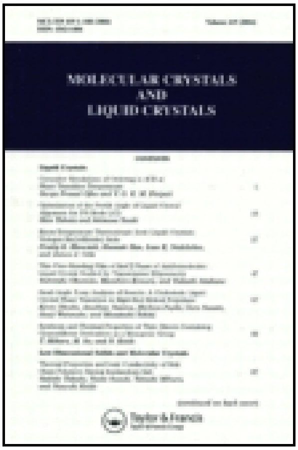


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# Novel Photonics Polymers in High-Speed Telecommunication

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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 at Keio University, and several methodologies to fabricate GI POF have been currently proposed. In this paper, we clarify the great advantage of perfluorinated polymer as the polymer matrix of low-loss and high bandwdith graded-index (GI) POF. It is generally known that the PF polymer can decrease the intrinsic absorption loss compared with poly methy methacrylate (PMMA), which is the conventional material of POF. Furthermode, it was found that low material dispersion of the PF polymer is another advantage to obtaind the high bandwidth GI POF.

It was clarified for the first time that the power distribution of modes formed by the mode dependent attenuation was the dominant factors of the higher bandwidth of the GI POF than theoretically predicted bandwidth, while the effect of the mode coupling was small.

*Keywords:* Graded-Index polymer optical fiber; perfluorinated polymer; modal dispersion; material dispersion; differential mode attenuation; mode coupling

## 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 (VCSEL)[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 infrared 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.



## PF POLYMER BASE GI POF

### Material Dispersion

Birth of the PF polmer having no carbon-hydrogen bonding in the molacule has brought a new concept of optical data link. Great advantage of the PF polymer is low intrinsic absorption loss. Because of the low intrinsic loss, very wide wavelength range from visible to near infrared region (for instance 1.3-μm) can be adopted for signal wavelegth in the PF polymer base GI POF link. Currently the lowest attenuation of the PF polymer base GI POF is around 30 dB/km at 1.3-μm[5, 6].

On the other hand, we found another advantage in the PF polymer, that is the low material dispersion. The material dispersion of the PF polymer estimated by measuring the wavelength dependence of the refractive index of polymer is shown in Fig. 1 compared with those of PMMA and silica. Since the material dispersion generally decreases with increasing the wavelength, operating wavelength of POF network should be in near infrared region rather than in visible region for high-speed data transmission. However, the light source of 0.65-μm wavelength has been required for the conventional PMMA base POF network so far, because one of low attenuation window is located at 0.65-μm.

Low attenuation of the PF polymer base GI POF at near infrared region gives an advantage even in the dispersion limitation because the material dispersion decreases with increasing the wavelength as mentioned above. In the case of the PF polymer, the material dispersion at 0.65-μm wavelength is 0.13 ns/nm·km which is much lower than that (0.32 ns/nm·km) of the PMMA at the same wavelength. Further, the material dispersions of the PF polymer at 0.85 and 1.3-μm wavelengths decrease to 0.054 and 0.009 ns/nm·km, respectively.

Although the material dispersion of silica is almost zero at 1.3-μm wavelength, the high material dispersion of the $GeO_2$ doped silica from visible to near infrared region limits the bandwidth of $GeO_2$-$SiO_2$ base fiber. On the other hand, it should be noteworthy that addition of dopant in the PF polymer causes little change in value of material dispersion.

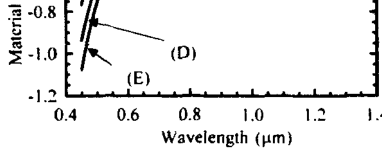


FIGURE 1 Material dispersion of PMMA, PF polymer and silica.
(A): PF homopolymer (B): 15 wt. % PF dopant added PF polymer (C): pure $SiO_2$ (D): 13.5 mol % $GeO_2$ doped $SiO_2$ (E): PMMA homopolymer

Since perfluorinated substance is used as the dopant, the material dispersion of the dopant is low. Furthermore, the material dispersion of PF homopolymer is almost the same as that of dopant added PF polymer in the wavelength range from 0.45 to 1.3 μm, which indicates that the higher bandwidth PF polymer base GI POF is expected in wide wavelength range from visible to near infrared region rather than the multimode silica fiber[7].

**Dispersion Induced by Refractive Index Profile**

Total dispersion is estimated by using WKB method, considering material, modal and profile dispersions, as described in detail in this section. Approximation of power-law index profile in eq. (1) enabled to calculate the root mean square (r.m.s.) width σ of the impulse response of GI POF as a function of index exponent g by the WKB method[8]-[10].

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

where, $n_1$ and $n_2$ are the refractive indices of center axis and the cladding, respectively, a is the core radius, g is index exponent, that is the parameter of the index profile, and Δ is called relative index difference which is expressed as Eq. (2)

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

Subsequently, the relation between the refractive index profile and the bandwidth of the GI POF was obtained by using the simple relation between the width of impulse response and the bandwidth as shown in eq. (3).

$$f_{-3dB} = \sqrt{\frac{\ln 2}{2\pi^2}}\frac{1}{\sigma} = \frac{0.188}{\sigma} \tag{3}$$

where, σ is the root mean square width of the impulse response function. Here, -3 dB bandwidth of the GI POF was calculated by assuming that the output pulse waveform was approximated by Gaussian shape.

It should be noted that the difference of the optimum index exponent value between 0.65 and 1.3-μm wavelengths is caused by the inherent polarization properties of material itself. The optimum index profile of the GI fiber for giving maximum bandwidth is described by eq. (4) when the index profile is approximated by the power-law equation shown in eq. (1)[8].

$$g_{opt} = 2 - \frac{2n_1}{N_1} \cdot P - \Delta \frac{\left(4 - \frac{2n_1}{N_1} \cdot P\right)\left(3 - \frac{2n_1}{N_1} \cdot P\right)}{5 - \frac{4n_1}{N_1} \cdot P} \tag{4}$$

$$N_1 = n_1 - \lambda \frac{dn_1}{d\lambda} \tag{5}$$

where $g_{opt}$ signifies the optimum index exponent, and P that is called as profile dispersion is written as follows.

$$P = \frac{\lambda}{\Delta} \frac{d\Delta}{d\lambda} \tag{6}$$

Since the profile dispersion P is the function of the differentiation of the relative index difference Δ with respect to wavelength λ, the optimum index profile depends on refractive index of the core material, which means that index increment by the dopant material is key issue. The wavelength dependence of the bandwidth characteristics of PF polymer base GI POF is shown in Fig. 2, compared with that of the $GeO_2$-$SiO_2$ base multimode glass fiber when the index profile is controlled to have the index exponents of 2.03, 2.075 and 2.23 in the PF polymer base GI POF, and 2.01 and 1.78 in the silica base multimode fiber. Selected index exponents of 2.03, 2.07 and 2.23 are the optimum index exponents of the PF polymer base GI POF when the source wavelengths are 0.65, 0.85 and 1.3 μm, respectively, while 2.01 and 1.78 are optimum for 0.85 and 1.3-μm wavelength, respectively, in the silica base multimode fiber. It was already confirmed that[3] if the index exponent g is controlled to around 2.0, several hundreds MHz·km can be achieved in wide wavelength rage from 0.6 to 1.3 μm, because of low material dispersion. On the other hand, in the case of the $SiO_2$-$GeO_2$ base GI multimode fiber, accurate index profile control for specified wavelength of used laser is necessary to achieve several hundreds MHz·km, since the wavelength dependence of the bandwidth is much stronger than that of the PF polymer as shown in Fig. 2. It can be emphasized that the low material dispersion of PF polymer allows the tolerance in the index profile of the PF polymer base GI POF even for higher-speed transmission rather than silica fiber.

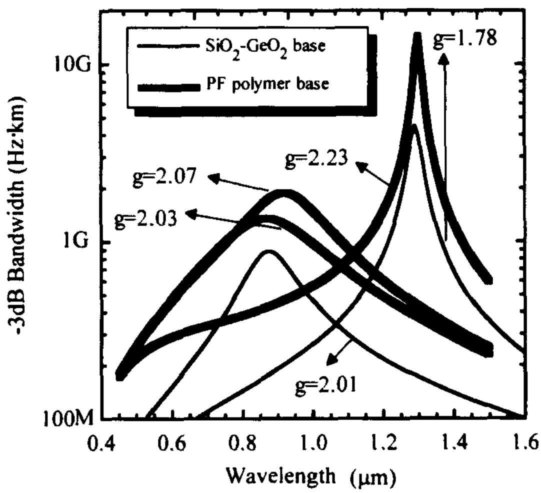


FIGURE 2 Wavelength dependence of the bandwidth of PF polymer base GI POF and $GeO_2$-$SiO_2$ base GI multimode glass fiber.

On the other hand, for 1.3-μm use, optimum index exponent $g_{opt}$ is 2.23, by which approximately 10 GHz·km can be achieved, while the same GI POF having 2.23 of index exponent exhibits only 400 MHz·km when the wavelength of the light source is 0.65 μm. In order to further decrease the wavelength dependence of the optimum index profile, suitable dopant which can decrease the profile dispersion (i.e. the wavelength dependence of the relative index difference. See Eq. (6).) should be selected. The shift of the optimum index exponent of the PF polymer base GI POF between 0.85-μm and 1.3-μm wavelengths is 0.16 (from 2.07 to 2.23) which is smaller than that (0.23) of $GeO_2$-$SiO_2$ base GI multimode glass fiber (from 2.01 to 1.78). This is because the profile dispersion of the PF polymer base GI POF is smaller than that of $GeO_2$-$SiO_2$ base GI multimode glass fiber.



## BANDWIDTH CHARACTERISTICS OF GI POF

To cover the high-bit rate such as several hundred mega bit per second, which must be required even in office and home-network, we proposed the high-bandwidth GI) POF for the first time[2], and have reported its bandwidth characteristic[3]. Recently interests focused on POF accelerates the research and development of POF particularly in its bandwidth improvement. In this paper, we clarified that the launch condition and mode dependent attenuation are the dominant factors determining the bandwidth of the GI POF. It was also shown that the mode coupling effect on the bandwidth characteristics of the GI POF is considered to be small compared to the above two factors within 100 m. We show a precise bandwidth prediction of the GI POF by considering the power distribution among the propagating modes and differential mode attenuation for the first time, resulting in a good agreement with the experimentally measured property.

We reported that the refractive index profile of the GI POF could be widely controlled by the interfacial-gel polymerization technique[2]. Bandwidth characteristics of the prepared GI POF were analyzed, and we succeeded in predicting the impulse response function of the GI POF having arbitral index profile. In this analysis, uniform launch of all modes is usually assumed because of easy calculation. Fig. 3 shows the experimental and calculated pulse broadening through 100-m PMMA base GI POF. Here, the GI POF whose index profile is slightly deviated from the ideal one was used for measurement in order to clearly observe the pulse broadening. Even for this GI POF, more than 1 GHz of bandwidth for 100m was obtained. The pulsed light signal was launched into the GI POF via a 1-m length, 1-mm core diameter step-index (SI) POF having NA of 0.5 which is much higher than that of the GI POF, in order to realize the uniform excitation of all modes including both meridional and skew modes. A large disagreement is observed between the calculated and measured output waveforms. It was confirmed by the detail analysis that the second peak existing in the calculated waveform shown by the open circle is attributed to the higher order modes having large group delay. On the other hand, an excellent agreement with the measured waveform was observed when the mode dependent attenuation obtained from the near-field power distribution was taken into consideration as shown by close circle.



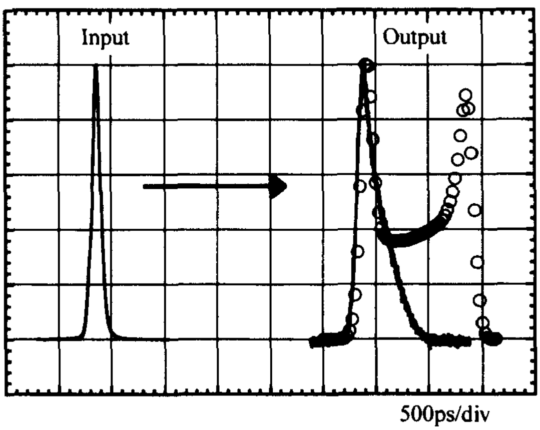


FIGURE 3 Comparison of measured and calculated bandwidth characteristics of the GI POF having an index exponent of 2.7
Solid line: measured waveform
●: Predicted waveform when all modes were assumed to equally launched.
O: Predicted waveform when the differential mode attenuation describe in the following section was taken into account

## PROPAGATING MODE CHARACTERISTIC

### Launch Condition Dependence of Far-Field Pattern from GI and SI POF

There have been several reports concerning the dispersion property of GI POF. In these articles, bandwidth characteristic of the POF was tried to theoretically calculated. However, the theoretical bandwidth properties of the GI POF often have some amount of disagreement with the measured one. The reason of the disagreement is generally explained by the mode coupling, which was derived from the similar discussion in the silica base multimode fiber. Although the detail modal property has not been analyzed, higher measured bandwidth than theoretically predicted bandwidth was reported as the result of strong mode coupling. However, we found that the mode coupling effect on the bandwidth characteristics in the GI POF is very smaller than that in the SI POF. In order to investigate the mode coupling effect on the bandwidth in both GI and SI POFs, the launch condition dependence and transmission distance dependence of the far-field pattern (FFP) were investigated at first. Schematic representation of the measurement is shown in Fig. 4. In this measurement, the lower order modes were selectively launched in both GI and SI POFs. In the case of GI POF, the order of mode number relates to both launching beam diameter and launching angle, while the launching angle directly corresponds to the mode number. Therefore, a single mode silica fiber was butted to the center of the GI POF to launch the lowest order mode group, while collimator lens are used for SI POF as the low order mode exciter. Results are shown in Figs. 5, 6, and 7. It was noteworthy that the angular distribution of the output power from the SI POF gradually expands with increasing the transmission distance, although the input NA is very small. This result indicates that strong mode coupling, which scrambles the mode power distribution within 40-m transmission, exists in the SI POF.

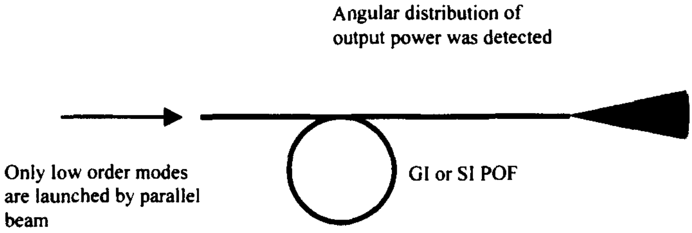


FIGURE 4 Schematic representation of the far-field pattern measurement.

On the other hand, the angle distribution from the GI POF with 50-m length is just the same as that with 10-m length, which means that the mode coupling in the GI POF is much weaker than that in the SI POF.

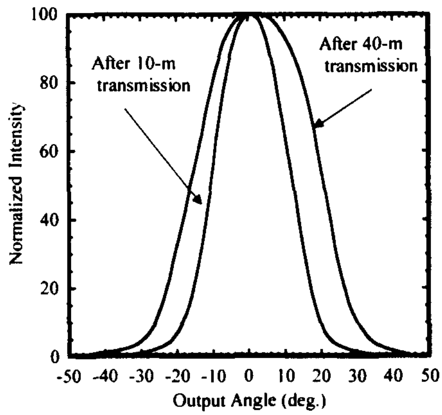


FIGURE 5 Fiber length dependence of the far-field pattern of the conventional SI POF when the collimated light (input NA is 0.06) was injected into POF.

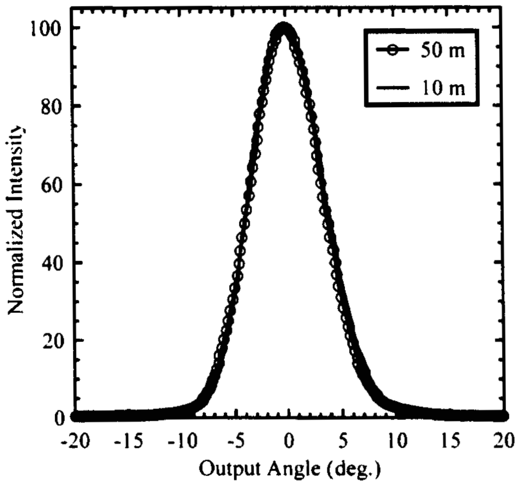


FIGURE 6 Fiber length dependence of the far-field pattern of the conventional GI POF when the collimated light (input NA is 0.06) was injected into POF.

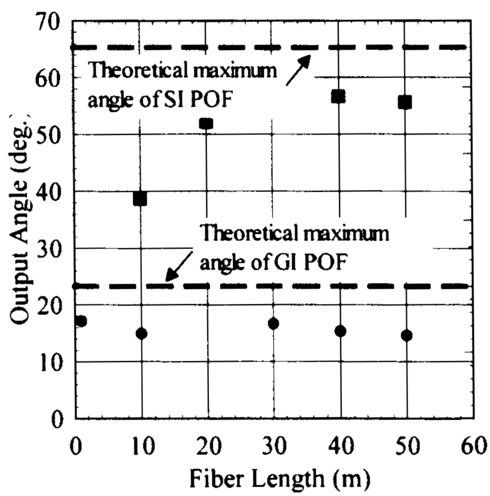


FIGURE 7 Comparison of fiber length dependence of the far-field pattern of the conventional SI POF and GI POF.

**Differential Mode Delay**

The group delay of each mode in the GI POF was investigated by the measurement of the differential mode delay (DMD). In the DMD measurement, optical pulse is coupled into the GI POF via a 1-m single mode silica fiber in order to launch a specified mode group of the GI POF. By shifting the position of the single mode fiber attaching to the GI POF from the core center to the periphery, each mode from the low order to high order is independently launched. The results of the DMD measurement in 100-m GI POF are shown in Fig.8. Here, the lengths 0 μm, 130μm, ⋯200 μm shown in Fig. 8 signify the distance from the core center to launching position by the single mode fiber. Output near-field patterns (NFPs), which directly relate to the mode number of transmitted mode, are also shown in Fig. 8. When the higher order modes are selectively launched by shifting the launch position 200 μm apart from the core center, the ring pattern is clearly observed, which indicates that the higher order modes are independently transmitted with little energy transfer to the lower order modes. The group delay of each mode in the GI POF was investigated by the measurement of the differential mode delay (DMD). It was observed that with increasing the mode number, larger time delay is observed in which each peak in Fig. 8 is exactly the same as the theoretical value assuming no mode coupling. The fiber length dependence of the DMD is shown in Fig. 9. A linear relation between the DMD and fiber length is observed, and the slope is almost 1, which indicates weak mode coupling.

Generally, the degree of mode coupling in the multi-mode optical fiber is evaluated by the relation between the fiber length and the output pulse width. When the output pulse width is plotted with respect to the fiber length, the slope is an important parameter. The slope close to 1 signifies weak mode coupling, while the slope less than 1 large mode coupling. However, the output pulse width decreases when the higher order modes have very high attenuation, which means that the slope between the fiber length and the output pulse width becomes less than 1 even if the mode coupling is much weak. On the other hand, it was reported that the strong mode coupling changes the output pulse shape from original near triangle shape to Gaussian shape with increasing the transmission distance. This pulse shape change to Gaussian is seen in the result of the conventional step-index type POF even within 50m. Output pulse shape of the GI POF with respect to the fiber length is shown in Fig. 10. Used fiber is the same as that used in Fig. 8. It is noteworthy that even after 100-m transmission, the steep edge in the leading part of the output pulse, which was originally shown in the input pulse is observed, while after 150-m transmission, it slightly changes to the Gaussian shape. Plots in Fig. 10 signify the calculated waveform in which the mode dependent attenuation was taken into account. It is noteworthy that a good agreement between the measured and calculated waveforms is observed within 100-m transmission although the mode coupling effect was not considered. On the other hand, a slight disagreement between calculated and measured is seen in the waveforms after 150-m transmission.

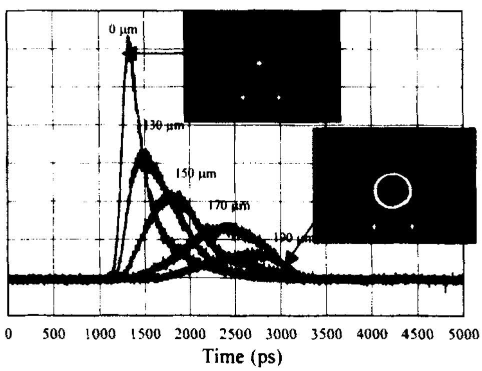


FIGURE 8 Measured result of differential mode delay in 100-m PMMA base GI POF Core diameter: 450μm. Photograph: Output Near-Field Pattern from the GI POF, where arrows show the core diameter

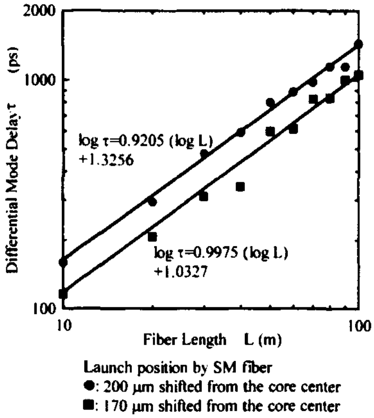


FIGURE 9 DMD versus fiber length of the GI POF.

This is considered to be due to the mode coupling. Therefore, it can be concluded that the mode coupling in the SI POF is stronger than that in the GI POF because the core-cladding boundary strongly affects the propagating mode characteristics. It is also concluded that the mode coupling effect on the bandwidth of the GI POF is very small for 100-m distance.

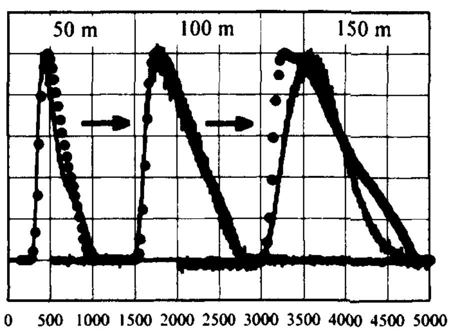


FIGURE 10 Fiber length dependence of the output pulse spread for the PMMA base GI POF. Solid line: Measured results
●: Calculated results considering differntial mode attenuation as described in next section.

**Differential Mode Attenuation**

Differential mode attenuation was measured directly with using the modified method of the DMD measurement. Similar to the DMD measurement, small mode groups were launched via a single mode fiber butted to the one end of GI POF. The output power distribution with respect to the fiber radius was measured. Since, the numerical aperture (NA) of the GI POF varies in the radial direction according to the refractive index profile, acceptable light power, which is highest at the core center, gradually decreases from the core center to periphery. In order to compensate such launch power difference along with the fiber radius, cut-buck method was adopted for differential mode attenuation measurement. Measured result of the differential mode attenuation of the GI POF used in the DMD measurement shown in Fig. 8 is shown in Fig. 11. The attenuation of the low order modes is about 150 dB/km, while abrupt increase was observed with increasing the mode number. It is calculated from Fig. 11 that approximately 17 dB of power difference exists between the lowest and the highest order mode after 100-m transmission. By considering the differential mode attenuation as shown in Fig. 11, output pulse waveform from 100-m GI POF was calculated with using WKB computation method as described above. The result is shown in Fig. 12. Excellent agreement between the measured and calculated waveforms is observed.

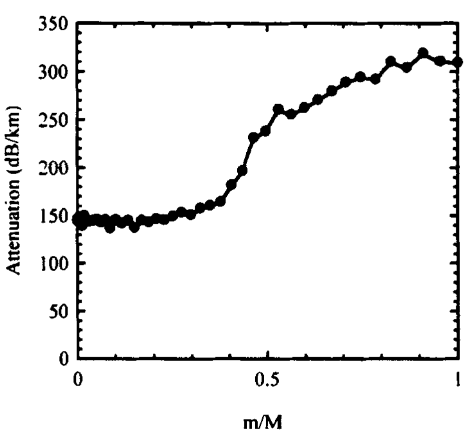


FIGURE 11 Measured differential mode attenuation of the GI POF. m is defined as the principal mode number: m=2μ+v, where μ and v are radial and azimuthal mode number, respectively. M is the maximum principal mode number.

This result of the differential mode attenuation was introduced into the calculation procedure of the output waveform. As shown in Fig.11, the mode group whose principal mode number is in 0≤m/M ≤0.5 have almost the same power, while the transmitted power by the modes whose principal mode number is larager than M/2 decreases dramatically. Calculated output waveform of the GI POF used in DMD measurement in Fig. 8 is shown in Fig. 14 compared with measured waveform. By taking into account the differential mode attenuation, excellent agreement was observed between measured and calculated waveforms.

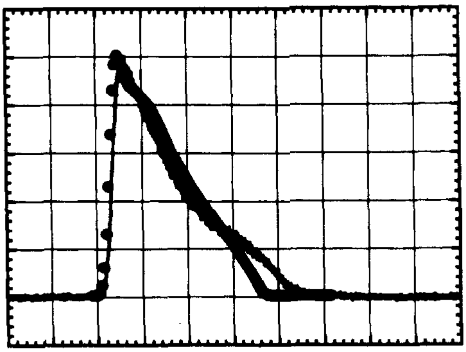


FIGURE 12 Comparison of measured output waveform from 100-m length GI POF used in DMD measurement shown in Fig. 8 and the calculated waveform by considering measured differential mode attenuation shown in Fig.11. ●: calculated waveform

## CONCLUSION

Lower material dispersion of the PF polymer than PMMA and even silica gives the great advantage in the bandwidth. It was clarified for the first time that higher bandwidth than PMMA base GI POF and $GeO_2$-$SiO_2$ base multimode fiber can be expected. Furthermore, low attenuation, which is another advantage of the PF polymer base GI POF, enabled much high bandwidth at 1.3 μm because the material dispersion decreases with increasing the wavelength.

It was theoretically and experimentally confirmed that the bandwidth characteristics of the PMMA base GI POF is strongly influenced by the mode dependent attenuation and not by the mode coupling. The conclusion that the effect of differential mode attenuation is large rather than the mode coupling on the bandwidth characteristic of the GI POF is derived from the following three reasons:

(1) Each mode are transmitted independently in the DMD analysis even after 100-m transmission, and their delay times are precisely predicted by the group delay calculation in which no mode coupling effect were considered.

(2) Linear relation between the DMD $\tau$ and fiber length L was observed in the DMD analysis.

Theoretically estimated output pulse waveforms showed an excellent agreement with that experimentally measured by considering the differential mode attenuation effect. Since the link POF link length is considered to be less than 100 m, the result of the weak mode coupling effect indicates that the steady state mode distribution is not necessarily established in the GI POF. Therefore, these propagating mode characteristics are very important issues for designing the POF data link system.



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