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Bandwidth and Transmission Distance Achieved by POF*

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SUMMARY Recent status of the polymer optical fiber (POF) for high speed data communication and telecommunication is reviewed. The GI POF was proposed for the first time 20 years ago at Keio University, and several methodologies to fabricate GI POF have been currently proposed worldwide. In this paper, we both theoretically and experimentally verify that the most transparent GI POF can be obtained by the polymer-dopant system. The relation between the refractive index profile and the dispersion characteristics of the GI POF was quantitatively clarified. The refractive index profile of the GI POF obtained by the interfacial-gel polymerization process was controlled to enable to transmit the order of gigabit per second bit rate. Furthermore, the accurate approximation of the refractive index profile and consideration of mode dependent attenuation enabled to precisely predict the dispersion characteristics of the GI POF.
key words: *graded-index plastic optical fiber, perfluorinated polymer, scattering loss, modal dispersion, material dispersion, mode dependent attenuation*

1. Introduction

Considerable research activity lately has been devoted to the development of the optical component and devices that have the capability to support the high-speed telecommunication. Silica base single mode optical fiber has been widely utilized in the long distance trunk area for the order of giga bit per second transmission because of its high bandwidth and transparency. Introduction of the single mode fiber into all trunk area in Japan was completed in December 1997, and construction of the fiber network in access area which is called "π system" has just started. In the π system, the single mode optical fiber system is introduced to the carve at first, and drop line is operated by the conventional metallic cables. Realization of all optical networks by the single mode fiber requires many breakthroughs in the total system cost. Because of the small core size such as 5 to 10 μm, accurate alignment is necessary in the light coupling to the fiber and the connection of fibers, which increases the total system cost including fiber connectors, transceiver, packaging, and installation, etc.

On the other hand, use of the silica base multimode fiber is a recent trend in the field of local area network (LAN) and interconnection, because the large core diameter of the multimode fiber such as 50 and 62.5 μm increases the tolerance of misalignment in the fiber connection compared to that of single mode fiber. However, even in the case of the multimode fiber, the accurate connection by using ferrule is still required by the following two reasons: One is that the misalignment of connectors even by precise injection molding is still ±20–30 μm and is too large for the core of 50 μm or 62.5 μm of multimode glass fiber. Second is the serious modal noise caused by coherent light source such as vertical cavity surface emitting laser (VICSEL) [1].

A large-core, high-bandwidth, and low-loss GI POF [2] was reported for the breakthrough of above issue. Large core such as 200–1000 μm of the GI POF enables the use of inexpensive plastic connector by the injection molding without a ferrule, eliminating the problem of the modal noise. The poly (methyl methacrylate) (PMMA) has been generally used as the core material of step-index type POF commercially available and its attenuation limit is approximately 100 dB/km at the visible region [2]. Therefore, the high attenuation of POF compared to the silica base fiber has been one of the big barriers for POF in data communication application for more than 100-m distance.

The development of the perfluorinated (PF) amorphous polymer base GI POF [3] opened the way for great advantage in the high-speed POF network. Since serious intrinsic absorption loss due to the carbon hydrogen vibration that existed in PMMA base POF was completely eliminated in the PF polymer base POF, the experimental total attenuation of the PF polymer base GI POF decreased to 40 dB/km even in the near infra-red region [4]. It was clarified that the theoretical attenuation limit of the PF polymer base POF is much comparable to that of the silica base fiber (0.3 dB/km).

In this paper, the bandwidth and transmission distance achieved by the POF is described by considering the inherent attenuation and dispersion factors.

2. Low-Loss Trial

Poly methyl methacrylate (PMMA) has been used for the core material of POF so far because it has been recognized as one of highly transparent polymers with

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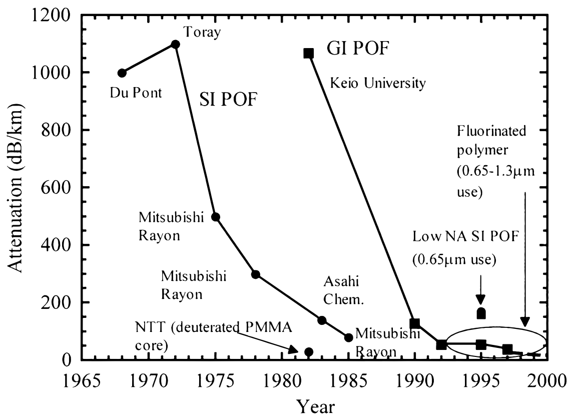

Fig. 1 Development in the attenuation of POF.

commodity. Great efforts lowering the attenuation of the POF have been devoted in 1980's by investigating the kind of polymer material and by improving the purification process of the materials. Historical development in the attenuation of the POF is summarized in Fig. 1. As shown in Fig. 1, the attenuation of the first POF developed by Du Pont was around 1000 dB/km. This was mainly due to the immature purification process of the materials. From 1970 to 1980, remarkable decrease was achieved by improving the purification and fabrication process. In 1982, it was clarified that the theoretical attenuation limit of the PMMA base POF was approximately 110 dB/km [5]. Furthermore, it was clarified that substituting the hydrogen atoms in POF for other heavier atoms such as deuterium or fluorine enabled to lower the attenuation of POF particularly at near infrared region. All these POFs were of Step-Index (SI) type.

On the other hand, the first GI POF proposed from Keio University in 1982 [6] was basically composed of PMMA having such a high attenuation as 1000 dB/km. In last decades, improvements of the fabrication process enabled the dramatic decrease of the attenuation, and the PMMA base GI POF with an attenuation of 110 dB/km at 0.65-μm wavelength was successfully obtained by the interfacial-gel polymerization in 1992 [7]. Investigation of new polymer materials has been simultaneously performed to decrease the attenuation of the GI POF. In 1990's, perdeuterated PMMA base and partially fluorinated GI POFs with an attenuation of 60 dB/km at 650-nm wavelength were successfully developed at Keio University [2]. It is noted that the attenuation decrease of the GI POF follows that of SI POF behind approximately 10 years. Finally, the attenuation of 40 dB/km even at 1.3-μm wavelength was achieved in by perfluorinated (PF) polymer base GI POF [3].

With growing interests in the GI POF, several fabrication methods of the GI POF have been proposed [8]–[10]. Almost methods basically consist of polymer blending or copolymerization of more than two kinds of monomer to form the refractive index profile. However, a problem of the large attenuation has not been dissolved in those methods. In this paper, it is theoretically and experimentally confirmed that the high attenuation of the blend polymer system and copolymer system is due to the inherent excess scattering loss. In order to clarify the inherent scattering loss of the GI POF, thermally induced fluctuation theory is introduced in this paper.

To analyze the inherent scattering loss from the amorphous polymer, it was reported that [11], [12] the isotropic scattering loss was divided into two: α_1^{iso} which comes from the isotropic background scattering independent of the scattering angle and α_2^{iso} which comes from the isotropic scattering depends on the scattering angle due to large size heterogeneities. The total scattering loss is obtained by adding α_1^{iso}, α_2^{iso}, and α^{aniso} which comes from the anisotropic scattering but is negligibly small in amorphous polymers. The isotropic scattering loss α_2^{iso} due to large-sized heterogeneities is written with using Debye's theory as

$$\alpha_2^{iso} = 4.342 \times 10^5 \times \frac{32a^3\langle\eta^2\rangle\pi^4}{\lambda_0^4} \left[\frac{(b+2)^2}{b^2(b+1)} - \frac{2(b+2)}{b^3}\ln(b+1)\right] (\mathrm{dB/km}) \tag{1}$$

with

$$b = 4\nu^2 a^2,\ \nu = \frac{2\pi n}{\lambda_0} \tag{2}$$

Here, $\langle\eta^2\rangle$ denotes the mean-square average of the fluctuation of all dielectric constants, λ_0 is the wavelength of light in vacuum and n is the refractive index of the sample. $\gamma(\boldsymbol{l})$ refers to the correlation function defined by

$$\gamma(\boldsymbol{l}) = \langle\eta(\boldsymbol{l}_A)\cdot\eta(\boldsymbol{l}_B)\rangle/\langle\eta^2\rangle \tag{3}$$

where $\eta(\boldsymbol{l}_i)$ and $\eta(\boldsymbol{l}_j)$ are the fluctuations of dielectric constant at i and j positions which are a distance l apart. In this paper, the correlation function $\gamma(\boldsymbol{l})$ is assumed to be approximated by Eq. (4) as suggested by Debye et al.:

$$\gamma(l) = \exp\left(-\frac{l}{a}\right) \tag{4}$$

where a is called correlation length and is a measure of the size of the heterogeneities. Here, it is assumed that these heterogeneities consist of two phases in which each volume fraction is ϕ_A and ϕ_B, and the refractive indices are n_A and n_B, respectively. In this case, a and $\langle\eta^2\rangle$ are given by

$$a = \frac{4V}{S}\phi_A\phi_B \tag{5}$$

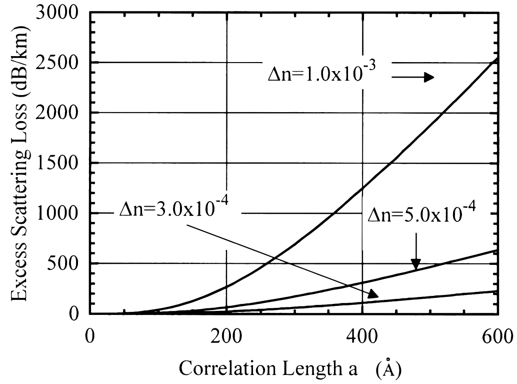

Fig. 2 Excess scattering loss due to heterogeneous structure in polymers.

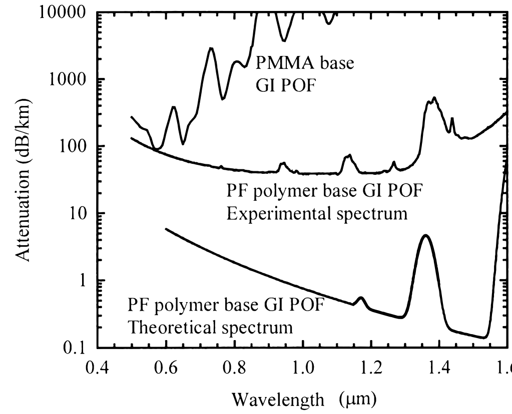

Fig. 3 Total attenuation spectra of GI POF.

$$\begin{aligned}\langle \eta^2 \rangle &\cong \phi_A \phi_B (n_A - n_B)^2 \\ &\cong 4\phi_A \phi_B n^2 (\Delta n)\end{aligned} \tag{6}$$

where S is the total surface area of the boundary between the two phases, V is the total volume, n is the average refractive index, and Δn is $(n_A - n_B)$, and $\phi_A + \phi_B = 1$. Equation (5) indicates that if the boundary surface of the two phases are intricate each other, the value of S increases to give a smaller value of the correlation length.

When the GI POF is assumed to be composed of two kinds of polymers, the two phases model described above can be adopted. Usually, one polymer molecular coil has a size of a few hundred Å. Therefore, if the refractive indices of adjacent polymer coils are different, the smallest size of the heterogeneities in refractive index is a few hundred Å. This is the case for the blend polymer and copolymer system. In order to obtain the refractive index gradient of the POF made by blend polymer or copolymer system, one polymer component having higher refractive index than the polymer matrix should have the concentration distribution in radial direction. Therefore, a few hundred Å size heterogeneities exist in the GI POF made by blend polymer of copolymer system.

Relation between the excess isotropic scattering loss and the correlation length is calculated with using Eq. (1). The results are shown in Fig. 2. Here, the volume fraction ϕ_1 and ϕ_2 were assumed to be 0.9 and 0.1, respectively, and the refractive index difference Δn shown in Eq. (6) is varied from 3×10^{-4} to 1×10^{-3}. It is noteworthy that a slight index difference such as the order of 10^{-3} causes significant excess scattering loss more than several hundred dB/km even if the correlation length is approximately several hundred Å. If the correlation length is the order of a few hundred Å, which is considered to correspond to the size of polymer coil, the excess scattering loss becomes more than a few hundred dB/km, even though the refractive index difference is small as the order of 10^{-4}.

On the other hand, when the correlation length is around several angstroms, the excess scattering loss becomes almost zero, even when the refractive index difference is the order of 10^{-3} as shown in Fig. 2. The interfacial-gel polymerization technique [2], [13] in which small size dopants molecules form the concentration distribution in the radial direction is the possible method to achieve such small correlation length. If each dopant molecule is randomly located in the polymer matrix without aggregation, the smallest size of the heterogeneity is the size of each small dopant molecule. That is the order of a few Å of the correlation length. In amorphous polymers, Debye equation mentioned above can be adopted, in the range of correlation length from a few hundred Å to a few μm. Therefore, when the size of the heterogeneity is smaller than a few hundred Å, the quantitative estimation of the scattering loss cannot be precisely made. However, it is suggested that the excess scattering loss is strongly dependent on the correlation length and that the polymer-dopant system would significantly minimize the scattering loss in the GI POF.

Even if the excess scattering loss can be reduced by adopting the polymer-dopant system, the minimum attenuation of the GI POF composed of PMMA is around 100 dB/km, because of the inherent absorption loss due to carbon-hydrogen stretching vibration. Use of perfluorinated (PF) polymer for the polymer matrix allows to decrease the inherent absorption [2], [3]. Figure 3 shows the experimentally obtained attenuation spectrum of PF polymer base GI POF compared to that of PMMA base GI POF. Several absorption peaks shown in the spectrum of PMMA base GI POF is completely eliminated in the PF polymer base GI POF. The minimum attenuation is 40 dB/km around 1.0-μm wavelength. Theoretical attenuation limit of the PF polymer base GI POF is investigated with using the Morse potential energy theory and thermally induced fluctuation theory to calculate the inherent absorption and scattering losses [2]–[4], respectively. The theoretical attenuation spectrum of the PF polymer base GI POF

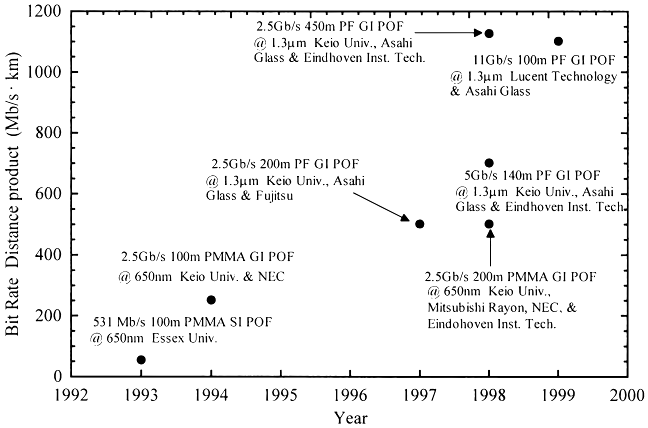

Fig. 4 Development in the high-bit rate trial in the POF link.

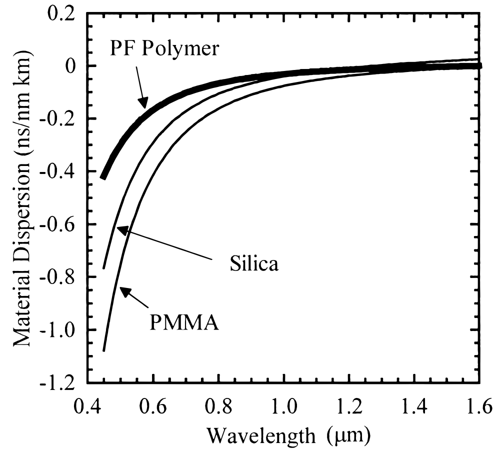

Fig. 5 Material dispersion of polymers compared with silica.

is also shown in Fig. 3. It was confirmed that the attenuation of less than 1 dB/km could be achieved by the PF polymer base GI POF.

3. High Bit-Rate Trial

3.1 Dispersion Properties of POF

Historical development in high bit-rate trial is summarized in Fig. 4. In the early 1990's, there was a few reports regarding the high bit-rate transmission by POF, because there was no appropriate devices such as laser diode and photodetector for POF. In 1994, since a 2.5 Gb/s data transmission was reported by Keio University and NEC, lots of interests have been focussed on the POF data link [14]. With the development of the low-loss PF polymer base GI POF, bit rate-distance product increased as shown in Fig. 4. Very recently, outstanding demonstration was reported from Lucent Technologies [15]. That is the experiment of 11 Gb/s data transmission by 100 m PF polymer base GI POF at 1.3-μm wavelength. In this subsection, the bandwidth property of the GI POF is described.

It is well known that the modal dispersion of the multimode optical fiber can be minimized by optimizing the refractive index profile of the core region. We have succeeded in a 2.5 Gb/s, 200 m data transmission by the PMMA base GI POF by controlling the refractive index profile [16]. The optimization of the dispersions of GI POF not only modal dispersion but also the material and profile dispersions is described. In order to design the optimum index profile of the GI POF, the index profile is approximated by the power-law form as described in Eq. (7)

$$n(r) = n_1 \left[1 - 2\Delta\left(\frac{r}{R}\right)^g\right]^{\frac{1}{2}} \tag{7}$$

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \approx \frac{n_1 - n_2}{n_1} \tag{8}$$

Here, n_1 and n_2 are refractive indices at center axis and cladding of the fiber respectively, R is radius of the core, and Δ is relative difference of the refractive-index. The profile of the refractive index was evaluated by the parameter g called index exponent. Power-law approximation of the index profile enables to analytically solve the wave equation derived from the Maxwell's equation. The material and profile dispersions of the POF were estimated by measuring the wavelength dependence of the refractive index of polymers. The result of the material dispersion was shown in Fig. 5, which is derived from the data of wavelength dependence of the refractive index with using Eq. (9)

$$D_{mat} = -\left(\frac{\lambda\delta\lambda}{C}\right)\left(\frac{d^2n}{d\lambda^2}\right)L \tag{9}$$

where $\delta\lambda$ is the root mean square spectral width of the light source, λ the wavelength of transmitted light, C the velocity of light in vacuum, $d^2n/d\lambda^2$ the second-order dispersion, and L length of the fiber. It is noteworthy that the material dispersion of the PF polymer is smaller than that of silica in the near IR region.

Figure 6 shows the relation between the bandwidth characteristics and refractive index profile of the PMMA and PF polymer base GI POF calculated by the WKB method [17], [18], in which both modal and material dispersions were taken into consideration. Here, the light source was assumed to be an LD with a 3-nm of spectral width. In the case of PMMA base GI POF, the optimum wavelength at which the lowest attenuation can be obtained is located at 0.65-μm. Therefore, the maximum bandwidth of the PMMA base GI POF is around 3 Gb/s for 100 m, which is dominated by the large material dispersion as shown in Fig. 5. On the other hand, the low material dispersion of PF polymer enables 9 Gb/s transmission in 100 m link at the same wavelength. Furthermore, the low intrinsic absorption loss of the PF polymer base GI POF permits 1.3-μm wavelength use. Since the material dispersion decreases with an increase in wavelength, the possible bit rate in

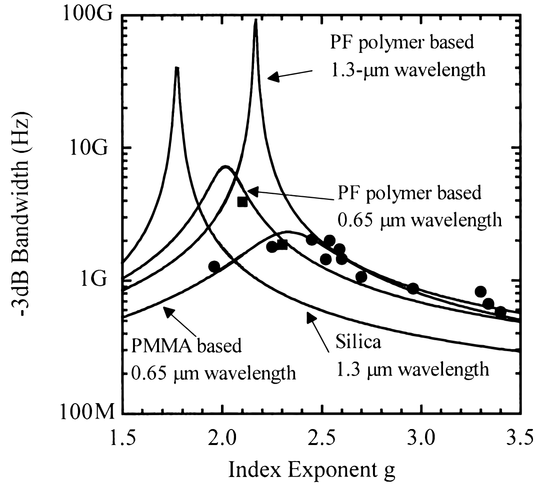

Fig. 6 Relation between the refractive index profile and bandwidth of 100 m GI POF. ●: Experimental data of PMMA polymer base GI POF at 0.65 μm, ■: Experimental data of PF polymer base GI POF at 0.65 μm.

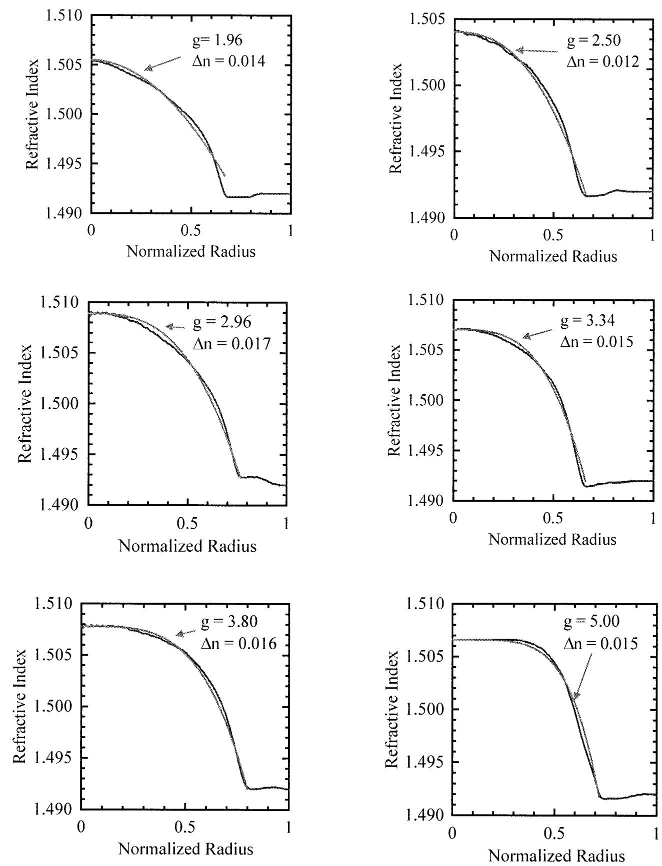

Fig. 7 Refractive index profile of GI POFs controlled in the interfacial gel polymerization process.

100 m link achieves 100 Gb/s. It is noteworthy that the value of 100 Gb/s is higher than the maximum bit rate of the silica fiber at 1.3-μm wavelength because the material dispersion of the PF polymer is smaller than that of the silica material [4].

In order to verify the theoretical estimation, the GI POF having different index profiles were fabricated by the interfacial-gel polymerization technique. Details of controlling method of the refractive index profile is described in elsewhere [13]. Obtained refractive index profile of the GI POF is shown in Fig. 7, in which the index exponent g is varied from 1.96 to 5.00. The bandwidth characteristics of these GI POFs were measured, and the results are compared with those theoretically estimated as shown in Fig. 6. Plots in Fig. 6 signify the experimental data of the PMMA base GI POFs, which show a good agreement with the theoretical curve. As shown in Fig. 6, it is obvious that even if the refractive index profile is deviated from the optimum profile, higher bandwidth than 1 GHz could be obtained. The PMMA base POF is currently expected to be a physical layer of home network which operates at more than 500 Mb/s. Therefore, the PMMA base GI POF fabricated by the interfacial-gel polymerization technique is considered as a promising candidate.

3.2 Propagating Mode Characteristics

As described above, the bandwidth characteristics of the GI POF is analytically estimated with using the power-law approximation of the index profile. However the obtained refractive index profile is not necessarily approximated by the power-law approximation. In order to accurately analyze the bandwidth characteristics of the GI POF, polynomial approximation of the index profile is adopted, and the group delay of each propagating mode is numerically calculated with using WKB method [19], [20]. In this numerical method, the group delay τ of the mode can be expressed as

$$\tau = \frac{Lk}{c\beta}\left\{\left[\int_{r_1}^{r_2} \frac{n(r)^2(1+D_1)-D_2}{R} dr\right] \int_{r_1}^{r_2} \frac{dr}{R}\right\} \quad (10)$$

where, c, L, β signify the light velocity in vacuum, fiber length and the propagation constant.

$$k = \frac{2\pi}{\lambda} \quad (11)$$

$$D_1 = -\left(\frac{\lambda}{n_1}\frac{dn_1}{d\lambda} + \frac{\lambda}{2\Delta}\frac{d\Delta}{d\lambda}\right) \quad (12)$$

$$D_2 = -\frac{n_1^2\lambda}{2\Delta}\frac{d\Delta}{d\lambda} \quad (13)$$

$$R = \sqrt{n(r)^2k^2 - \beta^2 - \frac{\nu^2}{r^2}} \quad (14)$$

In Eq. (10), the poles of r_1 and r_2 in the integrand are defined as the solutions of Eq. (15)

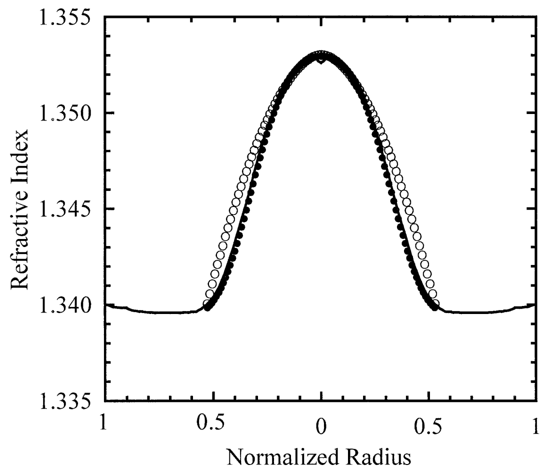

Fig. 8 Refractive index profile of the PF polymer base GI POF. Solid Line: Experimentally measured data ○: approximated index profile by power-law equation, ●: approximated index profile by polynomial equation.

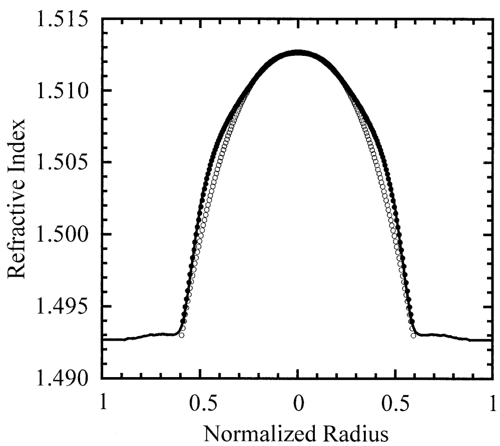

Fig. 9 Refractive index profile of the PMMA base GI POF. Solid Line: Experimentally measured data, ○: approximated index profile by power-law equation, ●: approximated index profile by polynomial equation.

$$n(r)^2k^2 - \beta^2 - \frac{\nu^2}{r^2} = 0 \tag{15}$$

where, ν is the azimuthal mode number which has to satisfy the eigenvalue equation expressed by Eq. (16).

$$\int_{r_1}^{r_2} \left[n(r)^2k^2 - \beta^2 - \frac{\nu^2}{r^2} \right]^{1/2} dr = \left(\mu + \frac{1}{2} \right) \pi$$

μ : radial mode number

$$\mu, \nu = 0, 1, 2, \cdots \tag{16}$$

Figures 8 and 9 show the measured and approximated refractive index profile of the PMMA base and PF polymer base GI POFs. The impulse response of the GI POF is constructed from the calculated group delay of each mode. In the time domain bandwidth measurement, the bandwidth characteristic is estimated by injecting the light pulse into the fiber and detecting the output pulse broadening. Therefore, the output pulse waveform was calculated by the convolution of input pulse and impulse response. The results of the PMMA base and PF polymer base GI POFs whose index profiles are shown in Figs. 8 and 9 are shown in Figs. 10 and 11. It is obvious in PF polymer base GI POF that a good agreement between the calculated and measured output waveforms, while in PMMA base GI POF, the calculated waveform having two large peaks is largely different from the measured waveform. In the output waveform calculation, all the modes were assumed to be launched equally.

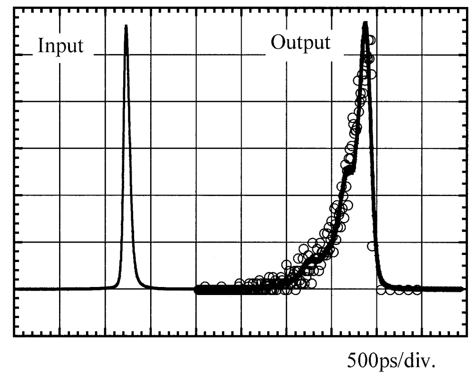

Fig. 10 Pulse broadening through 100-m PF polymer base GI POF whose index profile is shown in Fig. 8. Signal wavelength is 0.65 μm. Solid Line: Experimentally measured data, ○: calculated output waveform in which uniform launch condition was taken into account.

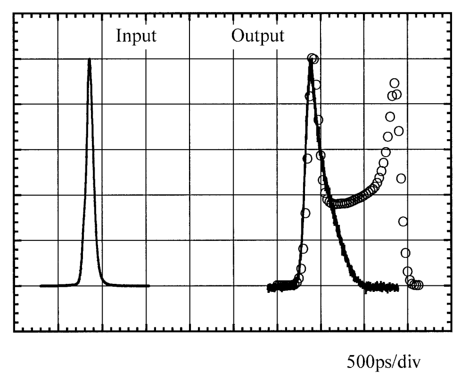

Fig. 11 Pulse broadening through 100-m PMMA base GI POF whose index profile is shown in Fig. 9. Signal wavelength is 0.65 μm. Solid Line: Experimentally measured data, ○: calculated output waveform in which uniform launch condition was taken into account.

In early investigation of the bandwidth characteristics of the silica base multimode fiber, such a difference between measured and calculated waveforms was also observed [18]. However, there have been few reports explaining the reason of such difference in detail. Therefore, it should be an important issue to clarify the

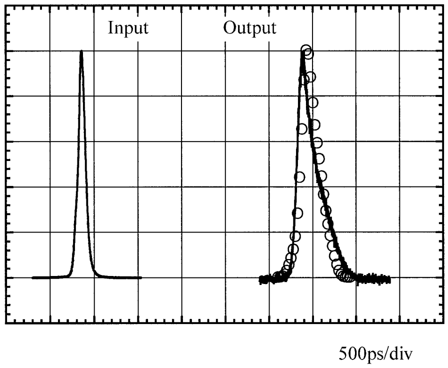

Fig. 12 Pulse broadening through 100-m PMMA base GI POF whose index profile is shown in Fig. 9. Signal wavelength is 0.65 μm. Solid Line: Experimentally measured data, ◯: calculated output waveform in which mode dependent attenuation was taken into account.

group delay of large core GI POF which can support huge number of modes compared to silica base multimode fiber.

In this paper, we focused on the effect of mode dependent attenuation, because the mode dependent attenuation was considered to seriously affect the bandwidth characteristics of the GI POF in such a short distance as 100 m.

Calculated output waveform from the GI POF in which the mode dependent attenuation is taken into account is shown in Fig. 12. As shown in Fig. 12, excellent agreement between experimental and calculated results is observed. Concerning the effect of the mode coupling on the bandwidth characteristics of the GI POF, the result of detail analysis will be described in elsewhere.

4. Conclusion

Bandwidth and transmission distance achieved by POF are theoretically and experimentally clarified. Although PMMA core step index POF has played a main role of POF for a long time, recent development of PMMA base GI POF and PF polymer base GI POF enables to design an innovative high-speed network architectures. The PMMA base GI POF is currently a promising candidate of the physical layer of high-speed home and office networks, because the PMMA base GI POF can cover the bit rate higher than several hundred Mb/s. On the other hand, low attenuation and low material dispersion of the PF polymer base GI POF can extend the bandwidth and transmission distance. High speed data link achieved by POF is summarized in Fig. 13 based on the attenuation and bandwidth potentials of POF described above. Remarkable interests are currently concentrated to a digital home network based on IEEE 1394 standards. For under 200 Mb/s data rates applications, SI POF links are already standardized. For more than 400 Mb/s, we believe that GI POF is one of the promising candidates of physical media in such home network.

Breakthrough in the attenuation and bandwidth of POF has been achieved by PF polymer base GI POF. With increasing possible bit rate and link length of POF network, premise wiring and access line can be realized by POF. It could be considered that several hundreds of mega bit per second of bit rate will be required for vertical line in the premise wiring. In addition to such high bit rate, more than 200–300 m link length is needed. For such application, the PF polymer base GI POF is possible one. Further improvement of the attenuation of PF polymer will enable to extend the PF polymer network to several kilometer distance that will be the area of access network.

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References

[1] R.E. Epworth, "The phenomenon of modal noise in analogue and digital optical fiber systems," Proc. 4th Eupropean Conf. on Opt. Commun., pp.492–501, Genoa, Italy, Sept. 1978.
[2] Y. Koike, T. Ishigure, and E. Nihei, "High-bandwidth graded-index polymer optical fiber," IEEE J. Lightwave Technol., vol.13, pp.1475–1489, 1995.
[3] Y. Koike, "Progress of plastic optical fiber technology," Proc. Eupropean Conf. on Opt. Commun., vol.I, pp.41–48, Oslo, Norway, Sept. 1996.
[4] Y. Koike and T. Ishigure, "Progress of low-loss GI polymer optical fiber from visible to 1.5-μm wavelength," Proc. Eupropean Conf. on Opt. Commun., vol.I, pp.41–48, Edinburgh, Scotland, Sept. 1997.
[5] T. Kaino, M. Fujiki, and K. Jinguji, "Preparation of plastic optical fibers," Rev. Electron. Commun. Lab., vol.32, pp.478–488, 1984.
[6] Y. Koike, Y. Kimoto, and Y. Ohtsuka, "Studies on the light-focusing plastic rod.13: Photocopolymerization of methyl methacrylate-vinyl esters of aromatic carboxylic acid," J. Appl. Pol. Sci., vol.27, no.9, pp.3253–3264, 1982.
[7] T. Ishigure, E. Nihei, and Y. Koike, "High-bandwidth (2 GHz·km), low-loss (56 dB/km) GI polymer optical fiber," Proc. SPIE, vol.1799, pp.67–78, 1992.
[8] US Patent 4,852,982, 1989.
[9] JP Patent H3-81708, 1991.
[10] F.G.H. van Duijnhoven and C.W.M. Bastiaansen, "Gradient refractive index polymers produced in a centrifugal field," Proc. 7th International Plastic Optical Fiber Conference '98 pp.55–58, Berline, Oct. 5–8, 1998.
[11] Y. Koike, N. Tanio, and Y. Ohtsuka, "Light scattering and heterogeneities in low-loss poly (methyl methacrylate) glasses," Macromolecules, vol.22, pp.1367–1373, 1989.
[12] Y. Koike, S. Matsuoka, and H.E. Bair, "Origin of excess light scattering in poly (methyl methacrylate) glasses," Macromolecules, vol.25, pp.4809–4815, 1992.

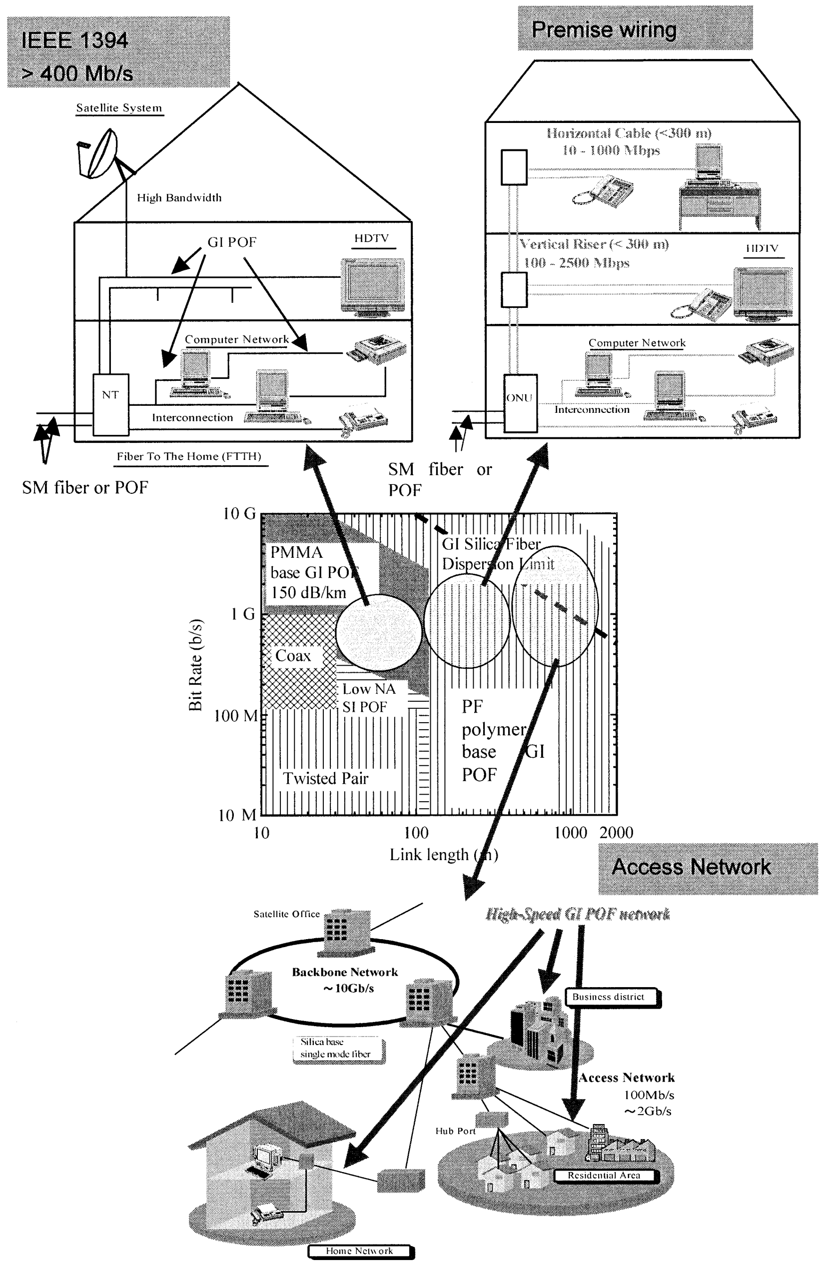


Fig. 13 Relation between the bit rate and link length of POF.

[13] T. Ishigure, M. Sato, O. Takanashi, E. Nihei, T. Nyu, S. Yamazaki, and Y. Koike, "Formation of the refractive index profile in the graded index polymer optical fiver for Gigabit data transmission," IEEE J. Lightwave Technol., vol.15, no.11, pp.2095–2100, 1997.

[14] T. Ishigure, E. Nihei, S. Yamazaki, K. Kobayashi, and Y. Koike, "2.5 Gb/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.

[15] G. Giaretta, W. White, M. Wegmueller, R.V. Yelamatry, and T. Onishi, "11 Gb/sec data transmission through 100 m of perfluorinated graded-index polymer optical fiber," Optical Fiber Communication Conference, Post Deadline Paper, PD14, San Diego, Feb. 1999.

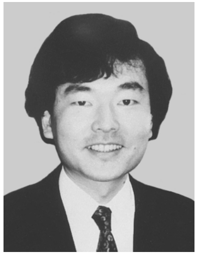
[16] W. Li, G.D. Khoe, H.P.A.v.d. Boom, G. Yabre, H. de Waardt, Y. Koike, M. Naritomi, N. Yoshihara, and S. Yamazaki, "Record 2.5 Gbit/s transmission via polymer optical fiber at 645 nm visible light," The 7th Intenational POF Conference, Post Deadline Paper, Berlin, Oct. 1998.

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

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

[19] D. Marcuse, "Calculation of bandwidth from index profiles of optical fibers. 1: Theory," Appl. Opt., vol.18, no.12, pp.2073–2080, 1979.

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



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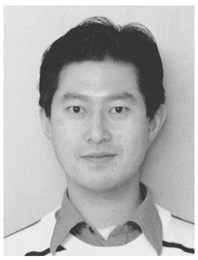

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