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## (54) OPTICAL FIBERS

(71) We, WESTERN ELECTRIC COMPANY, INCORPORATED, of 222 Broadway and formerly of 195 Broadway, New York City, New York State, United States of America, a Corporation organized and existing under the laws of the State of New York, United States of America, do hereby declare the invention for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:–

This application relates to graded index optical fibers comprising an inner core region having a plurality of layers whose refractive indices decrease in a radial direction, surrounded by an outer cladding.

In order to transmit information in the form of light pulses along an optical fiber transmission line the transmitted pulses must be individually resolvable at the receiving end of the transmission line. However, in a multimode fiber a light ray can take different paths as it traverses the optical fiber. For example, a light ray associated with lower order modes will tend to proceed down the center of the fiber whereas a ray associated with a higher order mode will be reflected off the fiber walls numerous times as it traverses the fiber. Since the distance travelled by these different light rays is significantly different, each transmission mode has a different transmission time associated with it. As a result, in a multimode fiber there is a general broadening of the pulse and a consequent loss in pulse resolution.

A method for reducing dispersion in a step-index multimode fiber waveguide is disclosed in Patent No. 1 521 541 (D. Marcuse). As described therein, dispersion is reduced by the introduction of fluctuations in the refractive index along the axis of the fiber core, which fluctuations deliberately enhance coupling among the various modes in the fiber. Conditions are imposed upon the axial, azimuthal and radial dependence of the core fluctuations. The axial fluctuations take the form of slight perturbations in the refractive index and have a period of approximately 1 mm. A fiber having such small perturbations is both difficult and expensive to fabricate. The present invention provides an improved form of such waveguide.

Mode dispersion can also be minimized by radially grading the index of refraction of the fiber core from a maximum at the center of the fiber to a minimum at the core-cladding interface. It has been determined that an optimum refractive index profile is approximately parabolic in shape. Such an index profile can be approximated by a plurality of different thin cylindrical layers, each having a uniform refractive index. The refractive indices of these core layers radially decrease from a maximum at the center of the core in a manner to approximate the optimum smooth profile. As can be readily appreciated, as the number of core layers increases, the smooth continuous profile is more closely approximated and the dispersion of a transmitted light impulse decreases. However, in such fibers the theoretical improvement expected from a continuous radial gradation can only be approached, resulting in increased pulse broadening that is proportional to the length of the fiber.

A multilayered graded index optical fiber of the type described hereinabove is readily fabricated using a chemical vapor deposition process. In this process, a preform is formed by continuously rotating a silica tube which is traversed by a hot zone. A vapor source material such as the chlorides or hydrides of silicon together with germanium, aluminum, boron phosphorus, et cetera, and oxygen, flows through the tube and reacts in the hot zone to produce glassy "soot" within the vapor and glass on the inner surface of the tube. For each traversal of the hot zone a cylindrical layer of glass is fused into the tube. By varying the composition of the vapor source for each hot zone traversal, a radially graded structure is formed. When the tube is collapsed and a fiber drawn therefrom, the resulting fiber has the same refractive index radial distribution as the preform. However, as noted above, a large number of layers are necessary to approximate the impulse response of a smoothly graded optical fiber. Since each layer is fused separately onto the tube, the fabrication time of a preform from which a satisfactory optical fiber can be drawn is quite long and correspondingly expensive.

According to the present invention there is provided a graded index optical fiber comprising a core member and a cladding surrounding said core member, said core member including a plurality of layers the refractive indicies of which radially decrease from a maximum at the center of the fiber to a minimum at the outside of the core member, wherein the index of refraction of each of said layers has spatial fluctuations of relatively long wavelength along a direction parallel to the longitudinal axis of said fiber with the minimum refractive index of each layer being substantially equal to the maximum index of the radially next outer adjacent layer, and the maximum refractive index of each layer being substantially equal to the minimum index of the next inner adjacent layer.

The above-noted difficulty in the fabrication of multilayered optical fibers is obviated, in the preferred embodiment of the present invention, by providing a graded index fiber which can have significantly less layers than the above mentioned large number of layers, and by introducing longitudinal variations of relatively long wavelength in the index of refraction of each layer. The index of refraction of each layer varies between a maximum value, which is approximately equal to the minimum value of the refractive index of the next inner adjacent layer, and a minimum value, which is approximately equal to the maximum value of the refractive index of the next outer adjacent layer. These variations occur with a spatial wavelength of between 0.1 and 400 meters, such wavelengths being long relative to the wavelength of fluctuations referred to in patent No. 1,521,541. The pulse dispersion in such a fiber is less than the pulse dispersion in a prior art fiber having the same number of core layers; and increases proportional to the square root of fiber length rather than directly with fiber length.

For a better understanding of the invention, reference is made to the accompanying drawing in which:—

Figure 1 shows the optimum smooth refractive index profile and a step approximation of the same;

Figure 2 is a graded index optical fiber in accordance with the embodiment having a finite number of layers; and

Figure 3 shows the relationship between the refractive 5 index of each radial layer and the longitudinal distance along the fiber axis for the fiber in Figure 2.

Figure 1 illustrates an index profile of an optical fiber comprising five layers. The indices are selected to approximate the optimum profile, but it is to be understood that many more than five layers would be required to closely approximate the optimum profile. The indices range from a maximum at the centre of the core to a minimum at the outside of the core. Since it is expensive to fabricate a fiber with the many layers required to approximate the smooth profile satisfactorily, it would be desirable to be able to reduce the dispersion in a graded index optical fiber by other means that permit the use of fewer layers with a resultant reduction in the cost of fiber fabrication. This is accomplished by spatially modulating the index of refraction along each of a plurality of layers making up the core of the fiber.

Figure 2 shows an optical fiber embodying the principles of the present invention. A core 201 includes *i* cylindrical layers 202-1 to 202-i, with individual refractive indices that decrease from a maximum at the center 202-1 to a minimum at the outer layer 202-i. The core 201 is surrounded by a cladding 203 having an index of refraction that is equal to or less than the index of layer 202-i. The fiber structure is modified in that longitudinal variations are introduced in the index of refraction of each layer. Figure 3 illustrates the index of refraction for each illustrative layer versus the longitudinal distance along the fiber. As can be noted, the index of refraction of each layer sinusoidally varies along the fiber axis between a maximum and minimum about the optimum value corresponding to the profile. In particular, the period, L, of such variations is in the range of 0.1 meter to 400 meters with a preferred range of 10 to 100 meters. In addition, as can be noted in Figure 3, the minimum refractive index of each layer is approximately equal to the maximum index of refraction of the next outer adjacent layer. Also, the maximum index of refraction of each layer is approximately equal to the minimum refractive index of the next inner adjacent layer.

As shown in Figure 3, the preferred periods of variation of the layers are equal, and the minima of each layer are spatially aligned with the maxima in the next outer adjacent layer. Similarly, the maxima are aligned with the minima of the next inner adjacent layer. Dispersion reduction, however, can also be achieved when the refractive index variations are aperiodic or when the periods of variations of the several layers are unequal and the maxima and minima are not spatially aligned longitudinally along the fiber axis.

The optical fiber structure of the embodiment advantageously results in gross distortion of the field configuration within the fiber that is unlike the prior art structures which result in only minimal perturbations in the field configuration. High frequency longitudinal variations (of the order of from 1 to 10 mm), result in adiabatic mode conversion and require no cross sectional nonuniformity in the index of refraction to effect the requisite mode conversion. In the present invention, the relatively low frequency longitudinal variations in the index of refraction, when coupled with a nonuniform cross sectional index of refraction, yield efficient nonadiabatic mode conversion. The resulting mode conversion results in a transmitted pulse width which increases with the square root of the fiber length rather than directly with fiber length, as is the case without efficient mode conversion. The invention provides the advantage of having both a radially graded fiber and a mode-mixing fiber in one single configuration.

The fiber of the embodiment can be fabricated using a modified chemical vapor deposition process. By varying the dopant such as the germanium or the boron as the flame traverses along the tube during the preform fabrication, the index of refraction of each layer is modulated between predetermined maximum and minimum values. Alignment of the maxima and minima is achieved by spatially registering the beginning of each flame traversal together with dopant concentration.

WHAT WE CLAIM IS:–

1. A graded index optical fiber comprising a core member and a cladding surrounding said core member, said core member including a plurality of layers the refractive indices of which radially decrease from a maximum at the center of the fiber to a minimum at the outside of the core member, wherein the index of refraction of each of said layers has spatial fluctuations of relatively long wavelengths along a direction parallel to the longitudinal axis of said fiber with the minimum refractive index of each layer being substantially equal to the maximum index of the radially next outer adjacent layer, and the maximum refractive index of each layer being substantially equal to the minimum index of the next inner adjacent layer.

2. A fiber as defined in claim 1, wherein the distance between maxima in the index of refraction of each layer is within the range of 10 meters to 100 meters.

3. A fiber as defined in claim 1 or 2, wherein said spatial fluctuations are periodic along the longitudinal axis of said fiber.

4. A fiber as defined in claim 3, wherein the periods of said spatial fluctuations are the same for all of the layers.

5. A fiber as defined in claim 4, wherein the longitudinal spatial positions of the minima in the refractive index of each layer are proximate to the longitudinal spatial positions of the maxima in the refractive index of the adjacent layers.

6. A graded index optical fiber as claimed in Claim 1, and substantially as hereinbefore described with reference to Figures 2 and 3 of the accompanying drawing.

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FIG.1

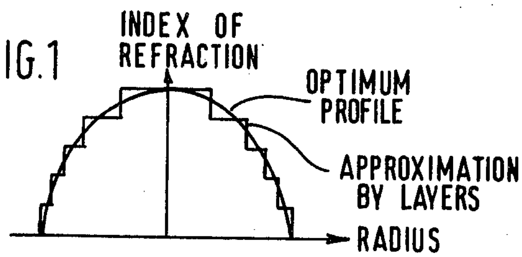


FIG.2

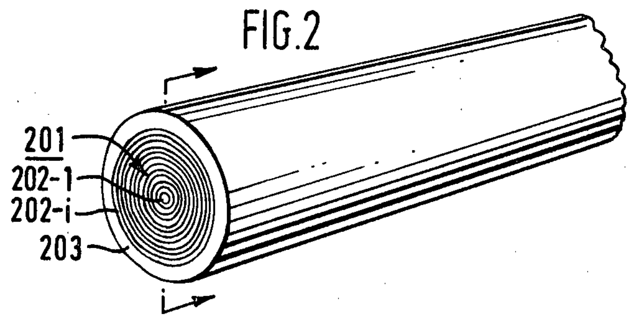


FIG.3