diameter between about 160 and 170 microns.

[00170] As discussed above, the optical fibers of the embodiments disclosed herein may also have a glass diameter of about 100 microns and a reduced coating diameter may have an outer diameter of about 175 microns or less, or about 170 microns or less, or about 165 microns or less, or about 160 microns or less, or about 145 microns or less. It is noted that the outer diameter of cladding region 50 is the glass diameter of optical fiber 46 and that the outer diameter of high-modulus coating 58 may be the outer overall diameter of optical fiber 46 (when an outer pigmented outer coating layer is not applied).

[00171] In some exemplary examples, cladding region 50 has an outer diameter of about 100 microns and high-modulus coating 58 has an outer diameter between about 155 and 175 microns, or cladding region 50 has an outer diameter of about 100 microns and high-modulus coating 58 has an outer diameter between about 160 and 170 microns.

[00172] As discussed above, the reduced diameter optical fiber profile designs of the present disclosure provide particular advantages, such as, for example, a higher fiber count in submarine cables and repeaters. However, a reduction in the cladding diameter of an optical fiber may allow some light to leak through the cladding, due to the reduced profile of the cladding. Thus, the off-set trench designs of the present disclosure have trench volumes of about 30 $\%\Delta$-micron^2 or greater to advantageously reduce "tunneling" or "radiation" losses caused by leaking of the light through the reduced diameter cladding.

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[00173] To facilitate a decrease in the diameter of the optical fiber, it is preferable to minimize the thickness $r_5 - r_4$ of the low-modulus inner coating or to eliminate it entirely. The thickness $r_5 - r_4$ of the low-modulus coating is less than or equal to about 8.0 microns, or less than or equal to about 7.0 microns, or less than or equal to about 6.0 microns, or less than or equal to about 5.0 microns, or in the range from about 4.0 microns to about 8.0 microns, or in the range from about 5.0 microns to about 7.0 microns. However, elimination or reduction in the thickness of the low-modulus inner coating of an optical fiber will increase microbending sensitivity. This increased sensitivity is mitigated in the disclosed design through the addition of an off-set trench with a volume greater than about 30 %Δ-micron^2.

[00174] The radius r_6 of the high-modulus coating is less than or equal to about 87.5 microns, or less than or equal to about 85.0 microns, or less than or equal to about 82.5 microns, or less than or equal to about 80.0 microns. It is also preferable to optimize the thickness $r_6 - r_5$ of the high-modulus coating to balance the reduction in the diameter of the fiber with having a sufficiently high cross-sectional area for high puncture resistance. The thickness $r_6 - r_5$ of the high-modulus coating is less than or equal to about 25.0 microns, or less than or equal to about 20.0 microns, or less than or equal to about 15.0 microns, or in the range from about 15.0 microns to about 25.0 microns, or in the range from about 17.5 microns to about 22.5 microns, or in the range from about 18.0 microns to about 22.0 microns. The total thickness of the low-modulus coating and the high-modulus coating is about 25 microns or less, preferably about 20 microns or less. In some embodiments, the total thickness of the low-modulus coating and the high-modulus coating is about 10 microns to about 25 microns. In some embodiments, the ratio of the thickness of the low-modulus coating layer coating to the thickness of the high-modulus coating layer is in the range of 0.8 to 1.2.

[00175] Thus, optical fibers in accordance with the embodiments of the present disclosure have reduced coating diameters compared to traditional optical fibers. The size reduction helps to increase the "fiber count" and fiber density within, for example, a submarine repeater or a cable.

[00176] Table 10 below shows an average coating thickness for five high-modulus coating samples. Examples 1 and 2 compared with Examples 3, 4, and 5 show that average high-modulus coating thicknesses in the range of 8.0 microns to 20.0 microns produced higher tensile strength than average thicknesses below this range. The higher tensile strength exhibited by Examples 1 and 2 enable use of thinner high-modulus coatings on optical fibers, such as those used in submarine cables and repeaters.

Table 10 – Thickness of High-modulus Coating

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Example No.	1	2	3	4	5
Average High-modulus Coating Thickness	10.2 microns	10.7 microns	6.7 microns	6.7 microns	6.0 microns
Tensile Strength (100 kpsi screening rate)	89%	93%	4%	26%	24%

[00177] **Exemplary Low-Modulus and High-Modulus Coatings**

[00178] Exemplary low-modulus and high-modulus coatings are discussed below, along with measurements of strength and puncture resistance of the coatings.

[00179] *Low-Modulus Coating - Composition.* The low-modulus coating composition includes the formulation given in Table 11 below and is typical of commercially available low-modulus coating compositions.

Table 11 – Reference Low-modulus Coating Composition

Component	Amount
Oligomeric Material	50.0 wt%
SR504	46.5 wt%
NVC	2.0 wt%
TPO	1.5 wt%
Irganox 1035	1.0 pph
3-Acryloxypropyl trimethoxysilane	0.8 pph
Pentaerythritol tetrakis(3-mercapto propionate)	0.032 pph

Where the oligomeric material was prepared as described herein from H12MDI, HEA, and PPG4000 using a molar ratio n:m:p = 3.5:3.0:2.0, SR504 is ethoxylated(4)nonylphenol acrylate (available from Sartomer), NVC is N-vinylcaprolactam (available from Aldrich), TPO (a photoinitiator) is (2,4,6-trimethylbenzoyl)-diphenyl phosphine oxide (available from BASF), Irganox 1035 (an antioxidant) is benzenepropanoic acid, 3,5-bis(1,1-dimethylethyl)-4-hydroxythiodi-2,1-ethanediyl ester (available from BASF), 3-acryloxypropyl trimethoxysilane is an adhesion promoter (available from Gelest), and pentaerythritol tetrakis(3-mercaptopropionate) (also known as tetrathiol, available from Aldrich) is a chain transfer agent. The concentration unit "pph" refers to an amount relative to a base composition that includes all monomers, oligomers, and photoinitiators. For example, a concentration of 1.0 pph for Irganox

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1035 corresponds to 1 g Irganox 1035 per 100 g combined of oligomeric material, SR504, NVC, and TPO.

[00180] The oligomeric material was prepared by mixing H12MDI (4,4'-methylene bis(cyclohexyl isocyanate)), dibutyltin dilaurate and 2,6-di-*tert*-butyl-4 methylphenol at room temperature in a 500 mL flask. The 500 mL flask was equipped with a thermometer, a $CaCl_2$ drying tube, and a stirrer. While continuously stirring the contents of the flask, PPG4000 was added over a time period of 30-40 minutes using an addition funnel. The internal temperature of the reaction mixture was monitored as the PPG4000 was added and the introduction of PPG4000 was controlled to prevent excess heating (arising from the exothermic nature of the reaction). After the PPG4000 was added, the reaction mixture was heated in an oil bath at about 70°C to 75°C for about 1 to 1 ½ hours. At various intervals, samples of the reaction mixture were retrieved for analysis by infrared spectroscopy (FTIR) to monitor the progress of the reaction by determining the concentration of unreacted isocyanate groups. The concentration of unreacted isocyanate groups was assessed based on the intensity of a characteristic isocyanate stretching mode near 2265 cm^{-1}. The flask was removed from the oil bath and its contents were allowed to cool to below 65 °C. Addition of supplemental HEA was conducted to insure complete quenching of isocyanate groups. The supplemental HEA was added dropwise over 2-5 minutes using an addition funnel. After addition of the supplemental HEA, the flask was returned to the oil bath and its contents were again heated to about 70°C to 75°C for about 1 to 1 ½ hours. FTIR analysis was conducted on the reaction mixture to assess the presence of isocyanate groups and the process was repeated until enough supplemental HEA was added to fully react any unreacted isocyanate groups. The reaction was deemed complete when no appreciable isocyanate stretching intensity was detected in the FTIR measurement.

[00181] *High-Modulus Coating – Compositions.* Four curable high-modulus coating compositions (A, SB, SC, and SD) are listed in Table 12.

Table 12 – High-modulus Coating Compositions

	Composition			
Component	A	SB	SC	SD
PE210 (wt%)	15.0	15.0	15.0	15.0
M240 (wt%)	72.0	72.0	72.0	62.0

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M2300 (wt%)	10.0	-	-	-
M3130 (wt%)	-	10.0	-	-
M370 (wt%)	-	-	10.0	20.0
TPO (wt%)	1.5	1.5	1.5	1.5
Irgacure 184 (wt%)	1.5	1.5	1.5	1.5
Irganox 1035 (pph)	0.5	0.5	0.5	0.5
DC-190 (pph)	1.0	1.0	1.0	1.0

PE210 is bisphenol-A epoxy diacrylate (available from Miwon Specialty Chemical, Korea), M240 is ethoxylated (4) bisphenol-A diacrylate (available from Miwon Specialty Chemical, Korea), M2300 is ethoxylated (30) bisphenol-A diacrylate (available from Miwon Specialty Chemical, Korea), M3130 is ethoxylated (3) trimethylolpropane triacrylate (available from Miwon Specialty Chemical, Korea), TPO (a photoinitiator) is (2,4,6-trimethylbenzoyl)diphenyl phosphine oxide (available from BASF), Irgacure 184 (a photoinitiator) is 1-hydroxycyclohexyl-phenyl ketone (available from BASF), Irganox 1035 (an antioxidant) is benzenepropanoic acid, 3,5-bis(1,1-dimethylethyl)-4-hydroxythiodi-2,1-ethanediyl ester (available from BASF). DC190 (a slip agent) is silicone-ethylene oxide/propylene oxide copolymer (available from Dow Chemical). The concentration unit "pph" refers to an amount relative to a base composition that includes all monomers and photoinitiators. For example, for high-modulus coating composition A, a concentration of 1.0 pph for DC-190 corresponds to 1 g DC-190 per 100 g combined of PE210, M240, M2300, TPO, and Irgacure 184.

[00182] *High-Modulus Coatings – Tensile Properties.* The Young's modulus, tensile strength at yield, yield strength, and elongation at yield of high-modulus coatings made from high-modulus compositions A, SB, SC, and SD were measured using the technique described above. The results are summarized in Table 13.

Table 13 – Tensile Properties of High-modulus Coatings

	High-modulus Composition			
Property	A	SB	SC	SD
Young's Modulus (MPa)	2049.08	2531.89	2652.51	2775.94
Tensile Strength (MPa)	86.09	75.56	82.02	86.08
Yield Strength	48.21	61.23	66.37	70.05

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(MPa)				
Elongation at Yield (%)	4.60	4.53	4.76	4.87
Fracture Toughness, K_c ($MPa*m^{1/2}$)	0.8580	0.8801	0.9471	0.9016

[00183] The results show that high-modulus coatings prepared from compositions SB, SC, and SD exhibited higher Young's modulus and higher yield strength than the high-modulus coating prepared from comparative composition A. Additionally, the high-modulus coatings prepared from compositions SB, SC, and SD exhibited higher fracture toughness than the high-modulus coating prepared from composition A. The higher values exhibited by composition SB, SC, and SD enable use of thinner high-modulus coatings on optical fibers without sacrificing performance. As discussed above, thinner high-modulus coatings reduce the overall diameter of the optical fiber and provide higher fiber counts in a given cross-sectional area (such as in submarine repeater).

[00184] **Exemplary Optical Fiber Embodiments**

[00185] The experimental examples and principles disclosed herein indicate that sufficiently low attenuation and high puncture resistance properties can be achieved in a reduced diameter optical fiber by tailoring the refractive index profile and coating properties of the optical fiber. More specifically, the high-modulus coating provides sufficient puncture resistance for the reduced diameter fiber in spite of the smaller cross-sectional area.

[00186] FIG. 8 is a plot of the dependence of the puncture load in grams versus the cross-sectional area of the high-modulus coating. The dashed line has a slope of 0.00263 g/microns^2 and corresponds to comparative fibers having a high-modulus coating having an *in situ* modulus of about 1500 GPa. The solid line is a linear fit to measured data for five fibers having a high-modulus coating with an *in situ* modulus of about 1850 GPa, The slope is 0.00328 g/microns^2, which is approximately equal to the slope for the reference fibers multiplied by the ratio of the *in situ* moduli, 1850/1500. The dotted line represents the modeled dependence of the puncture load in grams versus the cross-sectional area of a high-modulus coating having an *in situ* modulus of 2200 GPa. The results indicate that an increase in the *in situ* modulus of the high-modulus coating enables a reduction in the cross-sectional area and thickness without a significant degradation of the puncture resistance of the smaller diameter fiber.

[00187] **Fiber Draw Process**

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[00188] The optical fibers disclosed herein may be formed from a continuous optical fiber manufacturing process, during which a glass fiber is drawn from a heated preform and sized to a target diameter. In fibers comprising a low-modulus inner coating, the glass fiber is then cooled and directed to a coating system that applies a liquid low-modulus coating composition to the glass fiber. Two process options are viable after application of the liquid low-modulus coating composition to the glass fiber. In one process option (wet-on-dry process), the liquid low-modulus coating composition is cured to form a solidified low-modulus coating, the liquid high-modulus coating composition is applied to the cured low-modulus coating, and the liquid high-modulus coating composition is cured to form a solidified high-modulus coating. In a second process option (wet-on-wet process), the liquid high-modulus coating composition is applied to the liquid low-modulus coating composition, and both liquid coating compositions are cured simultaneously to provide solidified low-modulus and high-modulus coatings. After the fiber exits the coating system, the fiber is collected and stored at room temperature. Collection of the fiber typically entails winding the fiber on a spool and storing the spool.

[00189] In some processes, the coating system further applies a pigmented outer coating composition to the high-modulus coating and cures the pigmented outer coating composition to form a solidified pigmented outer coating. Typically, the pigmented outer coating is an ink layer used to mark the fiber for identification purposes and has a composition that includes a pigment and is otherwise similar to the high-modulus coating. The pigmented outer coating is applied to the high-modulus coating and cured. The high-modulus coating has typically been cured at the time of application of the pigmented outer coating. The low-modulus, high-modulus, and pigmented outer coating compositions can be applied and cured in a common continuous manufacturing process. Alternatively, the low-modulus and high-modulus coating compositions are applied and cured in a common continuous manufacturing process, the coated fiber is collected, and the pigmented outer coating composition is applied and cured in a separate offline process to form the pigmented outer coating.

[00190] **Coating Application, Coating Material Viscosity and Coating Die Size**

[00191] In some embodiments, optical fiber drawn from a pre-form within a draw furnace, is passed through a coating system where a polymer coating is applied to the optical fiber. The coating system may comprise an entrance and a sizing die. Disposed between the entrance and the sizing die is a coating chamber. The coating chamber is filled with the polymer coating material in liquid form. The optical fiber enters the coating system through the entrance and passes through the coating chamber where the polymer coating material is applied to the surface of the optical fiber. The optical fiber then passes through the sizing die where any excess coating

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material is removed as the optical fiber exits the coating system to achieve a coated optical fiber of a specified diameter in accordance of some embodiments described herein.

[00192] FIG. 12 shows the effects of coating material viscosity and die size on the coating thickness for a given constant drawing speed (60 m/min in this case). As shown in FIG. 12, the coating thickness is mainly affected by the diameter of the sizing die, while the coating material viscosity has only marginal effects. For example, the coated fiber diameter varies from 127 μm to 169 μm when the sizing die changes from 5.1 mil (129.54 μm) to 8.0 mil (203.2 μm), while the coating thickness only varies slightly with a wide range of coating material viscosity given a certain die size. In some embodiments, the viscosity of the coating material is greater than 20 poise at 50 rpm and 25°C, or greater than 40 poise at 50 rpm and 25°C.

[00193] FIG. 13 depicts an exemplary parameter window for forming a targeted final coated diameter of 132 ± 1 μm on a 125 micron glass optical fiber. As shown in FIG. 13, the sizing die is identified in the range from 5.35 mil (135.89 μm) to 5.51 mil (140 μm), while the coating material viscosity can range widely within the parameter window. Thus, while the coating material viscosity has only marginal effect on the final coating thickness, the effective magnitude differs for different die size systems. FIG. 14 shows the coating thickness standard deviation resulting from various coating material viscosity for different die size systems. FIG. 14 shows that the standard deviation slightly increases with increasing die size and rises dramatically when the die size is larger than 7mil. FIG. 15 depicts the effect of drawing speed on coating thickness in accordance with some embodiments of the current disclosure. As seen in FIG. 15, the drawing speed of the fiber has only limited effects on the coating thickness.

[00194] With respect to coating concentricity, lubrication pressure within the coating die is assumed to act as the centering force to make sure that the optical fiber is centered in the coating applicator. A higher lubrication pressure represents a larger centering force, which would produce a better coating concentricity. FIG. 16 depicts a graph plotting the correlation between lubrication pressure and the die size for a series of coating material viscosity. FIG. 16 shows that the lubrication pressure decreases with the increasing of die size and increases with the increasing of the coating material viscosity. In addition, FIG. 17 shows the correlation between lubrication pressure and drawing speed. As shown in FIG. 17, the lubrication pressure firstly increasing dramatically and then increases at a slow pace with the increasing of the drawing speed. Therefore, combined with the viscosity effect on the coating thickness as discussed above, increasing the drawing speed and using materials with larger viscosity with a given die size can improve coating concentricity without degrading the coating thickness quality.

[00195] **Performance Data for Optical Fibers with Thin Coatings**

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[00196] Key performance metrics for these optical fibers with thin coatings include their total outer diameter, the thickness of the polymeric coating, the number of breaks per unit length in 50 kpsi strength screening, and the longest saved lengths after 50 kpsi screening. A high-modulus coating layer was applied onto a 125 μm single mode fiber (SMF) fiber with about 7 μm overall coating thickness (See Table 15 Reel ID 121-6599-3 and Reel ID 122-6645-4). The lower the screening force is, the longer the segment of unbroken fiber. The high-modulus coated fiber (Reel ID 121-6599-3) has similar fiber strength to that of the fresh high-modulus coated fiber (Reel ID 122-6645-4). The inventors have found that the thin acrylate hard fiber coating using a fresh high-modulus coated fiber has concentricity greater than about 70%, and in some embodiments greater than about 80%, or greater than about 85%, or greater than about 90%, or greater than about 95%.

TABLE 15 Performance Data for Optical Fibers with High-Modulus Coating

	Reel ID	121-6599-3	121-6599-4	122-6645-3	122-6645-4
Draw Run Data	Glass Type	SMF	SMF	SMF	SMF
	Glass Diameter (μm)	125	125	125	125
	Draw Speed (m/min)	50	50	50	50
	Total fiber saved (m)	6000	6000	6000	6160
	Total fiber screened (m)	5000	5000	5000	5000
	High-modulus Coating Die Size (mil)	5.4	6	6	5.4
	High-modulus Coating Diameter (μm)	132	140	140	132
Fiber Screening	Screen Weight (kpsi)	50	50	50	50
	Number of Breaks	22	1	1	21
	Longest save length (m)	694	4659	4646	396
	Number of strip sections	6	0	0	6

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	Meter screened/(Number of breaks+1)	217	2500	2500	227

[00197] Compared to a thin acrylate coating of an aged high-modulus coated fiber applied onto a 125 µm SMF fiber with about 7 µm overall coating thickness (See Table 16 Reel ID 121-6602-10 and Reel ID 121-6602-12), a fresh high-modulus coated fiber shown in Reel ID 121-6599-3 showed much higher number of both the longest save length (m) and the ratio of meters of the thin coated fiber screened / (Number of Breaks +1) when the thin coated fibers were screened at 50 kpsi force. The breaks of these three fibers are pretty evenly distributed throughout the fiber screening length. This indicates that the old high-modulus coated fiber is most likely degraded partially during storage. Yet all these three thin acrylate coated fibers have good concentricity (i.e. >70%).

TABLE 16 Performance Data for Optical Fibers with High-Modulus Coating

	Reel ID	121-6602-10	121-6602-12
Draw Run Data	Glass Type	SMF	SMF
	Glass Diameter (µm)	125	125
	Draw Speed (m/min)	40	35
	Total fiber saved (m)	1200	1200
	Total fiber screened (m)	1200	2950
	High-modulus Coating Size Die (mil)	5.4	5.4
	High-modulus Coating Diameter (µm)	132	132
Fiber Screening	Screen Weight (kpsi)	varied	50
	Number of Breaks	27	21

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	Longest save length (m)	132	189
	Number of strip sections	4	3
	Meter screened/(Number of breaks+1)	43	134

[00198] A thin acrylate coating of a fresh high-modulus coating layer was applied onto a 125 µm SMF fiber with 15 µm overall coating thickness (See Table 15 Reel ID 121-6599-4 and Reel ID 122-6645-3). By increasing the coating thickness from 7 µm in Reel ID 121-6599-3 to 15 µm in Reel ID 121-6599-4 using a fresh high-modulus coating layer, the thin coated fiber is much stronger as indicated by significant increasing of both the longest save length (m) and the ratio of meters of the thin coated fiber screened / (Number of Breaks +1) when the thin coated fibers were screened at 50 kpsi. By increasing the coating thickness from 7 µm in Reel ID 122-6645-4 to 15 µm in Reel ID 122-6645-3 using a fresh high-modulus coating layer, the thin coated fiber is much stronger as indicated by significant increasing of both the longest save length (m) and the ratio of meters of the thin coated fiber screened / (Number of Breaks +1) when the thin coated fibers were screened at 50 kpsi force. Furthermore, the thin acrylate hard fiber coating has good concentricity (i.e. >70%). These thin acrylate coated fibers with 15 µm overall coating thickness (Reel ID 121-6599-4 and Reel ID 122-6645-3 in Table 15) are strong enough to survive the ribbon cable process.

[00199] A thin two-layer acrylate fiber coating drawing of a fresh low-modulus coating layer and a fresh high-modulus coating layer was also carried out (See Table 16 Reel ID 121-6599-5). The thickness of the low-modulus coating layer is 9 µm and the thickness of the high-modulus coating layer is 8µm. The overall thickness of the low-modulus coating layer plus the high-modulus coating layer thickness is 17 µm. The thin acrylate coating running is smooth and the coating on fiber has no defects. This thin coated fiber was screened at 50 kpsi and the screening results are similar to a fresh high-modulus coating layer on 125 µm SMF fiber with 15 µm overall coating thickness (See Reel ID 121-6599-4 in Table 15). The thin acrylate hard fiber coating has good concentricity (i.e. >70%). This thin acrylate coated fiber is also strong enough

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to survive the ribbon cable process. With the presence of a soft thin low-modulus coating layer, this two-layer thin coated fiber has improved microbending performance over a one-layer thin hard coating fiber.

TABLE 17 Performance Data for Optical Fibers with Low-Modulus Coating and High-Modulus Coating

	Reel ID	121-6599-5
Draw Run Data	Glass Type	SMF
	Glass Diameter (μm)	125
	Draw Speed (m/min)	50
	Total fiber saved (m)	6300
	Total fiber screened (m)	5000
	Low-modulus Coating Die Size (mil)	5.4
	Low-modulus Coating Diameter (μm)	134
	High-modulus Coating Die Size(mil)	6
	High-modulus Coating Diameter (μm)	142
Fiber Screening	Screen Weight (kpsi)	50
	Number of Breaks	3
	Longest save length (m)	4652
	Number of strip	0

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	sections	
	Meter screened/(Number of breaks+1)	1250

[00200] A thin two-layer acrylate fiber coating drawing of a fresh low-modulus coating layer and a fresh high-modulus coating layer was carried out on a standard single mode fiber on a graded index core with a silica inner cladding and an updoped outer cladding with a relative refractive index profile as shown in FIG. 18. The fiber coating parameters and measured optical parameters are shown in Table 18 below. The table below shows three thin coating configurations having low-modulus coating diameter/ high-modulus coating diameter of 145 μm/175 μm, 140 μm/160 μm, and 0 μm/140 μm. The fiber having a low-modulus coating diameter / high-modulus coating diameter of 190 μm/250 μm is the standard coating used as a control. For the thin coated fibers, the measured cable cutoff wavelengths, MFDs are similar to the control fibers, which indicates that the thin coatings did not impact these parameters. For the fibers having a low-modulus inner coating diameter / high-modulus coating diameter of 145 μm/175 μm and 140 μm/160 μm, the attenuation at 1310 and 1550 nm is the same as the control fibers, which shows that these thin coating configurations did not result in any attenuation penalty. The attenuation of the fibers having a low-modulus coating diameter / high-modulus coating diameter of 0 μm/140 μm is slightly higher than the other fibers due to the single coating layer but is acceptable for many applications using short fibers such as data centers.

TABLE 18 Performance Data for Optical Fibers with Low-Modulus Coating and High-Modulus Coating Diameter of 145 μm/175 μm, 140 μm/160 μm, and 0 μm/140 μm

Fiber ID	Coating diameters Low-modulus/High-modulus	Cable cutoff (nm)	1310 nm MFD (μm)	1550 nm MFD (μm)	1310 nm OTDR Attenuation (dB/km)	1550 nm OTDR Attenuation (dB/km)
142-1918-1001	145 μm/175 μm	1223.7	9.1	10.3	0.333	0.188
142-1918-901	140 μm/160 μm	1190.0	9.0	10.2	0.332	0.188
142-1918-1101	0 μm/140 μm	1218.5	9.0	10.1	0.336	0.195
142-1918-801	190 μm/250 μm	1208.8	9.1	10.4	0.333	0.188
142-1918-1201	190 μm/250 μm	1221.0	9.1	10.2	0.333	0.188
142-1918-301	145 μm/175 μm	1210.0	9.0	10.3	0.334	0.188
142-1918-201	140 μm/160 μm	1220.0	9.1	10.2	0.333	0.188
142-1918-401	0 μm/140 μm	1220.0	9.0	10.3	0.337	0.195
142-1918-101	190 μm/250 μm	1180.0	9.1	10.2	0.333	0.188
142-1918-501	140 μm/160 μm	1197.0	8.5	9.88	0.333	0.188

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142-1918-601	145 μm/175 μm	1189.9	9.0	10.2	0.333	0.188
142-1918-701	190 μm/250 μm	1189.1	9.0	10.3	0.333	0.188

[00201] It will be apparent to those skilled in the art that various modifications and variations can be made without departing from the spirit or scope of the invention. Since modifications combinations, sub-combinations and variations of the disclosed embodiments incorporating the spirit and substance of the invention may occur to persons skilled in the art, the invention should be construed to include everything within the scope of the appended claims and their equivalents.

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What is claimed is:

1. An optical fiber, comprising:

a core region;

a cladding region surrounding the core region, the cladding region comprising: an inner cladding directly adjacent to the core region, and an outer cladding surrounding the inner cladding, wherein a radius of the cladding region is less than about 62.5 microns; and

a polymer coating comprising a high-modulus coating layer surrounding the cladding region and a low-modulus coating layer disposed between the cladding region and the high-modulus coating layer, wherein a thickness of the low-modulus inner coating layer is in a range of 4 microns to 20 microns, the modulus of the low-modulus inner coating layer is less than or equal to about 0.35 MPa, a thickness of the high-modulus coating layer is in a range of 4 microns to 20 microns, the modulus of the high-modulus inner coating layer is greater than or equal to about 1.6 GPa, and wherein a puncture resistance of the optical fiber is greater than 20 g, and wherein a microbend attenuation penalty of the optical fiber is less than 0.03 dB/km, and wherein an outer diameter of the coated optical fiber is less than or equal to 175 microns,

wherein the puncture resistance of the optical fiber is calculated by equation $P_R=P_0 + C_1E_sA_s$, wherein A_S is the cross-sectional area of the high-modulus coating, wherein E_S is the elastic moduli of the high-modulus coating, wherein P_0 is a coefficient having a value of 11.3 g and C_1 is a coefficient having a value of 2.1 g/MPa/mm^2,

wherein the microbend attenuation penalty of the optical fiber is calculated by equation: $MAP = C_0 f_0 \sigma \frac{f_{RIP} f_g (E_g \cdot R_g) f_p (E_p \cdot t_p)}{f_{cs}\left(\frac{E_s}{E_p}, R_s, t_s\right)}$, wherein f_0 is the average lateral pressure of the external surface in contact with the high modulus coating, wherein σ is the standard deviation of the roughness of the external surface in contact with the high modulus coating, wherein $C_0 = 4x10^{25}\left[\left(\frac{\pi}{4}\right)^{1.625}\right]^{-1}$, and wherein $f_g = \frac{1}{E_g^2 R_g^5}$, and wherein $f_p = \frac{E_p}{t_p^2}$, and wherein $f_{cs} = \left[1 + \frac{E_s}{E_p}\left(\frac{t_s}{R_s}\right)^3\right]^{0.375}\left\{\frac{E_s}{E_p}\left[R_s^4 - (R_s - t_s)^4\right]\right\}^{0.625}$, wherein R_g is the radius of the glass, R_s is the outer radius of the high-modulus outer coating, t_p is the thickness of the inner low-modulus coating, t_s is the thickness of the high-modulus outer coating, E_g is the elastic moduli of the glass, E_p is the elastic moduli of the low-modulus inner coating, and E_S is the elastic moduli of the high-modulus coating.

2. The optical fiber of claim 1, wherein the microbend attenuation penalty of the optical fiber is ≤ 0.01 dB/km.

3. The optical fiber of claim 1, wherein the microbend attenuation penalty of the optical fiber is ≤ 0.007 dB/km.

4. The optical fiber of claim 1, wherein the microbend attenuation penalty of the optical fiber is ≤ 0.003 dB/km.

5. The optical fiber of claim 1, wherein the puncture resistance of the optical fiber is ≥ 25 g.

6. The optical fiber of claim 1, wherein the puncture resistance of the optical fiber is ≥ 30 g.

7. The optical fiber of claim 1, wherein a radius of the cladding region is less than 52.5 microns and the puncture resistance of the optical fiber is greater than 40 g.

8. The optical fiber of claim 1, wherein the thickness of the high-modulus coating layer is 9 microns to 18 microns.

9. The optical fiber of claim 1, wherein an attenuation of the optical fiber is less than 0.20 dB/km.

10. The optical fiber of claim 1, wherein a mode field diameter of the optical fiber at 1310 nm is ≥ 8.6.

11. An optical fiber, comprising:

a core region;

a cladding region surrounding the core region, the cladding region comprising: an inner cladding directly adjacent to the core region, and an outer cladding surrounding the inner cladding, wherein a radius of the cladding region is between about 45 microns and 55 microns; and

a polymer coating comprising a high-modulus coating layer surrounding the cladding region and a low-modulus coating layer disposed between the cladding region and the high-modulus coating layer, wherein a thickness of the low-modulus inner coating layer is in a range of 6 microns to 20 microns, the modulus of the low-modulus inner coating layer is less than or equal to about 0.35 MPa, a thickness of the high-modulus coating layer is in a range of 12 microns to 18 microns, the modulus of the high-modulus inner coating layer is greater than or equal to about 1.6 GPa, and wherein a puncture resistance of the optical fiber is greater than 30 g, and wherein a microbend attenuation penalty of the optical fiber is less than 0.03 dB/km, and wherein an outer diameter of the coated optical fiber is less than or equal to 175 microns,

wherein the puncture resistance of the optical fiber is calculated by equation $P_R=P_0 + C_1E_sA_s$, wherein A_S is the cross-sectional area of the high-modulus coating, wherein E_S is the elastic moduli of the high-modulus coating, wherein P_0 is a coefficient having a value of 11.3 g and C_1 is a coefficient having a value of 2.1 g/MPa/mm^2,

wherein the microbend attenuation penalty of the optical fiber is calculated by equation: $MAP = C_0 f_0 \sigma \frac{f_{RIP} f_g(E_g, R_g) f_p(E_p, t_p)}{f_{cs}\left(\frac{E_s}{E_p}, R_s, t_s\right)}$, wherein f_0 is the average lateral pressure of the external surface in contact with the high modulus coating, wherein σ is the standard deviation of the roughness of the external surface in contact with the high modulus coating, wherein $C_0 = 4x10^{25}\left[\left(\frac{\pi}{4}\right)^{2.625}\right]^{-1}$, and wherein $f_g = \frac{1}{E_g^2 R_g^6}$, and wherein $f_p = \frac{E_g}{t_p^2}$, and wherein $f_{cs} = \left[1 + \frac{E_s}{E_p}\left(\frac{t_s}{R_s}\right)^3\right]^{0.375}\left\{\frac{E_s}{E_p}\left[R_s^4 - (R_s - t_s)^4\right]\right\}^{0.625}$, wherein R_g is the radius of the glass, R_s is the outer radius of the high-modulus outer coating, t_p is the thickness of the inner low-modulus coating, t_s is the thickness of the high-modulus outer coating, E_g is the elastic moduli of the glass, E_p is the elastic moduli of the low-modulus inner coating, and E_S is the elastic moduli of the high-modulus coating.

12. The optical fiber of claim 11, wherein the microbend attenuation penalty of the optical fiber is $\leq$ 0.01 dB/km.

13. The optical fiber of claim 11, wherein the microbend attenuation penalty of the optical fiber is $\leq$ 0.007 dB/km.

14. The optical fiber of claim 11, wherein the microbend attenuation penalty of the optical fiber is ≤ 0.003 dB/km.

15. The optical fiber of claim 1, wherein the puncture resistance of the optical fiber is ≥ 25 g.

16. An optical fiber comprising:

a core region;

a cladding region surrounding the core region, the cladding region comprising: an inner cladding directly adjacent to the core region, and an outer cladding surrounding the inner cladding; and

a polymer coating having a thickness of 25 um or less, wherein the polymer coating comprises a high-modulus coating layer surrounding the cladding region, wherein the high-modulus coating layer has a Young's modulus of 1.5 GPa or greater, wherein an outer diameter of the coated optical fiber is less than or equal to 175 microns.

17. The optical fiber of claim 16, further comprising a low-modulus coating layer surrounding the cladding region, wherein the low-modulus coating layer has a Young's modulus of 0.5 MPa or less and is disposed between the cladding region and the high-modulus coating layer.

18. The optical fiber of claim 17, wherein a ratio of the thickness of the low-modulus coating layer coating to the thickness of the high-modulus coating layer is in the range of 0.8 to 1.2.

19. A method of coating an optical fiber, comprising:

drawing an optical fiber from a draw furnace along a first vertical pathway;

routing the optical fiber through a coating system wherein a polymer coating is applied to the optical fiber, wherein the coating system comprises an entrance, a sizing die having a diameter of 129 μm to 203 μm opposite the entrance, and a coating chamber disposed between the entrance and the sizing die, wherein the coating chamber is filled with a coating material in liquid form; and

curing the coated optical fiber to form an outer diameter of the coated optical fiber that is less than or equal to 175 microns.

20. The method of claim 19, wherein the polymer coating has a concentricity of greater than 70%.

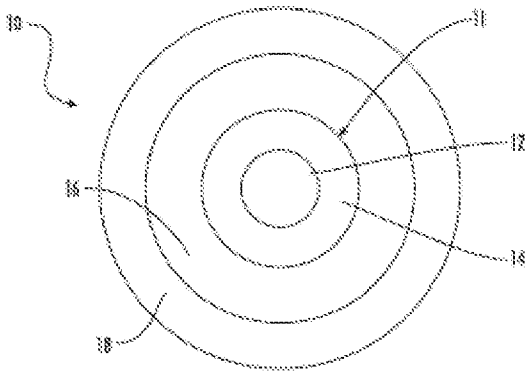


Figure 1

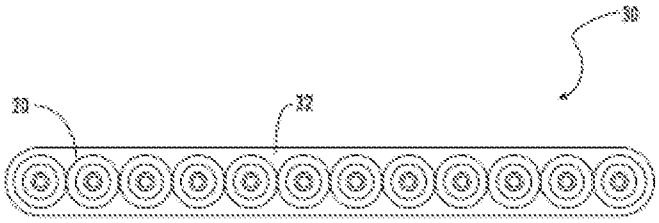


Figure 2

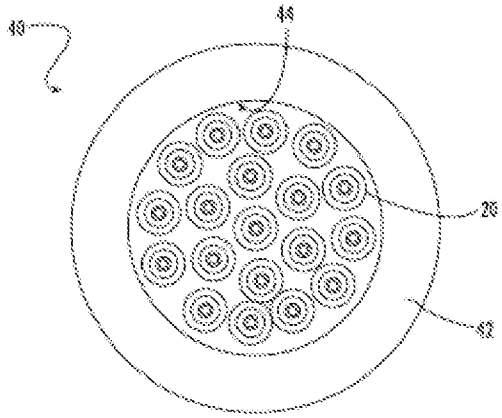


Figure 3

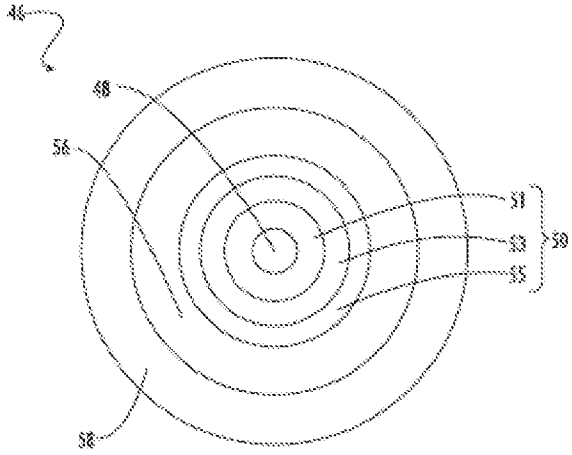


Figure 4

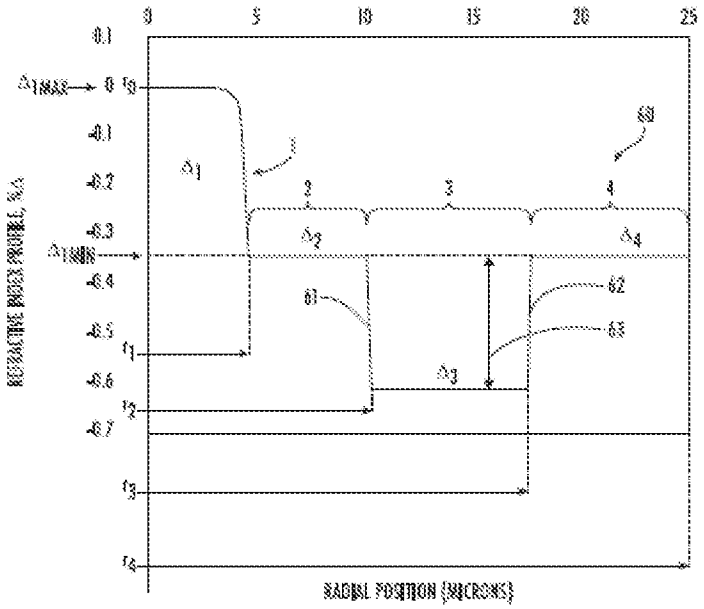


Figure 5

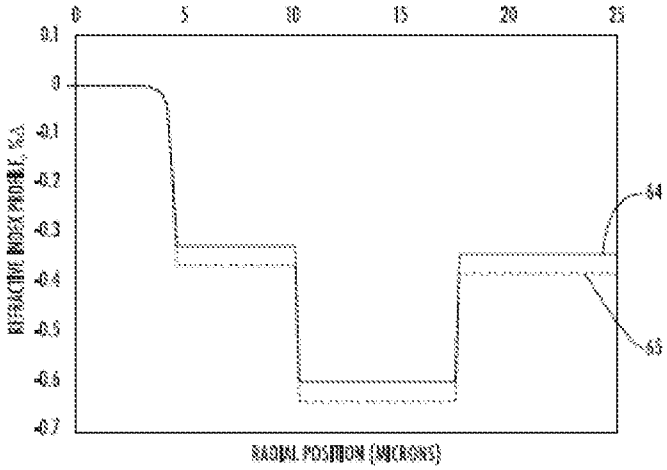


Figure 6

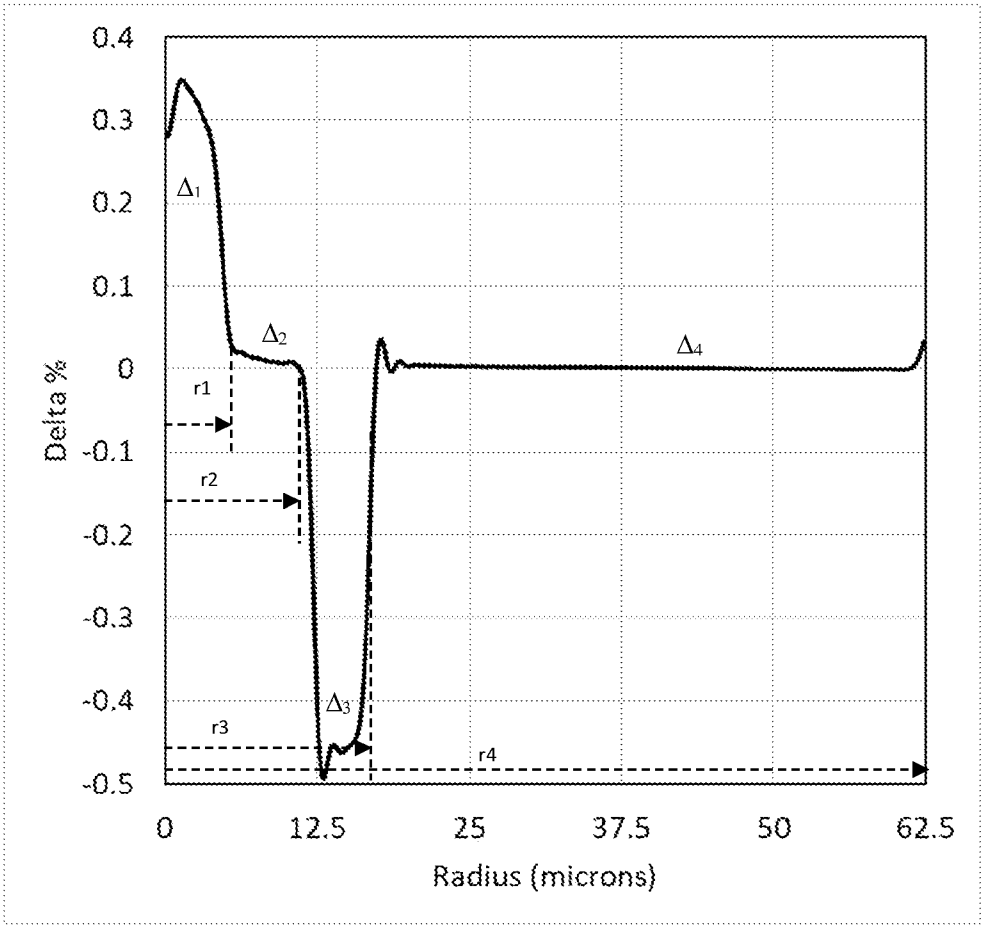

0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Delta %
Δ1
Δ2
Δ3
Δ4
r1
r2
r3
r4
0
12.5
25
37.5
50
62.5
Radius (microns)

Figure 7

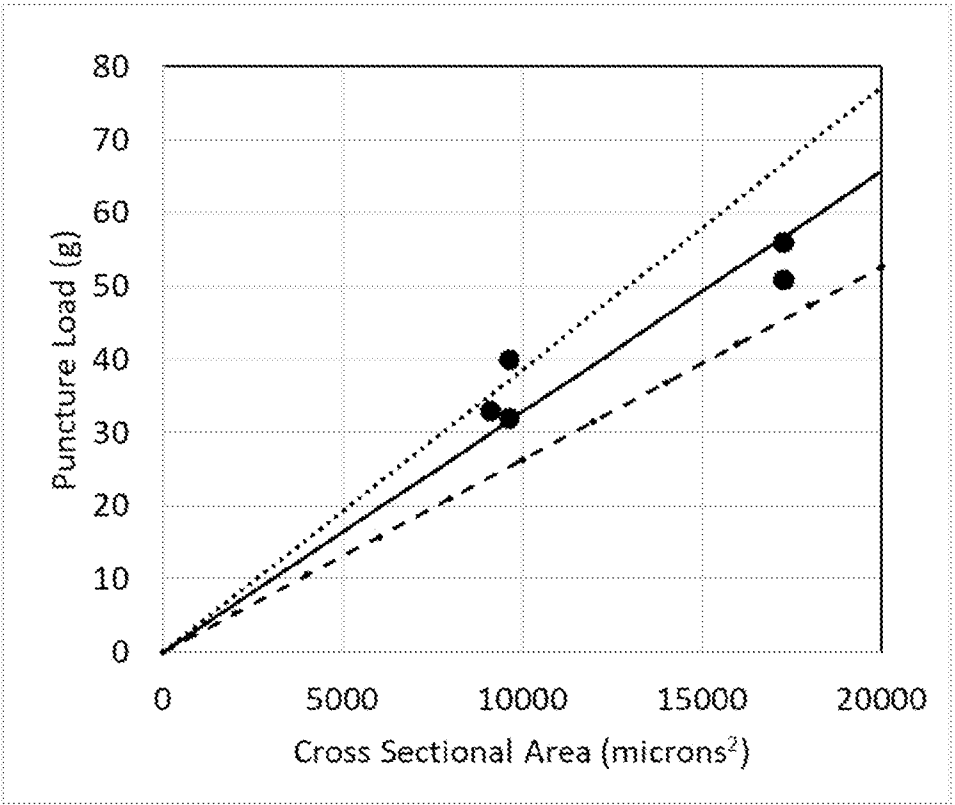


Figure 8

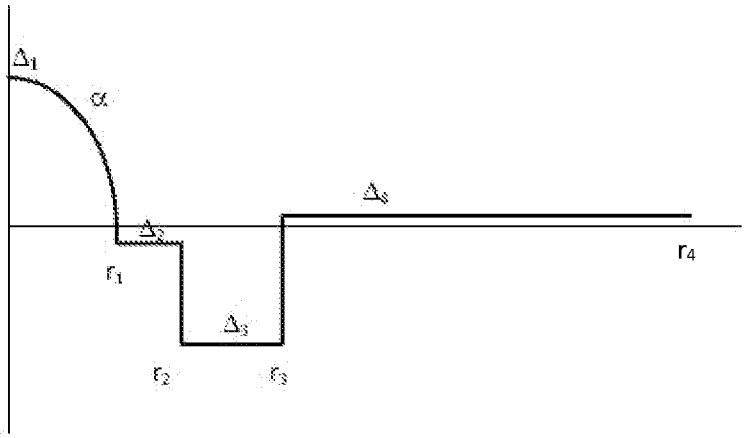


Figure 9

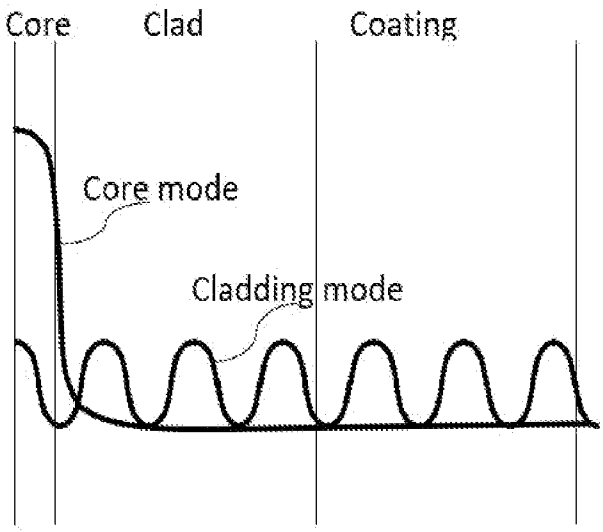


Figure 10

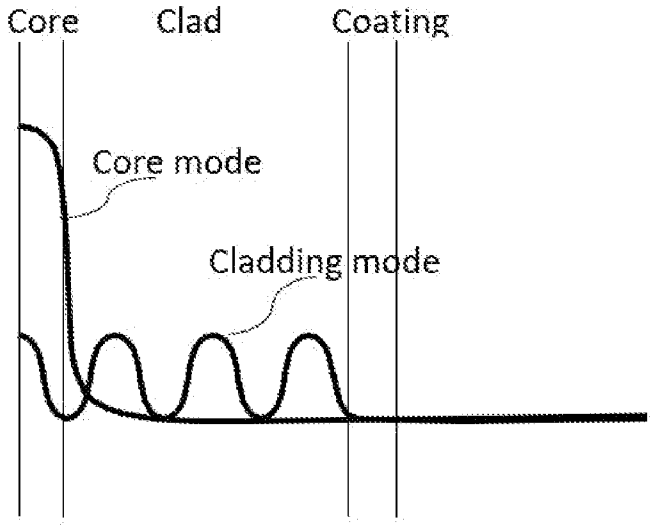


Figure 11

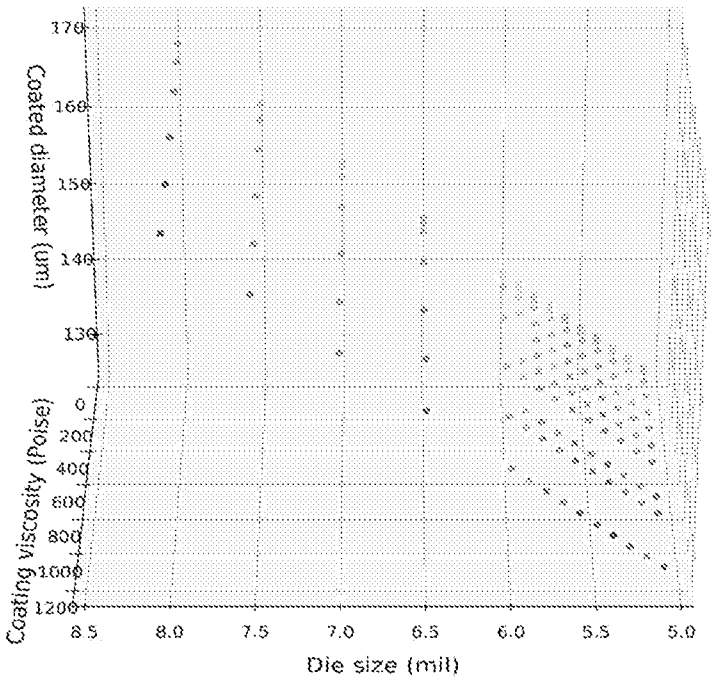


Figure 12

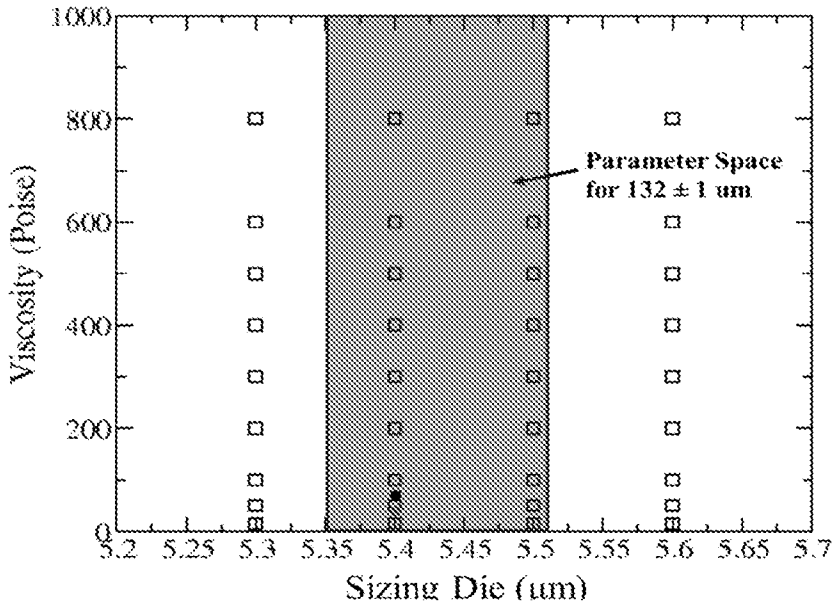


Figure 13

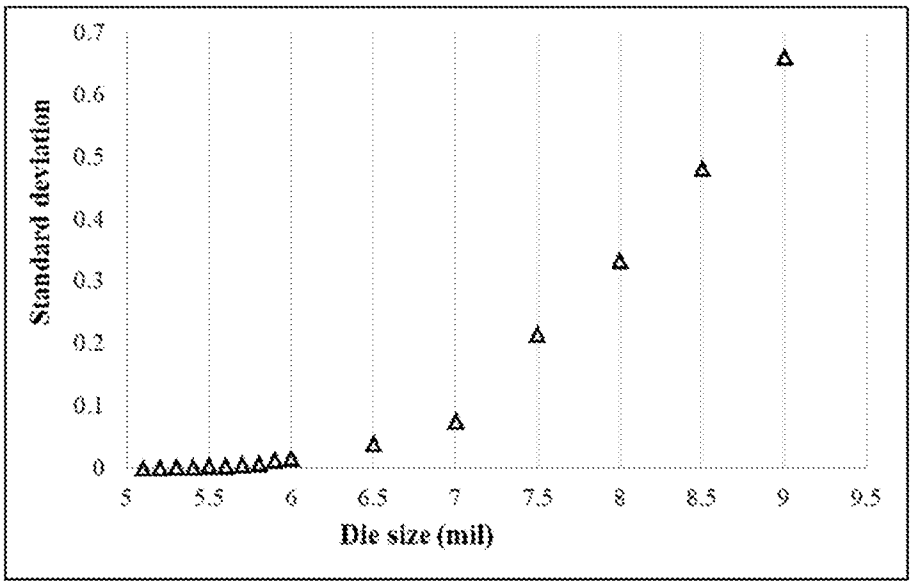


Figure 14

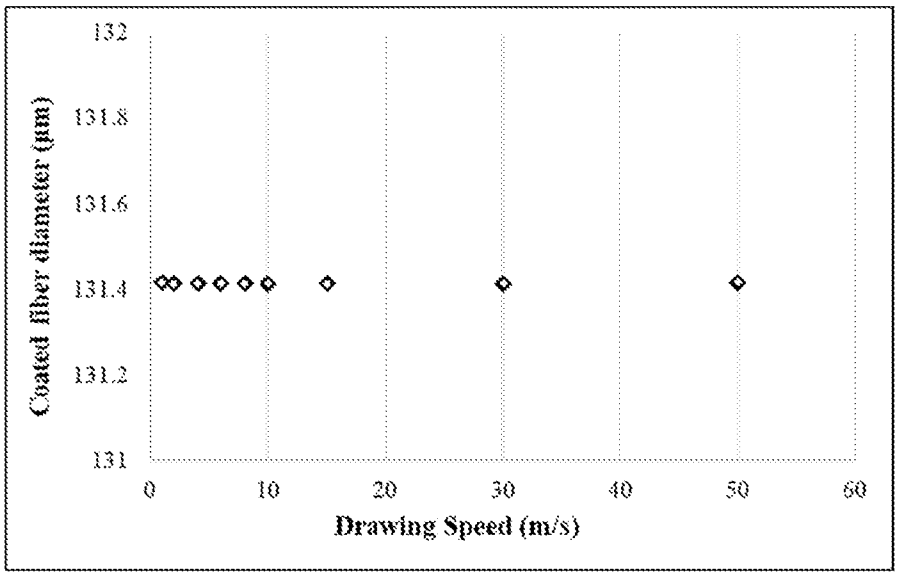


Figure 15

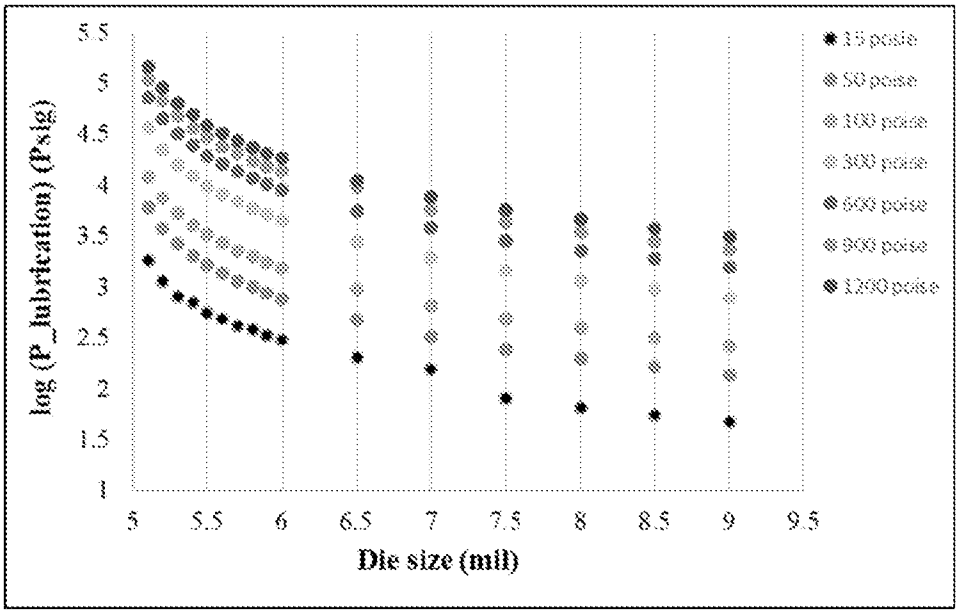


Figure 16

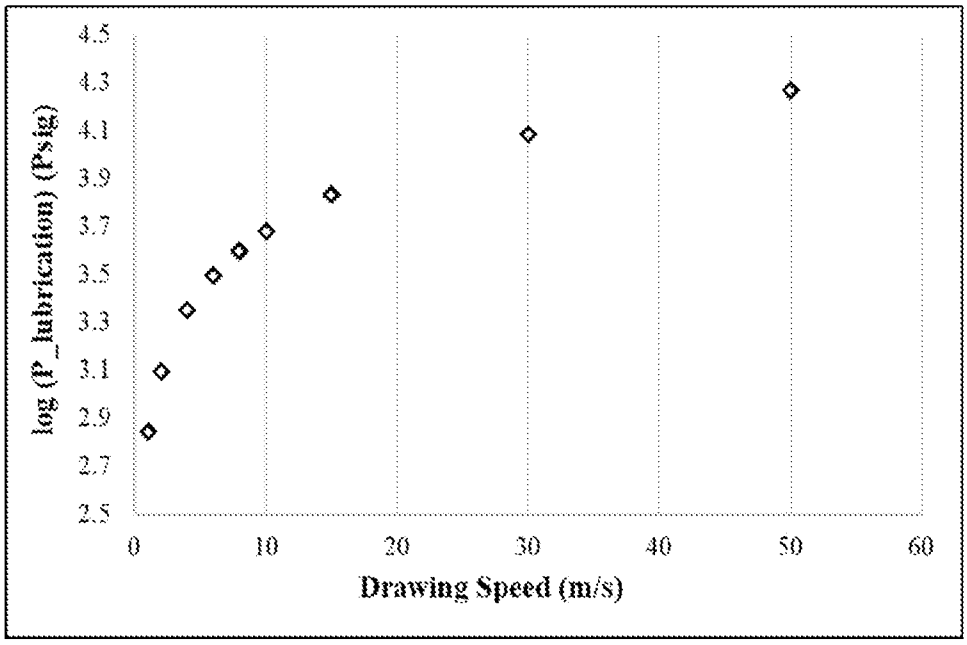


Figure 17

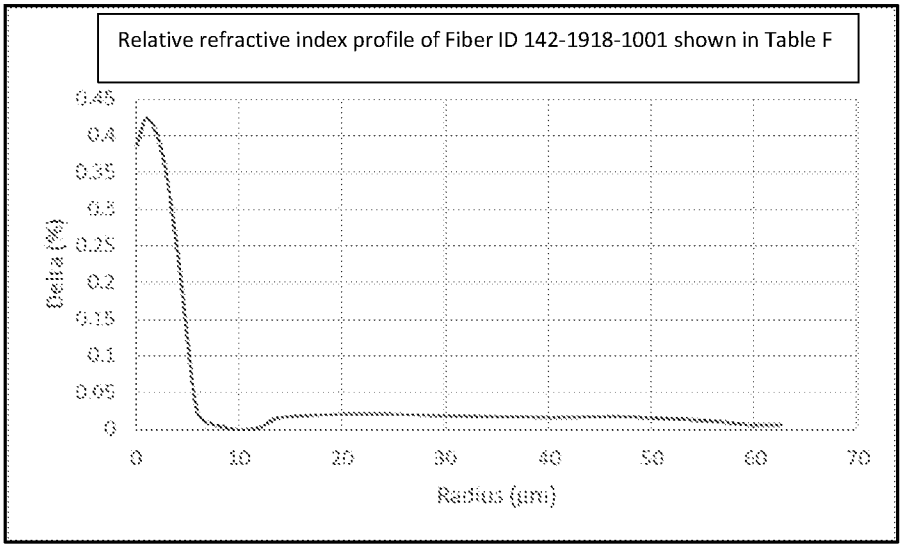


Figure 18

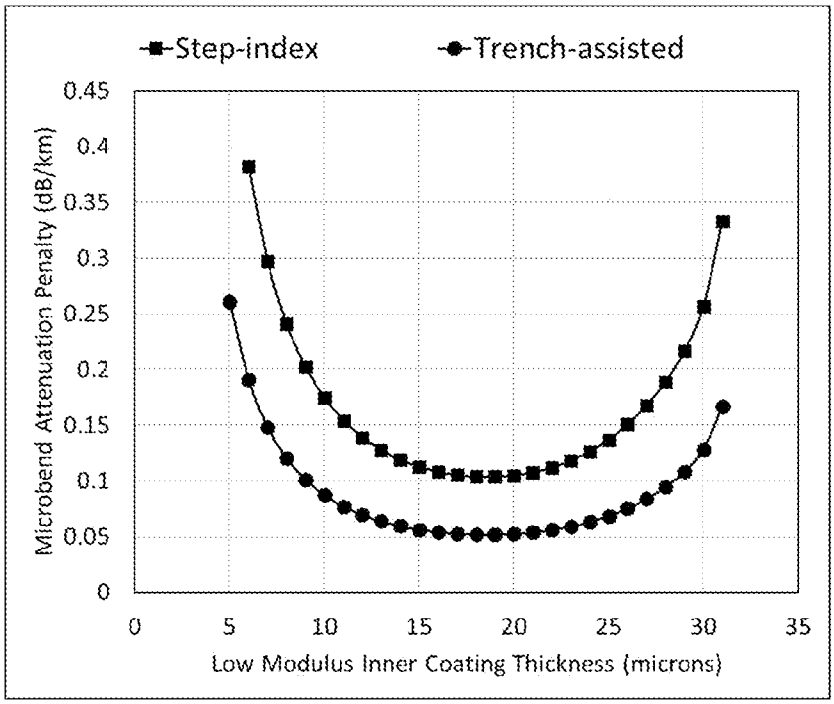


Figure 19

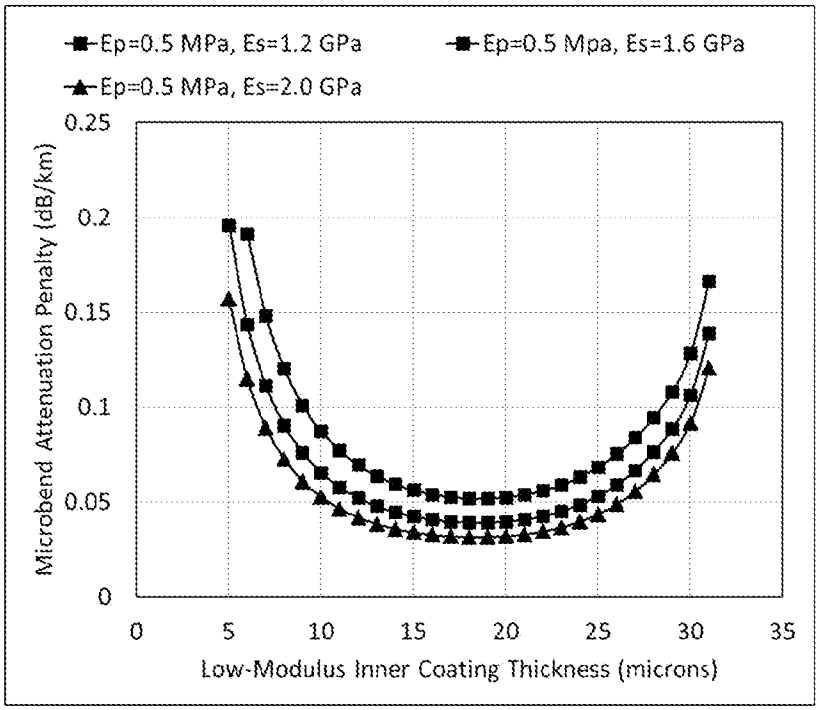


Figure 20

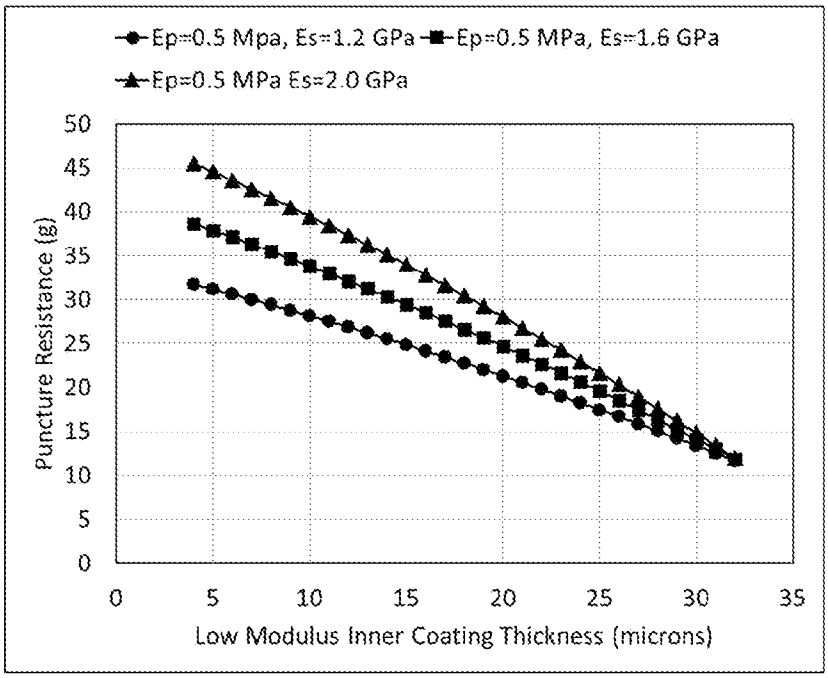


Figure 21

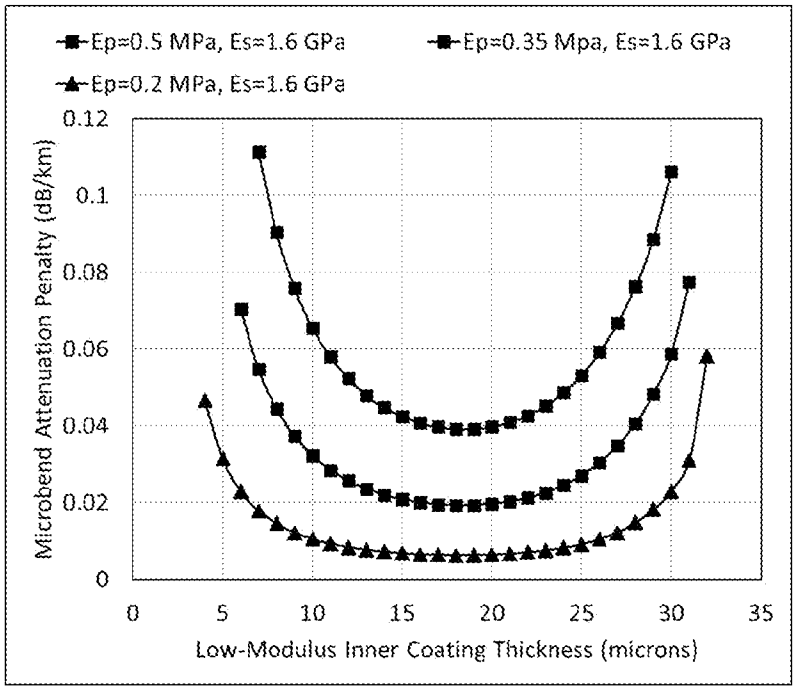

Ep=0.5 MPa, Es=1.6 GPa
Ep=0.35 Mpa, Es=1.6 GPa
Ep=0.2 MPa, Es=1.6 GPa
Microbend Attenuation Penalty (dB/km)
0.12
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20
25
30
35
Low-Modulus Inner Coating Thickness (microns)

Figure 22

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2021/042473

A. CLASSIFICATION OF SUBJECT MATTER

G02B 6/036(2006.01)i

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 6/036(2006.01); B05D 1/18(2006.01); B05D 3/06(2006.01); G02B 6/02(2006.01); G02B 6/44(2006.01)

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

Korean utility models and applications for utility models
Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) & Keywords: optical fiber, cladding, coating, high-modulus, puncture resistance, diameter

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2019-0331848 A1 (CORNING INCORPORATED) 31 October 2019 (2019-10-31) paragraphs [0007]-[0010], [0025]-[0038], [0066]-[0070], claims 1, 16 and figure 1	16-18
Y		19,20
A		1-15
Y	US 2018-0304304 A1 (CORNING INCORPORATED) 25 October 2018 (2018-10-25) paragraphs [0041]-[0045], [0064]	19,20
A	US 2019-0384000 A1 (SUMITOMO ELECTRIC INDUSTRIES, LTD.) 19 December 2019 (2019-12-19) paragraphs [0023]-[0068] and claim 1	1-20
A	JP 2016-522428 A (CORNING INC.) 28 July 2016 (2016-07-28) paragraphs [0006]-[0019]	1-20

☑ 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
"D" document cited by the applicant in the international application
"E" earlier application or patent 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	Date of mailing of the international search report
11 November 2021	**11 November 2021**

Name and mailing address of the ISA/KR	Authorized officer
Korean Intellectual Property Office **189 Cheongsa-ro, Seo-gu, Daejeon** **35208, Republic of Korea**	**PARK, Hye Lyun**
Facsimile No. **+82-42-481-8578**	Telephone No. **+82-42-481-3463**

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2021/042473

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/US2021/042473

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		JP 6031276 B2	24 November 2016

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/US2021/042473

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
		US 8879878 B2	04 November 2014