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(54) **Large effective area waveguide fiber**

Lichtleitfaser mit grosser effektiver Fläche

Fibre optique ayant une grande surface effective

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Description

[0001] The invention relates to a single mode optical waveguide fiber having a large effective area, A_{eff} , for light transmission. The large effective area reduces non-linear optical effects, including self phase modulation, four wave mixing, cross phase modulation, and non-linear scattering processes, which can cause degradation of signals in high power systems. In general, a mathematical description of these non-linear effects includes the ratio, P/A_{eff} , where P is optical power. For example, a non-linear optical effect usually follows an equation containing a term, $\exp [PxL_{\text{eff}}/A_{\text{eff}}]$, where L_{eff} is effective length. Thus, an increase in A_{eff} produces a decrease in the non-linear contribution to the degradation of a light signal.

[0002] The requirement in the telecommunication industry for greater information capacity over long distances, without regenerators, has led to a reevaluation of single mode fiber index profile design.

[0003] The focus of this reevaluation has been to provide optical waveguides which:

- reduce non-linear effects such as those noted above;
- are optimized for the lower attenuation operating wavelength range around 1550 nm;
- are compatible with optical amplifiers; and,
- retain the desirable properties of optical waveguides such as high strength, fatigue resistance, and bend resistance.

[0004] A waveguide fiber, having at least two distinct refractive index segments was found to have sufficient flexibility to meet and exceed the criteria for a high performance waveguide fiber system. The genera of segmented core designs are disclosed in detail in U. S. patent 4,715,679, Bhagavatula. Species of the profiles disclosed in the '679 patent, having properties especially suited for particular high performance telecommunication systems, are disclosed in applications S.N. 08/323,795 and S.N. 08/287,262.

[0005] The present invention is yet another core index profile species which reduces non-linear effects and which is particularly suited to transmission of high power signals over long distances without regeneration. The definition of high power and long distance is meaningful only in the context of a particular telecommunication system wherein a bit rate, a bit error rate, a multiplexing scheme, and perhaps optical amplifiers are specified. There are additional factors, known to those skilled in the art, which have impact upon the meaning of high power and long distance. However, for most purposes, high power is an optical power greater than about 10 mw. For example, a long distance is one in which the distance between electronic regenerators can be in excess of 100 km.

[0006] Considering the Kerr non-linearities, i.e., self

phase modulation, cross phase modulation and four wave mixing, the benefit of large A_{eff} can be shown from the equation for refractive index. The refractive index of silica based optical waveguide fiber is known to be non-linear with respect to the light electric field. The refractive index may be written as,

$n = n_0 + n_2 P/A_{\text{eff}}$, where n_0 is the linear refractive index, n_2 is the non-linear index coefficient, P is light power transmitted along the waveguide and A_{eff} is the effective area of the waveguide fiber. Because n_2 is a constant of the material, increase in A_{eff} is essentially the only means for reducing the non-linear contribution to the refractive index, thereby reducing the impact of Kerr type non-linearities.

[0007] Thus there is a need for an optical waveguide fiber designed to have a large effective area. The window of operation of greatest interest at this time is that near 1550 nm.

Definitions- The effective area is

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

[0008] An effective diameter, D_{eff} , may be defined as,

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

- An alpha profile is

$n = n_0(1 - \Delta(r/a)^\alpha)$, where n_0 is the refractive index at the first point of the alpha index profile, Δ is defined below, r is radius, and a is the radius measured from the first to the last point of the alpha index profile, and r is chosen to be zero at the first point of the alpha index profile.

- The width of an index profile segment is the distance between two vertical lines drawn from the respective beginning and ending points of the index profile to the horizontal axis of the chart of refractive index vs. radius.

- The % index delta is $\% \Delta = [(n_1^2 - n_c^2)/2n_1^2] \times 100$, where n_1 is a core index and n_c is the clad index. Unless otherwise stated, n_1 is the maximum refractive index in the core region characterized by a % Δ .

- A tapered step index profile, is a step index profile which has been modified by dopant diffusion during the waveguide fiber manufacturing process. The dopant diffusion causes the substantially right angles at the top and bottom of the step to become rounded and the sides of the step to be tapered. The amount of diffusion depends upon several variables including the details of the process steps and upon the initial height and width of the step index profile.

[0009] The exact amount of taper is not a critical determinant of the waveguide fiber properties herein discussed. However, a general description of degree of ta-

per may be given.

- * A sharply tapered step is one in which the width at half the $\% \Delta$ is in the range of about 30 to 50 % of the base width and the width at 0.9 of the $\% \Delta$ is in the range of about 15 to 25 % of the base width.
- * A moderately tapered step is one in which the width at half the $\% \Delta$ is in the range of about 60 to 80 % of the base width and the width at 0.9 of the $\% \Delta$ is in the range of about 35 to 50 % of the base width.

[0010] The index profiles discussed herein, in general, are in the ranges of sharply or moderately tapered profiles. However, the invention is not limited to profile segments having a particular degree of taper.

Summary of the Invention

[0011] This invention meets the need for a waveguide fiber having an index profile tailored for high performance operation in the 1550 nm window while maintaining a relatively large effective transmission area. It is noteworthy that a large effective area is achieved while maintaining good bend resistance.

[0012] A first aspect of the invention is a single mode waveguide fiber having an operating range from about 1500 nm to 1600 nm. A waveguide designed for operation in this wavelength range may be called a dispersion shifted waveguide. That is, the zero of total dispersion lies in range of about 1500 nm to 1600 nm.

[0013] The waveguide has a core glass region comprising at least two segments surrounded by a clad glass layer of refractive index n_c . The index profiles of the segments comprising the core region are tailored to provide an effective area of at least 70 microns².

[0014] An embodiment of the invention has a core region comprising two segments. The central segment is an alpha profile of maximum refractive index n_0 . Surrounding this central segment is a segment having a substantially constant refractive index n_1 and a width. This surrounding segment may also slope from a higher innermost $\% \text{ index } \Delta$, n_1' , to a lower outermost $\% \text{ index } \Delta$. The indexes are such that $n_0 > n_1$ or $n_1' > n_c$. The central segment may have a centerline index depression, due to dopant diffusion, approximating the shape of an inverted cone. Example 3 gives the allowed ranges of refractive index profile and profile shape.

Brief Description of the Drawings

[0015]

FIG. 1 is a modelled index profile showing a two segment core region.

FIG. 2 is a modelled index profile showing a two segment core region wherein the second segment has a negative slope.

Detailed Description of the Invention

[0016] The segmented core design has been shown to be sufficiently flexible to meet a wide range of waveguide fiber specifications as is shown in the patent and patent applications referenced above.

[0017] Changing the shape and location of the refractive index profiles of the segments of a core region, changes the mode power distribution of the propagating light and the waveguide dispersion. Combining a pre-selected waveguide dispersion with a material dispersion allows one to obtain a wide range of shapes and magnitudes for the total or chromatic dispersion of the waveguide. Thus, one can change the location of the total dispersion zero or alter the magnitude or slope of the total dispersion over a pre-selected wavelength range.

[0018] In addition, changing the mode power distribution produces changes in mode field diameter, bend resistance and effective area for light transmission.

[0019] In general, the mode power distribution and the shape of the waveguide dispersion, cannot be changed completely independently. The variables which define the segmented core structure must be adjusted to obtain the best trade off of properties for a given telecommunication system application. Of the essentially infinite number of possible segmented core designs, a design is sought which provides the desired values for:

- zero dispersion wavelength;
- cut off wavelength;
- magnitude and sign of total dispersion for a pre-selected wavelength range;
- slope of total dispersion over a pre-selected wavelength range;
- effective area; and,
- bend resistance.

[0020] It is assumed that other essential properties such as maximum attenuation over a pre-selected wavelength range, fatigue resistance and strength are not affected by the core region segmented profile.

[0021] The feature of particular importance in the inventive segmented core waveguide is the effective area of the waveguide. As noted above, increasing effective area for transmission of light, decreases the deleterious non-linear effects.

[0022] A segmented core design has been found, which increases the effective area by about 40 % relative to waveguides designed for use in the dispersion shifted window, 1500 nm to 1600 nm, and having analogous index profile shapes. In general, the increase in A_{eff} is greater than 40%.

[0023] A typically effective area for a dispersion shifted waveguide is about 50 microns². The inventive segmented profiles provide an effective area of at least 70 microns². As will be seen in the following embodiments, the effective area can be made much larger than 70

microns² while maintaining acceptable bend resistance.

[0024] The compromise which is made in the index profile design involves the size and position of the profile segments. A segment having a relatively high maximum refractive index and positioned away from the waveguide centerline will tend to broaden the light power distribution, thereby increasing the effective transmission area. However, as the light power distribution is broadened, the resistance of the waveguide fiber to bend loss decreases. The inventive waveguide fiber provides good bend resistance and larger A_{eff} .

Example - Two Segment Core

[0025] The two segment core illustrated in FIG. 1 has a central core segment 24, having an alpha profile with maximum refractive index n_0 .

[0026] Annular segment 26, adjacent said central segment, has a substantially constant index n_1 .

[0027] The relative magnitudes of the indexes are $n_0 > n_1 > n_c$.

[0028] The central core segment has a radius in the range of about 1.75 microns and a $\% \Delta$ in the range of about 0.8 to 0.9 %. The annular segment has a width in the range of about 7.5 to 9.5 microns and a $\% \Delta$ in the range of about 0.075 to 2 %. Analogous to example 2, the effective area of the inventive profile is 75 microns² as compared to about 55 microns² for dispersion shifted fiber, having this index profile type.

[0029] In this case the effective area is increased by reducing the alpha profile radius and by increasing the width of the adjacent annulus. The power distribution curve 30 is higher than that for standard dispersion shifted fiber, curve 28, over the radius range from about 2.5 to 8 microns.

[0030] This index profile can also be modelled including a centerline refractive index depression, having a minimum $\% \Delta$ in the range 0 to 0.4 %, and having a shape which is essentially an inverted cone having a base radius in the range of about 1 to 1.75 microns. Again effective area can be increased while maintaining the required waveguide fiber properties.

[0031] A further embodiment of this two segment design is shown in FIG. 2. In this case the $\% \Delta$ of the annular segment, 31, decreases from about 0.09 % at point 33, to about 0.05 % at point 35. The properties of the index profile of FIG. 2 are calculated to be:

- A_{eff} about 86 microns²;
- Cut off wavelength about 1600 nm;
- Zero dispersion wavelength about 1562 nm; and,
- Dispersion slope about 0.12 ps/nm²-km.

Claims

1. A single mode optical waveguide fiber which is dispersion shifted for use over a wavelength range of

1500 nm to 1600 nm and which reduces non-linear optical effects, comprising:

a core region including a central core segment having an alpha profile with maximum refractive index n_0 ; and,
an annular segment, adjacent said central segment, having a maximum index n_1 , wherein $n_0 > n_1 > n_c$;
a clad layer, having refractive index n_c , surrounding said core region;
said single mode waveguide fiber having a centerline which is the axis of symmetry along the length of said waveguide fiber and a total dispersion zero outside the limits from 1540 nm to 1557 nm;

characterized in that said refractive index profiles are configured to provide an effective area of 70 microns² or greater and a dispersion slope of 0.12 ps/nm²-km or less.

2. The single mode optical waveguide fiber of claim 1 wherein n_1 is substantially constant.

3. The single mode optical waveguide fiber of claim 2 wherein,

said central core segment has a radius in the range of 1.75 microns and a $\% \Delta$ in the range of 0.8 to 0.9 %; and,

said annular segment has a width in the range of 7.5 to 9.5 microns and a $\% \Delta$ in the range of about 0.075 to 0.2 %.

4. The single mode optical waveguide fiber of claim 3 further including a centerline refractive index depression having a minimum $\% \Delta$ in the range 0 to 0.4 % and having a shape which is essentially an inverted cone having a base radius in the range of 1 to 1.75 microns.

5. The single mode optical waveguide fiber of claim 1 wherein said core region includes:

a central core segment having an alpha profile with maximum refractive index n_0 ; and,
an annular segment, adjacent said central segment, having a refractive index which decreases linearly as waveguide radius increases.

6. The single mode optical waveguide fiber of claim 5 wherein, the maximum $\% \Delta$ of said central core segment is in the range 0.9 % to 1 % and has a radius range in the range of 1.75 microns to 2.0 microns, and,

said annular segment has an $\% \Delta$ which decreases substantially linearly from about 0.09 %, at a radius in the range of 1.75 to 2.0 microns, to

about 0.05 %, at a radius in the range of 11.75 to 12 microns.

7. The single mode optical waveguide fiber of any preceding claim, wherein the total dispersion zero is within the wavelength range of 1500 to 1600 nm.

Patentansprüche

1. Eine optische Singlemode-Wellenleiterfaser mit einer Dispersionsverschiebung zur Verwendung über einen Wellenlängenbereich von 1500 nm bis 1600 nm, welche nicht lineare optische Effekte reduziert, mit

einem Kernbereich, der ein mittiges Kernsegment aufweist mit einem Alpha-Profil mit einem maximalen Brechungsindex n_0 , und einem Ringsegment benachbart zu dem mittigen Segment und mit einem maximalen Brechungsindex n_1 , wobei $n_0 > n_1 > n_{ci}$ ist, einer Mantelschicht mit einem Brechungsindex n_c , welche den Kernbereich umgibt; wobei die Singlemode-Wellenleiterfaser eine Mittellinie aufweist, welche die Symmetrieachse entlang der Länge der Wellenleiterfaser darstellt und eine Gesamtdispersion von 0 außerhalb der Grenzen von 1540 nm bis 1557 nm, **dadurch gekennzeichnet, dass** die Brechungsindexprofile so konfiguriert sind, dass sie eine effektive Fläche von 70 Mikrons² oder größer und eine Dispersionsneigung von 0,12 ps/nm²-km oder weniger liefern.

2. Wellenleiterfaser nach Anspruch 1, bei dem n_1 im Wesentlichen konstant ist.

3. Wellenleiterfaser nach Anspruch 2, bei der das mittige Kernsegment einen Radius im Bereich von 1,75 Mikron und a % Δ in dem Bereich von 0,8 bis 0,9 & aufweist und bei der das Ringsegment eine Breite in dem Bereich von 7,5 bis 9,5 Mikron und a % Δ in dem Bereich von etwa 0,075 bis 0,2 % aufweist.

4. Wellenleiterfaser nach Anspruch 3, die eine Brechungsindexabsenkung entlang der Mittellinie mit einem Minimum % Δ im Bereich 0 bis 0,4 % aufweist und eine Form, die im Wesentlichen einen invertierten Konus darstellt mit einem Basisradius im Bereich von 1 bis 1,75 Mikron.

5. Wellenleiterfaser nach Anspruch 1, bei welcher der Kernabschnitt beinhaltet:

Ein mittiges Kernsegment mit einem Alpha-Profil mit einem maximalen Brechungsindex n_0 -Index, und ein Ringsegment, benachbart zum mittigen Segment, mit einem Brechungsindex, der im

Wesentlichen linear abnimmt mit einer Zunahme des Wellenleiterradius.

6. Wellenleiterfaser nach Anspruch 5, bei dem der maximale Prozentindex Δ des mittigen Kernsegments im Bereich 0,9 % bis 1 % liegt und einen Radiusbereich im Bereich von 1,75 Mikron bis 2,0 Mikron aufweist und wobei das Ringsegment einen Prozentindex Δ aufweist, welcher im Wesentlichen linear von etwa 0,09 % bei einem Radius im Bereich von 1,75 bis 2,0 Mikron, bis etwa 0,05 % bei einem Radius im Bereich von 11,75 bis 12 Mikron abnimmt.

7. Wellenleiterfaser nach einem der vorangehenden Ansprüche, bei dem die totale Dispersion 0 ist innerhalb des Wellenlängenbereichs von 1500 bis 1600 nm.

Revendications

1. Une fibre de guide d'ondes optique monomode qui est décalée en dispersion pour être utilisée sur un domaine de longueurs d'onde de 1500 nm à 1600 nm et qui réduit les effets optiques non linéaires, comprenant :

une région de coeur comprenant un segment de coeur central présentant un profil en alpha avec un indice de réfraction maximum n_0 ; et un segment annulaire, adjacent audit segment central, ayant un indice maximum n_1 , avec $n_0 > n_1 > n_{ci}$;

une couche de gainage, ayant un indice de réfraction n_c , entourant ladite région de coeur ; ladite fibre de guide d'ondes monomode ayant une ligne centrale qui est l'axe de symétrie longitudinal de ladite fibre de guide d'ondes et présentant un zéro de dispersion totale extérieur aux limites de 1540 nm à 1557 nm ;

caractérisée en ce que lesdits profils d'indice de réfraction sont configurés pour fournir une section efficace de 70 microns² ou plus et une pente de dispersion de 0,12 ps/nm² ou moins.

2. La fibre de guide d'ondes optique monomode de la revendication 1 dans laquelle n_1 est sensiblement constant.

3. La fibre de guide d'ondes optique monomode de la revendication 2 dans laquelle

ledit segment de coeur central a un rayon se situant dans le domaine de 1,75 micron et un pourcentage d'écart d'indice % Δ dans l'intervalle de 0,8 à 0,9 % ; et

ledit segment annulaire présente une largeur se situant dans l'intervalle de 7,5 à 9,5 microns et

un pourcentage d'écart d'indice $\% \Delta$ se situant dans l'intervalle d'environ 0,075 à 0,2 %.

4. La fibre de guide d'ondes optique monomode de la revendication 3 comportant en outre un creux d'indice de réfraction de ligne centrale présentant un pourcentage d'écart d'indice minimum se situant dans l'intervalle de 0 à 0,4 % et ayant sensiblement la forme d'un cône renversé ayant un rayon de base se situant dans l'intervalle de 1 à 1,75 microns. 5
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5. La fibre de guide d'ondes optique monomode de la revendication 1 dans laquelle ladite région de coeur comporte : 15
un segment de coeur central ayant un profil en alpha d'indice de réfraction maximum n_0 ; et
un segment annulaire, adjacent audit segment central, ayant un indice de réfraction qui diminue linéairement lorsque le rayon du guide d'ondes augmente. 20
6. La fibre de guide d'ondes optique monomode de la revendication 5 dans laquelle le pourcentage d'écart d'indice maximum dudit segment de coeur central se situe dans l'intervalle de 0,9% à 1 % et a un domaine de rayons se situant dans l'intervalle de 1,75 micron à 2,0 microns; et ledit segment annulaire a un pourcentage d'écart d'indice qui diminue de façon sensiblement linéaire d'environ 0,09%, pour un rayon se situant dans l'intervalle de 1,75 à 2,0 microns, à environ 0,05%, pour un rayon se situant dans l'intervalle de 11,75 à 12 microns. 25
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7. La fibre de guide d'ondes optique monomode de l'une quelconque des revendications précédentes dans laquelle le zéro de dispersion totale est compris dans le domaine de longueurs d'onde de 1500 à 1600 nm. 35
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FIG. 1

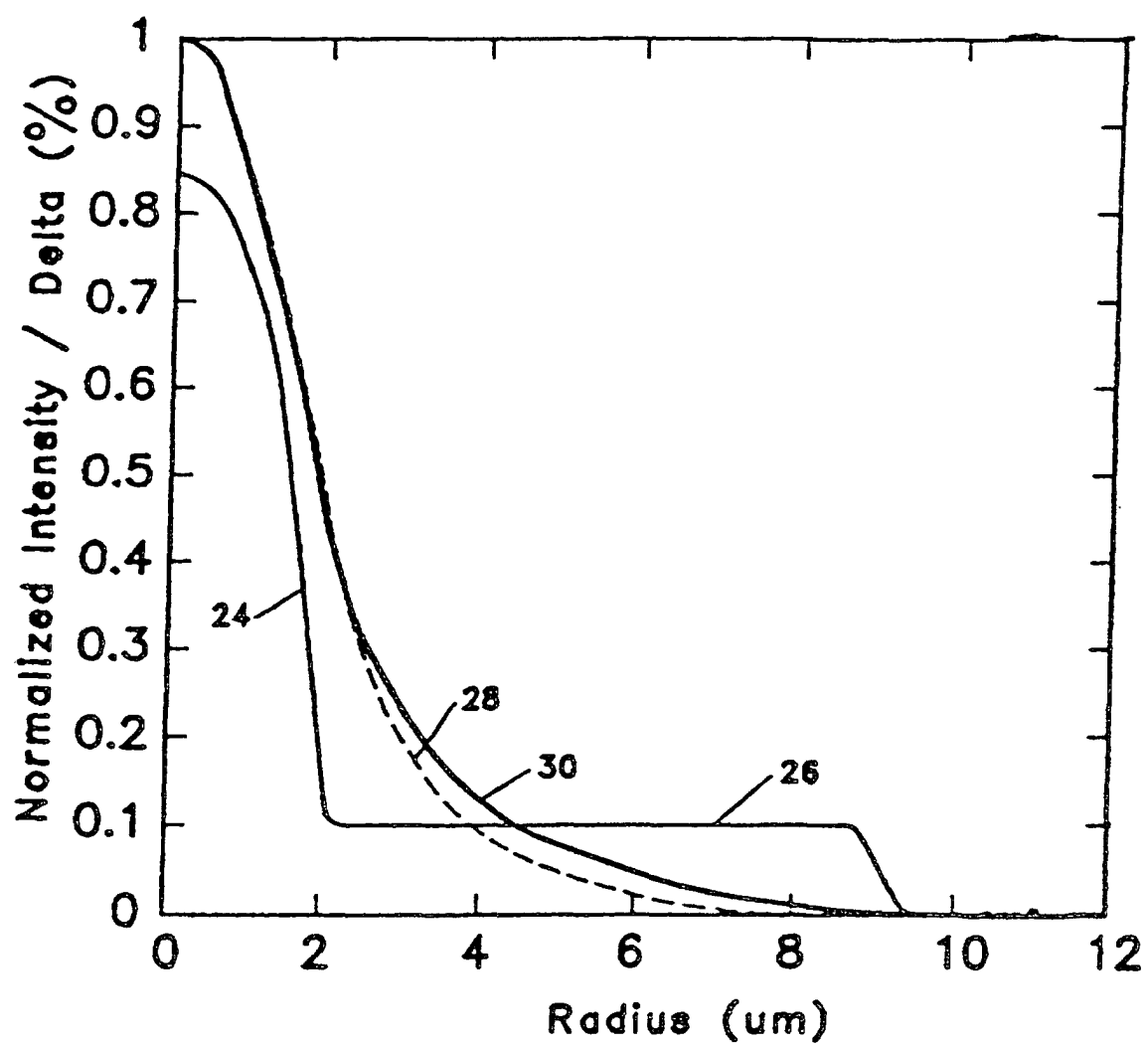


FIG. 2

