Design Consideration on Broad-Band *W*-Type Two-Mode Optical Fibers

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Abstract—**Structural design for broad-band *W*-type two-mode optical fibers is investigated. The optimum parameters are numerically determined as follows: the operating *V*-value with zero group delay time difference $\Delta\tau$ between the LP_{01} and LP_{11} modes is 6.7, the ratio of core radius to inner cladding radius is 0.6, and the index profile parameter is 2.02. Then, the core radius is 12.3 μm for $\Delta=0.3$ percent at the operating wavelength of 1.3 μm. The *V*-value deviation tolerance from the optimum to maintain $\Delta\tau$ less than ± 20 ps/km is 21 percent, which is 20 times larger than that of the earlier design made on two-layer index profile.**

I. Introduction

IT IS certified from the theoretical and experimental studies [1]–[3] that the two-mode optical fiber provides a large transmission capacity and feasibility of low splice loss. Design principle of the two-mode fiber is that the *V*-value where the group delay times of the two guided modes, LP_{01} and LP_{11} modes, coincide is chosen as the operating *V*-value V_0, and that group delay time difference $\Delta\tau$ between LP_{01} and LP_{11} modes caused by the *V*-value deviation from V_0 is made as small as possible. Here, $\Delta\tau$ is defined by

$$\Delta\tau = \tau(LP_{11}) - \tau(LP_{01})$$

where $\tau(LP_{11})$ and $\tau(LP_{01})$ denote the group delay times of LP_{11} and LP_{01} modes, respectively. For the practical use of the two-mode fibers, therefore, it is important to know how to obtain a large tolerance in *V*-value deviation for maintaining $\Delta\tau$ small over a wide *V*-value region. In the preceding papers [1],[2], designs were made on a two-mode fiber with the two-layer index profile consisting of core and cladding. In this type of index profile, V_0 and the optimum index profile parameter α_{opt} have been determined 6.45 and 2.24, respectively, [4] and the tolerance of operating *V*-value deviation is found to be 11 percent for $\Delta\tau$ less than ± 100 ps/km.

In order to provide larger tolerance of operating *V*-value deviation, further design consideration is newly made on various index profiles, so-called *W*-type profiles, composed of three layers; core, inner cladding, and outer cladding. This investigation clarifies extremely larger extension of the small $\Delta\tau$ region in comparison with that calculated for the two-layer type index profile. For convenience of practical use, the optimum fiber parameters are determined for the *W*-type two-mode fiber from the view point of attaining large deviation tolerances for *V*-value and α.

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II. $\Delta\tau$ Characteristics for *W*-Type Two-Mode Fiber

Let us consider *W*-type graded-index fibers consisting of core, inner cladding, and outer cladding. The index profile is expressed by

$$n(r)=\begin{cases} n_1\left[1-2\Delta\rho(r/a)^{\alpha}\right]^{1/2}, & 0\leq r\leq a \\ n_1\left[1-2\Delta\rho\right]^{1/2}, & a\leq r\leq b \\ n_1\left[1-2\Delta\right]^{1/2}=n_2, & r>b \end{cases} \quad (1)$$

where k denotes the wavenumber in vacuum. The parameters chosen are as follows: (a) $\alpha=3.08$, $\rho=1$, $a=b$; (b) $\alpha=2.04$, $\rho=2$, $a=b$; (c) $\alpha=2.01$, $\rho=2$, $a/b=0.8$. Calculations are made by numerically solving the vector-wave equation with the matrix method [5]. For simplicity, Δ is chosen 0.3 percent in calculations throughout the paper. Cutoff *V*-value V_{c2} of the LP_{21} mode for each index profile is also shown in Fig. 2. In case (*a*), the operating *V*-value

$$V=kan_1\sqrt{2\Delta} \quad (2)$$

where k denotes the wavenumber in vacuum. The parameters chosen are as follows: (a) $\alpha=3.08$, $\rho=1$, $a=b$; (b) $\alpha=2.04$, $\rho=2$, $a=b$; (c) $\alpha=2.01$, $\rho=2$, $a/b=0.8$. Calculations are made by numerically solving the vector-wave equation with the matrix method [5]. For simplicity, Δ is chosen 0.3 percent in calculations throughout the paper. Cutoff *V*-value V_{c2} of the LP_{21} mode for each index profile is also shown in Fig. 2. In case (*a*), the operating *V*-value V_0 where $\Delta\tau=0$ coincides with V_{c2} for $\alpha=3.08$ [2]. While, as seen from the results for $\rho=2$ given by the curves (*b*) and (*c*), V_0 is smaller than V_{c2}. Therefore, it is found that the two-mode *V*-value region is expanded for $\rho>1$ in comparison with that for $\rho=1$. Furthermore, comparing curves (*b*) and (*c*) where $\rho=2$, small $\Delta\tau$ characteristics over a wide *V*-value range around v_0 is obtained for $a/b=0.8$. As is evident from the curve (*b*), *V*-value tolerance is enlarged to about 10 times the case with $\rho=1$ and $a=b$. Furthermore, the curve (*c*) shows that *V*-value toler-

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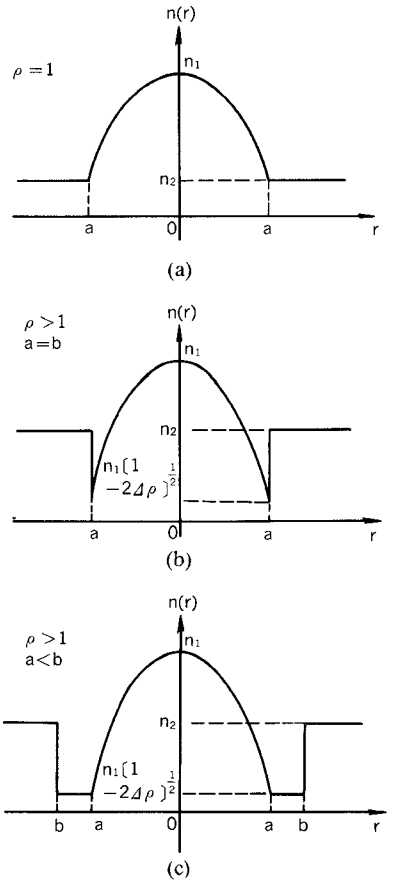

Fig. 1. Three types of index profiles. (a) Two-layer index profile. (b) W-type index profile with $\rho>1$ and $a=b$. (c) W-type index profile with $\rho>1$ and $a<b$.

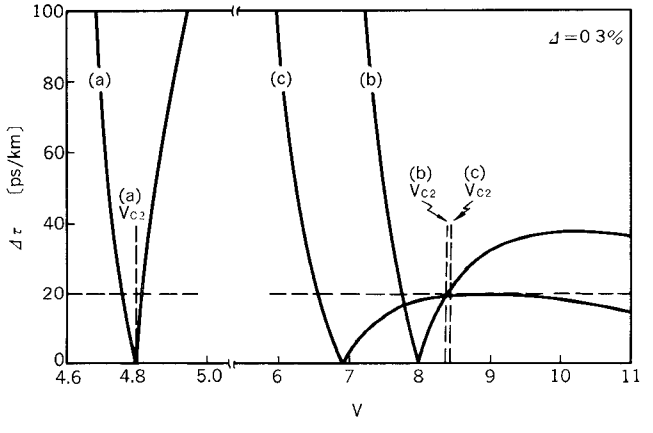

Fig. 2. V-value dependence of group delay time difference $\Delta\tau$ between LP_{01} and LP_{11} modes, for: (a) $\alpha=3.08$, $\rho=1$, $a=b$; (b) $\alpha=2.04$, $\rho=2$, $a=b$; and (c) $\alpha=2.01$, $\rho=2$, $a/b=0.8$. V_{c2} denotes the cutoff V-value of the LP_{21} mode. Refractive index difference Δ is chosen 0.3 percent.

ance is exceedingly extended, compared with the other two index profiles.

III. Parameter Tolerance for Maintaining Small $\Delta\tau$ Characteristics

Design considerations to optimize the fiber parameters are made on W-type two-mode fiber. In this section, tolerance of operating V-value region is numerically evaluated.

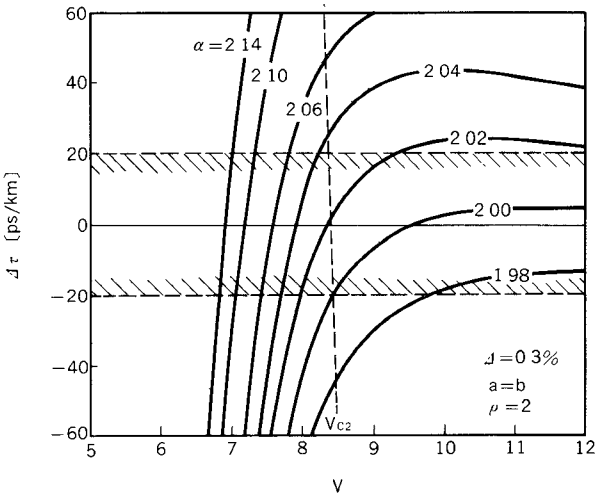

Fig. 3. Relation between $\Delta\tau$ and V-value for various values of α where $a=b$.

It is assumed that the allowable limit of $|\Delta\tau|$ is 20 ps/km, which corresponds approximately to 45 GHz·km in baseband 3-dB bandwidth [4]. Furthermore, operating V-value region is considered to be restricted below V_{c2}. Then the tolerance B_v is defined as

$$B_v=\begin{cases}2(V_1-V_2)/(V_1+V_2), & V_{c2}>V_1\\ 2(V_{c2}-V_2)/(V_{c2}+V_2), & V_1>V_{c2}>V_2\\ 0, & V_2>V_{c2}\end{cases} \quad (3)$$

for three possible cases, where V_1 and V_2 are V-values giving $\Delta\tau=20$ ps/km and -20 ps/km, respectively. Note that V_1 is always larger than V_2.

A. Index Profile with $\rho>1$ and $a=b$

Fig. 3 shows the relation between $\Delta\tau$ and V for various values of α where $\rho=2$. The shaded area denotes the V-value region where $|\Delta\tau|$ is less than 20 ps/km. V_{c2} is indicated by the almost vertical dashed line. It is seen from Fig. 3 that there exists the two-mode propagation region ($V<V_{c2}$) with $|\Delta\tau|<20$ ps/km for $\alpha>2$, while for $\alpha\leqslant 2$ no two-mode propagation region with $|\Delta\tau|<20$ ps/km exists. For an index profile having the inner cladding with the refractive-index lower than that of the outer cladding, guided mode power is still confined to some degree in a core region at its cutoff V-value [6]. Thus the LP_{21} mode can propagate with relatively low loss near V_{c2}, compared with the case of $\rho=1$. Therefore, it is considered appropriate at present that V_0 is chosen below V_{c2} for $\rho>1$, in contrast with the case of $\rho=1$ where the operating V-value region was extended to $V_0>V_{c2}$ [4]. In Fig. 4, the operating V-value tolerance B_v defined by (3) is plotted against α for various values of ρ. It is found that as ρ increases value of the maximum B_v becomes large, accompanied with the decrease in the value of α giving the maximum B_v. It is noted that B_v larger than 0.2 is achieved for $\rho=2.5$ with $\alpha\simeq 2$. This value is 20 times larger than that obtained by the previous design with $\rho=1$ and $\alpha=3.08$ [2]. As shown by the dotted line in Fig. 4, value of 0.5 is

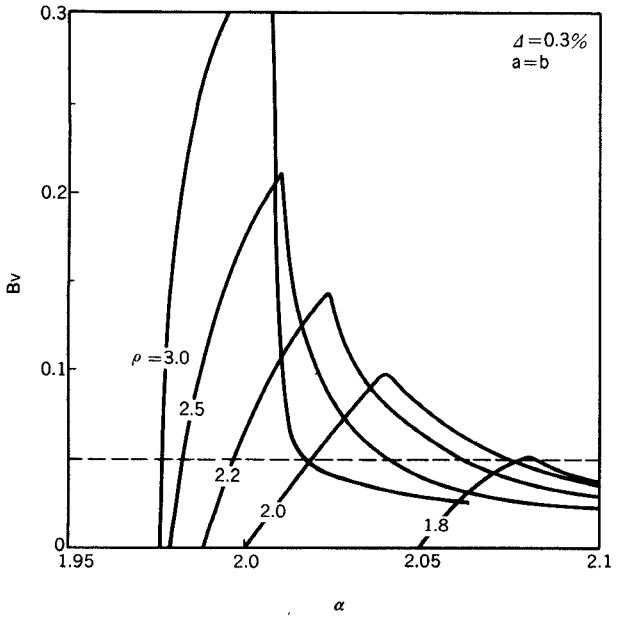

Fig. 4. The operating V-value tolerance against α for various values of α where $a=b$.

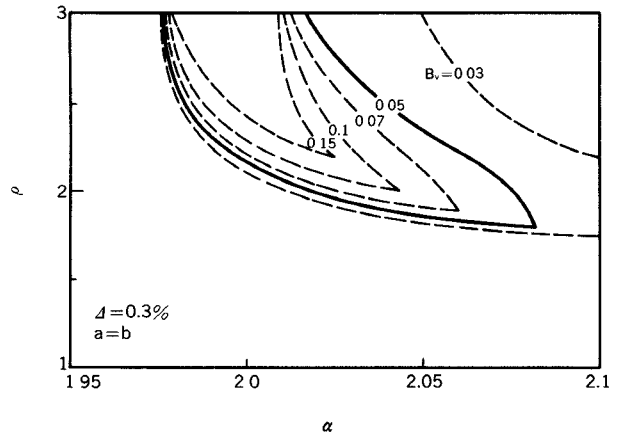

Fig. 5. Combinations of ρ and α for various values of B_v where $a=b$.

introduced for the lower limit of the tolerable B_v. Combinations of ρ and α for various values of B_v are plotted in Fig. 5. It is found from this figure that $\rho>1.8$ and $1.97<\alpha<2.08$ are required for satisfying $B_v>0.05$ (the region surrounded by the solid curve).

B. Index Profile with $\rho>1$ and $a<b$

Fig. 6 shows the numerical $\Delta\tau$ against V for various values of α, where ρ and a/b are assumed 2 and 0.8, respectively. It is found that for α smaller than 2 two-mode propagation V-value region with $|\Delta\tau|<20$ ps/km still exists due to the presence of inner cladding ($a/b=0.8$). As a result, remarkable increase in B_v is observed as shown in Fig. 7. For example, for $\rho=2$ the maximum B_v is 0.25, which is 2.5 times larger than that with $a=b$. Fig. 8 shows the combinations of ρ and α for $B_v=0.05$ with a/b as a parameter. Within the contours, the condition $B_v>0.05$ is satisfied. It is found that as lowering a/b, the minimum tolerable ρ for giving $|\Delta\tau|$ less than 20 ps/km slightly decreases. The values of ρ are 1.48, 1.35, 1.28 for $a/b=0.8$,

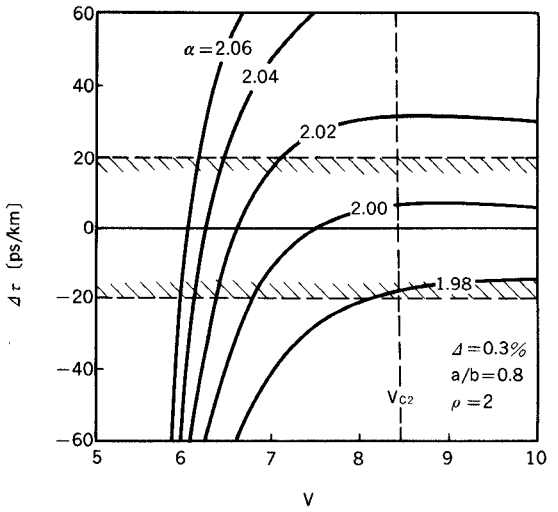

Fig. 6. Relation between $\Delta\tau$ and V-value for various values of α where $a/b=0.8$.

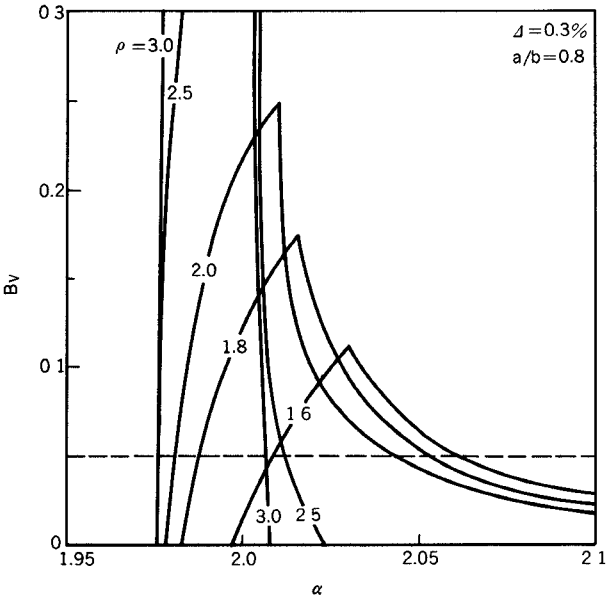

Fig. 7. The operating V-value tolerance against α for various values of ρ where $a/b=0.8$.

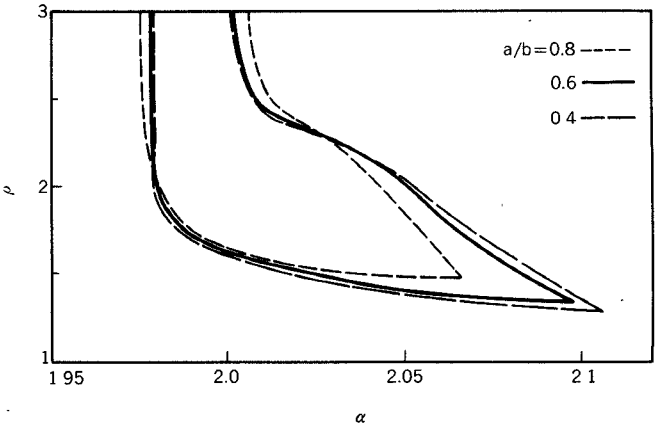

Fig. 8. Combinations of ρ and α for various values of a/b where $B_v=0.5$ and $\Delta=0.3$ percent.

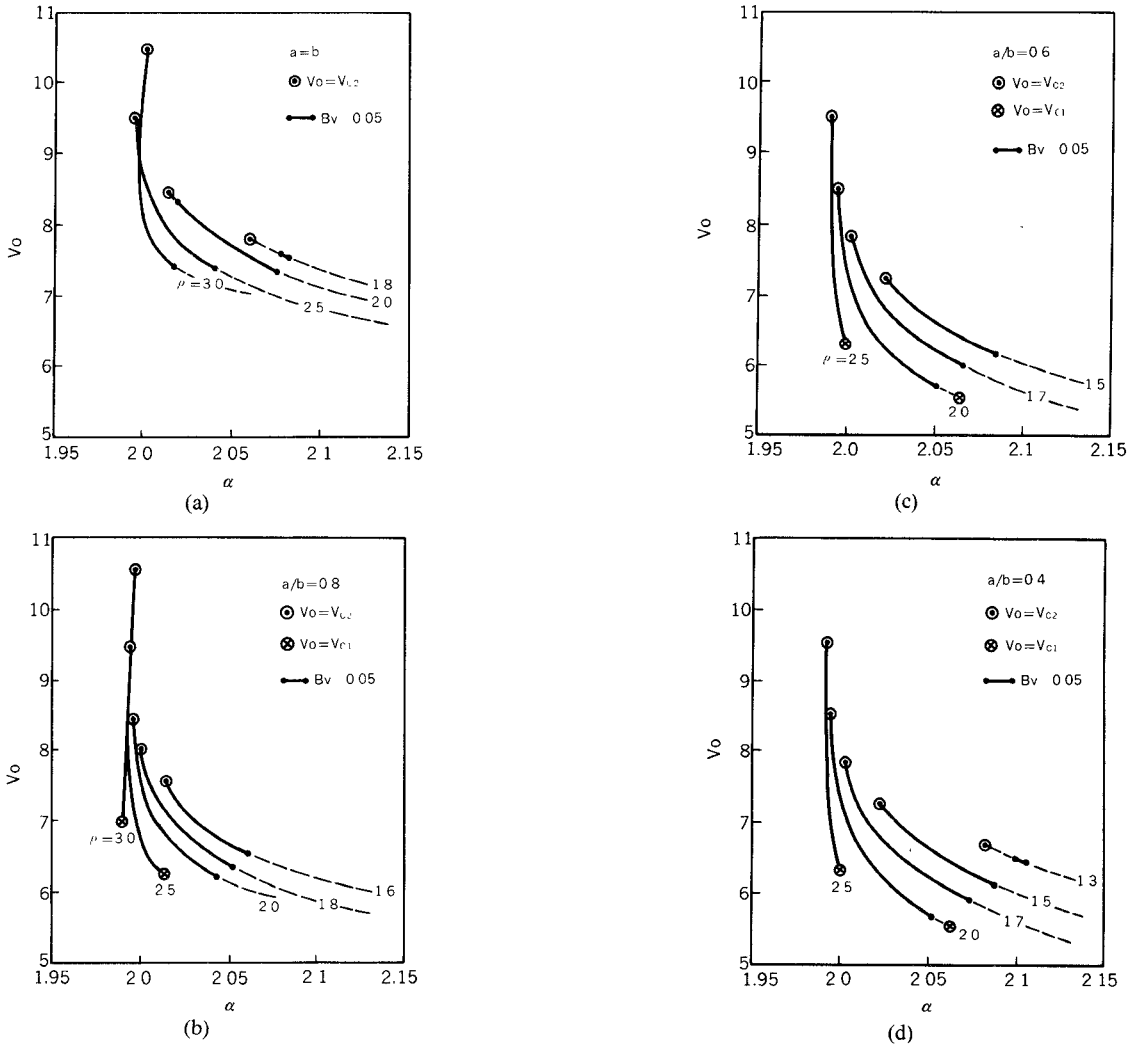

Fig. 9. Dependence of the optimum operating V-value V_0 where $\Delta\tau=0$ on α for various values of ρ.

0.6, and 0.4, respectively, while $\rho>1.8$ in the case of $a=b$ (Fig. 5).

IV. Determination of the Optimum Parameters

It is practically required in view of fabrication ease that the two-mode fiber provides a large α deviation tolerance as well as the large B_v. For the convenience of design, the optimum operating V-value V_0 where $\Delta\tau=0$ is shown as functions of α and ρ in Fig. 9 (a)–(d) for various values of a/b. The solid curves indicate the useful combinations of α and ρ, satisfying the conditions $V_0 \leqslant V_{c2}$ and $B_v \geqslant 0.05$, and the dotted curves denote the region where $B_v < 0.05$. As seen from the figures, V_0 tends to change rapidly against α for large ρ. This feature is unpreferable to obtain a large tolerance in α deviation, and suggests that the optimum ρ is less than 2.5. Fig. 10 shows tolerable α deviation $\Delta\alpha(=\alpha_{max}-\alpha_{min})$ to maintain B_v larger than 0.05. The optimum ρ for the maximum $\Delta\alpha$ is determined around 2 for each value of a/b, as listed in Table I. Using the values, the optimum α and V_0 are calculated. The results are summarized in Table I. The value of B_v against ρ_{opt} has the maximum for $a/b=0.6$, and decreases for smaller a/b.

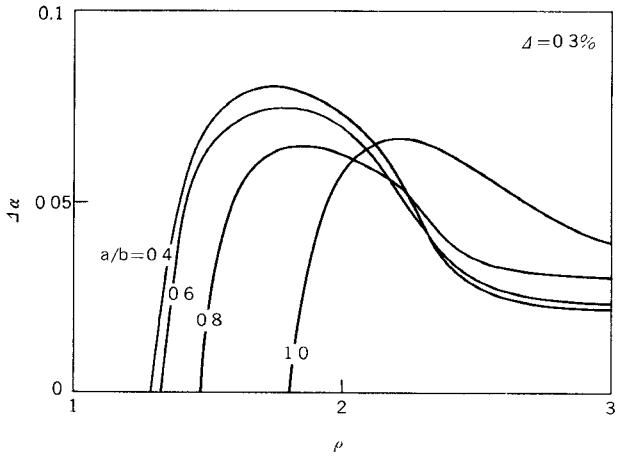

Fig. 10. The tolerable α deviation $\Delta\alpha$ as a function of ρ, to maintain B_v larger than 0.5.

Furthermore, for small a/b, the inner cladding radius becomes large, for instance $b=30$ μm for $a/b=0.4$ at 1.3 μm. Such a large b is not advantageous from the viewpoint of fiber fabrication economy. It is considered from the above discussion that the optimum value of a/b is chosen

TABLE I
THE OPTIMUM α AND V_0 DETERMINED USING THE OPTIMUM ρ FOR VARIOUS VALUES OF a/b

a/b	ρ_{opt}	α_{opt}	V_{opt}	Bv	a^*(μm)	b^*(μm)
1	2.2	2.02	8.1	0.14	14.8	-
0.8	1.8	2.02	7.0	0.18	12.8	16.0
0.6	1.8	2.02	6.7	0.21	12.3	20.5
0.4	1.7	2.02	6.6	0.17	12.1	30.2

* For λ=1.3μm and Δ=0.3%

as 0.6. Then, core radius a and inner cladding radius b are 12.3 μm and 20.5 μm, respectively, for $\lambda=1.3$ μm and $\Delta=0.3$ percent. If both α and V_0 are set optimum at the wavelength of 1.3 μm, tolerable range of wavelength with $|\Delta\tau|<20$ ps/km extends from 1.18 μm to 1.45 μm for $\rho=1.8$ and $a/b=0.6$. While, the permissible variation in α ($\Delta\alpha_{opt}/\alpha_{opt}$) is 4 percent when the other parameters are fixed at their optimum values.

V. Conclusion

New design of two-mode optical fiber has been presented for W-type fibers having wide tolerances of V-value and α with group delay time difference between the LP_{01} and LP_{11} modes less than ± 20 ps/km. The optimum values of ρ are found to change with the variation of inner cladding thickness. While it is interesting that the optimum α is fixed at 2.02 regardless the inner cladding thickness. As a result of the theoretical investigation, along with the consideration on the fiber fabrication ease, the optimum parameters of the W-type two-mode fiber has been determined as $a/b=0.6$, $\rho=1.8$, $\alpha=2.02$, and $V=6.7$. Then, core radius and inner cladding radius are 12.3 μm and 20.5 μm, respectively, at the wavelength of 1.3 μm. In the present paper, discussion is restricted to the case where the optimum operating V-value V_0 is chosen within a theoretical two-mode region. However, the previous design consideration for the two-layer index profile [4] has shown that the operating V-value is extended up to the effective cutoff V-value [7] of the LP_{21} mode. The same idea may be applied to further extension of the optimum operating V-value for the present W-type index profile. If the structural parameters are determined using the idea, this will result in the improvements of B_v and α deviation tolerance. This future problem will be appropriately solved on the basis of the experimentally confirmed effective cutoff V-value of the LP_{21} mode for the W-type index profile.

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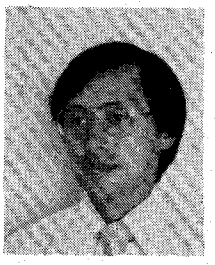

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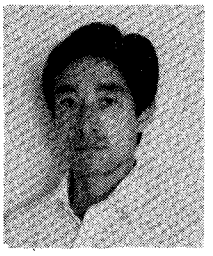

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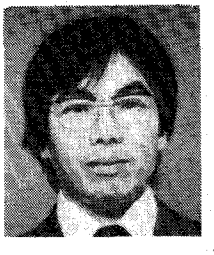

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