

Low loss graded index polymer optical fiber with high stability under damp heat conditions

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Abstract: A low loss graded index polymer optical fiber (GI POF) with a wide wavelength range around 650 nm is fabricated using a copolymer of methyl methacrylate and pentafluorophenyl methacrylate as a polymer matrix. Dopant hydrophobicity similar to that of the polymer matrix is an important factor in maintaining the low loss of the GI POF. No loss increment is observed under damp heat conditions of 75°C and 85% relative humidity when using 9-bromo phenanthrene as the high refractive index dopant required to form the GI profile. The copolymer based GI POF can provide an inexpensive premise network with long-term stability.

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1. Introduction

Optical fibers and waveguides have become increasingly important technologies in data communication, not only in long haul networks, but also in premise networks or inter-racks,

backplanes, cards, and chips, especially in supercomputers and high performance servers, because electrical wiring induces critical problems such as electromagnetic interference, high power consumption, bandwidth limitations, high attenuation, and heat generation [1]. Graded index polymer optical fibers (GI POFs) are attracting a great deal of attention in premise networks, because the GI POF has high bandwidth, low bending loss, high flexibility, and a large core, which allows easy handling and rough connections, and thus enables easy installation of a high speed network at a low cost [2–7]. Several home gateways equipped with optical ports for POF and many media converters (*e.g.*, from UTP or High-Definition Multimedia Interface (HDMI) cable to POF) to be attached to traditional home gateways are already commercially available [8]. Do-it-yourself terminations and connections for the GI POFs without well-trained techniques are developed to install in already constructed buildings. The GI POFs provide no fear to stick into human skin, and to be broken by bending and physical impact, which is a great advantage for residential use. Therefore, the GI POFs can be used easily and safely for various cables such as LAN, HDMI, and TV with radio over fiber (RoF) in premise networks. The GI POF is expected to be used even in automotive or aircraft networks, because the GI POF, in principle, has no electromagnetic interference problems and because the GI POF is lighter in weight than a metal cable, which leads to higher energy efficiency [1,9]. Conventionally, a poly(methyl methacrylate) (PMMA) based GI POF has been used as a transmission medium, because PMMA has high mechanical strength and attenuation that is low enough for a short reach network at a wavelength of 650 nm, and because PMMA is one of the most popular and cost effective polymers. However, a shift in the emission wavelength of the light source because of a temperature change induces a significant increase in the attenuation of the PMMA based GI POF, because the PMMA based GI POF has a narrow low attenuation window at a wavelength of around 650 nm based on the carbon-hydrogen (C-H) vibrational absorption [10]. Therefore, the PMMA based GI POF may not guarantee an optical link long enough for even an intra-building network with long-term reliability. The C-H vibrational absorption can be decreased dramatically by substituting deuterium or fluorine for the hydrogen. Although perdeuterated and perfluorinated polymer based GI POFs exhibit quite low absorption loss from the visible region to the near infrared region [11], these polymers are relatively expensive for consumers or end-users. Also, such extremely low attenuation is not necessarily required for a short reach network.

We previously proposed and reported a copolymer of MMA and pentafluorophenyl methacrylate (PFPMMA) as a polymer matrix for a less expensive and low loss GI POF with a wide wavelength range centered around 650 nm [12]. On the other hand, the transmission loss stability is a significant issue for installation of GI POFs in a premise network.

In this paper, we investigate the attenuation stability of the MMA-*co*-PFPMMA based GI POF under damp heat conditions. This paper clarifies that the copolymer based GI POF can maintain low transmission loss at a wide wavelength range around 650 nm even under high-temperature and high-humidity atmospheric conditions, and confirms that the dopant characteristics are important factors in maintaining the low attenuation of the GI POF under damp heat conditions.

2. Fiber fabrication

The GI POF was obtained by heat drawing of a preform with a graded refractive index profile. The GI preform was fabricated by a rod-in-tube method. In the rod-in-tube method, a core rod including a dopant and a cladding tube are prepared separately. The core rod is inserted into the cladding tube, and heated at a temperature of 150°C for 24 h. During the heat treatment, the core rod and cladding tube adhere to each other, and the dopant diffuses into the cladding layer. The dopant has a higher refractive index than the polymer matrix. The distribution of the dopant concentration corresponds to the refractive index profile. Thus, the GI preform was obtained after this diffusion process. The mechanism of forming the GI profile (*i.e.*, heat diffusion of dopant) in the rod-in-tube method is similar to that of a coextrusion method that

is adopted in mass production of commercially available GI POFs [13]. Thus, this copolymer based GI POF could be fabricated by the coextrusion method for mass production. The MMA-*co*-PFPMA (65/35 mol%) composition used here in the feed was experimentally determined to achieve the highest glass transition temperature (T_g) [12]. Diphenyl sulfide (DPS) was selected as the high refractive index dopant. The dopant concentration was adjusted to provide a numerical aperture (NA) of 0.20.

3. Results and discussion

Figure 1 shows the attenuation spectrum of the fabricated MMA-*co*-PFPMA based GI POF, compared with that of the PMMA based GI POF. The measured attenuation of the MMA-*co*-PFPMA based GI POF is approximately 100 dB/km at a wavelength of 650 nm, and the transmission loss is less than 200 dB/km over a wider wavelength range of 630-690 nm. On the other hand, the PMMA based GI POF exhibits a transmission loss of less than 200 dB/km at a narrower wavelength range of 640-660 nm, although the attenuation at 650 nm is below 150 dB/km. This is because polyPFPMA has a smaller number of C-H bonds per unit volume than PMMA, which results in low C-H vibrational absorption, and because PMMA and polyPFPMA have almost the same refractive index, which indicates that the MMA-*co*-PFPMA induces low excess light scattering, even if the MMA-*co*-PFPMA includes microphase separation similar to general copolymers. Therefore, the MMA-*co*-PFPMA based GI POF is expected to be a suitably low loss transmission medium for premise networks, even if the emission wavelength from the light source is shifted by temperature changes.

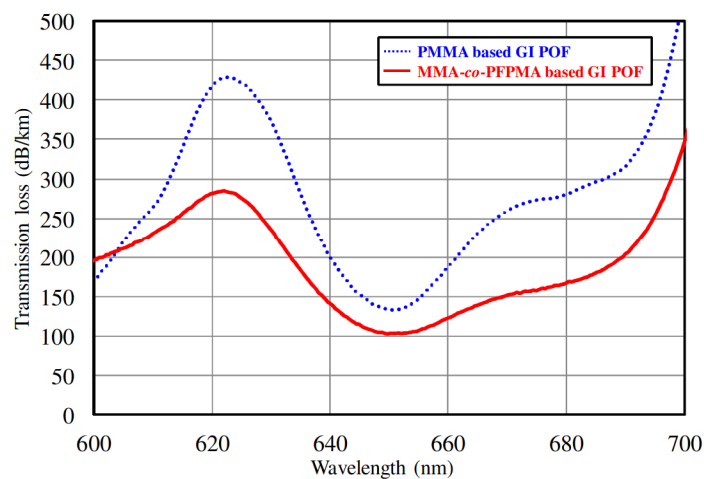


Fig. 1. Transmission loss spectra of PMMA and MMA-*co*-PFPMA based GI POFs.

The long-term stability of the GI POF is of great concern in practical applications for premise networks. We investigated the stability of the low loss characteristics in the MMA-*co*-PFPMA based GI POF. The International Electrotechnical Commission (IEC) defines two environmental test conditions for POF [14], and we adopted the more severe condition, which requires an attenuation increase of less than 5 dB/100 m under damp heat conditions of 75°C and 85% relative humidity (RH). We evaluated the attenuation stability by continuously measuring the output optical power from the GI POF as a function of time under the damp heat conditions. Figure 2 shows the measured attenuation increments of PMMA and MMA-*co*-PFPMA based GI POFs, compared with those of step index (SI) POFs. It was expected that since polyPFPMA was more hydrophobic than PMMA because of its fluorine content, MMA-*co*-PFPMA would absorb smaller amounts of water than PMMA, and therefore, the MMA-*co*-PFPMA based GI POF would have higher resistance to damp heat conditions than the PMMA based GI POF. However, the MMA-*co*-PFPMA based GI POF exhibited a much

larger loss increment, exceeding the IEC specification, than the PMMA based GI POF. Such a large loss increment is unacceptable in a link design. The difference in attenuation spectra before and after the damp heat test confirmed that the loss increment did not strongly depend on the wavelength in the range we concerned about. On the other hand, almost no loss increment was observed in both the PMMA and MMA-*co*-PFPMA based SI POFs without dopants. These results suggest that the polymer provides no inherent problems in both the PMMA and MMA-*co*-PFPMA cases, and that it is the addition of the dopant that leads to the loss increment.

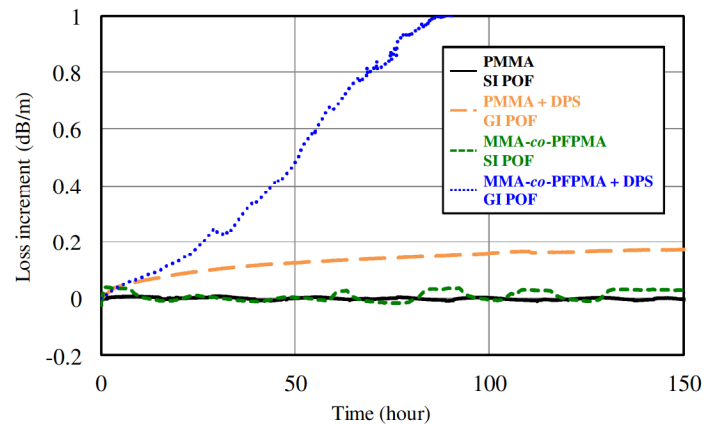


Fig. 2. Loss increment under damp heat conditions (75°C, 85% RH).

We performed a cause and correlation analysis of the loss increment under damp heat conditions. Figure 3 shows the water absorption of the core polymers in a water bath at a temperature of 75°C. The water absorption was determined by the difference between the sample weights before and after the damp heat test. It was experimentally confirmed that the MMA-*co*-PFPMA absorbed much smaller amounts of water than the PMMA, because PFPMA contains five fluorines, which show high hydrophobicity. The water absorption was reduced by the addition of DPS for both PMMA and MMA-*co*-PFPMA, which indicates that the DPS is more hydrophobic than both of the polymers. On the other hand, both the PMMA and MMA-*co*-PFPMA based GI POFs containing DPS exhibited large loss increments, despite the reduction in water absorption. In contrast, almost no loss increment was observed in both the PMMA and MMA-*co*-PFPMA based SI POFs without DPS doping, despite the greater degree of water absorption. The MMA-*co*-PFPMA with DPS doping absorbed the smallest amount of water; nonetheless, the MMA-*co*-PFPMA based GI POF doped with DPS exhibited the greatest loss increment. In contrast, although the PMMA absorbed the largest amount of water, the PMMA based SI POF showed almost no loss increment. These results suggest that the loss increment under the high-temperature and high-humidity conditions is not strongly affected by the absolute amount of water absorbed into the POF, especially at the wavelength of interest.

On the other hand, the PMMA based GI POF showed high attenuation stability under the high-temperature and high-humidity conditions by selection of an appropriate dopant with similar hydrophobicity to PMMA [15]. This is because, in the case of an inappropriate dopant, the absorbed water cannot be homogeneously dispersed in the polymer, and thus aggregates to form large heterogeneous structures, which induce excess light scattering and result in loss increments, even if the amount of water absorption becomes much smaller because of the dopant. We therefore selected 9-bromo phenanthrene (BPT) as the dopant to maintain the low loss of the MMA-*co*-PFPMA based GI POF under damp heat conditions, because the MMA-*co*-PFPMA doped with BPT has almost the same water absorption as the MMA-*co*-PFPMA

without the dopant, as shown in Fig. 3, which means that BPT has a hydrophobicity level close to that of MMA-co-PFPMA.

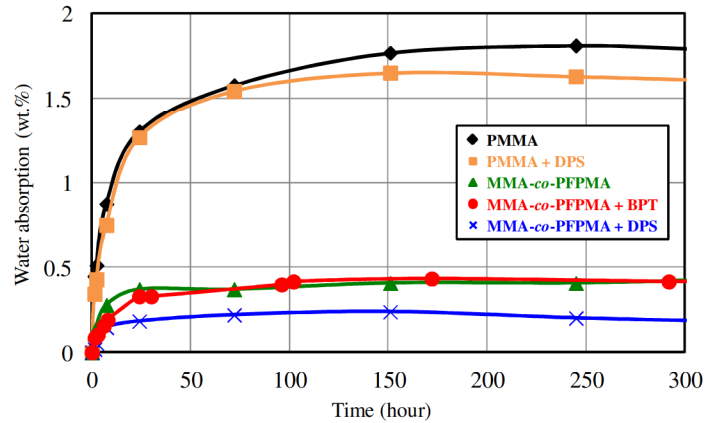


Fig. 3. Water absorption of bulk core polymers in water bath at 75°C.

Figure 4 shows the refractive index and T_g of MMA-co-PFPMA doped with BPT at various concentrations in comparison to those doped with DPS. Figure 4(a) clarifies that the concentration of BPT required to obtain a certain refractive index is lower than that for DPS, because BPT has a higher refractive index than DPS. This reduction in dopant concentration decreases the plasticization effect, and thus increases the T_g in the core region of the GI POF. Figure 4(b) reveals that BPT exhibits lower plasticization efficiency, corresponding to the absolute value of the slope, than DPS. Therefore, MMA-co-PFPMA doped with BPT exhibits a higher T_g value than that doped with DPS, even if the same doping concentration is used. In addition to similar hydrophobicity, BPT offers the valuable advantage of providing a higher T_g to the MMA-co-PFPMA based GI POF because of the two effects described above. The higher T_g would lead to higher thermal stability. Consequently, BPT is expected to be an excellent dopant and will provide the MMA-co-PFPMA based GI POF with high long-term stability.

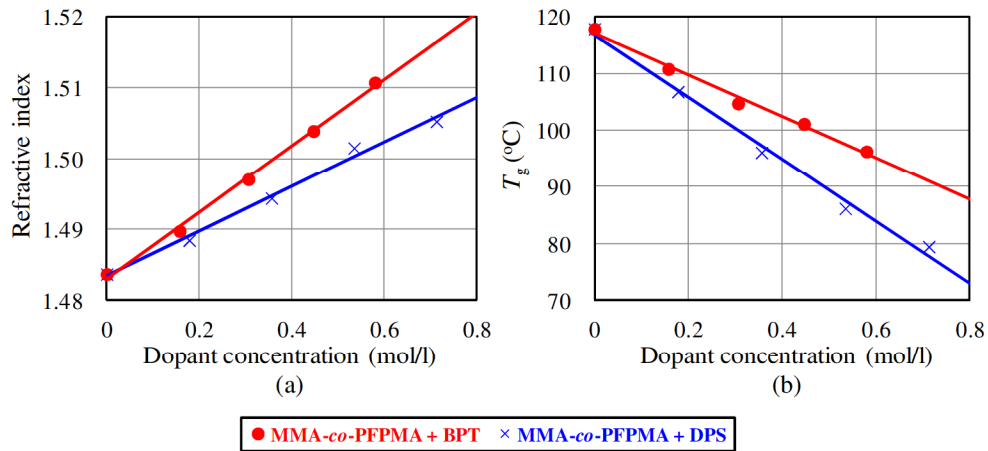


Fig. 4. (a) Refractive index and (b) T_g dependence on dopant concentration of MMA-co-PFPMA.

We fabricated the MMA-co-PFPMA based GI POF doped with BPT, and confirmed that its attenuation is comparable to that of the copolymer based GI POF doped with DPS.

Figure 5 shows the attenuation stabilities of the MMA-*co*-PFPMA based GI POFs doped with DPS and BPT under damp heat conditions. The attenuation stability of the MMA-*co*-PFPMA based GI POF is dramatically improved by adopting BPT as a dopant, compared to DPS. No loss increment is observed in the MMA-*co*-PFPMA based GI POF doped with BPT. The GI POF obtained is a promising candidate for inexpensive premise networking. We can also conclude that the loss increment mechanism under damp heat conditions explained in the PMMA based GI POF applies to the MMA-*co*-PFPMA based GI POF, and that the dopant hydrophobicity, similar to the polymer matrix, plays an important role in maintaining the low loss of the MMA-*co*-PFPMA based GI POF.

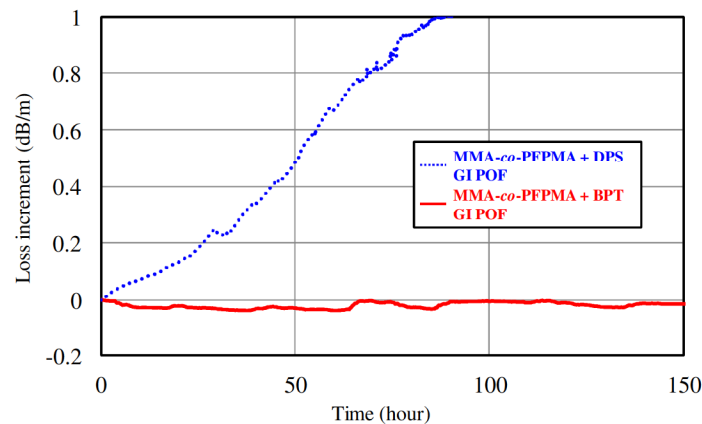


Fig. 5. Attenuation stability of MMA-*co*-PFPMA based GI POF doped with BPT under damp heat conditions (75°C, 85% RH).

4. Conclusions

We successfully obtained a BPT doped MMA-*co*-PFPMA based GI POF with low loss at a wide wavelength range around 650 nm, and with high stability under damp heat conditions of 75°C and 85% RH. The dopant selection is a significant issue in maintaining the attenuation under the damp heat conditions, because a change in hydrophobicity induces aggregation of the water absorbed into the GI POF, forming large heterogeneous structures, and leading to a loss increment because of excess light scattering. We demonstrated that the MMA-*co*-PFPMA based GI POF doped with BPT could be used to provide a premise network with long-term reliability.

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