Accurate Refractive Index Profiling in a Graded-Index Plastic Optical Fiber Exceeding Gigabit Transmission Rates

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***Abstract*—An optimum index profile offering the highest bit rate communication was formed in a poly methyl methacrylate (PMMA)-based graded-index plastic optical fiber (GI-POF) by modifying the polymerization process. The interfacial-gel polymerization process we have proposed to fabricate the PMMA-based GI-POF is capable of forming a nearly optimum refractive index profile. However, the theoretically calculated bandwidth from the measured index profile was reduced compared with the GI-POF having optimum index profile. In this paper, we report how to obtain a PMMA-based GI-POF having exactly the optimum index profile. The bandwidth of this ideal GI-POF was experimentally measured and the very high bandwidth of 2.88 GHz even for a 150-m fiber length was confirmed. The calculated bandwidth agreed well with the experimentally measured one. These results indicate that very low modal dispersion can be expected in a GI-POF fabricated by the modified interfacial-gel polymerization process.**

***Index Terms*—Differential mode delay, graded-index plastic optical fiber (GI-POF), interfacial-gel polymerization process, refractive index profile.**

I. INTRODUCTION

THE demand for bandwidth continues its rapid increase due to the continued growth of data communications. Since the recent growth of data traffic is exponential, innovative technology is needed that allows network capacity to scale exponentially while requiring at most only a modest cost increase. Silica-based optical fiber networks are widely utilized in the long haul telecommunication field and currently even in the metropolitan area network. However, in the case of the silica-based single-mode fibers, the core diameter is approximately 10 μm, which requires accurate alignment for optical coupling and fiber connection. For this reason, a resurgence of interest in multimode fibers has accompanied the proposal for gigabit and 10 Gb Ethernet multimode fiber-based physical media dependent (PMD) combined with inexpensive vertical cavity surface emitting laser (VCSEL)-based transceivers. Therefore, it would not necessarily be the best solution to distribute such silica-based optical fibers even to office- and home-networks because of the cost of fiber optic devices such as connectors and transceivers.

On the other hand, plastic optical fibers (POF) having a much larger core than silica fibers are expected to be the office- and home-network media because their large core allows the use of inexpensive injection-molded plastic connectors, which can dramatically decrease the total link cost. We proposed the high-bandwidth graded-index (GI) POF for the first time [1], and have reported its bandwidth [2], [3]. By forming the optimum refractive index profile in the perfluorinated (PF) polymer-based GI-POF, a greater than 10 Gb data transmission rate is possible over a 1-km distance, because the PF polymer-based GI-POF has advantages such as low intrinsic loss and low material dispersion [4]. In silica-based multimode fibers fabricated by the conventional modified chemical vapor deposition (MCVD) process, modal dispersion dominates the bandwidth because of refractive index profile perturbations like a central dip [5], [6]. In this paper, we report the precise control of the refractive index profile in a GI-POF by adopting a two-step interfacial gel polymerization process. The ideal refractive index profile in a multimode fiber provides the minimum modal dispersion. The experimentally obtained GI-POF having the ideal index profile exhibited a high bandwidth that was almost independent of the launch conditions. This remarkably high bandwidth was theoretically confirmed by calculating the propagating modal characteristics. The potential to control precisely the refractive index profile is one of the advantages of the interfacial-gel polymerization process in the preparation technology of the GI-POF.

II. EXPERIMENTAL

A. Formation of a Refractive Index Profile by the Interfacial-Gel Polymerization Process

The GI-POF was obtained by the heat-drawing of the graded-index preform whose diameter was 22 mm. Although this diameter can be increased to 30 mm, the preform diameter was slightly smaller than the maximum value because it is easier to control the heat of polymerization.

The preform rod in which the refractive index gradually decreases from the center axis to the periphery was prepared by the interfacial-gel polymerization technique whose procedure is described as follows [1], [7]: A PMMA tube was prepared by the bulk polymerization from the purified MMA monomer; its outer diameter was 22 mm and, its inner diameter was 60% of the outer diameter. The PMMA tube was filled with a mixture of MMA monomer, dopant, polymerization initiator, and chain transfer agent. The PMMA tube filled with this monomer

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mixture was heated from the surrounding to induce polymerization. The inner wall of the PMMA tube is slightly swollen by the monomer dopant mixture to form the polymer gel phase. The reaction rate of the polymerization is generally faster in the gel phase due to the "gel effect." Therefore, the polymer phase grows from the inner wall of the tube to the center. During this process, the MMA monomer can easily diffuse into the gel phase compared to the dopant molecules because the molecular volume of dopant, which has benzene rings in it, is larger than that of the monomer. Thus, the dopant molecules are concentrated in the center region of the core to form nearly a quadratic refractive index profile [1]. The polymerization reaction rate plays an important role to control the refractive index profile [7] because it affects the diffusion process of MMA monomer and dopant molecules into the polymer gel phase formed from the inner wall of the tube. The index profile of the GI-POF was controlled by changing the kind and concentration of the dopant, polymerization initiator, and chain transfer agent. The GI-POF was obtained by the heat-drawing the GI preform. The heat-drawing of the GI preform was carried out at 220–230 °C. The fiber diameter was controlled to be 750 μm. In this fiber, the core diameter became approximately 500 μm.

B. Refractive Index Distribution and Dispersion Analysis

The refractive index profile formed in the core region of multimode optical fiber plays a great role determining in its bandwidth, because modal dispersion is generally dominant in the multimode fiber. We have reported that the GI-POF prepared by the interfacial-gel polymerization process enabled a gigabit data transmission rate [1], [8]. Furthermore, we have analyzed the bandwidth potential of the GI-POF by taking all modal, material and profile dispersions into account. The material and profile dispersions are induced by the wavelength dependence of the refractive index of fiber material. For instance, in the case of a poly methyl methacrylate (PMMA)-based GI-POF, we showed theoretically that the large material dispersion limited the maximum bandwidth to be approximately 3 GHz for a 100-m distance at 650-nm wavelength when a light source with a 2-nm spectral width was used [2]. As the material dispersion limitation is significant in the PMMA-based GI-POF at 650-nm wavelength, as we mentioned before in [2], the theoretical bandwidth limitation is improved to approximately 6 GHz for a 100-m distance with a light source having a 1-nm spectral width. We previously measured the material dispersion of PMMA [2] and found that the material dispersion of the PMMA was 0.305 ns/nm/km at 650-nm wavelength. Compared with the silica-based multimode fiber, data transmission at 650-nm seems somewhat disadvantageous, because the material dispersion is smaller at a longer wavelength such as 850 nm or 1300 nm. However, as the low attenuation window of the PMMA-based GI-POF is located at 650 nm where the attenuation is 145 dB/km, the bandwidth at this wavelength was evaluated in this paper.

For such a bandwidth analysis of the GI-POF, it was necessary to quantitatively approximate the refractive index profile of the GI-POF. For designing the optimum index profile of the GI-POF, the approximation of the index profile by the well known power-law form described by (1) is suitable

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

where n_1 and n_2 are the refractive indexes of the core center and cladding, respectively, a is the core radius, 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 called the index exponent determines the refractive index profile. However, for analyzing the bandwidth of the experimentally obtained GI-POF, it was found that the power-law form in (1) could not precisely represent the measured refractive index profile. The power-law approximation is not necessarily suitable for the index profile formed by the interfacial-gel polymerization technique. Therefore, the approximation of the index profile by a ten-term polynomial function of the distance r from the center axis of the fiber as shown in (3) was adopted [3].

$$\begin{aligned} n(r) = n_1 \Bigg[1 - 2\cdot\Delta\cdot\Bigg\{ & A_{10}\cdot\left(\frac{r}{a}\right)^{10} + A_9\cdot\left(\frac{r}{a}\right)^9 \\ & + \cdots + A_2\cdot\left(\frac{r}{a}\right)^2 + A_1\cdot\left(\frac{r}{a}\right)\Bigg\}\Bigg]^{1/2} \end{aligned} \tag{3}$$

here $A_{10}, A_9, \ldots, A_2, A_1$ are constants independent of the wavelength of the transmitting light. By introducing this approximation method, it became possible to fit the experimentally measured index profile.

C. Dispersion Calculation

By quantitatively approximating the index profile, the bandwidth characteristics of the GI-POF could be theoretically estimated. In this paper, the WKB numerical computation process was adopted for calculating the impulse response function [3], [9], [10], and the calculated results were compared with that experimentally measured by the time domain measurement method. In this numerical method, the group delay τ of the mode having the propagation constant β can be expressed as

$$\tau = \frac{L}{c}\frac{k}{\beta}\left\{\frac{\left[\int_{r_1}^{r_2} \frac{n^2 + nk\frac{dn}{dk}}{R}\, dr\right]}{\int_{r_1}^{r_2} \frac{dr}{R}}\right\} \tag{4}$$

where, n, c, and L signify the refractive index profile determined by (3), the light velocity in a vacuum, and the fiber length, respectively, and k and R are described in (5) and (6), respectively.

$$k = \frac{2\pi}{\lambda} \tag{5}$$

$$R = \sqrt{n(r)^2k^2 - \beta^2 - \frac{\nu^2}{r^2}}. \tag{6}$$

Here, λ in (5) is the wavelength of light in free space, and ν in (6) is called as the azimuthal mode number. In (4), the limits of r_1 and r_2 in the integrand are defined as the solutions of (7).

$$n(r)^2k^2 - \beta^2 - \frac{\nu^2}{r^2} = 0. \tag{7}$$

After calculating the group delay τ of each mode, the time range between the group delay of the fastest and slowest mode is divided into 30 to 40 time slots. The impulse response function was constructed by counting the number of modes whose group delay was involved in each time slot. The output waveform was calculated by the convolution of the input pulse waveform and the impulse response function in which all the modes were assumed to be equally excited.

D. Bandwidth Measurement of the GI-POF

The bandwidth of the GI-POF was measured by a time domain measurement method, in which the bandwidth was estimated by measuring the output pulse waveform when a narrow pulse was inserted into the fiber. As the light source, an InGaAsP laser diode at 655-nm wavelength and 1-nm spectral width was used. The input pulse generated by the pulse generator was inserted into the GI-POF, and the output pulse was measured with a sampling head (Hamamatsu OOS-01), and recorded and analyzed using a sampling oscilloscope.

The launch condition of the GI-POF is a very important issue in the measurement of the bandwidth. Generally in bandwidth measurements of multimode silica fibers, an establishment of the steady state mode power distribution was advocated in several previous works when the multimode fiber was intended to be adopted in telecommunication networks, because its actual long distance use forms a steady-state mode power distribution. On the contrary, with increasing interests in multimode fibers to be used in the data communication area, the overfilled launch (OFL) condition to excite all the modes is not necessarily required. However, as this paper focuses on the accurate control of the index profile in whole core region of the GI-POF, the bandwidth that is measured under the OFL condition should be rather important. If the high bandwidth is achieved by the GI-POF even under the OFL condition, high-speed data transmission is enabled by the GI-POF with a wide range of the optical transceivers at the specified wavelength, because its high bandwidth characteristic is independent of the launch condition. In order to achieve a steady-state mode power distribution, all modes should be fully launched followed by mode scrambling, by which mode coupling is deliberately induced. In this paper, a short step-index(SI) POF (1-m length) was used as the mode exciter to establish uniform launching conditions of all the modes. A pulsed signal was directly launched into the 1-m SI POF followed by the tested GI-POF sample by butt-coupling on a V-groove. Since the power distribution at the output end of the 1-m SI POF is uniform in its core region, and the numerical aperture of the SI POF (0.5) is sufficiently higher than that of the GI-POF (0.2–0.3), the 1-m SI POF is considered as an ideal mode exciter for a uniform launch.

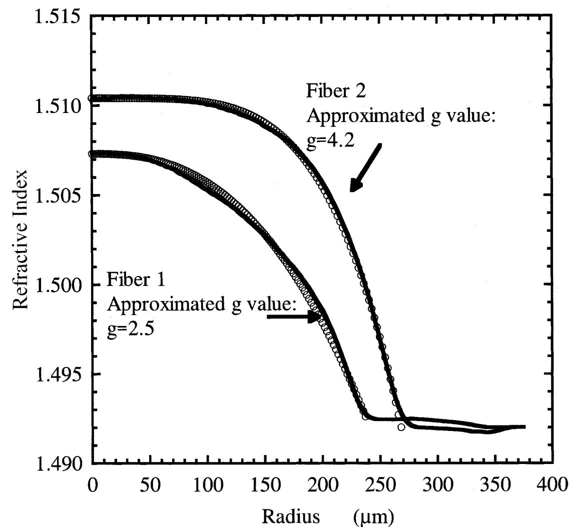

Fig. 1. Refractive index profile of a PMMA-based GI-POF prepared by the interfacial-gel polymerization process. Solid line: measured index profile ◯: Approximated profile using power-law form.

III. Results and Discussion

A. Interfacial-Gel Polymerization Technique

Representative examples of the refractive index profiles of the PMMA-based GI-POF are shown in Fig. 1, in which curves fitted to the power-law form are also indicated. The best fitted curves to the measured profile were obtained by the least-squares method. These GI-POFs were drawn from a 22-mm diameter preform that was prepared by the interfacial-gel polymerization process. As we already reported [7], it is almost possible to control the g value by regulating the polymerization reaction rate in the core region. Therefore, we theoretically and experimentally investigated the optimum refractive index profile of the PMMA-based GI-POF. For modeling the optimum index profile, we already proposed that all modal, material and profile dispersions should be taken into consideration. Since the PMMA-based GI-POF should be utilized in an optical link whose wavelength experiences low attenuation (650 nm), the material and profile dispersions are much larger than those at longer wavelengths such as 1.3 μm or 1.55 μm which are used for conventional silica-based single-mode fibers. Therefore, although the optimum index exponent (g_{opt}) is almost 2.0 when only modal dispersion was taken into account, the g_{opt} of the PMMA-based (MMA-diphenyl sulfide (DPS) system) GI-POF was 2.5 at a 650-nm wavelength after considering the profile dispersion. As shown in Fig. 1, the GI-POFs having an almost optimum index exponent (2.5) and a larger index exponent (1.2) were experimentally obtained.

It was experimentally confirmed that the refractive index profile of the measured GI-POF prepared by the interfacial-gel polymerization process was not necessarily well-fitted to the power-law form shown by (1). [3] In order to evaluate the accuracy of the power-law approximation, the difference between the measured and approximated refractive index profiles was plotted with respect to the normalized core radius in Fig. 2. It

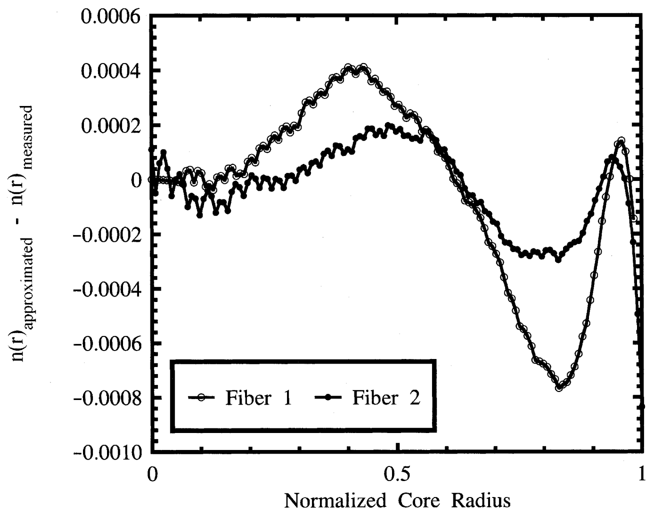

Fig. 2. Refractive index differences between the approximated $(n(r)_{\mathrm{approximated}})$ and measured $(n(r)_{\mathrm{measured}})$ profiles shown in Fig. 1. Fiber 1: Approximated index exponent g is 2.5. Fiber 2: Approximated index exponent g is 4.2.

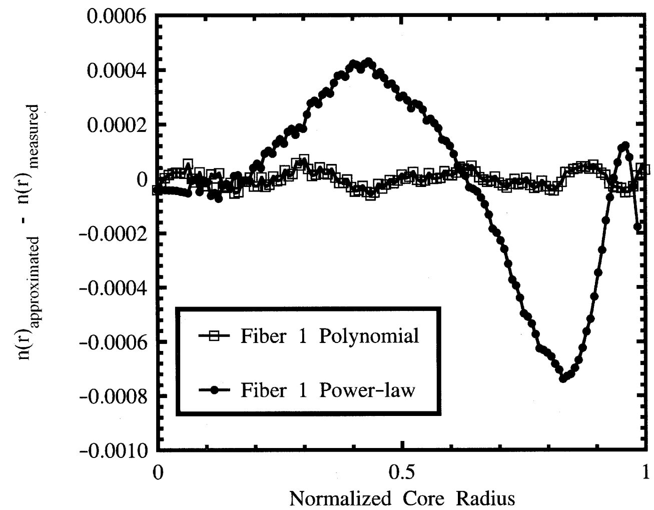

Fig. 3. Comparison of approximation accuracy between power-law and polynomial fittings for the refractive index profile of Fiber 1.

is found from Fig. 2 that both Fiber 1 and 2 showed positive deviation of the refractive index profile in the range of 0 – 0.6 of the normalized core radius, and negative deviation in 0.6 – 1.0 of the normalized core radius. It was found by investigating many GI-POFs prepared by the interfacial-gel polymerization process that a similar deviation was observed in almost all of the PMMA-based GI-POFs drawn from an 18 – 22 mm diameter preform. This result indicates that the measured index profile cannot be described by only one index exponent value. In the case of Fiber 1 shown in Fig. 1, although the best fitted index exponent g is 2.5, which was determined by the least-squares method, it can be found from the result shown in Fig. 2 that the measured index profile should be expressed by using g value smaller than 2.5 in the range of 0 – 0.6 of the normalized radius, while g value larger than 2.5 in 0.6 – 1.0 of the normalized radius.

In order to precisely approximate the refractive index profiles of Fiber 1 and 2, a ten-term polynomial fit was carried out, and their bandwidth characteristics were calculated by following the above process. In the case of Fiber 1, the difference of the refractive index between the approximated and measured profiles $[(n(r)_{\mathrm{approximated}} - n(r)_{\mathrm{measured}})]$ is plotted with respect to the normalized core radius in Fig. 3. It is noted that the value of $[(n(r)_{\mathrm{approximated}} - n(r)_{\mathrm{measured}})]$ is almost 0 over the whole core region. This means that the polynomial fitting more precisely approximates the refractive index profile than the power-law approximation.

The bandwidth characteristics of both Fiber 1 and 2 were theoretically calculated by utilizing the ten-term polynomial fitting. As the refractive index profiles are not described by the power-law form, a numerical computation procedure was required in the group delay calculation. In this paper, the WKB method was adopted. The detailed calculation procedure was mentioned elsewhere [3], [8], [9]. The bandwidth characteristics of the GI-POFs were experimentally investigated by a time-domain measurement method. Figs. 4 and 5 show the experimental and calculated results of the output pulse from the GI-POFs whose index profiles are shown in Fig. 1. The calculated output pulses were obtained by calculating the impulse response function following the procedure mentioned above, followed by the convolution with the input pulse waveform. When the index profile exhibits large deviations from the optimum ($g = 4.2$, Fiber 2), a significant output pulse broadening is observed, while little pulse distortion is observed in the GI-POF having an almost ideal index profile ($g = 2.5$, Fiber 1). On the other hand, both calculated output waveforms (closed circles) in Figs. 4 and 5 have two peaks, which is different from those measured. Thus, even if the refractive index profile was precisely approximated by a ten-term polynomial fitting, the calculated output waveforms disagreed with those measured experimentally.

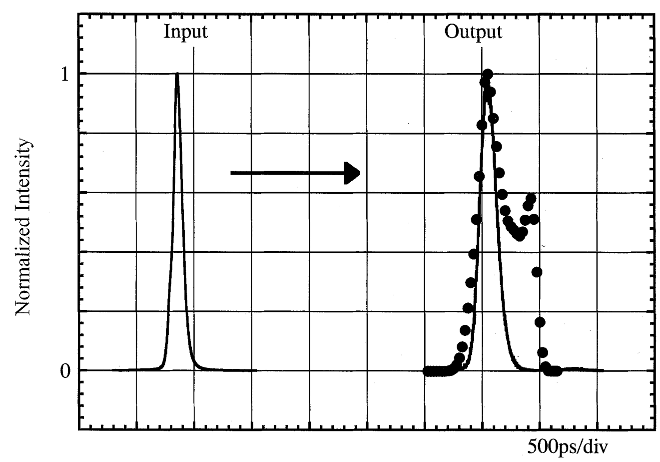

Fig. 4. Output pulse waveform from a 100-m PMMA-based GI-POF (Fiber 1) compared with that of the input pulse. Solid line: Measured input and output waveforms. •: Calculated output waveform when the index profile of the GI-POF was approximated by a ten-term polynomial form and all the modes were assumed to be uniformly launched.

We already reported that this difference between the measured and calculated bandwidth characteristics are not caused by mode coupling but by differential mode attenuation [3]. In this paper, a more detailed modal analysis was carried out to clarify the reason why two output peaks were observed in the calculated output waveforms. Fig. 6 shows the calculated

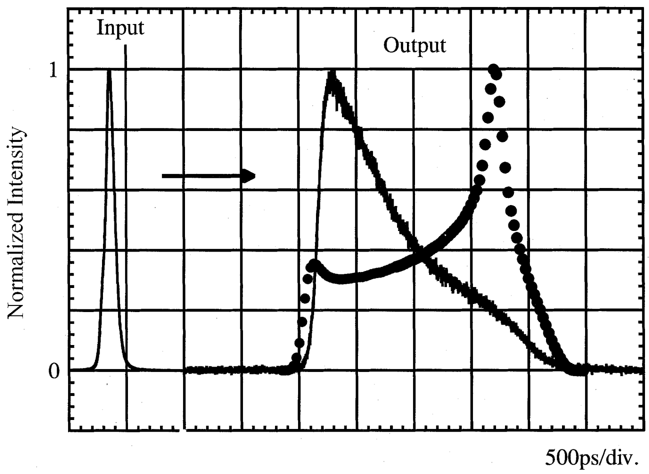

Fig. 5. Output pulse waveform from a 100-m PMMA-based GI-POF (Fiber 2) compared with that of the input pulse. Solid line: Measured input and output waveforms. ●: Calculated output waveform when the index profile of the GI-POF was approximated by a ten-term polynomial form and all the modes were assumed to be uniformly launched.

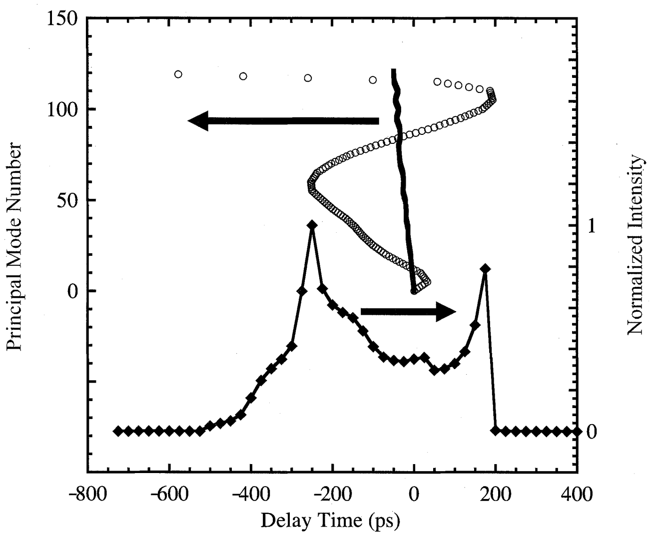

Fig. 6. Calculated differential mode delay (DMD) of the meridional mode in Fiber 1 compared with its impulse response function waveform. ——: Calculated DMD when the index profile was approximated by a power-law form ($g = 2.5$) ○ : Calculated DMD when the index profile was approximated by a polynomial form. —◆— : Calculated impulse response function waveform when the index profile was approximated by polynomial form and all modes were assumed to be uniformly launched.

differential mode delay (DMD) of Fiber 1 by the WKB method compared with its impulse response function, which was also theoretically calculated. Here, the calculated DMD means the delay time of meridional modes whose azimuthal mode numbers ν are zero. In Fig. 6, the open circles signify the DMD with respect to the principal mode number calculated by utilizing the ten-term polynomial approximation for its index profile, whereas the filled circles show the DMD when the index profile was assumed to be a power-law profile ($g = 2.5$). The horizontal axis shows the arrival time difference of each mode compared with the lowest order mode at the end of the 100-m GI-POF. Therefore, negative time delay means a faster arrival than the lowest order mode, while the positive arrival time means a delayed arrival compared with the lowest

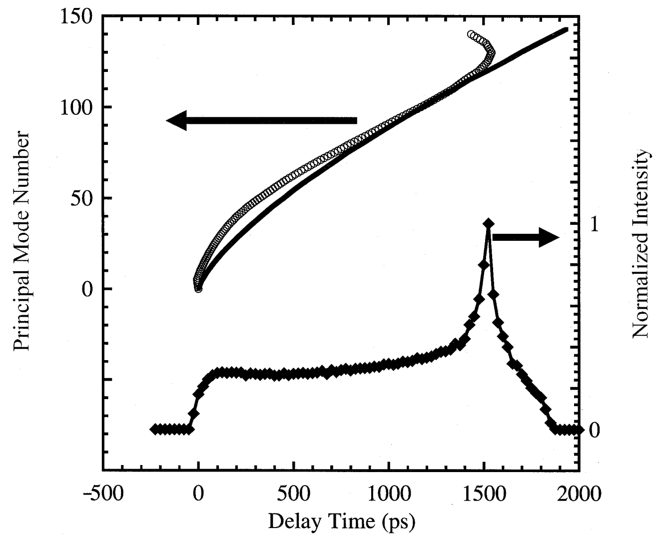

Fig. 7. Calculated differential mode delay (DMD) of the meridional mode in Fiber 2 compared with its impulse response function waveform. ——: Calculated DMD when the index profile was approximated by a power-law form ($g = 4.2$) ○ : Calculated DMD when the index profile was approximated by a polynomial form. —◆— : Calculated impulse response function waveform when the index profile was approximated by a polynomial form and all modes were assumed to be uniformly launched.

order mode. It is found in the DMD curve shown by open circles that with increasing principal mode number the delay time decreases at first when the principal mode number is less than 60, then increases when the principal mode number is up to 110, and finally decreases again when the principal mode number is larger than 110. Hence, there are two major turning points in the DMD curve (open circles) at -250 ps and 200 ps of delay time as shown in Fig. 6. On the other hand, if the GI-POF has a power-law profile, the DMD (solid line) monotonically decreases with increasing principal mode number. This considerable difference in DMD shown by open circles and solid lines is attributed to the refractive index profile deviation from the power-law form as shown in Fig. 2. As it was shown in Fig. 2, the refractive index profile of Fiber 1 in the range of 0 – 0.6 of core radius could be fitted to the power-law curve in which an index exponent g of less than 2.5 is used. Since the ideal index exponent of the PMMA-based GI-POF at 650-nm wavelength is 2.5, an index exponent lower than 2.5 creates an over-compensated GI-POF, which means that the higher order modes propagate faster than the lowest order mode. Therefore, the negative DMD was observed in the lower order modes of Fiber 1 when the principal mode number is less than 60. On the other hand, the high order modes in Fiber 1 show positive DMD because the index profile can be well-fitted to the power-law profile having a g value larger than 2.5 as shown in Fig. 2, which creates an under-compensated GI-POF.

The same comparison between the DMD and the impulse response function of Fiber 2 is shown in Fig. 7. In the case of Fiber 2, the DMD shown by open circles increases with increasing the principal mode number in almost the same manner as that shown by the solid line. However, only one turning point is observed at 1500 ps. This also corresponds to the index profile deviation from the power-law curve of the experimentally obtained fiber.

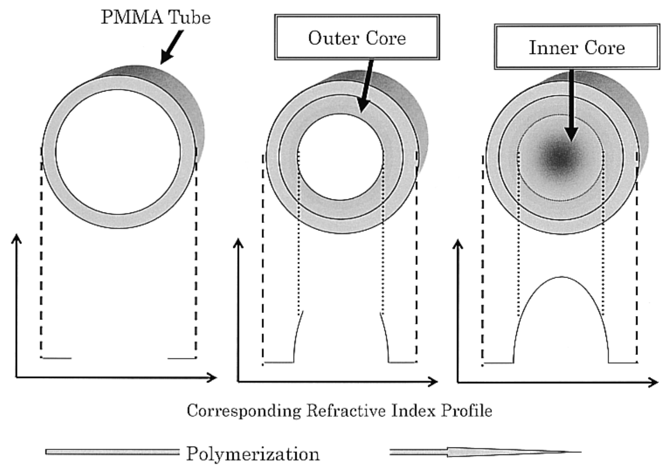

Fig. 8. Schematic representation of the two-step interfacial-gel polymerization process.

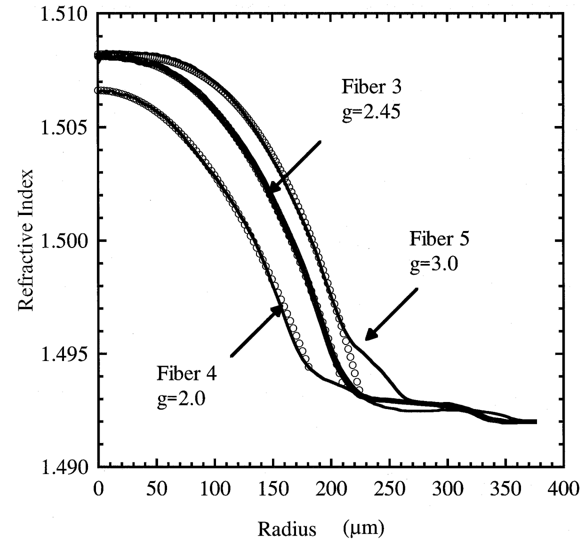

Fig. 9. Refractive index profiles of the PMMA-based GI-POFs prepared by the two-step interfacial-gel polymerization process. Fiber 3 Thickness and dopant concentration in the outer core layer were optimized. Fiber 4 Thickness of the outer core layer was larger than the optimum one. Fiber 5 Dopant concentration of the outer core region was slightly higher than the optimum one.

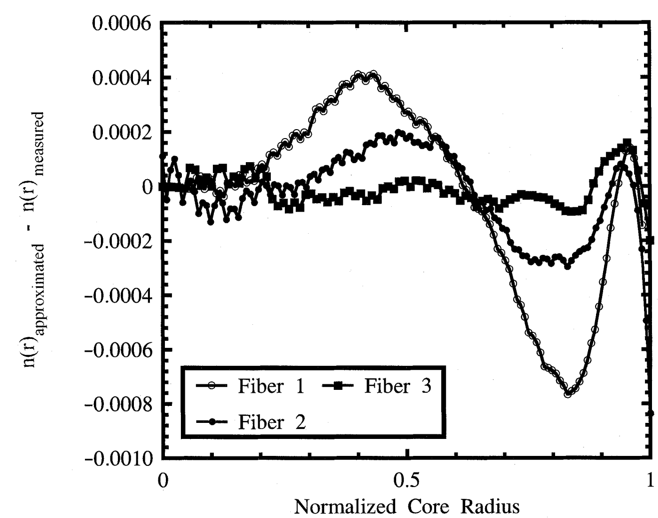

Fig. 10. Refractive index differences between the approximated ($n(r)_{\mathrm{approximated}}$) and measured ($n(r)_{\mathrm{measured}}$) profiles of Fiber 3 shown in Fig. 8 compared to those of Fiber 1 and Fiber 2. Approximated index exponent g of Fiber 3 is 2.45.

In the case of the power-law approximation, it was assumed that the profile was discontinuous at the boundary of the core and cladding, whereas a real fiber has a continuous index variation at the boundary. Consequently, the profile necessarily has a point of inflection, which causes such a turning point in the DMD curve as shown in Fig. 7.

It is noteworthy that the two peaks in the impulse response function curve appear at the same times as the turning points of the DMD curve mentioned above. The impulse response functions shown in Figs. 6 and 7 were constructed by counting the number of modes that arrived in a time slot having a 25-ps width. As the vertical axis in Figs. 6 and 7 shows the principal mode number, it is obvious that the number of modes arriving in one time slot becomes large at the turning point of the DMD. In fact, each plot in Figs. 6 and 7 signifies one mode. It is shown by the two figures that the number of modes allotted to one time slot is greater around the turning point where many modes arrive within a very short time range than other times. Therefore, the large peak is formed if the relation between the DMD and the principal mode number shows an abrupt change (turning point). Furthermore, the peaks in the output waveforms shown in Figs. 6 and 7 are mainly formed by the high-order modes. We also measured the differential mode attenuation, and found out that the high-order modes had almost twice the attenuation as the low-order modes [3]. From those results, we concluded that the difference in the measured and calculated output waveforms was induced by differential mode attenuation.

B. Two-Step Interfacial-Gel Polymerization Process

By the above detailed analysis, it was found that the accurate control of the refractive index profile was difficult in the whole core region of the GI preform by the previous interfacial-gel polymerization process, particularly when the preform diameter increases to more than 20 mm. Even if it is calculated that the GI-POF has a nearly optimum power-law profile by the least-squares method, some parts of the profile slightly deviate from a completely optimum one. Therefore, we developed a two-step interfacial-gel polymerization technique to realize a completely optimum refractive index profile. In this process, the polymerization of core region was divided into two steps: the polymerization of the outer core region and the polymerization of the inner core region. After polymerizing the first PMMA tube having a 22–mm diameter, a specified amount of MMA monomer-dopant mixture was injected into the PMMA tube and the tube was rotated on its axis at 3000 rpm in an oven at 70°C to complete the polymerization. After the polymerization, the PMMA tube having an outer core region was obtained. Subsequently, the PMMA tube was filled with the MMA monomer-dopant mixture to form the refractive index profile of both the inner and outer core regions. A schematic representation of this process is summarized in Fig. 8. Since the thickness of the outer core and/or the dopant concentration of the outer and the inner core layers can be varied, the refractive index profile, particularly at the boundary of the core and the (outer)

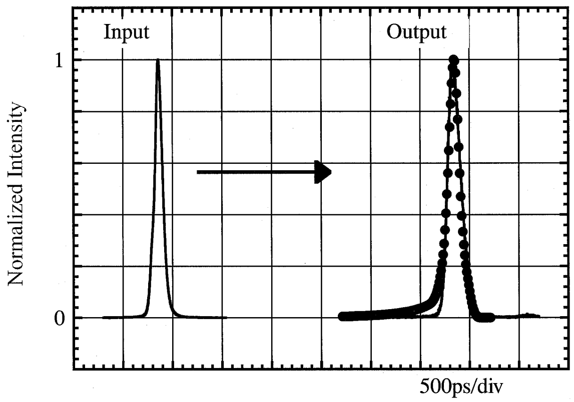

Fig. 11. Output pulse waveform from a 150-m PMMA-based GI-POF (Fiber 3) compared with that of the input pulse. Solid line: Measured input and output waveforms. • : Calculated output waveform when the index profile of the GI-POF was approximated by a ten-term polynomial form and all the modes were assumed to be uniformly launched.

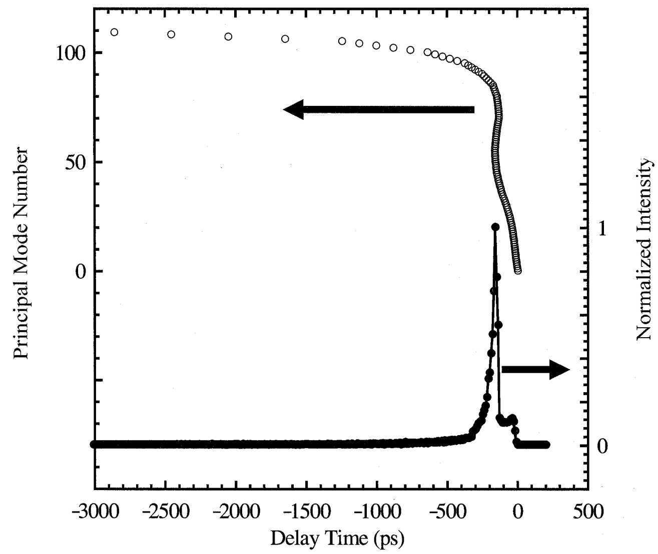

Fig. 12. Calculated differential mode delay (DMD) of the meridional mode in Fiber 3 compared with its impulse response function waveform. ○: Calculated DMD when the index profile was approximated by a polynomial form. —♦—: Calculated impulse response function waveform when the index profile was approximated by a polynomial form and all modes were assumed to be uniformly launched.

core region is freely controlled. Refractive index profiles of the GI-POFs fabricated by the two-step interfacial-gel polymerization process are shown in Fig. 9. A large deviation in the index profile from the power-law profile, particularly at the outer core region, is observed if the thickness and the dopant concentration are not optimized (Fiber 4 and Fiber 5). However, by optimizing those parameters, a nearly ideal refractive index profile without such distortions was obtained. The difference of the refractive index profile between the measured and approximated $[(n(r)_{\mathrm{approximated}} - n(r)_{\mathrm{measured}})]$ in the case of Fiber 3 is plotted with respect to the normalized core radius in Fig. 10 and is compared to those of Fiber 1 and 2. It should be noted that Fiber 3 shows little deviation of the refractive index profile in the range of 0 – 0.9 of normalized core radius, which means that the index profile of Fiber 3 is precisely approximated by a power-law profile. As the index exponent g of Fiber 3 is 2.45, the index profile of Fiber 3 is completely optimized.

Theoretically estimated output pulses from 150-m of Fiber 3 are shown in Fig. 11 compared with an experimentally measured one. Here, the calculated waveform was obtained by approximating the index profile of Fiber 3 with a ten-term polynomial form. Even though all the modes were assumed to be uniformly launched, the calculated output pulse shows a good agreement with the experimentally measured one. These results show that the group delay of all the propagating modes in Fiber 3 is almost the same, which means that the refractive index profile of Fiber 3 is almost completely optimized. The -3 dB bandwidth of the Fiber 3 was calculated from the experimentally measured output pulse by Fourier transform, to be 2.88 GHz even for a 150-m length, which is almost the maximum theoretical bandwidth limit of a PMMA-based GI-POF. Fig. 12 shows the comparison of the calculated DMD and the impulse response function of Fiber 3. In the range of 0 to 100 of principal mode number, the DMD shows little change; consequently, the impulse response function has a small pulse width. Modes with principal mode number greater than 100 show slightly larger time delays. However, they have little influence on the impulse response function, namely on the bandwidth characteristics of the fiber. From these results, by adopting the two-step interfacial-gel polymerization process, the optimization of the refractive index profile can be achieved even in a preform with a diameter larger than 20 mm.

IV. Conclusion

A completely optimum refractive index profile was formed in a PMMA-based GI-POF for the first time by adopting a two-step interfacial-gel polymerization process in a 22-mm diameter preform. The accurate control of the index profile in silica-based multimode fibers has been a key issue. It is well known that the refractive index profile of silica-based multimode fibers obtained by the MCVD method normally contains some distortions such as a central dip or ripples [5], [6].

Accurate index profiling in GI-POFs by the interfacial-gel polymerization process has also been a key issue, particularly when increasing the preform diameter up to 20–50 mm. It has been shown in this paper that the optimum refractive index profile can be obtained even in such a large diameter preform. This result indicates that very low modal dispersion can be expected in a GI-POF fabricated by the interfacial-gel polymerization process.

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