Method for improving the resolution and accuracy against birefringence dispersion in distributed polarization cross-talk measurements

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Received April 2, 2012; revised May 13, 2012; accepted May 14, 2012;
posted May 15, 2012 (Doc. ID 165977); published June 29, 2012

We present a novel method for improving the spatial resolution and amplitude accuracy of distributed polarization cross-talk measurements in a polarization maintaining (PM) fiber against its birefringence dispersion. We show that the broadening of measured polarization cross-talk peaks caused by birefringence dispersion can be restored by simply multiplying the measurement data with a compensation function. The birefringence dispersion variable in the function can be obtained by finding the widths of measured cross-talk envelopes at known distances along the fiber. We demonstrate that this method can effectively improve spatial resolution and amplitude accuracy of the space-resolved polarization cross-talk measurements of long PM fibers.

OCIS codes: 060.2310, 060.2300, 060.2370, 060.2420, 060.2800.

Space-resolved polarization cross-talk measurements along a polarization maintaining (PM) fiber have multiple important applications, including distributed stress sensing [1], fiber gyro coil inspection [2], PM fiber birefringence and beat length measurement [3], polarization cross-talk location identification in a PM fiber interferometer system, and PM fiber quality inspection [4]. Scanning Michelson white light interferometers can be used to obtain such distributed polarization cross-talk measurements [3,5]. Unfortunately, as the length of the fiber under test (FUT) increases, the measured cross-talk peaks will be broadened due to birefringence dispersion [6], resulting in reduced spatial resolution and degraded cross-talk amplitude measurement accuracies [7–9] for PM fibers with a length exceeding a few hundred meters.

Birefringence dispersion of PM fibers can be obtained using several different methods, including those of white-light spectral interferometry [10], wavelength scanning [11,12], and dispersive Fourier transform spectroscopy [13]. However, few attempts have been made to reduce the degrading effect of birefringence dispersion on the spatial resolution and amplitude accuracy of measured cross-talk peaks along the PM fiber.

In this Letter, we report a novel method to mathematically compensate the birefringence dispersion in polarization cross-talk measurements of a PM fiber to improve the spatial resolution and measurement accuracy. We first derive a compensation function to prove that the effect of birefringence dispersion on polarization cross-talk measurements can be compensated mathematically. We next use a white light interferometer based distributed polarization cross-talk analyzer (General Photonics PXA-1000) to obtain the initial space-resolved polarization cross-talk peaks along the PM fiber and then get the birefringence dispersion by measuring the widths of the cross-talk peaks as a function of their location along the fiber to complete the dispersion compensation function. Finally, we numerically multiply the compensation function with the original measured cross-talk data to eliminate the dispersion induced broadening of the cross-talk peaks. Our experiment with a PM fiber coil of 1.05 km length demonstrates that the method is effective in improving the spatial resolution and cross-talk amplitude measurement accuracy and can be readilyincorporated in the analysis software. This method is especially useful for obtaining accurate polarization cross-talk measurements of PM fiber coils with lengths of longer than a few hundred meters.

Figure 1 illustrates the basic configuration of a distributed polarization crosstalk analyzer [3]. A polarized super luminescent diode source (SLED) at 1310 nm with a short coherence length about 32.5 μm is coupled into the slow axis of a PM fiber (point A of inset in Fig. 1). Assume at point B, a polarization cross talk is induced by an external disturbance and some light is coupled into

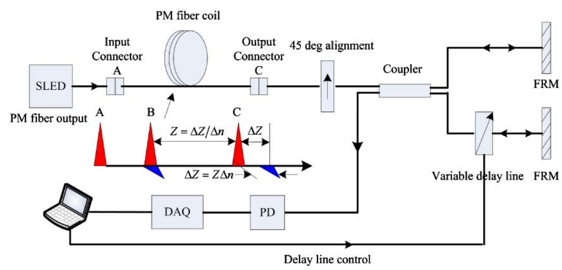

Fig. 1. (Color online) Illustration of a distributed polarization cross-talk analyzer based on a scanning white light Michelson interferometer. The inset shows the delay relation between the original and the cross talk components. Light with a short coherence length travelling in the fiber is polarized along its slow axis at input point A. Crosstalk is induced by a stress at point B where a small portion of light is coupled into fiber's fast axis. The relative delay at output point C between the two polarization components is ΔZ. The location $Z$of cross-talk point B can be obtained from a measurement of ΔZ. FRM, PD, and DAQ are Faraday rotation mirror, photodetector, and data acquisition card, respectively.

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the fast axis of the PM fiber with a coupling coefficient parameter $h = I_1/I_2$, where I_1 and I_2 are the powers in the fast and slow axes of the PM fiber, respectively. Because light polarized along the fast axis travels faster than that along the slow axis, at the output of the fiber, the faster component will be ahead of the slow component by ΔnZ, where Δn is the group birefringence of the PM fiber and Z is the fiber length between the cross-talk point and the fiber end (point C in Fig. 1). A polarizer oriented at 45 deg to the slow axis placed at the output of the fiber projects both polarization components onto the same direction to cause interference between the two components in a scanning Michelson interferometer. When the relative optical path length is scanned, an interference peak appears when the polarization components overlap in space and disappears when they are separated more than the coherence length of the light source. The location where the cross-talk occurs can be calculated from $Z = \Delta Z/\Delta n$ and cross-talk amplitude h can be obtained from the interference signal amplitude.

The envelope of a measured cross-talk peak (the interference peak) is influenced by the SLED's spectral distribution and the birefringence dispersion ΔD of the PM fiber [6–8]. Assume that the SLED has a Gaussian spectral shape; the cross-talk envelope (the degree of coherence) γ can be derived as the function of birefringence dispersion ΔD and the distance Z of cross-talk point measured from the output [6–8]:

$$|\gamma(Z, \Delta D)| = \frac{\sqrt{h - h^2}}{(1+\rho^2)^{1/4}} \exp\left\{-\left[\frac{2\delta d}{(1+\rho^2)^{1/2} W_0}\right]^2\right\}, \quad (1)$$

where

$$\delta d = (\Delta nZ - d), \quad (2)$$

$$\rho = 2\pi c(\Delta\lambda/\lambda_0)^2 \Delta DZ = \alpha \Delta DZ, \quad (3)$$

$$\Delta D = d\tau/d\lambda = -[\omega^2/2\pi c](d^2\Delta\beta/d\omega^2)_0. \quad (4)$$

In the equations above, d is the path length imbalance of the scanned Michelson interferometer, ρ is the accumulated birefringence dispersion along the fiber, α is a parameter accounting for the contribution of the light source's characteristics to the total dispersion effect, c is the speed of light in free space, $\Delta\lambda$ and λ_0 are the spectral width and center wavelength of the light source, $\Delta\beta$ is the propagation constant difference of two polarization eigenmodes, and W_0 is the $1/e$ width of the interference envelope when the dispersion ρ is zero. This width is also the coherence length of the light source. From Eq. (2), one can see that δd can be adjusted by varying the path length difference d of the delay line in the interferometer. The interference signal appears when the path length imbalance d compensates for optical path length difference ΔnZ between two polarization modes.

Inspecting Eqs. (1)–(4), we can learn that both the magnitude and the shape of the measured cross-talk envelope are functions of ΔD and Z. The degrading effects of birefringence dispersion ΔD on a cross-talk measurement are the reduction of the cross-talk envelope's amplitude and the broadening of its shape as Z increases.

Fercher *et al.* described a complicated Fourier domain numerical dispersion compensation technique for removing dispersion in optical coherence tomography signals [14]. Here we find that the effects of birefringence dispersion can be directly removed by multiplying the cross-talk measurement data with a dispersion compensation function $K(\rho)$:

$$K(\rho) = \sqrt[4]{1+\rho^2} \exp\left\{-\left[\frac{2\delta d\rho}{(1+\rho^2)^{1/2} W_0}\right]^2\right\}. \quad (5)$$

As can be seen, the original cross-talk envelope can be completely restored by simply multiplying Eq. (5) with Eq. (1):

$$\gamma(Z, \Delta D) \cdot K(\rho) = \sqrt{h - h^2} \exp\left[-\left(\frac{2\delta d}{W_0}\right)^2\right]. \quad (6)$$

In order to complete the compensation function, the birefringence dispersion ΔD or ρ must be obtained first. From Eq. (1), one yields the relation between envelop broadening and birefringence dispersion as

$$W/W_0 = (1+\rho^2)^{1/2} = (1 + (\alpha\Delta D)^2 Z^2)^{1/2}. \quad (7)$$

Therefore, in principle, the birefringence dispersion ΔD can be readily calculated by measuring the widths of cross-talk envelops at input $(Z = L)$ and output $(Z = 0)$ ends of the PM fiber. In practice, in order to increase the accuracy of ΔD, widths of cross-talk envelops

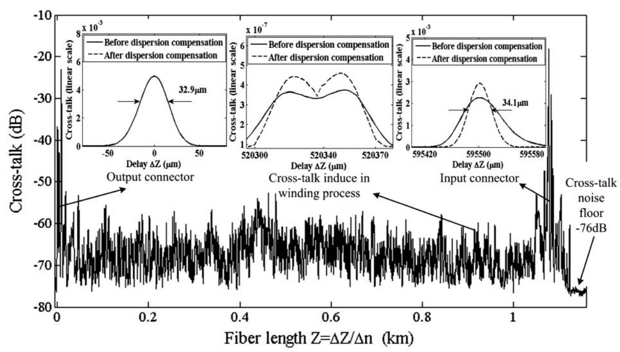

Fig. 2. Polarization cross-talk curve of a PM fiber coil. The insets show the zoom-in view of both the amplitude and width of cross-talk envelopes at output and input connectors, as well as in the middle region of the fiber, where two irresolvable peaks before dispersion compensation (solid line) can be clearly resolved after dispersion compensation (dotted line). The 9/125 μm PANDA fiber under test has a birefringence of $\Delta n = 6.1 \times 10^{-4}$ and the cross-talk measurement curve has dispersion-free spatial resolution of 5.4 cm. Note that our system has a noise floor of −76 dB, so that the noise has negligible effect on the measurements of cross-talk peaks larger than −66 dB.

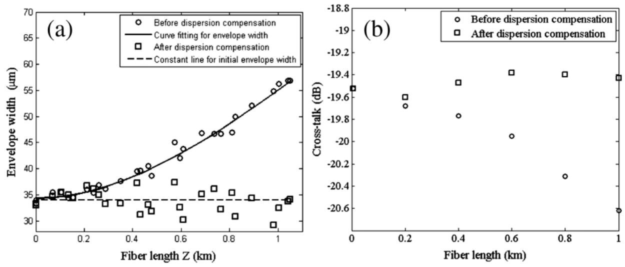

Fig. 3. (a) Envelope widths of cross-talk peaks induced by stress at various locations along the fiber; (b) measured cross-talk amplitude of the input connector with six different fiber lengths (5 m, 205 m, 405 m, 605 m, 805 m, and 1005 m). The cross-talk of the input connector is fixed; however, five segments of fibers with a length of 200 m each are sequentially spliced to the pigtail of the input connector for increased dispersion. The amplitude of polarization cross-talk decreases with the fiber length Z due to birefringence dispersion ΔD and is restored after performing the compensation.

at multiple locations along the PM fiber are measured, and ΔD is obtained by curve-fitting to Eq. (7).

Figure 2 is a measured polarization cross-talk curve of a PANDA PM fiber coil, showing the effects of birefringence dispersion on the measured cross-talk peaks and how the compensation removes those effects. The peaks at far left and far right correspond to cross-talks induced at output and input connectors from slight fiber axis misalignment. The small peaks in between are the cross-talks induced by stresses during the fiber winding process. The solid line on the right inset shows that birefringence dispersion broadens the envelop and diminishes the amplitude of the cross-talk peak occurring at input connector. The dotted line shows that both the envelope and the amplitude of the cross-talk peak are restored after dispersion compensation is performed.

In particular, the envelope width of the peak at the input connector is 34.1 μm after dispersion compensation, which is very close to 32.4 μm of the left peak induced by the output connector with zero dispersion ($Z = 0$).

Figure 3 shows the measured cross-talk peaks (both the width and amplitude of the cross-talk envelope) as a function of distance Z. In experiment, we measured multiple polarization cross-talks at different locations along the PM fiber. Clearly the width increases quadratically with distance Z due to the effect of birefringence dispersion, in agreement with Eq. (7). Such a width broadening starts to degrade the spatial resolution of polarization cross-talk measurements for a distance larger than 200 m.

The birefringence dispersion ΔD of the PM fiber is then accurately obtained by the least-squares fitting the data to Eq. (7) to be 0.0014 ps/(km nm). Substituting the fitting obtained values of $\alpha\Delta D$ into Eq. (5), we complete the dispersion compensation function. Finally, we numerically multiply the function with the original measured cross-talk data to cancel the dependence of polarization cross-talk on birefringence dispersion ΔD. The squares in Fig. 3(a) show that the width broadenings of the cross-talk peaks are removed after dispersion compensation is performed. Figure 3(b) shows the dependence of polarization cross-talk amplitude on the birefringence dispersion before and after dispersion compensation. It is evident that the cross-talk amplitude reduction caused by the dispersion is also removed by the dispersion compensation. Therefore, the compensation technique can effectively improve the spatial resolution and accuracy of cross-talk amplitude measurements using a white-light interferometer based polarization cross-talk analyzers. The fluctuations of data in Fig. 3 may be caused by the slight nonuniformity of birefringence dispersion along the fiber and some measurement errors.

In conclusion, we propose and demonstrate a novel method for compensating the degrading effects of birefringence dispersion on polarization cross-talk measurements by multiplying the original cross-talk data with a compensation function. The compensation function can be obtained by simply measuring the width of cross-talk envelops at known distances. We experimentally verify that the method is effective in improving the spatial resolution and amplitude accuracy of polarization cross-talk measurements of long PM fibers.

This work was supported by the National Basic Research Program of China (973 Program) under grant 2010CB327806, the International Science & Technology Cooperation Program of China under grants 2009DFB10080 and 2010DFB13180, and the China Postdoctoral Science Foundation under grant 20100470782.

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