High-Bandwidth PVDF-Clad GI POF With Ultra-Low Bending Loss

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

***Abstract*—We propose a poly vinylidene fluoride (PVDF)-clad graded index plastic optical fiber (GI POF) which exhibits excellent mechanical strength and low bending loss property. A main concern of PVDF-clad GI POFs is the bandwidth degradation due to its specific waveguide structure compared to the conventional poly-methyl-methacrylate (PMMA)-based GI POF. We design the index profile of PVDF-clad GI POFs to maintain high bandwidth under a restricted mode launch condition. However, when mode coupling exists in PVDF-clad GI POFs, the bandwidth can be degraded. Hence, for high bandwidth performance, we investigate a way to reduce the mode coupling in PVDF-clad GI POFs. We find that the fiber numerical aperture (NA) is a key factor in controlling the mode coupling. By adjusting the NA of the GI core region to be as high as 0.17, bandwidth higher than 2 GHz for 100 m distance is achieved by the PVDF-clad GI POF. In addition, the propagating mode properties of the optimized PVDF-clad GI POF are investigated, particularly when the fiber is statically bent, because such a fiber bending can enhance mode coupling. We find that the high bandwidth performance is maintained in the PVDF-clad GI POF, even under severe bending conditions if the GI core region has an NA of 0.17.**

***Index Terms*—Bending loss, graded index plastic optical fiber (GI POF), mode coupling, numerical aperture (NA), poly vinylidene fluoride (PVDF), restricted mode launch condition (RML).**

I. Introduction

As broadband network technologies develop rapidly, data transmission media that allow the transmission of a huge amount of information are highly desirable. It is expected that plastic optical fibers (POFs) will be used in short to middle distance transmission media [1], [2] because its large core and great mechanical flexibility allow for easy network installations. We have proposed graded-index (GI) POFs that are capable of data transmissions at a data rate greater than 1 Gb/s [3], [4]. GI POFs are one of the cable candidates for home-network, premises wiring, and for high-resolution displays such as digital video interface (DVI) [5] or high-definition media interface (HDMI) standards. For such applications, the stability in its optical and mechanical properties against static fiber bendings is necessary. In order to satisfy these demands, a novel GI POF is investigated, which can improve the properties of conventional poly-methyl-methacrylate (PMMA)-based GI POF. Thus, in this paper, we propose a poly vinylidene fluoride (PVDF)-clad GI POF.

This PVDF-clad GI POF utilizes a polymer blend of PVDF and PMMA in its cladding layer, since PVDF has distinguished properties, such as excellent mechanical strength, thermal resistance, compatibilily with PMMA, and low refractive index [6], [7]. PVDF-clad GI POFs are expected to have overall mechanical strengths such as tensile and knot strengths. Furthermore, a high thermal stability in the attenuation is also achieved by PVDF-clad GI POFs because of its sufficiently high numerical aperture (NA) [8]. As we illustrated in [8], the attenuation increment of GI POFs under high-temperature atmosphere attributed to the bending loss due to random kinks of the fibers that were caused by a relaxation of the axial orientaion of polymer molecules that compose the GI POF. Basically, high-NA GI POFs maintain low bending loss. Therefore, the high-NA GI POFs showed high temperature stability in the attenuation. Detailed explanation is available in [8]. On the other hand, PVDF-clad GI POFs have flat refractive index regions in the core periphery, by which the refractive index profile of PVDF-clad GI POFs is deviated from the ideal power-law profile with the index exponent g value of 2.45. Thus, the bandwidth performance of PVDF-clad GI POFs can be affected by large modal dispersion.

The focus of this paper is a restricted mode launch condition [9]–[11] that excites only low-order modes to retain the high bandwidth perforemance. Actually, laser diode (LD) or vertical cavity surface eitting laser (VCSEL) is supposed to be utilized in high-speed optical links at data rates of 1 Gb/s and beyond [12]. When mode coupling exists in PVDF-clad GI POFs that are lauched by the restricted mode launch condition, the low-order modes can couple to higher order modes that are transmitted mainly through the flat refractive index region. Thus, the bandwidth performance can be degraded. Therefore, in this paper, we investigate how to reduce mode coupling and how to achieve high bandwidth in PVDF-clad GI POFs. The obtained PVDF-clad GI POFs are not necessarily capable of supporting 10-Gb/s transmission because of the modal and material dispersion. However, the PVDF-clad GI POFs maintain high-bandwidth, enabling a $1 \sim 2.5$-Gb/s transmission for 100 m under a restricted mode launch condition, which can cover the data rate required for DVI [1.65 Gb/s/channel, display resolution: Ultra eXtended Graphics Array (UXGA)] [5]. In addition, PVDF-clad GI POFs exhibit both high mechanical-strength and very low bending loss, which are not achieved by conventional PMMA-clad GI POF.

Manuscript received April 3, 2006; revised June 28, 2006.

The authors are with the Faculty of Science and Technology, Keio University, Yokohama 223-8522 Japan, and also with the Japan Science and Technology Agency (JST) ERATO-SORST, Kawasaki 212-0054 Japan (e-mail: ishigure@appi.keio.ac.jp).

Digital Object Identifier 10.1109/JLT.2006.886666

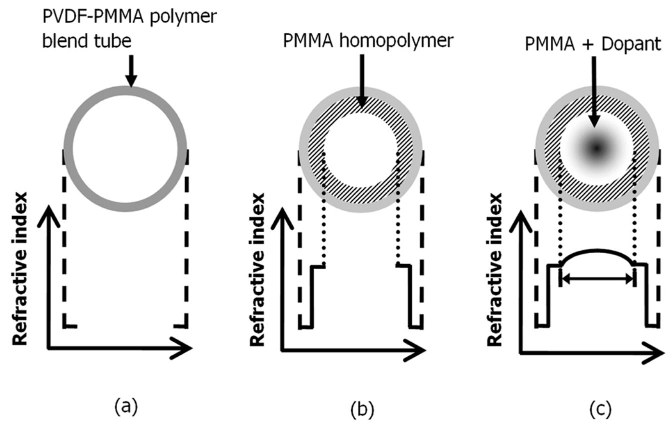


Fig. 1. Formation process of PVDF-clad GI preform rod by the Interfacial-gel polymerization technique. (a) Clad region. (b) Flat refractive index region. (c) GI core region.

II. Experimental

A. Fiber Preparation

A PVDF-clad GI POF is obtained by heat drawing a preform with a graded refractive index profile. A detailed description about the fabrication method of conventional GI POFs is described in [4]. In order to observe the bandwidth change due to mode coupling more clearly, we fabricate several GI POFs with refractive index profiles which deviate from optimum. In addition, we have confirmed in [10] and [11] that the fiber NA is a key factor to control the mode coupling strength in GI POFs. We have also theoretically confirmed in [10] and [11] that the difference of the propagation constants between adjacent modes ($\Delta\beta$) in high NA GI POFs is larger than that in low NA GI POFs. The large $\Delta\beta$ decreases the possibility of energy transfer between the modes, and then, the mode coupling strength in high NA GI POFs is weak. Hence, we fabricate several GI POFs with different fiber NAs (different relative index difference in the GI core region) as follows: A PVDF-PMMA polymer blend tube is formed in a glass tube from pelletized polymer. The blend ratio of the PVDF-PMMA blend is PVDF/PMMA = 65 / 35 by weight. Several kinds of blend polymers with different blend ratios have already been investigated. The mechanical strength provided by the PVDF-PMMA blend polymer was almost the same when the blend ratio was in the range of 60 to 70 wt. %. On the other hand, the NA of PVDF-clad GI POFs is high enough if the blend ratio of PVDF is higher than 50% [13] because PVDF-PMMA blend polymer employed for the cladding layer has a very low refractive index, such as 1.45 compared to PMMA. Therefore, the blend ratio of PVDF is determined to be 65% by weight in this paper. The refractive index ($\mathrm{n_d}$) of the PVDF-PMMA blend cladding layer is 1.445. At first, a specified amount of pelletized PVDF-PMMA blend polymer is inserted in a glass tube with an inner diameter of 22 mm. The air in the tube is evacuated, and then, the top of the glass tube is sealed by a flame. Next, the glass tube is placed horizontally in an oven at 240°C and rotated on its axis with a speed of 3000 r/min. Thus, a polymer tube from molten state polymer is obtained by centrifugal force, as shown in Fig. 1(a).

On the inner wall of the PVDF-PMMA blend polymer tube, a thin PMMA layer is prepared by the same process as the conventional PMMA-clad GI POFs described in [4] [see Fig. 1(b)]. Finally, a graded refractive index profile in the core region is formed by the same interfacial-gel polymerization technique as the conventional PMMA-clad GI POFs, as shown in Fig. 1(c).

In this process, if the PMMA layer formed in the second step is thin enough, the flat refractive index region can be removed after polymerizing the center of the core shown in Fig. 1(c). However, in the interfacial-gel polymerization process, sufficient thickness of the PMMA layer is required to form the refractive index profile at the center of the core region. Therefore, it is difficult to completely eliminate the flat index region from the preform, and a small part of this region remains, as shown in Fig. 1(c). Detail of the refractive index profile formation mechanism is described in [4].

In this paper, the core (including the flat index region) and fiber diameters are controlled in the heat-drawing process to be 700 and 750 μm, respectively.

B. Mechanical Strength of GI POFs

The mechanical strength of the GI POFs is evaluated by drawing their stress-strain curves, as described in [14] and [15]. A stress-strain curve is obtained by continuously measuring the force developed as the sample fiber is elongated at a constant rate of extension. In stress-strain curves, the yield strength is determined from the point where the stress (indicated in the vertical axis) shows the local maximum against the strain of the fiber sample (horizontal axis), whereas the sample breakage point in the curve shows the tensile strength. The conditions are the same as those described in [14] and [15].

In order to demonstrate the superior mechanical properties of PVDF-clad GI POF to that of the conventional PMMA-clad GI POF, knot tensile strength is also evaluated. Knot tensile strengths are widely utilized for evaluating mechanical strengths of fishing lines and climbing ropes. Knot tensile strengths are also known as a measure of brittleness of commercially available synthetic fiber. The measurement method of knot tensile strength is shown in Fig. 2. The knot tensile strength is estimated from the stress-strain curve of the fiber with a knot.

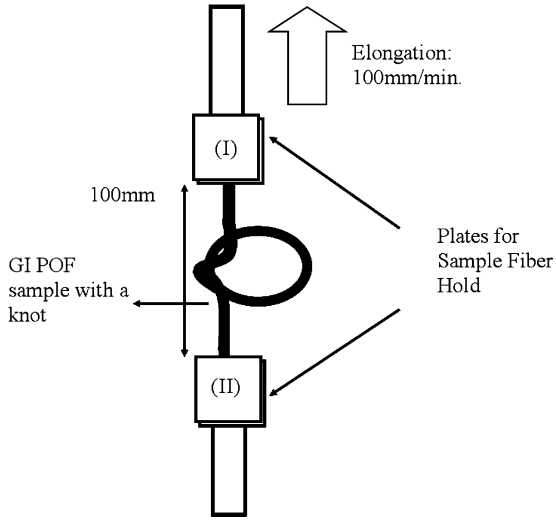


Fig. 2. Schematic representation of the measurement condition of knot tensile strength.

C. Refractive Index Profile and Bandwidth Measurements

The refractive index profiles of GI POFs are experimentally measured by the transverse interferometric technique [16]. We have already confirmed that this method has the highest accuracy in measuring the graded refractive index distribution formed over such a wide area. A detailed procedure to measure the refractive index profiles in the GI POFs is described in [16]. To analyze the bandwidth performance of the PMMA-clad and PVDF-clad GI POFs, the refractive index profile in the core region is approximated by the well-known power law form described by (1) [17],

$$\begin{aligned} n(r) &= n_1 \left[1 - 2\Delta \left(\frac{r}{a_1}\right)^g\right]^{\frac{1}{2}}, && 0 \le r \le a_1 \\ &= n_2, && a_1 \le r \le a_2 \\ &= n_3, && a_2 \le r \end{aligned} \tag{1}$$

where n_1, n_2, and n_3 are the refractive indexes of the core center, flat refractive index region of the core, and cladding, respectively, a_1 and a_2 are the only graded index core and total core radii, respectively, and Δ is the relative index difference defined as

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

The parameter g, which is called the index exponent, determines the refractive index profile over the region of $0 \le \boldsymbol{r} \le \boldsymbol{a}_1$ in (1). In the case of PMMA-clad GI POFs, the following condition should be applied:

$$n_2 = n_3. \tag{3}$$

The bandwidth of the conventional PMMA-clad GI POFs and the PVDF-clad GI POFs is measured by a time-domain method. In this measurement, a short pulse from an InGaAlP laser diode (LD) at 650 nm (a full width of half maximum of 50 ps) is coupled to the GI POFs. Then, the output pulse waveforms are measured by a sampling oscilloscope (Hamamatsu C-8188-03) with bandwidth as high as 3 GHz. Its detector is large enough to collect all the optical power emerging from such large core POFs (up to 1 mm core diameter). After measuring the waveforms of the input and output pulses, the 3-dB bandwidth of the GI POFs and PVDF-clad GI POFs are calculated by the Fourier transform of these waveforms followed by the deconvolution of them.

The launching condition of the PVDF-clad GI POFs is an important issue, as mentioned in the previous section. In this paper, the following restricted condition is adopted as the restricted mode launch (RML) condition: The optical signal from the LD is focused on the core center at the input end of the GI POFs with a 6.47-μm spot size and an NA of 0.16.

On the other hand, an over-filled mode launch (OML) condition is realized with a short-length (1–m) step-index POF probe. Optical output pulse from the laser is coupled to the SI POF probe, and then, the output pulse from the probe is coupled to the GI POFs to be evaluated. The core diameter and fiber NA of the SI POF are larger than those of the GI POFs prepared in this paper, even if a PVDF layer exists as a cladding. Thus, the SI POF probe is appropriate for uniformly launching all the modes in the GI POFs, as described in our previous articles [10], [18]

D. Fiber NA Dependence of Mode Coupling Strength

In order to investigate the fiber NA dependence of the mode coupling strength in more detail, the transmission length dependence of the output pulse broadening is evaluated. The mode coupling phenomenon can be clearly observed by increasing the transmission length, even if it is hard to observe at a short distance. In this method, the output pulse waveforms are measured by an optical sampling oscilloscope by varying the transmission length. The launching condition is fixed to RML through the measurement. After measuring the output waveforms, the root-mean square (r.m.s.) width σ of each pulse is calculated by the following equation:

$$\sigma^2 = \frac{\int_{-\infty}^{\infty} (t-\bar{t})^2 P_{out}(t)dt}{\int_{-\infty}^{\infty} P_{out}(t)dt} \tag{4}$$

where $P_{out}(t)$ is the pulse waveform with respect to time t, and $\bar{t}$ is given by

$$\bar{t} = \frac{\int_{-\infty}^{+\infty} tP(t)dt}{\int_{-\infty}^{+\infty} P(t)dt}. \tag{5}$$

The effective pulse broadening $(\Delta 2\sigma)$ through the POF transmission is calculated by

$$\Delta(2\sigma) = \left((2\sigma_{out})^2 - (2\sigma_{in})^2\right)^{\frac{1}{2}} \tag{6}$$

TABLE I
MECHANICAL PROPERTIES OF GI POFs

	Yield strength (kgf)	Tensile strength (kgf)	Elongation at Break (%)	Knot yield strength (kgf/)	Knot tensile strength (kgf)	Elongation at Break (%)
PMMA cladding GI POF (diameter:0.75 mm)	3.69 (0.04)	5.05 (0.18)	73 (5.3)	3.60 (0.03)	4.23 (0.22)	54 (5.8)
PVDF and PMMA blend polymer cladding GI POF (diameter:0.75 mm)	3.79 0.03	4.69 (0.11)	87 (4.0)	3.45 (0.13)	4.62 (0.24)	83 (8.5)
Standard Silica Single mode fiber (diameter:0.25 mm)	-	4.8 (0.2)	6.3 (0.2)	-	0.18 (0.003)	0

Standard deviation is shown in bracket.

where σ_{out} and σ_{in} are the r.m.s. widths of the output and input pulse waveforms, respectively.

When mode coupling is strong, the output pulse width under the RML condition increases abruptly with respect to the transmission distance and closes rapidly to those measured under the OML condition in a short distance. Since the pulse broadening itself is mainly caused by the modal dispersion in the GI POFs, the pulse broadening is observed when the GI POFs have the index profiles which deviate from the optimum [4].

E. Propagating Mode Analysis

Since mode coupling can greatly degrade bandwidth performances of PVDF-clad GI POFs measured under the RML condition, the analysis on the propagating modes is a very important issue. Near-field patterns (NFPs) are utilized to visualize which order of the mode groups is propagated. To measure the NFP of different mode groups, light from an LD at 650 nm is coupled to the sample fiber via a 1-m silica based single-mode fiber. The single-mode fiber probe is used to selectively launch specified mode groups. Here, the single-mode fiber probe satisfies the single-mode condition at a wavelength of 650 nm. By scanning the position of the single-mode fiber over the core of the GI POF, the NFP of each of the mode groups is measured with a CCD camera system (Hamamatsu LEPAS-11) at the output end after 100-m transmission. Thus, the launch condition dependence of NFP is measured, from which the mode coupling strength can be evaluated.

F. Optical Characteristics After Fiber Bending

Many static fiber bendings are inevitable for applications of GI POFs in home network, premises wiring, and cables for displays. Such fiber bendings can cause mode coupling in GI POFs. Even if the bandwidth of PVDF-clad GI POFs is increased by adopting the RML condition, mode coupling can degrade the bandwidth performance, as mentioned above. Therefore, it is of great concern that the high bandwidth performance of the PVDF-clad GI POFs can be degraded by static fiber bendings.

In order to investigate the stability of PVDF-clad GI POFs against static fiber bendings, the loss and bandwidth degradations after fiber bendings are evaluated as follows: A 100-m sample of PVDF-clad GI POF is statically bent at a position 50-m from the input end, as shown in Fig. 3. The bending angle is 90°, and the bending radius is varied from 5 to 50 mm. Then,

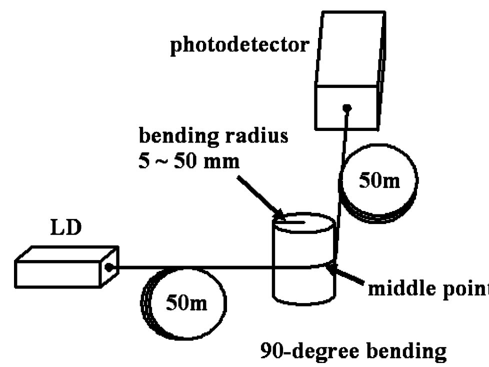


Fig. 3. Schematic representation of the measurement condition of bending loss of GI POF.

the bending losses and bandwidth are measured. The launching condition is fixed to the RML throughout the measurement as well. The bending loss is determined by the difference of the output power before and after bending. The output power is measured by an optical power meter (ANDO AQ2140).

III. RESULT AND DISCUSSION

A. Mechanical Strength of PVDF-Clad GI POF

The mechanical properties of the PVDF-clad GI POFs and conventional PMMA-clad GI POFs are summarized in Table I. We have already reported that mechanical strength of GI POFs is strongly dependent on the heat-drawing tension and the dopant concentration [14], [15]. Hence, in order to illustrate only the effect of the cladding polymer on the mechanical strength, the drawing tension and the dopant concentration are fixed in all the GI POFs. The heat-drawing tension is 100 gf, and the dopant concentration is 11 wt.%. The results of the mechanical strength shown in Table I are obtained from 20 different samples in the same fiber, and the numerical values in Table I are their averaged values. Although some amount of drawing tension variation is observed during the heat-drawing process of each fiber, the similar results are almost obtained in the mechanical strength measurements.

It is obvious from Table I that little degradation of the tensile strength is observed by using PVDF and PMMA blend polymer for the cladding of the GI POF. On the other hand, for the

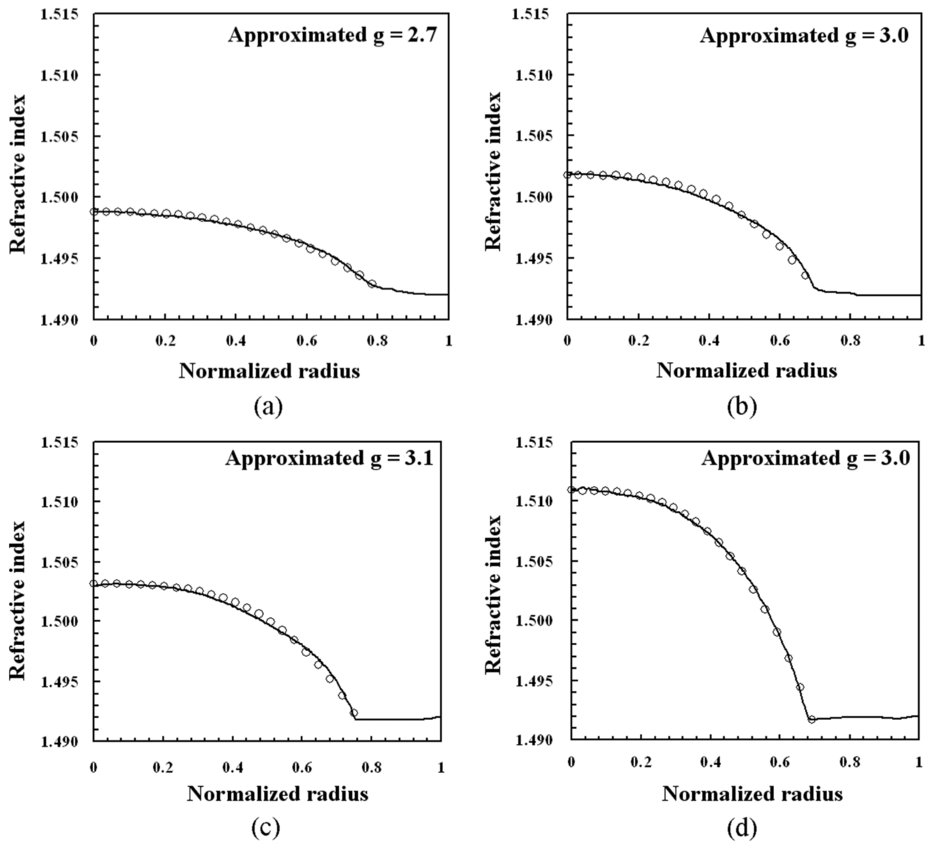


Fig. 4. Refractive index profiles of the PMMA-clad GI POFs with different NA. Solid line: Measured index profile. Open circle: Approximated curve by power law form. (a) Fiber A $\mathrm{NA} = 0.14$. (b) Fiber B $\mathrm{NA} = 0.17$. (c) Fiber C $\mathrm{NA} = 0.19$. (d) Fiber D $\mathrm{NA} = 0.22$.

practical usage of GI POFs, particularly in premises wiring, the fibers would be bent with very small radii. Therefore, not only the optical loss due to the bending but also the mechanical toughness is required. The toughness when the fiber is bent can be estimated by measuring the knot tensile strength. Comparison of the knot tensile strength between the PMMA- and PVDF-clad GI POFs is also shown in Table I. In the case of the PMMA-clad GI POF, the tensile strength is decreased by adding a knot. Thus, the PMMA-clad GI POF has a high tensile strength against the axial fiber elongation, whereas it cannot maintain the high mechanical strength when the fiber is bent.

On the other hand, it is noteworthy that the PVDF-clad GI POF shows almost the same knot yield and knot tensile strengths as the normal yield and tensile strengths, respectively. In addition, the value of elongation at break shows little change despite a knot addition. Compared to the PMMA-clad GI POF, the PVDF-clad GI POF has higher knot tensile strength, although the tensile strength of the PVDF-clad GI POF (4.69 kgf) is lower than that of the PMMA-clad GI POF (5.05 kgf). A large deterioration is observed in the knot tensile strength from the tensile strength in the PMMA-clad GI POF (5.05 kgf to 4.23 kg), whereas there is little change (4.69 to 4.62 kgf) in the PVDF-clad GI POF. Furthermore, a large difference is also observed between the elongation at break before and after providing a knot in the PMMA-clad GI POF (from 73% to 54%). The deterioration of knot tensile strength and a significant decrease in the elongation at break indicate that the PMMA-clad GI POF is easily broken before the fiber is sufficiently elongated if a knot is provided. The reason why the fiber is easily broken is the stress concentration to the knot. On the other hand, it is noteworthy that the elongation at break of the PVDF-clad GI POF is maintained to be higher than 80%, even if a knot is added. The PVDF polymer has higher mechanical toughness than PMMA, and thus, PVDF polymer is easily elongated without breakage. Therefore, even if the PVDF-clad layer is as thin as approximately 25 $\mu\mathrm{m}$, the PVDF-clad layer prevents the fiber from breaking during the knot tensile strength measurement.

These results mean that PVDF-clad GI POFs have greater mechanical flexibility than PMMA-clad GI POFs, particularly for the fiber bending, and PVDF-clad GI POFs are mechanically stable, even under many fiber bendings.

As another comparison, the normal and knot tensile strengths of a standard silica-based single mode fiber with a primary coat (0.25-mm diameter) is also shown in Table I. Although the silica-based fiber has an excellent tensile strength against the axial fiber elongation, the silica-based fiber shows its brittleness in the knot tensile strength measurement, despite the existence of the primary polymer coating on it.

B. Fiber NA Dependence of Mode Coupling Strength

In order to design the optimum refractive index profile in the core region of PVDF-clad GI POF, fiber NA is very important. This is because fiber NA is one of the key parameters to control the mode coupling strength in GI POFs, as shown in [10]

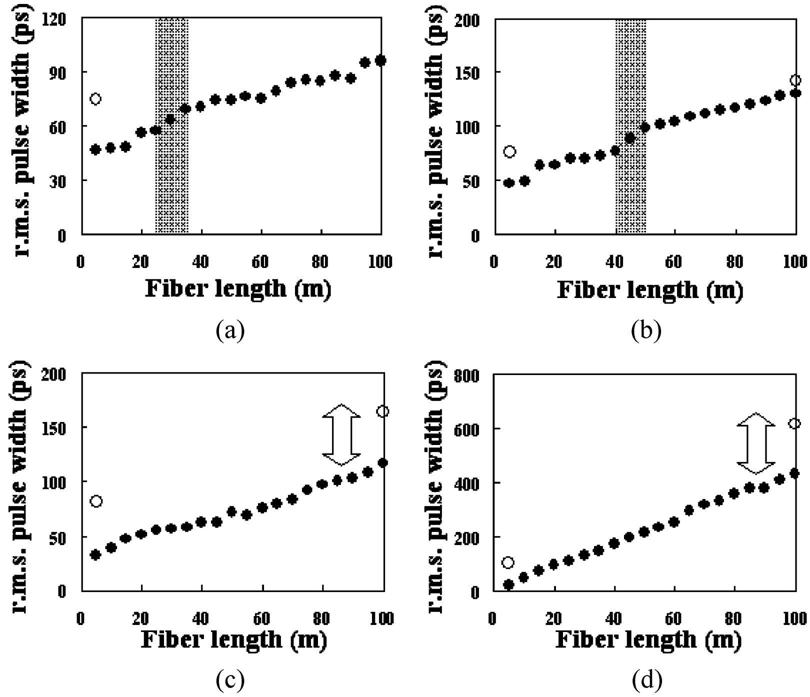


Fig. 5. Relationship between output pulse width and fiber length from GI POFs with different NA. Closed circle: Measured under the RML condition. Open circle: Measured under the OML condition. (a) Fiber A $\mathrm{NA} = 0.14$. (b) Fiber B $\mathrm{NA} = 0.17$. (c) Fiber C $\mathrm{NA} = 0.19$. (d) Fiber D $\mathrm{NA} = 0.22$.

and [11]. Thus, the fiber NA dependence of the mode coupling strength is investigated not by the PVDF-clad GI POFs but by the conventional PMMA-clad GI POFs with various fiber NA ($\mathrm{NA} = 0.15$, 0.17, 0.19, and 0.21). These fibers are fabricated under the same condition, except for the concentration of the dopant. Refractive index profiles of Fibers A, B, C, and D are shown in Fig. 4. In order to analyze the modal dispersion of GI POFs, we have adopted the power law approximation of the index profiles [4], [18]. The index profiles obtained in this paper have index exponents g from 2.7 to 3.1, as shown in Fig. 4, which deviate from the optimum value ($g = 2.45$).

The r.m.s. output pulse widths 2σ are plotted in Fig. 5 with respect to the fiber length. In Fig. 5, the open circles show the output pulse widths measured under the OML condition. Since the RML condition is fixed throughout the cut-back process, the OML condition is adopted only at the beginning and the end of the cut-back measurement, which correspond to the plots by open circles at the longest and shortest lengths, respectively, in Fig. 5.

As shown in Fig. 5(c) and (d), in the high NA GI POFs ($\mathrm{NA} \geq 0.19$), the output pulse widths under RML are not close to those under the OML condition, even after 100-m transmission. The large difference between the output pulse widths under RML and OML is emphasized by the arrows in Fig. 5(c) and (d). On the other hand, in the low NA GI POFs ($\mathrm{NA} \leq 0.17$), the pulse widths under RML are close to those under OML after 100-m transmission, as shown in Fig. 5(a) and (b). In Fig. 5(b) ($\mathrm{NA} = 0.17$), we focus on the distance l_c (indicated by the highlighted region), where the slope of the output pulse widths under RML increases rapidly. The l_c is located between 40 m and 50 m in Fig. 5(b), whereas in the GI POF with an NA of 0.15 shown in Fig. 5(a), the l_c is between 20 and 30 m. This abrupt change in the slope at l_c means that large mode coupling exists, and after the l_c, an equilibrium mode power distribution (EMB) is established. Consequently, the pulse broadenings measured under RML and OML are almost the same values after 100-m transmission, as shown in Fig. 5(a) and (b). In lower NA fiber, l_c is smaller than that in higher NA fiber.

On the other hand, explicit existence of l_c is not recognized in Fig. 5(c) and (d), which indicates that mode coupling is weak in the high NA GI POFs. These results coincide with the results confirmed in [11]. Hence, it is found that there can be a critical fiber NA around 0.17, below which strong mode coupling is clearly observed.

C. Bandwidth of PVDF-Clad GI POFs

In the Introduction, we mention that the high temperature stability in the attenuation is achieved by high-NA GI POFs. However, for high-temperature stability in the index profile (corresponding to bandwidth stability), low-NA is rather effective. For obtaining high-NA, a concentration as high as 20 wt.% or higher of dopant has to be adopted. Such high-concentration doping decreases the glass transition temperature of the polymer composing the core of GI POF. Therefore, the low-NA GI POF obtained by low dopant concentration has higher thermal stability in the index profile. Thus, the NA of the GI core region in PVDF-clad GI POFs has been initially designed to be 0.15 or lower because low NA can provide a good thermal resistance in the refractive index profile, as shown in [13]–[15].

In the case of PVDF-clad GI POFs proposed in this paper, even if the NA of the GI core region is as low as 0.15, the total NA including the PVDF-cladding can be as high as 0.4 because

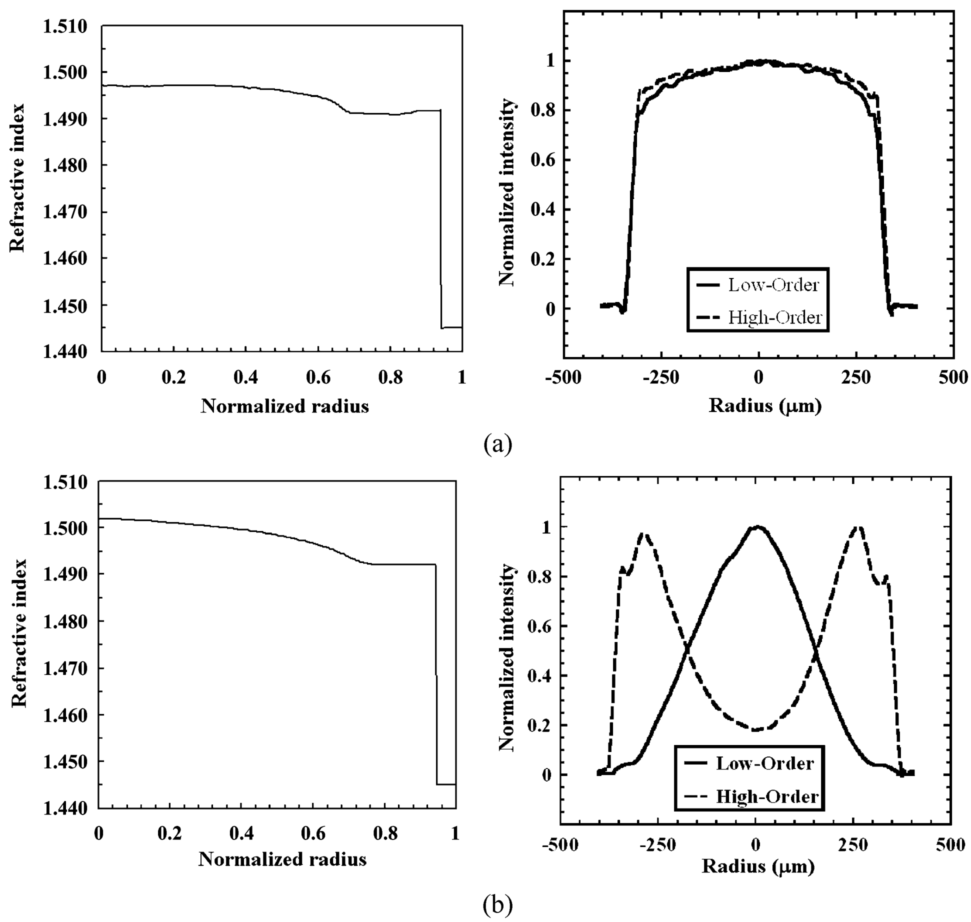


Fig. 6. Refractive index profile of PVDF clad GI POFs with different NA and their output near field patterns (NFP) of low-order and high-order mode groups launched separately. (a) Fiber E $\mathrm{NA}_{\mathrm{GI\ core}} = 0.15$. (b) Fiber F $\mathrm{NA}_{\mathrm{GI\ core}} = 0.17$.

n_1 and n_3 in (1) are 1.502 and 1.455, respectively. If the optical energy that is initially coupled to the low-order modes in the GI core region is leaked out to the flat-index region [$a_1 < r < a_2$, given by (1)] due to mode coupling, the PVDF layer plays the role of the cladding. Hence, the total NA can be calculated with the values of n_1 and n_3. An NA of 0.4 is believed to be high enough to maintain low bending loss [8], [14], [19]. However, as mentioned in the above section, the low NA in the GI core region can cause the large mode coupling from the GI core region to the flat index region in the PVDF-clad GI POF. Thus, large modal dispersion is observed even under the RML condition in such a PVDF-clad GI POF with a low-NA GI core region. Therefore, by applying the results of the fiber NA dependence of the mode coupling strength shown in Fig. 5, the GI core region of the PVDF-clad GI POFs is increased slightly to have an NA of 0.17, and then, its propagating mode properties are measured.

Refractive index profiles of the PVDF-clad GI POFs with different fiber NAs are shown in Fig. 6. In the low-$\mathrm{NA}_{\mathrm{GI\ core}}(= 0.15)$ fiber, the NFP after 100-m transmission is independent of the launch condition, as shown in Fig. 6(a). This result means that strong mode coupling in the low-$\mathrm{NA}_{\mathrm{GI\ core}}(= 0.15)$ fiber randomizes the transmission properties of all the modes. On the other hand, the modal power distribution in the PVDF-clad GI POF with high $\mathrm{NA}_{\mathrm{GI\ core}}(= 0.17)$ is dependent on the launching condition, as shown in Fig. 6(b). The high-NA reduces the mode coupling.

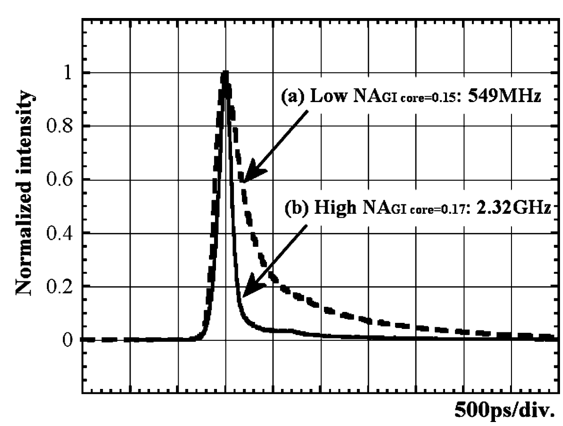


Fig. 7. Output pulse waveforms from the 100-m PVDF-clad GI POFs with different NA in their GI core regions when they are launched under the RML condition.

The output pulse waveforms of the PVDF-clad GI POFs with different fiber NAs (0.15 and 0.17) in the GI core region are shown in Fig. 7. A long tail is clearly observed in the output pulse waveform of the low $\mathrm{NA}_{\mathrm{GI\ core}}$ PVDF-clad GI POF, which decreases the bandwidth to 549 MHz. Such a long tail is

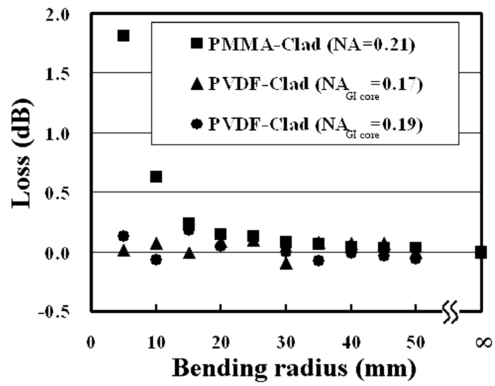


Fig. 8. Comparison of bending losses between the PVDF-clad GI POF and the conventional PMMA-clad GI POF.

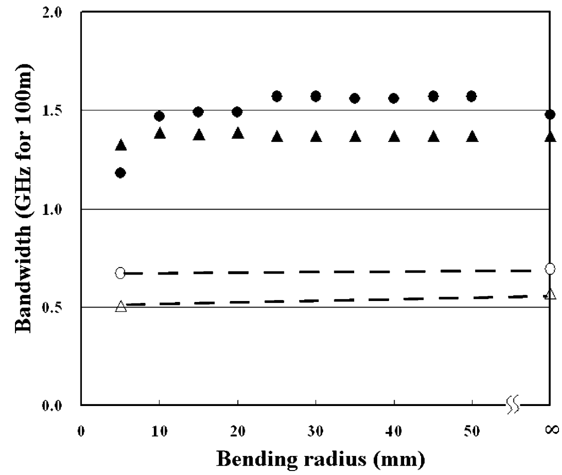


Fig. 9. Bandwidth stability of the PVDF-clad GI POFs with different NA in their GI core region. Closed circle: $\mathrm{NA}_{\mathrm{GI\ core}} = 0.19$ under RML closed triangle: $\mathrm{NA}_{\mathrm{GI\ core}} = 0.17$ under RML open circle: $\mathrm{NA}_{\mathrm{GI\ core}} = 0.19$ under OML open triangle: $\mathrm{NA}_{\mathrm{GI\ core}} = 0.17$ under OML.

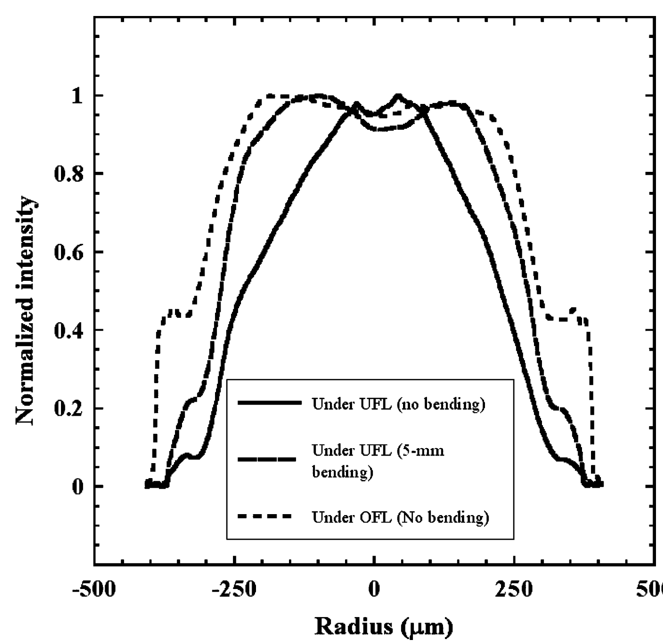


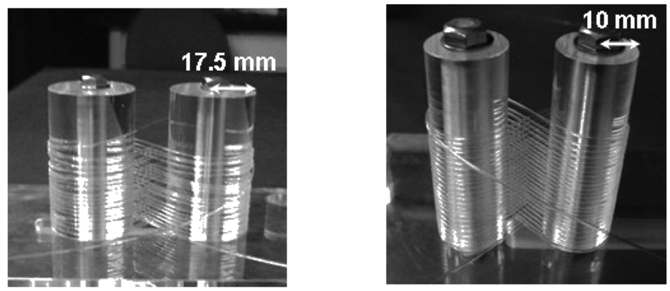
Fig. 10. Output near field patterns (NFPs) of the PVDF-clad GI POF under the RML condition before and after static fiber bending.

not observed in the output pulses from the low-NA PMMA-clad GI POFs (Fiber A: $\mathrm{NA} = 0.14$, during the measurement in Fig. 5). Therefore, the long tail shown in Fig. 7 is composed of the higher order modes with large group delays, which are confined in the flat index region. On the other hand, reduction of mode coupling from the GI core region to flat index region by high $\mathrm{NA}_{\mathrm{GI\ core}}(= 0.17)$ decreases the modal dispersion. Therefore, the bandwidth value as high as 2.32 GHz for 100 m can be achieved in the PVDF-clad GI POF for the first time. Although the index exponent g of the GI core region shown in Fig. 6(b) is not necessarily optimized (optimum g value of PMMA-based GI POFs at a wavelength of 0.65 $\mu\mathrm{m}$ is 2.45), the bandwidth of 2.32 GHz for 100 m obtained by high $\mathrm{NA}_{\mathrm{GI\ core}}$ PVDF-clad GI POF is almost the same value as that of the theoretical limit [4]. Although, in principle, the bandwidth degradation after a long distance transmission through the PVDF-clad GI POF is a concern, we do not have to guarantee the worst-case performance in POF links, because the link distance achieved by POFs composed of PMMA core is limited to less than 100 m due to its attenuation property. Strong mode coupling that can be caused by physical perturbation such as static fiber bending is, rather, of great concern. Therefore, the mode coupling by fiber bending is discussed in the next sections.

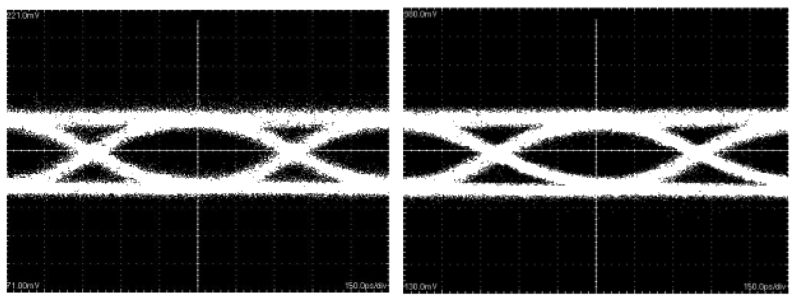
D. Propagating Mode Characteristics Under Fiber Bending

The bending losses and bandwidth performances under the fiber bending are investigated in the PVDF-clad GI POFs with different NAs in their GI core regions $(\mathrm{NA} = 0.17, 0.19)$ and are then compared to that of the conventional PMMA-clad GI POF $(\mathrm{NA} = 0.21)$. Measured results of the bending loss are shown in Fig. 8. The bending losses of the PVDF-clad GI POFs with an $\mathrm{NA}_{\mathrm{GI\ core\ region}}$ higher than 0.17 are almost 0 dB, even under the severe bending condition such as 5-mm bending radius. On the other hand, large bending loss (approximately 1.8 dB at highest) in the PMMA-clad GI POF is observed. We already reported in [19] that an NA as high as 0.25 is appropriate for reducing the bending loss of GI POFs if the core diameter is less than 200 $\mu\mathrm{m}$. If the NAs of the GI core region are simply compared in Fig. 8, the PMMA-clad GI POF has the highest $\mathrm{NA}_{\mathrm{GI\ core}}(= 0.21)$. Nevertheless, the PMMA-based GI POF shows the highest bending loss. Therefore, the optical energy that couples to the center of the GI core region under the RML leaks out to the flat refractive index region when the fiber is bent. In the case of the PMMA-based GI POF, such leakage of the optical power corresponds to the bending loss. On the other hand, since the PVDF-clad provides sufficiently high NA (approximately 0.4), even if the optical power is leaked out to the flat refractive index region, the PVDF-clad confines the optical power inside the core region (including the flat index region.)

This flat index region is the part where the index profile is deviated from the optimum power-law profile. Therefore, the bandwidth of the PVDF-clad GI POFs deteriorates if the leaked optical signal from the GI core region is confined in the flat index



(a)



(b) (c)

Fig. 11. (a) Photo of the bending condition of the PVDF-clad GI POFs and eye patterns after a 1.25 Gb/s data transmission by the PVDF-clad GI POFs with static fiber bendings. (b) Bending radius = 17.5 mm. (c) Bending radius = 10 mm.

region. Instead, such a low bending loss (less than 0.2 dB) is achieved despite the low $\mathrm{NA}_{\mathrm{GI\ core\ region}}$ (0.17) and the large core diameter (GI core region has a diameter of 560 $\mu\mathrm{m}$ surrounded by the flat index region with approximately 70 $\mu\mathrm{m}$ thickness).

Fig. 9 shows the bandwidth degradation of the PVDF-clad GI POFs due to the static fiber bendings. In Fig. 9, the bandwidth of the PVDF-clad GI POFs measured under the OML condition is also shown by the open circle and open triangle plots. In many types of GI POFs, the OML condition generally provides the worst case of their bandwidth performances [11], [18] when their index profiles deviate from the optimum. Although the bandwidth under the OML condition is less than 1 GHz for 100 m, the RML condition increases the bandwidth to approximately 1.5 GHz for 100 m in both PVDF-clad GI POFs, as shown in Fig. 9. The low bandwidth under the OML condition shows little change under a static fiber bending with a radius of 5 mm. On the other hand, the original high bandwidth under the RML condition (shown by closed circles and triangles) is maintained even after a static fiber bending with 10-mm radius and larger. Furthermore, in the range of bending radius of 10 mm and larger, the PVDF-clad GI POF with a high $\mathrm{NA}_{\mathrm{GI\ core}}$ (= 0.19, indicated by a closed circle) maintains the bandwidth higher than that of the low-$\mathrm{NA}_{\mathrm{GI\ core}}$ counterpart indicated by a closed triangle, as shown in Fig. 9. These results agree with the results of bandwidth measurement without fiber bending shown in Fig. 7. However, a slight bandwidth degradation is observed under the severest bending condition (5-mm radius), as shown in Fig. 9. This result indicates that such a severe bending causes large mode coupling and that bandwidth degradation is caused by the modal dispersion of the coupled higher order modes. Even in this case, the bandwidth of the PVDF-clad GI POFs is not degraded to the worst case value that is measured under the OML condition in both POFs in Fig. 9.

To analyze the reason why the high bandwidth is maintained even under such severe fiber bending, the output modal power distribution from the PVDF-clad GI POF is evaluated in the NFP. The results are shown in Fig. 10. Although an NFP broadening is observed under 5-mm bending, the NFP of bent fiber (given by long broken line) is not spread out as wide as the profile measured under the OML condition (illustrated by short broken line), as shown in Fig. 10. The NFP deformation after 5-mm bending shown in Fig. 10 is due to the mode coupling from the low-order modes (in the GI core region) to high-order modes (even in the flat index region). In the case of the PMMA-clad GI POF, (no PVDF-cladding layer), such an NFP deformation after fiber bending corresponds to the mode coupling to radiation modes, and consequently, the bending loss is caused as shown by a closed square in Fig. 8. Thus, the optical signal coupled to the lower order mode group of the PVDF-clad GI POF is confined in the core region (GI and flat index region) with little coupling to radiation modes, even if the fiber is statically bent. From the NFP shown in Fig. 10, although the optical power is even coupled to the flat index region after 5-mm bending, it is not as high as the power of lower order modes confined in the GI core region. Therefore, the bandwidth is still maintained higher than 1 GHz for 100-m length, even under the severe bending condition. It is demonstrated that the high bandwidth obtained by the RML condition is not degraded significantly by static fiber bendings.

E. 1.25 Gb/s Data Transmission Demonstration

1.25-Gb/s data transmission by the PVDF-clad GI POF is demonstrated. The stability of the high bandwidth of the

PVDF-clad GI POF is confirmed by the following method: A random data pattern signal modulated at 1.25 GHz from an LD at 650 nm is coupled to the PVDF-clad GI POF, and the output signal is detected by a high-speed photo detector.

Furthermore, eye patterns are measured after static fiber bendings added by using two mandrels. The fiber is turned on the two mandrels alternately, as indicated in Fig. 11(a). Two different set of the mandrels with different radii of 10 and 17.5 mm are used.

The measured eye diagrams are shown in Fig. 11(b) and (c). Although the bandwidth degradation by the bendings is concered because the bandwidth under OML is narrower than 1 GHz, good eye opening is maintained even under such a severe bending condition as ten turns on the mandrels with 17.5- and 10–mm radii, shown in Fig. 11(b) and (c), respectively. Thus, the advantages of PVDF-clad GI POFs in high-speed optical links are demonstrated.

IV. Conclusion

A novel GI POF, PVDF-clad GI POF, with excellent mechanical strength and low bending loss is proposed. In order to achieve high bandwidth transmission through PVDF-clad GI POFs, the RML condition is adopted, and the appropriate NA in the GI core region to reduce the mode coupling is discussed. To evaluate the dependence of the mode coupling strength on NA, the output pulse broadening from the conventional PMMA-clad GI POFs is measured with respect to the transmission distance. It is found that there is a critical fiber NA below which the mode coupling is observed clearly. The critical fiber NA exists around 0.17. By applying these results to the NA of the GI core region in the PVDF-clad GI POFs, bandwidth as high as 2.32 GHz for 100-m transmission can be achieved, which is almost the same value as the theoretical maximum limit of PMMA-clad GI POFs.

Also, the propagating mode characteristics of PVDF-clad GI POFs with static fiber bendings are investigated. The bending loss observed in the PVDF-clad GI POFs is almost 0 dB, even under the severe bending condition, because of the sufficiently high NA provided by the PVDF. Even under the severe bending condition, the modal power distribution at the input end is maintained for 100-m transmission. Consequently, the high bandwidth achieved under the RML condition is maintained even if static fiber bendings exist. Hence, the high bandwidth performance in the PVDF-clad GI POF is achieved even under a conceivable bending condition.

References

[1] J. Goudeau, G. Widawski, M. Rossbach, B. Bareel, R. Helvenstein, and L. Huff, "GI POF for Gb ethernet links," in *Proc. 13th Int. Plastic Optical Fibre Conf.*, Nurnberg, Germany, Sep. 2004, pp. 76–81.

[2] A. M. J. Koonen, H. van den Boom, L. Bakker, J. Zeng, and G. D. Khoe, "Integration of services in short-range multimode polymer optical fibre networks by exploiting the higher-order fibre passbands," in *Proc. 13th Int. Plastic Optical Fibre Conf.*, Nurnberg, Germany, Sep. 2004, pp. 90–97.

[3] T. Ishigure, E. Nihei, S. Yamazaki, K. Kobayashi, and Y. Koike, "2.5 Gb/s 100 m data transmission using graded-index polymer optical fiber and high-speed laser diode at 650 nm wavelength," *Electron. Lett.*, vol. 31, no. 6, pp. 467–468, Mar. 1995.

[4] 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. 1449–1556, Aug. 2002.

[5] Y. Nakamura, Y. Mizushima, M. Satou, M. Katoh, and Y. Ohashi, "The development of graded-index plastic optical fiber (LUMISTAR) and high speed optical transmission system," *Fuji Film Res. Dev.*, no. 50, pp. 64–68, 2005, (in Japanese).

[6] A. Tanaka, H. Sawada, and Y. Kojima, "Application of poly (vinylidene fluoride) and poly methyl methacrylate) blends to optical material," *Polymer J.*, vol. 22, no. 6, pp. 463–467, Jun. 1990.

[7] *Modern Fluoropolymers West Essex*J. Scheirs, Ed. New York: Wiley, 1997.

[8] M. Sato, T. Ishigure, and Y. Koike, "Thermally stable high-bandwidth graded-index polymer optical fiber," *J. Lightw. Technol.*, vol. 18, no. 7, pp. 952–958, Jul. 2000.

[9] D. G. Cunningham and W. G. Lane*, Gigabit Ethernet Networking*. Indianapolis, IN: Macmillan, 1999.

[10] 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.

[11] T. Ishigure, K. Ohdoko, Y. Ishiyama, and Y. Koike, "Mode-coupling control and new index profile of GI POF for very-short-reach networks," *J. Lightw. Technol.*, vol. 23, no. 12, pp. 4155–4168, Dec. 2005.

[12] S. Junger, M. Schrader, A. Ploetz, W. Tschekalinskij, and N. Weber, "High linearity CATV transmission with GI-POF and SI-POF," in *Proc. 13th Int. Plastic Optical Fibre Conf.*, Nurnberg, Germany, Sep. 2004, pp. 106–112.

[13] T. Ishigure, M. Sato, A. Kondo, and Y. Koike, "High-bandwidth graded-index polymer optical fiber with high-temperature stability," *J. Lightw. Technol.*, vol. 20, no. 8, pp. 1443–1448, Aug. 2002.

[14] T. Ishigure, M. Hirai, M. Sato, and Y. Koike, "Graded-index plastic optical fiber with high mechanical properties enabling easy network installations. I," *J. Appl. Poym. Sci.*, vol. 91, no. 1, pp. 404–409, Jan. 2004.

[15] ——, "Graded-index plastic optical fiber with high mechanical properties enabling easy network installations. II," *J. Appl. Poym. Sci.*, vol. 91, no. 1, pp. 410–416, Jan. 2004.

[16] Y. Ohtsuka and Y. Koike, "Determination of the refractive-index profile of light-focusing rods: accuracy of a method using Interphako interference microscopy," *Appl. Opt.*, vol. 19, pp. 2866–2872, Aug. 1980.

[17] D. Gloge and E. A. J. Marcatili, "Multimode theory of graded-core fibers," *Bell Syst. Tech. J.*, vol. 52, no. 9, pp. 1563–1578, Nov. 1973.

[18] T. Ishigure, M. Kano, and Y. Koike, "Which is a more serious factor to the bandwidth of GI POF: differential mode attenuation or mode coupling?," *J. Lightw. Technol.*, vol. 18, no. 7, pp. 959–966, Jul. 2000.

[19] K. Makino, T. Ishigure, and Y. Koike, "Waveguide parameter design of graded-index plastic optical fibers for bending-loss reduction," *J. Lightw. Technol.*, vol. 24, no. 5, May 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 from Keio University, Yokohama, Japan, in 1991, 1993, and 1996 respectively.

He is currently an Assistant Professor of 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 high-bandwidth plastic optical fibers and waveguides for high-speed optical interconnections.

Yuta Aruga was born in Aichi, Japan on Feb. 24, 1981. He received the B. S. and MS degrees in Applied Physics and physico-informatics and Integrated Design Engineering from Keio University, Japan in 2004 and 2006, respectively. He joined ITOCHU Techno-Solutions Corporations in 2006.

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 of Keio University, where he has developed the high-bandwidth GI polymer optical fiber. He has been concurrently the director of the JST ERATO-SORST project since 2005. He was a visiting researcher at AT&T Bell Laboratories from 1989 through 1990.

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