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Intermodal group velocity dispersion of few-mode fiber

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Abstract: The intermodal dispersion of few-mode fiber limits the propagation distance of mode division multiplexing (MDM). We numerically investigate the propagation constant and group velocity of few-mode fibers. The refractive index profile of few-mode fibers should be designed to achieve long and dense MDM transmissions with digital coherent receivers.

Keywords: few-mode fiber, intermodal dispersion, index profiles

Classification: Optical fiber

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1 Introduction

Mode division multiplexing (MDM) is theoretically and experimentally studied to increase the transmission capacity of optical fiber transmission systems [1, 2, 3]. When there is a large difference between the propagation constants of two modes, the coupling between the two modes is weak and each mode is treated as an independent transmission line. If all the modes used for the transmission can be separated in some way, the transmission capacity is multiplied by the number of modes. The space distributions of the fiber modes overlap each other making it difficult to decompose each mode of a multimode transmission in terms of the spatial power distribution. The development of a digital coherent optical transmission system incorporating the MIMO technique [4, 5] is a promising way of decomposing every mode.

Mode separation using the MIMO technique requires massive computation especially when the group delay difference (δT) is large. Frequency domain equalization (FDE) is proposed to reduce the computational complexity involved in compensating for the large dispersion. The chromatic dispersion of a 12.5 Gbaud signal of more than $\pm$70,000 ps/nm, which corresponds to a $\pm$7 ns group delay difference, was compensated for by the digital signal processor (DSP) of 512 taps using FDE [6]. Assuming that DSP can compensate for a $\pm$10 ns delay and if our goal is a 40 km transmission, the δT should be smaller than $\pm$0.25 ns/km.

The group delay difference of step-index multi-mode fiber (SI MMF) increases with the relative index difference (Δ) [7]. Assuming an MMF of $\Delta = 0.5\%$ and $a = 25\,\mu$m, δT becomes as much as 21 ns/km. The figures in reference [7] also indicate that δT among some selected modes can be small if we select an appropriate v-value. Graded index (GI) fiber is also a well-known way of reducing intermodal dispersion in multimode fiber to less than that in SI fiber [8]. We numerically studied the fiber modes of few-mode fiber (FMF) of SI profile and a parabolic index profile, and discovered the possibility of realizing FMF with a δT smaller than $\pm$0.25 ns/km.

2 Numerical Method

We calculate the effective indices (n_{eff}) and group velocities (v_g) of the fiber by using the MIT Photonic Bands [9]. The group delay was obtained from the v_g. Figure 1 shows the n_{eff} (open circles) and v_g (closed circles) of FMF, where the index profile was a step index profile, $a = 14\,\mu$m and $\Delta = 0.3\%$. Each point represents a fiber mode, and the points are sorted in descending order by the n_{eff} of the mode. Four groups of similar n_{eff} and one group of continuous n_{eff} can be seen in the figure. The four groups correspond to the fiber modes of the LP_{01}, LP_{11}, LP_{21}, and LP_{02} modes and the last group corresponds to cladding modes, as indicated in the figure. Modes belonging to the same group degenerate. Here we put aside the degeneracy, and we can say that this FMF has four propagation modes. Of these modes, it is natural to measure δT relative to the LP_{01} mode as the LP_{01} mode will be commonly used in MDM transmissions.

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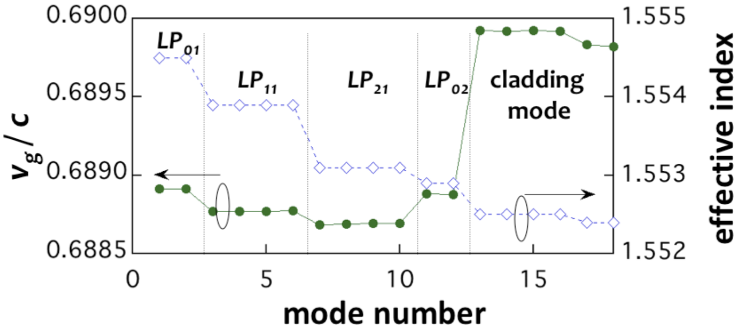

Fig. 1. Group velocities and effective indices of each fiber mode of step-index few mode fiber, where $a = 14\,\mu$m and $\Delta = 0.3$

3 Modal dispersion of FMF

The group velocity of each mode of an FMF is not a monotonous function of the mode number as shown by the closed circles in Fig. 1. Thus the δT between two FMF modes can be much smaller than the δT estimated for MMF. Figure 2 shows the δT of the LP_{11} (circles), LP_{21} (triangles), and LP_{02} (squares) modes relative to the LP_{01} mode for various core radii. The left figure (Fig. 2 a) shows the δT of SI-FMF, and the right figure (Fig. 2 b) shows that of GI-FMF. The solid, dashed, and dotted lines indicate fiber where $\Delta = 0.3\%$, 0.45%, and 0.6%, respectively. A δT of less than ± 0.25 nm/km is indicated by the shaded area. For an SI-FMF of $\Delta = 0.3\%$, δT can be smaller than ± 0.25 ns/km by using a core radius of around 9.5, 12 and 14 μm for the LP_{11}, LP_{21}, and LP_{02} modes, respectively, as shown in Fig. 2 (a). Note that for a Δ of 0.6% and even higher, the δT between LP_{01} and any of

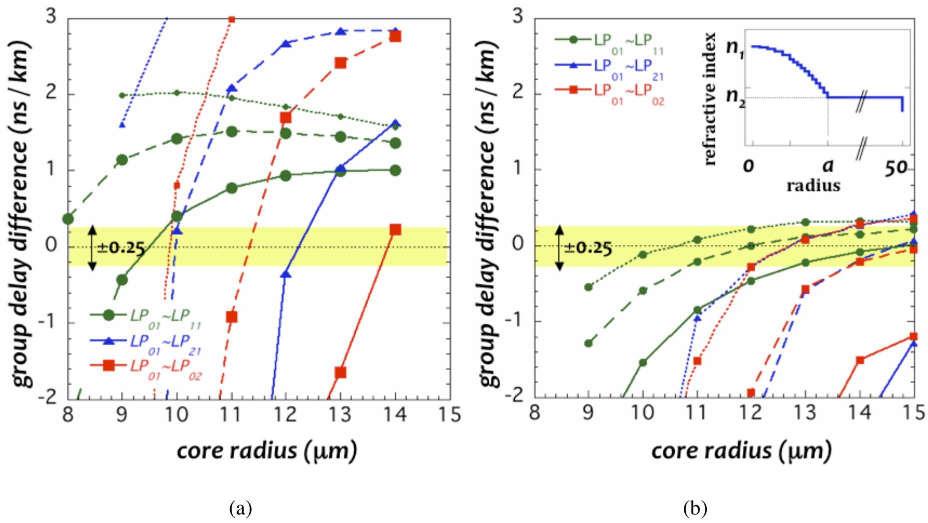

Fig. 2. Group delay difference between LP_{01} mode and other modes for various core radii. The index profile is a step-index profile. Solid, dashed and dotted lines indicate fiber with $\Delta = 0.3$, 0.45 and 0.6%, respectively. (a) Step-index profile, (b) Parabolic index profile

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these modes can be smaller than ±0.25 ns/km if we set an appropriate core radius. Appropriate Δ and a selection successfully reduces the intermodal dispersion between two arbitrarily selected modes even when the SI profile is used, but it is hard to reduce the intermodal dispersion for three or more modes simultaneously. At $\Delta = 0.3\%$ and $a = 14\,\mu$m, the δT of the LP_{02} mode was 0.2 ns/km but it was 1 and 1.6 ns/km for the LP_{11} and LP_{21} modes, respectively.

Figure 2 (b) shows results for the same calculations as in Fig. 2 (a) except that we assumed a parabolic GI profile. In the calculation, the core region was divided into 15 ring segments to emulate a parabolic index profile as shown in the inset of the figure. δT at a large core size was significantly reduced compared with that in Fig. 2 (a). Consequently, the δT distribution for each mode was also reduced. At $\Delta = 0.45\%$ and $a > 14\,\mu$m all the δT values for the LP_{11} through LP_{02} modes became smaller than ±0.25 ns/km.

Figure 3 shows the maximum group delay difference among these four LP modes of GI-FMF for various Δ and a values. A δT of less than ±0.25 nm/km for all of the four modes was possible at around $\Delta = 0.8\%$, $a = 11\,\mu$m through $\Delta = 0.4\%$, $a = 16\,\mu$m. A further reduction in δT may be possible by adjusting the index profile. The parabolic index profile used this calculation is the ideal profile for an MMF with an infinite core radius but we have not proved whether it is ideal for a finite core radius.

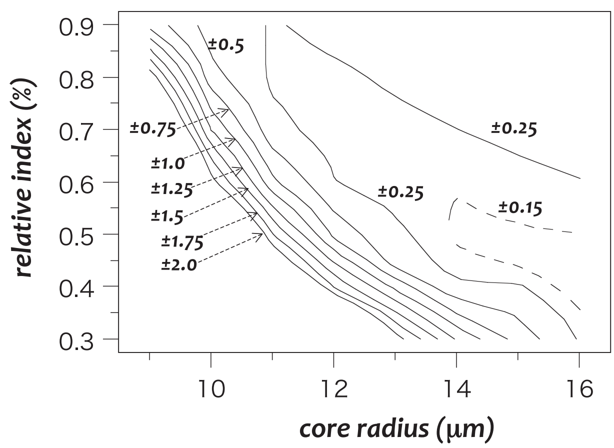

Fig. 3. Maximum group delay difference in ns/km among first four LP modes for various Δ and a values

4 FMF propagation constants

Mode conversion to an unused mode induces transmission loss in a long distance transmission. To avoid such conversion, a large propagation constant (or effective index) difference between the used and unused modes should be maintained.

Under a weakly guided approximation, the propagation constant of parabolic index GI fiber is a linear function of the principal mode number m. m is defined as $m = 2\mu + \nu + 1$ for the $LP_{\nu(\mu+1)}$ mode [10]. Propagation modes

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with the same m value have similar propagation constants, and those with different m values have very different propagation constants. The LP_{31} mode has an m of 4, while the LP_{02} and LP_{21} modes belong to a group where $m = 3$. So the difference between the propagation constants of the LP_{02} and LP_{31} modes is naturally large. This provides a simple guideline for discriminating propagation modes by the m value in mode division multiplexing.

Using the LP_{02} mode with the LP_{01} mode in FMF appears to be a good alternative for MDM. As with the LP_{01} mode, the LP_{02} mode has two-fold degeneracy. A polarization beam splitter can separate two polarization modes even though their propagation constants degenerate. This property is useful for incorporating mode division multiplexing with polarization mode multiplexing to increase transmission capacity. With this application, we must be aware of the transmission loss caused by mode conversion from the LP_{02} to LP_{21} mode because the effective index difference between the LP_{02} and LP_{21} modes tends to be small as described above.

5 Conclusion

We numerically investigated the effective index and group velocity of few-mode fibers with a step index profile and a parabolic index profile. Step-index fiber is applicable for up to two-mode mode-division multiplexing transmissions. A parabolic index profile can reduce the intermodal dispersion of few-mode fiber and can be used for “dense” mode-division multiplexing transmission with digital coherent receivers.

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