High-Bandwidth Graded-Index Polymer Optical Fiber Enabling Power Penalty-Free Gigabit Data Transmission

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***Abstract*—A relation between the -3 dB bandwidths of graded-index plastic optical fibers (GI POFs) and the total power penalty of 50-m GI POF links is investigated in detail. The bandwidth of the GI POF is deliberately varied by controlling the index profile. It is theoretically and experimentally confirmed that sufficiently high bandwidth on the order of gigahertz is necessary for the GI POF, even for several hundreds of megabit per second (Mb/s) data rate, in order to achieve the power penalty free in the bit error rate performance of the link. In the case of silica-based multimode fiber links, it has been reported that the launch condition strongly affects the bit error rate performances; hence, a special launching technology for the silica-based multimode fiber is developed to achieve a 1-Gb/s transmission in the gigabit Ethernet protocol. In this paper, it is also found that the power penalty-free state is realized in the GI POF link, which is independent of the launch condition, when a GI POF with a nearly ideal index profile is used. The GI POF is a promising physical layer for realizing stable, high-speed and low-cost data-com networks.**

***Index Terms*—Bit error rate, graded-index plastic optical fiber (GI-POF), power penalty, refractive index profile, 3-dB bandwidth.**

I. INTRODUCTION

SINCE the development of lightwave communications with fibers in the mid-1970s, the major emphasis of research has been on the technology of lightwave devices for long-distance telecommunications. The single-mode glass optical fiber is one of the most predictable and stable communication channels ever developed and characterized for such areas. Over the past five years, on the other hand, the data communications market has risen to the forefront in lightwave communications because of the ever-increasing need for more bandwidth. The Ethernet is now used on more than 80% of the world's local-area network (LAN) connected personal computers and workstations, and the capability for priority-based transmission at 1000 Mb/s ensures that Ethernet remains well ahead of other LAN technologies [1]. As a physical media dependent (PMD) issue of the gigabit Ethernet, the silica-based multimode fiber is adopted to provide an inexpensive optical link in combination with vertical cavity surface emitting laser (VCSEL) based transceivers. Therefore, it would not necessarily be the best solution to distribute such silica-based optical fibers even in premises and home networks.

On the other hand, the plastic optical fiber (POF), having much larger core than that of silica fibers, has been expected to be the office- and home-network medium because its large core allows the use of inexpensive injection-molded plastic connector, which can dramatically decrease the total link cost. We proposed a high-bandwidth graded-index (GI) POF for the first time [2], and have reported its bandwidth characteristic [3], [4]. For evaluating the optical links in the PMD issue of Ethernet and/or IEEE1394 network protocols, maintaining a bit error rate as low as 10^{-12} is required. It has not been a trivial task to specify and design the optical PMD portions of the gigabit Ethernet. In particularly, the 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 multimode fiber link could dominate the limited optical power budget [1]. The restricted bandwidth of the silica-based multimode fiber has been one of the main causes that makes the specification and designing of the PMD portions very difficult. In order to cover the conventional multimode fiber having a restricted bandwidth in the PMD of gigabit Ethernet standard, the "offset launching" technology was proposed as a bandwidth improvement method [5], [6].

In this paper, the relation between the bandwidth characteristics of the GI POF and the bit error rate characteristics of the GI POF link is investigated in detail by focusing on the power penalty of the GI POF link. It is found that the high-bandwidth GI POF enables the power penalty-free data transmission even in any launching condition.

II. EXPERIMENTAL

A. Formation of the GI POF by the Interfacial-Gel Polymerization Process

The GI POF was obtained by the heat-drawing of the graded-index preform whose diameter was 22 mm. The preform rod in which the refractive index gradually decreases from the center axis to the periphery was prepared by the interfacial-gel polymerization technique, whose procedure is described as follows [2], [3]; A polymethyl methacrylate (PMMA) tube was prepared by the bulk polymerization from the purified MMA monomer; its outer diameter was 22 mm, and its inner diameter was 60% of the outer diameter. The PMMA tube was filled with a mixture of MMA monomer, dopant, polymerization initiator, and

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chain transfer agent. In this paper, diphenyl sulfide was used as the dopant. The PMMA tube filled with this monomer mixture was heated from the surrounding in an oil bath at 90 °C to induce polymerization. The inner wall of the PMMA tube is slightly swollen by the monomer dopant mixture to form the polymer gel phase. The reaction rate of the polymerization is generally faster in the gel phase due to the "gel effect." Therefore, the polymer phase grows from the inner wall of the tube to the center. During this process, the MMA monomer can easily diffuse into the gel phase compared to the dopant molecules because the molecular volume of dopant, which has benzene rings in it, is larger than that of the monomer. Thus, the dopant molecules are concentrated in the center region of the core to form nearly a quadratic refractive index profile [2]. The polymerization reaction rate plays an important role to control the refractive index profile because it affects the diffusion process of MMA monomer and dopant molecules into the polymer gel phase formed from the inner wall of the tube. The index profile of the GI POF was controlled by changing the kind and concentration of the dopant, polymerization initiator, and chain transfer agent [3]. The GI POF was obtained by the heat-drawing of the GI preform, carried out at 220–230 °C. The fiber diameter was controlled to be 750 μm. In this fiber, the core diameter became approximately 500 μm.

B. Refractive Index Distribution

The modal dispersion is generally dominant in the distortion of the output optical pulse waveform from the multimode optical fibers. However, it is well known that the modal dispersion can be minimized by forming a quadratic refractive index profile in the multimode fiber, and that the bandwidth of the multimode fiber is strongly influenced 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 described by (1)

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

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \tag{2}$$

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 shape of the refractive index profile. We already showed that the optimum refractive index exponent (g_{opt}) of the PMMA-based GI POF became almost 2.4 [7] by taking the material dispersion into consideration for a 650-nm wavelength use.

We reported that the refractive index profile of the GI POF could be precisely controlled by the interfacial-gel polymerization technique [3], [8]. The index profile was deliberately varied from almost ideal $(g = 2.7)$ to almost step-index (SI) $(g = 8.4)$ by changing the polymerization conditions in the interfacial-gel polymerization technique. A detailed preparation process is described in [3]. The refractive-index profile of the GI POF was experimentally measured by the longitudinal interferometric technique [2].

C. Bandwidth Measurement

The bandwidths of the SI and GI POFs were measured by the time-domain measurement method. As the light source, an InGaAsP laser diode (LD) at a 650-nm wavelength was adopted. An input pulse generated by a pulse generator was injected into the POF. The output pulse was measured by a sampling head, and recorded and analyzed by a sampling oscilloscope (Hamamatsu OOS-01). Here, the launch condition of the POF is an important factor in the investigation of its bandwidth characteristics. To measure the bandwidth of the silica-based multimode fiber, a steady-state mode power distribution should be achieved, because the steady-state mode power distribution is generally established in the real field of silica-based multimode fiber links that have a longer than several-kilometer distance [9]. Therefore, in order to achieve a steady-state mode power distribution, all modes should be fully excited by using a mode scrambler. In this paper, two launch conditions were adopted: underfilled launch (UFL) and over-filled launch (OFL). In the UFL condition, a pulsed optical signal from the LD that already included a lens system in order to focus the output beam was directly focused on the input end of the test fiber. At the focal point of the lens, the beam with a 5.7-μm beam spot diameter and a 12° radiation angle was coupled to just the core center of the GI POF. In OFL, a pulsed signal from the LD was injected into a 1-m SI POF first, and then the output signal from the SI POF was coupled to the GI POF by directly butting to the test fiber (GI POF) on a V-groove. Since the power distribution at the output end of the 1-m SI POF is uniform in the whole core region (980-μm diameter), and since the numerical aperture of the SI POF (0.5) is sufficiently higher than that (0.2–0.3) of the GI POF, the 1-m SI POF is considered as an ideal all-modes exciter of the GI POF. Hence, the OFL condition was achieved.

D. Link Performance Evaluation: Bit Error Rate, Power Penalty, and Eye Diagram

Currently, the PMMA-based GI POF is a candidate for the physical medium for high-speed office and home networks, where more than 500-Mb/s 50-m transmission is required, i.e., IEEE1394 S-400 and/or gigabit Ethernet. In the IEEE S100 and S200 protocols, a low numerical aperture (NA) SI POF link was taken as the PMD standards in less than 50-m distances. In the physical layer of such high-speed network protocols as IEEE 1394 S400 and/or gigabit Ethernet, maintaining the bit error rate (BER) as low as 10^{-12} is inevitable [1], [5] in their standards. Therefore, the BER in the GI POF link is a key characteristic.

The BER was experimentally measured in a 50-m PMMA-based GI POF link. As the optical transmitter, a custom-made electric-to-optic converter was used in which a Fabry–Perot type LD at 650-nm wavelength was utilized for generating the random optical bit signals at data rates of 500 Mb/s to 1.25 Gb/s. The output power from the LD was set to +4 dBm. The optical transmitter was modulated with $2^{15}-1$

pseudorandom bit signals, and the output signal was detected by a custom-made optic-to-electric converter composed of a 0.4-mm diameter Si PIN photodiode (Hamamatsu S 5973-01) with a ball lens for the eye diagram measurement and the BER test. The eye diagram was measured with a sampling oscilloscope, while the BER characteristics were measured by the BER test sets. The link power penalty in dB was determined from the ratio in the minimum received optical power between two link lengths: 1 m (back to back) and 50 m. The minimum received power is defined as the minimum optical power that satisfies $\mathrm{BER} = 10^{-12}$.

III. RESULTS AND DISCUSSION

A. Relation Between Bandwidth and Power Penalty

Six 50-m pieces of GI POF whose index profiles were deliberately varied were prepared by adjusting the polymerization conditions of the core of the GI preform rod [3]. Three representative index profiles are shown in Fig. 1, and their bandwidths are shown in Fig. 2 and Table I. The bandwidth of the GI POF (Fiber A) having an almost optimum profile $(g = 2.7)$ shown in Fig. 1 exhibited a higher bandwidth than 3 GHz for a 50-m length, while Fiber B having a large index exponent $(g = 8.4)$ showed a bandwidth as narrow as 300 MHz for a 50-m length, which is only slightly higher than that of the conventional SI POF (240 MHz for 50 m).

Furthermore, it is noteworthy that most of these fibers showed a large launch condition dependence on the bandwidth. For instance, Fiber B in Fig. 1, which has an index exponent of 6.4, exhibited an 840-MHz bandwidth under the UFL condition. However, it is reduced to less than half (250 MHz) under the OFL condition. Even in the case of Fiber A, as shown in Fig. 2 and Table I, the bandwidth measured under OFL is slightly lower than that measured under UFL, although the difference is almost negligible. On the other hand, we recently reported that the completely ideal index profile could be formed in the PMMA-based GI POF by utilizing a two-step interfacial-gel polymerization process [8]. Its refractive index profile is shown in Fig. 3. As shown in Fig. 3, the index profile is in good agreement with the best fitted curve to the power-law profile approximation with an index exponent of 2.45. The launch condition dependence of the output pulse waveforms from this GI POF is shown in Fig. 4. There is no significant dependence on the launch condition. In fact, the bandwidth under OFL is rather slightly higher than that under UFL, which is completely opposite to the results shown in Fig. 2. This means the group delays of all the modes are well controlled to have almost the same values.

These results indicate that the BER performance of the link composed of the POF having nonideal and step-index profile would show a strong optical transmitter dependence, because the launch conditions in the real optical link are determined by the light source and other optical components. On the other hand, in the case of the GI POF having an almost ideal index profile $(g = 2.45$ to $2.7)$, little launch condition dependence on the bandwidth was observed. As we reported previously, the interfacial-gel polymerization process is an easy way to obtain the ideal index profile [3], [8]. Therefore, the GI POF is

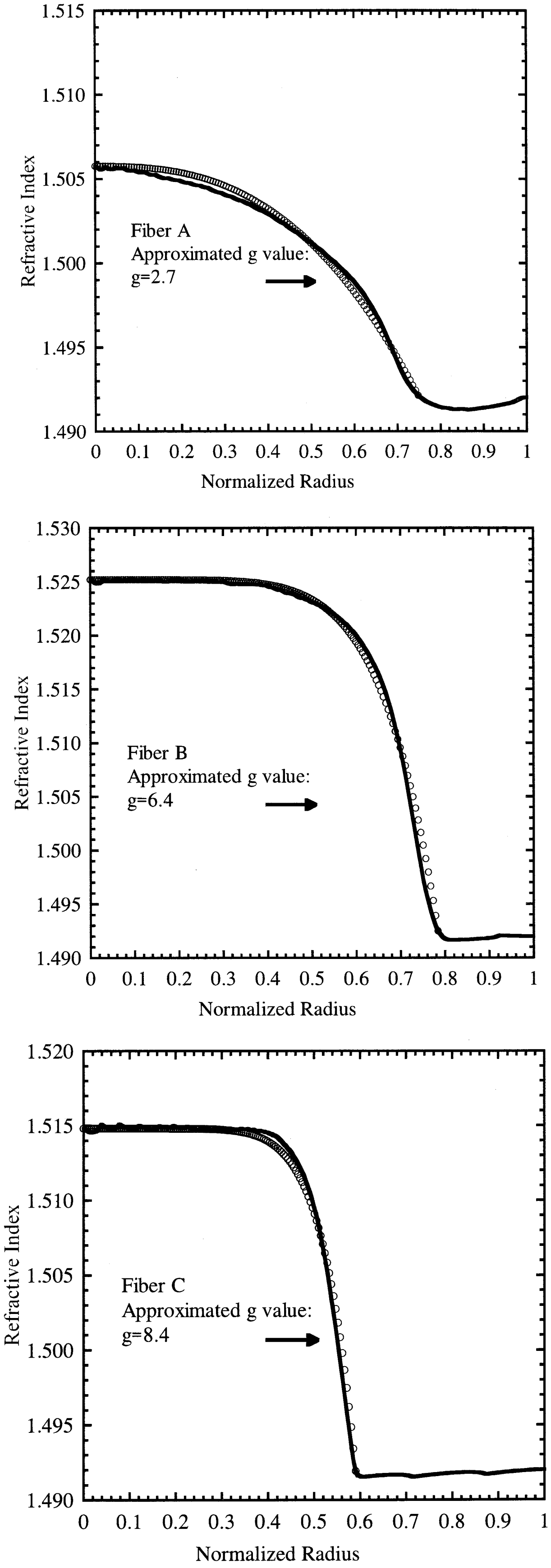

Fig. 1. Representative refractive index profiles of the GI POF prepared by the interfacial-gel polymerization process. Open circles signify the best fitted curve to the power-law profile approximation.

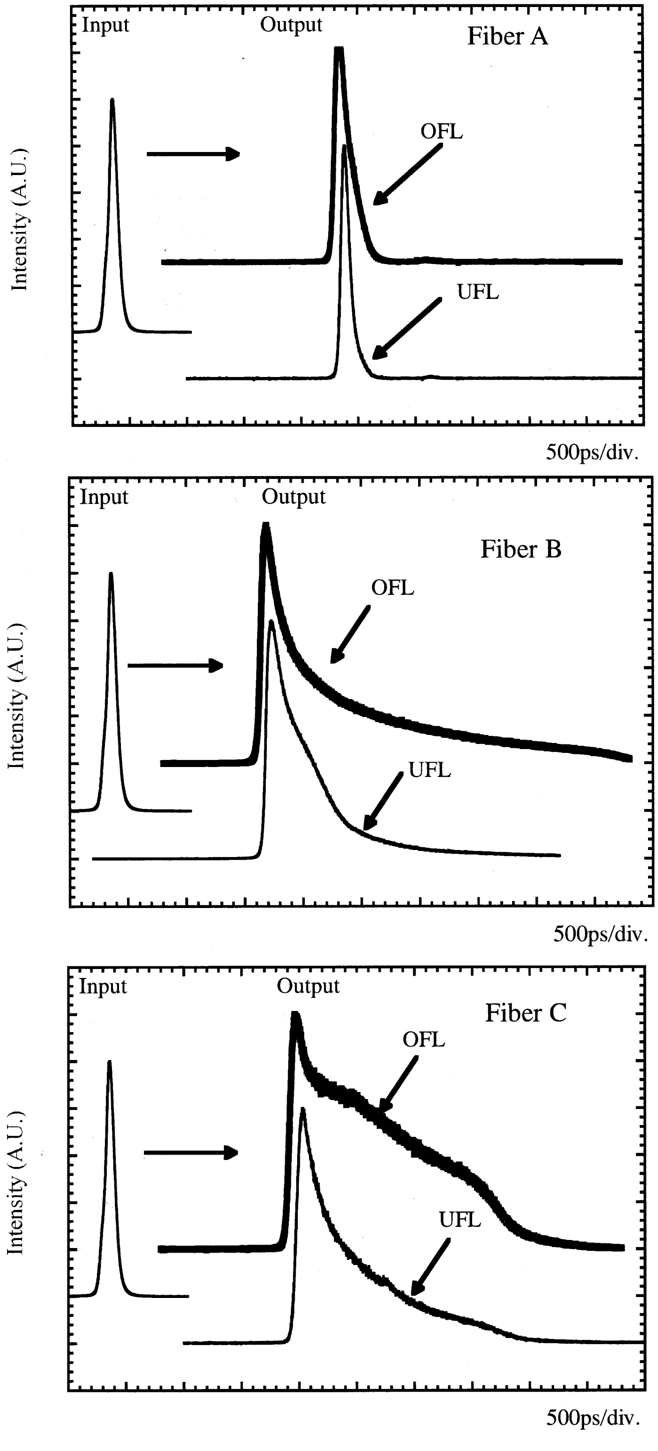

Fig. 2. Output pulse waveform from 50-m GI POFs whose index profiles are shown in Fig. 1.

expected to be a promising physical medium for constructing stable high-speed and low-cost data-com systems.

TABLE I

RELATION BETWEEN THE −3 dB BANDWIDTH OF GI AND SI POFS AND POWER PENALTY OF A 50-m POF LINK AT 500 Mb/s

	Index exponent g	-3dB Bandwidth (GHz for 50m)		Power Penalty (dB)	
		UFL	OFL	UFL	OFL
Fiber A	2.7	3.32	2.52	0.0	0.0
GI POF	3.4	2.48	1.32	0.0	0.3
Fiber B	6.4	0.84	0.25	0.6	4.4
Fiber C	8.1	0.39	0.30	1.8	3.0
Fiber D for 100m	2.45	3.76	2.76	0.0	0.0
SI POF	Infinity	0.24	0.24	7.1	7.1

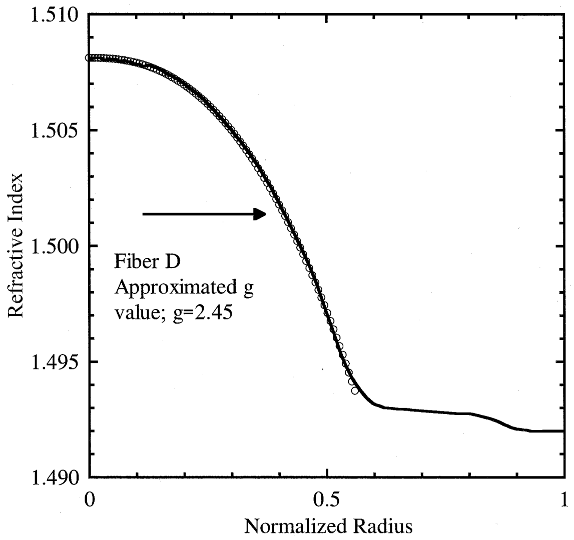

Fig. 3. Refractive index profile of the GI POF with the ideal index exponent $(g = 2.45)$. Open circles signify the best fitted curve to the power-law profile approximation.

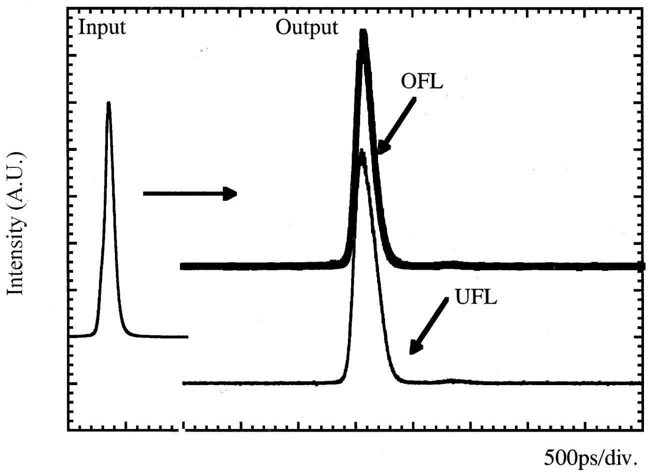

Fig. 4. Output pulse waveform from a 50-m GI POF whose index profile is shown in Fig. 3.

Using these six GI POFs and an SI POF as the test fibers, the relation between the bandwidths and the power penalties of 50-m POF links was evaluated. The BER performances of the links based on these fibers are shown in Fig. 5, and the relation between the bandwidth of the fiber and the BER is summarized in Table I. Because of the large modal dispersion in the conventional SI POF, a 500-Mb/s transmission through a 50-m SI POF was difficult; consequently, a critical link power penalty was observed. On the other hand, even if the GI POF has nearly 500 MHz of bandwidth, which seems sufficient for a 500-Mb/s

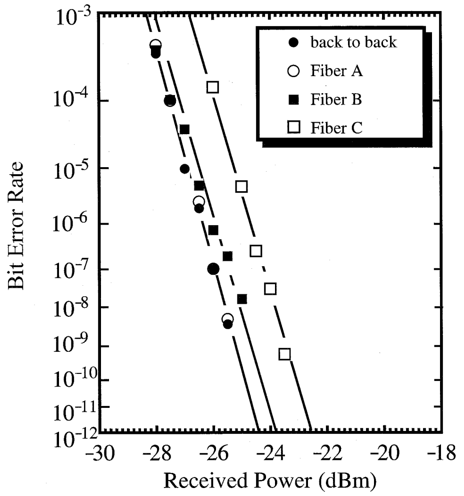

Fig. 5. Bit error rate performance in 500-Mb/s 50-m GI POF link when the fiber was launched by UFL condition.

transmission, the observed link power penalty was larger than 1.0 dB. Furthermore, the GI POF with a bandwidth higher than 2.5 GHz exhibits the power penalty-free transmission. It was verified that a bandwidth higher than 1 GHz was required even for several hundreds of Mb/s transmission in order to maintain the power penalty-free condition.

B. Launch Conditions Effects on Link Power Penalty

The launch condition dependence of the link power penalty was also examined in detail. In the case of the silica-based multimode fibers (MMFs), it is reported that the bandwidth is strongly affected by the launch condition [6]. Therefore, in order to achieve a gigabit data transmission in the MMF link in the gigabit Ethernet protocol, an offset launch condition is specified, by which only a small group of modes can be selectively excited.

In the case of Fiber B, the bandwidths under UFL and OFL conditions were 840 and 250 MHz, respectively, and the experimentally measured link power penalty is shown in Fig. 5 and Table I. In Fig. 5, we showed the results only under UFL. It can be seen in Table I that as the launch condition was varied from UFL to OFL, the link power penalty increased from 0.6 to 4.4 dB in the Fiber B link. Eye diagrams of a 50-m fiber (Fiber B) link at 1.25 Gb/s are also shown in Fig. 6. A good eye opening is observed under the UFL condition even at a 1.25-Gb/s transmission, while serious degradation in the eye diagram is observed under the OFL condition, which is attributed to the critical bandwidth limitation. As a comparison, the launch condition dependence on the bit error rate performance in the GI POF link having an ideal refractive index profile (Fiber D) even in a 100-m link is summarized in Table I. No link power penalty is observed in either UFL or OFL condition. Eye diagrams in a 100-m Fiber D link at a 1.25-Gb/s transmission are also shown in Fig. 7. Despite the higher data rate and longer distance, very good eye openings are observed in both launching conditions. In the case of Fiber A, measured bandwidths under both launch conditions (3.32 GHz under UFL and 2.52 GHz under OFL) would be obviously higher than that required. Thus, the power penalty-free transmission is accomplished under any launch conditions when the GI POF with an ideal index profile is used. The GI POF with the ideal refractive index profile ensures the highly stable communication link.

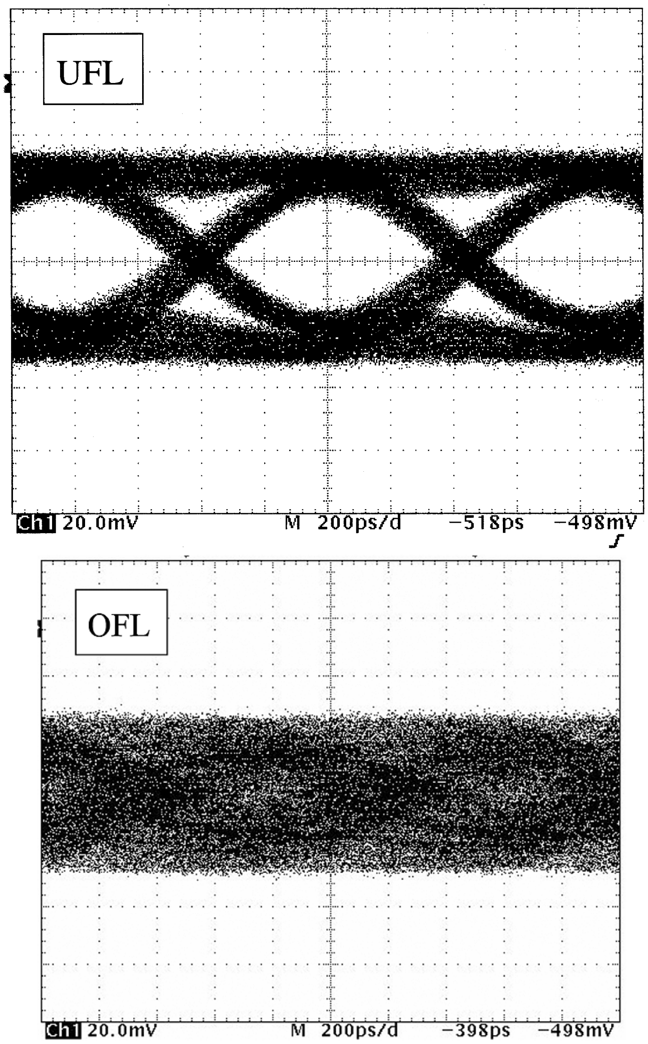

Fig. 6. Launching condition dependence of the received eye diagram in a 50-m GI POF (Fiber B) link at 1.25 Gb/s.

C. Theoretical Calculation of Power Penalty

The link power penalty was theoretically calculated by using the model based on a power budget calculation [1]. Power penalties are assigned as link impairments such as noise and dispersion. The power penalties are added linearly to determine the total link power penalty as a function of the bandwidth of fiber. In the power budget model, it was assumed that the laser and fiber impulse responses had a Gaussian shape. The model expresses the conversion process from the rms impulse width of the laser, fiber, and optical receiver to rise times and bandwidths. These calculated rise times and bandwidths are used to determine the fiber and composite channel exit response and the intersymbol interference (ISI) penalty of the optical communication links. The link power penalty was calculated to account for the effects of some factors such as ISI $(P_{\rm ISI})$, mode partition noise (MPN) $(P_{\rm MPN})$, relative intensity noise (RIN) $(P_{\rm RIN})$,

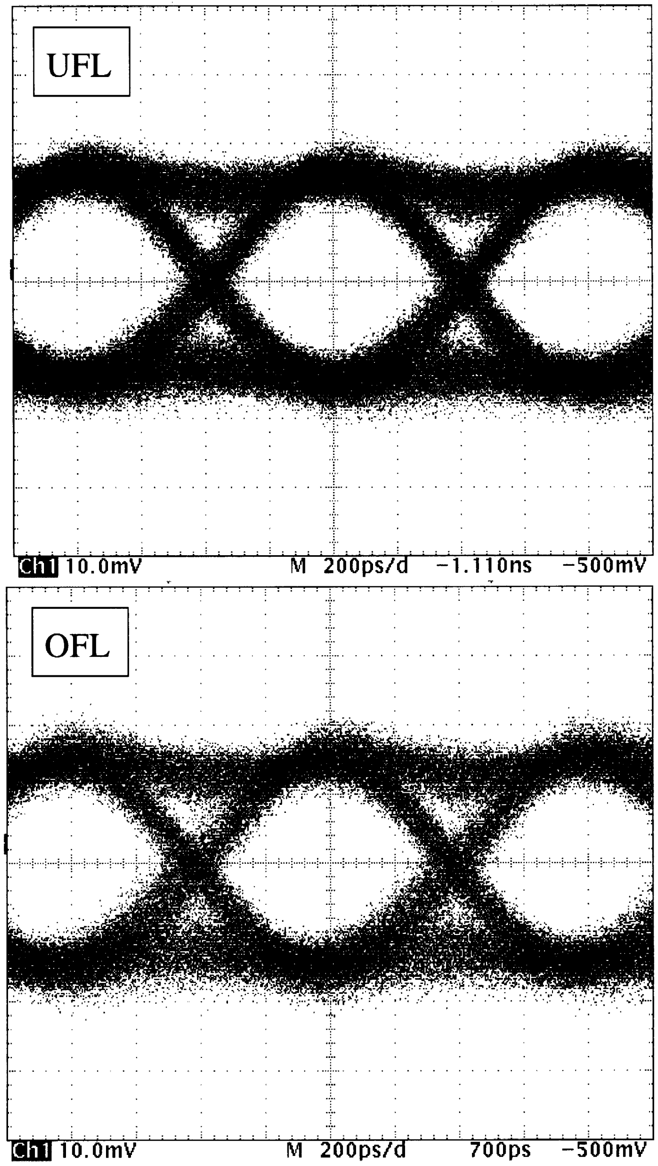

Fig. 7. Launching condition dependence of the received eye diagram in a 100-m GI POF (Fiber D) link at 1.25 Gb/s.

and modal noise (P_{MN}). The penalties are calculated by the following equations [1], [5]:

$$P_{\mathrm{ISI}} = \frac{1}{1 - 1.425 \cdot \exp[-1.28(T/T_c)^2]} \tag{3}$$

$$P_{\mathrm{MPN}} = \frac{1}{\sqrt{1 - (Q\sigma_{\mathrm{MPN}})^2}} \tag{4}$$

$$P_{\mathrm{RIN}} = \frac{1}{\sqrt{1 - (Q\sigma_{\mathrm{RIN}})^2}} \tag{5}$$

where T is the bit period, T_c is the approximate 10–90% composite channel exit response time, Q is the value of the digital signal-to-noise ratio, and σ_{MPN} and σ_{RIN} are the MPN and RIN noise variances, respectively. There is the following relation among T_c, modal bandwidth $\mathrm{BW_m}$, chromatic bandwidth $\mathrm{BW_{cd}}$, and receiver bandwidth $\mathrm{BW_r}$:

$$T_C = \sqrt{\left(\frac{0.48}{\mathrm{BW}_m}\right)^2 + \left(\frac{0.48}{\mathrm{BW}_{\mathrm{cd}}}\right)^2 + T_s^2 + \left(\frac{0.35}{\mathrm{BW}_r}\right)^2}. \tag{6}$$

TABLE II

CALCULATED ELEMENTAL PENALTIES FOR A 50-m GI POF LINK

$\mathrm{BW_{Total}}$ (MHz)	$\mathrm{P_{ISI}}$ (dB)	$\mathrm{P_{MPN}}$ (dB)	$\mathrm{P_{RIN}}$ (dB)	$\mathrm{P_{Total}}$ (dB)
200	5.81	1.34×10^{-6}	0.0002	5.81
500	0.9	1.34×10^{-6}	0.0006	0.9

Therefore, the link power penalty is estimated by (3)–(6) if the modal and chromatic bandwidths of the fiber are measured.

Modal noise also induces a degradation of optical signal. The modal noise that is caused by a time-varying speckle pattern formed by the interference of propagating modes has been one of the serious problems in the multimode fiber links [10]. When a mode selective loss (MSL) such as a misaligned connector exists in a multimode fiber link, the speckle causes the modal noise. Modal noise penalties depend on the laser characteristics and the link configurations, which makes it difficult to express the modal noise inducing penalty by a simple equation. Furthermore, we already reported that the modal noise in a large-core GI POF link is virtually eliminated [11]. Consequently, the power penalty due to the modal noise was neglected in the estimation of this paper.

Some parameters required to calculate the power penalty were determined experimentally, such as the bandwidth of the fiber, the rms spectral width of the laser, etc. (rms width of the laser $= 0.94$ nm, $\mathrm{BW_{cd}} = 9.4$ GHz for 50-m fiber) The others were set to be their typical values referring to [5]. Before calculating the total link power penalty, all elemental penalties shown by (3)–(6) should be calculated. All the calculated penalties were summed up linearly in dB to obtain the total link power penalty as a function of the fiber bandwidth. Calculated elemental penalties are summarized in Table II, where -3 dB bandwidth of the fiber was supposed to be 200 and 500 MHz for 50-m fiber. From the calculated results of the elemental penalties, it was found that the penalty due to ISI $(\mathrm{P_{ISI}})$ was the dominant factor causing the link power penalty, particularly when the fiber had a narrow bandwidth. The calculated relation between the fiber bandwidth (fiber length $= 50$ m) and the link power penalty is shown in Fig. 8 compared with the measured penalties.

A good agreement is observed between the measured results (open circles for OFL condition and closed circles for UFL condition) and calculated results for a 500-Mb/s transmission (solid line) and for a 1.25-Gb/s transmission (broken lines), although the effect of the modal and mode partition noises was neglected. Therefore, the link power penalty of the large-core POF link is dominated only by the bandwidth of the fiber, not by the other characteristics of the fiber, such as modal noise and/or mode partition noise. In fact, it was experimentally confirmed that no modal noise was observed in the GI POF link, even when a large misalignment on the order of half a core radius was deliberately created in the connection of two GI POFs, because the large core diameter (500 μm) of the GI POF supports a huge number of modes. Therefore, it has been shown in this paper that the power penalty due to the modal noise was 0 dB in a large-core GI POF link.

The broken line in Fig. 8 shows the calculated relation between the fiber bandwidth and the link power penalty at the

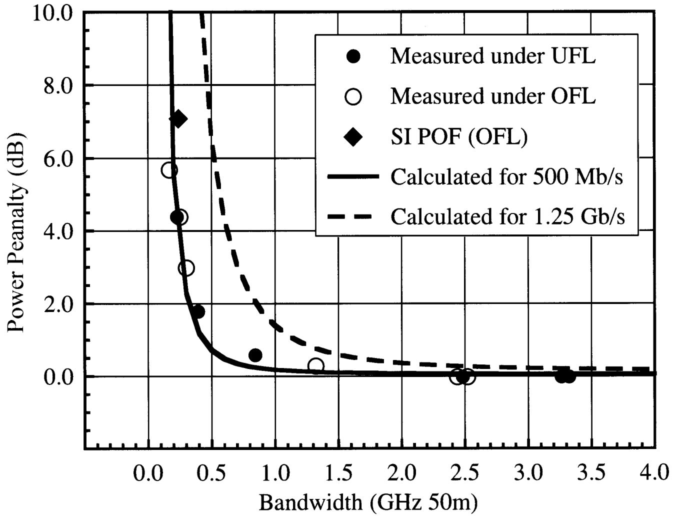

Fig. 8. Relation between the −3 dB bandwidth of 50-m POFs and the power penalty in a 50-m POF link. Closed circle: measured under the UFL condition at 500 Mb/s. Open circle: measured under the OFL condition at 500 Mb/s. Closed lozenge: measured result in an SI POF link at 500 Mb/s. Solid line: calculated result at 500 Mb/s. Broken line: calculated result at 1.25 Gb/s.

data rate of 1.25 Gb/s that is estimated for the gigabit Ethernet application. As the data rate increases from 500 Mb/s to 1.25 Gb/s, the bandwidth required for the GI POF to achieve the power penalty-free condition also increases from 1.5 to 3 GHz, as shown in Fig. 8. It was already shown theoretically and experimentally that the PMMA-based GI POF could cover as high a bandwidth as 2.5–3 GHz even for a 100-m distance at a 650-nm wavelength [3], [7], [8], despite the large material dispersion. Furthermore, it was also shown that the perfluorinated polymer-based GI POF with a very small material dispersion potentially exhibited a bandwidth higher than 10 GHz [4]. Therefore, we believe that the high-bandwidth GI POF is a promising candidate for the physical medium in very short-reach super-gigabit data links.

IV. CONCLUSION

The relation between the bandwidth of the fiber and the link power penalty was clarified both experimentally and theoretically for the first time in the PMMA-based GI POF link. It is noteworthy that a fiber bandwidth on the order of a gigahertz is necessary, even in the several hundreds of megabit per second data communications, in order to realize a power penalty-free transmission. We concluded that there was no link power penalty of the GI POF link in practice, because it is easy to achieve gigahertz order of the bandwidth over a 100-m transmission through a PMMA-based GI POF. It was also confirmed that the bandwidth of the GI POF and bit error rate performance of the GI POF link were not influenced by the launch conditions when the GI POF had the optimum refractive index profile. Therefore, the GI POF with an ideal index profile provides considerable freedom in designing a high-speed optical network, because its power penalty-free transmission offers an extra power budget. It was theoretically found that the penalty due to the intersymbol interference is the dominant factor causing the link power penalty. In this paper, it was theoretically and experimentally confirmed that the GI POF has a great advantage in high-speed optical data communications because of its high bandwidth.

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