Mitigation of the birefringence dispersion on polarization coupling measurement in a long distance high birefringence fiber

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Abstract

Due to the birefringence dispersion, the polarization coupling parameter measurement in high birefringence fiber descends obviously with the fiber length, especially for long distance fibers. In this paper, two methods for mitigating the birefringence dispersion in a long distance fiber are proposed. The first method is a spectrum domain measurement method. The experimental setup and results are described detailedly. The other method is a time domain numerical dispersion compensation algorithm to amend the coupling strength calculation equation. It is based on the fact that the interferogram envelope area is a constant even with the existence of birefringence dispersion. The experimental result shows that the time domain algorithm has a high accuracy, and the absolute deviation is less than 1%. The two methods are validated to mitigate the birefringence dispersion in the long distance high birefringence fiber effectively.

Keywords: birefringent dispersion; high birefringence fiber; polarization-maintaining fiber, spectral domain; polarization coupling

Introduction

High birefringence polarization maintaining fibers (PMFs) can reserve a linear polarization state over a long fiber length and have been widely employed in interferometric fiber-optic sensors, polarization sensitive optical devices and so on[1]. The orientation of birefringence in PMFs can be changed by external transverse forces, which leads to the phenomenon of polarization coupling. The coupling strength has a definite relationship with the external transverse forces, therefore, the distributed stress sensor can be realized by a polarization coupling detection system[2-4]. It is very important to detect the polarization-mode coupling parameter between the two orthogonally polarized normal modes[5-6].

Several techniques including polarization optical time domain reflectometry[7], white light scanning interferometry (WLSI)[8-10], frequency modulated continuous wave method[11], optical Kerr effect method[12], and synthesis of optical coherence function (SOCF)[4] have been developed to measure the distributed polarization coupling (DPC). Among them, WLSI becomes one of the most important methods because of high spatial resolution and sensitivity[13]. Usually, the birefringence in PMFs is considered to be wavelength independent, namely, the velocity difference between two orthogonal eigenmodes of PMFs is invariable. But in practical measurement, the birefringence is related to the transmitted wavelength[14]. Due to birefringence dispersion, the polarization-mode coupling parameter and the spatial resolution of coupling point descends obviously with fiber distance. So the negative influences of birefringence dispersion on the long distance birefringence fiber can not be ignored.

In this paper, two methods for mitigating birefringence dispersion in coupling mode detection of a long distance high birefringence fiber are proposed. The first method is a spectrum domain measurement[15,16] and the other is a time domain numerical dispersion compensation algorithm. The theoretical analysis and experimental results are described in detail. The two methods are analyzed comparatively.

1 Influence of birefringence dispersion

The detection principle of polarization coupling is illustrated in Fig. 1. Polarized broadband light is coupled into the employed PMFs with only one polarization mode excited. When there is a force exerted on the sensing fiber, a little fraction of light is coupled into the unexcited mode. Due to the phase birefringence $\Delta n_b(\lambda)$ in the fiber, two polarization modes propagate through the fiber with different group velocities. Thus, the two orthogonally polarized modes have an optical path difference (OPD) of $\Delta n_b(\lambda)\cdot l$ at the output end of fiber, where l is the distance from the force point to the output end of fiber. After passing through an analyzer, the two modes are projected to the same polarization direction. The OPD $\Delta n_b(\lambda)\cdot l$ is compensated by a scanning Michelson interferometer and the white light interferograms are read out during the scanning process.

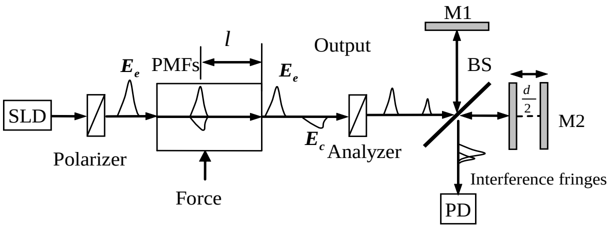


Fig. 1 principle of the polarization coupling detection in PMFs

If the phase birefringence is wavelength independence and one coupling point is occurred, the optical intensity of the interferogram is expressed as

$$I_{out} = I_0\{1+\exp[-(\frac{d}{L_{c0}})^2]\cos(k_0 d) + \sqrt{h-h^2}\exp(-\frac{d^2}{2L_{c0}^2})\cos(\Delta\beta l - k_0 d)\} \quad (1)$$

where I_0 is the DC component of the interference, L_{c0} is the coherent length of the light source. d is the compensated OPD of the scanning Michelson interferometer, k_0 is the wave number in free space, and h is the coupling strength.

The interferogram with one coupling point in the PMFs is shown in Fig.2. The central interferogram A represents the OPD between the two modes is zero. The bilateral interference envelop B are caused by the interference between excited mode and coupling mode.

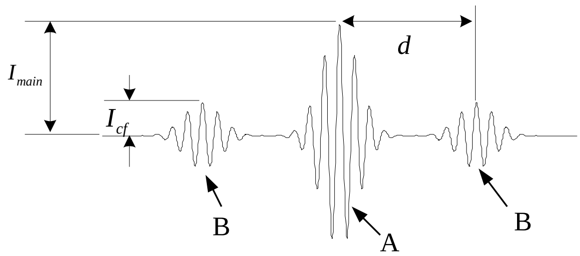


Fig.2 Read out of the interferogram for one coupling point

The bilateral interferogram is caused by

$$\Delta\beta l - k_0 d = 0 \quad (2)$$

So the position of the coupling point is

$$l = \frac{k_0 d}{\Delta\beta} \quad (3)$$

In general case $h \ll 1$, so the coupling intensity

$$h = 10\lg(\frac{I_{cf}}{I_{main}})^2 \quad (4)$$

But in practice, the phase birefringence is wavelength dependent. Propagation constant difference $\Delta\beta(\omega)$ can be expanded in a Taylor series to the second-order near the frequency of ω_0 :

$$\begin{aligned}\Delta\beta(\omega) &= \beta_x(\omega) - \beta_y(\omega) \\ &= \frac{\omega_0}{c}\Delta n_b + \frac{\omega-\omega_0}{c}\Delta N - \pi c\frac{(\omega-\omega_0)^2}{\omega_0^2}\Delta D\end{aligned} \qquad (5)$$

Where ΔN and ΔD are group birefringence and birefringence dispersion of the PMFs respectively. Therefore, the optical intensity of interferogram can be expressed as

$$\begin{aligned}I_{DS-out} = I_0\Big\{1 + \exp\left[-(\frac{d}{L_{c0}})^2\right]\cos(k_0 d) + \frac{\sqrt{h-h^2}}{\sqrt[4]{1+\eta^2}}\exp\left[-\frac{1}{1+\eta^2}\frac{2(\Delta Nl-d)^2}{L_{c0}^2}\right] \\ \times\cos\left[-\frac{\eta}{1+\eta^2}\frac{2(\Delta Nl-d)^2}{L_{c0}^2} + \frac{\omega_0}{c}(\Delta n_b l - d) + \frac{1}{2}\arctan\eta\right]\Big\}\end{aligned} \qquad (6)$$

Where $\eta = 2\pi c\cdot\Delta D(\lambda_0)\cdot l\cdot\left(\frac{\Delta\lambda}{\lambda}\right)^2$.

The birefringence dispersion will cause the envelope change in two aspects: the broadening of envelope width and the loss of interference contrast. The loss of contrast reduces measurement sensitivity of the system and the broadening of envelope decreases the spatial resolution [18].

2 Spectral domain method

In spectral domain, the output frequency-dependent spectral interferogram of the Michelson interferometer can be expressed as:

$$\begin{aligned}\langle I(\omega)\rangle &= (1-h(\omega))\left\langle|E(\omega)|^2\right\rangle + h(\omega)\left\langle|E(\omega)|^2\right\rangle \\ &\quad + 2\sqrt{h(\omega)(1-h(\omega))}\left\langle|E(\omega)|^2\right\rangle\cos(\phi(\omega))\end{aligned} \qquad (7)$$

In general case $h \ll 1$, so the equation can be simplied

$$\begin{aligned}\langle I(\omega)\rangle &= \left\langle|E(\omega)|^2\right\rangle + 2\sqrt{h(\omega)}\left\langle|E(\omega)|^2\right\rangle\cos(\phi(\omega)) \\ &= \langle I_{dc}(\omega)\rangle + \langle I_{ac}(\omega)\rangle\end{aligned} \qquad (8)$$

where $I_{dc}(\omega)$, $I_{ac}(\omega)$ and $\phi(\omega)$ are the DC , AC and the relative phase difference of the interferogram and $\langle\ \rangle$ denotes the ensemble average. Similarly, the spectral domain coupling intensity can be expressed as

$$h(\omega) = 10\log(\langle I_{ac}(\omega)\rangle)^2\cdot(2\langle I_{dc}(\omega)\rangle\cos[\phi(\omega)])^{-2}) \qquad (9)$$

The experimental setup used in spectral domain in PMFs is shown in Fig.3[19]. A superluminescent diode (SLD) emitting at 1328nm was used as the light source. Its spectrum followed a Gaussian distribution and the spectral half-width was approximately 36.5nm. An in-line polarizer was fusion spliced to the input end of the fiber under test to assure only one mode was excited. The output light from the fiber was collimated, passed through a polarization state adjustment, which contains a rotatable wavelength-independent half wave plate (HWP) driven by stepping motor(SM) and a wavelength-independent Glan analyzer. Then the output light was injected into the Michelson interferometer. The interferometer contains beam splitter (BS), stable mirror (M1) and movable mirror (M2). The M2 can scan with the precise linear stage driven by stepping motor (SM).The interference signal was detected with the Optical Spectrum Analyzer (OSA) and then transferred to a personal computer by a data acquisition card (DAQ). The OSA is HP86145B and the wavelength resolution is 0.06nm. The rotatable HWP is adjusted to optimize the rotation angle between the two polarization eigenmodes and the principal axis of the linear analyzer to assure the highest visibility of spectral interferogram[20].

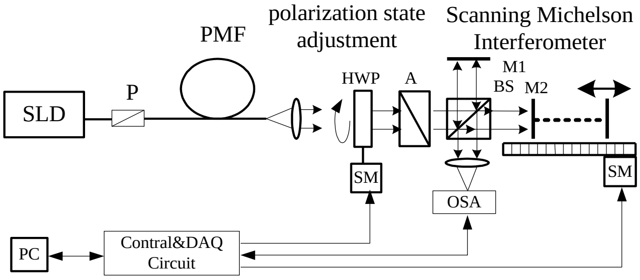


Fig.3 Spectral domain experiment arrangement

SLD: superluminescent diode; P:polarizer; HWP:half wave plate ; A:analyzer; SM: Stepping motor; BS:beam splitter; OSA: optical spectrum analyzer; DAQ: data acquisition

The 1m PMFs patch cord is fusion spliced in front of the test PMFs fiber. The PMFs patch cord is connected with the in-line polarizer with APC adapter, but the deliberate angular misalignment between the patch cord and the polarizer will cause two excited eigonmodes propagating in the fiber. The connecting point between the in-line polarizer and the PMFs patch cord can be regarded as an intrinsic permanent coupling point.

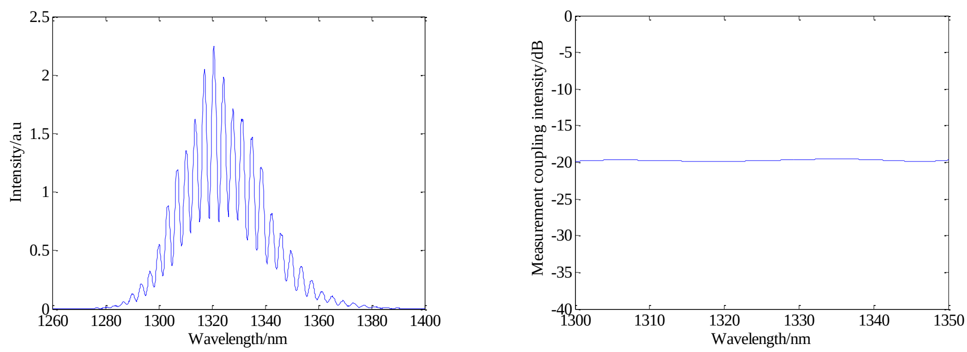
Tab.1 the parameter of the PMFs

Central wavelength	1310 nm
Single mode cutoff wavelength	1208.1 nm
Mode Field Diameter (MFD)	6.04μm
Birefringence B	5.038×10^{-4}
Optical diameter(OD)	123.6μm
h-parameter	2.1×10^{-6} m^{-1}
PMD	0.06ps(1500m)
PDL	0.8dB/km
spectral attenuation	-32.2dB/km
polarization extinction ratio	25 dB
bending loss	< 0.5dB/km

Tab.2 the parameters of the inline polarizer

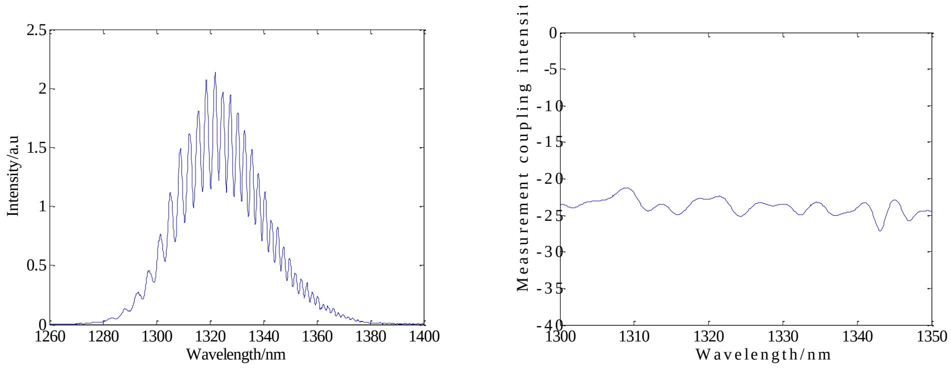
Typical central wavelength	1310nm
Working wavelength range	+50nm
Typical insertion loss	0.3dB
Maximum insertion loss	0.5dB
Return Loss	50dB
Typical extinction ratio	30dB
Maximum incident optical power	300mw

The 110m and 750m length test PMFs is fusion spliced to the output end of the PMFs patchcord. The PER of the two tested PMFs is measured and both are smaller than the coupling strength of permanent coupling point. The measured spectral interferograms recorded by an OSA with 110m and 750m PMFs are shown in Fig.4(a) and Fig.5(a). At first, Fourier transform is adopted. It contains three items in the Fourier transform. The central item and the bilateral items are the DC and AC items respectively. The band-pass filter is adopted and the inverse Fourier transform is applied. The $I_{dc}(\omega)$ and $I_{ac}(\omega)$ can be directly obtained. A polynomial curve fit are applied to retrieve the phase function[19]. The calculated coupling strength is shown in Fig.4(b) and Fig.5(b) using Equation (9) .



(a) (b)

Fig. 4 Spectral domain coupling strength measure with 110m PMFs (a) Measured spectral interferogram recorded by an OSA (b) spectral coupling strength



(a) (b)

Fig. 5 Spectral domain coupling strength measure with 750m PMFs (a) Measured spectral interferogram recorded by an OSA (b) spectral coupling strength

From the experimental results, the spectral domain coupling strength curve in 110m fiber is much smoother than the same curve in 750m fiber. The coupling strength value in 110m fiber is closer to the true value than that in 750m fiber. Due to the increment of the PMFs length, the fiber loss and birefringence dispersion will influence much obviously.

3 Time domain numerical dispersion compensation

In the time domain, according to Eq. (6), the interferogram envelope area is a constant considering the influence of birefringence dispersion, so the coupling strength can be refined as

$$h = 10\log(S_{cf} / S_{main})^2 \tag{10}$$

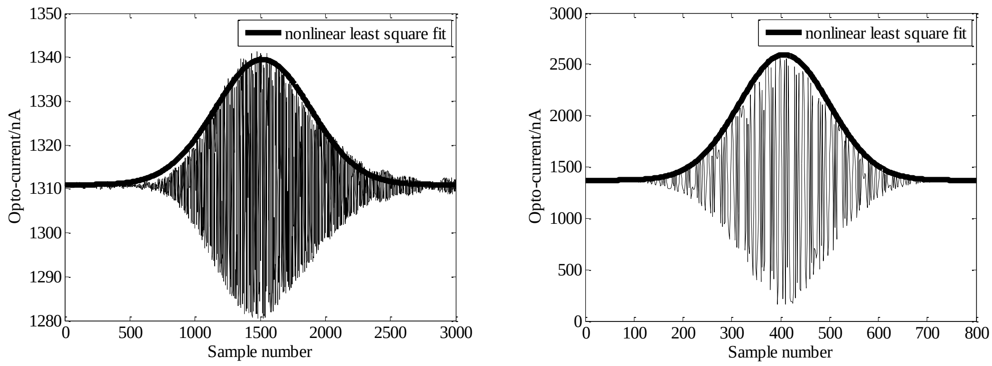
where S_{cf} and S_{main} are the area of the interference envelope of B and A respectively. The interferogram envelope area can be obtained by the Hilbert envelope retrieval and nonlinear least square fitting. Due to the interference envelope is regarded as the cosine signal modulated by Gaussian envelope and the interference envelope can be expressed by

$$f(x) = a\exp\left[-\left(\frac{x-b}{c}\right)^2\right] \tag{11}$$

Where a, b and c are the amplitude, the central position and the envelope width of the interference envelope respectively.

The time domain experimental setup is similar as Fig.3, except that the detector PD (photodiode) has replaced the OSA and the mirror M2 is scanned with the precise linear stage driven by SM. The interference envelope B after transmitting 300m fiber propagation is shown in Fig.6(a) and the corresponding the interference envelope A is shown in Fig.6(b).The nonlinear least square method is adopted to fit the envelope curve and the results are regarded as

$$f_B(x) = 28.56\exp\left[-\left(\frac{x-1521}{517.74}\right)^2\right], \qquad f_A(x) = 1222.76\exp\left[-\left(\frac{x-407}{130.68}\right)^2\right] \tag{12}$$



(a) (b)

Fig. 6 Nonlinear least square fit of white light interference envelope (a) interferogram envelope B (b) interferogram envelope of A

Five repeatable measurements have been tested for PMFs of 10m, 110m, 310m respectively. The experimental results and absolute error are shown in Table 3. The calculated coupling strength is -30.28dB using the Eq. (4), while the coupling strength is -20.95dB using the Eq.(10) with numerical dispersion compensation. The relative error of the coupling strength is less than 0.63dB.

Tab.3 Results and errors coupling intensity measurements at different fiber length

Measurement times	Measurement of coupling intensity/dB					
	Before dispersion compensation			After dispersion compensation		
	10m	110m	310m	10m	110m	310m
1	-22.20	-22.83	-30.21	-21.48	-20.57	-20.51
2	-21.88	-23.26	-30.50	-21.72	-21.73	-20.68
3	-22.54	-23.15	-29.77	-21.37	-21.19	-21.37
4	-22.08	-23.09	-30.46	-20.76	-21.84	-20.83
5	-22.32	-23.49	-30.47	-20.71	-21.43	-21.38
Mean/dB	-22.20	-23.16	-30.28	-21.21	-21.35	-20.95
Std/dB	0.25	0.24	0.31	0.45	0.51	0.40
Absolute error/dB	1.48	2.44	9.56	0.49	0.63	0.23

The PMFs with different length are fusion spliced to the output end of the PMFs patchcord. The birefringence dispersion of the test PMFs is measured as $0.018 ps/(km \cdot nm)$ with temperal Michelson interference. The experimental result is shown in Fig.7. The triangle, the circle and the real line are the experimental coupling strength with Eq. (4), the same with Eq. (10) and the theoretical value with Eq. (6) respectively. It can be seen the coupling strength will decrease drasticly with the fiber length. The difference of the experimental value and theoretical value is more and more obvious with the fiber length. The loss of optical fiber is not considered.

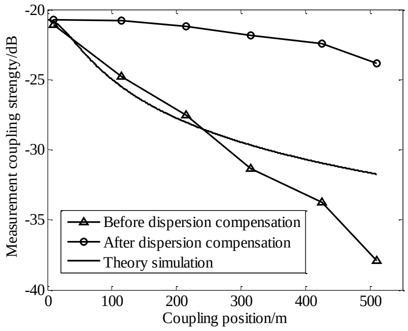


Fig. 7 Dispersion compensation result in the time domain

Discussion

The spectral domain measurement of coupling point in a long distance high birefringence fiber only requires one spectral interferogram. Because the spectral interferogram involves phase information, the coupling strength can be measured in arbitrary length fiber without the influence of birefringence dispersion in theory. However, in practical measurement, the coupling strength is dependent on wavelength, and not suitable to be expressed by a concrete value. According to the experimental results, the spectral coupling strength decreases with the increment of the fiber length.

The time domain measurement with PD detector requires the mirror M2 to scan to acquire the optical intensity. The numerical compensation algorithm can solve the broadening of envelope width and the loss of interference contrast. The spectral domain measurement precision mainly depends on the high visibility interferogram and the accuracy of phase retrieving. It can acquire the coupling intensity of all wavelengths which is only limited by the source bandwidth. The time domain measurement is a purely numerical compensation method which can only be used to amend the coupling intensity according to the time domain experimental results.

However, for both the time and the spectral domain measurement, the deliberated adjustment to obtain high visibility interferogram is obligatory. Furthermore, once the fiber is too long in the experiments, either the time or the spectral domain can not detect the interferograms effectively due to the signal loss. The fiber, space and element loss is not considered in this paper, and further work will be done.

Conclusion

Due to the birefringence dispersion, the polarization coupling strength measurement descends obviously with fiber distance, especially for long distance PMFs. Two methods for mitigating the influence of birefringence dispersion in DPC measurement are proposed. The first method is the spectrum domain measurement. Fourier-transform and a polynomial curve fit are applied to retrieve the phase function in the spectral interferogram. The experimental results validate the effectiveness of the spectral domain measurement. On the other hand, the time domain numerical dispersion compensation algorithm is presented to amend the coupling strength calculation equation, which is based on the fact that interferogram envelope area is a constant even with the existence of birefringence dispersion. The envelope area can be obtained by the Hilbert envelope retrieval and nonlinear least square fitting. The experimental result shows that the algorithm has a high accuracy, and the absolute deviation is less than 1%.The merits and the faults of the two methods are discussed comparatively.

Acknowledgments

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