Analysis of Graded-Index Polymer Optical Fiber Link Performance Under Fiber Bending

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***Abstract*—Bending effects on bandwidth and loss of a graded-index polymer optical fiber (GI POF) were investigated, and those influences on the optical link performance were discussed simultaneously for the first time. The numerical apertures (NAs) of the GI POFs were deliberately varied from 0.154 to 0.292. A bending radius larger than 10 mm induced little mode coupling and little change in the bandwidth of the GI POF. A bending radius smaller than 10 mm caused degradation in the bandwidths of the higher NA GI POFs. On the other hand, in the lower NA GI POFs, even more severe bending could cause little change in their bandwidths. Thus, the lower NA GI POF seemed preferable in suppressing the bandwidth change. However, the higher NA GI POF exhibited the lower bending loss. The preferable NAs for both characteristics were completely opposite. Moreover, the bending loss under underfilled launch (UFL) could be lower than that under overfilled launch (OFL). On the other hand, the bending loss was equivalent to the bandwidth degradation in view of the link power penalty. Therefore, the bandwidth change and loss caused by the bending were the critical factors to optimize the optical link considering the link power budget. The high-NA GI POF with almost ideal refractive-index profile could provide stable high performance in overgigabit communication even under any bending conditions.**

***Index Terms*—Bending loss, fiber bending, graded-index polymer optical fiber (GI POF), link power penalty, mode coupling, numerical aperture (NA).**

I. Introduction

DATA traffic over private intranets and the Internet has been recently growing explosively, accompanied by a great increase in the available network bandwidth. The Ethernet is now used in most local area networks (LANs) all over the world. In the physical media-dependent (PMD) issues of the Gigabit Ethernet, the silica-based multimode fiber (MMF) has been adopted to provide an inexpensive optical link with a combination of vertical-cavity surface-emitting laser (VCSEL)-based transceivers [1]. However, it would not be necessarily the best solution to distribute such silica-based optical fibers even in home networks.

On the other hand, a polymer optical fiber (POF) having a much larger core than that of silica fibers has been expected to be the office- and home-network media [2], because its large core allows the use of an inexpensive injection-molded plastic connector, which can dramatically decrease the total link cost. A high-bandwidth graded-index polymer optical fiber (GI POF) was proposed for the first time [3] and its bandwidth characteristics have been reported [4], [5].

In the PMD issues of the Ethernet and/or IEEE 1394, a bit-error rate (BER) lower than 10^{-12} is specified in order to achieve reliable data transmission [1]. Actually, such a BER performance has been very important in specifying and designing the optical PMD portions of the Gigabit Ethernet. In particular, a power penalty due to the dispersion of the fiber has been fully discussed in the Gigabit Ethernet standardization process because the power penalty in the MMF link could dominate the limited power budget [1]. The silica-based MMF with a central index dip had a reduced bandwidth, which was one of the main reasons why the specification and designing of the PMD issue were very difficult. The "offset launch technique," which can selectively excite a specified mode group, has been developed to improve the bandwidth [6], [7]. However, in LANs such as office and home networks, many fiber bendings, embranchments, and junctions are expected. Such mechanical bendings of MMFs cause mode coupling by which optical power transfers among the propagating modes. Then, severe mode coupling reduces the advantage of the restricted launch condition and causes a significant degradation in the bandwidth. In this paper, therefore, the bending effects on the bandwidth and loss of the GI POF were investigated, and those influences on the optical link performance were discussed simultaneously for the first time.

II. Experimental

A. Formation of GI POF

A GI POF was obtained by the heat-drawing of a graded-index preform at 220–240 °C. The fiber and core diameters were set to 750 and 500 μm, respectively, throughout this paper. The preform was prepared by the interfacial-gel polymerization process. A parabolic refractive-index profile could be formed in the preform by the process. The process consisted of the steps described as follows [3], [4]. A poly methyl methacrylate (PMMA) tube was prepared by bulk polymerization from purified MMA monomer. The tube was filled with a mixture of MMA monomer, dopant, polymerization initiator, and chain transfer agent. The tube was heated in an oil bath at 90 °C to induce polymerization. The inner wall of the tube was swollen by the monomer mixture to form a polymer gel phase on the inner wall of the tube. The polymerization proceeded from the inner wall to the center of the tube due to the gel effect. During

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TABLE I
CHARACTERISTICS OF THE PREPARED GI POFs

Fiber		1	2	3	4	5
NA		0.292	0.252	0.208	0.187	0.154
Index exponent: g		4.0	2.3	3.7	2.9	3.3
Bandwidth (GHz)	UFL	0.347	3.08	1.02	2.97	2.50
	OFL	0.133	2.62	0.565	3.12	2.35

the polymerization process, the dopant molecules were concentrated into the center of the tube to provide a nearly quadratic refractive-index profile in the core region [3]. The polymerization reaction rate could control the refractive-index profile. The rate was controlled by changing the kind and concentration of the dopant, polymerization initiator, and chain transfer agent [4]. A lot of GI POF samples having various NAs were experimentally obtained, and their properties were evaluated. Then, five representative GI POFs were selected, and their characteristics are shown in Table I.

B. Refractive-Index Profile

The modal dispersion is generally a dominant factor in distorting the output pulse waveform through multimode optical fibers. However, the modal dispersion can be minimized by forming a quadratic refractive-index profile. The bandwidth of the MMF is strongly affected by the perturbation of the index profile. In order to analyze the relation between the refractive-index profile and the bandwidth of the GI POF, the refractive-index distribution in the core of the GI POF was approximated by the well-known power-law equation

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

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, called the refractive-index exponent, can determine the refractive-index profile. We already reported that the optimum value of the index exponent $(g_{\rm opt})$ was 2.0 when only modal dispersion was considered in a Wentzel–Kramers–Brillouin (WKB) analysis, while the $g_{\rm opt}$ of the PMMA-based GI POF shifted to around 2.4 at 650-nm wavelength when both modal and material dispersions were taken into account [8].

We also reported that the refractive-index profile of the GI POF could be precisely controlled by the interfacial-gel polymerization technique [4], [9]. The refractive-index profile of the fabricated GI POF was experimentally measured with an interferometric microscope [3].

C. Bandwidth Measurement

The bandwidths of the GI POFs were measured by a time-domain method. An InGaAsP laser diode (LD) at a 650-nm wavelength was utilized as the light source in which a lens system was used to focus the beam. A short light pulse was injected into the GI POF, and the output pulse waveform was measured by a sampling head, recorded and analyzed by a sampling oscilloscope (HAMAMATSU OOS-01). In the bandwidth measurement of the GI POFs, a launch condition was one of the important issues. The bandwidth measurement of a silica-based MMF required steady-state mode power distribution in 1970s research, because the steady-state mode power distribution was generally established in the silica-based MMF links combined with light-emitting diode (LED)-based transceivers [10]. Therefore, all modes should be fully excited in order to achieve the steady-state mode power distribution. However, current interests in MMF links are in the restricted launch condition [7] because the MMF is adopted in high-bit-rate ($>$ 1 Gb/s) links where LD- or VCSEL-based transceivers are used.

In this paper, two launch conditions were adopted: underfilled launch (UFL) and overfilled launch (OFL). In the UFL condition, the beam focused by the lens system in the LD was directly coupled onto the core center of the GI POF. The measured beam spot size was 6.48 μm, and the measured NA was 0.157. Therefore, the UFL condition could selectively excite only lower order mode groups. In another condition (OFL), a pulsed signal from the LD was injected into a 1-m step-index (SI) POF first, and then the output pulse from the SI POF was coupled to the GI POF by directly butting their ends on a V-groove. The power distribution at the output end of the 1-m SI POF was uniform in the whole core region whose diameter (980 μm) was much larger than that of the GI POF (500 μm). Moreover, the NA of the SI POF (0.5) was sufficiently higher than that of the GI POF ($<$ 0.3). Therefore, the 1-m SI POF was considered as an ideal all modes exciter for the GI POF.

D. Link Performance Evaluation

The PMMA-based GI POF is a prime candidate for a physical media for the high-speed office and home networks. A link power penalty is a very important parameter in designing such optical networks. The link power penalty was theoretically calculated by a power budget calculation model [1], [6].

The modal noise has been one of the serious problems in silica-based MMF links, because the modal noise also induces a degradation of optical signal. The modal noise was caused by the interference of propagating modes that create a time-varying speckle pattern. When a mode selective loss such as a misaligned connector exists in the MMF links, the speckle causes the modal noise. The modal noise penalty depends on the laser characteristics and the link configurations, which make it difficult to express the modal noise penalty by a simple equation. Furthermore, we have reported that the modal noise in the large core GI POF link is practically eliminated [11], [12]. Consequently, the penalty due to the modal noise was neglected in the estimation in this paper.

Some parameters required to calculate the power penalty were determined experimentally, such as bandwidth of the fiber, root-mean-square (rms) spectral width of the laser, etc. The others were set to their typical values [5].

E. Bending Condition

A static bending of the GI POF was provided at a 1-m distance from the laser (650-nm wavelength) input end with a 90°

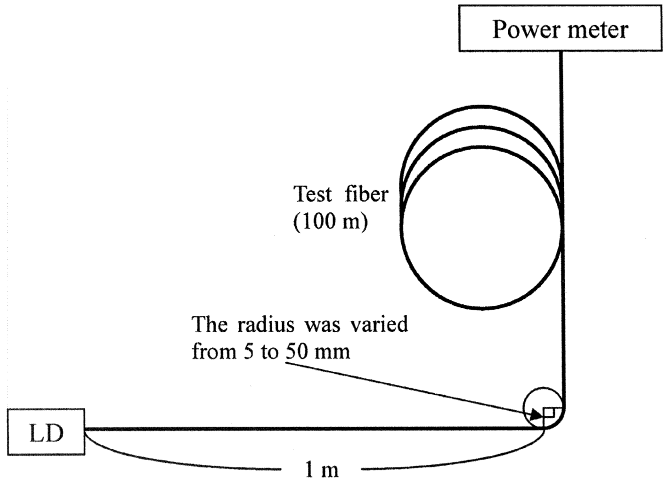


Fig. 1. Schematic diagram of the bending condition.

bending angle, and the bending radius was varied from 5 to 50 mm in 5-mm steps, as shown in Fig. 1. A bending loss was determined by the difference of the output optical powers before and after the bending. The output power was measured by an optical power meter (ANDO AQ2140). The bending influence on the bandwidth was also investigated by comparing the results before and after the bending.

III. Results and Discussion

A. Optical Power Distribution

The mode power distributions under UFL and OFL were evaluated by an encircled-flux (EF) calculated from a two-dimensional near-field pattern [13]. The EF signifies the normalized total optical power propagating in an optical fiber as a function of the fiber radius. Fig. 2(a) shows the EFs of the 100-m GI POFs with small mode coupling (fiber 2) measured under UFL and OFL, compared with those of 5-m [Fig. 2(b)]. As a comparison, the EF of 100-m GI POF with large mode coupling is also shown in Fig. 2(c).

At the input end [Fig. 2(b)], the quite different EFs are observed according to the launch conditions (UFL and OFL). On the other hand, in the 100-m GI POF, the difference in EFs between UFL and OFL is small, even if the small mode coupling was observed in the GI POF by the other measurement method. This is because the input optical power was redistributed to not only the low-order modes but also the intermediate-order modes in proportion to the normalized mode intensity. That means the power redistribution to the propagating modes is completed after the propagation longer than 5-m distance. Therefore, the EF under UFL after 100 m is wider than that after 5 m. That is why even the core–cladding boundary has some amount of optical power. Another reason is that the EF under OFL after 100-m transmission becomes narrower due to the differential-mode attenuation. The EF under OFL after 100 m is narrower than that observed after 5 m. This narrow EF despite the OFL condition is due to the highly attenuated high-order modes. Because of these two effects, the EF profiles under UFL and OFL after 100-m transmission became close compared with those after 5-m transmission.

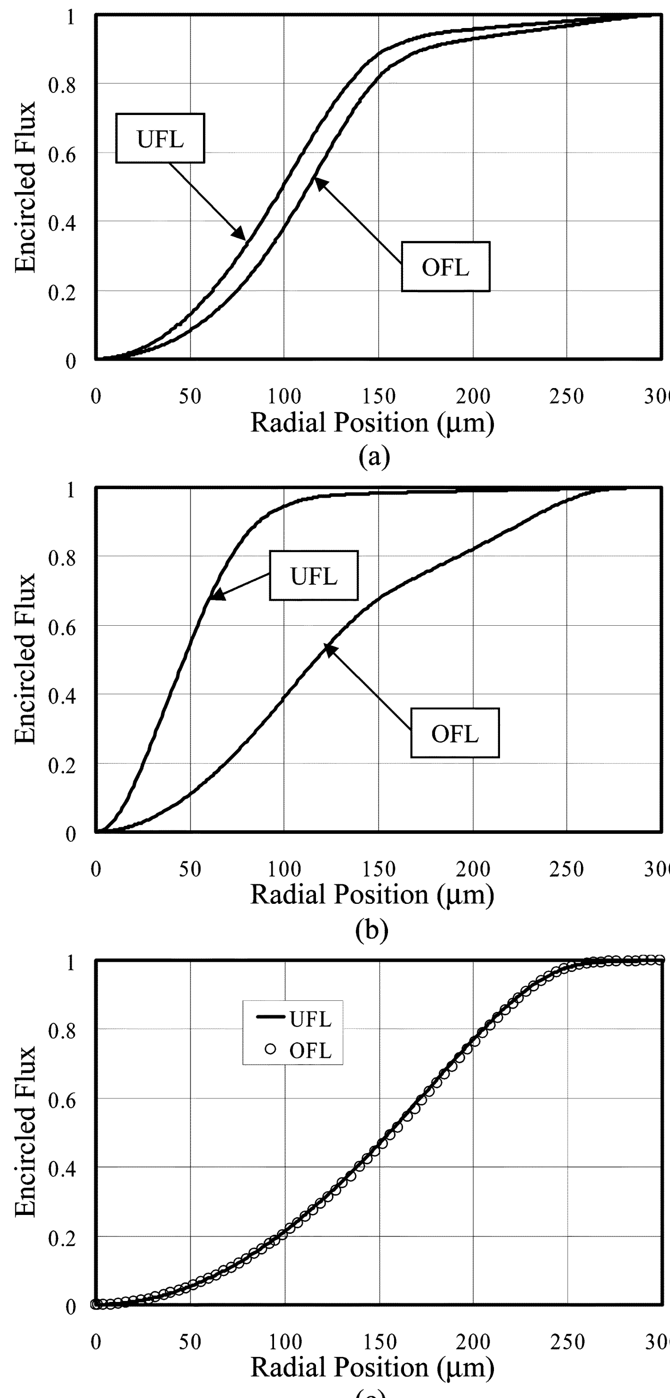


Fig. 2. EFs of the (a) 100-m and (b) 5-m GI POFs with small mode coupling (fiber 2) under UFL and OFL, compared with that of (c) a 100-m GI POF with large mode coupling.

It should be noted that the EFs of the 100-m GI POF with large mode coupling under UFL and OFL exhibit completely the same profile. In this case, the EF shows gradual increase with respect to the radial position, and optical output is observed even at the core–cladding boundary. This is because the strong mode coupling averaged the differential-mode attenuation.

The EF under UFL of fiber 2 had a steeper slope than that under OFL even after 100-m transmission, as shown in Fig. 2(a),

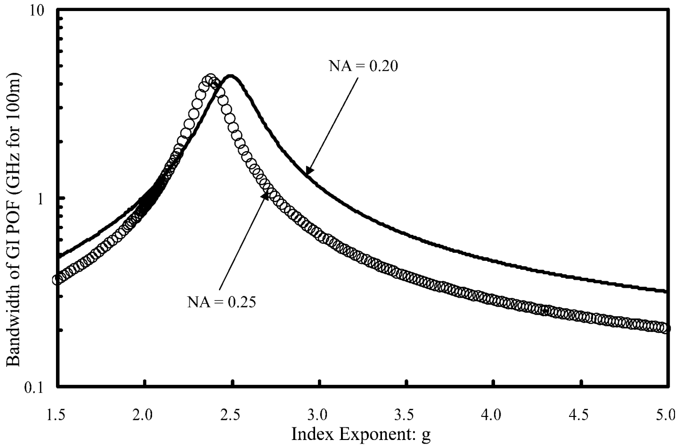


Fig. 3. Relation between index exponent g and bandwidth of 100-m PMMA-based GI POF with different NAs: 0.20 and 0.25.

because of the small mode coupling, which meant that the optical power distribution under the UFL was more concentrated in near the core center, while that under the OFL showed a power profile that extended to the core–cladding boundary. Therefore, the EFs clarified that the modes excited by both the launch conditions were different. The launch conditions were maintained even after 100-m GI POF transmission.

B. Bending Effect on Bandwidth

Fig. 3 shows the calculated relation between the g value and the bandwidth of the PMMA-based GI POF with different NAs: 0.20 and 0.25 by assuming the OFL condition. The g value to achieve a bandwidth higher than 1 GHz for 100-m GI POF when the NA is 0.20 was in the range of 2.0–3.1, which indicated that an accurate index profiling was required. Moreover, the refractive-index profile of the GI POF could be precisely controlled by the two-step interfacial-gel polymerization technique [9]. On the other hand, our recent research has shown that the modal dispersion of the GI POF was strongly influenced by the NA of fiber when two GI POFs had the same index exponent value that was slightly deviated from the optimum value. In Fig. 3, if the index exponent is 3.0, the high-NA GI POF $(\mathrm{NA} = 0.25)$ theoretically shows the bandwidth of 500 MHz for 100 m, which is much lower than that (1 GHz for 100 m) of low-NA GI POF $(\mathrm{NA} = 0.20)$ with an index exponent of 3.0. In addition to the calculation, it was also verified experimentally. Fig. 4(a) shows the measured index profiles of the GI POFs having almost the same index profile $(g = 4.8)$, but with different NAs. In order to show the good agreement of g value in these two GI POFs, the profile function defined by (2) was calculated from the measured index profile in Fig. 4(a) and is plotted in Fig. 4(b). If measured index profile is well fitted to the power-law form described by (1), the profile function is equal to $(r/a)^g$

$$\text{Profile function}: f(r) = \frac{1 - \frac{n(r)^2}{n_1^2}}{2\Delta}. \tag{2}$$

Fig. 5 shows their bandwidth performances for 50 m under UFL and OFL. The index profiles of both GI POFs are indeed almost the same as shown in Fig. 4. Nevertheless, the bandwidth of the lower NA GI POF $(\mathrm{NA} = 0.21)$ is almost two times higher than that of the higher NA GI POF $(\mathrm{NA} = 0.30)$. Thus, even

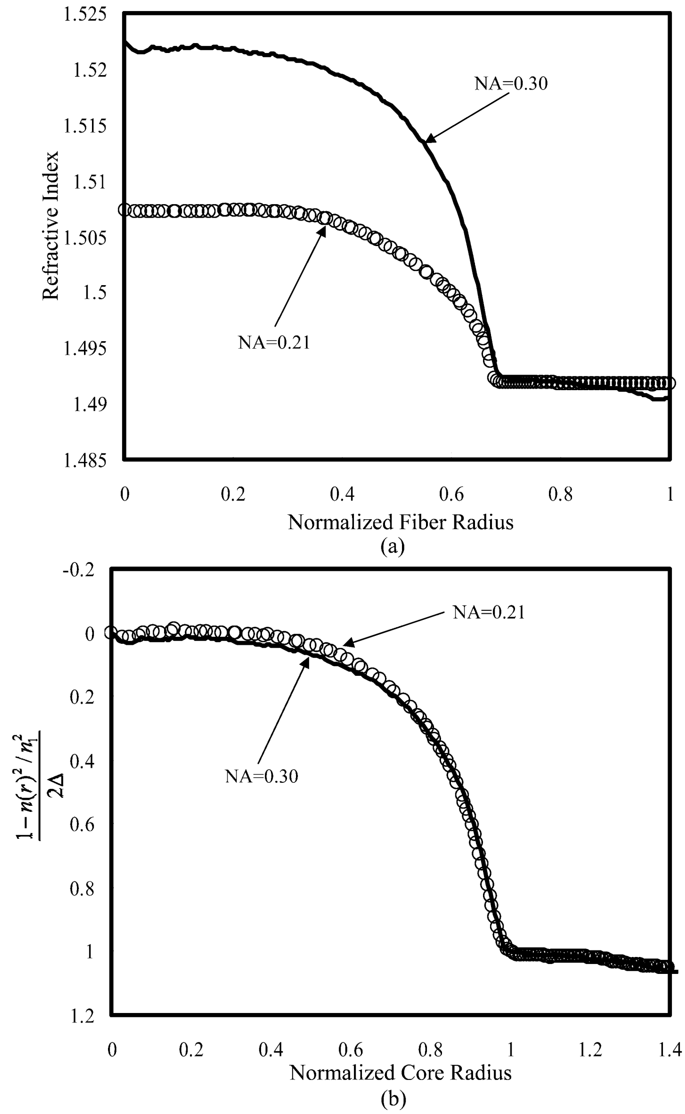


Fig. 4. (a) Measured refractive-index profile and (b) calculated profile function of the GI POFs having almost the same index profile $(g = 4.8)$ and different NAs.

if the refractive-index profile deviation from the optimum was small, a significant output pulse distortion is observed, particularly in the case of a high-NA GI POF. This is because the modal dispersion broadened the output pulse waveform and because the middle- and high-order modes had low attenuation in the high-NA GI POF. In the low-NA GI POF, the high-order modes tended to be greatly attenuated, while those in the high-NA GI POF were not attenuated but remained at high powers even after a 100-m transmission. Therefore, the high-order modes having large group delay maintained their powers, which degraded the output pulse waveform from the high-NA GI POF. Moreover, our recent research has also shown that the high-NA GI POF exhibits smaller mode coupling than the low-NA GI POF [14].

For instance, fiber 2 having high NA and fiber 4 having low NA showed almost the same bandwidth ($\sim$ 3.0 GHz) for 100 m under the UFL condition, as shown in Table I, although the g value of fiber 4 deviated more from the optimum value compared with that of fiber 2, as shown in Fig. 6. On the other hand, under the OFL condition, the bandwidth of fiber 4 was higher than that of fiber 2. Furthermore, the output pulse waveforms in

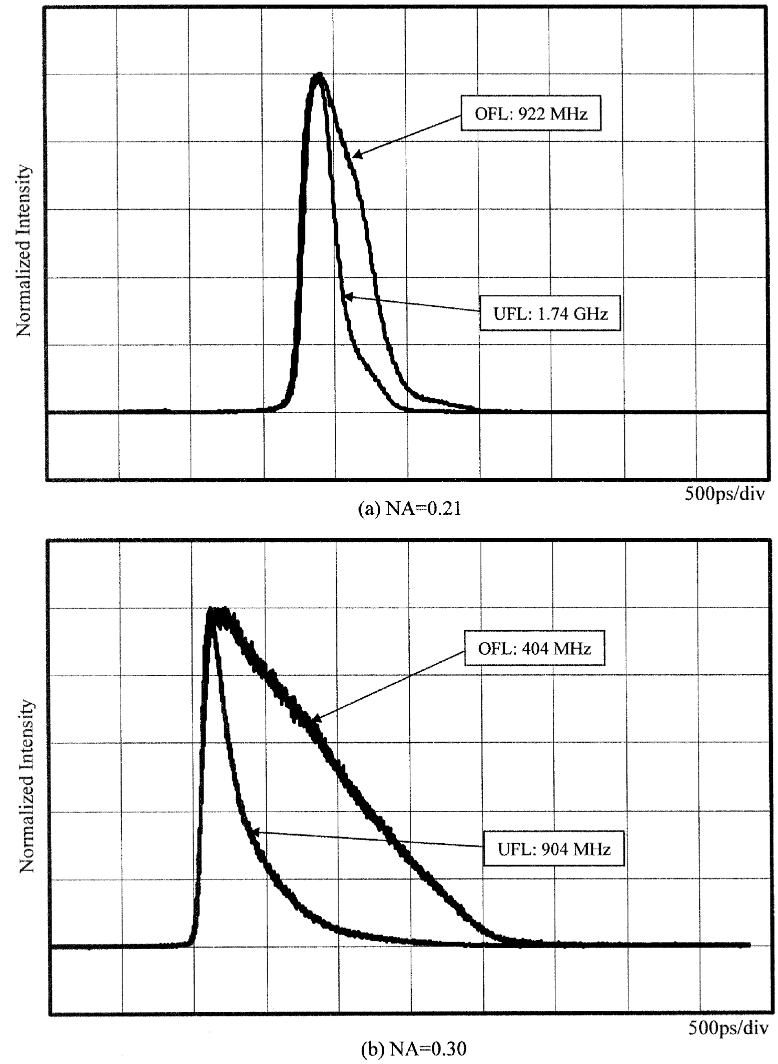


Fig. 5. Bandwidth performances of the 50-m GI POFs having almost the same index profile ($g = 4.8$) and different NAs.

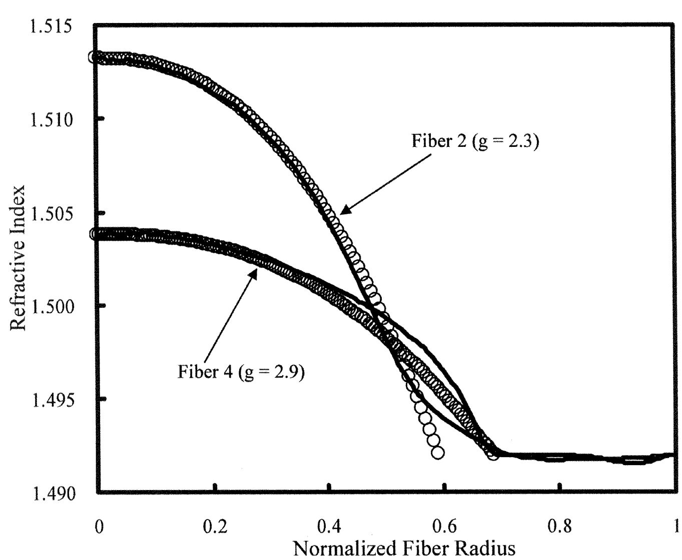


Fig. 6. Measured (solid line) refractive-index profiles of fibers 2 and 4 compared with optimum one (open circle: $g = 2.4$).

differential-mode delay (DMD) measurements of fibers 2 and 4 are shown in Fig. 7, where the rms width of each pulse is summarized. The high-order modes (m/M close to 1.0) of high-NA GI POF (fiber 2) show the broadened output pulse waveforms, and those are maintaining relatively high optical power compared with those of fiber 4. Those high-order modes with broadened waveforms degraded the bandwidth of fiber 2 under OFL. On the other hand, the bandwidth of fiber 4 under OFL is slightly higher than that under UFL, which is different from the others listed in Table I. The following four issues are currently under consideration as the reason.

1) In fiber 4, the rms pulsewidths of the high-order modes are narrower than those of the low-order modes, as shown in Fig. 7(b).
2) Almost all of the modes of fiber 4 have nearly the same group delay because of its near-ideal index profile and low NA.
3) The number of the propagating modes increases drastically with increasing principle mode number. That means the effect of the high-order modes on the output pulse is larger than that of low-order modes.
4) The output pulse waveform under OFL is formed by superposing the pulses of all modes. Therefore, in fiber 4, the output pulse waveform under OFL became narrower than that under UFL.

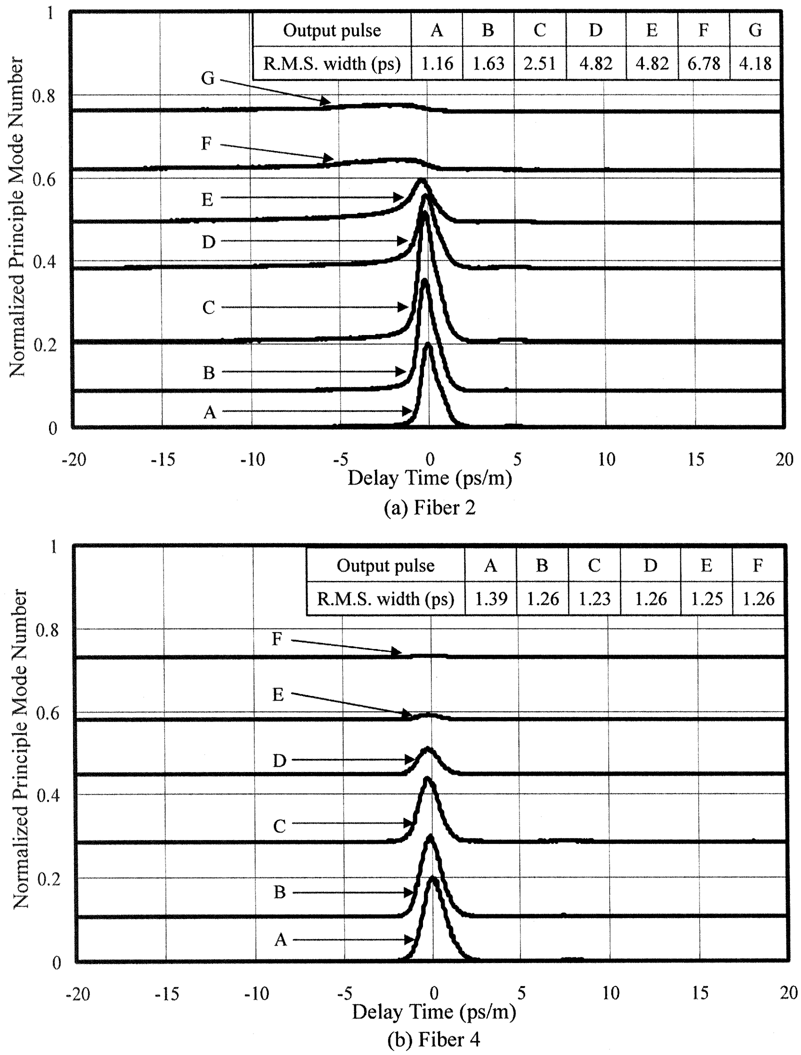


Fig. 7. Output pulse waveforms and their rms widths of differential-mode delay measurements of 100-m (a) fiber 2 and (b) fiber 4.

These results indicated that the refractive-index profile of the high-NA GI POF had to be more precisely controlled to be optimum in the whole core region to obtain a high bandwidth. However, the index profiles formed in the GI POFs are actually sensitive to the polymerization condition, and some profiles experimentally obtained were not necessarily controlled to that designed. Such a GI POF with nonideal index profile showed that the bandwidth under UFL was higher than that under OFL. This large launch condition dependence was observed in fiber 3, as shown in Table I, and the measured refractive-index profile of fiber 3 is shown in Fig. 8, where the approximated index exponent is 3.7, which is far from the optimum. The bandwidth performance of fiber 3 is shown in Fig. 9. Measured bandwidths for 100 m were 1.02 GHz under UFL and 565 MHz under OFL. Despite the nonideal index profile, more than 1 GHz of bandwidth for 100 m could be achieved when UFL was adopted. Thus, by utilizing the UFL condition, a range of the g value to cover a bandwidth higher than 1 GHz for 100 m is tolerated.

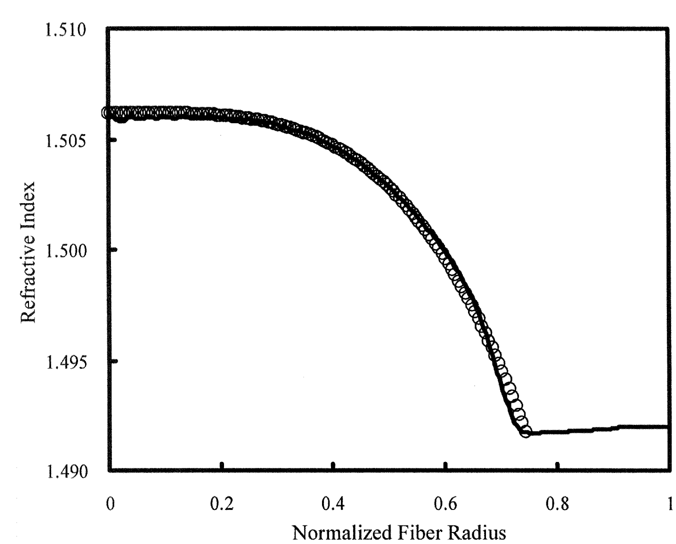


Fig. 8. Measured (solid line) and approximated (open circle: $g = 3.7$) refractive-index profiles of fiber 3.

However, even if a high bandwidth is observed under the UFL condition, mode coupling is a great concern, and bending of the fiber is generally considered to induce mode coupling [15]. If the GI POF is launched under the UFL condition, the mode coupling from the lower order modes to the higher order modes might lead to a mode power distribution close to that under OFL

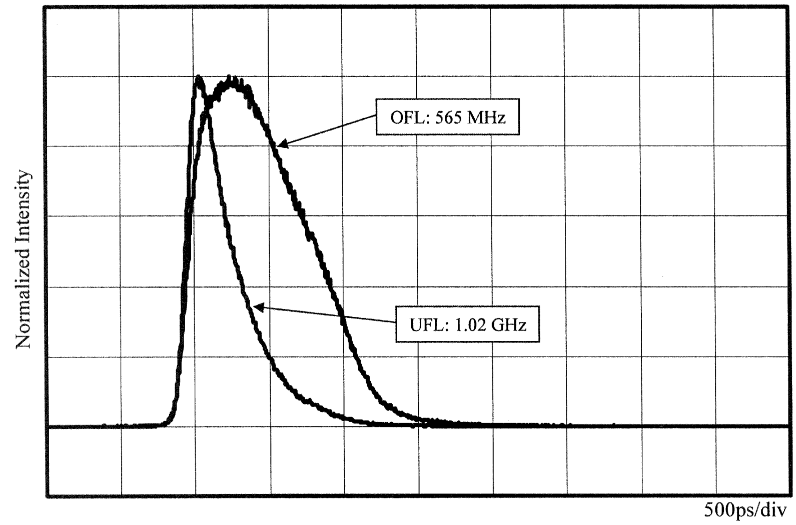


Fig. 9. Output pulse waveforms through 100-m fiber 3 under UFL and OFL.

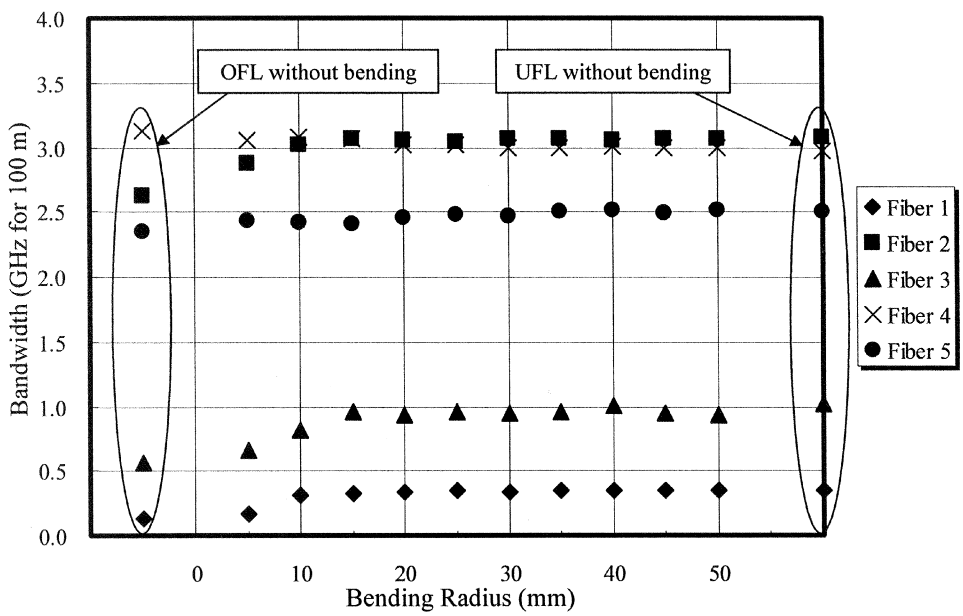


Fig. 10. Bandwidths of the GI POFs under UFL before and after bending compared with the one under OFL without bending.

condition, which could cause bandwidth degradation. Thus, it is a great concern that severe bending induces a serious degradation in the bandwidth of GI POF, particularly when the refractive-index profile is far from the optimum one.

Therefore, the effect of 90° bending on the bandwidths of the various GI POFs was investigated. The GI POFs (100 m) having different NAs and profiles were prepared by changing the conditions in the interfacial-gel polymerization process. The NA of the GI POF was deliberately varied from 0.154 to 0.292 by changing the dopant concentration. Fig. 10 shows the bandwidths of the GI POFs under UFL before and after bending compared with the one under OFL without bending. In the case of fiber 1, which has the representative nonideal index profile, the bandwidth under OFL without the bending is 133 MHz for 100 m, which can be regarded as the worst-case bandwidth, and 347 MHz for 100 m under UFL. The UFL bandwidth is approximately 2.5 times higher than the OFL bandwidth. It is found from Fig. 10 that a bandwidth higher than 300 MHz for 100 m is maintained even under the 10-mm bending condition in fiber 1. Thus, the bending caused little change in the bandwidths of the GI POFs when the bending radius was larger than 10 mm. From these results, it was confirmed that little mode coupling was caused by fiber bending even with such a small bending radius.

However, the bending with the radius smaller than 10 mm induces degradation in the bandwidth. This is clearly observed in a high-NA GI POF when we compare the results of fibers 1, 3, and 5. Since fibers 1 and 3 have nonideal index profiles ($g = 3.5$–4.0), a large difference is observed in the bandwidths between UFL and OFL. Therefore, the severe fiber bending degraded the bandwidth, even if the UFL condition was adopted as shown in Fig. 10. These results were explained by the mode coupling. The severe bending caused large mode coupling from the lower order mode group to the higher order mode group and made the mode power distribution close to that under the OFL condition. Thus, the number of the excited modes after

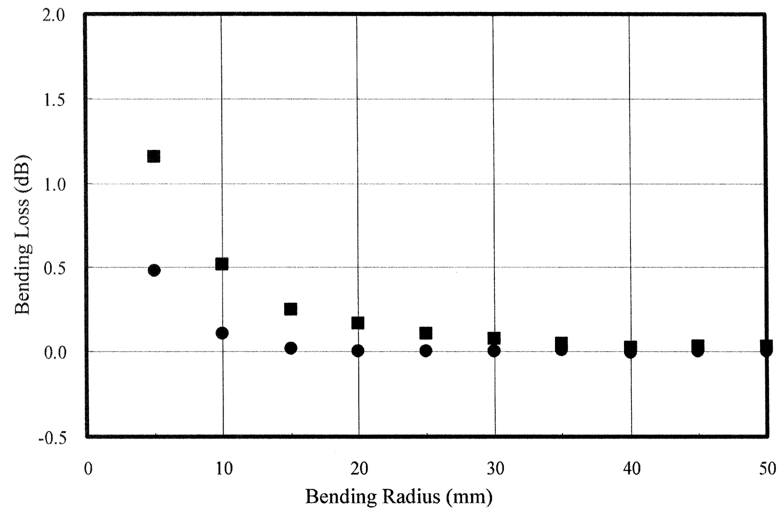


Fig. 11. Bending losses of fiber 2 under UFL and OFL.

bending became larger than that under the UFL condition without bending.

On the other hand, in the lower NA GI POFs, even more severe bending, for instance, multiple 90° bendings with a 5-mm bending radius, could cause little change in the bandwidths. Fiber 5 has a lower NA than the others, which reduces the modal dispersion despite the nonideal index profile ($g = 3.3$). This small modal dispersion of fiber 5 is indicated by the small difference of its bandwidths between UFL and OFL. Therefore, even under the severe bending, the bandwidth of a low-NA GI POF is less influenced. In addition to the small bandwidth difference between UFL and OFL in a low-NA GI POF, these GI POFs exhibited high attenuation in the middle- to high-order modes. Therefore, even the severe bending caused little change in their bandwidths. The same relation can be seen in the results of fiber 2 (high NA) and fiber 4 (low NA). From these results, the low NA of the GI POF seemed preferable to suppress the change in the fiber bandwidth due to the bending.

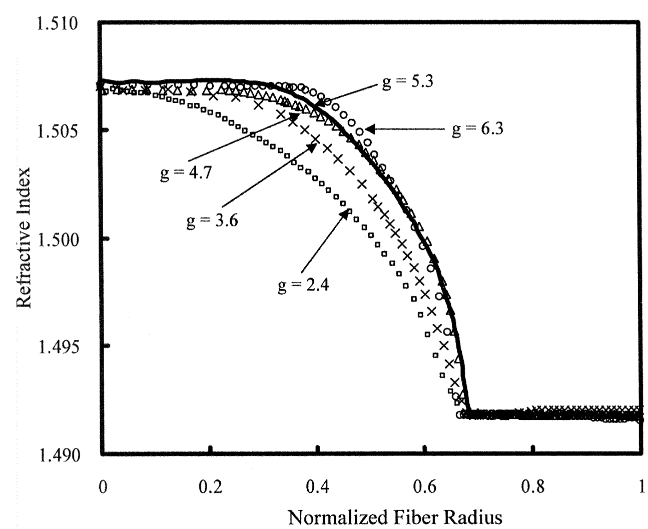


Fig. 12. Refractive-index profiles of the GI POFs with almost the same NA and core diameter.

C. Bending Loss

By the bending mentioned previously, an optical bending loss is caused as well as a bandwidth change. The bending loss of an MMF has been evaluated under an equilibrium modal distribution (EMD) similar to the bandwidth measurement. Fig. 11 shows the bending losses of fiber 2 under UFL and OFL with respect to the various bending radii when they are statically bent with a 90° bending angle. The bending loss under UFL is lower than that under OFL. The result indicated that even if the fiber that was launched under UFL was bent, the optical power remained in the core as a propagating mode (not a leaky mode), although it could transfer from the low-order mode to a high-order mode. In addition, the UFL condition was examined as a real launch condition in the Gigabit Ethernet. Therefore, in this paper, the UFL condition was also adopted in the bending loss measurement.

The bending losses of the GI POFs having the same NA and core diameter, while different index profiles were investigated in order to clarify the influence of the index profile on the bending loss. Fig. 12 shows the refractive-index profiles ($g = 2.4$–6.3) of the GI POFs having almost the same NA and the same core diameter. Fig. 13 shows their bending losses. The bending loss is theoretically derived to be dependent on the index profile [16]. However, the bending loss of the GI POF did not strongly depend on the refractive-index profile experimentally as shown in Fig. 13. The reason why the bending loss is independent on the index profile is considered that the launch condition was UFL different from the assumption in the theory, or this characteristic can be original in large core GI POF. This index profile independence of the bending loss will be investigated in more detail in different article. Therefore, in this paper, the influence of the index profile was negligible even in such a wide variance in the g value, although particular index profiles such as W-shaped [17] or double g profile [14] might exhibit large effects on the bending loss. Therefore, the effect of the NA on the bending loss was investigated by using the five GI POFs shown in Table I as the test fibers.

Fig. 14 shows the bending losses of the GI POFs having different NAs. The higher NA allows the lower bending loss as expected theoretically, which is observed in the results of fibers 3–5. On the other hand, fibers 1 and 2 exhibit almost the same

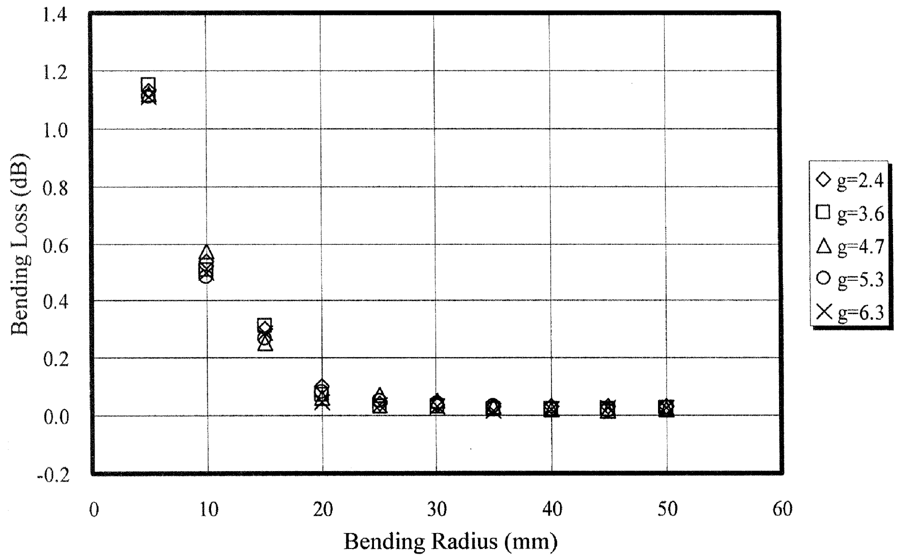


Fig. 13. Bending losses of the GI POFs with different index profiles.

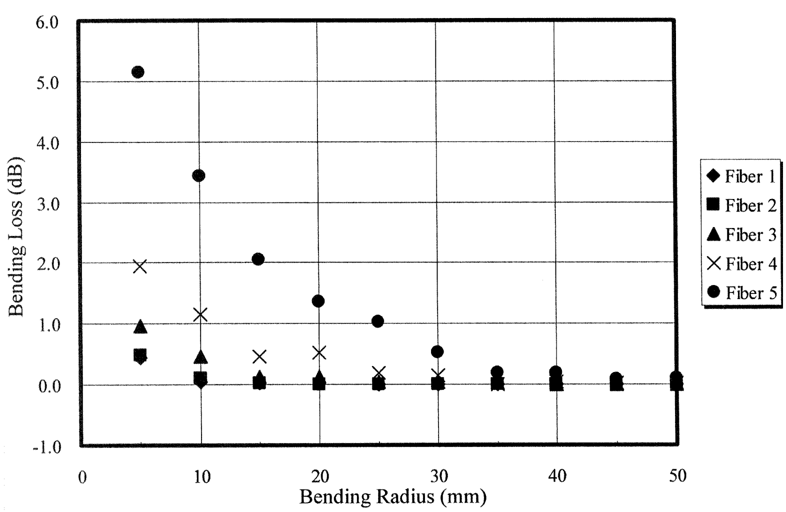


Fig. 14. Bending losses of the GI POFs with different NAs.

bending losses, which means that the NA of fiber 2 (0.252) is high enough for the GI POF with a 500-μm diameter under the UFL condition. Thus, the GI POFs with a NA higher than 0.25 seemed preferable to suppress the bending loss.

D. Optical Link Performance Under Bending

In the previous discussion in this paper, the bending loss and bandwidth degradation due to bending were evaluated independently. The preferable NAs for both characteristics are completely opposite. In this paper, those effects on the optical link performances were discussed simultaneously for the first time. In order to quantitatively evaluate the optical link performance, the link power penalty was theoretically calculated. In the calculation process, two basic factors (data rate and BER) were determined first, as 1.25 Gb/s and 10^{-12}, respectively, which are adopted in a standard of the Gigabit Ethernet PMD [1], [6]. Fig. 15 shows the calculated relation between the fiber bandwidth and the link power penalty for 1.25-Gb/s transmission.

The optical link performance was quantitatively evaluated using the relation shown in Fig. 15 when a fiber bending was involved in the link. Since the bandwidth of fiber 5 was 2.50 GHz for 100 m without bending, as shown in Fig. 10, it was found from Fig. 15 that the power penalty in the link of fiber 5 was 0.24 dB, as shown by the open circle in Fig. 15. When the bending radius was 10 mm, the bending of fiber 5 caused degradation in the bandwidth to 2.42 GHz for 100 m, where the power penalty increment was only 0.02 dB, which seemed negligible. However, the bending loss of fiber 5 was 3.44 dB, as shown in Fig. 14. The bending loss is generally included in the power budget as a power margin, which means the bending loss could be substituted for the power penalty; hence the bending loss is equivalent to the change in the fiber bandwidth. Therefore, the power penalty of fiber 5 became 3.70 dB under the bending shown by the closed circle in Fig. 15, which corresponded to the penalty when the fiber bandwidth was 687 MHz with no bending. This large bending loss played the same role as the degradation in the fiber bandwidth from 2.50 GHz to 687 MHz.

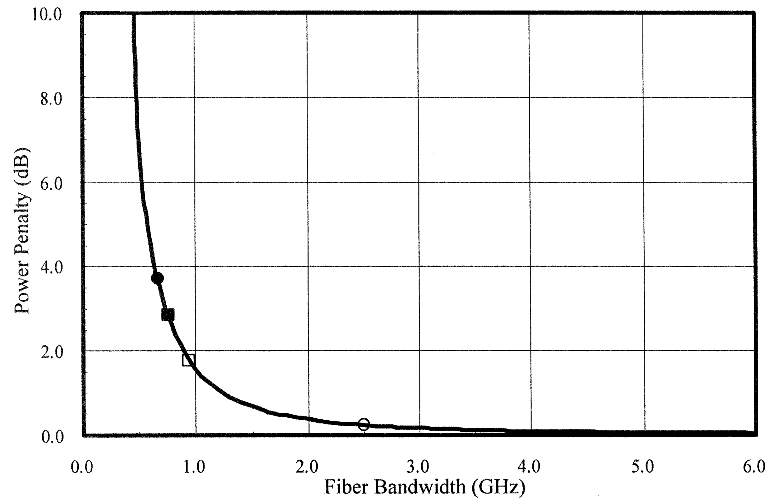


Fig. 15. Calculated relation (solid line) between the fiber bandwidth and the power penalty for 1.25-Gb/s transmission (fiber length = 100 m). ○: The link performance of fiber 5 without bending. ●: The link performance of fiber 5 under the 90° bending with 10-mm radius. □: The link performance of fiber 3 without bending. ■: The link performance of fiber 3 under the 90° bending with 10-mm radius.

On the other hand, the bandwidth of fiber 3 was 944 MHz for 100 m without bending shown by the open square in Fig. 15, which caused a power penalty of 1.77 dB (larger than the original value of fiber 5). Such a large penalty, in general, is not preferable. When the bending radius was 10 mm, the bandwidth was degraded to 819 MHz for 100 m by the bending, where the power penalty increment was 0.61 dB; however, the bending loss was only 0.45 dB (much lower than that of fiber 5). Therefore, the power penalty of fiber 3 became 2.83 dB under the bending shown by the closed square in Fig. 15, which corresponded to the penalty when the fiber bandwidth was 754 MHz without bending.

Note that although fiber 5 originally had a much higher bandwidth than fiber 3, fiber 3 showed a superior link performance to fiber 5 under the bending because of its low bending loss. Thus, the low bending loss is required for the GI POF as a LAN medium even if the bending radius is smaller than 10 mm, because both mechanical strength and optical performance are very important to enable user friendly wiring.

On the other hand, in the Gigabit Ethernet standard, a power penalty lower than 3.6 dB is allotted for the fiber. Therefore, the fiber 5 link performance under the bending is not acceptable. When the GI POF has a higher NA than 0.25, the bending loss under UFL is at most 0.5 dB, as shown in Fig. 14, and then the penalty increment caused by the bandwidth degradation is allowed to be 3.1 dB, which means a bandwidth higher than 720 MHz is acceptable. Therefore, the allowed range of the g value for 100-m GI POF is from 1.9 to 2.9, even when the GI POF is launched under the OFL condition, which is considered as one of the worst cases.

These results were attributed to the difference of the NAs of the GI POFs. Therefore, the NA is very important parameter in designing the GI POF for reliable high-speed networks, even if the UFL is adopted as a launch condition. We concluded that a high-NA GI POF with a near-ideal refractive-index profile, just like fiber 2, could provide stable, high performance in high-speed data transmission, even under any bending conditions.

IV. Conclusion

The effects of bending loss and bandwidth change due to bending on the optical link performance were discussed simultaneously for the first time. A fiber bending with the radius as small as 10 mm caused little mode coupling, because little change was observed in the bandwidth of the GI POF. The severe bending resulted in the mode coupling and made the mode power distribution close to that under the OFL condition; hence, it induced the degradation in the fiber bandwidth, particularly when the GI POF had a high NA and the refractive-index profile was far from the optimum one. A low NA of the GI POF seemed preferable to suppress the change in the fiber bandwidth due to bending. Although it was experimentally confirmed that the higher NA allowed a lower bending loss, an NA of 0.25 was high enough, for the GI POF having a core diameter of 500 μm under the UFL condition, to maintain a sufficiently small bending loss. The low NA could suppress the bandwidth change; however, it could also induce a much higher bending loss, which would make it difficult to design the optical link. The preferable NAs for both characteristics are completely opposite. By considering the link power penalty, the required NA is approximately 0.25, and the index exponent should be within 1.9 to 2.9 for a reliable high-speed performance in short-reach and overgigabit communications under any bending conditions. Both the bandwidth change and loss caused by the bending became critical factors to achieve stable optical link in the view of the link power penalty.

References

[1] D. G. Cunningham and W. G. Lane, *Gigabit Ethernet Networking*. New York: Macmillan, 1999.

[2] *Proc. 13th Int. Plastic Optical Fiber Conf.*, Nurnberg, Germany, Sep. 2004.

[3] T. Ishigure, E. Nihei, and Y. Koike, "Graded-Index polymer optical fiber for high speed data communication," *Appl. Opt.*, vol. 33, no. 19, pp. 4261–4266, 1994.

[4] T. Ishigure, M. Sato, O. Takanashi, E. Nihei, T. Nyu, S. Yamazaki, and Y. Koike, "Formation of the refractive index profile in the graded index polymer optical fiber for gigabit data transmission," *J. Lightw. Technol.*, vol. 15, no. 11, pp. 2095–5100, Nov. 1997.

[5] T. Ishigure, Y. Koike, and J. W. Fleming, "Optimum index profile of the perfluorinated polymer based GI polymer optical fiber and its dispersion properties," *J. Lightw. Technol.*, vol. 18, no. 2, pp. 178–184, Feb. 2000.

[6] M. C. Nowell and D. G. Cunningham, "Evaluation of Gb/s laser based fiber LAN links: Review of the Gigabit Ethernet model," *Optical Quantum Electron.*, vol. 32, pp. 169–192, 2000.

[7] L. Raddatz, I. H. White, D. G. Cunningham, and M. C. Nowell, "An experimental and theoretical study of the offset launch technique for the enhancement of the bandwidth of multimode fiber links," *J. Lightw. Technol.*, vol. 16, no. 3, pp. 324–331, Mar. 1998.

[8] T. Ishigure, E. Nihei, and Y. Koike, "Optimum refractive index profile of the graded-index polymer optical fiber, toward gigabit data links," *Appl. Opt.*, vol. 35, no. 12, pp. 2048–2053, 1996.

[9] T. Ishigure, S. Tanaka, E. Kobayashi, and Y. Koike, "Accurate refractive index profiling in a graded-index plastic optical fiber exceeding gigabit transmission rates," *J. Lightw. Technol.*, vol. 20, no. 8, pp. 1449–1456, Aug. 2002.

[10] D. Marcuse, "Coupled mode theory of round optical fiber," *Bell Syst. Tech. J.*, vol. 52, no. 6, pp. 817–42, 1973.

[11] Y. Koike, E. Nihei, and T. Ishigure, "High-Bandwidth, low-loss graded-index polymer optical fiber," in *Proc. Eur. Conf. Optical Communications (ECOC 1998)*, Madrid, Spain, 1998, pp. 231–232.

[12] T. Ishigure, K. Makino, S. Tanaka, and Y. Koike, "High-Bandwidth graded-index polymer optical fiber enabling power penalty-free gigabit data transmission," *J. Lightw. Technol.*, vol. 21, no. 11, Nov. 2003.

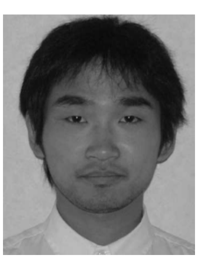
[13] "Launched Power Distribution Measurement Procedure for Graded-Index Multimode Fiber Transmitters,", FOTP-203, TIA/EIA-455-203, 2001.

[14] K. Ohdoko, T. Ishigure, and Y. Koike, "Propagating mode analysis and design of waveguide parameters of GI POF for very short-reach network use," *IEEE Photon. Technol. Lett.*, vol. 17, no. 1, pp. 79–81, Jan. 2005.

[15] H. F. Taylor, "Bending effects in optical fibers," *J. Lightw. Technol.*, vol. 2, no. 10, pp. 617–628, Oct. 1984.

[16] D. Gloge, "Bending loss in multimode fibers with graded and ungraded core index," *Appl. Opt.*, vol. 11, pp. 2506–2512, Nov. 1972.

[17] T. Ishigure, H. Endo, and Y. Koike, "High-bandwidth plastic optical fiber with W-refractive index profile," *IEEE Photon. Technol. Lett.*, vol. 16, no. 9, pp. 2081–2083, Sep. 2004.



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