Distributed Measurement of Mode Dispersion of SDM Fibers

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Abstract: Nondestructive methods for measuring the mode dispersion distribution of SDM fiber that utilize Rayleigh backscattering observed with coherent optical frequency-domain reflectometry are reviewed. Experiments on few-mode and coupled multicore fibers are presented.
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1. Introduction

Space division multiplexing (SDM) technologies using few-mode fibers (FMFs) or uncoupled/coupled multicore fibers (MCFs) are attracting considerable attention with a view to leaping over the capacity limit of single-mode fiber (SMF). To realize the capacity improvement offered by SDM, we must counter the transmission performance impairment created by the mode dispersion, which causes a difference in detection timing or an increase in the complexity of signal processing [1,2]. Mode dispersion can be expected to fluctuate along the transmission line due to fiber macro-/micro-bending, twisting, or splicing conditions along the SDM fibers caused by cabling or cable installation [3-6]. If the mode dispersion could be measured at arbitrary fiber positions nondestructively, it would provide a powerful tool for characterizing SDM fibers in many scenarios such as identifying which portions of transmission line are determining the end-to-end characteristic, which is essential for system design.

Recently, we have proposed several methods for realizing distributed measurement of the distribution of differential mode delay (DMD) of FMF [7] and the delay spread of coupled MCF [8,9]. In this paper, we review our proposed methods and discuss likely enhancements.

2. Differential mode delay measurement along FMF

Figure 1 shows a schematic diagram of our DMD measurement scheme for FMF. This scheme utilizes the Rayleigh backscattering spectra with different modes captured by coherent optical frequency-domain reflectometry (C-OFDR). The backscattering spectra are sensitively and synchronously shifted in response to local environmental disturbances such as temperature and strain [10,11]. In the C-OFDR results, the spectral shifts of different modes exhibit different delay times. The spectral shifts are correlated between modes with delay times that correspond to the accumulated DMD since the position at which any particular environmental disturbance occurs is the same for each mode.

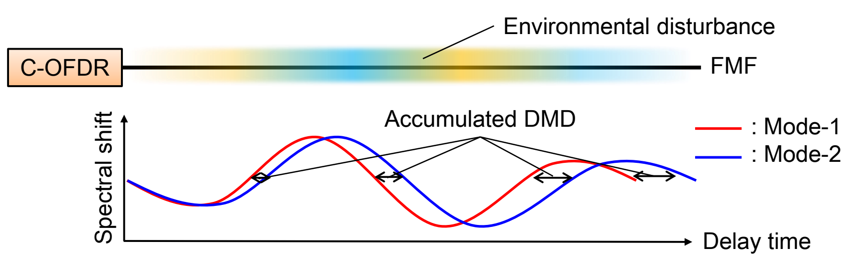

Fig. 1. Schematic diagram of DMD measurement.

Figure 2 shows the distributed spectral shifts measured around 120-m positions of two fibers under test (FUTs). We used two kinds of two-mode fibers (TMFs) as FUTs; TMF-1 and 2 were composed of step-index (SI) and graded-index (GI) TMFs in the sequences of SI-GI-SI and GI-SI-GI, respectively. DMDs per unit length of SI- and GI-TMF were 2.2 and 0.07 ps/m, respectively. It could be seen that the spectral shifts varied along the FUTs because of local environmental disturbances, and the traces between the LP_{01} and LP_{11} modes were shifted with respect to the horizontal axes due to the accumulated DMD. Figure 3 shows the accumulated DMDs obtained from the spectral shift distributions shown in Figs. 2. The red squares show the accumulated DMDs analyzed by calculating the cross-correlations of the data sets of the spectral shifts for every 40-m fiber section between the LP_{01} and LP_{11} modes; that is, the spatial resolution of the accumulated DMD was 40 m. The blue squares also show the results measured by the Fresnel reflection approach as described in [12] (destructive method). The solid lines are the calculations using the DMDs per unit lengths. A clear difference was observed between the DMDs in SI and GI, and the accumulated DMDs were good agreement with the results obtained with the destructive method and calculations.

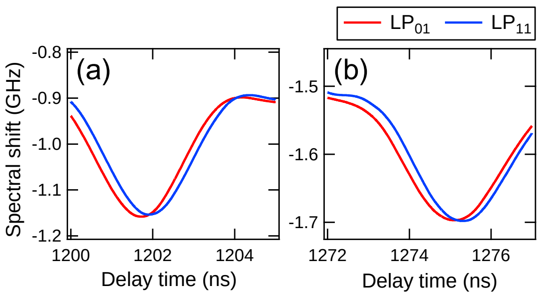

Fig. 2. Spectral shift distribution measured around 120-m position of (a) TMF-1, (b) TMF-2.

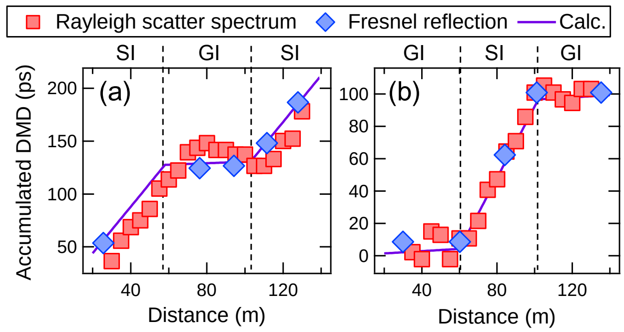

Fig. 3. Accumulated DMDs along (a) TMF-1, (b) TMF-2.

3. Spatial mode dispersion measurement along coupled MCF

One interesting property of coupled MCF is its Gaussian-like delay spread; its width increases in proportion to the square root of the propagation distance as a result of the random mode coupling along the fiber. Spatial mode dispersion (SMD) has been defined for coupled MCF in a similar manner to polarization mode dispersion (PMD) [3]. Figure 4 shows a schematic diagram of our SMD measurement scheme. This scheme also utilizes the Rayleigh backscattering amplitude captured by C-OFDR. The backscatter amplitude has a randomly jagged appearance, which is indicative of the interference pattern of the backscattered lights [11,13,14]. When we subject an arbitrary core to C-OFDR measurement, the measured backscattering amplitude is a superposition of randomly delayed replicas of the interference pattern because the backscattered lights propagate with multiple modes that randomly couple to each other. By auto-correlating the backscattering amplitude of an arbitrary portion of the fiber, small correlation peaks with a Gaussian-like distribution appear around the central peak, where the square root of the second moment of the delay distribution corresponds to the SMD; the appearance is similar to that found in a low coherence interferometry for PMD measurement [15,16].

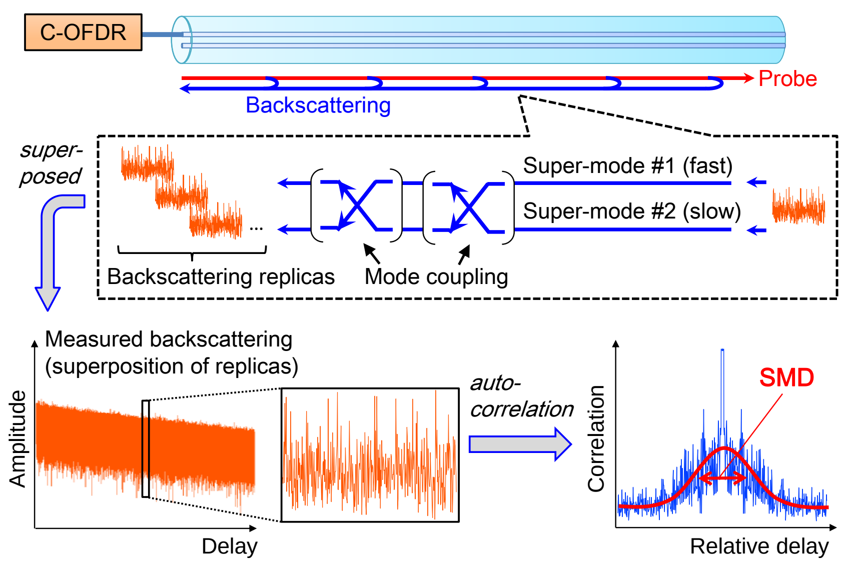

Fig. 4. Schematic diagram of SMD measurement.

Figure 5 shows auto-correlation fringes measured at 0.5-, 2- and 4-km positions of our FUT, a coupled two-core fiber with core pitch of 20 μm. We could see a Gaussian-like correlation distribution, and their widths increased with distance. Figure 6 shows the SMDs along the FUT characterized by calculating the square root of the second moment of the auto-correlation fringes. The auto-correlation of each position was calculated for a 23-m fiber section; that is, the spatial resolution of the SMD distribution was 23 m. We observed that the SMD growth was proportional to the square root of distance, as expected. The SMD coefficient was estimated to be 40 ps/√km, which was in good agreement with the result of an end-to-end measurement [3,9]. We also applied frequency-shift averaging (FSAV) for this measurement, plotted by the blue squares in Fig. 6. With FSAV, multiple correlation fringes obtained with different optical frequencies (wavelengths) were averaged to reduce the correlation noise caused by the phase difference between the backscattering replicas, before calculating SMD. As shown in Fig. 6, clear SMD growth could be observed by applying FSAV 10 times, compared to the results without FSAV. It should be noted that our SMD measurement scheme has a trade-off relationship between the measurement accuracy and spatial resolution, since a large section of backscattering amplitude is required for suppressing the correlation noise. FSAV is also an attractive option for improving the spatial resolutions as the auto-correlation can be performed on short sections and averaging the results.

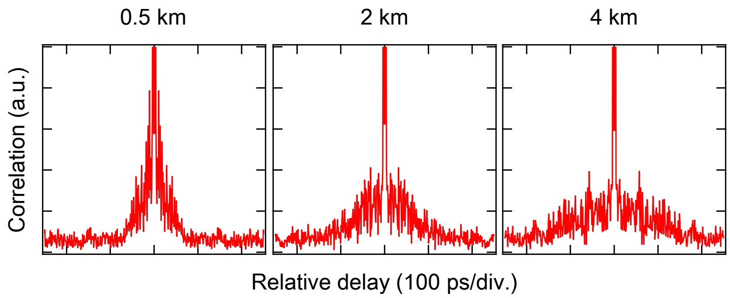

Fig. 5. Auto-correlation fringes of backscattering amplitudes.

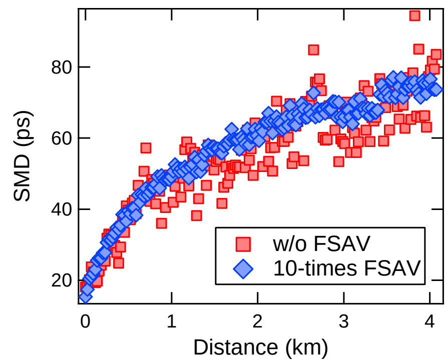

Fig. 6. SMDs along FUT with/without FSAV.

4. Conclusion

We reviewed distributed measurement methods of mode dispersion for FMF and coupled MCF. Both methods utilize the sensitive and unique characteristics of Rayleigh backscattering observed with C-OFDR. We believe that our methods will play important roles for designing SDM cables and systems. It is expected that a future progress in C-OFDR measurement range will extend the applicability of our methods.

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