AN IDEAL REFRACTIVE-INDEX-DISTRIBUTION AND MODE FILTER FOR BAND BROADENING OF MULTIMODE OPTICAL FIBER

Kazuhito FURUYA, Yasuharu SUEMATSU, Tsuneo TANAKA, and Sigeta ISHIKAWA

Department of Physical Electronics
Tokyo Institute of Technology
Meguro-ku, Tokyo 152

Abstract

The focusing fiber whose refractive index distribution has the valley at the periphery of the core, as the ideal index distribution with respect to the bandwidth, is analyzed exactly, by which the group delay spread caused by the core-cladding boundary can be eliminated, and, therefore, the bandwidth can be broadened.

Introduction

The focusing fiber or graded index fiber[1], is promising as a broadband multimode optical fiber due to its group-velocity-equalization property. However, as it was pointed out in reference 2, even in the focusing fiber, the group velocities of higher order modes are different from those of the lower order modes due to the effect of core-cladding boundary. These differences are very large and prevent higher-bit-rate pulse transmission in the optical communication systems.

In this paper, an ideal refractive-index-distribution of the optical fiber is described to eliminate the boundary effect, which can overcome the above mentioned group velocity-difference, in the focusing fiber.

Ideal Refractive-Index-Distribution

Group delay spread in focusing fiber

The focusing fiber has the refractive index distribution of;

$$n^2(r) = \begin{cases} n_1{}^2\{1 - 2\Delta(r/a)^2\} & r \le a \\ n_1{}^2\{1 - 2\Delta\} & r > a \end{cases} \qquad (1)$$

as shown by the curve (A) in Fig.1. A group velocity characteristics of the focusing fiber is obtained numerically with a new exact-method or very accurate method using (4x4) or (2x2) matrices, respectively, in which the gradient of the index and the boundary conditions at r = a are taken into account. These methods for the exact mode-analysis will be also very important for precise determination of the propagation constants which can be applied to estimate the refractive index distribution.

Figure 2 is an example of the group delay characteristics. Guided modes are separated into three groups on the axis of propagation constants. But, exactly speaking, none of the guided modes, $HE_{l,m}$, $EH_{l,m-1}$, $TE_{0,m-1}$ or $TM_{0,m-1}$, are degenerated contrary to the results of the conventional scalar analysis neglecting the gradient of the refractive index.

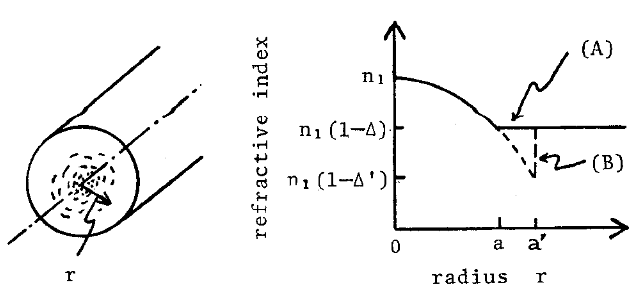

Fig.1. Refractive index distribution of fiber.

(A) Ordinary focusing fiber ,
(B) Focusing fiber whose index distribution has the valley at the periphery of the core.

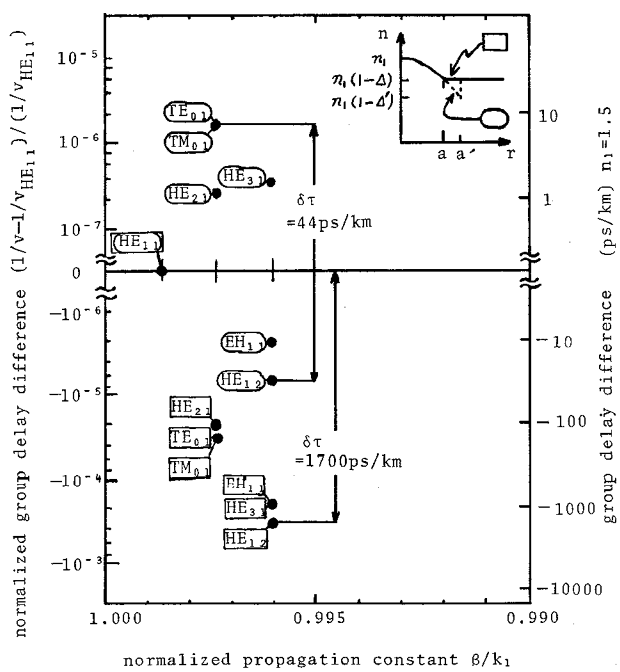

Fig.2. Group delay differences in focusing fiber with and without the valley.

Group delay spread defined in Eq.(5) is reduced by the factor 38 due to the valley. $a=11.9\lambda/n_1$, $a'=16.9\lambda/n_1$, $\Delta=0.5\%$, $\Delta'=1\%$.

The group delay spread among all guided modes is as large as 1.7nsec/km, in our numerical example. This large group delay spread is due to the existence of the boundary at r = a between the core and the cladding[2], and has never been revealed with the conventional scalar analysis neglecting the boundary.

This boundary effect restricts severely the bandwidth of the focusing fiber , and is desired to be excluded. However, this effect cannot be eliminated by only adjusting the index distribution inside the core.

In our numerical example, as shown in Fig.2, there are a few number of modes. But, as will be shown later, the boundary effect appears also in larger core-size focusing fiber, which supports larger number of modes.

Focusing fiber with valley in its index distribution

In order to improve the group delay characteristics we devise the parabolic-index-distribution with the valley as shown by the curve (B) in Fig.1 , which is described by;

$$n^2(r) = \begin{cases} n_1^2\{1 - 2\Delta(r/a)^2\} & r \le a' \\ n_1^2\{1 - 2\Delta\} & r > a' \end{cases} \qquad (2)$$

where a' > a.

Group delays are analyzed with the method mentioned previously, and is shown in Fig.2. Total delay spread is reduced by the factor 38, in our numerical example. Therefore, the valley in the index distribution seems to be the solution to elimination of the boundary effect. Then, firstly , we investigate the mechanism of this group delay equalization.

Mechanism of group delay equalization

The group delay characteristics in the focusing fiber with core-radius a' instead of a, is shown in Fig.3. The group delay spread among lower order modes is very small. However, the higher order modes have large delay differences of 5 nsec/km, due to the boundary effect.

If the index of the cladding material is made higher, then the index distribution as shown by the curve (B) in Fig.1 is obtained, and simultaneously the guided modes whose propagation constants are lower than the wave number in the cladding material, turn to be cut off. Therefore, by appropriately making the index of the cladding material higher than that just inside the boundary, we can suppress the higher order modes whose group velocities are much different from those of the lower order modes, and decrease the group delay spread among all of the guided modes.

However, the important question is remained;how rapidly do the cutoff-modes decay in the index distribution with the valley ? Because, if the decay constant is as small as several dB/km, then the cutoff-modes propagate almost like guided modes.

Decay characteristics of cutoff modes

The decay constants of the cutoff-modes can be estimated by using the results of the analysis[3,4] for the two-dimensional model.

For the three dimensional case, the decay constants L [dB/m] of modes, $HE_{l,m}$, $EH_{l,m-1}$, $TE_{0,m-1}$, $TM_{0,m-1}$ are;

$$L_{(l+2m)} > 2\frac{n_1}{\lambda}\, C\left(\frac{l+2m-2}{2M}\right)^{0.85M} \qquad (3)$$

where λ is the wavelength, C is a constant depending on Δ' and as an example, C = 0.07 for Δ' = 0.01. M is the number of mode-groups(formed on the axis of propagation constants) given by;

$$M = \sqrt{2\Delta}\cdot a\cdot\pi\, n_1 / \lambda. \qquad (4)$$

The losses of the cutoff modes are almost independent of the refractive index of the cladding material, as far as the wave number in the cladding material is larger than the propagation constants of the modes under consideration.

Applying these results to our numerical example, the lower limit of the decay constants of cutoff-modes is shown in Fig.3. It is obvious that undesired higher order modes, even if generated, can be eliminated very rapidly.

Therefore, the refractive index distribution with the valley as shown by the curve (B) in Fig.1, is an ideal distribution by which the group delay spread due to the boundary between the core and the cladding can be eliminated.

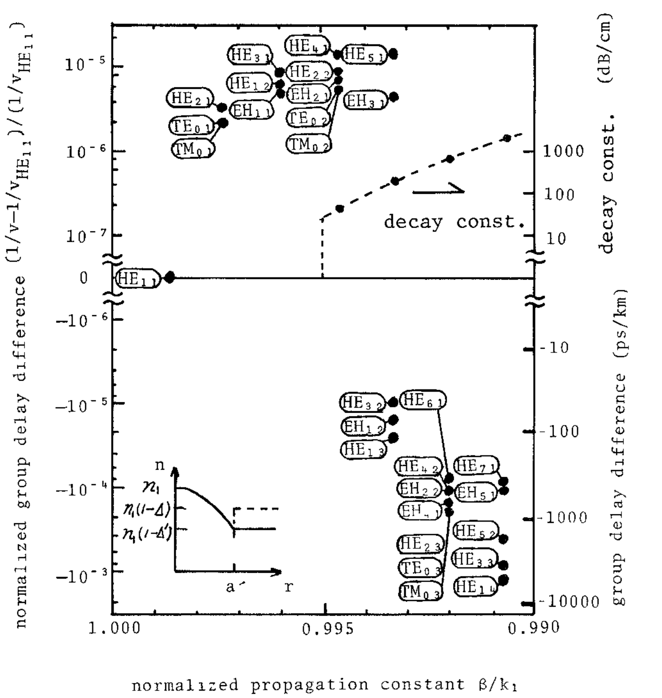

Fig.3. Group delay differences and decay constants.

Higher order modes whose group velocities are much different from those of lower order modes, are cut off when the index of the cladding material is increased as shown by the broken line.
Cutoff modes decay very rapidly.

a'=16.9 λ/n_1, Δ=0.5%, Δ'=1%.

Depth of the valley

Lastly, we consider the valley-depth for the elimination of the boundary effect. For this purpose, group-delay characteristics are analyzed numerically for focusing fiber with valleys of various depthes. As the results of this analysis, Figure 4 shows the relation between the valley-depth and the group delay spread $\delta\tau$ defined as follows;

$$\delta\tau = 1/v_{min.} - 1/v_{max.} \quad (5)$$

where $v_{min.}$ and $v_{max.}$ are the minimum and maximum group velocities, respectively. Broken line in Fig.4 indicates the delay spread in the absense of the boundary effect. According to Fig.4, perfect elimination of the boundary effect is attained when the value of the normalized valley-depth is larger than 1.5. The level of the broken line can be lowered further, by adjusting the index distribution in the core of the fiber appropriately, taking the material dispersion[5] or higher order terms of refractive index distribution[6] into account.

Ideal refractive index distribution

Finally, it is concluded that an ideal refractive index distribution is as follows. Firstly, the boundary effect is excluded with the valley in the index distribution at the periphery of the core, whose depth is about 1.5Δ. Secondary, the remained group-delay-differences are reduced by adjusting the index distribution inside the core appropriately. As an example, in the case of pure parabola, the group-delay-spread $\delta\tau$ is less than $0.4\Delta^2 z n_1/c$ (z is fiber-length).

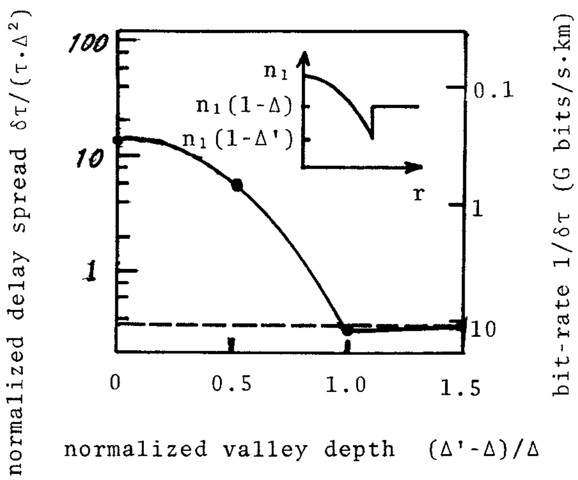

Fig.4 Group delay spread vs. valley-depth.

Broken line indicates the limiting case of large Δ', i.e., in absense of the boundary-effect.

τ is the group delay given by n_1/c.
The vertical axis on the right-hand-side is the numerical example corresponding to the case of $n_1=1.5$, $\Delta=1\%$.

Mode Filter

According to Eq.(3), the focusing fiber with higher index cladding acts as a very sharp mode-filter. By inserting short sections of this type of filter in the axial direction of the focusing fiber , transmission mode number can be limited, and therefore, the bandwidth of the fiber can be broadened. Figure 3 shows one example of mode filter characteristics of the focusing fiber with higher index cladding.

We carried out pulse transmission experiments, by the insertion of the mode filter in front of the detector. The pulse broadening due to the group delay spread was reduced almost five times[7].

Conclusion

The focusing fiber whose refractive index distribution has the valley at the periphery of the core is analyzed exactly as the ideal refractive index distribution. By this type of index distribution, the group delay spread caused by the boundary between the core and the cladding can be eliminated completely. Furthermore, this type of distribution can also be used as a very sharp mode filter. Bandbroadening effect due to the mode-filter-insertion was confirmed experimentally.[7]

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