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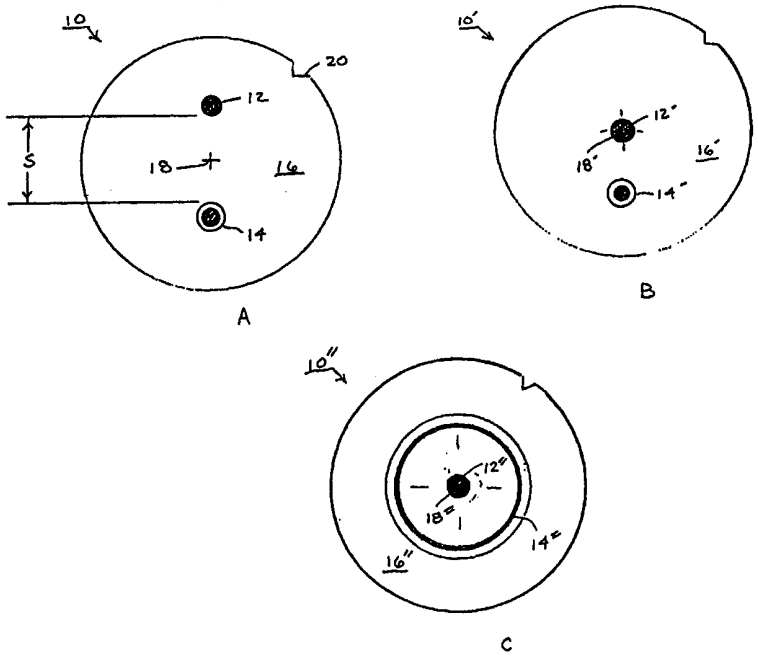
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(57) Abstract

Optical pathways along optical fibers, including multiple cores or multiple modes, are arranged with positive and negative dispersion characteristics. Coupling or connecting mechanisms regulate relative lengths of travel between the pathways having different dispersion characteristics so the total dispersion of the combined pathways approaches zero dispersion over a range of signal wavelengths intended for transmission.

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MULTICORE AND MULTIMODE DISPERSION MANAGED FIBERS

Technical Field

This application is based upon the provisional application S.N. 60/100,495, filed 9/16/98, which we claim as the priority date of this application.

Optical signals traveling in standard fiber optic media undergo small changes, which over distance can result in a significant loss of signal quality. One such change involves chromatic dispersion. Dispersion managed fiber possesses positive and negative dispersion characteristics, which are mixed to produce a length-weighted average close to zero dispersion.

Background

Chromatic dispersion varies along waveguides as a function of waveguide material and structure, as well as of signal wavelength. Zero dispersion is possible at particular wavelengths, but zero dispersion is also associated with a phenomena known as "four-wave mixing" that produces crosstalk in adjacent wavelength channels. Four-wave mixing is most pronounced at zero dispersion but also increases with optical power and reduced channel spacing.

Both chromatic dispersion and four-wave mixing are avoided by dispersion managed fiber that combines lengths of positive and negative

dispersion fiber (rated at the wavelengths intended for transmission). Four-wave mixing is avoided because only non-zero dispersion fiber is used. Chromatic dispersion is avoided because a length-weighted average of the positive and negative dispersions is close to zero.

One such approach employs positive dispersion fiber to transmit optical signals over distances and dispersion compensating modules containing rolls of negative dispersion fiber to periodically interrupt the positive dispersion fiber for reducing the average dispersion of the combined optical pathway. However, the compensating modules reduce signal power without advancing the signals toward their intended destination.

Lengths of positive and negative dispersion fiber have been spliced together end to end to more efficiently transmit optical signals with reduced chromatic dispersion. However, mapping is required to keep track of the dispersion characteristics of the combined fiber, and two different fibers must be kept in inventory.

Dispersion managed fibers have also been made in continuous lengths with alternating sections having opposite dispersion signs at the wavelengths intended for transmission. Only one fiber must be inventoried, but the dispersion period (i.e., the length over which the two sections are repeated) must be chosen at the time of manufacture and is not subject to later change. Contamination can also enter the fiber at interfaces between the sections, which must be separately polished and assembled before being drawn into final form.

Dispersion managed cables contain one or more pairs of fibers having opposite dispersion signs. Sections of the cables are spliced together so that the positive dispersion fibers of one section are joined to the negative dispersion fibers of the adjacent section. Again, dispersion mapping is needed to keep track of the section lengths, and the design of the individual fibers is limited because the opposite sign dispersions must be of equal magnitude at the transmitted wavelengths.

Summary of Invention

My invention includes various embodiments of fiber optic systems that compensate for chromatic dispersion and avoid four-wave mixing, while minimizing fiber inventories and providing more flexibility in the design and performance of the fibers. Also possible are shorter dispersion periods (i.e., lengths over which the dispersion changes are repeated) without complicating manufacture and additional dispersion options after manufacture.

One embodiment is a dispersion-compensated fiber optic system that includes a single optical fiber having a plurality of continuous optical pathways with different dispersion characteristics for conveying optical signals. One of the optical pathways exhibits a positive dispersion at a central wavelength of the optical signals, and another of the optical pathways exhibits negative dispersion at the central wavelength of the optical signals. A coupling mechanism shifts the optical signals between ongoing portions of the two pathways producing a length-weighted average dispersion approaching zero at the central wavelength of the optical signals. Preferably, both dispersion and dispersion slope are matched (e.g., equal but opposite in sign) at the central wavelength so that the average dispersion throughout a range of wavelengths also remains near zero dispersion.

The continuous optical pathways can extend parallel or concentric to each other; and beyond the presence of any intruding coupling structures, the shifting of optical signals between the pathways does not require interruption of either pathway. For example, a single fiber can be constructed with a plurality of cores surrounded by a cladding. Each of the cores forms one of the optical pathways with different dispersion characteristics.

The signals can be positively shifted between the cores by fashioning the coupling mechanism as one or more long period gratings. The coupling mechanism can also be fashioned as a consequence of core spacing by positioning the cores close enough together to support signal transfers. The latter mode of coupling requires symmetric dispersion characteristics between the cores and has a dispersion period equal to the coupling length between the

cores. The former coupling mode allows more flexibility in the dispersion characteristics of the cores by shifting the signals between the cores at unequal intervals. Regardless of the coupling mode, the dispersion slopes of the positive and negative dispersion cores are preferably matched (e.g., low magnitudes or opposite signs) so that the resulting average dispersion remains near zero throughout the intended range of signal wavelengths.

Another embodiment includes fiber segments having one or more pairs of cores having opposite sign dispersion characteristics. The segments are spliced together end to end with the positive dispersion core of one segment aligned with the negative dispersion core of the other segment. Segment lengths are chosen to achieve a length-weighted average close to zero dispersion. Both cores of each pair can be used for transmitting signals in parallel by equating the absolute magnitudes of the positive and negative dispersions and by aligning both the positive and negative dispersion cores in one segment with their opposite counterparts in adjacent segments. Multiple pairs of positive and negative dispersion cores can be separately arranged to support the transmission of more than one bit rate or application. More flexibility in dispersion mapping is also possible by controlling angular indexing between adjacent sections for aligning various combinations of cores having differing dispersion characteristics.

The single fiber can also be constructed as a multimode fiber having a fundamental mode path and a higher-order mode path with different dispersion values for forming concentric optical pathways with different dispersion characteristics. The coupling mechanism of this further embodiment includes one or more mode couplers, which can also be fashioned as tapered couplings or long period gratings, for shifting optical signals between the fundamental and higher-order mode paths.

The fundamental mode can be arranged to exhibit positive dispersion, and the higher-order mode can be arranged to exhibit a higher magnitude of negative dispersion. Accordingly, the mode couplers of this arrangement are positioned for shifting the optical signals into the fundamental mode for longer intervals than the higher-order modes. However, with appropriate core profile

design and choice of normalized frequency, the dispersion and dispersion slopes of the fundamental and second-order modes can be made equal but opposite in sign. Also, better signal confinement is possible at normalized frequency values away from the mode cut-off values.

Various connectors can be used to pass signals transmitted in multicore or multimode fiber into a single-mode single-core fiber. For example, optical gratings can be used to shift an optical signal from one core to another that is aligned with the single-mode single-core fiber or from a higher mode to the fundamental mode for further transmission by the single-mode single-core fiber. Tapered couplings can also be used to urge signals into a single core or into a fundamental mode. In addition, separate single-mode single-core fibers can be attached to the different cores of a multicore fiber, and a switch can be used to further transmit signals from one of the attached fibers to a common single-mode single-core fiber.

The multimode fiber can be made with conventional processes having regard for the dispersion characteristics of the modes. The multicore fiber can be made by assembling two or more core canes within a preform prior to conventionally drawing the fiber. Various arrangements of tubes or rods can be used for aligning and spacing the core canes, and an overcladding of soot can be consolidated around the core structures to seal the structures within the preform.

Drawings

FIG. 1A is a greatly enlarged end view of a multicore optical fiber having two offset cores with different dispersion characteristics.

FIG. 1B is a similarly enlarged end view of another multicore optical fiber having one centered core and one offset core with different dispersion characteristics.

FIG. 1C is a similarly enlarged end view of another multicore optical fiber having two concentric cores with different dispersion characteristics.

FIG. 2 is a less enlarged side view showing two segmented lengths of the multicore fiber relatively rotated and spliced together.

FIGS. 3A and 3B contain refractive index profiles of the two cores of the multicore fiber with refractive index plotted as a function of core radius "r".

FIGS. 3C-3F contain alternative refractive index profiles that are particularly suitable for achieving negative dispersion.

FIG. 4 is another side view of the multicore fiber schematically modified to include a long period grating for optically coupling the two cores.

FIG. 5 is a greatly enlarged end view of a multicore fiber having four cores -- two with positive dispersion characteristics and two with negative dispersion characteristics.

FIG. 6 is a side view of a tapered coupling for connecting two cores of the multicore fiber of FIG. 1A to a conventional single-core fiber.

FIG. 7 is a side view of a coupling that shifts signals between the two cores of the multicore fiber and a connector that joins one of the two cores of the multicore fiber to the core of a conventional single-core fiber.

FIG. 8 is a side view of a multimode fiber having a succession of long period gratings for shifting signals between modes having different dispersion characteristics.

FIG. 9 is a graph of normalized propagation constant "b_n" plotted against the normalized frequency "V" of the multimode fiber exemplified by a step profile core design.

FIG. 10 is a graph of normalized waveguide dispersion "d_n" plotted against the normalized frequency "V" of the waveguide for the same step profile core design.

FIG. 11 is a greatly enlarged end view of a preform supporting two core canes within a bored-out rod.

FIG. 12 is a similarly sized end view of a preform supporting two core canes within a tube.

FIG. 13 is a similarly sized end view of view of two core canes tacked together by a specially shaped rod.

FIG. 14 is another similarly sized end view showing two core canes tacked together prior to fusing the preform around the two cores.

Detailed Description

A multicore optical fiber 10 shown in FIG. 1A has a positive dispersion core 12 and a negative dispersion core 14 surrounded by a common cladding 16. The opposite sign dispersions of the two cores 12 and 14 are referenced with respect to a central wavelength of a range of wavelengths (typically corresponding to the erbium amplifying window) intended for transmission by the fiber 10. For dispersion management over a wavelength range from 1530 nm to 1560 nm, the positive core can be designed similar to an SMF 1528 fiber, and the negative core can be designed similar to a 1585 LS or leaf product. Both fibers are available from Corning Incorporated, Corning, New York. For other wavelength ranges, different types of known core designs can be used, as will be described shortly.

The two cores 12 and 14 extend parallel to an optical axis 18 of the fiber 10 and are separated by a distance "S" that can be adjusted to either prevent or promote automatic coupling between the cores 12 and 14. As shown, the distance "S" is presumably large enough to prevent automatic coupling. During manufacture, core canes with core-clad ratios of 0.4 or more are generally spaced sufficiently apart to provide the required isolation. An optional notch 20 in a periphery of the fiber 10 provides a point of reference for angularly indexing segmented lengths of the fiber 10.

In FIG. 2, two segmented lengths 10A and 10B of the originally continuous fiber 10 are aligned axially and are relatively rotated around their aligned axes 18A and 18B before being spliced together, such as with splicers

designed for polarization-maintaining fibers. The amount of rotation is selected to align the positive dispersion core 12A of the fiber segment 10A with the negative dispersion core 14B of the fiber segment 10B. In addition, design symmetry can also permit the simultaneous alignment of the negative dispersion core 14A of the fiber segment 10A with the positive dispersion core 12B of the fiber segment 10B. The segments 10A and 10B can be adjusted in length so than an average dispersion along the combined length of the two segments 10A and 10B, as well as along any succeeding segment pairs, approaches zero dispersion.

If the two cores 12A, 14A and 12B, 14B in each segment 10A and 10B are used to convey different signals, then the positive and negative dispersions of the two cores should be equal in magnitude and the two segments 10A and 10B should be equal in length. However, if only one of the cores of each segment conveys signals (e.g., core 12A of segment 10A and core 14B of segment 10B), then the dispersions of the two cores can be optimized at different magnitudes and different length segments can be combined to achieve an average dispersion approaching zero. The dispersion slopes of the two cores are also preferably matched to maintain an average dispersion approaching zero throughout a range of wavelengths intended for transmission.

Instead of splicing segmented lengths of the fiber 10 to alternate the optical pathway between the positive and negative dispersion cores 12 and 14, passive or active coupling can be provided between ongoing lengths of the cores 12 and 14. Passive coupling can be accomplished by reducing the separation "S" between the cores so that power transfers occur between the cores at a desired dispersion period, which is equal to the coupling length. The positive and negative dispersions of the cores 12 and 14 should be symmetrical about the central wavelength (i.e., equal in magnitude), because the signals spend half of their time in each of the cores 12 and 14. Also, the propagation constants of the two cores 12 and 14 considered in isolation should be as close as possible to support more complete transfers of power. The coupling length is determined by the difference in the propagation

constants of the two lowest order super-modes of the composite waveguides and can be designed to be achromatic or chromatic.

FIGS. 3A and 3B illustrate index profiles of the positive and negative dispersion cores 12 and 14 modified to equate an effective index "n(eff)" between the two cores 12 and 14. The positive dispersion core 12 has a simple step profile (GeO_2-SiO_2 core with SiO_2 cladding) and an effective index "n(eff)" sized between core and cladding values. The negative dispersion core 14 has a "w-type" or segmented core (SEGCOR) profile design with some slight up-doping of the cladding to match the effective index "n(eff)" of the positive dispersion core 12. For example, the doped cladding can be composed of GeO_2-SiO_2 or TiO_2-SiO_2. (Note: The dashed line of FIG. 3B represents the index level of the surrounding silica cladding 16.)

Generally, more complex profile shapes are required to produce negative dispersion and a dispersion slope opposite to that of a core with positive dispersion. Four more examples are depicted in FIGS. 3C-3F, each capable of supporting negative dispersion without unduly compromising other optical properties such as effective area, mode field diameter, bending, and microbending. Arrows crossing the profile lines indicate design flexibilities for altering individual line segments of the profiles.

The profile of FIG. 3C can be used to achieve either positive or negative dispersions with positive or negative dispersion slopes. The design of FIG. 3D is particularly useful for achieving positive or negative dispersions with relatively large effective areas. The latter two designs, FIGS. 3E and 3F, can also be considered for dispersion control with low loss fabrication.

Active coupling between the cores 12 and 14 can be accomplished by forming one or more long period gratings 24 between the cores as shown in FIG. 4. The coupling function is localized, so the two cores 12 and 14 can be independently designed. For example, the core dispersion magnitudes and propagation constants between the cores 12 and 14 can vary. Spacing between gratings 24 can be adjusted to compensate for the different magnitudes of the core dispersions so the length-weighted average still

approaches zero dispersion. Tapering can be used in conjunction with the long period gratings 24 to augment the coupling function.

The long period gratings 24 can be formed from photosensitive core materials that are exposed to a pattern of actinic radiation for producing index perturbations in the fiber 10. The cladding area between the cores 12 and 14 can also be made photo-refractive to enhance the coupling function. The long period grating 24 can be written by a high-power excimer laser during a fiber draw operation. Dispersion periods can be quite small and numerous, because the coupling mechanisms do not add contamination to the fiber 10.

Grating accuracy is not very critical, because the required spectral response band is quite wide and long period gratings typically have periods on the order of a few hundred microns. Also, the magnitudes of the index perturbations can be quite low (obviating the need for hydrogen loading), because the long period grating 24 can occupy a relatively large distance (e.g., one or two meters) along the fiber 10 without deleterious effects. The index perturbations can be written one spot at a time or several spots at once, especially at higher draw speeds. Index or curvature perturbations could also be written by a high-power CO_2 laser during the draw operation to accomplish a similar coupling function. Other perturbations can be used to form similar gratings including stress-induced variations by periodically squeezing the fiber or path length variations by periodic microbending.

Additional information on long period gratings and mode couplers can be found in a paper entitled "Long-Period Fiber Gratings as Band-Rejection Filters" by Vengsarkar et al., published in Journal of Lightwave Technology, Vol. 14, No. 1, January 1996, pages 58-65, and in another paper entitled "Helical-Grating Two-Mode Fiber Spatial-Mode Coupler" by Poole et al., also published in Journal of Lightwave Technology, Vol. 9, No. 5, May 1991, pages 598-604. Both papers are hereby incorporated by reference.

More than two cores can be formed in a single fiber, as shown in FIG. 5. Two positive dispersion cores 32 and 34 and two negative dispersion cores 36 and 38 of a fiber 30 are surrounded by a common cladding 40. The cores 32-

38 can be paired in groups of positive and negative dispersion cores (e.g., 32, 36 and 34, 38), and the paired cores can be optimized for individual bit rates or applications. Alternatively, the pairings can be varied to provide more flexibility for dispersion mapping by varying angular indexing between adjacent sections of the fiber 30. In other words, the same fiber 30 can be used to support a plurality of different dispersion maps. A dummy core 44 provides a point of reference for angularly indexing the fiber 30 around an optical axis 46.

Similar to the cores 12 and 14 of the fiber 10, the cores 32, 34, 36, and 38 of the fiber 30 are offset from the optical axis 46, which can cause polarization mode dispersion problems. Periodic twisting or continuous rotation of the fibers 10 or 30 can be used to reduce this problem. The cores 12 and 14 of the fiber 10 or the cores 32, 34, 36, and 38 of the fiber 30 can be surrounded by individual cladding zones for optimizing the performance of the separate optical pathways through the fibers 10 and 30.

When connected to conventional single-mode fiber or similar waveguide structures such as at in-line amplifier stations or at link ends, the two cores of each pairing are related to a single core of the conventional waveguide. FIG. 6 depicts a tapered coupling 60 connecting the dispersion managed fiber 10 to a conventional single-mode fiber 70. Two waveguides 62 and 64 are aligned with the positive and negative dispersion cores 12 and 14 of the fiber 10, but only the waveguide 64 is aligned with a single core 66 of the conventional fiber 70. Within the coupling, the two waveguides 62 and 64 are tapered together to transfer power to the waveguide 64.

The long period grating 24 can also be used in place of the tapered coupling 60 as shown in FIG. 7 to direct optical signals into the appropriate core (e.g., core 12) prior to interfacing with the conventional fiber 70. The core 66 of the conventional fiber 70 is aligned with the core 14 of the dispersion managed fiber 10 for receiving optical signals propagating along the dispersion managed fiber 10. A V-groove substrate 72 supports the desired alignment between the fibers 10 and 70.

The conventional fiber 70 can be aligned with either of the cores 12 or 14 of the dispersion managed fiber 10, or each of the cores 12 and 14 can be aligned with a separate conventional fiber. In the latter case, an optical switch (not shown) can be used to alternately connect the separate conventional fibers to a single conventional fiber. The switch can be controlled by a sensor that detects the presence or absence of a signal in either of the separate conventional fibers.

FIG. 1B depicts an alternative fiber 10' having two similar cores 12' and 14' embedded within a common cladding 16'. In contrast to the core 12 of the fiber 10 (shown in FIG. 1A), the core 12' is centered along an optical axis 18' of the alternative fiber 10'. The other core 14' is offset from the axis 18'.

The centered core 12' is easier to align with the cores of standard fiber. However, end-to-end splicing of sections of the alternate fiber 10' for shifting the signals between the centered core 12' and the offset core 14' is more difficult. Accordingly, signal transfers between the cores 12' and 14' preferably take place by lateral coupling. Prior to any end-to-end connections, the signals are preferably shifted into the central core 12' such as by tapering the fiber 10' or by using a tapered coupling as shown in FIG. 6.

Instead of centering just one of the cores 12' about the optical axis 18', FIG. 1C shows another alternative fiber 10" having two cores 12" and 14" centered about an optical axis 18" in a concentric pattern. Lateral couplers can be used to shift signals between the concentric cores 12" and 14". The fiber 10" with concentric cores 12" and 14" exhibits less birefringence and is easier to manufacture using conventional fabrication techniques. Additional concentric cores or concentric cores in combination with offset cores can also be used.

Another approach to the management of dispersion in optical fibers is depicted in FIG. 8. A multimode optical fiber 80 is shown having a central core 82 and a surrounding cladding 84 designed for supporting more than one mode of optical transmission. One mode, such as a fundamental mode, exhibits positive dispersion; and another mode, such as a second-order mode,

exhibits negative dispersion. Long period gratings 86 are written into the fiber 80 along an optical axis 88 in a repeating pattern that regulates the relative duration of optical signals in each of the modes so that the length-weighted average dispersion approaches zero.

Consistent with the depiction of FIG. 8, a negative dispersion of the second-order mode has a greater magnitude than a positive dispersion of the fundamental mode. Accordingly, a spacing L_F measuring the length of travel between gratings 86 in the fundamental mode is greater than a spacing L_H measuring the length of travel between gratings 86 in the second-order mode. Other combinations are possible, including opposite sign dispersions of equal magnitude between two operating modes. Equally spaced gratings can be used to evenly distribute optical travel lengths between the two different modes. Also, modes above second order can be used for such purposes as reducing polarization mode dispersion. The gratings can shift the signals to and from the third and higher-order modes, but unintended losses to intervening modes can limit the usefulness of the higher-order modes.

FIGS. 8 and 9 graph exemplary performance of the multimode fiber 80 considered with a step-index profile core. In FIG. 8, a normalized propagation constant "b_n" is plotted against normalized frequency "V", which can be mathematically defined as follows:

$$b_n = \frac{\beta/k - n_2}{n_1 - n_2} \qquad V = \frac{2\pi a}{\lambda} \sqrt{n_1^2 - n_2^2}$$

where "β" is the propagation constant, "n_1" is the core index, "n_2" is the cladding index, "λ" is the central wavelength of a range, and "k" is the constant $2\pi/\lambda$, and "a" is the waveguide core radius. The normalized propagation constant, which is related to "n(eff)", varies between "0" and "1" with "0" representing propagation entirely in the cladding and "1" representing propagation entirely in the core. Propagations that take place more in the core are more tightly bound than propagations that take place more in the cladding. The normalized frequency value "V" has an inverse relationship with the central wavelength "λ".

The curves LP_{01}, LP_{11}, and LP_{02} represent the fundamental, second, and third order modes, respectively. According to the exemplary graph of FIG. 9, a normalized frequency greater than 2.4 is required to support more than one mode; but an even larger value in the vicinity of 3.5 is needed to appropriately confine the signal for most practical applications.

As shown in FIG. 10, the normalized frequency of approximately 3.5 also provides an operating region with opposite sign normalized waveguide dispersion "D_n", which is empirically defined as follows:

$$D_n = \frac{V\, d^2\, V\, b_n}{d\, V^2}$$

Although normalized frequencies less than 3.5 provide the possibility for much higher dispersion, the second-order mode signal confinement is reduced. Operating away from the cutoff of the second-order mode (i.e., significantly higher than V = 2.4) reduces bending and microbending losses and polarization splitting as well. Periodic or continuous twisting of the fiber 80 can also be used to reduce polarization mode dispersion.

The waveguide dispersion "D" measured in units of ps/km nm can be calculated as follows:

$$D = D_n \frac{-n_1\, \Delta}{c\, \lambda}$$

where "Δ" is a relative index difference. The waveguide dispersion "D" has a sign opposite to the normalized waveguide dispersion "D_n", so the waveguide dispersion of the fundamental mode "LP_{01}" is positive and the waveguide dispersion of the second-order mode "LP_{11}" is negative.

At normalized frequencies greater than 2.4, the waveguide dispersion "D" for the fundamental mode LP_{01} of step index fiber is quite low so any significant chromatic dispersion is mostly attributable to material dispersion. In the 1550 nm window, the chromatic dispersion of the fundamental mode for

step index fiber is limited to around 17-20 ps/km nm. However, more complex core profile designs including segmented core and ring profiles can be used to produce higher dispersion values. Core designs between the positive and negative dispersion cores are also selected to appropriately relate dispersion slope so that the average dispersion remains near zero throughout a range of signal wavelengths. For example, the dispersion slopes can be equal in magnitude but opposite in sign or low in absolute magnitude.

Multimode and multicore designs can also be combined within individual fibers to provide even further control over dispersion while optimizing other design criteria as well. For example, either or both of the cores 12 and 14 of the fiber 10 depicted in FIG. 1A or the other cores depicted in FIGS. 1B and 1C could be formed as multimode cores, and the dispersion requirements could be divided between the modes and the cores.

Conventional fabrication techniques can be used to produce the multimode fiber 80, and photo-refractive techniques similar to those described above for multicore fibers can be used for writing the gratings. Although long period gratings 86 are preferred for mode coupling, other patterns and forms of perturbations including variations in diameter can also be used to shift signals between the different modes.

The remaining drawing figures, FIGS. 11-14, illustrate various preforms (also referred to as "blanks") for manufacturing my earlier described multicore optical fibers using various rod-in-tube and OVD (optical vapor deposition) techniques developed for polarization retaining fibers.

A fiber preform 90 shown in FIG. 11 has a rod 92 that is drilled to receive two glass core canes 94 and 96. The rod 92 is made of a cladding material, and the two glass core canes 94 and 96 include core and cladding materials applied in sequence by optical vapor deposition in index profile distributions that produce different dispersion characteristics. A glass soot 98, which is also made of the cladding material, is applied to the outside of the rod and consolidated to complete the preform 90. A multicore fiber drawn from the

preform has at least two cores that extend parallel to one another and that exhibit different dispersion characteristics.

A fiber preform 100 shown in FIG. 11 has two glass core canes 102 and 104 and two filler rods 106 and 108 mounted within a tube 110, and a consolidatable soot 112 surrounds the tube 110. The two core canes 102 and 104 have core and cladding distributions that support different dispersion characteristics. The filler rods 106 and 108, the tube 110, and the soot 112 are all made of cladding materials that are fused together with the core canes 102 and 104 for completing the preform.

FIG. 12 depicts a preform 120 that includes a specially shaped rod 114 of cladding material supporting two core canes 116 and 118 with different dispersion characteristics. A consolidatable soot 122, which is also made of a cladding material, surrounds the rod 114 and two core canes 116 and 118. The two core canes 116 and 118 can be tacked to the rod 114 to support the two core canes in desired relative positions until the preform 120 is consolidated.

A preform 130, as shown in FIG. 13, includes two core canes 132 and 134 that are tacked together and surrounded by a consolidatable soot 136. The core canes 132 and 134 have different dispersion characteristics and index profiles that can either promote or prevent automatic coupling between the eventual cores drawn from the preform 130.

The soot overcladdings 98, 112, 122, and 136 contract during consolidation producing both axial and radial forces that seal components within the preforms 90, 100, 120, and 130. During the subsequent drawing process, photo-refractive techniques can be used to produce couplings between the cores and polarization mode reducing techniques can be used to compensate for cladding asymmetries surrounding the cores. Index marks can be formed in the periphery of the preforms, or filler rods made from materials distinguishable from the cladding can be mounted in observable positions to provide angular points of reference.

The paired core canes 94-96, 102-104, 116-118, and 132-134 within the four preforms have opposite sign dispersions with equal or unequal absolute magnitudes. Either periodic or continuous coupling can be used to achieve a length-weighted average dispersion approaching zero for equal magnitude dispersions. However, unequal magnitude dispersions require periodic couplings that force unequal lengths of travel in the different dispersion cores to achieve the same length-weighted average dispersion approaching zero.

I claim:

1. A multicore fiber for managing chromatic dispersion comprising:
a plurality of cores surrounded by a cladding;
said cores having a refractive index different from said cladding for conveying optical signals; and
said cores exhibiting a difference in dispersion values among said cores.

2. The fiber of claim 1 in which one of said cores exhibits a positive dispersion value and another of said cores exhibits a negative dispersion value.

3. The fiber of claim 2 in which said cores also exhibit positive and negative dispersion slopes.

4. The fiber of claim 2 in which the positive and negative dispersion values are symmetric about a central wavelength of the optical signals.

5. The fiber of claim 4 in which said cores are positioned close enough together to support coupling between the cores.

6. The fiber of claim 5 in which propagation constants between said cores are approximately equal.

7. The fiber of claim 1 in which one of said cores is a multimode core.

8. The fiber of claim 7 in which said multimode core includes a first mode that exhibits a positive dispersion and a second mode that exhibits a negative dispersion.

9. The fiber of claim 1 in which said cores are spaced sufficiently far apart to avoid coupling between said cores.

10. The fiber of claim 9 in which the fiber also includes portions that are tapered to promote transfer of the optical signals between said cores.

11. The fiber of claim 9 in which perturbations are formed in said cores to promote transfer of the optical signals between said cores.

12. The fiber of claim 11 in which said perturbations are also formed in a cladding region between said cores to facilitate coupling between said cores.

13. The fiber of claim 11 in which said perturbations are arranged to form a plurality of optical gratings for transferring optical power between said cores.

14. The fiber of claim 11 in which said perturbations are arranged to shift the optical signals between said cores in a pattern that produces a length-weighted average dispersion approaching zero at a central wavelength of the optical signals.

15. The fiber of claim 11 in which fiber tapering is used in conjunction with said perturbations to promote transfer of the optical signals between said cores.

16. The fiber of claim 1 in which said fiber is divided into two lengths that are relatively rotated with respect to each other and are spliced together in the relatively rotated positions for aligning a first pairing of said cores exhibiting different dispersion values.

17. The fiber of claim 16 in which said two lengths of fiber are relatively rotatable to another angular position for aligning a second pairing of said cores exhibiting different dispersion values.

18. The fiber of claim 17 in which said first pairing of cores is optimized for a first bit rate and said second pairing of cores optimized for a second bit rate.

19. The fiber of claim 1 further comprising a fiber interface for connecting one of said plurality of cores that is not centered within said cladding with a core of an appended fiber that is centered within a cladding.

20. The fiber of claim 1 in which said fiber is at least periodically twisted to avoid polarization mode dispersion.

21. The fiber of claim 1 further comprising a coupling mechanism that transfers the optical signals between ongoing portions of said cores providing a length-weighted average dispersion approaching zero at a central wavelength of the optical signals.

22. The fiber of claim 21 in which said cores exhibit dispersion slopes that are relatively matched so that the length-weighted average dispersion approaches zero for a range of wavelengths of the optical signals.

23. A multimode fiber for managing chromatic dispersion comprising:

a core surrounded by a cladding supporting multimodal transmissions of light along an optical axis;

a first mode path along said optical axis having a first dispersion value;

a second mode path along said optical axis having a second dispersion value;

said first and second dispersion values differing from one another; and

a plurality of mode couplers along the optical axis for coupling light back and forth between said first and second mode paths.

24. The fiber of claim 23 in which said first mode path is a fundamental mode path having a positive dispersion value.

25. The fiber of claim 24 in which said second mode path is a higher-order mode having a negative dispersion value.

26. The fiber of claim 23 in which said dispersion values between the first and second mode paths have opposite signs and unequal absolute magnitudes.

27. The fiber of claim 26 in which the coupling of light between said first and second mode paths takes place at unequal path lengths to compensate for the unequal absolute magnitudes of the dispersion values.

28. The fiber of claim 23 in which said dispersion values between the first and second mode paths have opposite signs and approximately equal magnitudes.

29. The fiber of claim 23 in which said mode couplers are formed by index perturbations.

30. The fiber of claim 29 in which said index perturbations form a long period grating.

31. The fiber of claim 23 in which said mode couplers are formed at least in part by tapering portions of the fiber.

32. The fiber of claim 23 in which said mode couplers are spaced to produce a length-weighted average dispersion approaching zero at a central wavelength of the transmissions of light.

33. The fiber of claim 32 in which said first and second mode paths exhibit dispersion slopes that are relatively matched so that the length-weighted average dispersion approaches zero for a range of wavelengths of the transmissions of light.

34. A dispersion compensated fiber optic system comprising:

a first multicore fiber section having a first core that exhibits a positive dispersion value and a second core that exhibits a negative dispersion value;

a second multicore fiber section having a first core that exhibits a positive dispersion value and a second core that exhibits a negative dispersion value; and

an optical interface between said first and second multicore fiber sections aligning said first core of the first fiber section with said second core of the second fiber section for controlling an average dispersion along a combined length of said fiber sections.

35. The optical system of claim 34 in which said first and second cores of each of the first and second fiber sections are sufficiently spaced apart to avoid undesirable coupling between said first and second cores.

36. The optical system of claim 34 in which said second core of the first fiber section is aligned with said first core of the second fiber section for controlling the average dispersion.

37. The optical system of claim 36 in which said second core of the first fiber section and said first core of the second fiber section exhibit dispersion slopes that are matched so that the average dispersion along a combined length of said fiber sections approaches zero for a range of wavelengths transmitted through the combined fiber sections.

38. The optical system of claim 34 in which said first and second multicore fiber sections also have third cores that exhibit positive dispersion values and a fourth core that exhibits negative dispersion values.

39. The optical system of claim 38 in which said first core of the first fiber section is aligned with said second core of the second fiber section for completing a first optical pathway between said fiber sections optimized for transmissions at a first bit rate and said third core of the first fiber section is alignable with said fourth core of the second fiber section for transmitting optical signals at a second bit rate.

40. The optical system of claim 38 in which said first and third cores of said first fiber section are separately alignable with said second core of the second fiber section for providing different dispersion compensations.

41. The optical system of claim 40 in which said first and third cores of said first fiber section are also separately alignable with said fourth core of the second fiber section for providing more choices for dispersion compensation.

42. The optical system of claim 34 in which index marks are applied to the fiber sections to assist desired angular indexing between the fiber sections at the optical interface.

43. The optical system of claim 34 in which splicers designed for polarization-maintaining fibers provide said optical interface.

44. The optical system of claim 34 in which said first and second fiber sections are substantially identical sections originating from the same fiber.

45. A dispersion compensated fiber optic system comprising:

a multimode fiber having a fundamental mode path and a higher-order mode path with different dispersion values;

a plurality of mode couplers along an optical axis of the fiber that shifts optical signals back and forth between said fundamental and higher-order mode paths;

an optical system component aligned with the optical axis of the fiber for further conveying the optical signals; and

one of said mode couplers being arranged for directing the optical signals into one of the mode paths at an interface with the system component.

46. The system of claim 45 in which said fundamental mode path has a positive dispersion value and said higher-order mode path has a negative dispersion value.

47. The system of claim 46 in which said negative dispersion value has a higher magnitude than said positive dispersion value.

48. The system of claim 47 in which said mode couplers shift the optical signals between said fundamental mode path and said higher-order mode path at unequal intervals between mode paths.

49. The system of claim 45 in which said one mode coupler directs the optical signals into said fundamental mode path in advance of said optical system component.

50. The system of claim 45 in which said optical system component is an optical amplifier and said one mode coupler directs the optical signals into said higher-order mode path following said optical amplifier.

51. The system of claim 45 in which said mode couplers include index perturbations along the optical axis for transferring optical signals between said mode paths.

52. A dispersion compensated fiber optic system comprising:

a single optical fiber having a plurality of continuous optical pathways with different dispersion characteristics for conveying optical signals;

a first of said optical pathways exhibiting positive dispersion at a central wavelength of the optical signals;

a second of said optical pathways exhibiting negative dispersion at the central wavelength of the optical signals; and

a coupling mechanism that shifts the optical signals between ongoing portions of said first and second pathways producing a length-weighted average dispersion approaching zero at the central wavelength of the optical signals.

53. The system of claim 52 in which said first and second optical pathways extend parallel to each other and said coupling mechanism shifts the optical signals between parallel portions of said first and second pathways.

54. The system of claim 53 in which said first and second optical pathways are formed by first and second cores surrounded by a cladding.

55. The system of claim 54 in which said single optical fiber has a central axis and said first core is aligned with said central axis and said second core is offset from said central axis.

56. The system of claim 54 in which said single optical fiber has a central axis and both said first and second cores are offset from said central axis.

57. The system of claim 54 in which said first core is a multimode core having a first mode that exhibits positive dispersion and a second mode that exhibits negative dispersion.

58. The system of claim 54 in which said coupling mechanism includes a plurality of couplers that positively shift the optical signals back and fourth between said first and second cores.

59. The system of claim 58 in which said first and second cores exhibit opposite sign dispersions of different magnitudes at the central wavelength of the optical signals and said couplers are arranged for shifting the signals between said first and second cores at unequal intervals.

60. The system of claim 54 in which said coupling mechanism is formed as a consequence of positioning said first and second cores close enough together to support transfers of the optical signals between said cores.

61. The system of claim 60 in which said first and second cores exhibit opposite sign dispersions of approximately equal magnitudes at the central wavelength of the optical signals.

62. The system of claim 52 in which said first and second optical pathways extend concentric to each other and said coupling mechanism shifts the optical signals between concentric portions of said first and second pathways.

63. The system of claim 62 in which said single fiber is a multimode fiber and said first and second optical pathways are a fundamental mode path and a higher-order mode path with different dispersion values.

64. The system of claim 63 in which said coupling mechanism includes a plurality of mode couplers that positively shift the optical signals back and fourth between said fundamental and higher-order mode paths.

65. The system of claim 63 in which said first and second cores exhibit opposite sign dispersions of approximately equal magnitudes at the central wavelength of the optical signals.

66. The system of claim 52 in which said coupling mechanism is formed by perturbations in said optical pathways.

67. The system of claim 66 in which said coupling mechanism includes a plurality of optical gratings.

68. The system of claim 52 including third and fourth optical pathways with different dispersion characteristics for conveying optical signals.

69. The system of claim 68 in which said coupling mechanism includes couplers for shifting the optical signals between said first and second pathways at a first dispersion period and couplers for shifting the optical signals between said third and fourth pathways at a second dispersion period.

70. The system of claim 52 in which said first optical pathway exhibits a positive dispersion slope and said second optical pathway exhibits a negative dispersion slope.

71. The system of claim 52 in which said first and second optical pathways exhibit dispersion slopes approaching zero.

72. A method of making a multicore fiber for transmitting optical signals with reduced chromatic dispersion comprising the steps of:

aligning at least two glass core canes having refractive index profiles that differ from one another;

surrounding the glass core canes with a glass cladding material;

fusing the surrounding cladding material to the core canes for forming a glass preform; and

drawing a multicore fiber from the preform having at least two cores that extend parallel to one another and that exhibit different dispersion characteristics.

73. The method of claim 72 in which a first of the cores exhibits positive dispersion and the second of the cores exhibits negative dispersion at a central wavelength of the optical signals.

74. The method of claim 72 in which said step of surrounding includes applying the cladding material as an optical soot.

75. The method of claim 72 in which said step of aligning includes aligning the two core canes with a glass rod having a refractive index similar to the surrounding cladding material.

76. The method of claim 75 in which the glass rod supports the two core canes.

77. The method of claim 72 including the further step of tacking the two core canes together prior to surrounding them with the glass cladding material.

78. The method of claim 72 including the further step of forming a coupling between the two cores.

79. The method of claim 72 including the further step of applying an index mark to provide an angular point of reference on the fiber.

80. A method of compensating for chromatic dispersion introduced into an optical signal propagating along an optical fiber comprising the steps of:

directing the signal along the fiber, which is arranged to have two parallel optical pathways with opposite sign dispersion characteristics at a central wavelength of the signal; and

coupling the signal back and forth between continuous portions of the two parallel pathways of the fiber so that the signal is exposed to an average dispersion approaching zero dispersion.

81. The method of claim 80 in which said step of coupling includes shifting the signal between different cores of a multicore fiber.

82. The method of claim 80 in which said step of coupling includes shifting the signal between different modes of a multimode fiber.

83. The method of claim 80 in which said step of coupling includes positively shifting the signal between the two parallel pathways at unequal intervals between the pathways.

84. The method of claim 80 in which said step of coupling includes arranging the parallel pathways to convey the signal for equal duration.

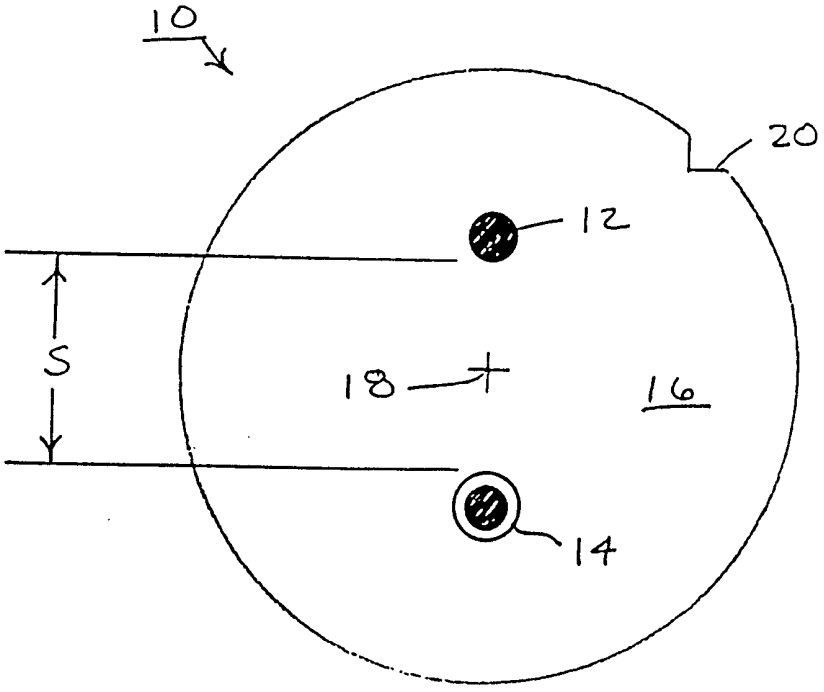


FIG. 1A

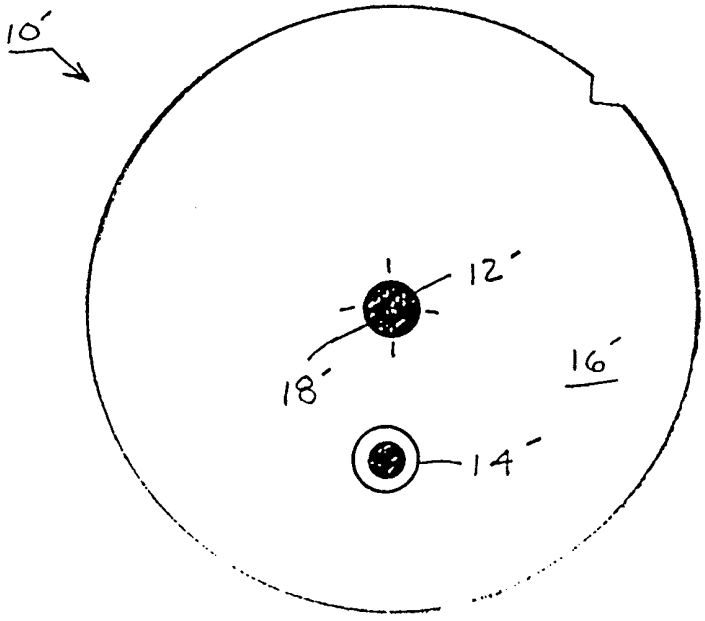


FIG. 1B

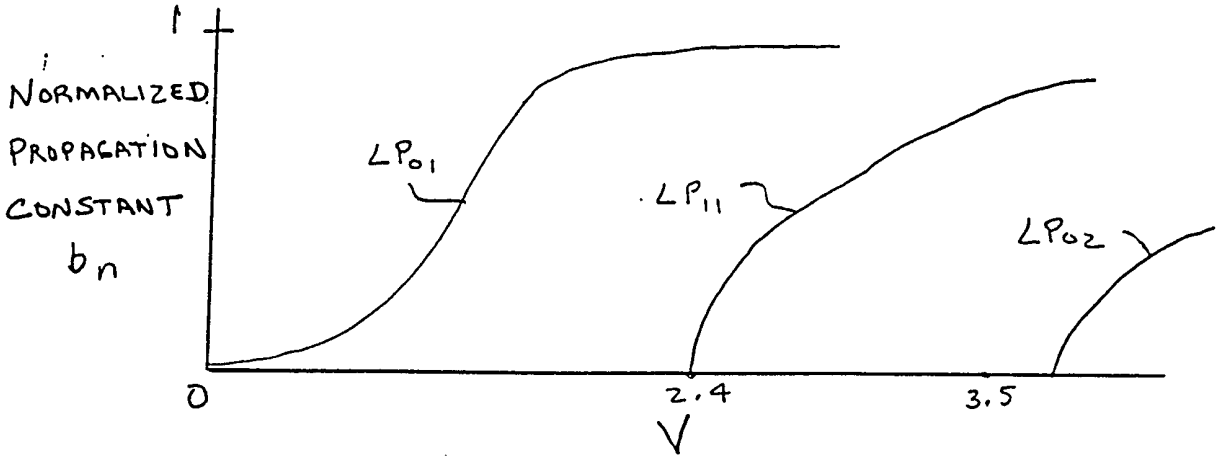

NORMALIZED
PROPAGATION
CONSTANT
b_n
LP_{01}
LP_{11}
LP_{02}
0
2.4
3.5
V

FIG. 9

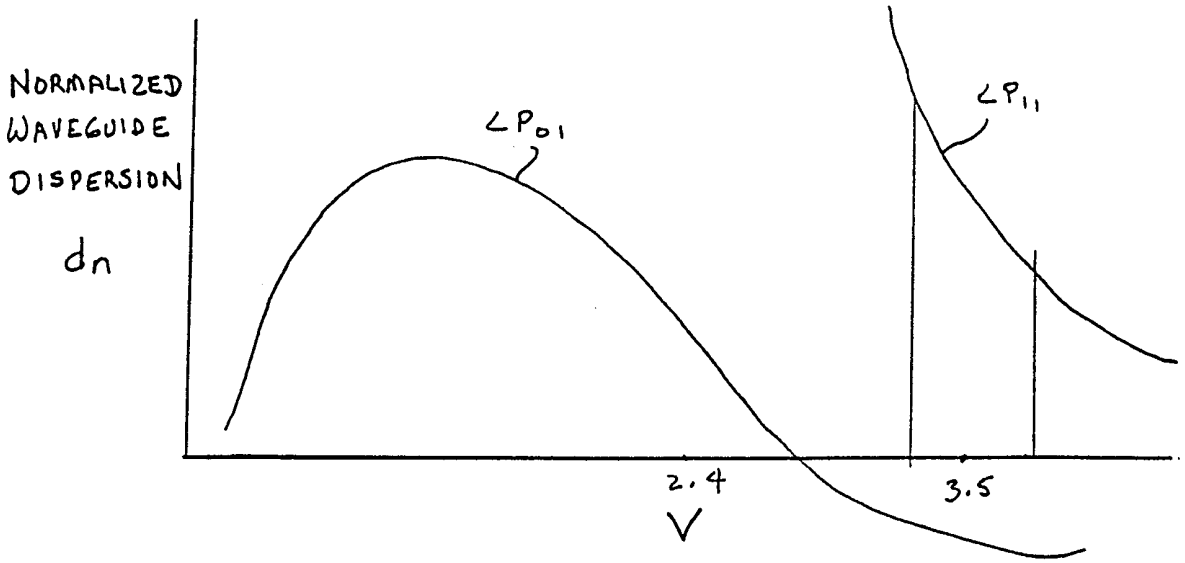

NORMALIZED
WAVEGUIDE
DISPERSION
d_n
LP_{01}
LP_{11}
2.4
3.5
V

FIG. 10

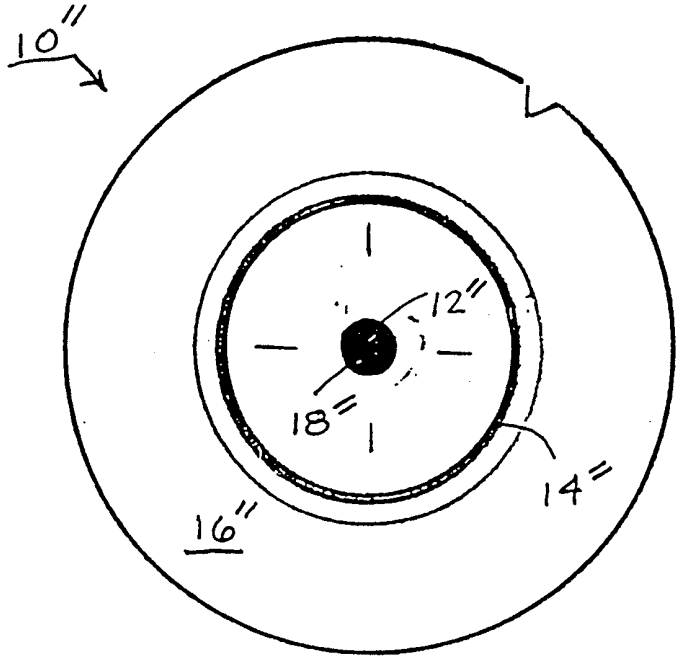


FIG. 1C

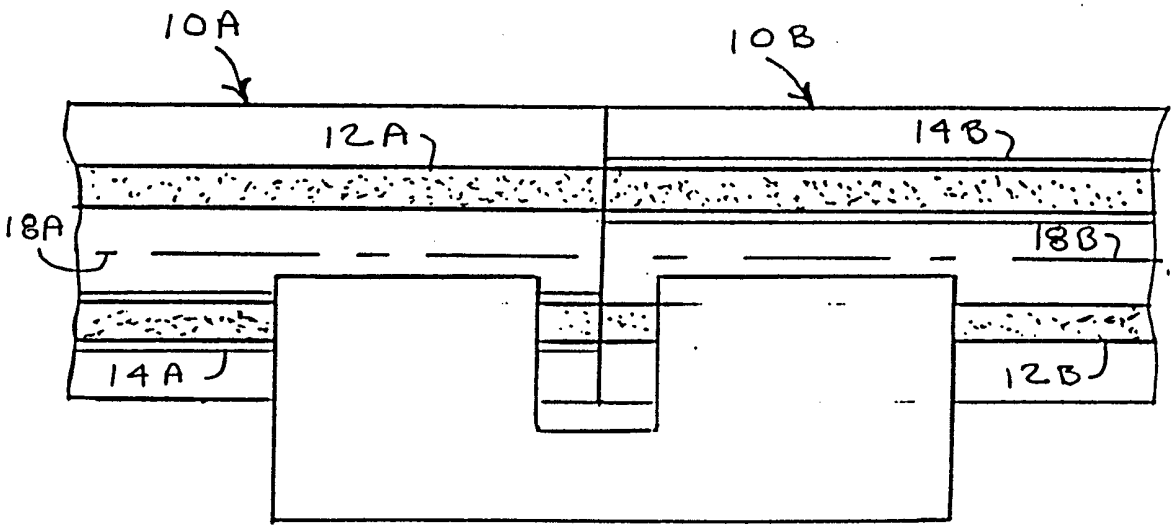


FIG. 2

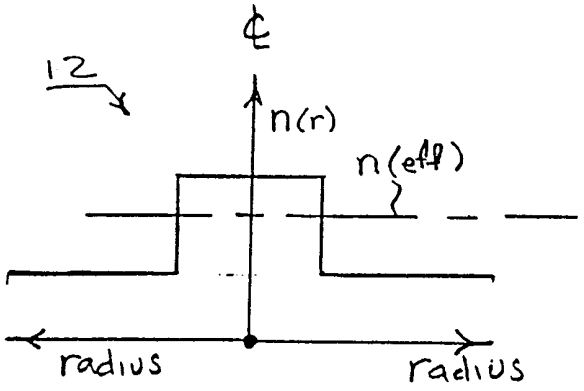


FIG. 3A

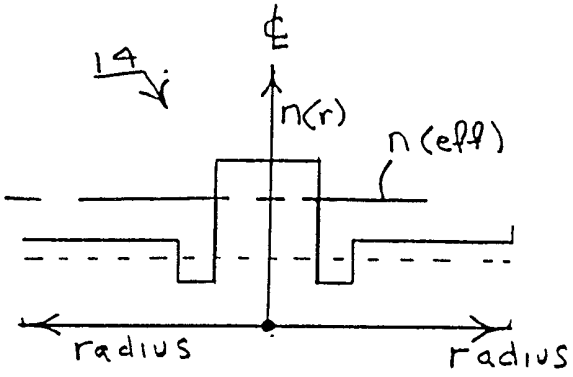


FIG. 3B

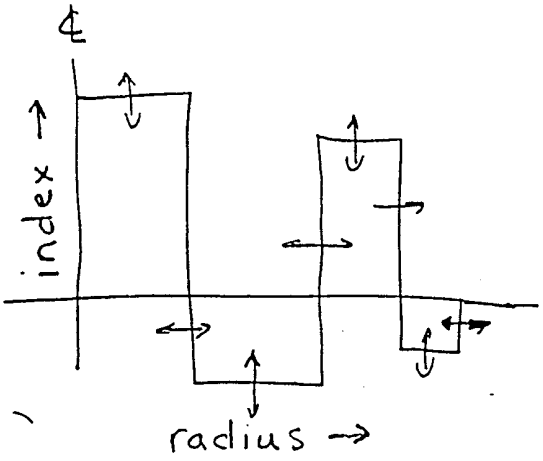


FIG. 3C

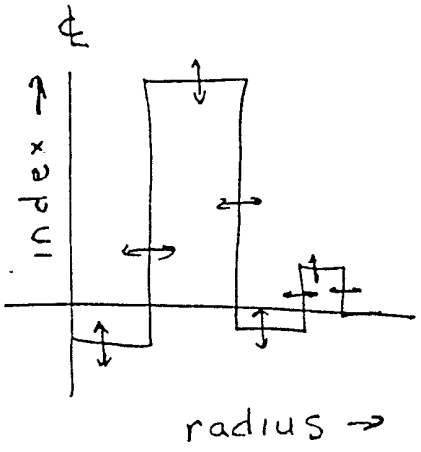


FIG. 3D

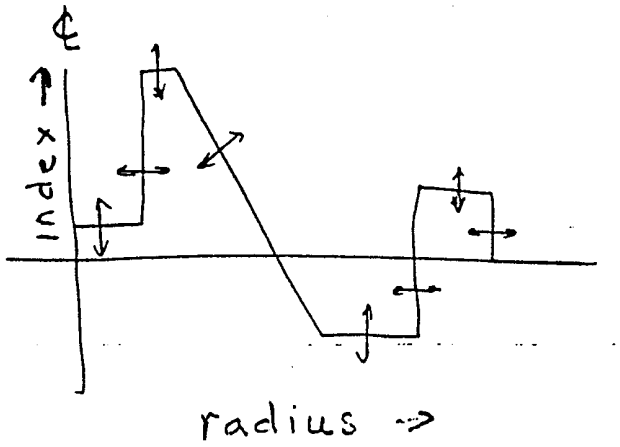


FIG. 3E

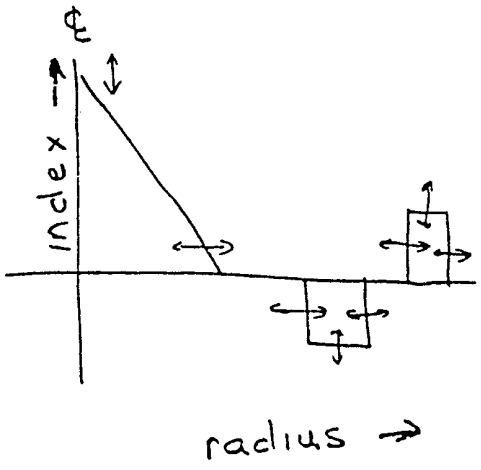


FIG. 3F

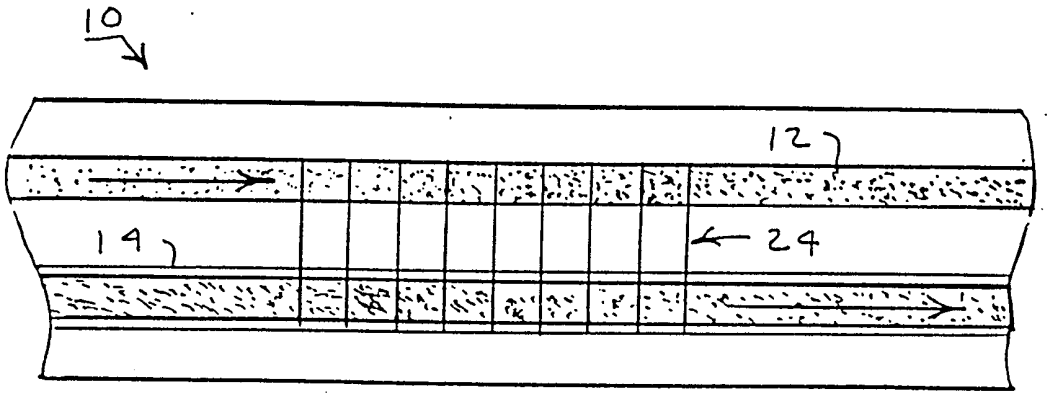


FIG. 4

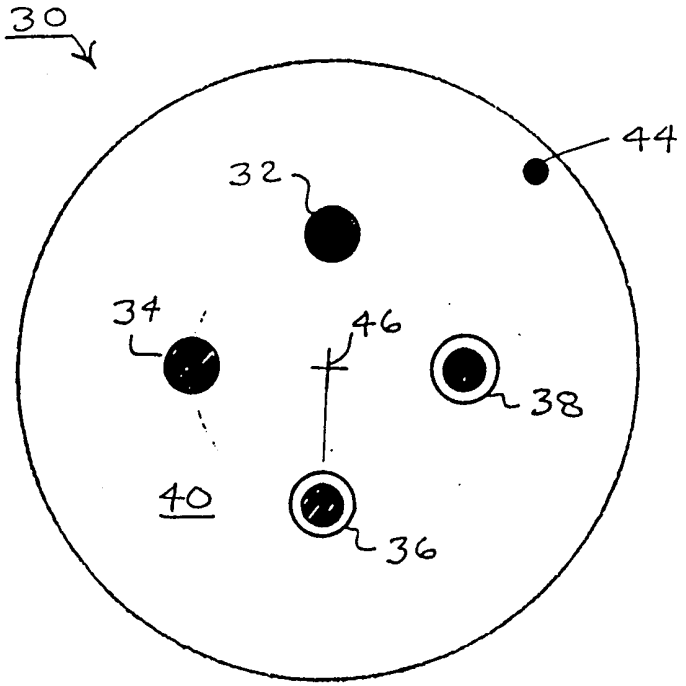


FIG. 5

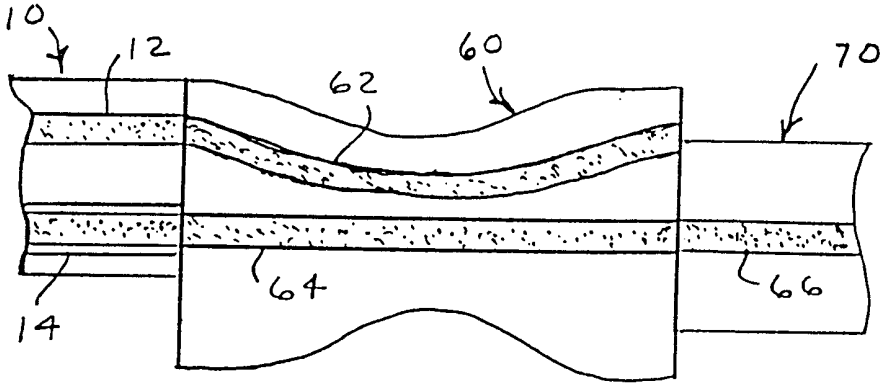


FIG. 6

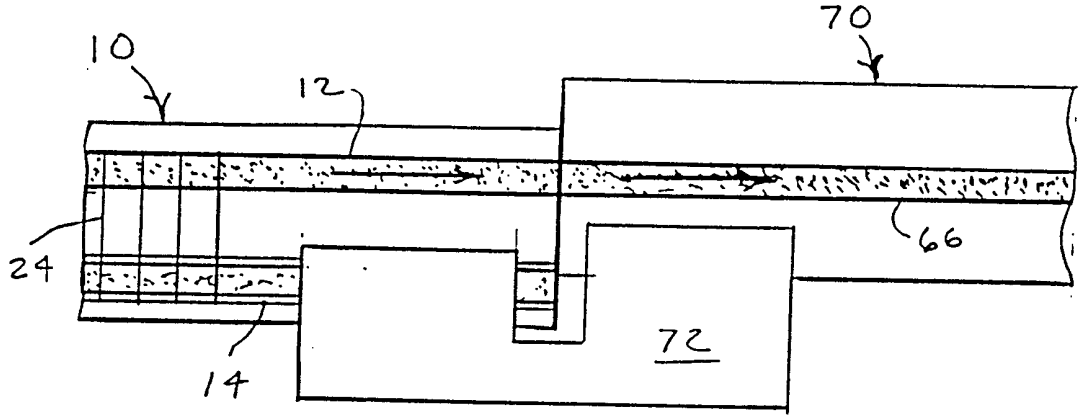


FIG. 7

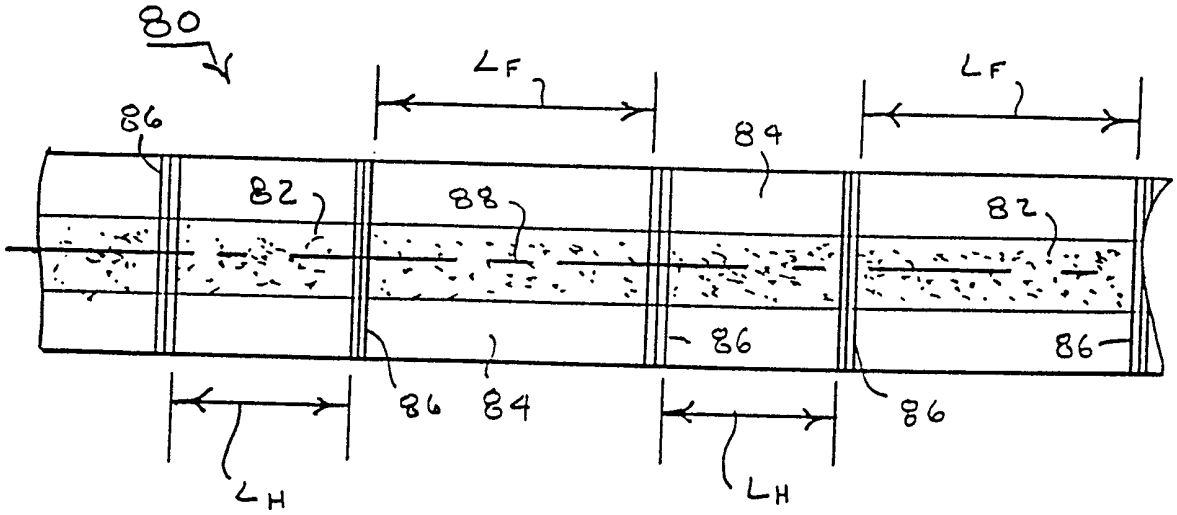


FIG. 8

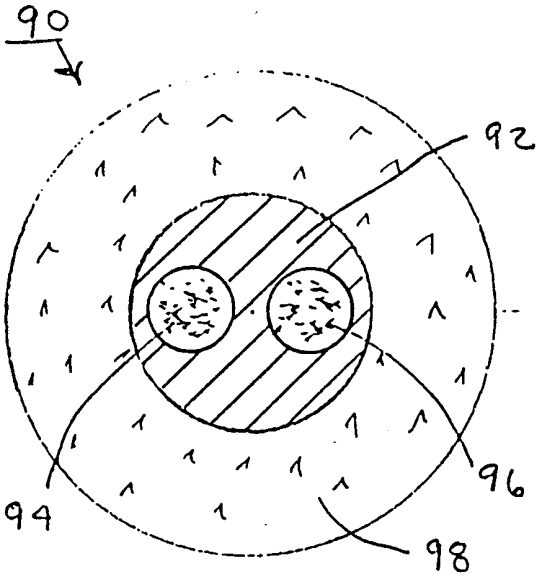


FIG. 11

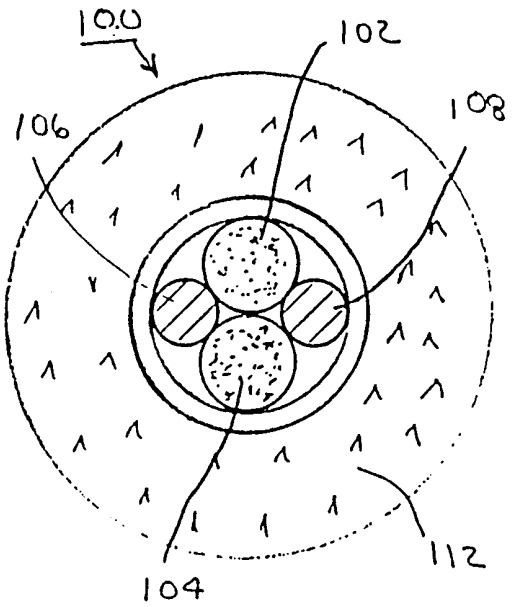


FIG. 12

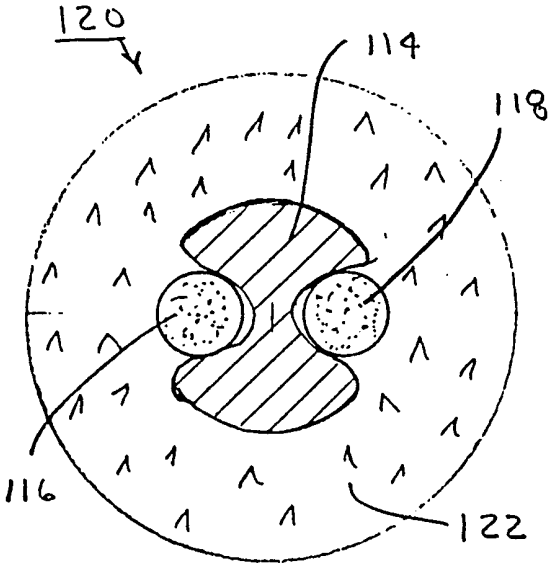


FIG. 13

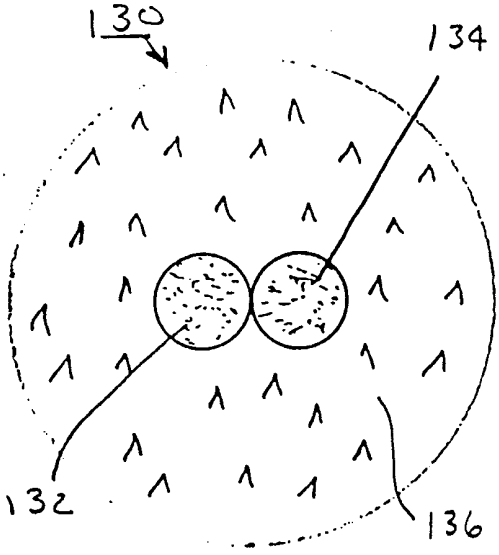


FIG. 14