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Distributed group birefringence measurement in a polarization-maintaining fiber using optical frequency-domain reflectometry

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ABSTRACT

We propose to use optical frequency-domain reflectometry to measure distributed group birefringence along a section of polarization-maintaining fiber. Frequency dependence of the propagation constant difference along the fiber between the fast and slow modes can be determined. The scanning frequency bandwidth has influences on the measurement of the phase modal birefringence and beat length. Besides phase modal birefringence and beat length can be measured, distributed group birefringence along the fiber is obtained with a spatial resolution of 7.8 cm.

1. Introduction

Polarization-maintaining fibers (PMFs) are capable of maintaining a state of polarization along their lengths when a linearly polarized light wave is propagating in one of the principal axes of the fiber. Such fibers have been widely used in optical fiber communication systems and optoelectronic devices, and also attracted intensive interests in fiber-optic sensing community. Nowadays, single-mode optical fibers with elliptical cladding or built-in stress rods have been successfully fabricated by inducing high internal birefringence along the fiber. This high modal birefringence, which is the effective refractive index difference between the two orthogonally polarized light field components, is one of the most important parameters to characterize the polarization-maintaining capability of the PMFs. Frequently, the beat length directly related to the modal birefringence is used as a practical parameter. Because of the stress rod or elliptical cladding nonuniformity, the stress gradient in PMF varies in position, so does the refractive index, and hence the model birefringence in PMF is often position dependent. It is important to investigate this property in distributed format and explore its wavelength dependence, especially for the purpose of reducing the position dependence of modal birefringence in new PMF design.

There are many methods proposed to measure the modal birefringence and beat length in the past. Many of them rely on measuring the transmission signals by manipulating the test fibers [1–3], modulating the optical phase or wavelength of the optical source, and using low coherence interferometric techniques [4–7]. The methods mentioned above can only give effective values contributed by the entire fiber under test owing to the transmission based measurement nature. However, it is very important to obtain distributed birefringence information along the PMFs, since such information can be used as a guideline in designing high quality PMF for fiber manufacturers to improve fabrication process. For example, some techniques using birefringence in PMFs to achieve phase-matching condition can benefit from a birefringence-uniform PMF, such as four-wave mixing process and Brillouin dynamic grating based applications. A more uniform birefringence can enhance the efficiency of such processes greatly [8,9]. Also, the birefringence variation along the PMF may limit certain practical applications, such as in distributed strain and temperature optical fiber sensors to measure the birefringence dependence on the temperature and strain. The coefficients are location dependent which limit the accuracy of the measurement [10,11].

Recently, optical frequency-domain reflectometry (OFDR) based on Rayleigh scattering has been widely studied to realize distributed sensing applications with very high spatial resolution. Moreover, it allows spatially distributed measurement of the phase modal birefringence in a short length of PMF [12]. This technique calculates the autocorrelation of the Rayleigh backscatter spectrum in a distributed manner along the PMF length. Since the responses from both the polarization modes are present in the spectrum, two side peaks are revealed in the autocorrelation. By

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determining the frequency difference between one of the side peaks and the central peak, birefringence information can be determined locally. In this paper, we propose to measure the distributed group birefringence of a PMF using OFDR technique, by investigating laser frequency dependence on the difference of propagation constants ($\Delta\beta = \beta_s - \beta_f$) from the two polarization modes, where β_s and β_f are the propagation constants of the slow and fast modes, respectively. The distributed group birefringence along a PMF can be measured with a spatial resolution of 7.8 cm.

2. Experimental setup

Fig. 1 shows the experimental setup. The OFDR configuration consists of a tunable laser source (TLS) with a continuous sweep mode and a ~100 kHz linewidth working in 1550 nm range. The trigger interferometer is used to sample the data in even frequency space to remove the errors introduced by scanning rate fluctuations from the TLS. The OFDR setup adopts polarization diversity measurement [11–13] through a polarization beam splitter (PBS) which splits the reference light evenly between two orthogonal polarization states (p and s). A section of Panda-type PMF of 5.925 m in length is sandwiched between two short sections of single-mode fibers with FC/APC connectors. At the far end of the single-mode fiber, a small circle is made on the fiber to reduce the Fresnel reflection. When the laser is tuned, the interference signals obtained from the combination of the Rayleigh scattering signal and the local laser beam is split by the PBS. The resultant s and p components are then received and digitized as a function of the TLS frequency by a two-channel acquisition. Fourier transform is then used to convert these frequency data into time-domain data which could be scaled to the length of the testing fiber; after performing a vector sum of the transformed s and p components, the Rayleigh backscatter pattern versus time or the length of the fiber under test can be obtained.

Fig. 2 shows the reflected Rayleigh backscattering signal amplitude as a function of time by performing fast Fourier transform (FFT) of the frequency-domain data within the overall laser tuning range of 6543 GHz (~1510–1561 nm). Reflections from the FC/APC connectors and the end circle are clearly resolved. Both the reflections from the APC connectors are shown in the inset. For the rear APC reflection, there are two peaks resolved, corresponding to the responses from the two polarization modes which have different propagation velocities. By measuring the delays from these two peaks of 28.942 ns and 28.934 ns for the slow and fast axes respectively, considering the length of the PMF of 5.925 m and light velocity in vacuum of 3×10^8 m/s, the group refractive indices for slow and fast mode can also be determined to be 1.4654 and 1.4650 respectively. Therefore, group birefringence can be obtained directly as $\Delta n^g = n_s^g - n_f^g = 4.1 \times 10^{-4}$ where n_f^g and n_s^g are the group refractive indices for the fast and slow modes, respectively. Note that the above group birefringence are average values contributed from the entire length of the PMF. It is worth mentioning that the wider the laser frequency scanning range, the higher time-domain resolution one can obtain. On the contrary, if 1/10 of data (654.3 GHz) is chosen to perform the FFT to obtain the group birefringence, similar results can be obtained, but with a 10 times worse resolution in time domain. In the next section, we will obtain distributed group birefringence which can be used to compare with the average value obtained above.

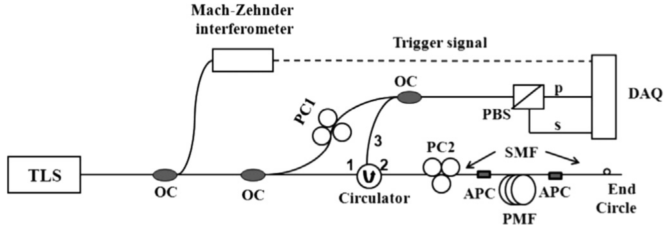

Fig. 1. Experimental setup. TLS: tunable laser source; OC: optical coupler; PC: polarization controller; PBS: polarization beam splitter; PMF: polarization-maintaining fiber; DAQ: data acquisition; APC: FC/APC angled fiber connector.

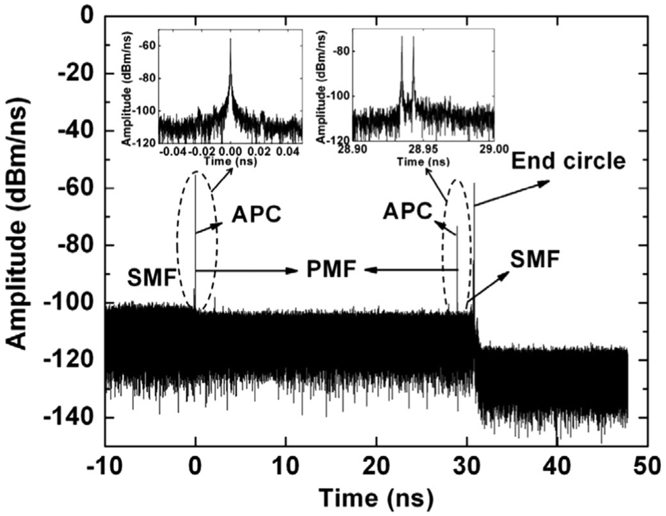

Fig. 2. Rayleigh backscatter amplitude as a function of time with a frequency bandwidth of 6543 GHz. Insets show the enlarged view of the reflection from the FC/APC connectors.

3. Measurement principle and results

In order to analyze the information in a distributed manner, a short section of time-domain data is chosen to transform back to frequency domain. By calculating the autocorrelation of the frequency-domain data, two side peaks show up from the responses of the two polarization modes, as shown in Fig. 3(a) for the total 6543 GHz bandwidth at PMF position of 1.175 m with a spatial resolution of 7.8 cm. This can be understood that the Rayleigh scattering of both the polarization modes results from the same underlying pattern of defects of the PMF. The frequency shift of the side peak, $\Delta\omega$, can be recognized as that the propagation constant for the fast mode equal to that for the slow mode at this frequency difference [12]:

$$\beta_f(\omega) = \beta_s(\omega - \Delta\omega), \tag{1}$$

where ω is the laser angular frequency. By Taylor expanding both sides of Eq. (1) and keeping to the first order, one can obtain

$$\beta_s(\omega_0) - \beta_f(\omega_0) = -\frac{n_s^g - n_f^g}{c}(\omega - \omega_0) + \frac{n_s^g}{c}\Delta\omega, \tag{2}$$

where c is the velocity of light in vacuum, and ω_0 is a constant frequency at which Eq. (1) expands. It is obvious that the frequency shift of the side peak, $\Delta\omega$, is laser frequency dependent. As an example, Fig. 3(b) shows the autocorrelation results using a narrower bandwidth (654.3 GHz) at the same location as that in Fig. 3(a) with the same spatial resolution. The frequency shift of the side peaks has different values compared to that in Fig. 3(a), since the covered frequency ranges are different for the two cases. Before we proceed to obtain the group birefringence, phase modal birefringence and beat length can be estimated based on current results first. For a narrower bandwidth of 654.3 GHz, the first term on the right hand side of Eq. (2) is rather small (less than 0.5%)