Waveguide Parameter Design of Graded-Index Plastic Optical Fibers for Bending-Loss Reduction

Kenji Makino, Takaaki Ishigure, *Member, IEEE*, and Yasuhiro Koike, *Member, IEEE*

***Abstract*—The waveguide structure of graded-index plastic optical fibers (GI POFs), such as index profile, numerical aperture (NA), and core diameter, is appropriately designed for eliminating bending losses, even under a severe bending condition. The bending loss of GI POFs under a severe bending condition is drastically reduced when the core diameter is smaller than 200 μm and when the NA is higher than 0.25. The bending loss of GI POFs even under a severe bending condition vanishes with a core diameter of 200 μm and an NA of 0.24. It is experimentally confirmed for the first time that the mode coupling due to the bending induces the bending loss. The mode coupling strength before the fiber is bent affects the bending loss seriously. Moreover, the mode-coupling strength is evaluated by the propagation constant difference $\Delta\beta$ between the adjacent modes. The $\Delta\beta$ value, which is a function of the core diameter and NA, affects the bending loss. Therefore, based on the calculation of the $\Delta\beta$, we propose a guideline for the appropriate design of waveguide parameters for GI POF, in order to suppress the bending loss.**

***Index Terms*—Bending loss, core diameter, fiber bending, graded-index plastic optical fiber (GI POF), mode coupling, numerical aperture (NA), refractive index profile.**

I. Introduction

AS INFORMATION technology progresses, available network bandwidth for end-users increases, and the demand for high bandwidth in data communications and multimedia applications is growing stronger. Silica-based optical fibers are widely utilized in backbone networks and are now found even in premise and access areas. Particularly in such local area networks (LANs), many fiber bendings and junctions are inevitable. A high-bandwidth graded-index plastic optical fiber (GI POF) is expected to be a medium for high-speed LANs because its excellent flexibility and large core allow for a low cost and user friendly installation [1]. We have reported the good mechanical strength and high-bandwidth performance of GI POFs under static bending [2], [3]. On the other hand, previous theoretical studies on the bending loss of silica-based multimode fibers (MMFs) have shown that the bending loss depends on the refractive index profile, core diameter, and numerical aperture (NA) of the fiber [4]. These parameters of GI POFs should be optimized in order to achieve a stable high-speed transmission, even under bendings. Therefore, the bending loss of the GI POFs with various parameters is investigated in detail by comparing the propagating mode characteristics before and after the bending.

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The authors are with the Faculty of Science and Technology, Keio University, Yokohama 223-8522, Japan, and also with Japan Science and Technology (JST) Corporation Exploratory Research for Advanced Technology (ERATO)-Solution-Oriented Research for Science and Technology (SORST), Kawasaki 213-0012, Japan (e-mail: k_makino@appi.keio.ac.jp; ishigure@appi.keio.ac.jp).

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II. Experimental

A. Fabrication of GI POF

The GI POF for a bending test is obtained by heat drawing a preform. The preform already has a refractive index profile that is formed by the interfacial-gel polymerization process. A detailed fabrication method is described in [5]–[7]. The core diameter can be controlled by changing the core-cladding ratio in the preform through the interfacial-gel polymerization process or by changing the fiber diameter in the heat-drawing process. The refractive index profile and NA of the obtained GI POF is controlled by changing the composition of the polymerization initiator, chain transfer agent, and dopant in the interfacial-gel polymerization process. We fabricate various samples of GI POF with different index profiles, NAs, and core diameters.

B. Refractive Index Profile

The refractive index profile of GI POFs generally affects various characteristics, such as bandwidth, etc. The index profile of the fabricated GI POF is experimentally measured by an interferometric microscope, which is the most accurate measurement method for determining refractive index distribution in such a large diameter fiber [8].

In order to evaluate the index profile, the index distribution in the core is approximated by the well-known power law form described by

$$n(r) = n_1\left[1 - 2\Delta\left(\frac{r}{a}\right)^g\right]^{\frac{1}{2}}; \qquad 0 \le r \le a$$
$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \tag{1}$$

where n_1 and n_2 are the refractive indexes of the core center and the cladding, respectively, r is the distance from the core center, a is the core radius, and Δ is the relative refractive index difference. The parameter g is called the index exponent and determines the index profile.

C. Launch Condition

In the evaluation of MMFs, the launch condition is a very important factor. In silica MMFs, a steady-state mode power distribution has been established in many previous investigations,

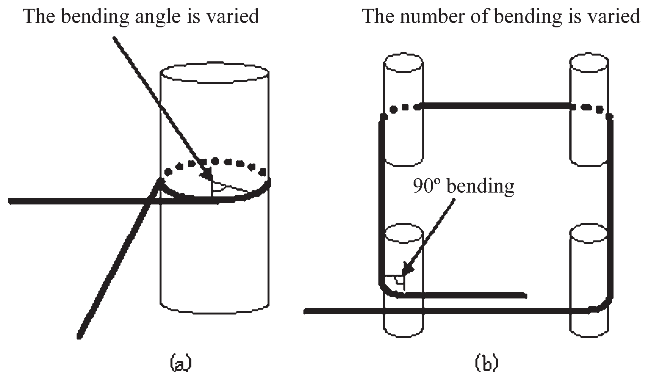

Fig. 1. Schematic diagrams of bending-loss measurement conditions. (a) Variation of the bending angle and (b) variation of the number of bendings.

because silica MMFs are expected to be utilized in long-haul networks in which a light-emitting diode (LED) is employed in the optical transmitter. Specifically, a steady-state mode power distribution has been established in MMFs during real use [9]. All the modes should be fully exited to satisfy the steady-state mode power distribution. However, the use of MMFs in high-speed and short-reach networks is a current trend. In such optical links, the laser diode (LD) or the vertical-cavity surface-emitting laser (VCSEL) is the candidate of light source for practical use. Since VCSELs, in general, have a very small radiation spot, restricted mode groups are excited [10], [11].

In this paper, two launch conditions are investigated: under-filled launch (UFL) and over-filled launch (OFL). In the UFL condition, the light beam focused by the lens system in the LD is coupled directly to the core center of the GI POF. The measured spot and NA of the beam are 6.5 μm and 0.16, respectively. Therefore, only low-order modes are excited selectively. On the other hand, in the OFL condition, a 1-m step-index (SI) POF is used as an all-mode exciter for the GI POF because the mode power distribution from the 1-m SI POF is uniform in the whole core region (980 μm) [12], which is much larger than that of the GI POF ($\sim$ 500 μm) and because the NA of the SI POF (0.5) is sufficiently higher than that of the GI POF ($\sim$ 0.3). An optical signal is first coupled to the 1-m SI POF, and then, the output light is coupled to the GI POF under test by directly butting them on a V-groove.

D. Bending Loss

A static bending is applied to the 100-m GI POFs at a 1-m distance from the input end with a 5-mm bending radius, and the bending angle and number of bendings are varied independently, as shown in Fig. 1. The bending loss is determined by the difference of the output optical powers before and after the bending. The output power is measured by an optical power meter.

E. Mode Coupling

Mode coupling is a significant issue in evaluating the optical characteristics of GI POFs, because when a strong mode coupling exists, the launched mode power distribution at the input end cannot be maintained after transmission through a certain distance of fiber. In this paper, the mode-coupling strength in GI POFs is evaluated by differential mode delay (DMD). In the DMD measurement, a 1-m single-mode fiber (SMF) is used as a specified mode-group exciter. An optical pulse is coupled to the GI POF via the 1-m SMF. The mode groups from a low order to high order can be separately excited by scanning the position of the SMF from the core center to the periphery of the GI POF. The DMD is measured by an optical sampling oscilloscope. Additionally, a near-field pattern (NFP) which shows optical power distributions of each mode group is also measured. Moreover, the mode coupling caused by the fiber bending is evaluated by comparing the output NA from GI POFs before and after bending. The output NA is estimated by a far-field pattern (FFP) measurement of the GI POF.

III. Results and Discussion

A. Bending Condition

Bending losses of silica MMFs have generally been evaluated under the steady-state mode power distribution, similar to the ones used for the bandwidth measurement. On the other hand, in the case of GI POFs, we have reported that the bending loss under UFL is lower than that under OFL [3]. Since the UFL condition is considered to be a realistic launch condition for MMF-based very short reach networks, the bending loss should be investigated under the UFL condition.

The bending losses under various bending angles and numbers of turns on a mandrel are shown in Fig. 2. The bending loss is proportional to the bending angle and number of turns. The bending loss under various bending angles is similar to that under various numbers of turns when the total bending angle is the same. Thus, the bending loss of the GI POF does not depend on the bending-loss measurement conditions but only on the total bending angle as far as GI POFs are launched under the UFL condition for bending-loss measurement. Therefore, in the following measurement, a 90° bending is provided at a 1-m distance from the LD input end of the GI POF, and the bending radius is varied from 5 to 50 mm, as shown in Fig. 3.

B. Bending Loss

The bending loss of silica MMFs has been derived theoretically and it has been shown that the bending loss depends on the index profile, core diameter, and NA [4]. However, we have already shown that the bending loss of GI POFs does not necessarily depend on the index profile when the index exponent g is in the range from 2.4 to 6.3 [3]. Therefore, the effect of the index profile (index exponent) on the bending loss is neglected in this paper. The index profiles of GI POFs (Fibers 1–3) with different core diameters and NAs are shown in Fig. 4(a), and their bending losses are shown in Fig. 4(b). It is experimentally confirmed that the smaller core diameter (compare Fibers 1 and 2) and higher NA (compare Fibers 2 and 3) reduce the bending loss as theoretically expected in silica MMFs.

Here, by fixing the NA to be 0.222, and by fixing the core diameter to be 500 μm, the core diameter and NA dependences

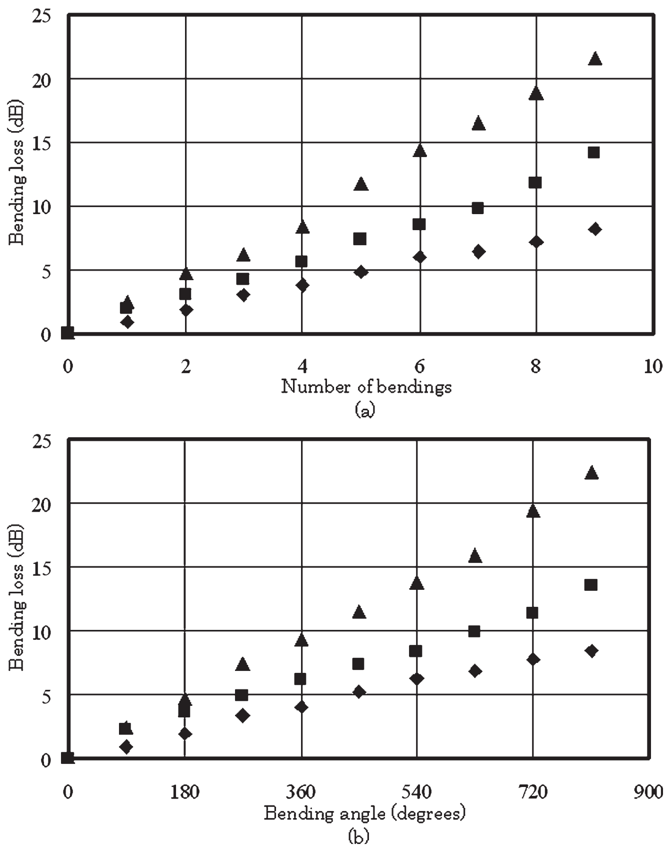

Fig. 2. Bending loss of GI POFs with various NAs with respect to (a) bending angle and (b) bending number; mandrel diameter is 10 mm. Fiber NA: ▲: 0.154 ■:0.187 ◆: 0.208.

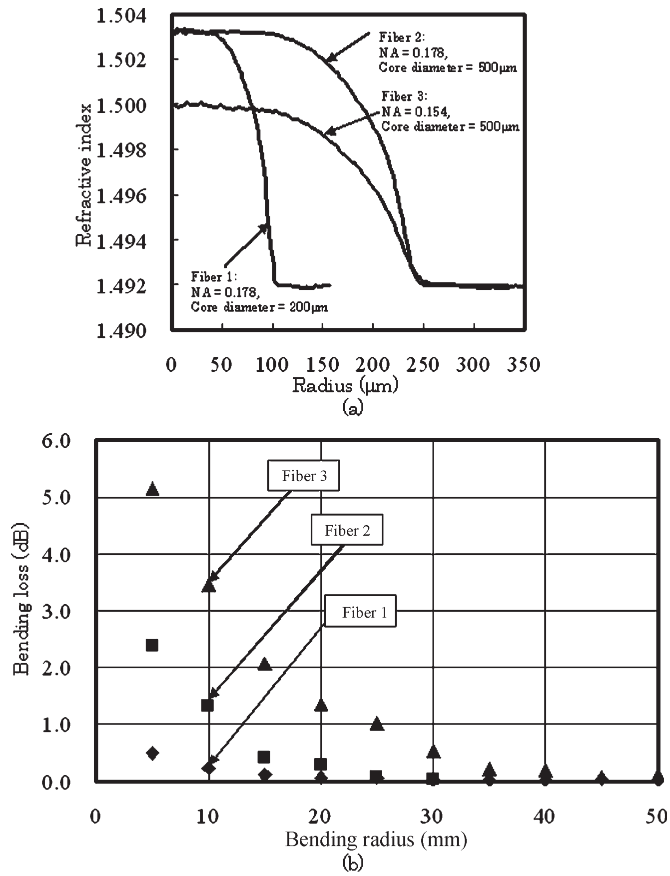

Fig. 4. Refractive index profiles (a) and bending losses (b) of GI POFs (Fibers 1–3) with different core diameters and NAs.

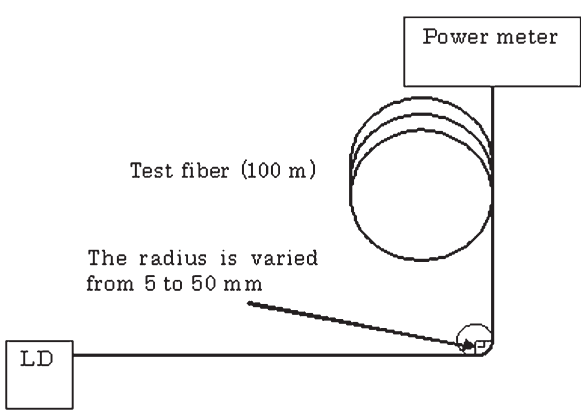

Fig. 3. Schematic diagram of the bending-loss measurement.

of the bending loss are evaluated in detail. The results are summarized in Fig. 5, where only the bending losses with the bending diameter of 5 mm are selected to compare, because the largest and distinguishable bending losses are obtained under this condition.

The bending loss increases exponentially when the core diameter is larger than 150–200 μm or when the NA is lower than 0.25. The same tendency is observed for the other bending radii; the reason is discussed in the next section. The GI POF with a core diameter of 200 μm and an NA of 0.24 (Fiber 4) exhibits effectively 0 dB of bending loss, even under 5-mm bending radius, as shown in Fig. 6. Thus, in order to reduce the bending loss in GI POFs to effectively 0 dB, an NA higher than 0.25 and a core diameter smaller than 200 μm are required.

C. Mode-Coupling Influence

The reason why the bending loss increases drastically when the core diameter is larger than 150–200 μm or when the NA is lower than 0.25, is investigated in detail by focusing on the mode coupling. This is because it is assumed in theoretical studies on silica MMFs that mode coupling from propagating modes to irradiative modes induces the bending loss [4]. For evaluating the mode-coupling strength in GI POFs, the NA of output light from GI POFs before and after bending is measured. In this evaluation, a static fiber bending is added near the output end, because the change in mode power distribution due to the bending can be observed clearly. If the point of the fiber bending is near the input side, redistribution of the modal power may occur during propagation through the rest of the fiber. The results are shown in Fig. 7, compared to those under OFL and to the theoretical limit of NA (broken line) calculated from the index profile. It is important that the restricted launch condition is adopted in this measurement. Therefore, almost all of the NAs obtained without fiber bendings are lower than those theoretically calculated. However, the output NA gradually increases with a decrease of the bending radius. This result means that the smaller bending radius (severe condition) enhances the mode coupling from low order to high order. When the GI

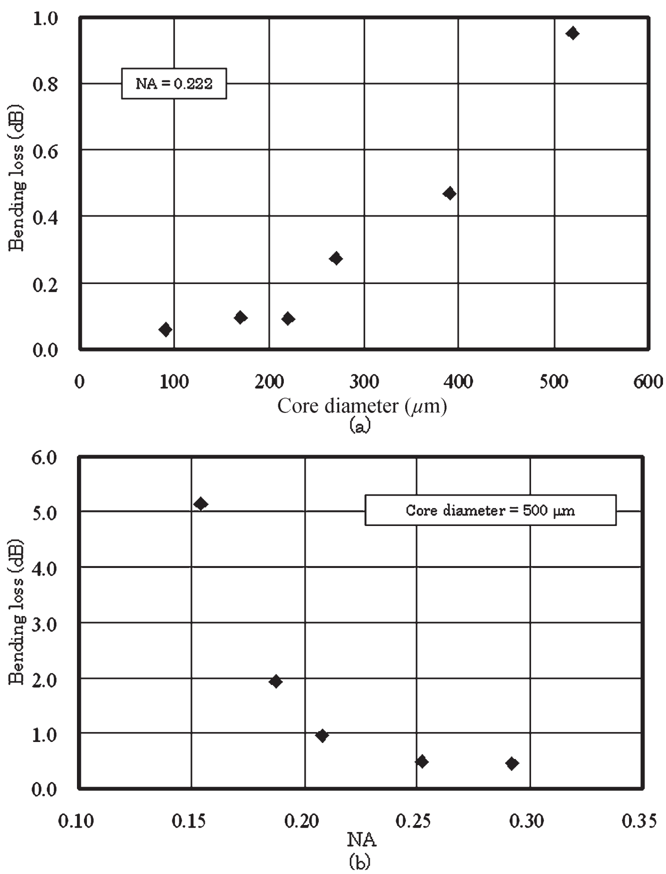

Fig. 5. Core diameter and NA dependence of bending loss (Bending radius = 5 mm). (a) Core diameter. (b) NA.

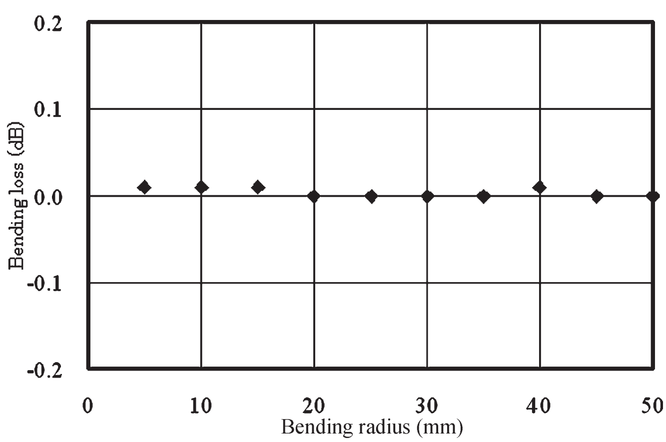

Fig. 6. Bending loss of GI POF (Fiber 4) with a core diameter of 200 μm and an NA of 0.24.

POF has an NA lower than 0.25 or a core diameter larger than 200 μm, the output NA under the most severe bending condition (5-mm radius) exceeds the NA theoretically calculated, as shown in Fig. 7 (■, ▲). This result indicates that the mode coupling is induced even between guided and leaky modes whose electric fields exist mainly in the cladding. On the other hand, in the GI POF with an NA of 0.252, as shown in Fig. 7 (♦), although the output NA increases with decreasing the bending radius, the output NA is still less than the value theoretically calculated even under the most severe bending condition. Therefore, in the GI POF with an NA of 0.252, the

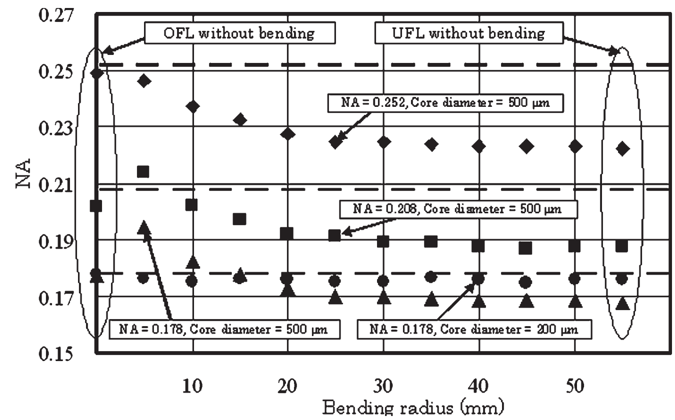

Fig. 7. NA of the GI POF determined by FFP before and after bending compared with the NA under OFL and with the theoretical limit of NA calculated from the index profile (broken line).

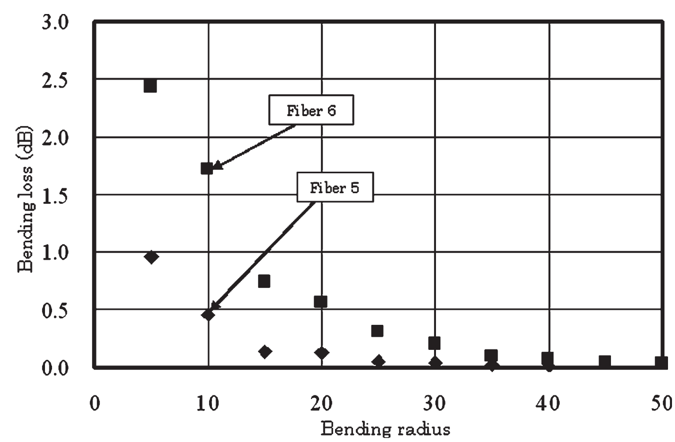

Fig. 8. Bending losses of the GI POFs with almost the same core diameter (500 μm) and NA (0.21).

mode coupling from the lower order to higher order modes is induced by the fiber bending, while almost all of the optical power is still confined in the core as the guided modes. Thus, the bending loss is small in such a high-NA GI POF.

If the NA is high enough, the bending loss is expected to be reduced, even when the mode coupling is induced by fiber bendings. However, since the higher order modes in GI POFs generally have higher attenuation than the lower order modes [12], some amount of bending loss is still observed when the mode coupling from lower order modes to the higher order modes occurs due to the bending, as shown in Fig. 5(b). On the other hand, in the GI POF with a core diameter of 200 μm, as shown in Fig. 7 (●), there is no change in the output NA, even under severe bending. The GI POF with a core diameter smaller than 200 μm exhibits a slight amount of bending loss that is caused by a little change in the propagating mode characteristics. On the other hand, the GI POF with a core diameter smaller than 200 μm and with an NA higher than 0.25 effectively exhibits 0 dB bending loss. Thus, it is experimentally confirmed for the first time that the mode coupling due to the bending induces the bending loss.

In some GI POFs, obviously different bending losses are observed, although they have the same core diameter and NA, as shown in Fig. 8. For analyzing the cause of the difference

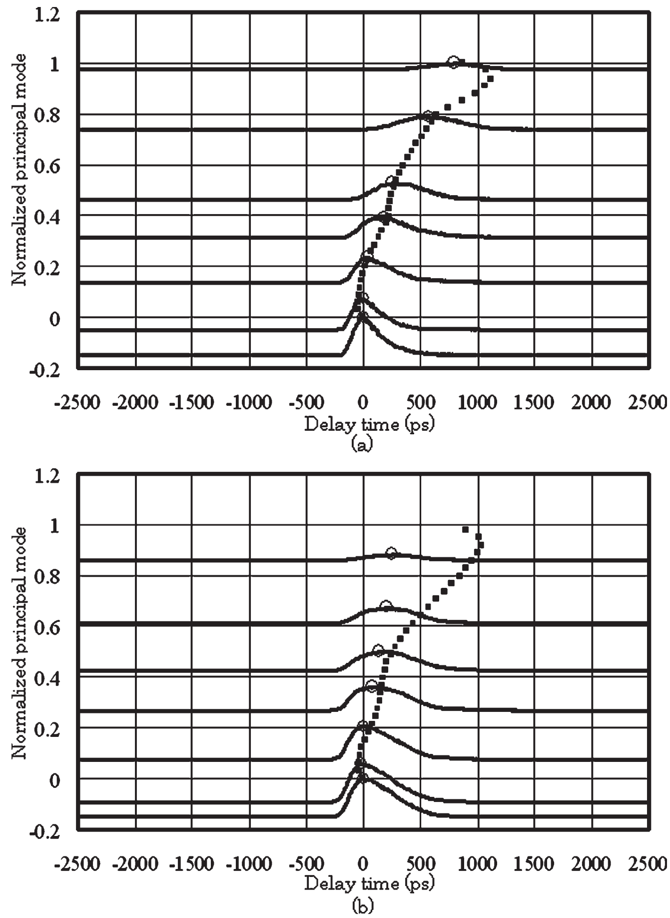

Fig. 9. Measured and calculated DMDs through (a) 100-m Fiber 5 and (b) 100-m Fiber 6 Solid line: Measured waveform, Open circle: Measured DMD, Closed square: Calculated DMD.

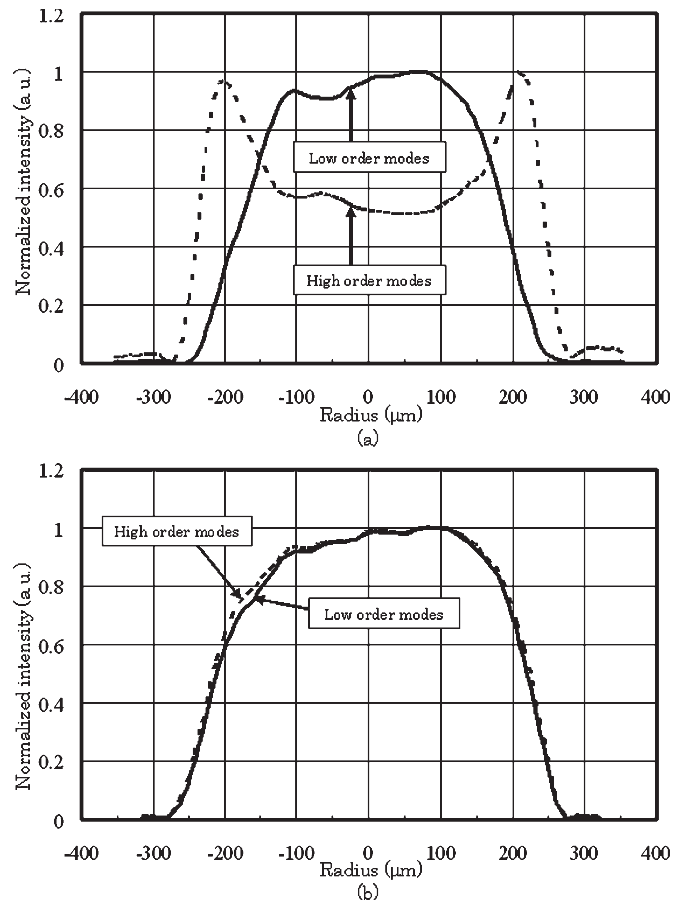

Fig. 10. NFPs of differential modes of (a) Fiber 5 and (b) Fiber 6.

in the bending losses, the propagating mode characteristics are analyzed in detail. The measured DMDs of the two representative 100-m GI POFs (core diameter $= 500\ \mu$m, NA $= 0.21$) are shown in Fig. 9, compared to those calculated. These DMD curves are theoretically calculated from their measured index profiles by the Wentzel–Kramer–Brillouin (WKB) method. In this calculation, the effect of mode coupling is not taken into consideration [4], [7]. Moreover, the NFPs of each mode group of the two GI POFs are shown in Fig. 10. In the case of Fiber 5, the measured DMD indicated by the open circles at the peak of waveform exhibit good agreement with the calculated one (closed square), as shown in Fig. 9(a), and the launch condition dependence of the NFP is clearly observed, as shown in Fig. 10(a). These results mean that the mode-coupling influence is small enough in Fiber 5. On the other hand, Fiber 6 shows almost the same delay time in all the mode groups, and they show large difference from the calculated curve (closed square), as shown in Fig. 9(b). In addition to the DMD results, almost the same NFP is observed when any mode group is launched selectively, as shown in Fig. 10(b). These results indicate that the mode-coupling influence is quite large in Fiber 6, even when no mechanical stress, such as bending, is provided. Therefore, we can conclude that the difference of mode-coupling strength before the fiber is bent causes the difference of the bending loss and that stronger mode coupling induces higher bending loss.

D. Optimum Design of Waveguide Parameter for Zero Bending Loss

The mode-coupling strength can be quantitatively analyzed by the propagation constant difference ($\Delta\beta$) between the adjacent modes. The propagation constant β is calculated by the following equation if the index profile is approximated by (1):

$$\beta = \left[k^2 n_1^2 - 2\left(\frac{g+2}{g}\frac{M}{a^2}\right)^{\frac{g}{g+2}} \left(n_1^2 k^2 \Delta\right)^{\frac{2}{g+2}}\right]^{\frac{1}{2}} \qquad (2)$$

where k is the wavenumber, n_1 is the refractive index of the core center, g is the index exponent, a is the core radius, and M is the normalized principal mode number [13]–[15]. If two modes have the same propagation constant, namely $\Delta\beta = 0$, these modes are called degenerate modes. On the other hand, if the value of the $\Delta\beta$ is large, the probability of energy transfer between these two modes decreases; thus, little mode coupling is observed. The $\Delta\beta$ is a function of a, n_1, and Δ, which determine the NA.

The $\Delta\beta$ values of the fabricated GI POFs are calculated numerically from their measured index profiles by the WKB method in this paper [4], [7]. The results of the GI POFs (Fibers 1–3) with different core diameters and NAs shown in Fig. 11. The $\Delta\beta$ increases with decreasing the core diameter (compare Fibers 1 and 2) and with increasing the NA (compare Fibers 2 and 3). The GI POF, which exhibits lower bending loss, has

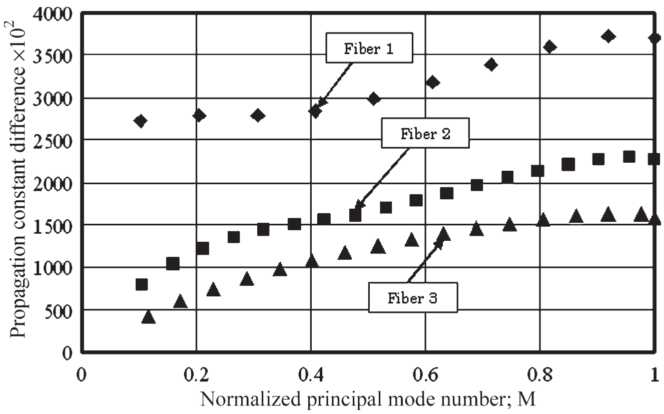

Fig. 11. Difference in propagation constant between adjacent modes ($\Delta\beta$) in Fibers 1–3, which have different core diameters and NAs.

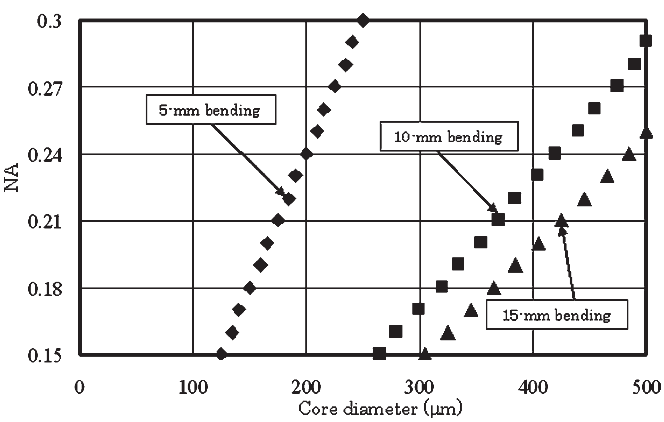

Fig. 12. Optimum waveguide parameters of GI POF to suppress the bending loss.

larger $\Delta\beta$ value, as shown in Figs. 4 and 11. Therefore, we can conclude that the $\Delta\beta$ value which is a function of the core diameter and NA affects the bending loss.

The $\Delta\beta$ values of the GI POFs with various core diameters and NAs are calculated by (2) and compared to the $\Delta\beta$ of the GI POF (Fiber 4) that shows effectively 0 dB of bending loss under 5-mm bending radius. Then, the sets of core diameter and NA which have the same $\Delta\beta$ as that of Fiber 4 are plotted (♦) in Fig. 12. Thus, the plots signify the combination of the maximum core diameter and the minimum NA to maintain the bending loss as low as, effectively, 0 dB, even under the severe (5 mm) bending condition. Additionally, the $\Delta\beta$ of the GI POF that shows effectively 0 dB bending loss under 10- and 15-mm bending radii are calculated from the experimental results. Subsequently, the sets of the maximum core diameter and the minimum NA are also shown in Fig. 12 in the same way as for the 5-mm bending radius. If the mode coupling without fiber bending is small enough, we can design the appropriate waveguide parameters of GI POF to achieve effectively 0-dB bending loss according to Fig. 12.

IV. Conclusion

The GI POF with a core diameter of 200 μm and an NA of 0.24 exhibits effectively 0 dB of bending loss, even under the severe bending condition. We experimentally confirm that the mode coupling due to the bending induces the bending loss. Further, we demonstrate that the original mode-coupling strength without bending seriously affects the bending loss and that stronger mode coupling induces higher bending loss. Therefore, the mode-coupling strength can be evaluated by the $\Delta\beta$ value, which is a function of the core diameter and NA. We confirm that the $\Delta\beta$ value affects the bending loss. For the first time, we propose an appropriate design of waveguide parameters of GI POF to suppress the bending loss from the $\Delta\beta$ value calculation.

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Kenji Makino was born in Tokyo, Japan, on February 8, 1978. He received the B.S. degree in applied physics and physico-informatics and the M.S. degree in integrated design engineering from Keio University, Yokohama, Japan, in 2001 and 2003, respectively. He is currently working toward the Ph.D. degree in integrated design engineering at Keio University.

His current research interests are in optimum design of high-speed GI POF link.

Takaaki Ishigure (M'00) was born in Gifu, Japan, on July 30, 1968. He received the B.S. degree in applied chemistry and the M.S. and Ph.D. degrees in material science from Keio University, Yokohama, Japan, in 1991, 1993, and 1996, respectively.

He is currently an Assistant Professor with Keio University. He has been, concurrently, a Group Leader of the Japan Science and Technology (JST) Agency Exploratory Research for Advanced Technology (ERATO)-Solution-Oriented Research for Science and Technology (SORST) project. In 2005, he stayed at the Department of Electrical Engineering, Columbia University, New York, NY, as a Visiting Research Scientist. His current research interests are in the preparation of high-bandwidth graded-index plastic optical fibers (GI POF) and their system design.

Yasuhiro Koike (M'03) was born in Nagano, Japan, on April 7, 1954. He received the B.S., M.S., and Ph.D. degrees from Keio University, Yokohama, Japan, in 1977, 1979, and 1982, respectively, all in applied chemistry.

He has been a Professor with Keio University and developed the high-bandwidth GI POF. He has been, concurrently, the director of Japan Science and Technology Agency ERATO-SORST project. He stayed as a visiting researcher at AT&T Bell Laboratories, Murray Hill, NJ, from 1989 through 1990.

Dr. Koike received the International Engineering and Technology Award of the Society of Plastics Engineers in 1994 and the Fujiwara Award in 2001.