High-Bandwidth Plastic Optical Fiber With W-Refractive Index Profile

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***Abstract*—A plastic optical fiber having a W-shaped refractive index profile [W-shaped plastic optical fiber (POF)] was prepared for the first time to realize a higher bit rate transmission than those of the conventional silica-based multimode fiber and graded-index (GI) POF links. Since the W-shaped POF has a valley of the refractive index at the boundary of the core and cladding of the conventional GI POF, the group delay of higher order modes is strongly influenced, thus compensating the modal dispersion that exists in the GI POF. The modal dispersion compensation effect by the W-shaped index profile was theoretically and experimentally confirmed.**

***Index Terms*—Differential mode attenuation, modal dispersion, mode coupling, plastic optical fiber (POF), W-shaped index profile.**

I. Introduction

The ENORMOUS growth of Internet traffic in the past several years has led to an increasing demand for data transmission capacity even in local area networks (LANs) and home networks. The data rate of the Ethernet (the most major LAN interface worldwide) will be upgraded to 1 Gb/s and for backbone networks; the 10-Gb Ethernet should be introduced. As a physical layer of gigabit and 10-Gb Ethernet, a silica-based multimode fiber (MMF) is proposed and standardized [1], because it can provide such a high-speed network with a lower cost than by single mode silica fibers.

On the other hand, 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 [2]–[4]. In this letter, a unique refractive index profile that includes an index valley at the core–cladding boundary (W-shaped) is proposed for the first time to maximize its modal bandwidth. The W-shaped index profile is widely utilized in a silica-based single-mode dispersion-shifted fiber. The W-shaped index profile in silica-based MMF was proposed by Okoshi and Okamoto [5] about 30 years ago to decrease the modal dispersion in GI fibers. They showed theoretically that the index valley in the W-shaped index profile enabled a lower modal dispersion than that of a GI fiber with an ideal index profile. However, there are few reports on the experimental verification of the advantage in a W-shaped MMF. In this letter, the advantage of the W-shaped profile in the bandwidth was confirmed both theoretically and experimentally in a large core POF that supported a huge number of modes.

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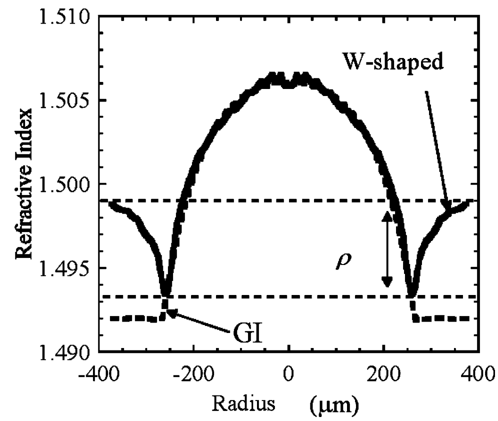

Fig. 1. Measured refractive index profile of the W-shaped and GI POFs. Solid line: W-shaped POF. Broken line: GI POF.

II. Bandwidth of W-Shaped POF

A. Fiber Preparation

The W-shaped POF was obtained by the heat-drawing of a preform, in which the W-shaped index profile was already formed. The fiber diameter was 0.75 mm. At first, a copolymer tube of methyl methacrylate (MMA) and benzyl methacrylate (BzMA) (= 9 : 1 by weight) was prepared from the purified monomers. After polymerizing the P(MMA-BzMA) tube, a specified amount of MMA monomer was injected into the tube, and the tube was rotated on its axis at 3000 r/min in an oven at 70 °C. After the polymerization, the tube having the index valley was obtained, because the refractive index ($n_d = 1.498$) of P(MMA-BzMA) copolymer is slightly higher than that ($n_d = 1.492$) of PMMA layer. Subsequently, the tube was filled with the MMA monomer–dopant mixture to form the quadratic refractive index profile. The mechanism for generating the quadratic refractive index profile in the core is described in [3] and [6].

B. Refractive Index Profile

It is well known that the modal dispersion of an MMF is lowered by a quadratic refractive index profile. We reported that the refractive index profile of the GI POF could be widely controlled by the interfacial–gel polymerization process [3]. Fig. 1 shows the experimentally measured refractive index profile of the W-shaped POF (solid line) compared with the conventional

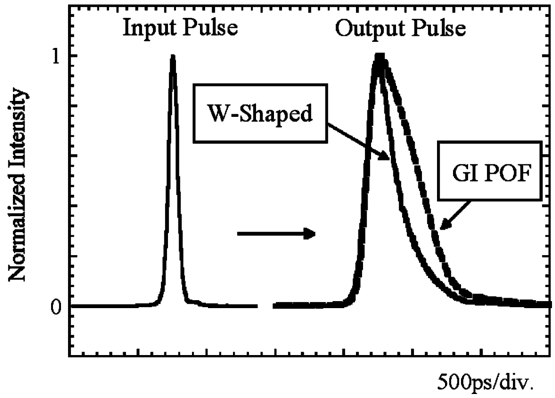

Fig. 2. Output pulse broadening from 100-m PMMA-based W-shaped and GI POFs at 0.65-μm wavelength. Solid line: W-shaped POF. Broken line: GI POF.

GI POF (broken line). To quantitatively analyze the bandwidth of the two POFs, the refractive index profile was approximated by the power-law equation shown by

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

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

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \qquad (2)$$

The parameter g, called the index exponent, determines the refractive index profile. The new parameter ρ in (1) signifies the depth of the index valley, as shown in Fig. 1. When ρ equals one, the profile is the same as the conventional quadratic refractive index profile followed by the uniform index cladding, while the W-shaped index profile has the parameter ρ that is larger than one.

The refractive index profiles of both W-shaped and GI POFs agree in the core region (except for the index valley), with $g = 2.9$. In the W-shaped POF, the approximated ρ value was 1.7. Therefore, we can confirm the effect of the index valley on the bandwidth by comparing their experimental results.

C. Comparison of Bandwidths

The measured results of the bandwidths of the two POFs at 0.65-μm wavelength are shown in Fig. 2. The bandwidth property of the MMF is strongly dependent of the launch condition. In current silica-based MMF links, restricted launch condition becomes important to obtain high bandwidth. Although it could be applied to the large diameter POF, the mode coupling is a great concern. Although the mode coupling was weak in the PMMA-based GI POF within 100-m distance [7], it was reported that a strong mode coupling existed in a low-loss perfluorinated GI POF [4], [8] whose link length could be longer than that of PMMA-based POF. In this case, high-order mode would be generated by the mode coupling. In order to verify the low modal dispersion even in such a case, the bandwidth measurement in this letter was performed by the over filled launch condition as described in [7]. The output pulsewidth from the W-shaped POF is narrower than that from the GI POF, despite the same index profile in the quadratic part of the core region, as shown in Fig. 1. The estimated -3-dB bandwidth of the W-shaped POF from the results was 1.5 GHz for 100-m that is approximately 1.5 times higher than that (1.1 GHz for 100-m) of the GI POF. Several factors such as mode coupling and/or differential mode attenuation have been considered [7], [8] to be the origins of such kind of unexpected bandwidth increase in the POFs. However, in the W-shaped POF, the modal dispersion itself is expected to be decreased by the index valley [5]. In order to clarify the effect of the index valley on the modal dispersion, the differential mode delays (DMDs) of these two POFs were analyzed [7].

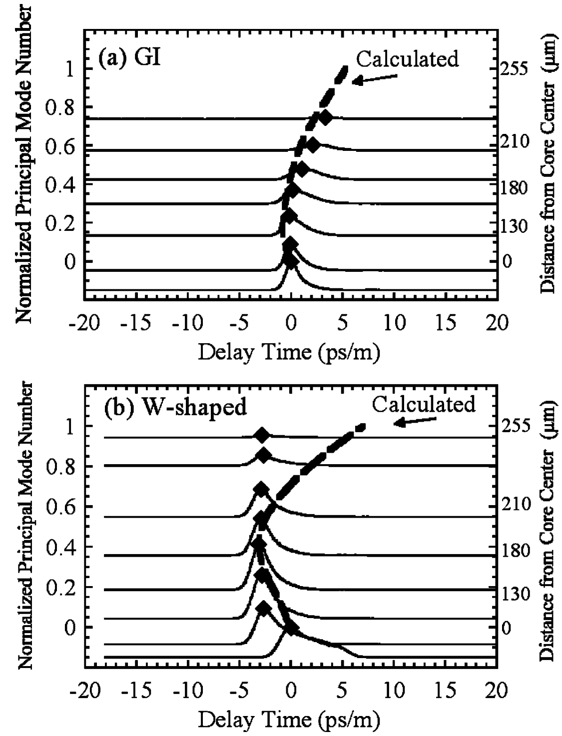

Fig. 3. Measured DMD after 100-m transmission through W-shaped and GI POFs at 0.65-μm wavelength. Broken line: calculated DMD.

The results are shown in Fig. 3(a) and (b). Since both index profiles $(g = 2.9)$ deviate slightly from the optimum $(g = 2.4)$ for PMMA-based GI POF at 0.65-μm wavelength use [3], the delay time difference of each mode is clearly observed. Therefore, the effect of the valley on the group delay could be easily analyzed. In the case of the conventional GI POF, each mode independently propagated having its own delay time, and the high-order mode showed a late arrival compared to the low order mode (under compensation), as shown in Fig. 3(a). In Fig. 3, the normalized principal mode number was related to the core radius, as described in [7]. This launch condition dependence in the DMD indicates that there is a small mode coupling in the GI POF [7]. The DMD was theoretically calculated by the Wentzel–Kramers–Brillouin method [7] from the measured index profile shown in Fig. 1, and the results are plotted in Fig. 3(a) by a broken line. A good agreement is observed between the calculated DMD curve and the measured values shown by the peak position in each pulse (⧫). Therefore, the large DMD observed in Fig. 3(a) is essentially caused by the modal dispersion of the GI POF.

On the other hand, in the W-shaped POF, each mode also propagated having its own group delay, which means a small mode coupling in the W-shaped POF as well. The group delay difference between the highest and lowest order modes is much smaller than that in the GI POF. This delay time contraction is caused not by the mode coupling but by the modal dispersion compensation effect of the refractive index valley.

The effect of the differential mode attenuation must be investigated, because it can virtually decrease the output pulsewidth [7]. It is noted that the DMD pulse of higher order modes whose normalized principal mode number is larger than 0.9 could be detected in the W-shaped POF, as shown in Fig. 3(b), because it maintains sufficient optical power after 100-m transmission. On the contrary, the power of higher order modes (normalized principal mode number > 0.8) in the GI POF is attenuated. From these results, it was found that the GI POF had high attenuation in the high-order modes compared to that in the W-shaped POF, and the differential mode attenuation exhibited less effect on the bandwidth of the W-shaped POF than on the bandwidth of the GI POF.

The calculated DMD is also plotted in Fig. 3(b) by a broken line for the W-shaped POF. In the DMD calculation for the W-shaped POF, the index valley was neglected, while only the quadratic part of the index profile was taken into account. Therefore, the core region was regarded from the core center to the point that had the lowest refractive index. Calculated DMD of W-shaped POF is slightly different from that of the GI POF. This difference is caused by slightly different index profile even in the quadratic part. Furthermore, a large disagreement between the calculated and measured DMD is observed, particularly in the high-order modes. Since the higher order modes carry more energy in their evanescent field than those in the lower order modes, the group delay of the high-order modes is considered to be strongly influenced by the index profile at the core–cladding boundary. It was confirmed that the group delay improvement in the high-order modes in the W-shaped POF was due to the effect of the index valley.

III. Conclusion

Modal dispersion compensation in a POF by a W-shaped refractive index profile was demonstrated for the first time. It was theoretically and experimentally confirmed that the higher order modes in the W-shaped POF were strongly influenced by the refractive index valley at the core–cladding boundary. The index valley in the W-shaped POF plays an important role in increasing the modal bandwidth.

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