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Present Prospect of Graded-Index Plastic Optical Fiber in Telecommunication

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SUMMARY The status of the plastic optical fiber (POF) for high-speed data communication is described. Very recently, the low-loss and high-bandwidth perfluorinated GI POF which has no serious absorption loss from visible to 1.3-μm wavelength was successfully prepared at Keio University. Since the core diameter (300-1000 μm) of the GI POF is much larger than that of the multimode silica fiber (62.5 μm), the serious modal noise in the conventional multimode silica fiber was virtually eliminated, resulting in stable giga bit order data transmission with inexpensive couplers and connectors.

key words: *graded-index plastic optical fiber, perfluorinated polymer, scattering loss, absorption loss, modal dispersion, material dispersion*

1. Introduction

Rapid progress has been made in the fabrication process of single mode silica optical fiber which has emerged allowing increased exploitation of the available bandwidth in the domain of the long term telecommunication. Recent advance in novel fibers and fiber devices have made the requirement of all optical network even in the premises area. When we consider the introduction of the single mode silica fiber into the premises area, coupling and connection come to be of great importance. Since the small core (5-10 μm diameter) of the single mode fiber requires highly accurate connectors, serious increase of the cost of the whole system is expected.

The large core (such as 200-1000 μm) of the polymer optical fiber (POF) offers the advantage in the coupling problem. The POF allows the use of inexpensive injection-molded polymer connectors, which makes it possible to dramatically decrease the total cost of the system.

We have proposed a large-core and high-bandwidth graded-index polymer optical fiber (GI POF) as a promising candidate for the transmission media in the premises area network [1], and succeeded in a 2.5 gigabit per second (Gbit/s) transmission in the 100 m GI POF link [1], [2] using an LD at 0.65-μm wavelength. However, the transmission distance was limited to approximately 100 m due to the intrinsic absorption loss. In this paper, recent progress of a new GI POF with low attenuation even at 0.7-1.3-μm wavelength region is described.

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2. Low-Loss Transmission Trial

Poly methyl methacrylate (PMMA) has been used for the core material of POF so far as highly transparent polymer. The first GI POF reported by us in 1982 [3] was basically composed of the PMMA with a 1000 dB/km attenuation. 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 [4]. However, the POF link length was limited to about 100 m because of the inherent absorption loss of PMMA base POF. The attenuation spectrum of the PMMA base GI POF is shown in Fig. 1. The attenuation of the PMMA base GI POF is abruptly increased in the range of 0.7-1.5 μm wavelength, which is caused by the absorption of overtones of carbon-hydrogen stretching vibration. It is highly desirable to extend the POF link length with using commercially available LD and LED which operate in the range of 0.7-1.5 μm of wavelength. However, the attenuation of the PMMA base GI POF at 1.3-μm wavelength is more than 10000 dB/km. Deuterated or fluorinated polymer base POF is one of the promising candidates to eliminate the serious absorption loss in such a wavelength.

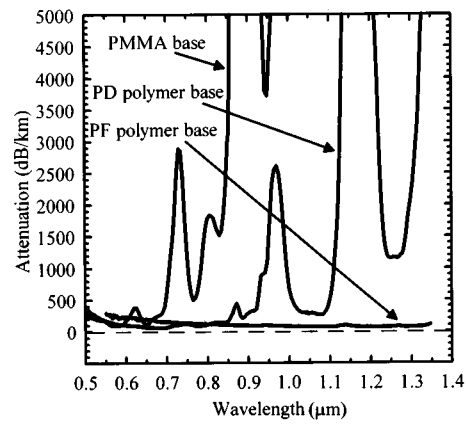

Fig. 1 Experimental attenuation spectra of GI POFs.

Very recently, we have succeeded in preparing both perdeuterated (PD) and perfluorinated (PF) polymer base GI POFs whose attenuation spectra of 0.5-1.3-μm wavelength are shown in Fig. 1. It is quite noteworthy that the attenuation of the PF polymer base GI POF even at 1.3-μm wavelength is about 50 dB/km.

Theoretical estimation of the attenuation of the PF polymer base GI POF is necessary in order to clarify the suitable application fields of the PF polymer base POF. Theoretical attenuation limit was investigated by dividing the attenuation factor to two: intrinsic scattering and absorption.

The theoretical scattering loss of the PF polymer was calculated by using the thermal fluctuation theory which was written as [5],

$$\alpha^{iso}(\mathrm{dB/km}) = \frac{1.29\times10^{5}\pi^{3}}{\lambda_0^{4}}(n^2-1)^2(n^2+1)^2kT\beta \qquad (1)$$

where α^{iso} is the isotropic scattering loss (dB/km), λ_o the wavelength of light in vacuum, k the Boltzmann constant, T the absolute temperature, n the refractive index, and β the isothermal compressibility. In order to estimate the scattering loss by Eq. (1), we propose the following relationship for calculating the isothermal compressibility at the glass transition temperature T_g of amorphous polymers.

1) Relation between the intrinsic molecular volume and actual molecular volume.
2) Relation between actual molecular volume and molecular weight between chain entanglements.
3) Relation between the number of chain atoms between physical entanglements and the cross-sectional area per polymer chain.
4) Relation between the cross-sectional area per polymer chain and the isothermal compressibility at a liquid-liquid transition temperature.

Therefore, combining the above relations, the isothermal compressibility β at liquid to liquid transition temperature T_{ll} can be calculated from the intrinsic molecular volume V_{int} (V_{int} is calculated from atomic radius and bond length of constituent atoms). In order to estimate the light scattering loss at glassy state, the isothermal compressibility β at T_g of polymer was estimated by using the empirical relation between T_{ll} and T_g ($T_{ll}=T_g+76$(K)), and the value $(1/\beta_{atT_{ll}})(d\beta/dT)=4.8\times10^{-3}\mathrm{K}^{-1}$ at $T_g<T<T_{ll}$). Table 1 summarizes the calculated isotropic light scattering loss of the amorphous PF polymer compared with typical transparent amorphous polymers (PMMA and polystyrene).

Table 1 Calculated isotropic light scattering loss of amorphous polymer glasses at various wavelengths.

	isotropic scattering loss (dB/km)			
	at 0.65 μm	at 0.85 μm	at 1.3 μm	at 1.5 μm
PF Polymer	4.2	1.45	0.26	0.15
PMMA	8.8	3.01	0.55	0.31
poly styrene	18.3	6.26	1.14	0.65

The molecular stretching vibration absorption and electronic transition absorption are the inherent absorption loss factors. Considering the near infrared use, the effect of the electronic transition absorption can be negligible. The molecular stretching vibration absorption loss was calculated by using Morse potential energy theory [6], [7]. The energy level, $G(v)$, belonging to the vibrational absorption between two atoms can be written as

$$G(v)=\nu_0(v+1/2)-\nu_0\chi(v+1/2)^2 \qquad (2)$$

where $v=1, 2, 3\cdots$ is the quantum number, χ the anharmonicity constant, and ν_0 the original vibration between only two atoms. Then the v-th harmonic vibration, ν_v, becomes

$$\nu_v=\frac{\nu_1 v-\nu_1\chi v(v+1)}{1-2\chi} \qquad (3)$$

Here, ν_1 denotes the fundamental vibration in real polymer and $\nu_1=\nu_0$ when $\chi=0$. The value of χ for carbon-hydrogen (C-H), carbon-deuterium (C-D), and carbon-fluorine (C-F) vibrations are 1.9×10^{-2}, 1.5×10^{-2}, and 4.0×10^{-3}, respectively. Therefore, the original vibrations peaks of C-H, C-D, and C-F bonds in real polymer exist at wavelengths of 3.390, 4.484, and 8.000-μm, respectively. Subsequently, the overtone positions of C-H, C-D, and C-F stretching vibrations are calculated by Eq. (3). Absorption losses of these overtones in the amorphous polymer were calculated by the Groh's method [7] where the empirical result of 3000 dB/km for 5th overtone of C-H bonding in PMMA was used. Figure 2 shows the calculated absorption loss of the PF polymer due to the C-F stretching vibration compared with C-H in PMMA

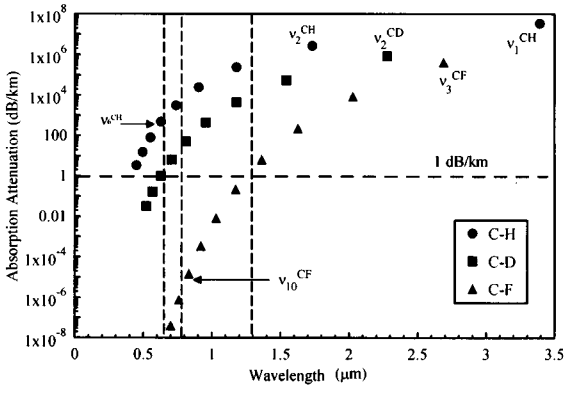

Fig. 2 Absorption attenuation due to different C-X vibrations vs. spectral overtone positions.

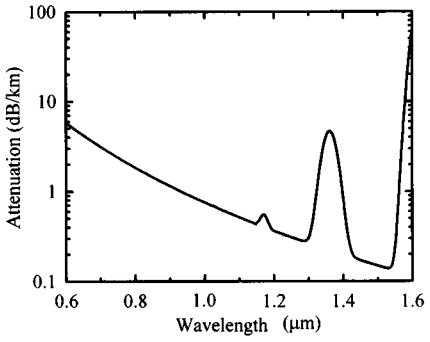

Fig. 3 Calculated attenuation spectrum of PF polymer base POF.

and C-D in PD polymer. It is quite noteworthy that the absorption loss of PF polymer at less than 1-μm wavelength region is almost zero (less than 10^{-3} dB/km).

Total attenuation spectrum of the PF polymer base POF was estimated by the summation of scattering and absorption losses. The result is shown in Fig. 3. Here, it was assumed that the absorption peak at 1.361 μm was the Gaussian profile with 0.020-μm full width half maximum. It is indicated that the attenuation limit of the PF polymer base GI POF at 1.3-μm wavelength is approximately 0.3 dB/km which is comparable with that of silica fiber (0.2 dB/km).

3. High Bit Rate Trial

It is well known that the modal dispersion is minimized by the quadratic refractive index distribution formed in the core of the fiber. Measured refractive index profile of the PF polymer base GI POF is shown in Fig. 4. Controlling the refractive index profile of the GI POF to the optimum profile should be the key technology for high bit rate transmission. The refractive index profile of the GI POF was approximated by the power law of the equation as:

$$n(r)=n_1\left[1-\left(\frac{r}{a}\right)^g \Delta\right] \tag{4}$$

$$\Delta=\frac{n_1^2-n_2^2}{2n_1^2}\approx\frac{n_1-n_2}{n_1} \tag{5}$$

Here, n_1 and n_2 are refractive-indices at center axis and cladding of the fiber respectively, "a" 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. Optimum refractive index profile was analytically investigated by considering not only the modal dispersion but also the material dispersion. The material dispersion of the POF was estimated by measuring the wavelength dependence of the refractive index of polymers. The result of the refractive indices of PMMA and PF polymer is shown in Fig. 5. The material dispersion

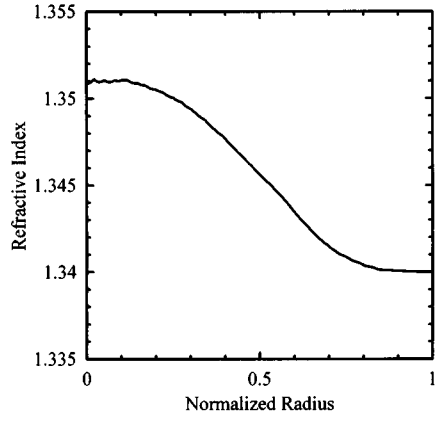

Fig. 4 Refractive index distribution of the PF polymer base GI POF.

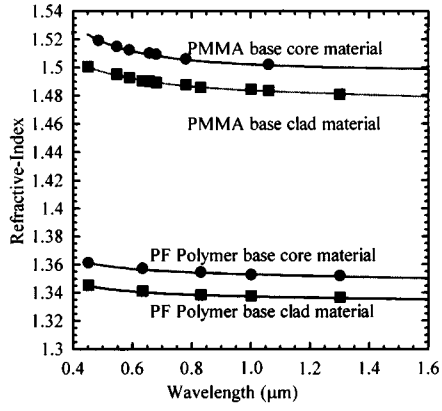

Fig. 5 Wavelength dependence of the refractive index of PMMA and PF polymer.

Table 2 Comparison of the material dispersion of polymer and silica.

Wavelength	0.65 μm	0.78 μm	0.85 μm	1.30 μm
PF polymer clad material	130	72	54	9.5
PF polymer core material	129	71	52	5.3
SiO_2*	223	118	84	2.7
SiO_2-GeO_2*	279	151	112	12
PMMA	320	177	133	23

* Ref. 8 ps/nm km

was estimated by using the data in Fig. 5, based on Eq. (6).

$$D_{mat}=-\left(\frac{\lambda\delta\lambda}{C}\right)\left(\frac{d^2n}{d\lambda^2}\right)L \tag{6}$$

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.

The result is shown in Table 2. 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 possible

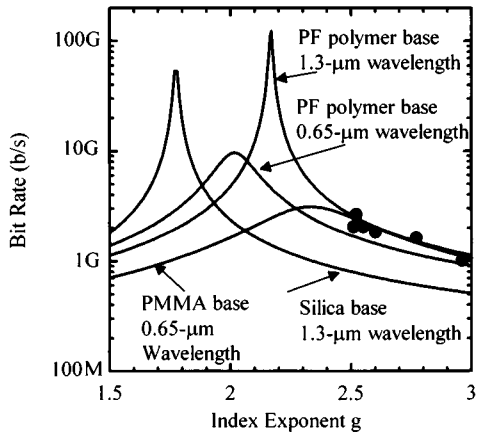

Fig. 6 Relation between the index exponent of the GI POF vs. possible bit rate of 100 m GI POF link.
Source spectral width was assumed to be 2-nm.
●: Experimental results

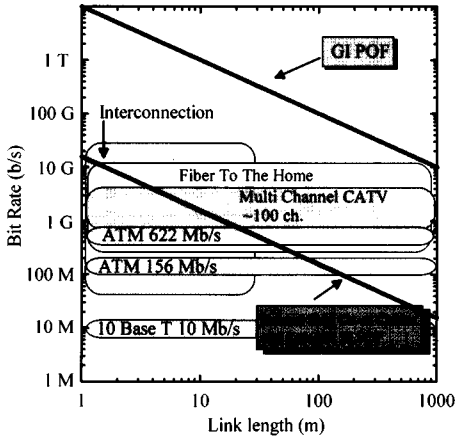

Fig. 7 Application area of POF link.

bit rate and refractive index profile of the PMMA and PF polymer base GI POF calculated by the WKB method [8], [9], in which both modal and material dispersions were taken into consideration. Here, the light source was assumed to be an LD with a 2-nm of spectral width. In the case of PMMA base GI POF, the material dispersion limits the maximum bit rate to 3 Gb/s in 0.65 μm use. The experimental data in the PMMA base GI POF is in good agreement with the theoretical curve. 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, as described before, 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 100 m link achieves to 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 [8].

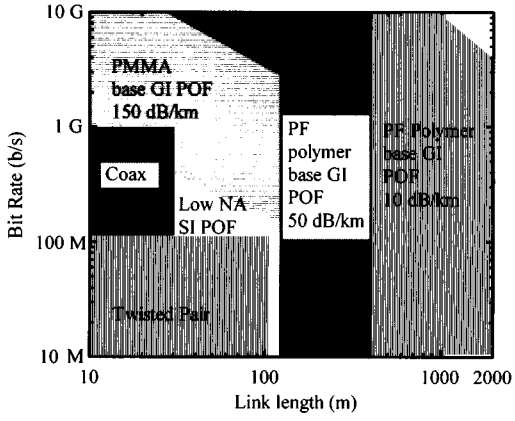

Fig. 8 Relation of data rate and link length of several physical media.

Required bit rate for several networks versus possible bit rate achieved by several media are summarized in Fig. 7. Although conventional metallic cables such as twisted pair and coaxial cables are useful because of easy handling, it takes additional cost for their interface and system to transmit such a high bit rate for ATM LAN standards (156,622 Mb/s). On the other hand, the GI POF can cover most network protocols and applications. Figure 8 shows the data transmission capacity of the PMMA base and PF polymer base GI POF, compared with coaxial and twisted pair cables and low NA SI POF.

4. Modal Noise

It has been concerned that the modal noise degraded the bit error rate in the case of multi mode fiber with laser diode in the fiber-optic links. However, we confirmed that the large core (300–1000 μm diameter) of GI POF which transmits more than 30,000 modes causes no such degradation of bit error rate even if a laser diode with high coherency was used. We investigated the modal noise effect on the bit error rate in the GI POF link as follows: a Fabry-Perot LD at 0.644 μm with a 0.001-μm spectral width was used as the light source, and the bit error rate of 156 Mb/s system in which one fiber-to-fiber joint had been deliberately misaligned was measured.

Figure 9 shows the result of the modal noise for both PMMA base GI POF with a 600-μm core diameter and GI glass fiber with a 62.5-μm core diameter. In the case of the GI POF, even when 200-μm misalignment was occurred, no significant degradation was observed. On the other hand, in the case of the conventional GI glass fiber, it was observed that a 10-μm of displacement caused large bit error rate degradation, and that it was impossible to obtain the accurate bit error rate curve in the case of 20-μm displacement because of a serious fluctuation of the output power from the fiber.

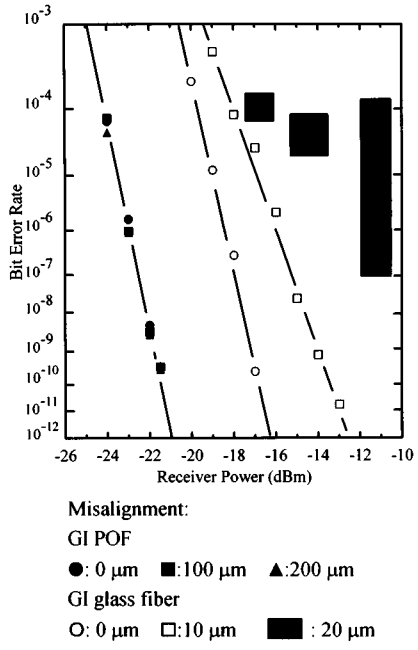

Fig. 9 Modal noise effect on bit error rate in PMMA base GI POF link.

It is concluded that the large core of the GI POF offers low modal noise as well as low coupling loss. The large core GI POF enables the usage of inexpensive connector made by injection molding which tends to cause 20 to 50-μm misalignment.

5. Conclusion

Perfluorinated polymer provided great advantage in the infrastructure of the POF network. Low intrinsic absorption loss of the PF polymer enabled the dramatic decrease in the attenuation of GI POF that is as low as 50 dB/km at 1.3-μm wavelength. The theoretical attenuation limit of the PF polymer base POF was estimated by the aspects of intrinsic scattering and absorption losses. The minimum attenuation of 0.3 dB/km of the PF polymer base GI POF indicates that the POF link is possible to cover several kilometers without repeaters. With increasing the link length, the pulse distortion due to the material dispersion comes to limit the bit rate of POF link. It was clarified that the low material dispersion of the PF polymer compared with PMMA and silica allows more that 10 Gb/s transmission even in 1 km link.

Furthermore, no modal noise effect was observed even when 200-μm misalignment was occurred at the fiber-to-fiber coupling because a large number of modes are transmitted in the large core GI POF. We believe that these experimental and theoretical aspects suggest that the PF polymer base GI POF will be one of the promising candidates for "the last one mile."

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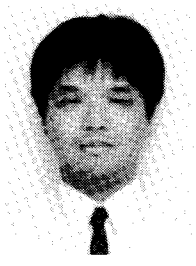

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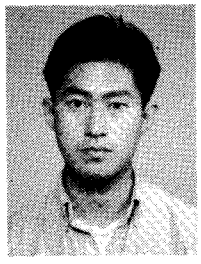

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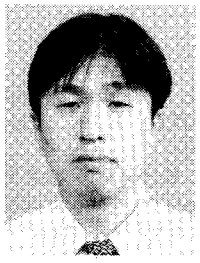

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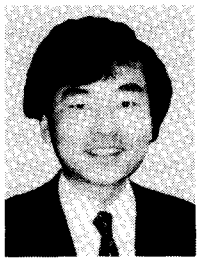

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