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Mode Analysis and Modal Delay Measurement of a Few-Mode Fiber by Using Optical Frequency Domain Reflectometry

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A novel mode analysis method and differential mode delay measurement technique for a multimode optical fiber based on optical frequency domain reflectometry has been proposed for the first time. We have used a conventional OFDR with a tunable external cavity laser and a Michelson interferometer. A few-mode optical multimode fiber was prepared to test our proposed measurement technique. The differential mode delay (DMD) of the sample fiber was measured to be 16.58 ps/m with a resolution of 1.5 ps/m. We have also compared the OFDR measurement results with those obtained using a traditional time-domain measurement method.

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I. INTRODUCTION

Many enabling technologies for an optical gigabit Ethernet system based on an 850 nm Vertical Cavity Surface Emitting Laser (VCSEL) have received much attention recently. The development of a multimode fiber (MMF) optimized for 850 nm wavelength operation is one of the most important components required for 10 Gb/s next-generation transmission local area network (LAN) systems [1]. In order to develop a high- bandwidth MMF for LAN applications, reliable techniques for the bandwidth measurement of an MMF are required. The concept of a differential mode delay (DMD), and its associated measurement techniques, have been the subject of many recent studies [1,2] and the time-domain DMD measurement method has already been developed and standardized [3] for an MMF. In the traditional time-domain DMD measurement method, a short pulse is transmitted to an MMF under test. Pulse spreading or broadening due to the propagation speed differences for each mode of an MMF is measured in the time domain using a fast time-domain detection technique. This conventional DMD measurement method is both complicated and expensive, because it utilizes ultra-short pulses from a laser source and it requires a fast detection system such as a streak camera or a fast detector combined with a sampling oscilloscope. The time-domain DMD measurement method, which uses a pulsed laser, has critical drawbacks, as the DMD for a fiber with large chromatic dispersion and the DMD for a short length of fiber are difficult to measured. In this paper, we present a simple, new differential mode delay measurement method in the frequency domain, where there is no limitation due to the chromatic dispersion of a fiber.

The principle of the conventional DMD measurement method is the same as that of an optical time domain reflectometer (OTDR), which measures fault positions, connection loss, and scattering loss distribution along a transmission line by analyzing reflected pulses from various reflection points [4,5]. An OTDR measures reflected pulses, whereas transmitted pulses are measured in a time-domain DMD measurement method. Recently, an optical frequency domain reflectometer (OFDR) has been used to evaluate several characteristics of optical fibers, such as fault positions, chromatic dispersion, and polarization mode dispersion [6-8]. Here we introduce a new optical frequency domain method to analyze the mode structure and the DMD of an MMF using an OFDR for the first time.

II. THE PRINCIPLES OF OFDR

An OFDR system is normally composed of a linear frequency sweeping laser source and a Michelson interferometer. A frequency sweeping laser light source is used instead of a moving stage, which is used in a conventional optical low-coherence reflectometer (OLCR) as a sweeping delay line. Frequency sweeping coherent laser light is injected into a fiber under test (FUT), and the reflected light from a fault is combined with another light from the reference arm of the interferometer. When this combined light is detected using a fast detector, a beating oscillation with a frequency proportional to the time delay between the two light sources is generated. In general, the purpose of this measurement technique is to determine the position of an irregularity with high sensitivity and high spatial resolution. Fig. 1 shows the basic operation principle of an OFDR. Reflected frequency-swept light at each fault position R1, R2, and R3 has a different time delay $\tau1$, $\tau2$, and $\tau3$, respectively after round-trip in a single mode optical fiber (SMF). These reflected lights are combined with the reference wave (shown as a Ref. symbol in Fig. 1) of the interferometer and interference signal data is collected in the time domain. Frequency spectrum of the time domain signal data is obtained by using the fast Fourier transformation (FFT). As shown in Fig. 1, there will be three different frequency components (f1, f2, and f3) in the frequency spectrum, which correspond to the three different reflection points (R1, R2, and R3, respectively). The time delay (τ) is estimated [9] from

$$\tau = \frac{f}{\gamma} = \frac{f}{\Delta v / T} \tag{1}$$

where f is the beating frequency and γ is the frequency-sweep rate, defined by the swept frequency range (Δv) divided by the swept time (T). The position can also be determined from the estimated time delay. In a multimode optical fiber each mode travels with a different propagation constant, and has a different time delay even when there is a single reflection position. Therefore the frequency component which corresponds to each mode in an MMF can be measured with an OFDR. The DMD as well as the mode structure of an MMF can be evaluated from this frequency domain data by using Eq. (1).

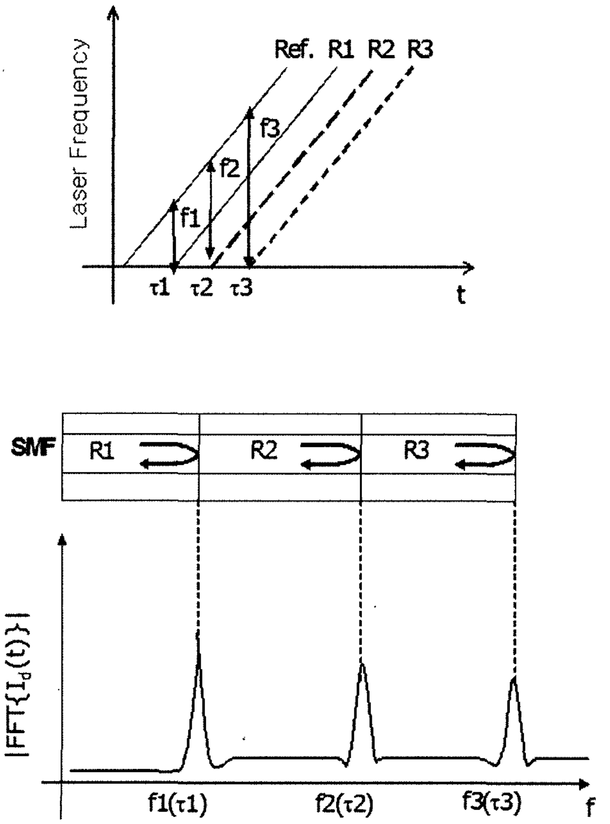

FIG. 1. A schematic diagram of an OFDR system for the measurement of the position of a fault in a SMF.

III. EXPERIMENT AND RESULTS

Fig. 2 shows a schematic diagram of our experimental set-up used for carrying out differential mode delay measurements of an MMF based on an OFDR. An Agilent TLS 81640A tunable light source (TLS) was used with a tuning range from 1549-1550 nm. The linear tuning rate was set to 500 pm/s (62.5 GHz/s). The tuning rate (γ) of the TLS could be estimated from the simple relationship, $\gamma = \Delta f / \Delta \tau$, where Δf and $\Delta \tau$ are the differences between the two beating frequencies and two time delays, respectively. The difference in beating frequency was about 610.3 Hz when the difference of a sample length was 1 m. We obtained an experimental tuning rate of our TLS of about 62.7 GHz/s when the refractive index of the sample fiber was assumed to be 1.46. This tuning rate is very close to the set value of the TLS. The optical power of the TLS was kept at 2 mW during the frequency tuning process. The sweep repetition number

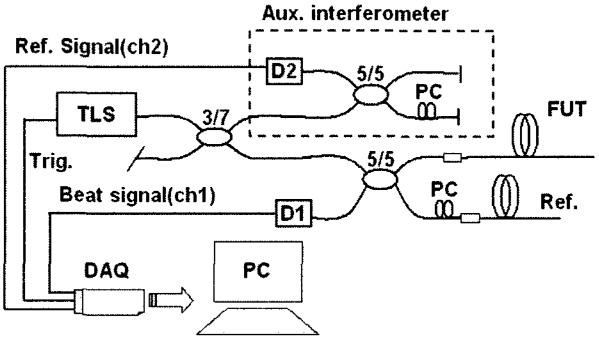

FIG. 2. Experimental set-up for DMD measurements of a multimode fiber.

employed was 100, and a trigger signal was generated each time the frequency sweep began. The beating signal was acquired using a data acquisition (DAQ) board with a triggering signal function.

Frequency-swept light from the TLS is split using a 30/70 optical coupler. Thirty percent of the optical power goes into an auxiliary interferometer, as shown in Fig. 2. The auxiliary interferometer is used to measure the nonlinearity of the frequency sweep process, and we used an auxiliary interferometer to reduce the effect of nonlinear frequency sweep in our experiments [6, 9]. In the main interferometer the remaining 70% of optical power is split once again using a 3 dB fiber coupler. A wave propagated through the FUT interferes with another wave reflected from the reference arm. A home-made few mode fiber (FMF) is used as a sample fiber. It is spliced to an SMF with the offset between the SMF and the FMF large enough such that each mode in the FMF can be easily excited [10]. A polarization controller is fixed at the optimum position to obtain a high visibility interference signal at the detector. The index profile of the FMF is shown in Fig. 3. The core diameter and the index difference were about 8 μm and 0.026, respectively. The core size of the FMF was designed to be same as that of the SMF to enable the coupling of the majority of reflected light from the FMF back into the SMF, whereas the refractive index of the FMF was designed to be higher than that of the SMF to support a few transverse modes. The length of the SMF in the reference arm was roughly same as the length of FUT, which made the frequency of the beating signal very low. This decreased the phase noise in the measured beating signal [11]. The frequency component in the beating signal corresponds to the temporal delay associated with the difference in propagation time between modes. The solid line in Fig. 4 shows the modal delay of the FMF measured using our OFDR method. The intensity is normalized to the maximum peak intensity, and the time delay shown was divided by the sample length (40 m). There were four peaks observed, and the time delay of the modes are 16.5, 23.8, 26.9, and 30.8 ps/m, respectively. This indicates that there exist four transverse modes in the FMF corresponding to these four different modal propagation speeds. This modal delay measurement can be used to calculate the propagation constant for each transverse mode of the fiber. Dashed line in Fig. 4 shows the modal delay of the same FMF measured using a conventional time-domain method. A gain-switched laser (Optune Inc.) was used as the input pulse source operating at λ = 1550 nm, with an FWHM = 28 ps and a 10 MHz repetition rate. It shows that the input pulse was split into three pulses in the time-domain, with time delays of 16.4, 27.9 and 32.0 ps/m, respectively. The waveforms shown in Fig. 4 are consistent with each other, except for the second peak from the right-hand side shown in the data measured using an OFDR. We carried out the same measurements when the FMF was slightly bent, and the data is shown in Fig. 5. Compared to the results shown in Fig. 4, both the third peak in the OFDR data and the second peak in the pulse measurement data are missing in the data shown in Fig. 5. This indicates that they correspond to higher order transverse modes in the FMF. However, the second peak from the right- hand side shown as solid line in Fig. 4 does not match any peak of dashed line in the figure, and it is not affected by the bending of the fiber. This peak arises from the cladding mode coupling of the back-reflected light in our interferometric OFDR system. We confirmed that the unknown peak disappeared by clearing the cladding modes in the

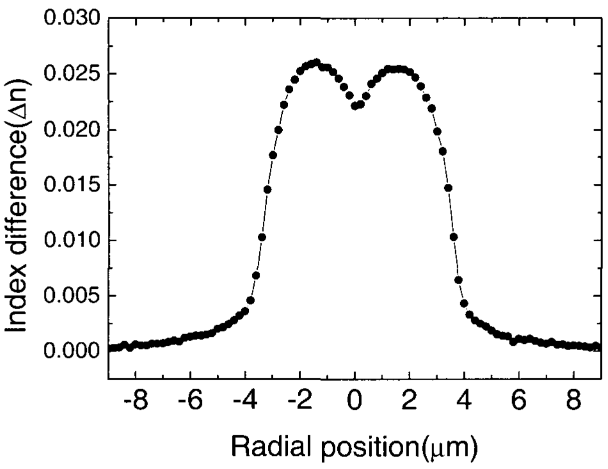

FIG. 3. Refractive index profile of a few-mode fiber with a core diameter of ~8 mm and a maximum core index difference of ~0.026.

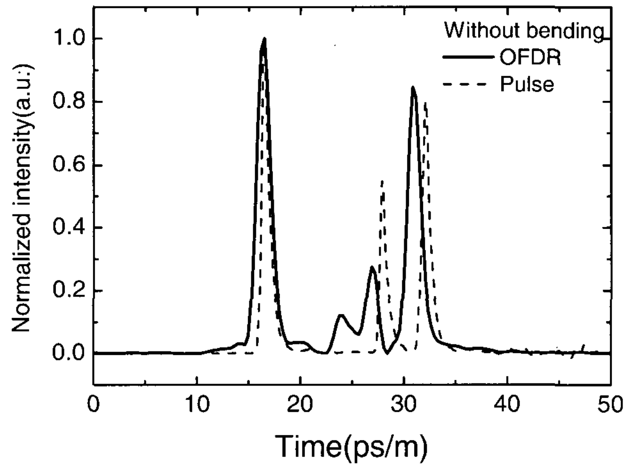

FIG. 4. Modal delay measurements of an FMF in frequency domain using an OFDR, and time domain using an optical pulse source without bending a sample fiber.

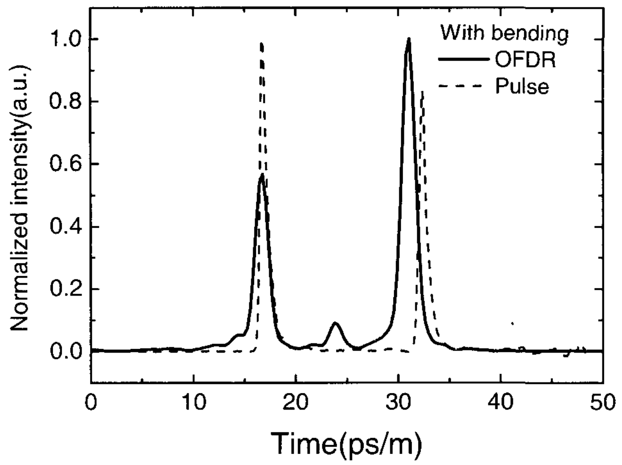

FIG. 5. Modal delay measurements of an FMF in frequency domain using an OFDR, and time domain using an optical pulse source with bending of a sample fiber.

SMF using an index matching oil in the sample arm. The third peak is a higher order mode than the fourth peak, since the higher mode has a higher loss when the fiber is bent. A quantitative comparison of our OFDR results with the results obtained using the time-domain measurement method is shown in Table 1.

The measured values of the time delay in the OFDR and the time-domain measurement methods are similar. The difference between both the second and the third peaks is about 3.8%. We think that this small discrepancy is introduced by the numerical conversion process of the beating frequency to the time delay, caused by dividing the beating frequency with the frequency sweep rate. We expect that a lower error in our OFDR measurement system can be obtained by calibrating the frequency sweep rate of the tunable laser source more accurately.

In the time-domain measurement method, DMD is measured by observing pulse width broadening after an ultrashort pulse is propagated through a FUT. Obtaining an ultrashort optical pulse source and an ultrafast detection method is important in improving the resolution. The resolution of the modal delay is about 0.7 ps/m for a 40-m long sample using a 28 ps optical pulse source. It is very hard to improve the resolution of the DMD measurement method in the time-domain because of difficulties in obtaining an ultrashort optical pulse source as well as an ultrafast electronic measurement method. Another very important limiting factor for the resolution in the time-domain DMD measurement method is the effect of chromatic dispersion in pulse width broadening. Reduction of an optical pulse width in time domain is always accompanied by the spectral broadening of the pulse in the frequency domain. The spectral broadening of an optical pulse increases pulse width in the time-domain after it is propagating through a FUT due to the chromatic dispersion of a FUT. The resolution of our demonstrated DMD measurement method in the frequency-domain using an OFDR is only 1.5 ps/m. However, the resolution of the OFDR is inversely proportional to the frequency sweep rate and the acquisition time. It is easy to obtain a tunable laser source with a 625 GHz/s frequency sweep rate and a 2 second acquisition time, which can provide 0.15 ps/m resolution in DMD measurement. Our proposed frequency-domain DMD measurement method is not affected by the chromatic dispersion of a FUT since we use a very sharp linewidth tunable laser source. We propose that our OFDR system is a very powerful alternative solution for DMD measurements in multimode fibers. To measure the modal delay of a commercial MMF for a gigabit Ethernet application, a transmission-type OFDR and a tunable coherent light source operating at $\lambda = 1310$ or 850 nm is required. A low-cost modal delay measurement system based on an OFDR can be realized by using a low-cost light source, such as a distributed feedback laser diode (DFB- LD) or a VCSEL.

IV. CONCLUSIONS

A new very powerful mode analysis method and a DMD measurement technique for an MMF using an OFDR system has been proposed. We have demonstrated the basic idea of our proposed method by measuring the modal delay of a few-mode fiber by using this method. Measured results of our proposed frequency-domain technique were compared to the results using a conventional time-domain measurement method. We have demonstrated the possibility of using our frequency-domain measurement method with an OFDR as a powerful tool for analyzing an MMF.

TABLE 1. A comparison of the results of the frequency-domain method with the results of the time-domain method.

	First Peak (ps/m)	Second Peak (ps/m)	Third Peak (ps/m)	ModalDelay (ps/m)	Measurement Resolution (ps/m)
Freq.-Domain Method	16.48	26.86	30.82	16.58	1.5
Time-Domain Method.	16.42	27.92	32.04	16.88	0.7

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