Large-Core, High-Bandwidth Polymer Optical Fiber for Near Infrared Use

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Abstract—**High bandwidth (more than 500 MHz·km) graded-index polymer optical fiber (GI POF) for near infra-red use was successfully fabricated by using partially fluorinated acrylate polymer. Since only three carbon-hydrogen bonds exist in a monomer unit, an absorption loss due to the stretching vibration of the carbon-hydrogen bond was remarkably reduced compared with the conventional POF's. The attenuation of the GI POF at 780-nm wavelength was 135 dB/km, which is much lower than that of the PMMA core POF (800 dB/km). The fluorinated polymer-based GI POF is satisfying a significant segment of high-speed multimedia network applications.**

I. Introduction

FOR expanded data communication networks, silica-based, single-mode optical fiber has been widely used, especially for long-haul communication. However, since the core diameter of the single-mode fiber is only 5–10 μm, the slightest amount of displacement in a fiber connection causes a large coupling loss, which will significantly increase the total costs in the fiber to the home (FTTH) and interconnection.

Much interest has been focused on polymer optical fibers (POF's) [1]–[3] as the candidates to solve this connection problem. We have proposed the high bandwidth PMMA graded-index (GI) POF [4], [5], which can cover the required bandwidth that all commercially available step-index (SI) POF's cannot cover. In this letter, we report the first fluorinated GI POF with high bandwidth and low attenuation even in the near infra-red (IR) region, which was fabricated by adopting our interfacial-gel polymerization technique to partially fluorinated acrylate monomer.

II. Experimental

The GI POF was prepared by the interfacial-gel polymerization technique, which was almost the same as that for the PMMA-based GI POF [6]. As the monomer, hexafluoro isopropyl 2-fluoroacrylate (HFIP 2-FA), in which only three carbon-hydrogen bonds exist, was used. Details of fabrication process have been described in [6].

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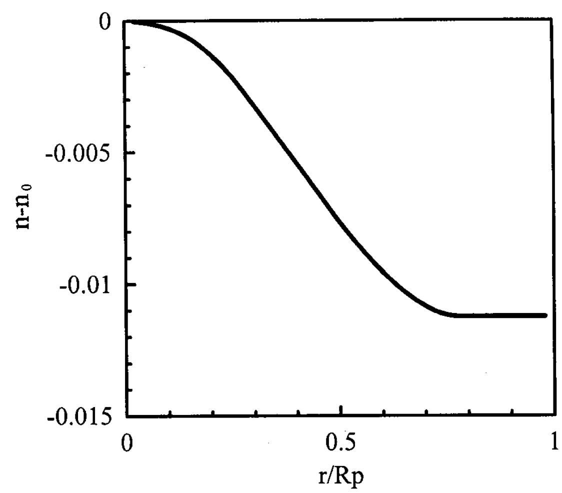

Fig. 1. Refractive-index distribution of the HFIP 2-FA-based GI POF with a 0.5-mm diameter. Monomer and dopant feed ratio: HFIP 2-FA/DBP = 10/1.

TABLE I
Total Attenuation of the GI POF

	650 nm (dB/km)	780 nm (dB/km)	Minimum (dB/km)
PMMA base	113	840.5	90 (572 nm)
HFIP 2-FA base	287	135	115 (773 nm)

III. Results and Discussion

The representative refractive-index distribution of the fiber measured by an interferometric method is shown in Fig. 1.

The total attenuation spectrum of light transmission through the HFIP 2-FA GI POF is shown in Fig. 2 (curve A) compared with that (curve B) of the PMMA-based GI POF we previously fabricated [6]. The minimum attenuation was 115 dB/km at 773-nm wavelength, and 135 dB/km even at 780-nm wavelength, which is matched to the emission wavelength of an inexpensive compact disk laser diode. A serious problem in the PMMA-based POF at the near-IR to IR regions is large attenuation due to the high harmonic absorption loss by C-H vibration (C-H overtone). These results are summarized in Table I. It should be noted that the large peak of the absorption loss is remarkably reduced in the HFIP 2-FA-based GI POF compared with that of PMMA base.

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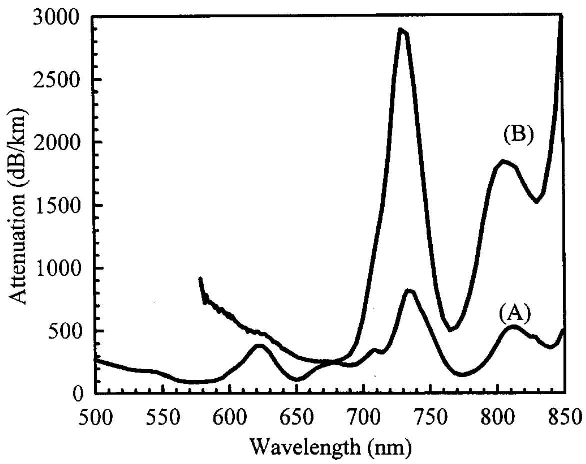

Fig. 2. Total attenuation spectra of the HFIP 2-FA-based GI POF and the MMA-based GI POF. (A) HFIP-2FA-base. (B) MMA-base.

High bandwidth and inexpensive laser diodes that have been adopted in glass fiber systems exist in the IR region. Very high absorption loss of PMMA-based POF rules out such laser diodes in POF system. Therefore, attention has been focused on substituting the hydrogen atom in the polymer molecules for other heavier atoms such as deuterium or halogen atoms. All-fluorinated polymer is much more attractive, but there has been a drawback that the perfect substitution of the hydrogen atoms in the acrylate monomer such as MMA strictly prevents its own monomer from radical polymerization. Furthermore, perfluorinated polymers are often partially crystallized, which dramatically increases the scattering loss. A reasonable solution that satisfies both easy polymerization and low attenuation in the near-IR region may be the use of partially fluorinated acrylate monomers such as the HFIP 2-FA monomer.

An estimation of the spectral position and the vibrational absorption loss may be made by assuming the bonds to be anharmonic oscillators and using the Morse Potential theory [7], described as follows. The energy level, $G(v)$, belonging to the vibrational absorption between two atoms can be written as

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

where $v = 1, 2, 3, \cdots$ is the quantum number, and χ the anharmonicity constant. ν_0, the original vibration between two atoms, is described as follows:

$$\nu_0 = \frac{\sqrt{\frac{K}{\mu}}}{2\pi c} \qquad (2)$$

K: force constant

μ: reduced mass

c: velocity of light

Then the vth harmonic vibration, ν_v, becomes

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

where ν_1 denotes the fundamental vibration in real polymer. The absorption loss in the polymer due to the overtone intensity is approximated by

$$D_{\max}(\nu_v^{\text{C-X}}) = 3.2 \times 10^8 \left(\frac{\rho}{M_G}\right) n_c \left(\frac{E_v}{E_1^{\text{C-H}}}\right)_{\text{C-X}} \qquad (4)$$

where $D_{\max}$ is the attenuation in dB/km of the vth overtone of the C-X bond, ρ is the density of absorbing species in g/cm^3, M_G is the molecular weight of a repeat unit in g/mol, n_c is the number of the bonds of interest in the repeat unit, and the ratio E_v/E_1^{C} – X is the overtone intensity related to the C-H fundamental.

For C-H, C-D, and C-F vibrations, χ is 1.9×10^{-2}, 1.5×10^{-2}, and 4.0×10^{-3}, respectively. From the literature [7], the fundamental vibrations ν_1 of C-H, C-D, and C-F bonds in real polymer exist at $\nu_1 = 3390$, 4484, and 8000 nm, respectively. Deuterium and halogen atoms are considered to be promising alternatives to shift the wavelength of the fundamental vibration to longer wavelength than that of carbon-hydrogen bond. In the Morse Potential calculation for the C-H bond for PMMA, the 6th harmonic vibration appears at the 627-nm wavelength, which corresponds to the absorption loss of 427 dB/km. On the other hand, the 8th harmonic absorption loss of the C-D bond appearing at almost the same wavelength (626 nm) for deuterated PMMA is about 0.82 dB/km, which is about 520 times smaller than that of the 6th harmonic C-H absorption. However, even for the C-D bond, when the wavelength is longer than 1000 nm, the absorption loss becomes serious. For instance, the calculation loss due to the 4th harmonic vibration of C-D at 1174-nm wavelength is as large as 3670 dB/km. It was also recognized that [5] all-deuterated PMMA-based POF had an absorption peak of O-H bond due to the slightly absorbed water molecules in the polymer.

On the other hand, it is well known that a fluoropolymer has very low water absorption. Furthermore, since the wavelength of the fundamental vibration of C-F bond is much longer than that of the C-D bond as mentioned above, the absorption loss even at the 1171-nm wavelength, due to the 7th harmonic C-F vibration for an imaginary fluorinated PMMA, is still as low as 0.12 dB/km. Fluoropolymer must be an ultimate material for fabrication of the low-loss polymer optical fiber in near-IR and IR regions.

As shown in Fig. 2, the absorption peak of the HFIP 2-FA polymer GI POF (curve B) due to the fifth harmonic generation of C-H is at the 735-nm wavelength 813 dB/km, which is one fourth of the value of PMMA based GI POF (2885 dB/km of attenuation).

Since the absorption strength should be proportional to the concentration of the C-H bond per unit volume, the absorption attenuation through the HFIP 2-FA GI POF can be also estimated from that of PMMA-based POF. The amount of C-H bond in the HFIP 2-FA polymer is 2.12×10^{-2} mol/cm^3, which is about one fourth of the value in PMMA (9.52×10^{-2} mol/cm^3). The calculated absorption loss at 735 nm for the HFIP 2-FA GI POF was 618 dB/km. This is a little lower than that of the measured value (813 dB/km) in Fig. 2, because the C-H bond belonging to the dopant is not considered in the core of the GI POF.

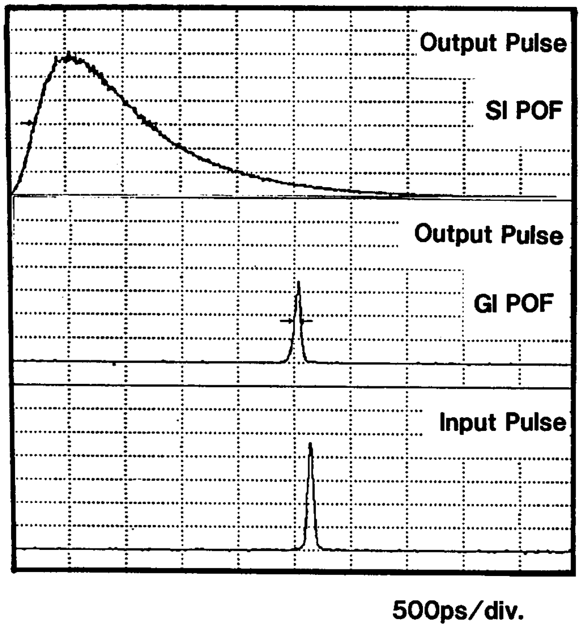

Fig. 3. Comparison of the output-pulse spread between the HFIP 2-FA-based GI POF and conventional SI POF. Both fiber lengths are 25 m.

The bandwidth measurement of the GI and SI POF's was performed as follows. A pulse of 1 MHz from an InGaAlP laser diode (wavelength = 660 nm) was injected (NA = 0.5) into the POF. The output pulse was detected by a sampling head (model OOS-01, Hamamatsu Photonics Co.). The result for the GI POF with an index profile indicated in Fig. 1 is shown in Fig. 3, compared with the SI POF with 0.5 NA. Both fiber lengths are 25 m. It is noteworthy that the output pulse through the SI POF is quite spread, while the pulse through the fluorinated GI POF is very narrow and has almost the same shape as that of the input pulse after 25 m signal transmission. The bandwidth of the SI POF estimated from the 3-dB level in the impulse response function is 5 MHz·km, while the bandwidth of the GI POF is 600 MHz·km which is about 120 times larger than that of the SI POF.

It is well known that the bandwidth can be maximized when $a \cong 2$ in (5).

$$n(r) = n_0[1 - (r/R)^\alpha \Delta]. \tag{5}$$

The index exponent α of Fig. 1 by a least-square method is 2.05.

IV. Conclusion

A high-bandwidth (600 MHz·km) fluorinated GI POF for near-IR use (especially at 780 nm) was successfully obtained by an interfacial-gel polymerization technique for the first time. The minimum attenuation of light transmission was 115 dB/km at the 773 nm-wavelength, which is about one fourth of the value in the case of PMMA based POF at the same wavelength. The HFIP 2-FA-based GI POF also maintains the advantage of large core (0.5–1.0 mm) and great flexibility which the conventional POF's have.

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