# High-Bandwidth Plastic Optical Fiber for Fiber to the Display

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

*Invited Paper*

***Abstract*—Novel photonics polymer devices for broadband technologies are described, focusing on the high-bandwidth graded-index plastic optical fiber (GI POF). Based on these photonics polymer device technologies, the concept of "Fiber to the Display" is proposed, where GI POF is directly distributed to display from main server in a building or house. Therefore, real-time face-to-face communication with high-definition-television quality becomes possible, which cannot be achieved by current technologies. The authors believe that new innovative concepts of broadband society in the 21st century will be realized by "the proposal from the material side."**

***Index Terms*—Fiber to the display (FTTD), material dispersion, modal dispersion, mode coupling, perfluorinated (PF) polymer, plastic optical fiber (POF).**

## I. Introduction

THE BIGGEST challenge in information technology will be how to install gigabit optical fibers to local area networks at homes, offices, and buildings.

It is estimated that the peripheral component of the communications network, which is referred to as "the last 1 mile," accounts for approximately 95% of the overall network, for which copper wire [unshielded twisted pair wire (UTP)] has chiefly been used to date. However, limits exist for both transmission bandwidth and transmission distance, and especially when 100 m is exceeded inside a building, handling communication speeds enabling transfers on the order of gigabits is difficult. On the other hand, silica-based single-mode (SM) fibers used for the backbone system can sufficiently respond to high speeds. However, due to its minute diameter of less than 10 $\mu$m, precision techniques are demanded for connection and branching, which necessitate high costs for peripheral systems where a substantial number of connection points exist. In contrast, plastic optic fiber (POF), which employs as its base material a very soft polymer of high flexibility compared to glass fibers, exhibits characteristics which easily enable a larger core diameter (100–1000 $\mu$m) despite its ease of bending (i.e., comparable to UTP), and presents the advantage that elaborate connection techniques and high installation costs are unnecessary.

In this paper, the current status and outlook of POFs as a communications medium capable of achieving broadband service in recent years is reviewed. The POFs developed for high-speed data communication are classified into four types: SM POF [1], multilayer (ML) step-index (SI) POF [2], multicore (MC) SI POF [3], and graded-index (GI) POF [4].

An SM POF was prepared by the interfacial-gel polymerization technique by forming a small core, and then, the SM condition was satisfied for the first time. On the other hand, other three types of POF have large cores, because of which huge number of modes (more than 50 000) is propagated. Therefore, reduction of modal dispersion has been a key issue in such multimode POFs. In ML POFs, the core region is composed of several layers with a different refractive index. This concentric ML structure decreases modal dispersion compared to a conventional SI-type POF, and a data rate as high as 500 Mb/s for 50-m transmission is achieved experimentally. On the other hand, MC POF has a core region composed of a bundle of tens of small core. By reducing the core diameter, not only modal dispersion but also bending loss is decreased. A data transmission at 500 Mb/s for 50 m is also achieved by the MC POF. Although a data rate of 500 Mb/s seems high enough for existing applications such as Web browsing and text-based communications, a 1-Gb/s data port is already equipped, even on some personal computers. For the backbone networks, switches and other equipment that cover the 10-Gb/s Ethernet are commercially available. The gigabit and 10-Gb Ethernet standards specify the use of multimode fibers and inexpensive vertical cavity surface emitting lasers (VCSELs) [5], [6]. However, the dispersion of existing multimode fibers was the serious problem, particularly in the 10-Gb transmission systems, and then, new-generation multimode fiber has been developed to cover such a high data rate [6]. On the other hand, a data rate of 1 $\sim$ 2.5 Gb/s has been already required for an interface of high-resolution digital display: digital video interface (DVI, 1.65 Gb/s/channel, display resolution: ultra extended graphics array) [7]. Thus, much higher data rate will be required in the area of consumer electronic appliances.

It has been demonstrated that the optimum refractive index profile enables GI POFs to transmit a data rate of 10 Gb/s and beyond. A low-loss perfluorinated (PF) polymer-based GI POF has been developed [8], and a PF polymer-based GI POF

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The authors are with the Faculty of Science and Technology, Keio University, Yokohama, Japan, and the Japan Science and Technology Agency (JST) Exploratory Research for Advanced Technology and Solution-Oriented Research for Science and Technology (ERATO-SORST), Kawasaki, Japan (e-mail: koike@appi.keio.ac.jp; ishigure@appi.keio.ac.jp).
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can also support such a high data rate because of its low material dispersion property [9]. In addition, the attenuation of the current PF polymer-based GI POF is decreased to10 dB/km over the 800 $\sim$ 1300-nm wavelength range.

Hence, we believe that GI POF is the only POF that can cover such a high data rate and that can seamlessly connect the backbone fiber-optic communication networks and electronic appliance in the home. Therefore, in the following sections, we focus on the characteristics and prospected applications of GI POFs.

This paper is organized as follows: Section II covers the development history of POF technologies. In Sections III and IV, details of polymethyl methacrylate (PMMA)-based GI POFs and PF polymer-based GI POF that we have proposed are discussed. Section V introduces the new concept of "Fiber to the Display (FTTD)" we have proposed recently. Section VI summarizes the future prospect of POF technologies. The gigabit technology which we propose will bring us back to "Face-to-Face Communication."

## II. History of POF Development

### A. Development in Attenuation of POF

The first idea of POF goes back to the 1960s before Corning demonstrated silica optical fibers with attenuation lower than 20 dB/km [10]. In 1966, Du Pont invented the first POF named "Crofon" that was of SI-type composed of PMMA core surrounded by a partially fluorinated-polymer cladding. Because of the rapid progress made in silica optical fiber technologies, fiber optics have become the backbones of long-distance telephone networks around the world. On the other hand, POFs have proved more practical for communications in very-short-reach (VSR) networks or for light guide and illumination applications, because of their advantages such as large diameter with great mechanical flexibility and high numerical aperture (NA). Particularly, the potential of polymer materials such as great mechanical flexibility and easy handling can reduce not only the cost of the fiber itself but also the cost of fiber installation. Therefore, great interest has been focused on such POF applications as the transmission media in VSR networks.

In 1975, Mitsubishi Rayon commercialized the first SI POF whose trade name was "Eska." Then, Asahi Chemical and Toray soon followed in 1970s. The POF market was originally dominated by these three-major Japanese companies who have been manufacturing SI-type POFs composed of PMMA core. Experimental analyses of the loss reduction in PMMA-core SI POF were conducted mainly in the 1980s [11]. Kaino *et al.* reported in 1984 that very low-loss SI POF was experimentally obtained by employing perdeuterated PMMA [12].

An impressive analysis was made at the end of 1980s. Groh theoretically calculated the overtone absorption loss due to carbon–hydrogen stretching vibration in PMMA and other polymers by introducing Morse's potential energy theory [13]. Actually, the calculated peak positions and the attenuation of the overtone absorption spectrum of PMMA agreed well with that experimentally obtained. Thus, the calculation process of the attenuation limit of POFs was developed. These reports set off a competition to make better POFs among the three major Japanese companies aforementioned, and almost the lowest level of the attenuation was achieved even by the commercial-based SI POFs in late 1980s. The development in the attenuation of SI POFs is summarized in Fig. 1 compared to that of GI POFs.

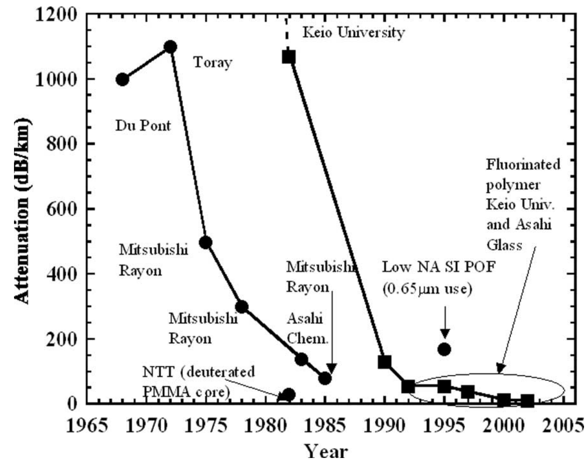


Fig. 1. Development in the attenuation of POFs. ● SI POF. ■ GI POF.

In terms of GI-type POF, the first report of PMMA-core GI POFs was presented from Keio University in 1976 [14]. A near-parabolic refractive index profile in the first GI POF was formed by copolymerizing methyl methacrylate (MMA) monomer (as $M_1$ monomer) with the other $M_2$ monomer with a refractive index higher than MMA. During the copolymerization process, the composition ratio of two polymers was gradually varied in the radial direction utilizing the difference of monomer reactivity between $M_1$ and $M_2$ monomers [15]. Actually, the attenuation first measured for GI POF composed of MMA and vinyl benzoate was 1000 dB/km, which was approximately ten times higher than that of SI POF [16]. However, it is revealed in this process that the resulting copolymer composition is mainly divided into two compositions, i.e., $M_1$ rich copolymer and $M_2$ rich copolymer, which largely increases the inherent excess scattering loss [17].

In order to decrease such an excess scattering loss caused by the difference of monomer reactivity, a new interfacial copolymerization process based on random copolymerization was developed [18], [19]. The attenuation of an MMA-benzyl methacrylate copolymer GI POF by this random copolymerization process is remarkably decreased to about 200 from 1000 dB/km. However, the excess scattering loss of about 100 dB/km due to heterogeneous structure in "copolymer" still remained. Based on the fundamental research on the relationship between scattering loss and heterogeneous structure in polymer materials [20], [21], we could break through the high-attenuation problem mentioned above. Instead of the copolymerization process, we invented the process of doping low-molecular weight compound [22]. The refractive index profile of the new GI POF is formed by the radial concentration distribution of the dopant. There were more freedoms in selecting the dopant materials compared to $M_2$ monomer selection. By designing the dopant structure to have a compatibility with PMMA, we could decrease the size of the heterogeneous structure in the polymer, and remarkable progress was made by

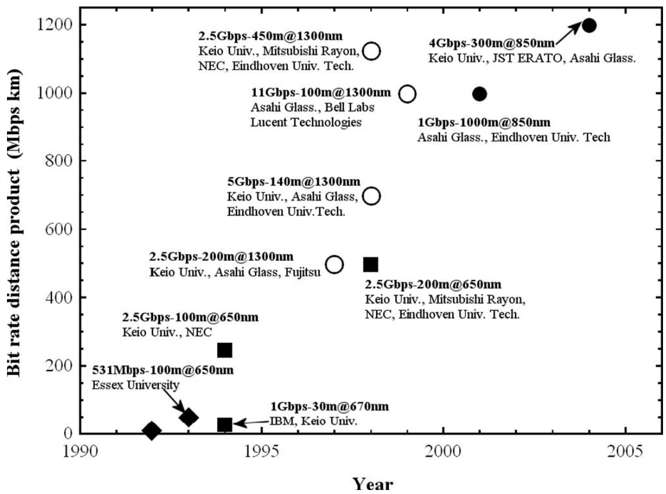


Fig. 2. Development of data rate achieved by POF links. ■ GI POF at 650 nm. ● GI POF at 850 nm. ○ GI POF at 1300 nm. ♦ SI POF.

the new GI POF [23] in decreasing the attenuation to be as low as the value which had been already achieved by PMMA-core SI POF.

The doping method triggered the research and development of low-attenuation polymer materials as well. A general aliphatic polymer has high absorption loss due to carbon–hydrogen stretching vibration. However, by substituting all hydrogen bonding in polymer molecules for fluorine, remarkably low attenuation was achieved by the PF polymer-based GI POF, even at a wavelength of 1.3 $\mu$m. The first PF polymer-based GI POF was reported in 1994 [8], and in 2000, a PF polymer-based GI POF named "Lucina" was commercialized from Asahi Glass Co., for the first time [24] using a PF polymer named CYTOP [25].

### B. Development in High-Speed Transmission by POF

Several attempts to employ POF for high-speed communication were advanced concurrently by many countries throughout the world, during the 1990s, mainly on SI-type POFs [26], [27]. On the other hand, the high-bandwidth characteristic of GI POFs was experimentally verified in 1990 for the first time (The −3-dB bandwidth was 17.3 GHz for 15 m at 670-nm wavelength.) [28]. The technological breakthrough was demonstrated in 1994 as shown in Fig. 2, following the successive development of the semiconductor edge-emitting red laser (NEC) [29] and VCSELs emitting at 670-nm wavelength (by IBM) [30] in Japan and the United States, respectively.

After 1994, gigabit-transmission experiments employing POF began to be actively conducted worldwide, by combining GI POF with one of these light sources for high-speed modulation. We reported the first 2.5-Gb/s transmission demonstration by 100-m PMMA-core GI POF as a cooperative work with NEC in 1994 [31].

The successful experimental transmission of 11 Gb/s for 100 m in 1999 [32] by Asahi Glass Co., Ltd. and Bell Laboratories in the United States was an extremely significant result, which demonstrated the high-bandwidth performance, surpassing that of silica-glass multimode optical fibers. The high-bandwidth and low-loss characteristics of the PF GI POF have been advanced further in the 2000s, and the successful experimental transmission of 1 Gb/s 1 km was reported [33]. Based on these experiments, it was demonstrated for the first time that PF GI POFs could cover broadband fields, from the areas of VSR networks to the access networks. The POF entered into actual use in various networks in the 2000s, when the high-bandwidth PF polymer-based GI POF also became commercially available. A 1-Gb/s campus LAN utilizing PF GI POF was constructed at Keio University in 2000 [34]. Subsequently, the GI POF has been used in Tokyo in housing complexes, hospitals, medical conference halls, etc. [35].

## III. PMMA-BASED GI POF

### A. Modal Dispersion

Modal dispersion is generally dominant in the impulse response function of multimode optical fibers. However, it is well known that the modal dispersion can be minimized by forming a quadratic refractive index profile in multimode fibers and that bandwidth of multimode fibers is strongly influenced by perturbation of the index profile [36]. Thus, optimization of the refractive index profile in GI POFs to reduce modal dispersion has been an important issue. We have conducted to develop GI POFs as a high-speed network medium by utilizing transparent polymer materials [9], [23]. In order to analyze the optimum refractive index profile of GI POF, a well-known power-law index profile approximation method is adopted [37]. In the power-law profile approximation, the refractive index distribution of a GI POF is approximated by

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

where $n_1$ and $n_2$ are the refractive indexes of center axis and the cladding, respectively, $a$ is the core radius, $g$ is the index exponent that is the parameter of the index profile, and $\Delta$ is the relative index difference given by

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

It has been already proved that high-bandwidth can be achieved when the index exponent $g$ is almost 2.0. However, the other dispersion factors such as material and profile dispersion are not considered.

### B. Chromatic Dispersion

Material dispersion is induced by the wavelength dependence of the refractive index of core center and the finite spectral width of light source, while the profile dispersion is dependent on the wavelength dependence of the relative index difference $\Delta$. Fig. 3 shows how these three dispersion factors affect the bandwidth characteristics of PMMA-based GI POFs. The maximum bandwidth ($>$ 80 GHz for 100 m) of

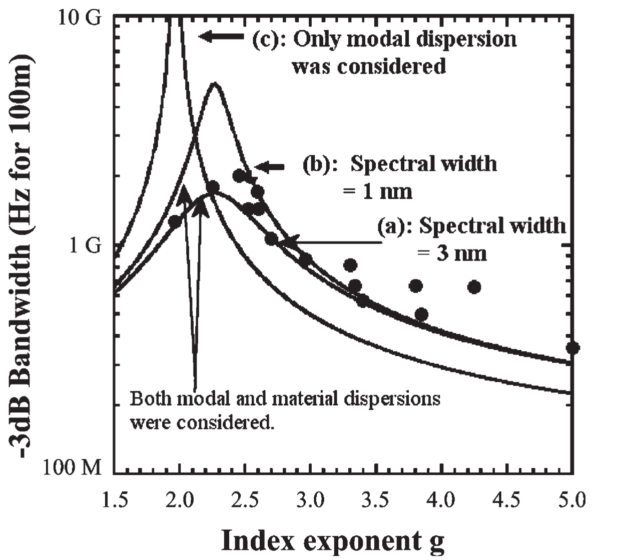


Fig. 3. Relation between the index exponent $g$ and $-3$-dB bandwidth of 100-m PMMA-based GI POF at 650-nm wavelength. • Experimentally measured data (spectral width $= 3$ nm).

PMMA-based GI POF is obtained when $g$ is almost 2.0 if the modal dispersion of PMMA is not taken into consideration. However, a disagreement is observed between the calculated bandwidth and those experimentally measured as shown by plots in Fig. 3. On the other hand, the relation between bandwidth and index exponent of PMMA-based GI POF is accurately estimated by the Wentzel–Kramers–Brillouin (WKB) method, where all the dispersion factors are taken into account: modal, material, and profile dispersion [38].

As shown in Fig. 3, experimentally measured bandwidth shown by closed circles is well predicted by taking into account the material dispersion of polymer and spectral width of the light source at 650-nm wavelength. It is obvious that the calculated maximum bandwidth varies from 5 to 2 GHz, depending on the spectral linewidth when the index exponent is optimized. This spectral width dependence of the bandwidth is induced by the large material dispersion of PMMA [38]. A significant dependence of bandwidth on the spectral width is mainly observed over the range of index exponent from 1.6 to 3, as shown in Fig. 3. When the index exponent is apart from the optimum value, i.e., $g > 3$, material dispersion has little effect on the bandwidth characteristics, as shown by two curves (a) and (b) in Fig. 3.

On the other hand, it is noted that the optimum index exponent which represents the highest bandwidth is shifted to around 2.3. The dopant employed in the GI POFs shown in Fig. 3 is benzyl benzoate [39]. This optimum index exponent $g_{\mathrm{opt}}$ is quantitatively discussed as follows: By analytically solving the Maxwell's wave equation, the optimum index exponent $g_{\mathrm{opt}}$ can be expressed as [37]

$$g_{\mathrm{opt}} = 2 - \frac{2n_1}{N_1} \cdot P - \Delta \frac{\left(4 - \frac{2n_1}{N_1} \cdot P\right)\left(3 - \frac{2n_1}{N_1} \cdot P\right)}{5 - \frac{4n_1}{N_1} \cdot P} \quad (3)$$

$$N_1 = n_1 - \lambda \frac{dn_1}{d\lambda} \quad (4)$$

where $P$, which is called profile dispersion, is given by

$$P = \frac{\lambda}{\Delta} \frac{d\Delta}{d\lambda}. \quad (5)$$

If we approximate that group index $N_1$ nearly equals $n_1$

$$g_{\mathrm{opt}} = 2 - 2P \quad (6)$$

is obtained from (3), where the effect of the last term in (3) is ignored, because $\Delta \ll 1$. Therefore, the $g_{\mathrm{opt}}$ is determined by the profile dispersion value $P$.

As shown in Fig. 3, if the bandwidth of the GI POF with an index exponent of 5.0 is theoretically estimated, it is approximately 200 MHz for 100 m by considering only modal dispersion. However, by considering all the dispersion factors, the estimated bandwidth is as high as 300 MHz for 100 m, which is less sensitive to the spectral width of the light source. This result indicates that the bandwidth characteristics are strongly influenced by the profile dispersion, even if the index profile is largely deviated from the ideal one. Thus, the effect of the spectral linewidth of the light source can be neglected.

### C. Propagating Mode Characteristics

It is well known that mode coupling (the energy transfer among the propagating modes) in multimode fibers strongly influences fiber bandwidth. In SI-type POFs, large mode coupling has been experimentally observed [40], [41], while we have proven that the mode coupling effect on bandwidth of GI POFs is smaller than that in SI POF [42]. As the origin of the mode coupling, several hypotheses such as large light scattering or perturbation of waveguide properties have been proposed [43], [44]. However, those have been mainly discussed in silica-based MMFs, and there have been few proposals for GI POFs. On the other hand, the propagating mode analysis and the management of propagating mode characteristics in GI POFs have become more and more important as well as the dispersion management techniques. We have confirmed that NA is a key factor in the mode coupling strength in PMMA-based GI POFs, and that providing high-NA in PMMA-based GI POF is a viable solution for reducing mode coupling [45]. In such a high NA GI POF with small mode coupling, the launch condition is an important issue for its bandwidth performance.

The mode coupling strength in PMMA-based GI POFs is investigated by the launch condition dependence of near-field pattern (NFP). The NFP measurement is carried out as follows: A specified mode group in the GI POF is launched by a 1-m single mode fiber connected to a laser diode at 650-nm wavelength. The SM fiber probe satisfies the SM condition at 650 nm. Here, two different mode groups: Lowest and highest order mode groups are selected to be launched, which are provided by the light couplings at the core center and near core–cladding boundary, respectively. Then, we measure the NFPs after 100-m GI POF transmissions with a CCD camera system (Hamamatsu LEPAS-11).

The launch condition dependence of the NFPs of GI POFs with different NA (0.15, 0.17, 0.20, and 0.30) are shown in Fig. 4. As we have already demonstrated in [45], a significant

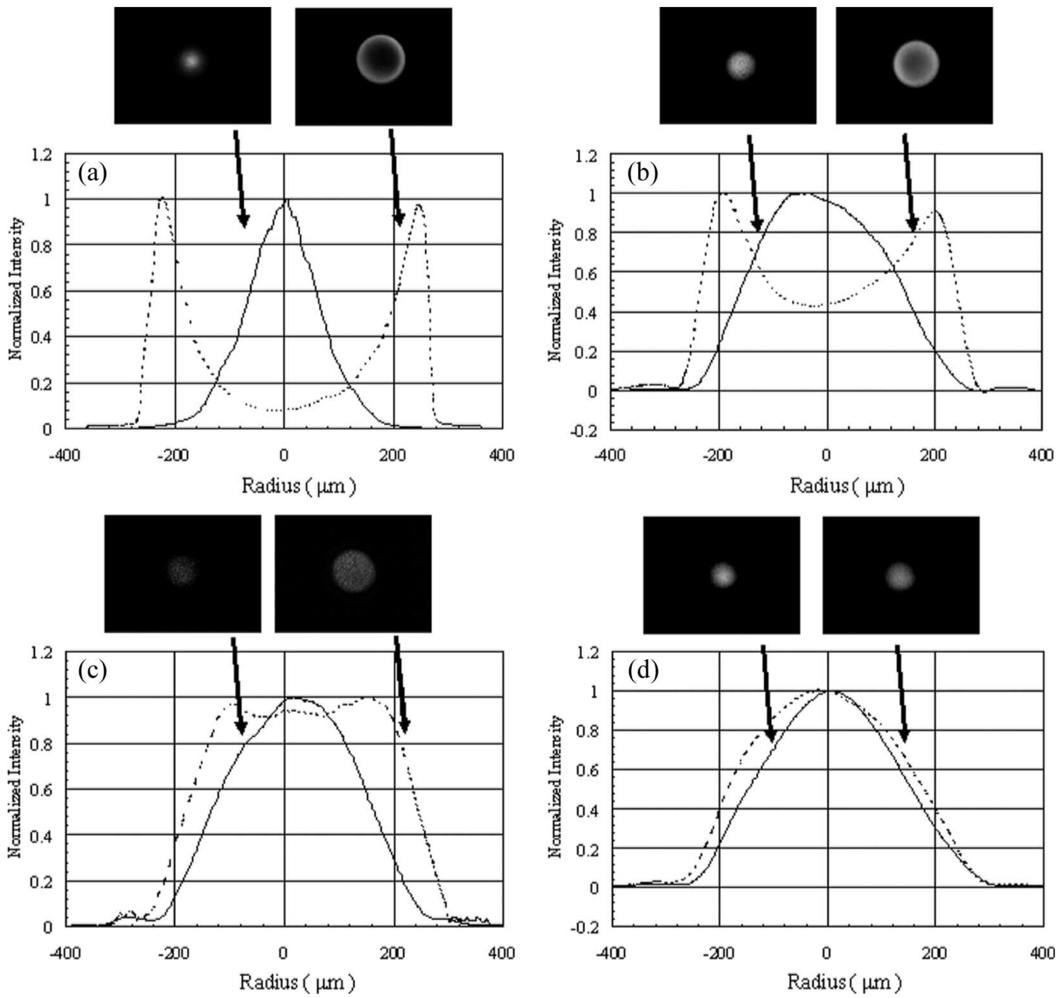


Fig. 4. Fiber NA dependence of NFPs of 100-m GI POF (NA: 0.15–0.30). Two-dimensional photos and normalized power distribution in radial direction. Solid line: center launch. Broken line: Peripheral launch (offset). (a) $\mathrm{NA} = 0.30$. (b) $\mathrm{NA} = 0.20$. (c) $\mathrm{NA} = 0.17$. (d) Fiber 2 $\mathrm{NA} = 0.15$.

profile difference between the low- and high-order modes is observed in the high-NA GI POF $(\mathrm{NA} = 0.3)$, while in the low-NA GI POF, the profiles are independent of the launch condition, as shown in Fig. 4.

From the results of wide variety of GI POFs, a relationship between the mode coupling strength and fiber NA is confirmed. It is also found that, as shown in Fig. 4, for an NA higher than 0.17, the launch condition dependence of NFP is obvious. This NA dependence of the mode coupling strength is analyzed quantitatively. It is found that the strength of the mode coupling can be related to the difference of propagation constant $(\Delta\beta)$ between the adjacent modes [45]–[47].

If the refractive index profile of GI POF can be approximated by the power-law form shown by (1), the propagation constant $\beta$ of the mode with a principal mode number $m$ is described by

$$\beta = n_1 k \left[1 - 2\Delta \left(\frac{m}{M}\right)^{\frac{2g}{g+2}}\right]^{\frac{1}{2}} \tag{7}$$

where $k$ is the wavenumber and $M$ is the maximum principal mode number. From (7), it can be derived that $\Delta\beta$, which is the difference between $\beta$ of the modes with different $m$, is a function of $n_1$ and $\Delta$. If two modes have the same propagation constants, namely $\Delta\beta = 0$, these modes are called degenerate modes. On the other hand, if the value of $\Delta\beta$ is large, the probability of energy transfer between these two modes decreases; thus little mode coupling can be observed. Therefore, large $n_1$ and $\Delta$ values are expected to decrease the mode coupling in the GI POF.

The fiber NA dependence of the $\Delta\beta$ values is calculated, and the results are shown in Fig. 5(a). Here, $\Delta\beta$ is defined as the propagation constant difference of $m$th and $m+5$th order modes, since the large-core GI POF propagates a huge number of modes. Each $\Delta\beta$ value is calculated from the refractive index profile shown in Fig. 5(b). In this case, the refractive index profile is approximated by the ten-term polynomial form. By utilizing the polynomial form, we can accurately calculate the propagation constant $\beta$ of the mode with arbitrary order with the WKB numerical computation process [48].

It can be seen that the $\Delta\beta$ values increase with increasing fiber NA. This is considered to be one of the reasons why small mode coupling is observed in the higher NA GI POF. Because both theoretical and experimental results show the same trend, it is verified that the NA is a key factor in mode coupling strength, and that the amount of mode coupling can be controlled by adjusting the NA of GI POFs.

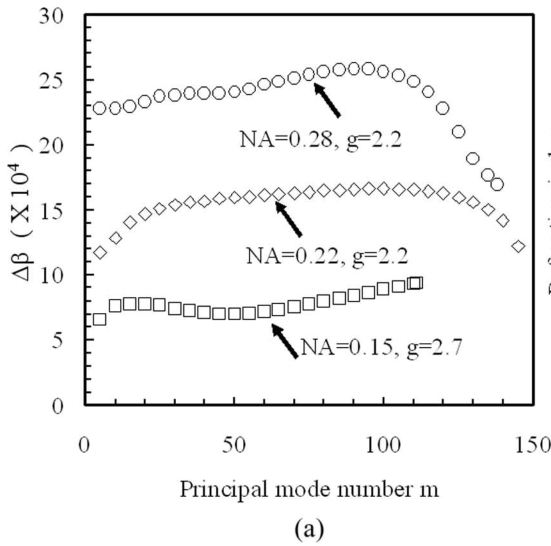


Fig. 5. (a) Fiber NA dependence of the difference between propagation constants $(\Delta\beta)$ of adjacent modes. (b) Refractive index profile of the GI POF used for the calculation of $\Delta\beta$ shown in (a).

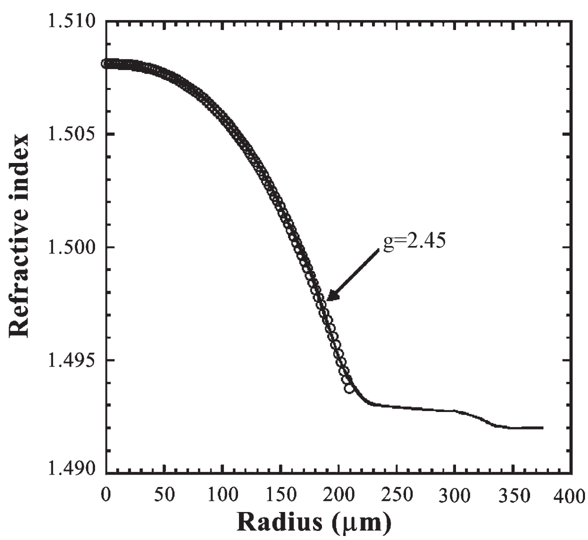


Fig. 6. Optimization of the refractive index profile of PMMA-based GI POF. Solid line: Measured index profile. Open circle: Approximated profile by a power-law form.

## D. Formation of the Ideal Index Profile

Index profiles obtained by the interfacial-gel polymerization process have tended to exhibit a steep refractive index change at the core-cladding boundary. Because of this deviation at the core-cladding boundary, the modal dispersion of the GI POF was not necessarily minimized even if the index profile around the core center region could be well fitted to the optimum index profile. Therefore, the refractive index profile of GI POF particularly at the core-cladding boundary could be precisely controlled by a two-step interfacial-gel polymerization technique we proposed previously [49]. Optimized refractive index profile by the two-step interfacial-gel polymerization process is shown in Fig. 6.

In Fig. 6, the measured index profile (solid line) is completely agreed with the approximated curve (open circles) by the power-law form with an index exponent $g$ of 2.45 in the whole core region. Since the dopant used for the fiber is diphenyl sulfide, the optimum index exponent $g_{\text{opt}}$ is given as $g_{\text{opt}} = 2.49$.

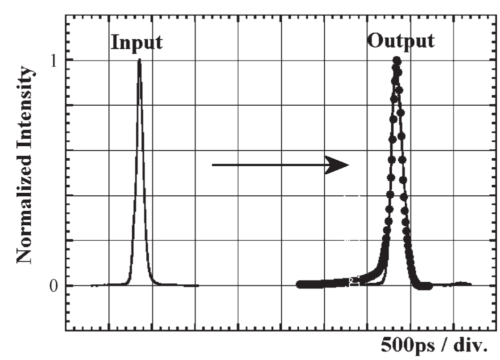


Fig. 7. Pulse broadening through 150-m fiber. Closed circle: estimated output waveform from the measured index profile. −3-dB bandwidth: 2.88 GHz.

The output pulse waveform from the 150-m fiber is shown in Fig. 7 compared to the input optical pulse at 650-nm wavelength. In this case, the optical pulse is coupled to the GI POF to launch the entire mode uniformly [overfilled launch (OFL)]. Despite the OFL condition (the worst-case launch condition), little pulse broadening is observed. Closed circles plotted in Fig. 7 signify the output waveform estimated by the WKB process from the measured index profile shown in Fig. 6. In the calculation, not only the modal dispersion but also the chromatic dispersion is taken into consideration [38]. A good agreement is observed between measured and calculated waveforms.

We also measure the differential mode delay (DMD) of the fiber shown in Fig. 6 to verify its small modal dispersion. The methodology is similar to that of the launch condition dependence of the NFPs mentioned above: An optical pulsed signal from an LD at a wavelength of 650 nm is coupled to the fiber via the SM fiber probe in the same way as the NFP measurement. By scanning the position where the single mode fiber probe is butted to the GI POF, from the core center to the periphery, each mode group from low order to high order

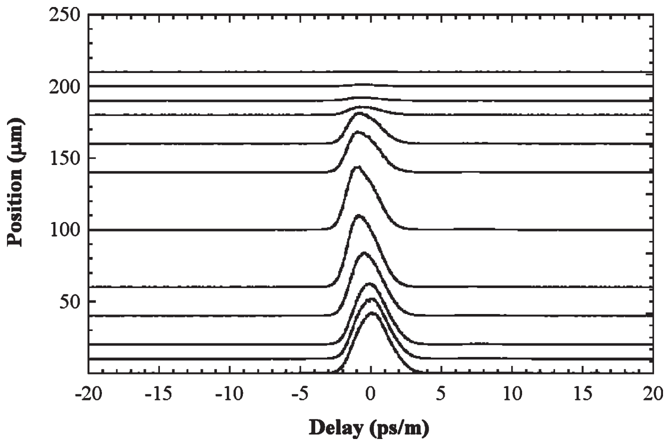


Fig. 8. DMD measurement results of 100-m fiber.

can be selectively launched. Then, we measure the differences in the time of flight of optical pulses among the different mode groups by an optical sampling oscilloscope. The result is shown in Fig. 8. The result shows that each mode group has almost the same group delay.

By a quantitative analysis of the pulse broadening shown in Fig. 7, we found only 124.8-ps broadening of root mean square (rms) pulsewidth of the measured output pulse compared to the input pulse. This pulse broadening is considered to be induced by the material dispersion. The material dispersion of the dopant-added PMMA at a 650-nm wavelength was estimated to be 423.8 ps/nm/km by our previous work [38]. The spectral width of the laser diode used for the output pulse measurement shown in Fig. 7 is 2.6 nm.

Therefore, the rms pulsewidth broadening due to the material dispersion is calculated to be 109.3 ps, which is almost the same value as the measured pulse broadening. These results indicate that the index profile formed in the fiber shown in Fig. 6 is almost optimum, and the modal dispersion is minimized.

### *E. Great Advantage of POF—Flexibility*

When GI POFs are applied to home- and premises wiring, the stability in its optical and mechanical properties against static fiber bendings is strongly required. We investigate bending losses and bandwidth performances under static bendings of GI POFs [50].

A 1.25-Gb/s data transmission by the GI POF with low bending loss is demonstrated, and eye patterns are measured after static fiber bendings are added, as indicated in Fig. 9(a). Measured eye diagrams are shown in Fig. 9(b). A good eye opening is maintained even under such a severe bending condition as ten turns on the mandrels with 10-mm radius [51]. Thus, the advantage of GI POF with low bending loss and great mechanical flexibility in high-speed optical links is demonstrated as shown in Fig. 10.

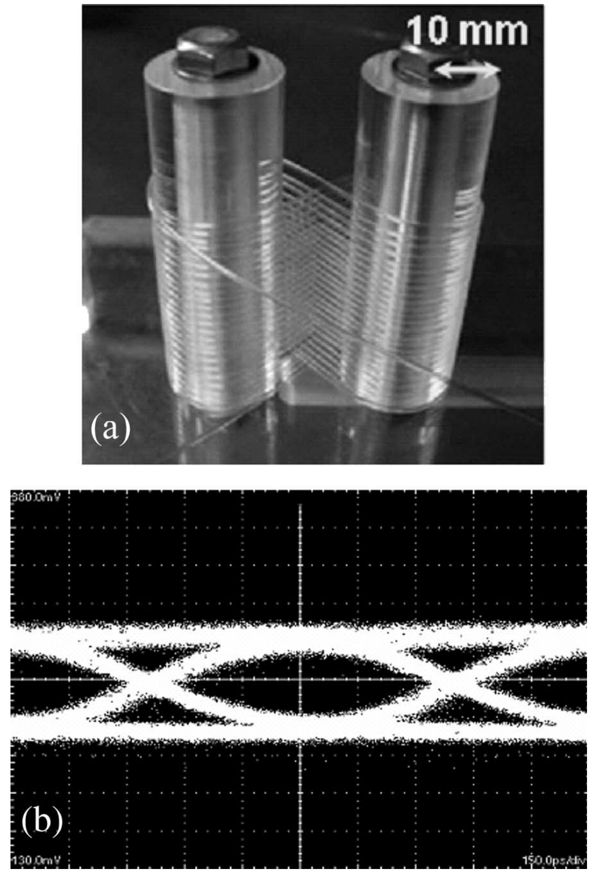


Fig. 9. (a) Bending condition of GI POF and (b) eye pattern after a 1.25-Gb/s transmission through 50-m GI POF with static bendings.

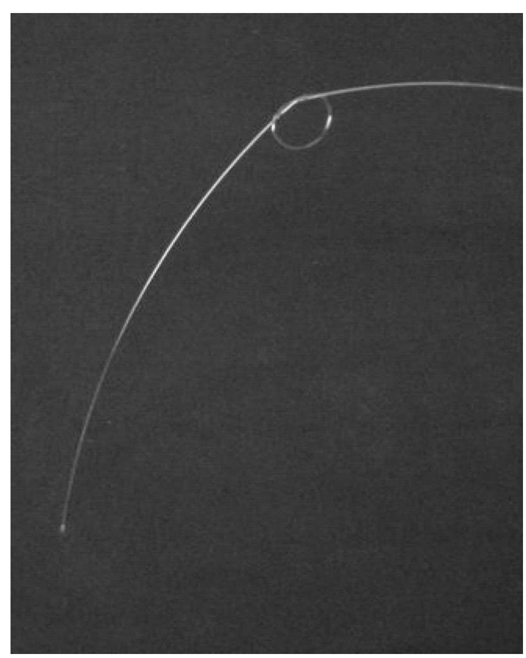

Fig. 10. Flexible GI POF. Optical signal is transmitted even if a knot is added in the GI POF.

## IV. PF Polymer Based GI POF

### *A. Attenuation*

It is well known that PF polymers have a great advantage in their attenuation compared with the conventional PMMA and other optically transparent polymers. Very low attenuation of PF polymer is realized by eliminating the intrinsic absorption loss of carbon–hydrogen stretching vibration that

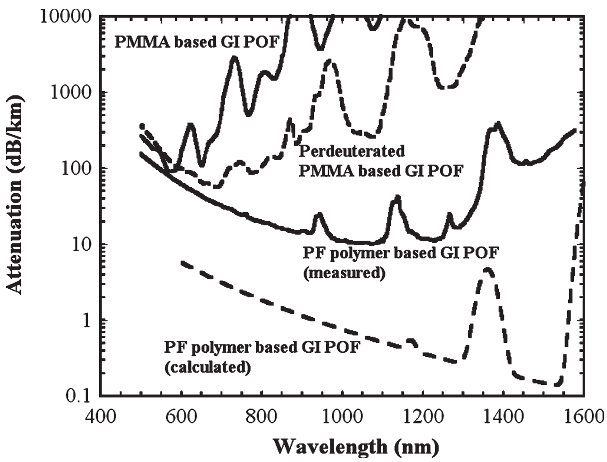


Fig. 11. Attenuation spectra of GI POFs.

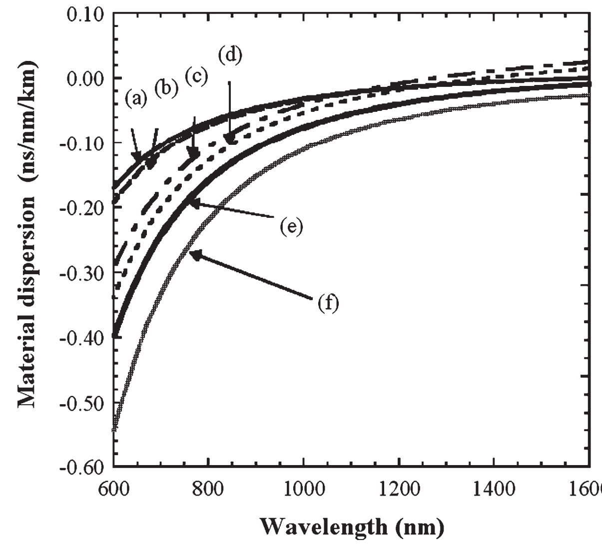


Fig. 12. Comparison of material dispersion of each polymer matrix. (a) PF homopolymer, (b) PF dopant-doped PF polymer, (c) pure silica, (d) $GeO_2$-doped silica, (e) PMMA, and (f) DPS-doped PMMA.

exists in PMMA. In general, as carbon–hydrogen stretching vibration absorption loss increases with the optical wavelength, the attenuation of PF polymer-based GI POFs, particularly at a wavelength from 800 to 1000 nm, is dramatically lowered compared to those of PMMA-based and PMMA-d8-based GI POFs, as shown in Fig. 11. Currently, attenuation as low as 10 to 15 dB/km has been successfully achieved at 1000- to 1300-nm wavelengths.

In Fig. 11, theoretical attenuation limit of PF polymer-based POF is also estimated. In the estimation, the attenuation factors are divided in two: material-inherent scattering loss and material-inherent absorption loss. A detailed explanation on the estimation processes is described in [52].

### *B. Dispersions of PF Polymer Based GI POF*

Another important characteristic of PF polymer-based GI POF is low material dispersion. We have already reported that the material dispersion of a PF polymer is much smaller than that of PMMA and even than that of silica, particularly in the short wavelength range ($\sim$0.85 $\mu$m) [9]. This means that the potential bandwidth of the PF polymer-based GI POF with an optimum refractive index profile is higher than that of silica-based MMF.

We have estimated the material dispersion of PF polymer-based-GI POFs by measuring the wavelength dependence of the refractive index of polymer bulk specimens. It is well known that the pulse broadening caused by the material dispersion is calculated by [53]

$$D_{\mathrm{mat}} = -\frac{\lambda\delta_\lambda}{c}\frac{d^2n}{d\lambda^2}L. \tag{8}$$

In (8), $\delta_\lambda$ is the rms spectral width of light source, $\lambda$ is the wavelength of light source, $c$ is the velocity of light, $d^2n/d\lambda^2$ is the second derivative of refractive index with respect to wavelength, and $L$ is the length of fiber. The refractive index data as a function of wavelength is fitted to the three-term Sellmeier equation to calculate $d^2n/d\lambda^2$ in (8).

The calculated material dispersion of PF homopolymer and PF dopant-doped PF polymer compared with pure silica, $GeO_2$-doped silica, PMMA, and diphenyl sulfide (DPS)-doped PMMA is shown in Fig. 12. The material dispersion curves shown in Fig. 12 are obtained by (8). A detailed measurement method is described in [54] and [55]. The material dispersion of the PF polymer is much smaller than those of silica and PMMA, particularly from the visible to near-infrared region. Although the material dispersion of silica is almost zero at 1300-nm wavelength, the material dispersion of $GeO_2$ doped silica is higher than pure silica.

On the other hand, it is noted that the addition of dopant in PF polymer causes little change in the value of its material dispersion. Since a PF compound is used as the dopant, the material dispersion of doped PF polymer is also low enough. Therefore, we can expect that the PF GI POF will exhibit higher bandwidth over the wide wavelength range, compared to the silica-based MMFs and PMMA-based GI POFs.

For realizing a 10-Gb/s transmission by the PF GI POF, the refractive index profile should be controlled to be the power-law form as well, and the index exponent $g$ of the PF polymer-based GI POF should be 2.1 for 0.85 $\mu$m use by taking the material dispersion into account.

Currently, the PF polymer-based GI POF is already commercially available called Lucina. However, the formation process of the refractive index profile in Lucina is a direct-diffusion (DD) process in which the dopant material is directly diffused into the molten polymer [56]. In the case of the DD process, since the dopant diffusion into the polymer is basically governed by Fick's diffusion theory, the refractive index profile formed by the DD method has not necessarily been controlled to the optimum power-law profile.

Fig. 13 shows the experimentally measured refractive index profile of the PF polymer-based GI POFs prepared by the interfacial-gel polymerization process (solid line) compared to that prepared by the DD process (broken line). The index profile obtained by the Interfacial-gel polymerization process is well fitted to the power-law form in whole core region, as shown in Fig. 13.

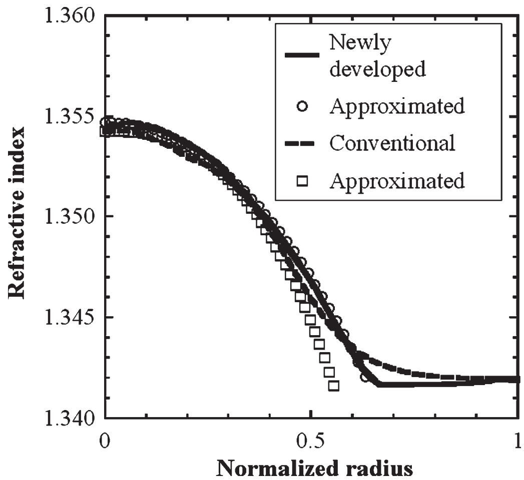


Fig. 13. Refractive index profiles of PF polymer-based GI POFs. Broken line: Measured profile formed by the conventional preparation process. □ approximated curve by power-law when $g = 1.9$. Solid line: Measured profile formed by newly developed process. ◯ approximated curve by power-law when $g = 2.1$.

On the other hand, the refractive index profile formed by the DD process shows a large deviation between measured and power-law approximation, particularly at the core-cladding boundary. The measured profile has a tailing part at the core-cladding boundary, which is the typical profile by Fick's diffusion with a constant diffusion constant. The effect of the index profile deviation at the core-cladding boundary on the bandwidth is investigated by measuring the DMD in the two GI POFs. The result of the DMD measurement in the PF GI POF prepared by the DD process is shown in Fig. 14(a) compared to the one prepared by the interfacial-gel polymerization process shown in Fig. 14(b).

In the case of the DD process, the higher order modes show faster arrival than the lower order modes, because its index profile exhibits a large deviation from power-law approximation, especially near core-cladding boundary. On the other hand, it is noted that all the modes have almost the same group delay in the case of the Interfacial-gel polymerization process, because the index profile is precisely controlled to almost optimum. Another remarkable advantage of the PF polymer-based GI POFs with low material dispersion is the low signal wavelength dependence of bandwidth. It is well known that the optimum refractive index profile $(g_{\rm opt})$ shows wavelength dependence. Particularly in the case of silica-based multimode fibers, the multimode fibers whose index profile was optimized for 1300-nm wavelength shows low bandwidth performance at 850 nm. That is why laser-optimized silica multimode fibers were developed recently to guarantee the data rate higher than 10 Gb/s [57], [58]. This wavelength dependence of the optimum index profile is caused by the profile dispersion.

Since the PF polymer has low material and profile dispersions, the wavelength dependence of the optimum profile could be decreased, and high bandwidth performance can be maintained over a wide wavelength range.

Fig. 15 shows the calculated bandwidth performances of both silica-based MMF and PF polymer-based POF. The index profiles ($g$ value) of those fibers are assumed to be optimized

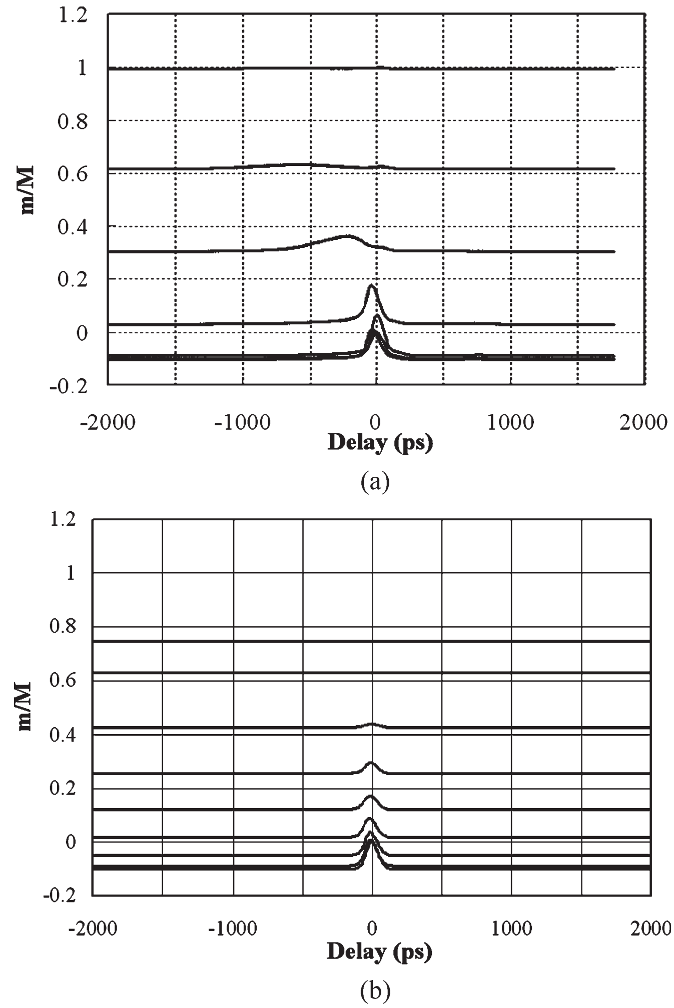


Fig. 14. DMD measurement results of 100-m PF GI POF at 650-nm wavelength. Vertical axis $(m/M)$ is the normalized principal mode number; $m$ is the principal mode number, and $M$ is the maximum principal mode number. (a) PF GI POF prepared by the conventional process. (b) PF GI POF prepared by the interfacial-gel polymerization process.

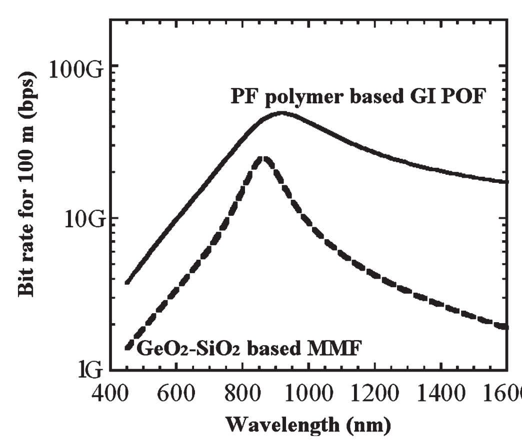


Fig. 15. Wavelength dependence of the possible bit rate in the PF GI POF link compared with that of silica-based MMF.

at a wavelength of 850 nm. Therefore, the bandwidth achieved by the silica-based MMF is the highest at 850 nm, while it is dramatically deteriorated at other wavelengths (e.g., 650 or 1300-nm wavelength). On the other hand, in the case of the PF

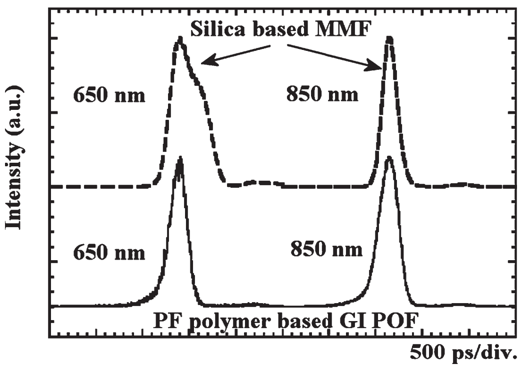


Fig. 16. Comparison of wavelength dependence of output pulse broadening from 300-m PF GI POF and silica-based MMF.

polymer-based GI POF, even if the wavelength is varied from 850 to 1300 nm, the possible bit rate remains higher than several gigabits per second. Consequently, PF polymer-based GI POF links can utilize light sources with large variety.

The signal wavelength dependence of the output pulse waveform from the obtained 300-m PF GI POF is measured and compared with that from the commercially available silica-based MMF with the same length as shown in Fig. 16.

As the silica-based MMF is the newly developed high-bandwidth version, its index profile is adjusted for 850-nm use. The output pulse broadenings are almost the same in both fibers at 850-nm wavelength. On the other hand, PF polymer-based GI POF shows a narrower pulsewidth than silica-based MMF at 650-nm wavelength because of the small material and profile dispersions. In silica-based MMF, the pulse broadening strongly depended on the signal wavelength, which means that the accurate index profile control for specified wavelength is necessary to achieve the high bandwidth, as indicated in Fig. 15.

Fig. 17 shows the eye diagrams of a 10 Gb/s for 100-m data transmission at 850-nm wavelength.

A good eye opening is observed even after 100-m data transmission at 10 Gb/s. If higher optical output power is available, much better eye opening would be observed. For such a high-speed data transmission as 10 Gb/s, the detection area (diameter) of the photodiode is as small as 50 to 60 $\mu$m, because of which a large coupling loss between the POF output end and the photodetector is caused. Here, the diameter of the PF polymer-based GI POF used for the transmission measurement is 120 $\mu$m. Despite the large coupling loss, sufficiently high bandwidth of the PF polymer-based GI POF allows a 10 Gb/s 100-m transmission.

## V. FTTD (Optical Fiber Connection to the Monitor)

Although efforts to achieve a highly networked information society have produced a steady stream of successful results, as explained earlier, it must be stressed that current broadband service is still far short of attaining the true sense of the term. Keyboard manipulation remains the technical base in much of the world of information transmission. Scenes in which a patient who suddenly feels sick late at night may employ a home communication system which supports one touch, immediate connection to a medical doctor on the other side of a large display who asks, "What is the matter?," remain within the realm of science fiction. Nevertheless, the communication distances between and among people are sure to approach zero if such dialogs, on a face-to-face basis, can be more easily realized, for which purpose connection of an optical fiber directly to the display will become the major key technology.

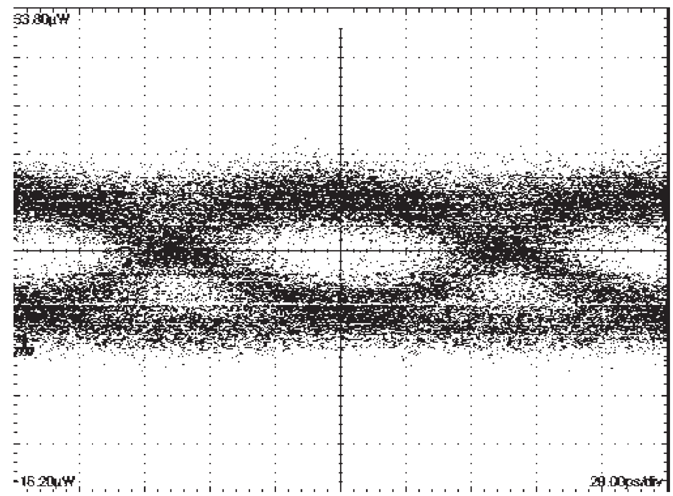


Fig. 17. Eye diagram of 10 Gb/s data transmission after a 100-m PF GI POF with ideal index profile at 850-nm wavelength.

In order to further promote broadband systems in the true sense of the term, programming research and development based on real-life situations should be necessary. These studies should be undertaken in collaboration with hardware fields, including those related to peripheral communications elements, home electronics, audiovisual (AV) equipment, etc., as well as technologies for optical fiber system installation, and should also involve simultaneous connection with software fields such as those related to data communications system technology, Internet service, contents, etc. Fig. 18 shows the concept of "Fiber to the display," where GI POFs are directly connected to a large sized flat panel display by hot plug and play basis, and then, high-resolution motion picture data is transmitted via backbone IP networks. A new standard of high-resolution display interface (high-definition multimedia interface) is requiring data rate as high as 10 Gb/s, which would be covered by GI POF. Thus, telemedicine and distance learning based on face-to-face real-time communication will be realized.

High-bandwidth GI POFs are about to accelerate a remarkable paradigm shift in network architecture. Typical copper-cable networks adopted in conventional buildings are dispersed network systems, where servers and switches are dispersed on each floor, which are connected by copper cables, as shown in a "conventional floor switch based network" in Fig. 19. On the other hand, with using high-speed GI POFs mentioned above, we have proposed a quite novel "centralized network," where there is only one main server, and GI POFs are directly distributed to any outlets and terminals from the main server [59], without any floor switches or servers in the intermediate, as shown in Fig. 19. Therefore, very simple processes of maintenance and troubleshooting for the networks can be

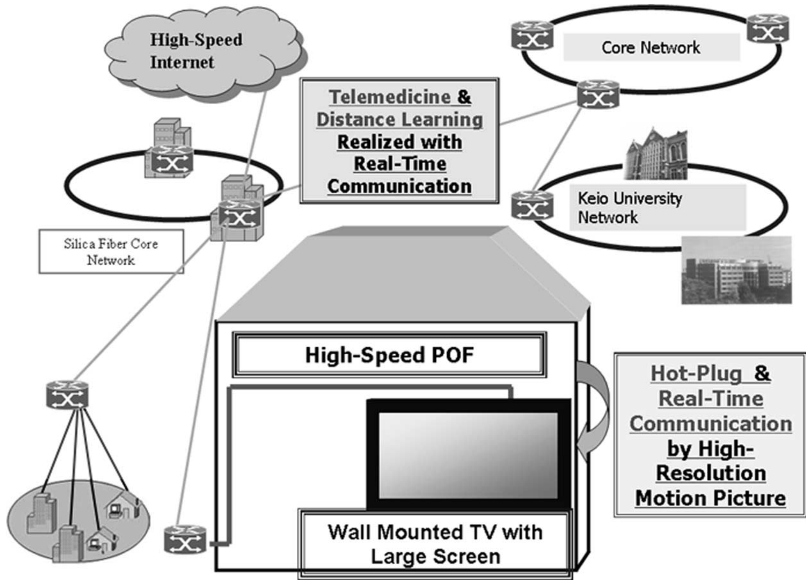


Fig. 18. Concept of FTTD.

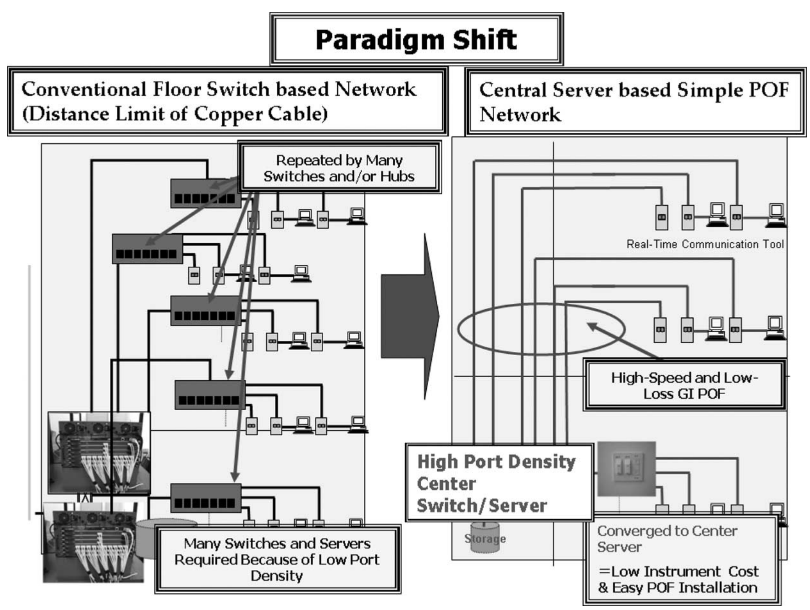


Fig. 19. Concept of centralized network architecture realized with high-bandwidth GI POF.

employed. As a result, the maintenance fee of it is one fifth of the case of a conventional dispersed network.

Such a world-first gigabit hospital system with the centralized network using all GI POF has been realized in a cardiac hospital with 320 beds, which is located in Tokyo, Japan, since 2003. Fig. 20 shows a patch-panel placed in the hospital where a huge amount of GI POF cables are connected. The total length of GI POF installed in this hospital is 230 km, which is likened to much longer branched veins compared to main veins of the human body.

## VI. Conclusion

The data capacity required to handle an image as information may easily be expected to drastically increase in the near future. For instance, the resolution of a photographic magazine, as seen by the human eye, is defined to be 350 ppi (pixels per inch), with 25 cm defined as the minimum distance of distinct vision. When transposed to a 22-in computer monitor display, this resolution is equivalent to $4192 \times 2624$ pixels, requiring the display of more than ten million pixels. However, human eye resolution decreases substantially during the transition from still image to animation.

Accordingly, the digital cinema standard for the next-generation cinema currently under development employs a maximum resolution of $4096 \times 2160$ pixels, with a single frame step function of 24 frames/s, amounting to $4096 \times 2160 \times 30(\text{bit RGB}) \times 24(\text{frame}) = 6.37$ Gb/s and requiring a transmission speed on the order of 10 Gb/s, unless image compression technology is employed. The DVI standard for display digitalization is also under development, which demands an interface transmission speed of approximately 2 Gb/s. In order

Fig. 20. Photo of a patch-panel placed in a cardiac hospital.

to cover areas over long distance at this transmission speed, the use of copper wire or UTP is difficult. For this reason, the alternative use of an optical DVI system employing GI-POF has been proposed.

Data communication at rates exceeding 10 Gb/s should be facilitated to enable free exchange of information at an individual level, as discussed above. For this purpose, a high-resolution display technology and a POF network that together implement a "Fiber to the Display" concept is thought to play an important future role.

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**Yasuhiro Koike** (M'02) was born in Tokyo, Japan, on April 7, 1954. He received the B.S., M.S., and Ph.D. degrees in applied chemistry from Keio University, Yokohama, Japan, in 1977, 1979, and 1982, respectively.

He is a Professor with Keio University, where he developed the high-bandwidth graded-index polymer optical fiber. Since 2005, he has been concurrently the Director of the Japan Science and Technology Agency (JST), Exploratory Research for Advanced Technology and Solution-Oriented Research for Science and Technology (ERATO-SORST) project. He was a Visiting Researcher with AT&T Bell Laboratories from 1989 to 1990.

Dr. Koike received the International Engineering and Technology Award of the Society of Plastics Engineers in 1994, the Fujiwara Award in 2001, and an honor of Medal with Purple Ribbon in Palace in 2006.

**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, all 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 Agency (JST), Exploratory Research for Advanced Technology and Solution-Oriented Research for Science and Technology (ERATO-SORST) project. In 2005, he was with the Department of Electrical Engineering, Columbia University, New York, NY, as a Visiting Research Scientist. His current research interests are in designing the optimum waveguide structure of high-bandwidth plastic optical fibers and its system design.