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Invited Papers

Few-mode optical fiber for mode-division multiplexing

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ABSTRACT

This paper describes the group delay difference and mode coupling of few-mode fiber for "uncoupled" mode division multiplexing. Optical mode separation is compatible with few-mode fiber. It has complementary characteristics with the MIMO technique.

1. Introduction

Long-haul optical communication systems have long been based on single-mode fibers (SMFs) to eliminate the bandwidth limitation imposed by the intermodal dispersion of multi-mode fibers (MMFs). The state of the art transmission capacity of SMF has now exceeded 69 Tbit/s [1] and this fully utilizes the fiber bandwidth of 10 THz with a high spectral efficiency modulation format. The degradation in OSNR tolerance caused by the multilevel modulation and transmitted optical power in the SMF will become an obstacle to further increases in transmission capacity. Recently, space division multiplexing has been studied to overcome the above limit.

Two kinds of space division multiplexing techniques are being investigated in relation to optical fiber communication systems. One is multi core fiber [2,3] where a fiber consists of a number of single mode cores, and each core acts as different channel and carries a different signal. The other is mode division multiplexing using MMF [4,5] where each fiber mode acts as a different channel. Both techniques have "coupled" and "uncoupled" regimes.

In coupled transmission, transmitted multiple data signals can be mixed during propagation and a mathematical procedure should be incorporated to separate the signals. Most high bit rate channel long-haul transmission experiments incorporate polarization multiplexing in single mode fiber [6]. The polarization multiplexing is considered as polarization based optical 2×2 multiple-input multiple-output (MIMO) system.

In principle, it is possible to recover tens of data channels transmitted over a single fiber with crosstalk, but this requires complex signal processing. The crosstalk results from non-orthogonal coupling at the transmitter end, receiver end, and connectors. It is also induced by mode mixing through propagation.

When an uplink and a downlink take the same path, channel characteristics can be estimated at both the transmitter and receiver ends. In this case, signals can be ideally orthogonalized by processing the signal at both ends. Optical communication systems use different fibers or different wavelengths for the uplink and downlink. The signals should be orthogonalized by post-detection signal processing only at the receiver end.

Another advantage of the optical MIMO techniques is that the coupler requirements are relaxed, which means there is no longer a need for selective orthogonal coupling to or from individual modes. The subsets of modes launched by different optical sources need not be disjoint nor do the subsets of modes collected in each of the multiple detectors.

However, in uncoupled transmission, the multiplicity is physically restricted to ensure that no coupling occurs. The coupling may occur not only at transmission fibers but also at couplers and connectors. In spite of these limitations, the uncoupled system has an advantage in that a conventional transmission scheme, without signal processing, can be applied in each channel. This is because multiplexed signals can be physically separated when the mixing crosstalk is sufficiently small.

Few-mode fibers (FMFs) and the few-mode operation of MMFs have been investigated for more than twenty years for fiber sensor applications. These approaches use the path difference between the two propagating modes induced by stress or temperature [7,8]. In these applications, the transmission distances are less than 1 km.

The single mode-like transmission of FMFs is being investigated to reduce the nonlinear penalty by employing a large mode area [9,10]. It has been reported that fewer than 10 modes can survive in 50 μm core MMF after a 10 km transmission. Other modes couple to dissipative cladding modes and become transmission loss. In

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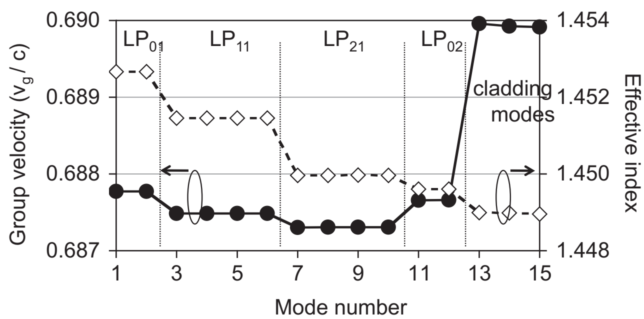

Fig. 1. Group velocity (filled circles) and effective index (open diamonds) of step index MMF where relative index Δ = 0.3% and core radius a = 10 μm.

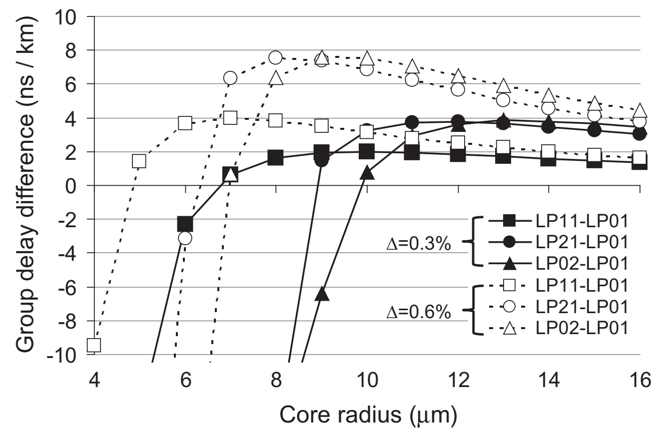

Fig. 2. Group delay difference of the LP_{11} (squares), LP_{21} (circles), and LP_{02} (triangles) modes relative to the LP_{01} mode of SI-MMF for various core radii. The relative index Δ = 0.3% (solid line) and 0.6% (dashed line).

an "uncoupled" MDM system, the transmission distance is limited by the highest fiber loss among the transmitted modes. It is important to minimize the mode dependent loss if we are to realize long-haul MDM transmission. In Ref. [8], a fiber was used with enhanced mode dependent loss, called MDL. This suggests that it may possible to reduce mode dependent loss by adopting an appropriate fiber design. The measurement of mode dependent loss may be possible using mode decomposition such as S^2 imaging [11,12]. However, we will not discuss fiber loss further here.

This paper focuses on the group delay difference, or differential mode delay (DMD), and mode coupling of FMF for "uncoupled" mode division multiplexing.

2. Modal dispersion

The group velocity of each mode of an FMF is not a monotonous function of the mode number. Fig. 1 shows the group velocity and effective index of each mode of step index MMF where Δ = 0.3% and the core radius a = 10 μm. The calculations were performed using MIT Photonic-Bands [18]. The normalized frequency v of the fiber at a wavelength of 1.55 μm is 4.53, which indicates this fiber supports four LP modes [13]. The effective index (open diamonds) decreases monotonously as the mode number increases but the group velocity shown by the filled circles is not a monotonous function of the mode number. Thus the group velocity difference (ΔT) between some FMF modes can be much smaller than that geometrically estimated for MMF.

Fig. 4 in [13] indicates that the group delay of two arbitrarily selected modes can be the same if we select an appropriate v-value. Here, we rewrite the figure in terms of ΔT as a function of core radius and index difference. Fig. 2 shows the ΔT of the LP_{11} (squares), LP_{21} (circles), and LP_{02} (triangles) modes relative to the LP_{01} mode for various core radii. The index profile is a step index profile, and the solid and dashed lines indicate fiber where relative index (Δ) is 0.3%, and 0.6%, respectively. All the six lines cross $\Delta T = 0$, which means that the mode has the same group delay as the LP_{01} mode. The point at which two lines with the same Δ cross indicates that the two modes have the same group delay. If the crossing point is near $\Delta T = 0$, three modes including the LP_{01} mode have the same group delay at that point. But there is no such point in the figure. Precise control of Δ and a, in other words the v value, 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.

Fig. 3 shows the maximum group delay difference among (a) the first three LP modes of SI-FMF and (b) the first four LP modes of GI-FMF for various Δ and a values. In the lower left part of the figures, the fibers have fewer modes than investigated here. For SI fiber, a substantially large delay remains only among three modes. In both figures, there is a tendency for the delay difference to decrease as Δ decreases. Such very low Δ fiber has a large bending loss so that a very low Δ is not a realistic parameter. In GI-FMF, a delay of less than ±0.25 nm/km for all of the four modes was possible at around Δ = 0.4%, a = 11 μm through Δ = 0.2%, a = 16 μm. 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.

Chromatic dispersion and polarization mode dispersion were successfully compensated for by signal processing, whereas DMD will be hard to compensate for in this way. The DMD of FMFs with an SI profile and a GI profile is a few orders of magnitudes larger than that induced by PMD. In "coupled" MDM, some DMD compensation may be required [14]. In "uncoupled" MDM, the DMD does not degrade the transmission characteristics. In addition, walk-off caused by DMD reduces the nonlinear penalty [15]. The

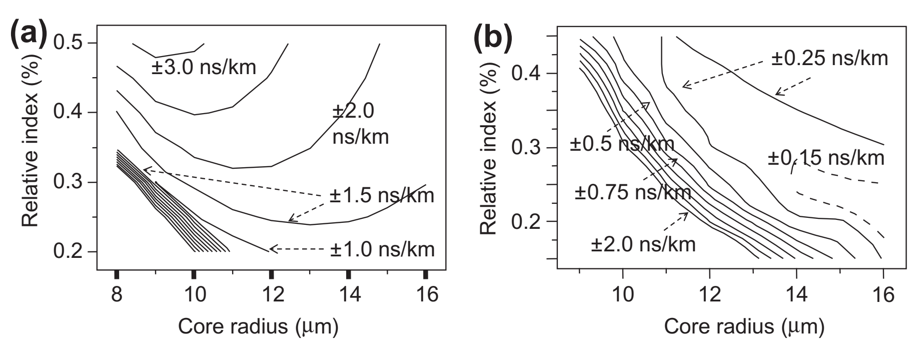

Fig. 3. Maximum group delay difference among (a) first three LP modes of SI-FMF and (b) first four LP modes of GI-FMF for various Δ and a values.