(19) DANMARK

Patent- og
Varemærkestyrelsen

(10) **DK/EP 2352047 T3**

(12) Oversættelse af
europæisk patentskrift

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(51) Int.Cl.: ***G 02 B 6/036 (2006.01)*** ***G 02 B 6/02 (2006.01)***

(45) Oversættelsen bekendtgjort den: **2019-11-11**

(80) Dato for Den Europæiske Patentmyndigheds
bekendtgørelse om meddelelse af patentet: **2019-09-25**

(86) Europæisk ansøgning nr.: **11152073.0**

(86) Europæisk indleveringsdag: **2011-01-25**

(87) Den europæiske ansøgnings publiceringsdag: **2011-08-03**

(30) Prioritet: **2010-02-01 FR 1050697**

(84) Designerede stater: **AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR**

(73) Patenthaver: **Draka Comteq B.V., Schieweg 9, 2627 AN Delft, Holland**

(72) Opfinder: **Molin, Denis, 55 Avenue Jean-Jaurès, 91210 Draveil, Frankrig**
Sillard, Pierre, 2 Square Raphaël Résidence Orsay, 78150 Le Chesnay, Frankrig

(74) Fuldmægtig i Danmark: **Larsen & Birkeholm A/S Skandinavisk Patentbureau, Banegårdspladsen 1, 1570 København V, Danmark**

(54) Benævnelse: **Ikke-nul dispersionsskiftet optisk fiber med et stort effektivt areal**

(56) Fremdragne publikationer:
EP-A1- 2 211 212
EP-A2- 1 739 063
WO-A1-2008/137150
FR-A1- 2 864 254

DESCRIPTION

FIELD OF THE INVENTION

[0001] The present invention relates to the field of optical-fiber transmissions and, more specifically, to a non-zero dispersion shifted fiber exhibiting low bending losses and a large effective area.

BACKGROUND

[0002] An optical fiber (*i.e.*, a glass fiber typically surrounded by one or more coating layers) conventionally includes an optical fiber core, which transmits and/or amplifies an optical signal, and an optical cladding, which confines the optical signal within the core. Accordingly, the refractive index of the core n_c is typically greater than the refractive index of the optical cladding n_g (*i.e.*, $n_c > n_g$).

[0003] For optical fibers, the refractive index profile is generally classified according to the graphical appearance of the function that associates the refractive index with the radius of the optical fiber. Conventionally, the distance r to the center of the optical fiber is shown on the x-axis, and the difference between the refractive index (at radius r) and the refractive index of the optical fiber's outer cladding (*e.g.*, an outer optical cladding) is shown on the y-axis. The refractive index profile is referred to as a "step" profile, "trapezoidal" profile, "alpha" profile, or "triangular" profile for graphs having the respective shapes of a step, a trapezoid, an alpha, or a triangle. These curves are generally representative of the optical fiber's theoretical or set profile. Constraints in the manufacture of the optical fiber, however, may result in a slightly different actual profile.

[0004] Generally speaking, two main categories of optical fibers exist: multimode fibers and single-mode fibers. In a multimode optical fiber, for a given wavelength, several optical modes are propagated simultaneously along the optical fiber. In a single-mode optical fiber, the signal propagates in a fundamental LP01 mode that is guided in the fiber core, while the higher order modes (*e.g.*, the LP11 mode) are strongly attenuated.

[0005] Conventionally, so-called "standard" single mode fibers (SSMFs) are used for land-based transmission systems. To facilitate compatibility between optical systems from different manufacturers, the International Telecommunication Union (ITU) defined a standard reference ITU-T G.652 with which a standard optical transmission fiber (*i.e.*, a standard single-mode fiber or SSMF) should comply. The ITU-T G.652 recommendations has several attributes (*i.e.*, A, B, C, and D).

[0006] Typically, an SSMF complies with specific telecommunications standards, such as the ITU-T G.652 recommendations. Conventionally, an SSMF exhibits the following properties: (*i*) at a wavelength of 1550 nanometers (nm), attenuation of about 0.190 decibels per kilometer (dB/km); (*ii*) at a wavelength of 1550 nanometers, an effective area of about 80 square microns (μm^2); (*iii*) a 22-meter cable cutoff wavelength (22m-λ_{cc}) of less than 1260 nanometers; (*iv*) a positive chromatic dispersion of about 17 picoseconds per nanometer kilometer (ps/(nm·km)); and (*v*) at a wavelength of 1550 nanometers, a positive dispersion slope of 0.058 picoseconds per nanometer square kilometer (ps/(nm^2·km)).

[0007] For wavelength division multiplexing (WDM) applications, single-mode non-zero dispersion shifted fibers (NZDSFs) are also used. An NZDSF exhibits a chromatic dispersion at a wavelength of 1550 nanometers that is less than the chromatic dispersion of an SSMF. A dispersion shifted fiber presenting non-zero chromatic dispersion that is positive for the wavelength at which it is used (*e.g.*, about 1550 nanometers) is commonly referred to as an NZDSF+. At a wavelength of 1550 nanometers, an NZDSF+ typically presents a chromatic dispersion of between about 3 ps/(nm·km) and 14 ps/(nm·km), and a chromatic dispersion slope of less than 0.1 ps/(nm^2·km). An NZDSF+ typically complies with specific telecommunications standards, such as the ITU-T G.655 and ITU-T G.656 recommendations.

[0008] Conventionally, an NZDSF has a triple-clad structure (*i.e.*, a triple-clad NZDSF). An example of an NZDSF includes: (*i*) a central core having a refractive index difference with respect to an outer cladding (*e.g.*, and outer optical cladding); (*ii*) a first inner cladding (*e.g.*, an intermediate cladding) having a refractive index difference with respect to the outer cladding; and (*iii*) a second inner cladding (*e.g.*, a ring) having a positive refractive index difference with respect to the outer cladding. The refractive indices in the central core, the intermediate cladding, and the ring are substantially constant over their entire widths. Conventional NZDSFs are commercially available, such as eLEAF®□fiber, TrueWaveRS® fiber, or Draka Communications' TeraLight® fiber.

[0009] An NZDSF may have a coaxial refractive index profile (*i.e.*, a coaxial NZDSF). The central core of an NZDSF having a coaxial refractive index profile includes two zones. The first zone is located in the center of the central core and has a refractive index difference with respect to the outer cladding that is less than that of the second zone. The second zone has a positive refractive index difference with respect to the outer cladding. The first zone's refractive index difference with respect to the outer cladding may be positive, negative or even zero.

[0010] An NZDSF may also include: a central core; an inner cladding; and a buried trench (*i.e.*, a cladding layer having a negative refractive index difference with respect to the outer cladding). Typically, this kind of profile is simpler to fabricate. Additionally, for approximately identical optical characteristics, this kind of NZDSF's central core has a refractive index difference that is less than a triple-clad NZDSF's central-core refractive index difference. Consequently, less central core doping is required to achieve this kind of NZDSF, which in turn reduces signal attenuation, particularly attenuation losses caused by Rayleigh diffusion.

[0011] In use, optical fibers may be subjected to bends that attenuate the signals conveyed by the optical fiber. Minimizing an optical fiber's bend loss typically improves the quality of the signal conveyed.

[0012] Increasing the effective area of an optical fiber allows signals to be transmitted through the optical fiber at higher powers without increasing the non-linear effects in the optical fiber. A transmission optical fiber having an enlarged effective area allows transmission over longer distances and/or increases the operating margins of the transmission system.

[0013] Generally speaking, improving certain optical characteristics can have a detrimental effect on other optical characteristics, which can reduce an optical fiber's compatibility with other optical fibers. Thus, it is generally desirable to improve certain optical characteristics while maintaining suitable compatibility between optical fibers.

[0014] The article "New Medium-Dispersion Fiber with Large Effective Area and Low Dispersion Slope" by S. Matsuo, et al., published in Optical Fiber Communication Conference and Exhibit 2002, OFC 2002, Vol., Issue, March 17-22, 2002, pp. 329-330, describes a coaxial NZDSF having an effective area of about 100 μm^2. Nevertheless, the optical fiber's central core includes a zone having a refractive index difference greater than 13×10^{-3}. Such a high refractive index difference can give rise to strong attenuation at a wavelength of 1550 nanometers, such as attenuation greater than 0.21 dB/km (*e.g.*, 0.22 dB/km or more).

[0015] European Patent No. 0,992,817 and its counterpart U.S. Patent No. 6,459,839 describe a triple-clad NZDSF that possesses low bending loss and a large effective area. Nevertheless, for comparable optical characteristics, the optical fiber's central core has a refractive index difference of about 13.7×10^{-3}, which is greater than in an optical fiber that includes a buried trench. At a wavelength of 1550 nanometers, the disclosed optical fiber, therefore, exhibits attenuation that is greater than 0.20 dB/km, or even greater than 0.21 dB/km. These attenuation values are greater than in an optical fiber that includes a buried trench. Additionally, the disclosed triple-clad NZDSF is more difficult to manufacture than an optical fiber that includes a buried trench, because the parameters of the triple-clad NZDSF's ring are more sensitive and require fabrication tolerances that are smaller than those for an effective buried trench.

[0016] European Patent No. 1,477,831 and its counterpart U.S. Patent No. 6,904,218 describe the use of a buried trench to improve the optical characteristics of an SSMF. Similarly, European Patent No. 1,978,383 and U.S. Patent Publication No. 2005/0244120 describe the use of a buried trench to improve the optical characteristics of an SSMF. Nevertheless, these documents fail to disclose an NZDSF with improved bending losses and an enlarged effective area.

[0017] U.S. Patent No. 4,852,968 describes the use of a buried trench placed close to the central core to decrease the values of chromatic dispersion and chromatic dispersion slope. Nevertheless, the disclosed optical fiber has a ratio of inside trench radius to central core radius that is between about 1.5 and 3.5, which can give rise to (*i*) large bending loss values for radii of 30 millimeters (mm), and (*ii*) at a wavelength of 1550 nm, an effective area of less than 55 µm^2.

[0018] International Patent Application Publication No. WO2008/106033 and its counterpart U.S. Patent No. 7,603,015 present NZDSFs that include a buried trench. One of the examples of NZDSFs has an effective area that is greater than 100 µm^2. Nevertheless, the central core has a refractive index difference that is too small and a radius that is too great. Furthermore, the inner cladding has a refractive index difference of zero with respect to the optical cladding. The characteristics of the central core and inner cladding give rise to excessive bending losses at large radii of curvature (*e.g.*, greater than 25 millimeters). For example, the present inventors have calculated that, at the wavelength of 1625 nanometers and a radius of curvature of 30 millimeters, the example of NZDSF exhibits bending losses of greater than 10 decibels per 100 turns (dB/100 turns).

[0019] European Patent No. 1,739,063 describes an NZDSF exhibiting low bending loss and a large effective area, having a core with a positive refractive index difference, a first intermediate cladding, a buried trench with an outer radius of about 16 microns, a second intermediate cladding with an outer radius of about 32 microns and an outer cladding. Therefore, a need exists for an NZDSF that permits higher transmission powers without increasing the non-linear effects, while maintaining suitable compatibility with other optical fibers and exhibiting low bending losses for large radii of curvature.

SUMMARY

[0020] In one aspect, the invention embraces a non-zero dispersion shifted optical fiber (NZDSF) that includes a central core, an inner cladding, and an outer cladding (e.g., an outer optical cladding). The central core has an outer radius r_1 and a maximum refractive index difference Dn_1 with respect to the outer cladding.

[0021] The present invention relates to a non-zero dispersion shifted optical fiber according to the wording of claim 1. Optionally, the optical fiber is a single mode optical fiber.

[0022] At a wavelength of 1550 nanometers, the optical fiber's effective area is at least about 95 µm^2.

[0023] For a radius of curvature of 30 millimeters at a wavelength of 1625 nanometers, the optical fiber exhibits bending losses of less than about 0.5 dB/100 turns.

[0024] In another embodiment, for a radius of curvature of 30 millimeters at a wavelength of 1550 nanometers, the optical fiber exhibits bending losses of less than about 0.01 dB/100 turns (*e.g.*, less than 0.005 dB/100 turns). Optionally, for a radius of curvature of 30 millimeters at a wavelength of 1625 nanometers, the optical fiber exhibits bending losses of less than about 0.1 dB/100 turns (*e.g.*, less than 0.05 dB/100 turns).

[0025] In yet another embodiment, the optical fiber possesses a 22-meter cable cutoff wavelength (22m-λ_{cc}) of less than about 1650 nanometers.

[0026] In yet another embodiment, the optical fiber possesses a 22-meter cable cutoff wavelength (22m-λ_{cc}) of less than about 1530 nanometers (*e.g.*, less than 1450 nanometers).

[0027] In yet another embodiment, at a wavelength of 1550 nanometers, the optical fiber possesses a chromatic dispersion slope of about 0.110 ps/(nm^2·km) or less.

[0028] In yet another embodiment, at a wavelength of 1550 nanometers, the optical fiber exhibits chromatic dispersion of between about 3 ps/(nm·km) and 14 ps/(nm·km) (*e.g.*, between about 4 ps/(nm·km) and 12 ps/(nm·km)).

[0029] Optionally, the central core has a step refractive-index profile.

[0030] According to the invention the optical fiber comprises a second intermediate cladding positioned between said burried trench and said outer cladding.

[0031] In this embodiment, the optical fiber's inner cladding includes a first intermediate cladding, a buried trench, and a second intermediate cladding. Typically, the first intermediate cladding is positioned between the central core and the buried trench (*e.g.*, immediately surrounding the central core). The buried trench is typically positioned between the first intermediate cladding and the second intermediate cladding (*e.g.*, immediately surrounding the first intermediate cladding). The second intermediate cladding immediately surrounds the buried trench. The first intermediate cladding has an outer radius r_2 and a refractive index difference Dn_2 with respect to the outer cladding. The buried trench has an outer radius r_3, a width w_3, and a negative refractive index difference Dn_3 with respect to the outer cladding. The second intermediate cladding has an outer radius r_4 and a refractive index difference Dn_4 with respect to the outer cladding. In this embodiment the central core may consist essentially of pure silica.

[0032] The optical fiber's inner cladding includes a second intermediate cladding having a refractive index difference Dn_4 with respect to the outer cladding of between about -10.5×10^{-3} and -6.5×10^{-3}.

[0033] The optical fiber's inner cladding includes a second intermediate cladding having an outer radius r_4 of about 41 microns or less.

[0034] The optical fiber's inner cladding includes a second intermediate cladding having a refractive index difference Dn_4 with respect to the outer cladding, and the difference between the central core's maximum refractive index difference Dn_1 and the second intermediate cladding's refractive index difference Dn_4 (*i.e.*, $Dn_1 - Dn_4$) is between about 6.5×10^{-3} and 10.5×10^{-3}.

[0035] The optical fiber's inner cladding includes a first intermediate cladding having a refractive index difference Dn_2 with respect to the outer cladding of between about 1×10^{-3} and 2.5×10^{-3}.

[0036] The optical fiber's inner cladding includes a buried trench having a refractive index difference Dn_3 with respect to the outer cladding and a second intermediate cladding having a refractive index difference Dn_4 with respect to the outer cladding, and the difference between the buried trench's refractive index difference Dn_3 and the second intermediate cladding's refractive index difference Dn_4 (*i.e.*, $Dn_3 - Dn_4$) is between about -15×10^{-3} and -4×10^{-3}. In yet another embodiment, at a wavelength of 1550 nanometers, the optical fiber exhibits attenuation of less than about 0.190 dB/km (*e.g.*, 0.180 dB/km or less).

[0037] The foregoing illustrative summary, as well as other objectives and/or advantages of the invention, and the manner in which the same are accomplished, are further explained within the following detailed description and its accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0038]

Figure 1 schematically depicts the set profile of an example of an optical fiber not according to the present invention.

Figure 2 schematically depicts the set profile of an example of an optical fiber according to the present invention.

DETAILED DESCRIPTION

[0039] In one aspect, the invention embraces a non-zero dispersion shifted fiber (NZDSF) that permits higher single-mode transmission powers without increasing non-linear effects, while maintaining suitable compatibility with other optical fibers and exhibiting low bending losses for large radii of curvature. To this end, NZDSFs according to the present invention typically possess large effective areas while preserving other optical characteristics (*e.g.*, dispersion values, cutoff wavelengths, and attenuation). Those of ordinary skill in the art will recognize that single-mode transmission typically refers to transmission of the fundamental propagation mode LP01.

[0040] Examples of optical fibers according to the present invention are NZDSFs that possess a chromatic dispersion that is less than the chromatic dispersion of a step-index standard single-mode fiber (SSMF). At a wavelength of 1550 nanometers, examples of optical fibers may possess a chromatic dispersion of less than about 14 ps/(nm·km) (*e.g.*, between about 3 ps/(nm·km) and 14 ps/(nm·km). Typically, optical fibers possess a positive chromatic dispersion.

[0041] The optical fiber includes a central core, an inner cladding, and an outer cladding (*e.g.*, an outer optical cladding). The inner cladding is typically position between the central core and the outer cladding.

[0042] At a wavelength of 1550 nanometers, the optical fiber's effective area is typically at least about 95 μm^2.

[0043] For a radius of curvature of 30 millimeters at a wavelength of 1625 nanometers, for example optical fibers exhibit bending losses of less than about 0.5 dB/100 turns. More typically, for a radius of curvature of 30 millimeters at a wavelength of 1625 nanometers, for example optical fibers exhibit bending losses of about 0.1 dB/100 turns or less (*e.g.*, about 0.05 dB/100 turns or less).

[0044] As previously discussed, manufactured optical fibers typically possess refractive index profiles that deviate slightly from their set profiles (*i.e.*, the theoretical refractive-index profiles).

[0045] Both Figure 1 and Figure 2 depict a central core having a step refractive-index profile. Thus, the central core's refractive index difference is constant and equal to the central core's maximum refractive index difference Dn_1. That said, the central core may also have a trapezoidal, triangular, or alpha profile (*i.e.*, a refractive index profile that varies as a function of radial position).

[0046] Furthermore, both Figure 1 and Figure 2 depict inner cladding layers, each having a constant refractive index difference with respect to the outer cladding. Optical fibers according to the invention, however, may have one or more refractive index differences that vary as a function of radial position (*e.g.*, a trapezoidal, triangular, or alpha profile). For inner cladding layers having non-constant refractive indices, the respective refractive index differences (*e.g.*, the buried trench's refractive index difference Dn_3) refer to the largest refractive index difference between an inner cladding layer and the outer cladding layer in terms of absolute value.

[0047] Generally speaking, a refractive index difference can also be expressed as a percentage using the following equation:

$$\Delta\%(r) = \frac{100 \times (n(r)^2 - n_{cladding}^2)}{2n(r)^2}$$

where n(r) is the comparative refractive index value as a function of radial position, and $n_{cladding}$ is the refractive index value of the outer cladding. Those of ordinary skill in the art will recognize that this equation can be used if the refractive index varies over a given section of the optical fiber (*i.e.*, the refractive index value varies as a function of radial position) or if the refractive index is constant over a given section.

[0048] Those of ordinary skill in the art will recognize that the outer cladding typically has a constant refractive index. That said, if the outer cladding has a non-constant refractive index, refractive index differences are typically measured with respect to the innermost portion of the outer cladding (*i.e.*, that portion of the outer cladding that is closest to the central core and that may affect the propagation of optical signals within the optical fiber).

[0049] A constant refractive index difference with respect to an outer cladding can also be expressed as a percentage using the following equation:

$$\Delta\% = \frac{100 \times (n^2 - n_{cladding}^2)}{2n^2}$$

where n is the comparative refractive index value (*e.g.*, the refractive index n_3 of the buriend trench), and $n_{cladding}$ is the refractive index value of the outer cladding.

[0050] As depicted in Figure 1, an example of an optical fiber includes a central core having an outer radius r_1 and a maximum refractive index difference Dn_1 with respect to the outer cladding. The optical fiber's inner cladding includes an intermediate cladding having an outer radius r_2 and a refractive index difference Dn_2 with respect to the outer cladding. As shown, the intermediate cladding immediately surrounds the central core. The optical fiber's inner cladding also includes a buried trench having an outer radius r_3, a width w_3, and a negative refractive index difference Dn_3 with respect to the outer cladding.

[0051] The central core's outer radius r_1 is typically between about 1 micron and 2.5 microns. The central core's profile facilitates reduced chromatic dispersion. The limited quantity of dopant in the central core also facilitates control over attenuation losses from Rayleigh diffusion.

[0052] In some embodiments, the ratio of the intermediate cladding's outer radius r_2 to the central core's outer radius r_1 (*i.e.*, the ratio r_2:r_1) is between about 5 and 9. Without being bound to any particular theory, the present inventors have found that increasing the ratio r_2:r_1 moves the buried trench farther away from the central core, thereby preventing the buried trench from disturbing the propagation of the fundamental mode. Adjusting the ratio r_2:r_i also facilitates control over the optical fiber's effective area and chromatic dispersion.

[0053] The buried trench may be directly adjacent to the intermediate cladding (*i.e.*, the buried trench may immediately surround the intermediate cladding). Typically, the buried trench's width w_3 is between about 3 microns and 6 microns. The buried trench's outer radius r_3 is typically less than about 19 microns. The characteristics of the buried trench can facilitate the achievement of reduced bending losses. The characteristics of the buried trench also facilitate control over the optical fiber's cutoff wavelength by controlling the losses of modes having an order directly greater than the fundamental mode (*e.g.*, the LP11 and LP02 modes).

[0054] The outer cladding is typically an optical cladding. The outer cladding has an outer radius r_5. Examples of optical fibers include an outer cladding with an outer radius r_5 of about 50 microns, and the glass fiber itself has an outer diameter of 100 microns. In other embodiments, the outer cladding has an outer radius r_5 of 62.5 microns, and the glass fiber itself has an outer diameter of 125 microns.

[0055] The central core and the inner cladding (*e.g.*, the intermediate cladding and the buried trench) may be manufactured using a chemical vapor deposition (CVD) method performed on the interior surface of a silica tube. In this regard, the outer cladding may be constituted by the silica tube and glass buildup on the silica tube (*e.g.*, via an overcladding or sleeving method). The silica tube and any buildup is typically natural or doped silica. The outer cladding may also be obtained by any other deposition techniques, such as vapor axial deposition (VAD) or outside vapor deposition (OVD).

[0056] In accordance with Figure 1, one example of an optical fiber includes a central core having a maximum refractive index difference Dn_1 with respect to the outer cladding of between about 6.5×10^{-3} and 10.5×10^{-3}. The intermediate cladding has a refractive index difference Dn_2 with respect to the outer cladding of between about 1×10^{-3} and 2.5×10^{-3}. The buried trench has a refractive index difference Dn_3 with respect to the outer cladding of between about -15×10^{-3} and -4×10^{-3}. The central core may be doped to raise its refractive index above the refractive index of the outer cladding. For example, the central core may be doped with germanium and/or any other suitable dopant(s). In some embodiments, the outer cladding may be doped with fluorine and/or any other suitable dopant(s). Similarly, the intermediate cladding's refractive index difference Dn_2 and the buried trench's refractive index difference Dn_3 may be obtained using suitable dopant(s).

[0057] In accordance with Figure 1, an example of an optical fiber not according to the invention includes a central core, an inner cladding, and an outer cladding serving as an optical cladding. The central core has an outer radius r_1 and a positive maximum refractive index difference Dn_1 with respect to the outer cladding. The inner cladding includes an intermediate cladding and a buried trench. The intermediate cladding has an outer radius r_2 and a refractive index difference Dn_2 with respect to the outer cladding of between about 1×10^{-3} and 2.5×10^{-3}. The buried trench has an outer radius r_3, a width w_3, and a negative refractive index difference Dn_3 with respect to the outer cladding.

[0058] As noted and in accordance with Figure 1, for a radius of curvature of 30 millimeters at a wavelength of 1625 nanometers, the optical fiber exhibits bending losses of less than about 0.5 dB/100 turns. More typically, for a radius of curvature of 30 millimeters at a wavelength of 1625 nanometers, the optical fiber exhibits bending losses of about 0.1 dB/100 turns or less (*e.g.*, about 0.05 dB/100 turns or less). At a wavelength of 1550 nanometers, the optical fiber's effective area is typically at least about 95 μm^2.

[0059] According to the invention, as depicted in Figure 2, the optical fiber's inner cladding includes a first intermediate cladding, a buried trench, and a second intermediate cladding. The second intermediate cladding has an outer radius r_4 and a refractive index difference Dn_4 with respect to the outer cladding.

[0060] In accordance with Figure 2, an example of an optical fiber's central core has a maximum refractive index difference Dn_1 with respect to the outer cladding that is substantially equal to zero (*i.e.*, the central core's refractive index is approximately equal to the outer cladding's refractive index). In this regard, the central core may be doped with fluorine, germanium, and/or any other suitable dopant(s) to obtain a refractive index difference that is substantially equal to zero. For example, the central core and the outer cladding may be made of pure silica. An optical fiber with a central core made of pure silica is commonly referred to as a pure silica core fiber (PSCF). Low core-doping and pure silica cores can facilitate the achievement of optical-fiber attenuation values of less than 0.190 dB/km (*e.g.*, less than 0.180 dB/km) at a wavelength of 1550 nanometers. Low attenuation is particularly advantageous in long distance transmission applications.

[0061] The difference between the central core's maximum refractive index difference Dn_1 and the second intermediate cladding's refractive index difference Dn_4 (*i.e.*, $Dn_1 - Dn_4$) is between about 6.5×10^{-3} and 10.5×10^{-3}. The difference $Dn_1 - Dn_4$ may be achieved by reducing the refractive index of the second intermediate cladding using a suitable dopant.

[0062] As depicted in Figure 2, the inner cladding is buried, *i.e.*, the inner cladding's refractive index is less than the outer cladding's refractive index. In this regard, the first intermediate cladding, the buried trench, and the second intermediate cladding each have a refractive index that is less than the outer cladding's refractive index. The inner cladding's refractive index may be decreased to less than the outer cladding's refractive index by doping with fluorine, germanium, and/or any other suitable dopant.

[0063] The difference between the first intermediate cladding's refractive index Dn_2 and the second intermediate cladding's refractive index Dn_4 (*i.e.*, $Dn_2 - Dn_4$) is between about 1×10^{-3} and 2.5×10^{-3}. The difference between the buried trench's refractive index difference Dn_3 and the second intermediate cladding's refractive index difference Dn_4 (*i.e.*, $Dn_3 - Dn_4$) is between about -15×10^{-3} and -4×10^{-3}. The differences $Dn_2 - Dn_4$ and $Dn_3 - Dn_4$ may be achieved by reducing the refractive indices respectively of the first intermediate cladding and of the buried trench by suitable doping. Additionally, the differences $Dn_2 - Dn_4$ and $Dn_3 - Dn_4$ may be achieved by reducing or increasing the refractive index of the second intermediate cladding by suitable doping.

[0064] The second intermediate cladding typically has a refractive index difference Dn_4 with respect to the outer cladding of between about -10.5×10^{-3} and -6.5×10^{-3}. The second intermediate cladding has an outer radius r_4 of less than about 41 microns. Reducing the second intermediate cladding's outer radius typically helps to reduce the manufacturing costs associated with doping the optical fiber's inner cladding.

[0065] Without being bound to any particular theory, the present inventors have found that, when the outer cladding's refractive index is approximately the same as the central core's refractive index, bringing the outer cladding closer to the central core (*i.e.*, reducing the difference between the central core's outer radius r_1 and the outer cladding's inner radius) increases the leakage loss of the fundamental propagation mode LP01. Nevertheless, in some optical fibers, it is possible to bring the outer cladding closer to the central core and reduce the buried trench's outer radius r_3, while preserving fundamental mode leakage losses of less than about 0.020 dB/km (*e.g.*, 0.010 dB/km or less) at a wavelength of 1550 nanometers.

[0066] In accordance with Figure 2, an optical fiber includes a central core, an inner cladding, and an outer cladding that functions as an optical cladding. The inner cladding is typically positioned between the central core and the outer cladding. The central core has an outer radius r_1 and a maximum refractive index difference Dn_1 with respect to the outer cladding.

[0067] The inner cladding includes a first intermediate cladding, a buried trench, and a second intermediate cladding. Typically, the inner cladding's buried trench is positioned between the first intermediate cladding and the second intermediate cladding. The first intermediate cladding has an outer radius r_2 and a refractive index difference Dn_2 with respect to the outer cladding. The buried trench has an outer radius r_3, a width w_3, and a negative refractive index difference Dn_3 with respect to the outer cladding. The second intermediate cladding has an outer radius r_4 and a refractive index difference Dn_4 with respect to the outer cladding that is less than the central core's maximum refractive index difference Dn_1. The difference between the first intermediate cladding's refractive index Dn_2 and the second intermediate cladding's refractive index Dn_4 (*i.e.*, $Dn_2 - Dn_4$) is between about 1×10^{-3} and 2.5×10^{-3}.

[0068] As noted and in accordance with Figure 2, for a radius of curvature of 30 millimeters at a wavelength of 1625 nanometers, the optical fiber exhibits bending losses of less than about 0.5 dB/100 turns. More typically, for a radius of curvature of 30 millimeters at a wavelength of 1625 nanometers, the optical fiber exhibits bending losses of about 0.1 dB/100 turns or less (*e.g.*, about 0.05 dB/100 turns or less). At a wavelength of 1550 nanometers, the optical fiber's effective area is typically at least about 95 μm^2.

[0069] The optical fiber's inner cladding may include only a first intermediate cladding, a buried trench, and a second intermediate cladding. In this regard, the first intermediate cladding immediately surrounds the central core, the buried trench immediately surrounds the first intermediate cladding, the second intermediate cladding immediately surrounds the buried trench, and the outer cladding immediately surrounds the second intermediate cladding.

[0070] Examples of optical fibers of the present invention exhibit low bending losses and have a large effective area. In this regard, for a radius of curvature of 30 millimeters at a wavelength of 1625 nanometers, optical fibers exhibit bending losses of less than about 0.5 dB/100 turns. More typically, for a radius of curvature of 30 millimeters at a wavelength of 1625 nanometers, optical fibers exhibit bending losses of about 0.1 dB/100 turns or less (*e.g.*, about 0.05 dB/100 turns or less). For a radius of curvature of 30 millimeters at a wavelength of 1550 nanometers, optical fibers exhibit bending losses of less than about 0.01 dB/100 turns (*e.g.*, 0.005 dB/100 turns or less). At a wavelength of 1550 nanometers, optical fibers have an effective area of about 95 μm^2 or more (*e.g.*, 98 μm^2 or more). Typically, the optical fiber's effective area is less than 130 μm^2 at a wavelength of 1550 nanometers. Thus, NZDSFs according to the invention typically accommodate large radii of curvature and permit higher transmission powers without increasing non-linear effects.

[0071] Additionally, the optical fibers of the present invention typically possess acceptable values for all of the optical parameters that enable good compatibility with other optical fibers. In particular, at a wavelength of 1550 nanometers, the optical fibers may present a chromatic dispersion of between about 3 ps/(nm·km) and 14 ps/(nm·km) (*e.g.*, between 4 ps/(nm·km) and 12 ps/(nm·km)) and a chromatic dispersion slope of about 0.110 ps/(nm^2·km) or less.

[0072] The 22-meter cable cutoff wavelength (22m-λ_{cc})is conventionally measured as the wavelength at which the optical signal is single mode after propagating along 22 meters of fiber, as defined by subcommittee 86A of the International Electrotechnical Commission in standard IEC 60793-1-44. The optical fiber typically has a 22-meter cable cutoff wavelength (22m-λ_{cc}) that is less than about 1650 nanometers. More typically, the optical fiber has a 22-meter cable cutoff wavelength (22m-λ_{cc}) that is less than 1530 nanometers (*e.g.*, less than 1450 nm).

[0073] The following tables (below) illustrate aspects of the present invention by providing both comparative and inventive optical-fiber examples (*e.g.*, prophetic examples). To facilitate the following discussion, for comparative optical-fiber examples having a refractive index profile similar to Figure 1, the intermediate cladding is referred to as the first intermediate cladding.

[0074] Table 1 (below) characterizes the index profiles of 11 optical-fiber examples. Table 1's first column provides a reference for each profile. The following three columns provide the central core's outer radius r_1, the first intermediate cladding's outer radius r_2, and the ratio r_i:r_2 of the central core's outer radius to the intermediate cladding's outer radius. The next two columns provide the buried trench's outer radius r_3 and width w_3. The following column provides the second intermediate cladding's outer radius r_4 where applicable, and the next column provides the outer cladding's outer radius.

[0075] Thereafter, Table 1 provides, for a wavelength of 633 nanometers and with respect to the outer cladding, the refractive index differences for: the central core Dn_1; the first intermediate cladding Dn_2; the buried trench Dn_3; and the second intermediate cladding Dn_4 where applicable. For the sake of completeness and to further illustrate the meaning of a refractive index difference as used herein, the last column provides the outer cladding's refractive index difference Dn_5 with respect to itself is equal to zero.

[0076] The values in Table 1 correspond to the set profiles of the optical-fiber examples. As previously discussed, manufactured optical fibers typically possess refractive index profiles that deviate slightly from their set profiles (*i.e.*, the theoretical refractive-index profiles).

Table 1

Examples	r_1 (μm)	r_2 (μm)	r_2/r_1 (μm)	r_3 (μm)	w_3 (μm)	r_4 (μm)	r_5 (μm)	Dn_1 @633nm (× 10^{-3})	Dn_2 @633nm (× 10^{-3})	Dn_3 @633nm (× 10^{-3})	Dn_4 @633nm (× 10^{-3})	Dn_5 @633nm (× 10^{-3})
1-std	1.81	12.65	7.00	18.00	5.35		62.5	8.70	1.50	-8.0		0.0
1b-std	1.81	6.35	3.50	11.70	5.35		62.5	8.70	1.50	-8.0		0.0
1c-std	1.81	12.65	7.00	18.00	5.35		62.5	8.70	0.50	-8.0		0.0
1 d-std	2.70	12.65	4.07	18.00	5.35		62.5	5.50	0.00	-8.0		0.0
1e-std	2.70	15.65	5.80	18.00	2.35		62.5	8.70	0.00	-8.0		0.0
1-PSC	1.81	12.65	7.00	18.00	5.35	40.0	62.5	0.00	-7.20	-16.7	-8.7	0.0
2-std	2.19	14.00	6.40	18.00	4.00		62.5	7.40	1.50	-6.5		0.0
3-std	1.56	11.82	7.60	17.47	5.65		62.5	10.00	1.70	-7.3		0.0
4-std	1.95	12.55	6.40	18.00	5.45		62.5	7.90	1.50	-8.0		0.0
5-std	2.14	12.72	5.90	18.00	5.28		62.5	7.10	1.50	-9.0		0.0
6-std	1.62	12.85	7.90	18.00	5.15		62.5	10.00	1.50	-9.0		0.0

[0077] Optical-fiber examples 1-std, 2-std, 3-std, 4-std, 5-std, and 6-std are examples of optical fibers not according to the invention that have an inner cladding that includes a first intermediate cladding and the buried trench (*e.g.*, similar to Figure 1). In these examples, the second intermediate cladding's outer radius r_4 and the second intermediate cladding's refractive index difference Dn_4 are not provided because the optical fiber's inner cladding does not include a second intermediate cladding.

[0078] Optical-fiber example 1-PSC is an example of an optical fiber according to the invention that has an inner cladding that includes a first intermediate cladding, a buried trench, and a second intermediate cladding (*e.g.*, similar to Figure 2). In this example, the second intermediate cladding's outer radius r_4 is less than 41 microns and the second intermediate cladding's refractive index difference Dn_4 is between about -10.5×10^{-3} and -6.5×10^{-3}.

[0079] Optical-fiber examples 1b-std, 1c-std, 1d-std, and 1e-std are comparative optical fibers that are presented for comparison with optical fiber 1-std.

[0080] Table 2 provides the optical properties of the optical fiber of the invention and comparative optical fibers of Table 1.

[0081] In Table 2, the first column repeats the references of Table 1. The following three columns provide, for each fiber profile at a wavelength of 1550 nanometers, the values of: chromatic dispersion (D); chromatic dispersion slope; effective area A_{eff}; and the fundamental mode leakage loss P_{leak}. The next two columns provide bending losses P_{10mm} and P_{30mm} for respective radii of curvature of 10 millimeters and 30 millimeters at a wavelength of 1550 nanometers. The next column provides bending losses P_{30mm} as measured at a wavelength of 1625 nanometers for a radius of curvature of 30 millimeters. The last column provides the 22-meter cable cutoff wavelength (22m-λ_{cc}).

Table 2

Examples	D @1550nm (ps/(nm·km))	Slope @1550nm (ps/(nm^2·km))	A_{eff} @1550nm (μm^2)	P_{leak} @1550nm (dB/km)	P_{10mm} @1550nm (dB/turn)	P_{30mm} @1550nm (dB/100 turns)	P_{30mm} @1625nm (dB/100 turns)	22m-λ_{cc} (nm)
1-std	7.3	0.102	97		<1	<0.005	<0.05	<1450
1b-std	13.3	0.079	53		<1	>0.01	>1	<1100
1c-std	2.3	0.105	77		>1	>1	>10	<1100
1 d-std	9.6	0.075	79		<1	>0.5	>1	<1100
1e-std	6.5	0.053	46		<1	<0.005	<0.05	<1150
1-PSC	6.3	0.102	98	<0.005	<1	<0.01	<0.1	<1500
2-std	8.0	0.091	100		<3	<0.005	<0.05	<1650
3-std	8.0	0.107	100		<1	<0.005	<0.05	<1450
4-std	9.0	0.096	99		<2	<0.005	<0.05	<1450
5-std	11.0	0.090	105		<1	<0.005	<0.05	<1450
6-std	5.0	0.110	95		<1	<0.005	<0.05	<1450

[0082] For a radius of curvature of 30 millimeters at a wavelength of 1625 nanometers, the optical fibers of the invention exhibit bending losses P_{30mm} that are less than 0.5 dB/100 turns, and even less than 0.1 dB/100 turns. For a radius of curvature of 30 millimeters at a wavelength of 1625 nanometers, optical fibers 1-std, 2-std, 3-std, 4-std, 5-std, and 6-std exhibit bending losses P_{30mm} that are less than 0.05 dB/100 turns.

[0083] For a radius of curvature of 30 millimeters at a wavelength of 1550 nanometers, the optical fibers of the invention exhibit bending losses P_{30mm} that are less than 0.01 dB/100 turns. Indeed, for a radius of curvature of 30 millimeters at a wavelength of 1550 nanometers, optical fibers 1-std, 2-std, 3-std, 4-std, 5-std, and 6-std exhibit bending losses P_{30mm} that are less than 0.005 dB/100 turns.

[0084] Additionally, at a wavelength of 1550 nanometers, the optical fibers of the invention have effective areas A_{eff} that are greater than or equal to 95 μm^2. At a wavelength of 1550 nanometers, the optical fibers of the invention also exhibit (*i*) chromatic dispersion values D of between 3 ps/(nm·km) and 14 ps/(nm·km), and (*ii*) chromatic dispersion slope values of 0.110 ps/(nm^2·km) or less.

[0085] The optical fibers of the invention possess 22-meter cable cutoff wavelengths (22m-λ_{cc}) that are less than 1650 nanometers. Optical fibers 1-std, 1-PSC, 3-std, 4-std, 5-std, and 6-std possess 22-meter cable cutoff wavelengths (22m-λ_{cc}) that are less than 1530 nanometers. Optical fibers 1-std, 3-std, 4-std, 5-std, and 6-std possess 22-meter cable cutoff wavelengths (22m-λ_{cc}) that are less than 1450 nanometers.

[0086] At a wavelength of 1550 nanometers, optical fiber 1-PSC exhibits a fundamental mode leakage loss P_{leak} that is less than 0.005 dB/km, while utilizing a second intermediate cladding having an outer radius of only 40 microns (see Table 1).

[0087] The comparative optical fibers 1b-std, 1c-std, 1d-std, and 1e-std are similar to optical fiber 1-std but certain refractive index profile characteristics are modified. The comparative optical fiber examples are described in comparison with optical fiber 1-std to further illustrate the advantages of the optical fibers of the invention.

[0088] Comparative optical fiber 1b-std differs from the optical fiber 1-std in that the buried trench is closer to the central core. The comparative optical fiber 1b-std's ratio r_2:r_1 is 3.5, whereas optical fiber 1-std's ratio r_2:r_1 is 7. Consequently, comparative optical fiber 1b-std's effective area is reduced to less than 55 μm^2, and, for a radius of curvature of 30 millimeters at a wavelength of 1625 nanometers, bending losses are increased to more than 1 dB/100 turns. The comparative optical fiber 1b-std's chromatic dispersion D is also higher than example of an optical fiber 1-std's chromatic dispersion D.

[0089] Comparative optical fiber 1c-std differs from the optical fiber 1-std in that the first intermediate cladding's refractive index difference Dn_2 is smaller. Indeed, in comparative optical fiber 1c-std, the first intermediate cladding's refractive index difference Dn_2 is 0.5 x 10^{-3}, whereas, in optical fiber 1-std the first intermediate cladding's refractive index difference Dn_2 is 1.5 x 10^{-3}. Consequently, comparative optical fiber 1c-std's effective area is reduced to less than 80 μm^2, and, for a radius of curvature of 30 millimeters at a wavelength of 1625 nanometers, bending losses are increased to more than 10 dB/100 turns.

[0090] Comparative optical fiber 1d-std differs from the optical fiber 1-std in that the characteristics of the central core are modified. In particular, comparative optical fiber 1d-std's maximum refractive index difference Dn_1 is 5.5 x 10^{-3}, as compared to optical fiber 1-std's maximum refractive index difference Dn_1 of 8.7 x 10^{-3}. In comparative optical fiber 1d-std, the central core's outer radius r_1 is increased to 2.7 microns. Additionally, in comparative optical fiber 1d-std, the first intermediate cladding's refractive index difference Dn_2 is zero, as compared to 1.5 x 10^{-3} in example 1-std. Consequently, comparative optical fiber 1d-std's effective area is decreased to less than 80 μm^2, and, for a radius of curvature of 30 millimeters at a wavelength of 1625 nanometers, bending losses are increased to more than 1 dB/100 turns.

[0091] Comparative optical fiber 1e-std differs from the optical fiber 1-std in that: (*i*) the central core's outer radius r_1 is increased to more than 2.5 microns; (*ii*) the first intermediate cladding's refractive index difference Dn_2 is zero; and (*iii*) the buried trench's width w_3 is reduced to less than 3 microns. The chromatic dispersion slope and the 22-meter cable cutoff wavelength (22m-λ_{cc}) are reduced. Bending losses are not significantly modified because the central core's maximum refractive index difference Dn_1 is unchanged, and the reduction of the first intermediate cladding's refractive index difference Dn_2 is compensated by the increased central core outer radius. Nevertheless, comparative optical fiber 1e-std's effective area is decreased to less than 50 μm^2.

[0092] The optical fiber according to the invention typically complies with the recommendations of ITU-T G.655 and G.656 standards for NZDSFs. In particular, the ITU-T G.655 and G.656 standards for NZDSFs recommend (*i*) an 22-meter cable cutoff wavelength (22m-λ_{cc}) of less than 1450 nanometers, and (*ii*) at a wavelength of 1550 nanometers, a mode field diameter of between about 7 microns and 11 microns, or between about 8 microns and 11 microns. Accordingly, optical fibers according to the present invention may be installed in numerous transmission systems and present good compatibility with the other fibers of the system.

[0093] Optical fibers of the invention are well-suited for long-distance transmission systems operating in the C-band, and particularly in wavelength division multiplex applications. The optical fiber's increased effective area, without significant degradation of other optical parameters, make it possible to increase the transmission power of the optical signals without increasing non-linear effects. Thus, signal-to-noise ratio of the transmission line may be improved, which is particularly desirable for long-distance optical transmission systems on land and undersea. The decrease in bending losses, in particular for large radii of curvature, also contributes to a better signal quality.

[0094] In the specification and/or figures, typical embodiments of the invention have been disclosed. The present invention is not limited to such embodiments. The figures are schematic representations and so are not necessarily drawn to scale. Unless otherwise noted, specific terms have been used in a generic and descriptive sense and not for purposes of limitation.

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- EP0992817A [0015]
- US6459839B [0015]
- EP1477831A [0016]
- US6904218B [0016]
- EP1978383A [0016]
- US20050244120A [0016]
- US4852968A [0017]
- WO2008106033A [0018]
- US7603015B [0018]
- EP1739063A [0019]

Non-patent literature cited in the description

- New Medium-Dispersion Fiber with Large Effective Area and Low Dispersion Slope**S. MATSUO et al.**Optical Fiber Communication Conference and Exhibit 2002OFC20020317329-330 [0014]

PATENTKRAV

1. Ikke-nul dispersionsskiftet optisk fiber, omfattende:

en central kerne med en ydre radius r_1 og en maksimal brydningsindeksforskel Dn_1 med hensyn til en ydre kappe, hvor den centrale kernes ydre radius r_1 er mellem 1,0 mikrometer og 2,5 mikrometer;
en første mellemliggende kappe, som er placeret mellem den centrale kerne og den ydre kappe, hvor den første mellemliggende kappe har en ydre radius r_2 og en brydningsindeksforskel Dn_2 i forhold til den ydre kappe;
en forsænket rende, som er placeret mellem den første mellemliggende kappe og den ydre kappe, hvor den forsænkede rende har en ydre radius r_3, en bredde w_3 og en negativ brydningsindeksforskel Dn_3 med hensyn til den ydre kappe;
hvor den optiske fiber for en krumningsradius på 30 millimeter ved en bølgelængde på 1625 nannometer har bøjningstab på mindre end 0,5 dB/100 viklinger; og hvor den optiske fibers effektive areal ved en bølgelængde på 1550 nanometer er 95 μm^2 eller større, hvor forholdet $r_2:r_1$ mellem den første mellemliggende kappes ydre radius r_2 og den centrale kernes ydre radius r_1 er mellem 5 og 9, hvor den forsænkede rendes bredde w_3 er mellem 3 mikrometer og 6 mikrometer, og den forsænkede rendes ydre radius r_3 er mindre end 19 mikrometer;
hvor den ikke-nul dispersionsskiftede optiske fiber endvidere omfatter en anden mellemliggende kappe, som er placeret mellem den forsænkede rende og den ydre kappe, hvor den anden mellemliggende kappe har en ydre radius r_4 og en brydningsindeksforskel Dn_4 med hensyn til den ydre kappe, hvor den anden mellemliggende kappes brydningsindeksforskel Dn_4 er mellem $-10,5 \times 10,3^{-3}$ og $-6,5 \times 10^{-3}$, hvor den anden mellemliggende kappes ydre radius r_4 er 41 mikrometer eller mindre, hvor forskellen Dn_2-Dn_4 mellem den første mellemliggende kappes brydningsindeksforskel Dn_2 og den anden mellemliggende kappes brydningsindeksforskel Dn_4 er mellem 1×10^{-3} og

$2{,}5 \times 10^{-3}$, hvor forskellen Dn_3-Dn_4 mellem den forsænkede rendes brydningsindeksforskel Dn_3 og den anden mellemliggende kappes brydningsindeksforskel Dn_4 er mellem -15×10^{-3} og -4×10^{-3}, og forskellen Dn_1-Dn_4 mellem den centrale kernes maksimale brydningsindeksforskel Dn_1 og den anden mellemliggende kappes brydningsindeksforskel Dn_4 er mellem $6{,}5 \times 10^{-3}$ og $10{,}5 \times 10^{-3}$.

2. Optisk fiber ifølge krav 2, hvor den optiske fiber for en krumningsradius på 30 millimeter ved en bølgelængde på 1550 nanometer har bøjningstab på mindre end 0,01 dB/100 viklinger.

3. Optisk fiber ifølge et hvilket som helst af de foregående krav, hvor den optiske fiber har en 22-meter-kabelafskæringsbølgelængde (22m-λ_{cc}) på mindre end 1650 nanometer, fortrinsvis mindre end 1530 nanometer.

4. Optisk fiber ifølge et hvilket som helst af de foregående krav, hvor den optiske fiber ved en bølgelængde på 1550 nanometer har en kromatisk dispersion på mellem 3 ps/(nm·km) og 14 ps/(nm·km), fortrinsvis mellem 4 ps/(nm·km) og 12 ps/(nm·km).

5. Optisk fiber ifølge et hvilket som helst af de foregående krav, hvor den optiske fiber ved en bølgelængde på 1550 nanometer har en kromatisk dispersionshældning på 0,110 ps/(nm^2·km) eller mindre.

DRAWINGS

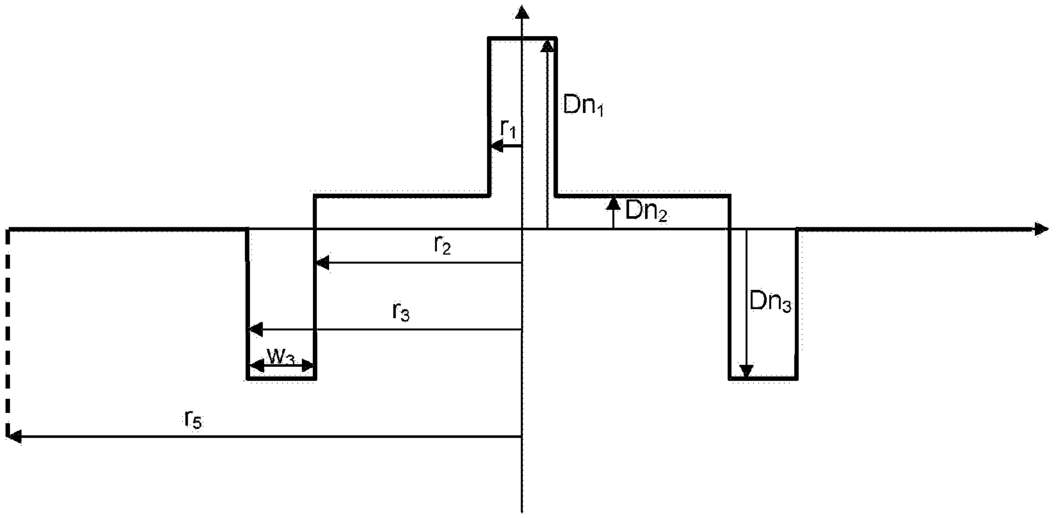

Figure 1

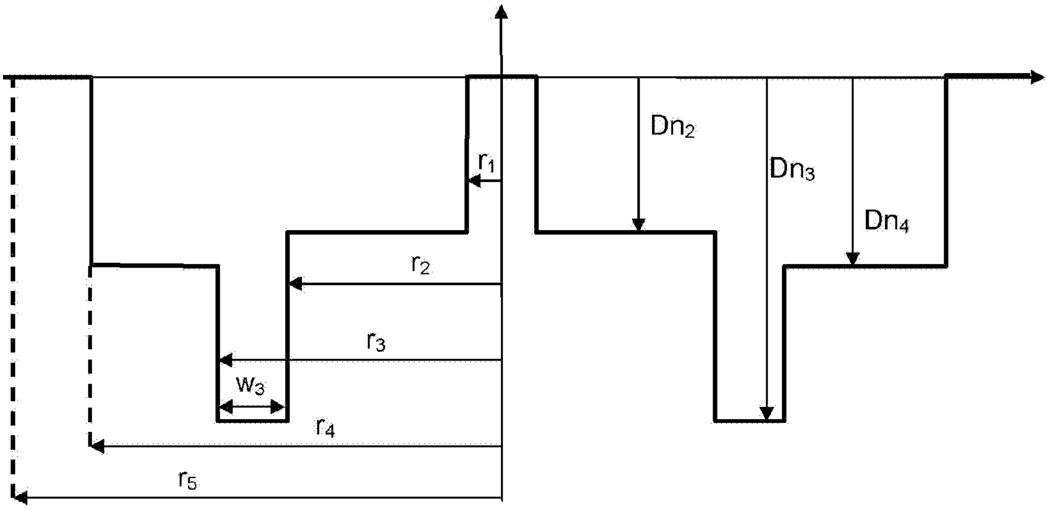

Figure 2