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High-resolution measurement of differential mode delay of few-mode fiber using phase reference technique for swept-frequency interferometry

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ABSTRACT

A method is described for the high-resolution measurement of the differential mode delay (DMD) of few-mode fiber based on the frequency-modulated continuous wave (FMCW) technique. With the conventional approach, a wider optical bandwidth is required for higher resolution, however, the effect of chromatic dispersion becomes critical and limits the actual resolution. This paper proposes and demonstrates a phase reference technique for FMCW signals that achieves high-resolution measurements without increasing the optical bandwidth. We can also further improve the resolution of our proposed method by reducing the phase fluctuation with signal averaging. The feasibility of the proposed method is confirmed experimentally with several kinds of FMFs including an offset-spliced fiber where mode couplings occur.

1. Introduction

Mode division multiplexing transmission using few-mode fiber (FMF) and multiple-input-multiple-output (MIMO) processing has been attracting considerable attention as a technique for realizing a large transmission capacity exceeding that of current single-mode fiber (SMF) based transmission line [1–4]. Differential mode delay (DMD), which is defined as a relative group delay within the propagation modes, is an important parameter for designing and/or characterizing the MDM system, because MIMO processing becomes more complicated as the DMD increases. Recent studies have proposed some DMD reduction techniques including low-DMD fibers designed with graded-index based profiles [2,3] and a DMD managed transmission line where positive- and negative-DMD fibers are combined [4] with the aim of reducing the complexity of MIMO processing. High-resolution DMD measurements are required if we are to characterize such low-DMD transmission lines accurately.

Certain DMD measurement methods have been reported including a time-domain method [5], and a frequency-domain method [6–9]. The time-domain method is standardized in Ref. [5] and has been widely used in previous works. It launches a short optical pulse into an FMF, and characterizes the DMD from the shape of the output pulse. Thus the temporal pulse width corresponds to the DMD resolution, and is typically a few tens of picoseconds. However, a shorter pulse width inevitably leads to a wider spectral width. As a result, the achievable resolution is limited by the pulse broadening caused by chromatic dispersion. Moreover, the setup needed for the time-domain method is complicated and expensive, because it requires an ultra-short pulse source and a fast detection system including a fast detector and a sampling oscilloscope. In contrast, the frequency-domain method, which is called a frequency-modulated continuous wave (FMCW) method, is very attractive because the DMD measurements can be easily performed by using a simple Mach-Zehnder interferometer and a frequency-sweeping continuous light source. Refs. [7,8] reported ps-order resolution measurements using the FMCW method. However, the resolution of the FMCW method is also limited by chromatic dispersion because it is inversely proportional to the frequency sweep range of the probe light [9,10]. We can compensate for the effect of chromatic dispersion by using an auxiliary interferometer where the dispersion of the delay fiber is equal to that of the FMF for the FMCW setup [9,10], however, such a delay fiber is not always available, and the dispersion is typically different for each propagation mode.

In this paper, we present a way of realizing a high-resolution DMD measurement in a narrower optical bandwidth than with the conventional FMCW method. With our proposed method, the DMD is characterized by referencing the phases of the FMCW signals for different modes, and the resolution depends not only on the frequency sweep range but also on the temporal phase fluctuations. We also employ signal averaging with the proposed method to enhance the resolution by reducing the phase fluctuations caused by random noises or mode couplings.

This paper is organized as follows. Section II reviews the principle of DMD measurement with the FMCW method using the conventional and proposed methods. Section III describes our FMCW configuration and

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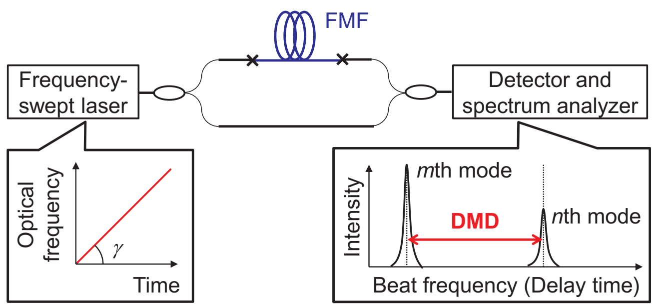

Fig. 1. Basic setup for conventional FMCW method.

experimental results. Section IV provides the conclusion.

2. Measurement principles

2.1. Fourier-transforming analysis with conventional method

In this subsection, we review the principle of the conventional FMCW method used to measure the DMD.

Fig. 1 shows an example setup for the FMCW method. A continuous light wave whose frequency is swept with respect to time is divided by the coupler and used as a probe light and a local light. The probe light is launched into an FMF with multiple propagation modes, and detected with a coherent receiver. When the interference between the probe and local lights is taken into account, the beat signal $I(t)$ can be written as

$$I(t) \propto \sum_m a_m \cos 2\pi\gamma\tau_m t, \tag{1}$$

where a_m and τ_m, respectively, are the amplitude and delay time of the probe light in the mth mode, and γ is the frequency sweep rate. The phase noise is ignored in Eq. (1) for simplicity. As described in Eq. (1), the beat frequency of $I(t)$ is proportional to the delay time, thus a Fourier transform of $I(t)$ is performed for DMD analysis. Since the spectral resolution of the Fourier transform is inversely proportional to the measurement time T, and the beat frequency is proportional to γ, the DMD resolution $\Delta\tau$ of the conventional method is

$$\Delta\tau = \frac{1}{\gamma T} = \frac{1}{F}, \tag{2}$$

where F is the frequency sweep range. The resolution is directly related to the sweep range, thus a widely swept light is required for a high-resolution measurement. However, a large F increases the effect of chromatic dispersion, and as a result, the resolution actually becomes larger than $1/F$.

2.2. Phase reference technique with proposed method

We introduce a phase reference technique for the FMCW method to realize higher-resolution DMD measurements without expanding F. Fig. 2 shows the FMCW setup we used for the proposed method. With this method, we obtain the FMCW signals of different modes individually by utilizing a mode multiplexer (MUX) and demultiplexer (DEMUX). After that, the phase component of each beat signal is extracted by performing a Hilbert transform, in which the phase of the signal shifts by $-\pi/2$, and by calculating an arc tangent with the original and transformed signals. The phase signal of the mth mode $\theta_m(t)$ can be written as

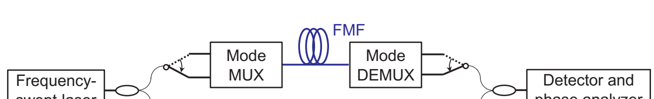

Fig. 2. Setup for phase-referencing FMCW method.

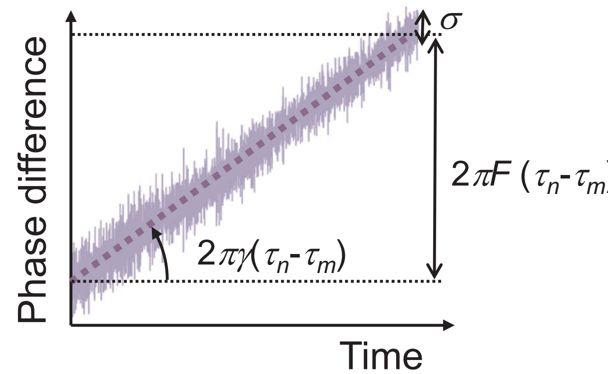

Fig. 3. Unwrapped phase difference of beat signals.

$$\theta_m(t) = \tan^{-1}\frac{H\{I_m(t)\}}{I_m(t)} = 2\pi\gamma\tau_m t + \varphi_m(t) + \xi_m, \tag{3}$$

where $I_m(t)$ and $H\{I_m(t)\}$ are the beat signal of the mth mode and its Hilbert-transformed function, respectively, $\varphi_m(t)$ is phase noise, and ξ_m is a phase constant. Then, the phase difference between the mth and nth modes is

$$\theta_n(t) - \theta_m(t) = 2\pi\gamma(\tau_n - \tau_m)t + \varphi_n(t) - \varphi_m(t) + \xi_n - \xi_m. \tag{4}$$

Fig. 3 shows an example of the phase difference after unwrapping. The phase difference increases linearly with respect to time while randomly fluctuating due to the phase noise. Then, the temporal phase change rate, which is the angular frequency difference between the mth and nth modes, is related to the DMD as $\tau_n - \tau_m$. Thus we can characterize the DMD by applying a linear fitting to the phase difference and analyzing the change rate. Since we can determine the change rate when the total phase change in the measurement time is larger than the phase noise, the DMD resolution of the proposed method can be defined as

$$\Delta\tau = \frac{\sigma}{2\pi F}, \tag{5}$$

where σ denotes the standard deviation of the phase fluctuation from linear fitting. The resolution depends not only on F but also on σ, thus we can realize a higher resolution without expanding F by reducing σ with certain methods such as the resampling technique reported in [10,11]. Moreover, the effect of chromatic dispersion on the proposed method depends on the differential dispersion between different modes, while the conventional method is affected by the individual dispersion of each mode. Since the differential dispersion is generally very small, the proposed method has the potential to achieve much higher resolution than the conventional method.

2.3. Mode coupling effect in proposed method

In Section 2.2, we assumed that the beat signals of different modes are detected individually. However, there are actually some undesired coupling modes in the fiber under test (FUT) or mode MUX/DEMUX. In this subsection, we describe the effect of mode coupling in our proposed method and a technique for its reduction.

When we take mode coupling into account, the beat signal obtained through the mth mode ports of the mode MUX/DEMUX can be written as a superposition of the signals whose beat frequencies (delay times) are different,

$$I'_m(t) \propto \cos\phi_m(t) + \sum_{i \neq m} \alpha_i \cos\phi_i(t), \tag{6}$$

$$\phi_m(t) \equiv 2\pi\gamma\tau_m t + \xi_m, \tag{7}$$

where α_i is the relative amplitude of the ith coupled mode. We