Propagating Mode Analysis and Design of Waveguide Parameters of GI POF for Very Short-Reach Network Use

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***Abstract*—We investigated the way to reduce the mode coupling (the energy transfer among the propagating modes) in a multimode fiber. It strongly influences the bandwidth in the graded-index plastic optical fiber (GI POF), and it was found that the mode-coupling strength in the GI POF depended on the numerical aperture of the fiber. Moreover, we propose a new optimum waveguiding design of GI POFs when only small mode groups are launched [under filled launch condition (UFL)], which is expected in a real high-speed GI POF link. We demonstrate greater than 1-GHz transmission by a 250-m polymethylmethacrylate (PMMA-d8)-based GI POF under the UFL condition.**

***Index Terms*—Graded-index plastic optical fiber (GI POF), mode coupling, numerical aperture (NA), under filled launch condition (UFL).**

I. INTRODUCTION

A PLASTIC optical fiber (POF), having a much larger core than silica fibers, is expected to be the office- and home-network medium because its large core and great mechanical flexibility allow an easy network installation, which can dramatically decrease the total system cost. We have proposed a high-bandwidth graded-index (GI) POF and demonstrated the optimum refractive index profile theoretically and experimentally [1]–[4]. However, it is well known that the mode coupling (the energy transfer among the propagating modes in a multimode fiber) strongly influences the fiber bandwidth. In the step-index (SI)-type POF, large mode coupling was experimentally observed, while we already clarified that the mode-coupling effect on the bandwidth in the GI POF was smaller than that in the SI POF [5]. Regarding the origin of the mode coupling, several hypotheses such as the large scattering and/or perturbation of the waveguide properties have been proposed [5], [6]. However, those are only for silica-based multimode fibers (MMFs) and there are few proposals for the POF. In this letter, we verified that numerical aperture (NA) is a key factor in mode-coupling strength, and that to provide a high NA was a viable solution to reduce the mode coupling in the GI POF. In such a high NA GI POF with small mode coupling, the launch condition becomes an important issue for its bandwidth performance. Therefore, a new optimum waveguiding design of GI POFs when only small mode groups are launched [under filled launch condition (UFL)], which is expected in a real high-speed GI POF link, is newly proposed in this letter.

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II. PROPAGATING MODE ANALYSIS AND DESIGN OF WAVEGUIDING PARAMETERS OF GI POF

A. Fiber Preparation and Refractive Index Profile

The GI POF was obtained by the heat-drawing of a preform, in which the GI profile was already formed. A detailed fabrication method of the GI POF is described in [1], [2], and [4]. In this letter, we controlled the NA and index profile by changing the core polymerization condition.

The refractive index profile of the GI POF was approximated by the well-known power-law equation shown by

$$\begin{aligned} n(r) &= n_1 \left[1 - 2\Delta \left(\frac{r}{a}\right)^g\right]^{\frac{1}{2}}, \qquad 0 \le r \le a \\ &= n_2 \quad r \ge a \end{aligned} \tag{1}$$

where n_1 and n_2 are the refractive indexes of the core center and cladding, respectively, a is the core radius, and Δ is the relative index difference defined as

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

The parameter g, called the index exponent, determines the refractive index profile. We already showed that the optimum refractive index exponent ($g_{\rm opt}$) of the poly methylmethacrylate (PMMA)-based GI POF is approximated by 2.4 by taking the material dispersion into consideration for 650-nm wavelength use [4].

B. NA Dependence of Mode-Coupling Strength

To estimate the mode-coupling strength in the GI POF, we measured the launch condition dependence of the near-field pattern (NFP) from the GI POFs with different NA. These launch condition dependences were measured as follows: An optical signal from a laser diode (LD) at 650-nm wavelength was 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 scanning the position where the single-mode fiber was butted to the GI POF from the core center to the periphery, each mode from the low order to high order can be independently launched.

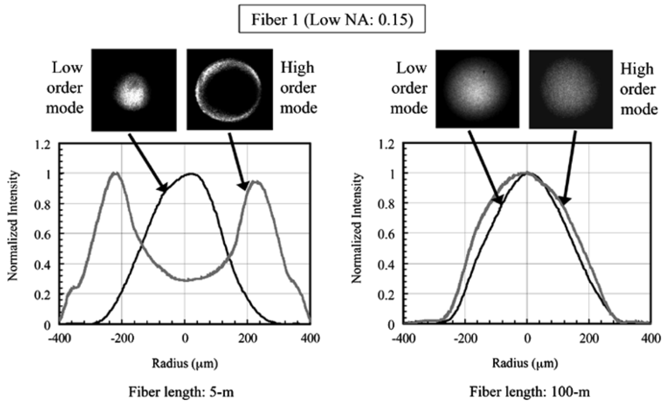

Fig. 1. Measured NFPs of each mode from 5- and 100-m Fiber 1 (NA $= 0.15$).

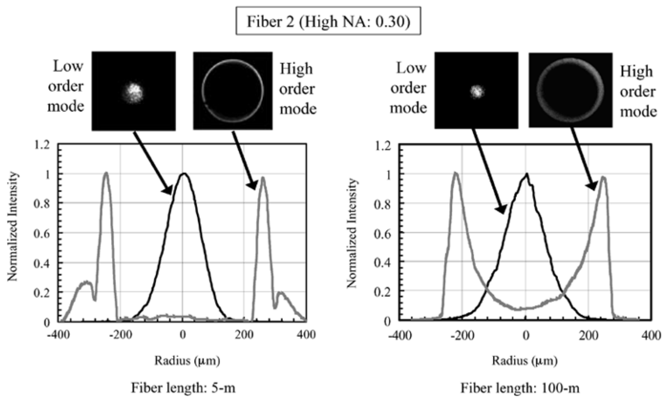

Fig. 2. Measured NFPs of each mode from 5- and 100-m Fiber 2 (NA $= 0.30$).

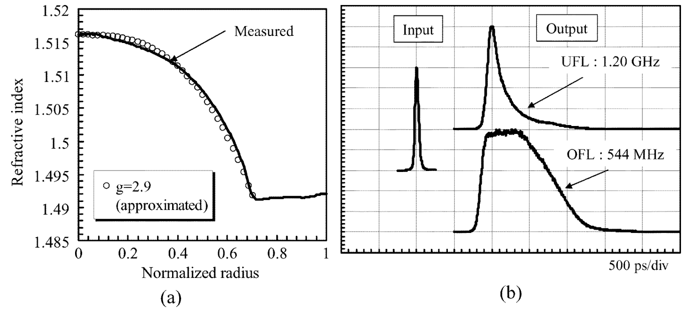

Fig. 3. Measured refractive index profile and output pulse waveforms from 100-m Fiber 3 (NA $= 0.27$) at 650-nm wavelength.

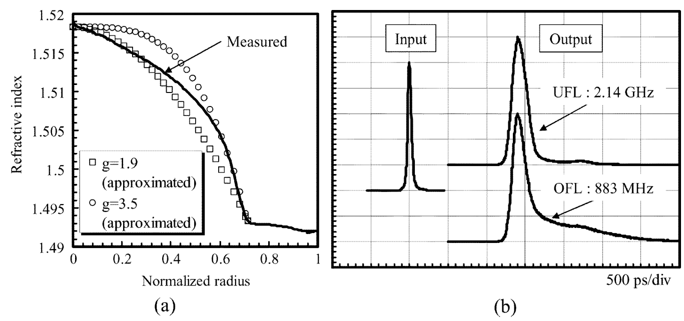

Fig. 4. Measured refractive index profile and output pulse waveforms from 100-m Fiber 4 (NA $= 0.28$) at 650-nm wavelength.

Then, the NFPs after very short distance (5-m) and 100-m transmissions were measured under two launch conditions mentioned above. Launch condition dependence of NFPs in low and high NA GI POFs are shown in Figs. 1 and 2. Both measured NFPs from 5 m, Fiber 1 (Fig. 1) and Fiber 2 (Fig. 2), show that each mode independently propagates and, particularly when only high order modes are launched by off-set launch, remarkable ring patterns are observed in both GI POFs. On the other hand, measured NFPs from 100 m show that each mode in the low NA (0.15) GI POF (Fiber 1) does not independently propagate, as shown in Fig. 1, despite the selectively launch condition with a small spot size and a few micrometers spatial off-set by the single-mode silica fiber, while each mode independently propagates in the high NA (0.30) GI POF (Fiber 2), as shown in Fig. 2. As a result, it was found that the NA was a key factor of mode-coupling strength; thus, the amount of mode coupling could be controlled by adjusting the NA of GI POFs.

C. New Optimum Waveguiding Design of GI POFs

We can reduce the mode coupling in the high NA GI POF mentioned above. However, the modal dispersion of the GI POF was also strongly influenced by NA. If the refractive index profile was slightly deviated from the optimum one, a significant output pulse distortion was observed in the case of high NA (0.25–0.3) GI POFs compared to that from low NA GI POFs with the same index exponent. Therefore, a completely optimum refractive index profile is required to obtain the high bandwidth high NA GI POF when all the modes are equally launched [over filled launch condition (OFL)]. On the other hand, for practical use in a high-speed optical link, an LD will be used as a light source. As the LD generally excites only small mode groups in the multimode fiber [7] because of its small radiation angle and radiating area, particularly in the GI POF with a much larger core diameter than the silica-based MMF, the modes excited by the small spot of a laser focused on the core center of the GI POF would be limited to only low order. Thus, the bandwidth performance should be investigated under the UFL condition. In this letter, as the UFL condition, a 6.48-μm spot size and 0.16-NA beam was focused on the input end of a GI POF. Even if the refractive index profile is not completely optimized, high bandwidth is expected under the UFL condition, when the mode-coupling effect is small enough.

At first, we investigated the bandwidth property of a PMMA-based GI POF having high NA (0.25–0.30) that will be used for the very short reach area (∼100 m). When the approximated index exponent g $(= 2.9)$ was larger than optimum $(g = 2.4)$ in whole core region as shown in Fig. 3(a) (Fiber 3), it was observed that the bandwidths under OFL and UFL conditions from the 100-m Fiber 3 were 544 MHz and 1.20 GHz, respectively, as shown in Fig. 3(b). It was found that the bandwidth was improved by adopting the UFL condition.

Next, the bandwidth performance of the GI POF whose index profile is not necessarily approximated by a single index exponent g is investigated by varying the launch conditions. A representative refractive index profile is shown in Fig. 4(a) (Fiber 4), where the profile only near the core center is approximated by a small g value (1.9) while a larger g value is required for fitting the index at the periphery region. This unique index profile was more easily obtained by the interfacial-gel polymerization process when the polymerization temperature was lower than 100 °C. It was noted that the bandwidths of the 100-m Fiber 4 under OFL and UFL conditions were 883 MHz and 2.14 GHz,

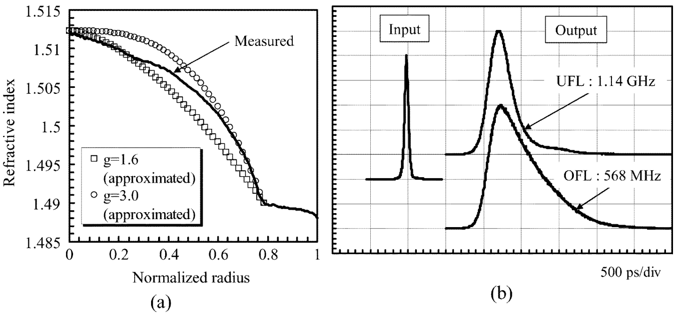

Fig. 5. Measured refractive index profile and output pulse waveforms from 250-m Fiber 5 ($\mathrm{NA} = 0.26$) at 650-nm wavelength.

respectively, as shown in Fig. 4(b). Although the bandwidth under the OFL condition was lower than 1 GHz since g (=3.5) at the periphery region was larger than optimum ($g = 2.4$), the bandwidth under the UFL condition was much higher than 1 GHz, and 2.5-times higher than that under the OFL condition. From the group delay analysis by a WKB numerical calculation [4], it was clarified that the combined profile with the index exponents lower and higher than optimum for the core center and periphery, respectively, was more effective for high bandwidth performance under the UFL condition than other profiles except for completely ideal one as demonstrated. Moreover, for the profile near the core center, the g value smaller than 2.4 (optimum) was much more effective for high-bandwidth under UFL even than optimum ($g = 2.4$) profile. These results were also confirmed theoretically, and they will be presented in another journal. Therefore, it was found that the GI POF exhibited sufficiently high bandwidth under the UFL condition, if the index exponent of only the core center region was controlled to have a small index exponent.

In this case, the mode coupling is a great concern. Even if lower order modes were launched under the UFL condition, the optical power gradually spreads to the high order modes due to the mode coupling after a certain propagation distance. Thus, the bandwidth performance would degrade and become close to that observed under the OFL condition. In order to clarify the mode-coupling effect mentioned above, the bandwidth performance of the GI POF with the distance longer than that (100 m) ever adopted for bandwidth evaluation should be investigated. Therefore, usage of a low-loss deuterated PMMA (PMMA-d8)-based GI POF is proposed. As the basic chemical properties such as polymerization reactivity of the deuterated monomer is almost the same as that of the hydrogenated one, we could apply the same interfacial-gel polymerization process to the deuterated MMA. We fabricated the PMMA-d8-based GI POF having the refractive index profile similar to that of Fig. 4(a), as shown in Fig. 5(a) (Fiber 5). The measured bandwidths under OFL and UFL condition from a 250-m PMMA-d8-based GI POF were 568 MHz and 1.14 GHz, respectively, as shown in Fig. 5(b). It was verified that the high bandwidth under UFL condition was still maintained even after 2.5-times longer distance transmission. Moreover, it was confirmed that the mode-coupling effect on the bandwidth performance of the GI POF under the UFL condition was still small even after 250-m transmission. As the bandwidth of the PMMA-d8-based GI POF with a completely optimum index profile theoretically estimated for 250-m transmission under the OFL condition is only 1.2 GHz, the observed bandwidth (1.14 GHz) is high enough. It was also confirmed that high-bandwidth property of the GI POF having a new index profile proposed above could be maintained even if misalignment of the UFL condition and/or fiber bending assumed in the very short-reach network use exit. This result will be published in another journal.

III. Conclusion

In this letter, we have verified that NA is a key factor of mode-coupling strength; consequently the amount of mode coupling can be controlled by adjusting the NA of GI POFs. Furthermore, we demonstrated higher than 1-GHz transmission with a 250-m PMMA-d8-based GI POF under the UFL condition using a new index profile design. It was also confirmed that the mode-coupling effect on the bandwidth performance of the GI POF under the UFL condition was small even after 250-m transmission.

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