Formation of the Refractive Index Profile in the Graded Index Polymer Optical Fiber for Gigabit Data Transmission

Takaaki Ishigure, Masataka Satoh, Osamu Takanashi, Eisuke Nihei, Takayuki Nyu, Shuntaro Yamazaki, and Yasuhiro Koike

***Abstract*—Bandwidth characteristics of the large core graded index polymer optical fiber (GI–POF) are theoretically and experimentally clarified in this paper. The refractive index profile of the GI–POF was controlled by the interfacial-gel polymerization to investigate the relation between the index profile and the bandwidth characteristics. It was experimentally confirmed that the maximum bandwidth of the poly methyl methacrylate (PMMA) base GI–POF is at most 3 GHz for 100 m transmission with using the typical laser diode emitting at 650-nm wavelength (3 nm source spectral width) when its refractive index profile is optimized. The maximum bandwidth theoretically estimated by considering both modal and material dispersions is approximately 3 GHz which is exactly the same as the measured value, while higher than 10 GHz for 100 m was expected if only modal dispersion was taken into account. The optimum refractive index profile of the PMMA base GI–POF is theoretically and experimentally clarified by further considering the profile dispersion.**

***Index Terms*—Graded index polymer optical fiber, interfacial-gel polymerization process, material dispersion, modal dispersion, profile dispersion, WKB method.**

I. Introduction

CONSIDERABLE research activity lately has been centered on the development of optical component and devices that have the capability to provide the high-speed multimedia network. In a long haul telecommunication system, a single-mode glass optical fiber network is well developed for several gigabit transmission. On the other hand, the development of the optical network in the premises area has been of great importance with the spread of the Internet. However, the single mode silica fiber network is not a necessarily suitable infrastructure of such short distance area. A small core of the single mode silica fiber requires highly accurate alignment in coupling of light source and fiber, and in fiber connection, which tend to increase the total network system cost.

Large-core, low-cost polymer optical fiber (POF) provides several advantages [1], [2]. The large core of the POF allows the use of inexpensive injection-molded plastic connectors, which makes it possible to dramatically decrease the cost of interface devices such as network interface card and installation cost.

We have proposed a large-core and high-bandwidth graded index plastic optical fiber (GI–POF) as a promising candidate for the transmission media in the premises area network [2], and succeeded in a 2.5 Gb/s transmission in the 100 m GI–POF link [2], [3] using an LD at 650-nm wavelength. Furthermore, we clarified the bandwidth characteristics of the GI–POF theoretically in which both modal and material dispersions were taken into consideration [4], [5]. It was found that the large material dispersion of poly methyl methacrylate (PMMA), typical polymer matrix of the GI–POF, significantly decreased the bit rate and that the optimum refractive index profile giving a maximum bit rate depended on the material dispersion [4], [5]. This paper describes the control of the refractive index distribution of the GI–POF and experimentally confirmed the effect of a slight amount of the refractive index profile deviation on the bandwidth of the GI–POF.

II. Experimental

A. Mechanism of the Interfacial-Gel Polymerization Process

The GI–POF was obtained by the heat-drawing of the graded index preform whose diameter was 18–30 mm. The preform rod in which the refractive index gradually decreases from the center axis to the periphery was prepared by the interfacial-gel polymerization technique whose process is described as follows [1], [5]: A PMMA tube was prepared by a bulk polymerization from the purified MMA monomer whose outer diameter was 18–30 mm and inner diameter was 60% of the outer diameter. The PMMA tube was filled with the mixture of MMA monomer, dopant material, polymerization initiator, and chain transfer agent. We used several kinds of aromatic compound as the dopant which should have higher refractive index than PMMA to form the refractive index distribution in the core region. The PMMA tube filled with above monomer mixture was heated from the surrounding for polymerization. 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 “gel effect.” Therefore, the

Manuscript received March 28, 1997; revised July 28, 1997.

T. Ishigure is with the Kanagawa Academy of Science and Technology, Yokohama 236 Japan.

M. Satoh, O. Takanashi, and Y. Koike are with the Faculty of Science and Technology, Keio University, Yokohama 223 Japan. They are also with the Kanagawa Academy of Science and Technology, Yokohama 236 Japan.

E. Nihei is with the Faculty of Science and Technology, Keio University, Yokohama 223 Japan.

T. Nyu and S. Yamazaki are with the NEC Corporation, Opto-Electronic Network Research Laboratory, Kawasaki 216 Japan.

Publisher Item Identifier S 0733-8724(97)08132-2.

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 the dopant which has benzene rings in it is larger than that of monomer. Thus the dopant molecules are concentrated around the center region of the core to form almost the quadratic refractive index profile [2]. Here, polymerization reaction rate plays an important role to control the refractive index profile because it affects the diffusion process of MMA monomer and dopant molecules into the polymer gel phase formed from the inner wall of the tube. The index profile of the GI–POF was controlled by changing the kind and concentration of the dopant, polymerization initiator, and chain transfer agent.

B. Characterization of Fiber Bandwidth

The bandwidth measurement of the GI and SI–POF's was performed by determining the transfer function of the fiber. The procedure of the time domain measurement involves generating and launching very short pulses of light into a sample and then detecting and recording the distorted pulses at the output of the fiber [2]. A pulse of 1 MHz from an InGaAlP laser diode (wavelength = 655 nm, source spectral width = 3 nm) was injected (N.A. = 0.3.) into the POF. The output pulse was detected by a sampling head (model OOS-01, Hamamatsu Photonics Co.). The transfer function of the fiber was obtained by the Fourier transform of both input and output pulse waveforms. The bandwidth of the fiber was determined as the frequency giving -3 dB of the transfer function.

C. Measurement of Bit Rate Characteristic of the GI–POF Link

Data transmission experiment was carried out by using the edge emitting red laser diode (LD) with 647-nm wavelength which was developed by NEC for high speed data transmission [2], [3], [6]. A 500 M–2.5 Gb/s, $2^{15}-1$, NRZ PN patterns were passed to the LD. The laser output was coupled into a POF with a graded index rod lens. Fiber launched power was approximately $+5.0$ dBm at maximum. The fiber output signal was coupled into the Si PIN photo diode with a 400 μm diameter via a graded index rod lens. A PIN FET optical receiver was used.

III. Results and Discussion

A. Refractive Index Distribution of the GI–POF

The refractive index distributions of the GI–POF's controlled by the kind of dopant are shown in Fig. 1. The curve (A), (B), and (C) correspond to the refractive index profile in which used dopants are diphenyl sulfide (DPS), benzyl benzoate (BEN), and benzyl n-butyl phthalate (BBP), respectively. As shown in Fig. 1, fiber numerical aperture as well as the refractive index profile can be controlled by changing the kind of dopant. For instance, since the refractive index of DPS is 1.633 which is higher than that (1.568) of BEN, high numerical aperture GI–POF can be obtained.

In order to quantitatively discuss the effect of the index profiles on the bandwidth, we introduce the parameter of the

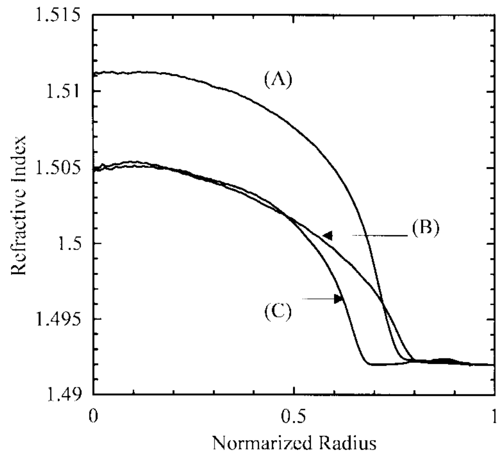

Fig. 1. Refractive index distribution of PMMA base GI–POF. (A): diphenyl sulfide (DPS) doped GI–POF, (B): benzyl benzoate (BEN) doped GI–POF, (C): benzyl n-butyl phthalate (BBP) doped GI–POF.

index exponent g that is in the power law approximation of the refractive index distribution written as

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

$$\Delta=\frac{n_1^2-h_2^2}{2n_1^2} \quad (2)$$

where n_1 and n_2 are the refractive indexes of the core center and cladding respectively, and "a" is the core radius. The parameter g signifies the difference of the refractive index profile. The index exponent g of the GI–POF was determined by a least-square method.

The refractive index profiles of the GI–POF in which BEN was used as the dopant are shown in Fig. 2. Three profiles in Fig. 2 were formed by changing the concentration of the polymerization initiator. The broken lines in Fig. 2 denote the approximated results by (1) where the index exponent g of curve (A), (B), and (C) are 1.96, 2.3, and 5.0, respectively. In the case of GeO_2-SiO_2 system GI glass fibers fabricated by CVD or MCVD process, it is said that the power law approximation is not an necessarily ideal method to describe the index profile because of the central dip made by the collapse process or of the interfaces of many deposited layers [8]. On the other hand, the power law of the form well describes the refractive index profile of the GI–POF as shown in Fig. 2.

As described in the experimental section, the refractive index profile of the GI–POF was controlled by the swelling process of the inner wall of the PMMA tube. A sufficient swelling of the inner wall of the tube leads to obtain the index profile close to parabolic. On the contrary, inadequate swelling provides little amount of polymer-gel phase on the inner wall of the tube resulting in the stepwise refractive index profile. Therefore, the reaction rate of the core polymerization has to be slow for sufficient swelling. In the free-radical polymerization process, the polymerization rate decreases with decreasing the polymerization initiator concentration. The relation between the index exponent g and the initiator concentration

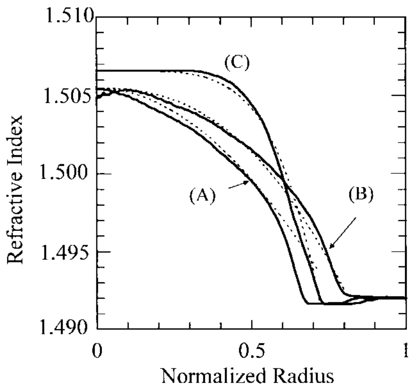

Fig. 2. Refractive index distribution of BEN doped PMMA core GI–POF (solid lines) and the approximated profile by the power law of the form (broken lines). (A): Approximated index exponent g is 1.96. (B): Approximated index exponent g is 2.45. (C): Approximated index exponent g is 5.00.

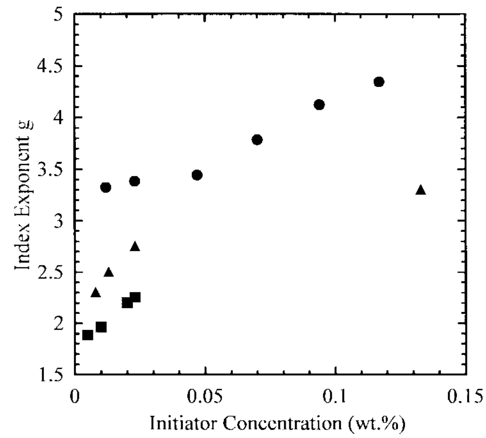

Fig. 3. Control of the refractive index profile of BEN doped (20%) PMMA core GI–POF. ●: initiator (A) ▲: initiator (B) ■: initiator (C).

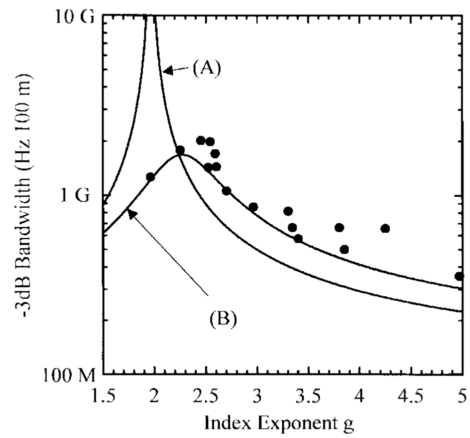

Fig. 4. Relation between the index exponent g and the bandwidth of 100-m PMMA base GI–POF at 650 nm wavelength. ●: Experimental —:Theoretical (A): Only modal dispersion was considered. (B): Both modal and material dispersions were considered.

is shown in Fig. 3. As the initiator concentration increases, the index exponent g also increases, namely the index profile is close to stepwise. The optimum index exponent g which is generally located around 2.0 is obtained in the range from 0.01 to 0.04 wt% of the initiator concentration as shown in Fig. 3.

Accurately controlled refractive index profile as described above has to be maintained for a long time in order to utilize the POF in the high speed network systems. Since the dopant concentration distirbution attributed to the refractive index profile of the GI–POF, migration or diffusion of the dopant molecule can cause the degradation of refractive index profile. We investigated the thermal and long term stability of the refractive index profile. It was experimentally confirmed that the parabolic refractive index profile of the GI–POF was maintained for more than 5000 hours even at 85 °C by selecting the suitable dopant material. The bandwidth of the aged GI–POF was simultaneously measured. Measured bandwidth was originally approximately 1 GHz for 100 m which was maintained during 85 °C aging for more than 5000 h. The themal stability of the refaractive index profile will be published in detail.

B. Bandwidth of the GI–POF

Relation between the measured bandwidth of the GI–POF by the time domain measurement method and the index exponent g is summarized in Fig. 4 in which the result of the theoretical estimation is compared to the experimental value [4], [5], [9]. The theoretical curve (A) was obtained by considering only modal dispersion, while both modal and material dispersions were taken into consideration in curve (B). In the theoretical estimation, it was assumed that 15 wt% of BEN were doped in the core center. The effect of the dopant concentration on the bandwidth characteristics of the GI–POF is discussed in the next section. The material dispersion was estimated by measuring the wavelength dependence of the refractive index of bulk specimen [10].

As the material dispersion strongly depends on the source spectral width [5], the measured source width (3 nm) was used in the analysis. Although the bandwidth estimated only by the modal dispersion is higher than 10 GHz at $g = 1.97$ as shown by curve (A), the material dispersion of the PMMA significantly decreases the bandwidth as shown by curve (B).

It should be noted that there is an excellent agreement between the theoretical result and experimental value. Measured bandwidth of the GI–POF with the index exponent of 1.96 is 1.3 GHz which has a good agreement with the approximated curve (B) in which the material dispersion is considered. It was observed from both theoretical curve (B) and the experimental plots that the optimum index exponent g giving the maximum bandwidth is located around 2.3. When the GI–POF has 2.70 of an index exponent g which is apart from the optimum value (2.3), 1.06 GHz of bandwidth is experimentally achieved. The bandwidth estimated by only modal dispersion is 671 MHz that is half of the experimental value, while 1.08 GHz of bandwidth, which is almost the same as the experimental value is expected by taking both modal and material dispersions into account.

C. Bit Error Rate Characteristics in 100 m GI–POF link

Fig. 5 shows the bit error rate characteristics of 1 Gb/s transmission by a 100-m length GI–POF with an index exponent of 2.96 which was deviated from the calculated optimum index exponent ($g_{\mathrm{opt}} = 2.3$). The eye diagram after 100-m GI–POF

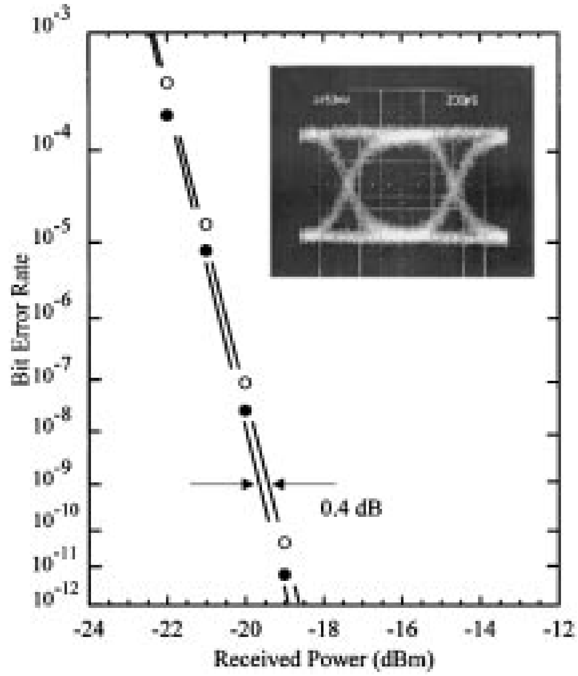

Fig. 5. Bit error rate characteristics of 100 m length BEN doped PMMA core GI–POF link. Signal wavelength was 647 nm and bit rate was 1 Gb/s.The eye diagram was taken after 100 m POF transmission. The index exponent g of the used GI–POF is 2.96. •: Back-to-back ○: After 100 m transmission.

transmission is also shown in Fig. 5. The receiver sensitivity at 1 Gb/s was −19.5 dBm and the received power penalty after 100 m transmission was 0.4 dB at 10^{-9} of bit error rate as shown in Fig. 5. A good eye opening was observed. The launched optical power was approximately +5 dBm at maximum. Therefore, the attenuation permitted to 100 m fiber was less than 20 dB including the coupling loss of fiber to photo diode. Since all GI–POF's used in this experiment had approximately 150 dB/km at 650 nm wavelength, about 5 dB of power penalty could be measured.

In Fig. 6, the relation of the possible bit rate versus the index exponent g is summarized. Here the possible bit rate of the GI–POF link was defined as the bit rate when the power penalty of the received power was 1 dB at the 10^{-9} of bit error rate [4], [5]. It was confirmed that higher than 1 Gb/s transmission can be achieved in the range from 1.96 to 3.4 of the index exponent g.

A little amount of disagreement between the experimental value and theoretical value was observed in Figs. 4 and 6. The mode dependent attenuation, mode coupling, variance of the numerical aperture, and the refractive index profile deviation along with the axial direction are considered to be factors of the disagreement. As shown in Figs. 1 and 2, the fibers made by the interfacial-gel polymerization process have different refractive index difference between the center axis and cladding (Δn) depending on the kind of dopant and polymerization condition. In this paper, the effect of the difference of the numerical aperture on the bit error rate characteristics in the GI–POF link is quantitatively discussed as follows:

The wavelength dependence of the refractive index of core and cladding is required in the WKB analysis [10], [11] in

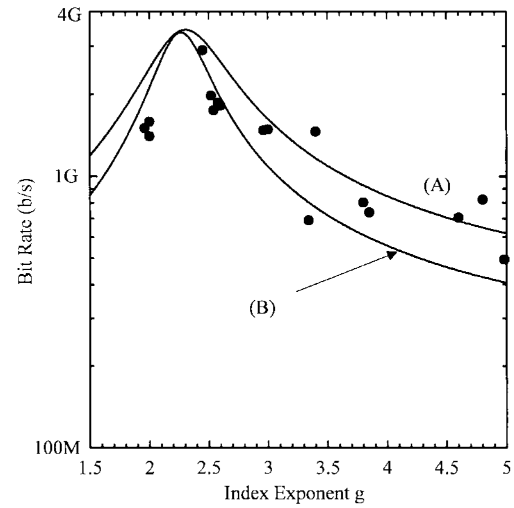

Fig. 6. Relation between the index exponent and calculated possible bit rate in 100 m PMMA base GI–POF link. Signal wavelength: 650 nm. Source width: 2 nm (LD). •: Experimental. —: Theoretical (A): Δn of the fiber is 0.012. (B): Δn of the fiber is 0.017.

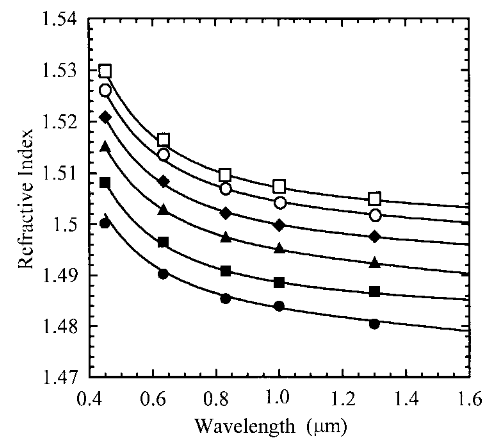

Fig. 7. Wavelength dependence of the refractive index of BEN doped PMMA bulk specimen. •: PMMA homopolymer. ■: 5% BEN doped PMMA. ▲: 10% BEN doped PMMA. ♦: 15% BEN doped PMMA. ○: 20% BEN doped PMMA. □: 25% BEN doped PMMA.

which both modal and material dispersions are taken into account. Therefore, 5, 10, 15, 20, and 25 wt% of BEN, DPS and BBP doped PMMA specimen were prepared and their refractive indexes at several wavelengths were measured. The result of the refractive index of BEN doped PMMA is shown in Fig. 7. Solid lines in Fig. 7 were determined by the approximation of Sellmeier equation described by (3)

$$n^2 - 1 = \sum_{i=1}^{3} \frac{A_i \lambda^2}{\lambda^2 - \lambda_i^2} \tag{3}$$

where n is the refractive index of polymer sample, A_i is the oscillator strength, and λ_i is the oscillator wavelength. Estimated possible bit rate is shown in Fig. 6. The curves (A) and (B) signify the possible bit rate when Δn of the GI–POF is 0.012, and 0.017. As shown in Fig. 2, Δn of the obtained GI–POF is generally in the range from 0.012 to 0.017.

It was estimated that the difference of the possible bit rate in the range from 0.012 to 0.017 of Δn is approximated to be 250 Mb/s at maximum as shown by curves (A) and (B). In the case that the index exponent $g = 2.3$, possible bit rate of the GI–POF link with 0.012 and 0.017 of Δn are almost the same value (3.3 Gb/s), while in the case that g equals 5.0, difference of the possible bit rate is approximately 200 Mb/s. When the index exponent is around the optimum value, the modal dispersion effect on the possible bit rate is minimized and the material dispersion dominates the possible bit rate. On the other hand, when the index exponent g is deviated from the optimum, the modal dispersion increases. With increasing the fiber numerical aperture, the number of transmitted mode in the GI–POF also increases. As the modal dispersion is defined by the time delay between the fastest and lowest modes reached at the fiber end, the modal dispersion also increases with the total number of transmitted mode. Consequently, the possible bit rate is affected by the fiber numerical aperture when the index exponent is apart from the optimum value. On the contrary, the possible bit rate when the GI–POF has an optimum index profile is almost independent on the Δn of the GI–POF even if the number of transmitted mode increases with increasing the fiber numerical aperture because the modal dispersion is minimized and because the dopant concentration dependence of the material dispersion is small.

In the theoretical estimation, we took into account the another dispersion property which is generally called "profile dispersion" [10], [11], as well as modal and material dispersions. The profile dispersion is induced by the wavelength dependence of the difference of core center and cladding of the fiber (Δ) defined as [10]

$$P = \frac{\lambda}{\Delta}\,\frac{d\Delta}{d\lambda} \tag{4}$$

where λ is the wavelength of light. The optimum refractive index exponent $g_{\rm opt}$ of the GI–POF can be written as (5)

$$\begin{aligned} g_{\rm opt} &= 2 - \frac{2n_1}{N_1}\cdot P - \Delta\frac{\left(4 - \frac{2n_1}{N_1}\cdot P\right)\left(3 - \frac{2n_1}{N_1}\cdot P\right)}{5 - \frac{4n_1}{N_1}\cdot P} \\ N_1 &= n_1 - \lambda\frac{dn_1}{d\lambda}. \end{aligned} \tag{5}$$

When we approximate

$$N_1 \cong n_1$$

the optimum index exponent can be rewritten as follows:

$$g_{\rm opt} = 2 - 2P - \Delta\frac{(4-2P)(3-2P)}{5-4P} \cong 2 - 2P. \tag{6}$$

In the case of BEN, DPS, and BBP-doped PMMA core, the derivative of Δ with respect to the wavelength λ is generally negative at the visible to near infrared region that is shown in Fig. 8 about BEN and DPS-doped PMMA. Therefore, the $g_{\rm opt}$ is larger than 2.0 for 650 nm wavelength use. The wavelength dependence of the refractive indexes of both core and cladding materials is required for designing the optimum profile of the GI–POF.

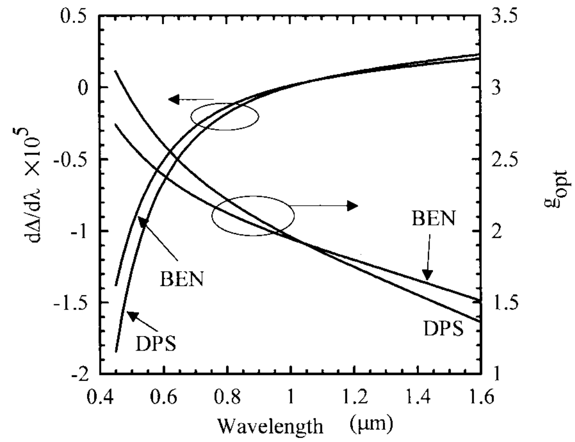

Fig. 8. Wavelength dependence of the relative index difference Δ and optimum index exponent $g_{\rm opt}$.

IV. Conclusion

The bandwidth characteristics of the GI–POF were experimentally investigated. The PMMA base GI–POF's which have various refractive index profile were prepared by the interfacial polymerization technique by changing the kind of dopant, initiator, and concentration of the initiator. The difference of the refractive index profile of the GI–POF was distinguished by a parameter of index exponent g which is in the approximation of power-law of the form. The index exponent g of the GI–POF was controlled in the range from 1.96 to 5.0. The relation between the index exponent g and the bandwidth of the GI–POF was experimentally investigated. The optimum index exponent g giving the maximum bandwidth in the case of the PMMA base GI–POF is located around $g = 2.3$ which is almost the same as the calculated one $(g = 2.33)$. The maximum bandwidth of 100-m PMMA base GI–POF was about 3 GHz. These bandwidth characteristics experimentally obtained have good agreements with the theoretically expected value.

The optimum index exponent was analyzed by taking the profile dispersion into account. Since the profile dispersion parameter P of the PMMA base GI–POF is negative in 650 nm wavelength use, it was revealed that the optimum index exponent $g_{\rm opt}$ defined by $g_{\rm opt} = 2 - 2P$ becomes larger than 2.0. It was indicated that these theoretical and experimental results clarified the potential bandwidth characteristics and capability of the control of the modal and material dispersions of the GI–POF.

References

[1] Y. Koike, "High-bandwidth graded-index polymer optical fiber," *Polymer*, vol. 32, no. 10, pp. 1737–1745, 1991.
[2] Y. Koike, T. Ishigure, and E. Nihei, "High-bandwidth graded-index polymer optical fiber," *J. Lightwave Technol.*, vol. 13, pp. 1475–1489, July 1995.
[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, 1995.
[4] T. Ishigure, E. Nihei, and Y. Koike, "Optimization of the refractive index distribution of high-bandwidth GI polymer optical fiber based on both modal and material dispersions," *Polymer J.*, vol. 28, no. 3, pp. 272–275, 1996.

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

[6] S. Yamazaki, H. Hotta, S. Nakaya, K. Kobayashi, Y. Koike, E. Nihei, and T. Ishigure, "A Gbps 100 m GRIN Plastic Optical Fiber Data Link at 650 nm wavelength," in *Proc. ECOC'94*, post deadline paper, pp. 1–4, 1994.

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

[8] L. G. Cohen, F. V. DiMarcello, J. W. Fleming, W. G. French, J. R. Simpson, and E. Weiszmann, "Pulse dispersion properties of fibers with various material constituents," *Bell Syst. Tech. J.*, vol. 57, no. 5, pp. 1653–1662, 1978.

[9] R. Olshansky and D. B. Keck, "Pulse broadening in graded-index optical fibers," *Appl. Opt.*, vol. 15, no. 2, pp. 483–491, 1976.

[10] J. W. Fleming, "Material and mode dispersion in $GeO_2 \cdot B_2O_3 \cdot SiO_2$ Glasses," *J. Ae. Cer. Soc.*, vol. 59, no. 11–12, pp. 503–507, 1976.

[11] J. W. Fleming, "Dispersion in GeO_2-SiO_2 glasses," *Appl. Opt.*, vol. 23, no. 24, pp. 4486–4493, 1984.

Takaaki Ishigure 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, Japan, in 1991, 1993, and 1996 respectively.

He is currently a Researcher of the "High-Speed POF Project" of Kanagawa Academy of Science and Technology, Japan. His current research interest is in fabrication and system application of the graded-index polymer optical fiber.

Masataka Satoh was born in Akita, Japan, on November 30, 1973. He received the B.S. degree in applied chemistry from Keio University, Japan, in 1996. He is currently working toward the Master degree at Keio University, Japan.

His current research interest is in optical and thermal properties of photonics polymer.

Osamu Takanashi was born in Kanagawa, Japan, on October 28, 1972. He received the B.S. degree in applied chemistry from Keio University, Japan, in 1996. He is currently working toward the Master degree at Keio University, Japan.

His current research interest is in designing graded-index profile of POF for high speed data transmission.

Eisuke Nihei was born in Fukushima, Japan, on October 17, 1962. He received the B.S., M.S. and Ph.D. degrees in applied chemistry from Keio University, Japan, in 1985, 1987, and 1990, respectively.

He has worked at Keio University where he was an Instructor. His current research interest is about photonics polymer and the numerical analysis of graded-index material.

Takayuki Nyu, photograph and biography not available at the time of publication.

Shuntaro Yamazaki, photograph and biography not available at the time of publication.

Yasuhiro Koike was born in Nagano, Japan, on April 7, 1954. He received the B.S., M.S., and Ph.D. degrees in applied chemistry from Keio University, Japan, in 1977, 1979, and 1982, respectively.

He has been an Associate Professor of Keio University and developed the high-bandwidth GI polymer optical fiber. He has been concurrently the leader of "High-Speed POF Project" of Kanagawa Academy of Science and Technology, Japan, since 1995. He stayed as a Visiting Researcher at 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.