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Fourier-domain mode delay measurement for multimode fibers using phase detection

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ABSTRACT

We have proposed a powerful method based on a phase detection reflectometric technique to solve the difficulty of the small signal discrimination in the amplitude-detection method for differential modal delay measurement of multimode optical fibers (MMFs). The phase is radically shifted to π at the time delay positions among the excited modes even when the amplitudes of the peaks cannot be distinguished with the noise level. The modal dispersion of the MMF under test can be simply determined by choosing the time delay in the last phase shift in the Fourier domain. In addition, we confirmed that the phase-sensitive interferometric measurement does not need to scramble the excited modes in the fiber. We subsequently conclude that a portable modal dispersion or mode analysis equipment can be developed by using the phase-detection intermodal interferometric technique proposed here.

1. Introduction

LOCAL area network (LAN) such as computer server system interconnection usually employ multimode optical fibers (MMFs) taking advantage of their high bandwidth compared to copper cable [1]. Recently, some kind of MMFs which have several propagation modes, named few-mode fibers (FMFs), have been employed in research on mode division multiplexing (MDM) communication for higher capacity [2–8]. In MDM communications, each mode plays a role of a channel in multiplexing. Several techniques for MDM communication have been reported in research [9–20]. Some techniques require very small modal dispersion [5–7], while others require large dispersion [8]. Differential mode delay (DMD) of an MMF is typically defined as the difference in group delay between the fastest and slowest mode per unit length [21]. It is strongly related to network performance for both conventional MMF-based local communication and MDM long-haul communications [22,23].

Modal dispersion measurement methods have been reported [21]. Typically, time-of-flight methods measure the spreading pulse through the fiber by using a short pulse laser, high-speed detection system in combination with a sampling oscilloscope or real-time data acquisition [21]. It is very expensive and complicate to build the time-of-flight measurement. In addition, it is difficult to bring the measurement system to the practical field. The portable and compact modal delay measurement equipment of the MMFs is needed in the MMF-based communication applications such as conventional LANs, MDM for long-haul networks, and polymer MMF communications for vehicles.

To simplify the measurement system and to improve its signal detection sensitivity and resolution, fiber interferometric modal delay measurement techniques have been reported [24–29]. First research, among these, measures modal delay using interferogram which produced between fundamental mode propagated in reference arm and every mode in fiber under test (FUT) [26]. It provided comparable or much better resolution with simple and low-cost system comparing with the time-of-flight measurement. However, environments such as temperature and/or vibration affects the system to be unstable fluctuating optical path length difference between reference arm and FUT. In order to solve the problem, we have suggested to measure a modal delay with spectral interferometric scheme included an MMF under test as a fiber interferometer itself. The excited modes in the MMF play roles of the single-mode-fiber (SMF) based different arms in an interferometer. Stable interferogram from intermodal interference among the modes provides the good accurate differential modal delay information because the intermodal interferometer has only one fiber arm in which all propagation modes experience same fluctuation on even the environment is unstable [27,28]. In addition, high sensitivity of the interferometer facilitates detection of small signal which related to a higher order mode in the fiber. Utilizing the advantage, modal dispersion of FUT can be measured even using light reflected from the fiber facet [27,28]. However,

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the returned signals of the higher order modes in the round-trip interferometric modal delay measurement system is not enough to measure modal dispersion accurately. It is difficult to distinguish the small returned signal to the background noises and to determine the last peak in the Fourier domain.

In the paper, we have proposed phase-sensitive modal delay measurement based on intermodal interferometric technique to

improve the discrimination of the returned signals related to mode beatings. The phase of an interference component between two modes among all propagating modes is radically shifted at the certain time corresponding to modal delay. Modal delay can be easily determined even when the excited modes have noise-like small intensities.

2. Theory

Intermodal interferometric modal delay measurement technique is composed of a broadband light source, a spectrum analyzer, and a simple fiber interferometer, i.e. MMF under test [30]. Modal interference components can be achieved by taking an inverse Fourier transform of a measured interferogram ($E(f)$) in the spectral domain coming from the intermodal interference among the excited modes in the MMF. Generally, Fourier transformation of the interfered signal gives the real and imaginary parts which denote A and B, respectively. The relation is mathematically expressed by [30]

$$F^{-1}\{E(f)\} = A + jB \tag{1}$$

Generally, the amplitude ($(A^2 + B^2)^{1/2}$) of the Fourier transform was used for determination of the last peak in the Fourier domain corresponding to the maximum modal delay of the MMF. Here we use the phase term ($\tan^{-1}(B/A)$) to discriminate the last peak even in noises.

We simply confirm the phase change caused by the intermodal interference between two modes that have different optical path through the MMF. Summation of those two electrical field can be described to ... Note that f indicates optical frequency of the light, t is a time, and Δt is an arriving time difference between two modes. The real and imaginary parameter of inverse Fourier transform of the electric field can be described as follows:

$$A = \frac{1}{\pi(t-\Delta t)} \cos\left(\pi\left(f_{\max} + f_{\min}\right)(t-\Delta t)\right) \times \sin\left(\pi\left(f_{\max} - f_{\min}\right)(t-\Delta t)\right) + g(t) \tag{2}$$

$$B = \frac{1}{\pi(t-\Delta t)} \sin\left(\pi\left(f_{\max} + f_{\min}\right)(t-\Delta t)\right) \times \sin\left(\pi\left(f_{\max} - f_{\min}\right)(t-\Delta t)\right) + h(t) \tag{3}$$

Note that $f_{\max}$ and $f_{\min}$ are respectively the upper and lower integration range in the spectrum of the broadband source. The functions of $g(t)$ and $h(t)$ are independent to Δt. Here we consider the phase shift of the modal interference at $t = \Delta t$. In Eqs. (2) and (3), both A and B are three different term as function of $t - \Delta t$. The $t - \Delta t$ term will be negative or positive value due to the value of t, so the A and B term also have negative or positive value determined by the sign of the $t - \Delta t$ value. Eqs. (4)–(7) show the determined sign of the A and B terms. The function A is composed of multiplying an inverse function, a cosine function, and a sine function, whereas the function B is composed of multiplying an inverse function, a sine function, and the other sine function. In Eq. (4), the first, second, and third terms of the function A become negative, positive, and negative value, respectively and then the sign of the function A is determined to be positive when time t is approaching to Δt from a negative infinite value. When time t is approaching to Δt from a positive infinite value (as described in

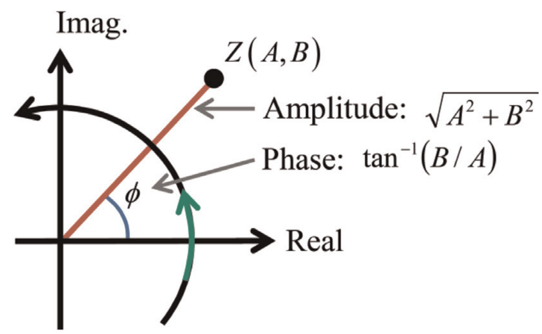

Fig. 1. Real and imaginary coordinate.

Eq. (5)), the sign of the function A becomes positive as well. On the other hand, the sign of the function B becomes negative and positive when the time t comes from a negative (Eq. (6)) and positive (Eq. (7)) infinite value, respectively (Fig. 1).

$$\lim_{t\to\Delta t-} A = (-)(+)(-) = (+) \tag{4}$$

$$\lim_{t\to\Delta t+} A = (+)(+)(+) = (+) \tag{5}$$

$$\lim_{t\to\Delta t-} B = (-)(-)(-) = (-) \tag{6}$$

$$\lim_{t\to\Delta t+} B = (+)(+)(+) = (+) \tag{7}$$

While the function A has plus sign for both positive and negative approaching, the function B has opposite sign due to the different approaching. In consideration of the phase term ($\tan^{-1}(B/A)$), the left hand side of the phase at the reference Δt is minus value and the right hand side is plus value, as shown in Fig. 2. In other words, the phase of the modal interference between two modes radically changes at the time delay between two modes. Therefore, we can consider that the positions of the phase changes in Fourier domain are corresponding to modal delays among the excited modes in the MMF. The last phase change is determined to the maximum modal delay between the fastest and slowest mode.

3. Experiments and results

3.1. Proof of concept

Superluminescent light diode (EXS8510-2411, EXALOS Inc.) operating at the wavelength of 853 nm with 56 nm FWHM is used as a wide spectral light source. We used mini-spectrometer (HR4000, Ocean Optics Inc.) to analyze the spectral intensity of the interfered signal instead of a conventional optical spectrum analyzer. Its measurable wavelength is ranging from 753 to 932 nm and it provides the resolution of up to 0.05 nm at 850 nm wavelength. It enables the construction of a portable modal delay measurement or mode analysis equipment for the field tests.

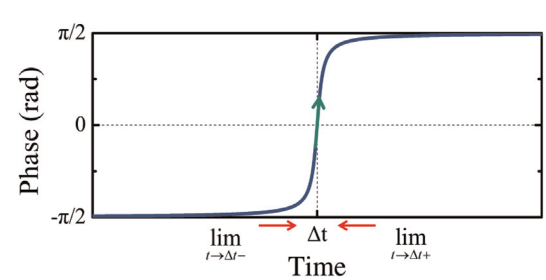

Fig. 2. Phase change with respect to time delay.