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Optimization of the Refractive-Index Distribution of High-Bandwidth GI Polymer Optical Fiber Based on Both Modal and Material Dispersions

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ABSTRACT: The optimum refractive-index distribution of the high bandwidth graded-index polymer optical fiber (GI POF) in which material dispersion is taken into account was clarified for the first time. Since modal dispersion remarkably decreases by GI POF, this paper focuses on the ultimate bandwidth achieved by POF, quantitatively estimating the material dispersion as well as modal dispersion. The results indicated that the bandwidth of the poly(methyl methacrylate) (PMMA) based GI POF was dominated by material dispersion when the required data rate becomes larger than a few $\mathrm{Gb\,s^{-1}}$. It was also confirmed that material dispersion strongly depends on the matrix polymer and that use of fluorinated polymer whose material dispersion ($-0.078\ \mathrm{ns\,nm^{-1}\,km^{-1}}$) is lower than that of PMMA ($-0.305\ \mathrm{ns\,nm^{-1}km^{-1}}$) allows for a $10\,\mathrm{Gb\,s^{-1}}$ signal transmission.

KEY WORDS Polymer Optical Fiber / Graded-Index / Bandwidth / Modal Dispersion / Material Dispersion / Sellmeier Equation / Fluorinated Polymer / W. K. B. Method / Bit Rate /

The growth in traffic on the communications network will eventually require greater exploitation of the potential bandwidth of physical media even in short range communication. In a local area network (LAN) in which the required bit rate and transmission distance are about 100 mega bit per second ($\mathrm{Mb\,s^{-1}}$) and 100 m, respectively, the twisted pair cable has been widely used as the transmission media. However, higher bit rate such as several hundred $\mathrm{Mb\,s^{-1}}$ has been required recently in the broadband residential network, ATM-LAN, and interconnection, etc.

For this high speed and short range communication media, we have proposed a high bandwidth graded-index polymer optical fiber (GI POF),[1,2] and succeeded in a $2.5\,\mathrm{Gb\,s^{-1}}$ transmission in the 100 m GI POF link.[3] Since the quadratic refractive-index distribution in the GI POF decreases the modal dispersion, we investigated the control of the refractive-index profile of GI POF by the interfacial-gel polymerization technique.[1,2] In order to analyze the ultimate bandwidth characteristics of the GI POF, the optimum refractive index profile is clarified in this paper in which not only modal dispersion but also the material dispersion are taken into account for the first time.

MATERIAL DISPERSION

In the case of the silica based optical fiber, factors of the pulse broadening in the light signal transmission have been analyzed in detail.[4–7] As modal dispersion is eliminated in the single mode fiber, the material dispersion which is induced by the variance of the refractive-index at different wavelengths can affect the bandwidth. However, as POFs commercially available have been of the step-index (SI) type, modal dispersion is so large that material and waveguide dispersions can be negligible.[8] In the GI POF, since the modal dispersion can be minimized by optimizing the refractive index profile, it is a concern that material dispersion affects the pulse spread when a light source as a light emitting diode (LED) is utilized in which the spectral width is as large as 10 to 20 nm. Therefore, the material dispersion of the POF was analyzed in this paper by measuring the refractive-index dependence on the wavelength of the polymer composing the core and cladding of the GI POF.

The material dispersion D is given by eq 1,[4]

$$D = -\frac{\lambda}{c}\frac{\mathrm{d}^2 n}{\mathrm{d}\lambda^2} \tag{1}$$

where, c, λ, and n are the velocity of light, wavelength of light, and refractive-index of the core of the POF, respectively.

To calculate the second derivative of the refractive-index by the wavelength in eq 1, the refractive-indices of the polymer at several wavelengths from 400 nm to 1000 nm were measured by an Abbe's refractometer, and these measured points were fitted to the three term Sellmeier equation[3] as shown in eq 2.

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

where A_i is the oscillator strength, and l_i is the oscillator wavelength.

The coefficients are shown in Table I.

RESULTS AND DISCUSSION

Material Dispersion

Refractive-index dependence on the wavelength of the poly(methyl methacrylate; PMMA) which is the polymer matrix of the GI POF and benzyl benzoate (BEN) doped PMMA (PMMA/BEN = 5/1 (wt/wt)) which composes

Table I. Coefficients of the Sellmeier equation

	A_1	l_1/nm^2	A_2	l_2/nm^2	A_3	l_3/nm^2
PMMA	0.4963	71.80	0.6965	117.4	0.3223	9237
PMMA-BEN	0.4855	104.3	0.7555	114.7	0.4252	49340
PHFIP 2-FA	0.4200	58.74	0.0461	87.85	0.3484	92.71
PHFIP 2-FA/DBP	0.2680	79.13	0.3513	83.81	0.2498	106.2

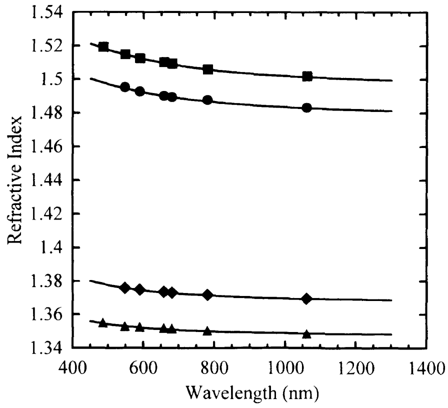

Figure 1. Refractive-index dependence of the polymers on wavelength. ■, benzyl benzoate doped PMMA; ●, PMMA; ◆, dibutyl phthalate doped PHFIP 2-FA; ▲, PHFIP 2-FA.

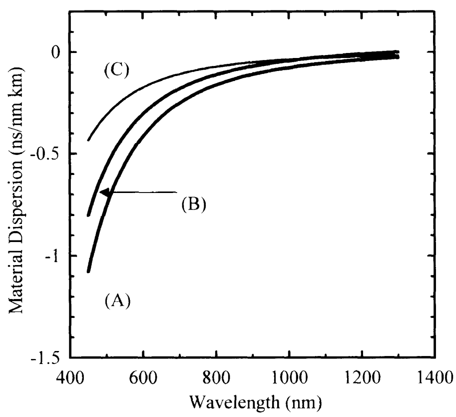

Figure 2. Comparison of material dispersion among poly methyl methacrylate (PMMA), PHFIP 2-FA, and silica. (A), PMMA; (B), silica; (C), PHFIP 2-FA.

the core of the GI POF are shown in Figure 1. The partially fluorinated polymer, poly (hexafluoroisopropyl 2-fluoroacrylate; PHFIP 2-FA) and dibutyl phthalate (DBP) doped PHFIP 2-FA are also shown in Figure 1. The solid lines were obtained by Sellmeier fitting.[5] In silica optical fibers, the Sellmeier fitting is used and is accurate.

The calculated material dispersions by eq 1 are shown in Figure 2 compared with that of the silica obtained from ref 5. It was confirmed that the material dispersion of the PMMA based GI POF is larger than that of the silica based GI POF at each wavelength. Furthermore, the signal wavelength for the PMMA based GI POF is located in an optical window of transmission loss around 650-nm wavelength. Therefore, the material dispersions of the silica based fiber at 1.3 μm or 1.55 μm which are signal wavelengths are much smaller than that of PMMA at 650-nm wavelength.

Substitution of the hydrogen atoms in the polymer for fluorine atoms offers two advantages. One is decrease in the material dispersion as shown in Figure 2. At a wavelength of 650 nm, the material dispersion of the PHFIP 2-FA is 0.136 ns nm^{-1} km^{-1}, while 0.305 ns nm^{-1} km^{-1} in the case of the PMMA. The other advantage is that attenuation of light transmission through POF dramatically decreases especially in near infrared region and the signal wavelength shifts to the longer wavelength. A comparison of the total attenua-

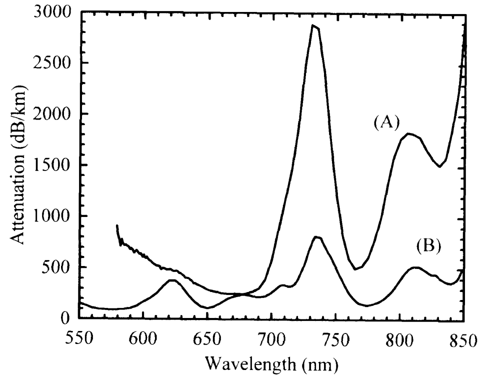

Figure 3. Total attenuation spectra of GI POFs. (A), PMMA-base; (B), PHFIP 2-FA-base.

tion of the PMMA based and PHFIP 2-FA based GI POFs is shown in Figure 3.[9] The large absorption peak around 730-nm wavelength in the PMMA based GI POF was induced by the 5th harmonic generation of the carbon–hydrogen stretching vibration. However, in the case of the fluorinated polymer based GI POF, this peak decreases and the optical window shifts to around 780-nm wavelength. Because the material dispersion decreases with increasing wavelength as shown in Figure 2, the shift of optical window to a longer wavelength in which inexpensive laser diode (LD) and light emitting diode (LED) are commercially available (*ex*. 780-nm for compact disk) is more effective for high speed optical communication by POF.

Refractive-Index Profile and Bit Rate

The refractive-index profile was approximated by power law of eq 3. The relationship between the index exponent α in eq 3 and pulse broadening is calculated.

$$n(r)=n_1\left[1-\left(\frac{r}{a}\right)^{\alpha}\Delta\right] \tag{3}$$

Here n_1 is refractive-index at center axis of fiber, a is radius of the core, r is the distance from the core center, α is index exponent, and Δ is relative difference of the refractive-index given by eq 4

$$\Delta=\frac{n_1^2-n_2^2}{2n_1^2}\approx\frac{n_1-n_2}{n_1} \tag{4}$$

Here, n_2 is the refractive index of the cladding of the fiber.

The output pulse width calculated by the solution of W. K. B method[4] in which both modal and material dispersions are taken into account is shown in eq 5, 6, and 7. Here, $\sigma_{\mathrm{Intermodal}}$, $\sigma_{\mathrm{Intramodal}}$, and σ_{total} signify the root mean square pulse width due to the intermodal dispersion, intramodal dispersion, and both dispersions, respectively.

$$\sigma_{\mathrm{Intermodal}}=\frac{LN_1\Delta}{2c}\cdot\frac{\alpha}{\alpha+1}\cdot\left(\frac{\alpha+2}{3\alpha+2}\right)^{1/2}\cdot\left[C_1^2+\frac{4C_1C_2\Delta(\alpha+1)}{2\alpha+1}+\frac{4\Delta^2C_2^2(2\alpha+2)^2}{(5\alpha+2)(3\alpha+2)}\right]^{1/2} \tag{5}$$

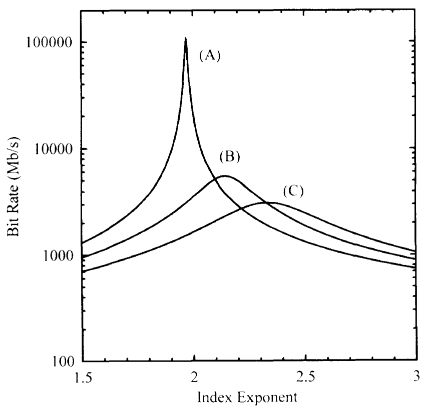

Figure 4. Relationship between the bit rate and index exponent of 100-m length PMMA based GI POF. (A), only modal dispersion is considered when 650-nm wavelength is used as the signal wavelength; (B), both modal and material dispersions are considered when 780-nm is used as the signal wavelength; (C), both modal and material dispersions are considered when 650-nm is used as the signal wavelength.

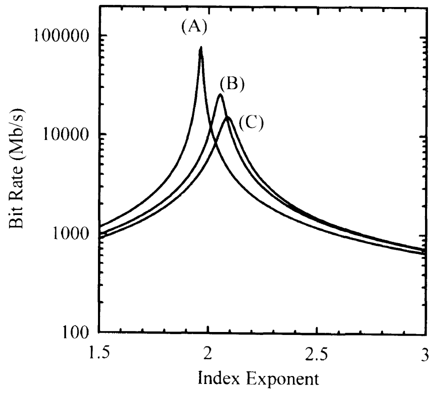

Figure 5. Relationship between the bit rate and index exponent of 100-m length PHFIP 2-FA based GI POF. (A), only modal dispersion is considered when 650-nm wavelength is used as the signal wavelength. (B), both modal and material dispersions are considered when 780-nm is used as the signal wavelength; (C), both modal and material dispersions are considered when 650-nm is used as the signal wavelength.

$$\sigma_{\text{Intramodal}}=\frac{\sigma_s L}{\lambda}\left[\left(-\lambda^2\frac{d^2 n_1}{d\lambda^2}\right)^2-2\lambda^2\frac{d^2 n_1}{d\lambda^2}(N_1\Delta)\cdot C_1\cdot\left(\frac{2\alpha}{2\alpha+2}\right)+(N_1\Delta)^2\left(\frac{\alpha-2-\varepsilon}{\alpha+2}\right)^2\cdot\frac{2\alpha}{3\alpha+2}\right]^{1/2} \tag{6}$$

where,

$$C_1=\frac{\alpha-2-\varepsilon}{\alpha+2}$$

$$C_2=\frac{3\alpha-2-2\varepsilon}{2(\alpha+2)}$$

$$\varepsilon=\frac{-2n_1}{N_1}\cdot\frac{\lambda}{\Delta}\cdot\frac{d\Delta}{d\lambda}$$

$$N_1=n_1-\lambda\cdot\frac{dn_1}{d\lambda}$$

Here, σ_s is root mean square spectral width of the light source (nm), and L is fiber length (m).

$$\sigma_{\text{total}}=[(\sigma_{\text{Intermodal}})^2+(\sigma_{\text{Intramodal}})^2]^{1/2} \tag{7}$$

The possible bit rate B_p was calculated based on receiver characteristic analysis reported by Personick.[10] With increase in the bit rate B, the power penalty of the receiver increased in order to obtain the low bit error rate ($<10^{-9}$). Personick reported that the power penalty reaches 1 dB when the pulse width exceeds the one fourth of the bit period ($1/B$ [s]). Therefore, the possible bit rate B_p is given by

$$B_p=\frac{1}{4\sigma_{\text{total}}}. \tag{8}$$

Figures 4 and 5 show the calculated possible bit rate *versus* index exponent α. Here, it was assumed that the fiber length and spectral width of the light source (laser diode) are 100 m and 2 nm, respectively.

The curve (A) in Figures 4 and 5 show the calculated bit rate in which only the modal dispersion is taken into account, namely, parameters ε and $\sigma_{\text{Intramodal}}$ are 0 and N_1 equals n_1 in eq 5, 6, and 7. The maximum bit rate is obtained when α equals 2 if the material dispersion is not taken into account. It is noteworthy that the optimum index exponent α which offers the maximum possible bit rate shifts to a larger value than 2 when both modal and material dispersions are taken into account, and that the maximum possible bit rate decreases by the material dispersion. For instance, in the case of PMMA based GI POF whose index exponent is 2.0, the calculated possible bit rate exceeds 100 Gb s^{-1} for 100 m length of fiber at 650 nm if the material dispersion is neglected. However, when the material dispersion effect is taken into account, the maximum bit rate decreases to approximately 3 Gb s^{-1} and the index exponent should be tightly controlled to 2.33 in order to transmit such a high bit rate. Furthermore, the longer the signal wavelength becomes, the higher the bit rate can be transmitted if the refractive index is accurately optimized for each wavelength. In the case of PMMA based GI POF, if 780 nm is used for signal wavelength, more than 5 Gb s^{-1} can be transmitted which is approximately twice higher than the maximum possible bit rate when the signal wavelength is 650 nm. The results in Figures 4 and 5 indicate that the index exponent should be controlled from 1.7 to 3 to transmit more than 1 Gb s^{-1} for 100 m by the GI POF.

The highest bit rate by PHFIP 2-FA based GI POF is 15.2 Gbit s^{-1} when α equals 2.08 at the wavelength of 780 nm, while in the case of PMMA based GI POF, 3.09 Gbit s^{-1} when α equals 2.33 at 650-nm wavelength. It should be noted that the maximum bit rate transmitted by the PHFIP 2-FA based GI POF is much higher than that transmitted by PMMA based GI POF because the material dispersion of the fluorinated polymer is lower than that of PMMA. Therefore, the fluorinated polymer as a matrix of the GI POF is advantageous in order to transmit more than 1 Gb s^{-1}.

CONCLUSION

The optimum refractive-index profile of the GI POF was clarified with both modal and material dispersions taken into account. To attain such a high speed transmission of more than 1 Gb s^{-1} of bit rate using the light source with more than 2-nm spectral width, the effect of the material dispersion should be taken into account and the refractive-index profile must be accurately controlled to have a limited value of the index exponent α (from 1.7 to 3) in the power law approximation. The fluorinated polymer based GI POF can transmit a higher bit rate than PMMA based GI POF because fluorinated polymer has low material dispersion and low attenuation at near infrared region.

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