Differential group delay measurements of few-mode fibers using an interferometric technique

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Abstract: We propose a simple technique for measuring the differential group delays (DGDs) between two different modes in a few-mode fiber (FMF) using an interferometric technique. We also experimentally demonstrate that the DGD between the two modes in the FMF with four modes can be successfully and simultaneously measured using the proposed technique.

Keywords: Interferometer, differential group delay, few-mode fiber

Classification: Optical Fiber for Communications

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1 Introduction

Space division multiplexing, including mode division multiplexing (MDM), has been intensively developed to expand its transmission capacity using few-mode fibers (FMFs) [1]. An FMF with a low differential group delay (DGD) and low mode coupling is required for MDM transmission systems that employ multiple-input, multiple-output processing [2, 3]. For designing MDM systems, the differential group delay (DGD) between modes, chromatic dispersion for each mode, and optical losses are important aspects to be considered.

Numerous reports have been published on techniques for determining dispersion characteristics, including the optical frequency-domain reflectometry [4], phase-sensitive optical low-coherence reflectometry [5], and modal interferometer method [6]. The interferometric technique for simultaneously measuring the DGD of each core in few-mode multi-core fibers (FM-MCFs) has been reported [7]. However, the feasibility of this technique for application to FMFs has not yet been experimentally confirmed.

In this paper, we propose a technique for measuring the DGD between modes in FMFs, and perform experiments on a four-mode fiber to confirm the feasibility of our technique.

2 Theoretical background

Fig. 1 shows a diagram of the interferometer that was used to measure the DGD between the modes in an FMF. The interferometer enabled the measurement of the wavelength dependency of the DGD.

The electric field $E_i(L,t)$ of the $i$ mode in an FMF with a length $L$ is expressed as follows:

![Fig. 1. Experimental setup for measuring the DGD.](image-url)
where $A$, $\omega$ and $\beta$ are the amplitude of the electric field, angular frequency, and propagation constant, respectively.

Assuming that $n$ modes can be launched into the FMF, the output power $I$ is given by the following equation:

$$
I(L,t) = |E_1 + E_2 + \cdots + E_n|^2 = \sum_{i=1}^{n} |E_i|^2 + \sum_{i,j=1 \ (i \neq j)}^{n} (E_i E_j^* + E_j E_i^*)
$$

(2)

where $E_i^*$ denotes the complex conjugate of $E_i$.

Based on Eq. (2), the interference between two different types of modes occurs in an FMF. The number of interferences is $n(n-1)/2$ in the fiber with $n$ propagation modes. The Fourier transformation of Eq. (2) is performed to obtain the spectrum component of the interference between each two modes [7]. Therefore, reproducing the interference waveform to obtain the DGD characteristic is possible by employing the inverse Fourier transformation of each spectral component [7]. As a result, we can simultaneously measure the DGD between every two modes in the FMF using the interference waveform.

The measurement procedure is described as follows.

**Step 1:** The interference waveform is measured by the optical spectrum analyzer (OSA) when all of the modes are launched into the test FMF.

**Step 2:** The Fourier transformation of the interference waveform is performed to obtain the spectrum component of the interference between each of the two modes.

**Step 3:** The inverse Fourier transformation of each spectral component without DC component is employed to reproduce the interference waveform to obtain the DGD characteristics.

**Step 4:** The difference $\Delta \lambda$ between the wavelengths of the adjacent minima in the interference waveform is measured between the two modes. The DGD $\Delta \tau$ between the two modes at wavelength $\lambda$ can be expressed as

$$
\Delta \tau = \frac{\lambda^2}{cL\Delta \lambda},
$$

(3)

where $c (= 3 \times 10^8 \text{ m/s})$ is the light velocity in free space, $L$ is the fiber length, and $\lambda$ is the center wavelength between the adjacent minima.

### 3 Experimental results

The experiment was performed for the DGD of the four-mode fiber with a length of 0.99 m using the proposed technique, as shown in Fig. 1. The index profile of the test FMF was a step-index profile. A super-luminescent diode (SLD) is coupled to a single-mode fiber (SMF) to obtain a point light source. The light beam emitted from the SMF is collimated and launched into the test FMF through polarizer $P_1$. Another polarizer $P_2$ is placed at the far end of the fiber. The transmitted power as a function of wavelength is observed with an OSA. Both polarizers are adjusted to give maximum dips in the OSA trace.
The interference waveform of the FMF with four modes is presented in Fig. 2(a). We observed that the interference waveform was composed of the sum of interferences between each of the two modes, as shown in Fig. 2(a). The Fourier spectrum of Fig. 2(a) is shown in Fig. 2(b). The six spectrum components of the interference waveform are shown in Fig. 2(b). This confirms that all combinations of the interference between the two modes in the fiber with the four propagation modes occurred. Using each spectrum component, as shown in Fig. 2(b), inverse Fourier transformation was performed to obtain the interference waveform.

Figs. 3(a) to (f) show the interference waveform between the two modes, which is obtained using inverse Fourier transformation. Fig. 3(g) shows the DGDs between the two modes estimated from the interference waveforms as shown in Figs. 3(a) to (f) [8]. The circles indicate the measured results and the solid lines indicate the fitted results to the measured results.

The number of DGDs shown in Fig. 3 correspond to that of the spectral component, as shown in Fig. 2(b).

We experimentally confirmed that our technique could successfully and simultaneously measure each DGD between the two modes in the FMF.
4 Conclusion

We proposed a simple technique for measuring the DGD between two different modes in the FMFs using an interferometric technique. We also performed experiments on the four-mode fiber to confirm the feasibility of our technique. The DGD between each of the two modes in the FMF with four modes was successfully and simultaneously measured using the proposed technique. Thus, it is confirmed that our technique is a powerful tool for measuring the DGD in the FMFs and FM-MCFs.
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