Fiber beat-length measurement for low- birefringence fibers based on polarized light interference

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Abstract: A new method to measure the beat-length in low-birefringence fibers was shown. The optical path was consisted of an amplified spontaneous emission (ASE) light source, a fiber Fabry-Perot tunable filter, two linear polarizes, the measured fiber and a phase compensation plate. Phase detection was chosen to reduce the error from environment influence. Phase compensation plate was applied to ensure the testing system always sensitive to the change of phase. The testing system was set up and tested in reality. The system performed well in the repeated test. It is simple and has no strict demand on these equipments. There is no limitation on the configuration and the length of the measured fiber. It is reliable for fibers witch's beat-length is up to 20 m. The beat-length precision of the measurement is 1%.

Key words: beat-length; low-birefringence fiber; phase detection

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基于偏光干涉效应的低双折射光纤拍长测试方法

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摘 要: 展示了一种低双折射光纤拍长测试方法。光路由ASE光源、可调F-P滤波器、两个线偏振器、待测光纤和相位补偿器组成。应用相位检测方法降低环境因素引入的误差,使用相位补偿器保证测试系统工作点位于光强对相位变化敏感处。搭建测试系统并进行了实际测量,系统检测可重复性良好。该方法对实验设备要求不高,对于待测光纤的长度没有限制,可测拍长范围达到20 m,测量精度达1%。

关键词: 拍长; 低双折射光纤; 相位检测

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0 Introduction

Low-birefringence fiber[1] (LBF) is a special kind of optical fiber with a long beat-length. LBF is widely used as a sensing element in fiber-optical current transducers (FOCT). The birefringence of LBF is the most important parameter. Beat-length reflects the characteristic of induced birefringence and evaluates the ability of polarization maintaining. There are several kinds of beat-length measurements: the pressure method[2], magnetic light modulation method [3], broadband light source method[4], Rayleigh scattering method[5], fiber Bragg gating method[6]. Most of these methods only go for high-birefringence fibers (beat-length 1 mm-10 mm). The accuracy of most methods can reach 0.1 mm. However, the beat-length of LBF can be longer than 100 m and it is sensitive to the environment factors. For some reason, these methods above can't match the test conditions of LBF. First, some measurements of Polarization Maintaining Fibers (PMF) are limited by the testing principle. Second, the theoretical accuracy decreases when the beat-length gets longer. Third, it is hard to fulfill the requirement in reality for some theoretical feasible methods.

Several beat-length measurements with long beat-length testing range were reported overseas. For example, Sagnac method[7], Polarization Shuttle Pulse method[8]. Both methods can test a fiber when the beat-length is 10 m under appropriate conditions. There are some limitations there: the theoretical testing range is less than 20 m, testing progress is complex and the precisions of the devices must be high enough.

A fiber beat-length measurement for low-birefringence fibers based on phase detection technology is presented in this study. The theoretical testing range can reach 100 m and the accuracy is 0.1 mm. In reality testing at present, the testing range was 20 m and the accuracy is 0.1 mm.

1 Testing principle

The polarized light interference effect is the foundation of this testing. According to the fiber birefringent characteristic, the testing fiber can be treated as a birefringent crystal. When a linearly polarized light pass through the fiber, it can be separated into two mutually orthogonal polarization modes $\mathbf{HE}_{11x}$, $\mathbf{HE}_{11y}$. A phase difference δ will generate between two orthogonal polarization modes depending on the propagation length. Then the ponderances of two orthogonal polarization modes get intervened at the polarizer. It is convenient to figure out the phase difference δ according to the interference.

The fiber beat-length measurement system is shown in Fig.1. In the next part Jones matrixes was used to analyse the testing principle.

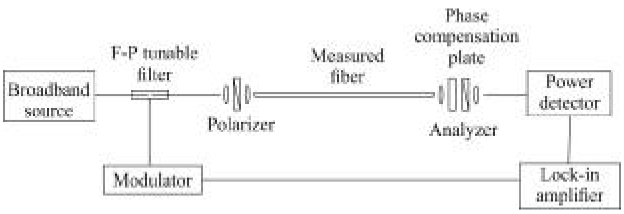

Fig.1 Principle diagram of the beat-length measurement for low- birefringence fibers

Suppose these devices idealized. There is no insertion loss (IL) or polarization dependent loss (PDL). The light out of the broadband light source injects into an F-P tunable filter. It creates a narrow-band light whose wavelength is modulated by the F-P tunable filter. The Jones matrix of the light through the filter is:

$$E=Ee^{i(2\pi c/\lambda+\varphi)}\begin{bmatrix}\cos\theta\\ \sin\theta\end{bmatrix} \quad (1)$$

In the formula, $\mathbf{E}_0$ for light amplitude, $\mathbf{c}$ for light speed in the vacuum, λ for the wavelength, φ is the initial phase, θ is the state of polarization.

The Jones matrix of the measured optical fiber is:

$$M=\begin{bmatrix}1 & 0\\ 0 & e^{i\delta}\end{bmatrix} \quad (2)$$

In formula (2):

$$\delta=2\pi \mathbf{LB}/\lambda \quad (3)$$

Where δ is the phase difference between the two mutually orthogonal polarization modes $\mathbf{HE}_{11x}$, $\mathbf{HE}_{11y}$ in the testing fiber. It is engendered by the fiber birefringence effect.

L is the length of measured optical fiber, **B** is the birefringence coefficient. So the beat-length $\mathbf{L_b}$ can be expressed as:

$$\mathbf{L_b}=\lambda/\mathbf{B} \tag{4}$$

The Jones matrixes of polarizer and analyzer are the same:

$$M_{pin}=\begin{bmatrix}\cos\theta_1 & -\sin\theta_1\\ \sin\theta_1 & \cos\theta_1\end{bmatrix} \tag{5}$$

$$M_{pout}=\begin{bmatrix}\cos\theta_2 & -\sin\theta_2\\ \sin\theta_2 & \cos\theta_2\end{bmatrix} \tag{6}$$

θ_1 (θ_2) is the angle between polarizer (analyzer) transmitting axis and the fast axis or the equivalent fast axis of measured fiber.

The phase compensation plate engenders an additional phase difference δ_m in the optical path. It changes the phase of output light. Use it or not depends on the phase difference δ produced by the fiber birefringence.

Without the phase compensation plate, the output light **E** is:

$$\mathbf{E}=M_{pout}\cdot M\cdot M_{pin}\cdot \mathbf{E_0} \tag{7}$$

Suppose that input light is natural light. The output light intensity **I** is:

$$\mathbf{I}=\mathbf{E}\cdot\mathbf{E}^*=I_0(\mathbf{K_1}+\mathbf{K_2}\cos\delta) \tag{8}$$

$I_0=|\mathbf{E}(\cos\theta_1+\sin\theta_1)|$ is the light intensity through the polarizer.

The position and capability of polarizer and analyzer decide two parameters:

$$\mathbf{K_1}=\cos^2\theta_1\cos^2\theta_2+\sin^2\theta_1\sin^2\theta_2$$
$$\mathbf{K_2}=2\cos\theta_1\cos\theta_2\sin\theta_1\sin\theta_2 \tag{9}$$

In the optical path, if the wavelength changes continuously, the phase of output light would change periodically as is shown in Fig.2. Depending on the output light intensity graph the beat-length of measured fiber will be worked out.

The environmental factors such as pressure, temperature changing, bending can affect the output light phase at a low frequency. To avoid the influence of environmental factors, a wavelength modulation device is applied in the testing system. A signal generator is used to create a sine-wave to modulate the filter. A lock-in amplifier is used to detect the output signal. It can remove the influence of the environment.

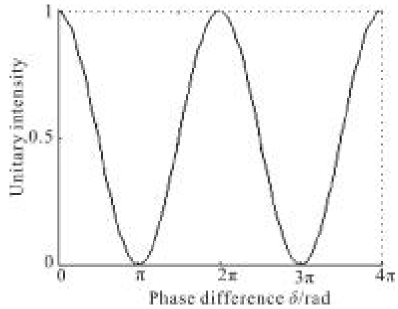

Fig.2 Output light intensity graph depending on the phase difference

2 Accuracy analyses

The experimental setup chose a broadband source and a fiber Fabry-Perot tunable filter to create the input light. The center wavelength of the broadband source is 1 550 nm and the bandwidth is about 35 nm. Set the bandwidth of the filter as 0.5 nm. The coherent length Δ of input light is:

$$\Delta=\lambda^2/\Delta\lambda=48.05\ \text{mm} \tag{10}$$

To achieve the experiment the optical path difference (OPD) of the two mutually orthogonal polarization modes must shorter than coherent length Δ. In math, it is described as:

$$\delta\lambda/2\pi<\Delta \tag{11}$$

Out of the formula (11) we get $\mathbf{L}<3\,100\mathbf{L_b}$, and it is practical in actual experiment.

Out of the formula (8), it is obvious when the polarizer and analyzer angle equals to $\pi/4$ ($3\pi/4$) the testing can reach the optimal contrast. In the experiment the polarizer and analyzer will be adjusted at the optimal angle depending on the variety of output light intensity.

Figure 3 shows the light intensity graphs at different polarizer and analyzer angles. No matter how the polarizer or analyzer angle changes, the periodicity of curve wouldn't change. The polarizer and analyzer angles affect only the contrast.

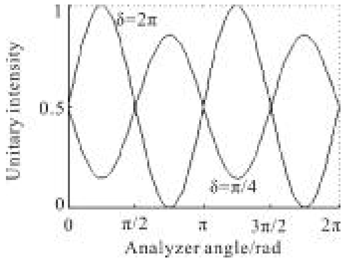

Fig.3 Light intensity graphs at different polarizer angles

The beat-length of the measured fiber is shown by the periodically change of the output light intensity. Different optical fibers have different beat-lengths; the periodicity is not the same as well. For general PMB the beat-length is 1 mm to 10 mm, the output light intensity graph is shown in Fig.4 (a). There are several periods in the graph; it is easy to figure out the beat-length by calculating the length of the Periods. For normal single-mode fibers the beat-length doesn't have an exact range, it can be 1 cm or 1 m. The output light intensity graph is shown in Fig. 4 (b). Usually the period is longer than the bandwidth; the graph only shows less than one period. In this situation a curve fitting should be applied to work out the beat-length. For low-birefringence fibers, the beat-length can be as long as 100 m or longer. The output light intensity graph is shown in Fig.4 (c). It is impossible to revert to the whole period from the graph. The phase difference is only about 0.001 rad. To distinguish the phase difference, phase detection technology is applied, for the precision of phase detection is 10^{-4} rad.

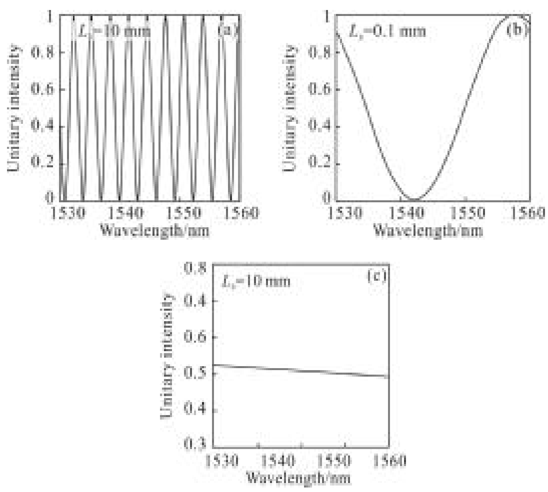

Fig.4 Fiber with different beat-length had different periods in output light

3 Input light intensity compensation

In formula (8), the output light intensity **I** is decided by the input light intensity $\mathbf{I_0}$ directly. Usual broadband light source have a curly spectrum curve. The wavelength changes, the input light intensity $\mathbf{I_0}$ changes. It changes smoothly and depending on the wavelength, it can't be removed by wavelength modulation or filter.

As broadband light source have good time stability, the power spectrum measured with the same setup except without the output polarizer is on record to compensate the output light intensity **I**.

4 Phase compensation

The experiment couldn't show a whole period of the curve if the beat-length is longer than 0.7 m. It becomes a matter that which part of the period is shown.

If the phase difference of the two mutually orthogonal polarization modes δ is close to π, the experiment graph includes a peak. It decreases the testing sensitivity seriously (Fig.5(a)). If the phase difference δ is close to $\pi/2$, the testing sensitivity is good (Fig.5(b)).

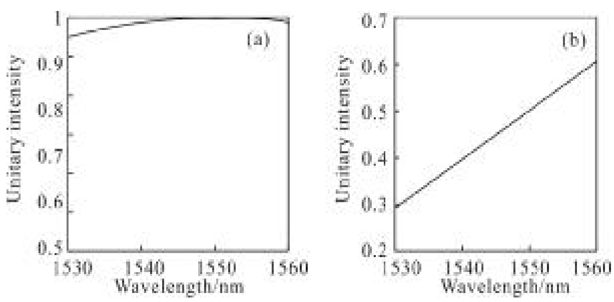

Fig.5 Phase difference affected testing sensitivity

A phase compensation plate is added to solve the problem. The Jones matrix is:

$$M_m=\begin{bmatrix}1 & 0\\ 0 & e^{i\delta m}\end{bmatrix} \quad (12)$$

In the formula (12) $\delta_m=2\pi\boldsymbol{\Delta nd}/\lambda$, it is the additional phase difference from the plate. Adjusting the plate let the axis of the plate and the axis of the measured fiber coupled and made a total phase difference $\delta+\delta_m$ near $\pi/2$, the testing position will avoid the peak of the curve.

The output light intensity becomes:

$$I=I_0[k_1+k_2\cos(\delta+\delta_m)] \quad (13)$$

Noticing than wavelength dependence of the additional phase difference and the phase difference are coherent, it is easy to identify the phase difference in the testing date.

5 Experimental date and analysis

In the experiment, an ASE source (1 525 -1 565 nm), a F-P tunable filter (bandwidth 0.5 nm, adjustable range 1 520 -1 620 nm), a polarizer and a analyzer (extinction ratio 30 dB) were applied. The F-P tunable filter was modulated by the signal generator. The modulation frequency was 1 Hz.

As there are several mature beat-length testing methods, a PMF was tested in the experiment as a judge of the testing precision. The measured fiber's length **L** was 650.1 mm. The origin date graph is shown in Fig.6.

For PMF, it is easy to identify the period of the curve. The beat-length can be calculated out by the equation:

$$L_b=\frac{L}{\lambda/\Delta\lambda+1} \quad (14)$$

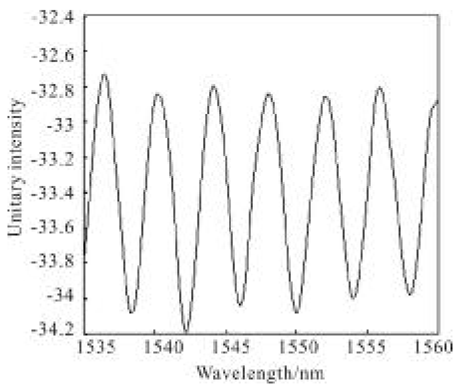

Fig.6 Origin date of PMF beat-length test

$\Delta\lambda$ is for the period, **L** is the length of measured fiber, λ is the average wavelength in the testing.

The beat-length was 1.76 mm. This result was insured in the repeated experiment with the precision 0.01 mm. The date sheet shown the beat-length was 1.80 mm. The testing result was highly coherence with the parameter from the workshop.

An ordinary single-mode fiber was tested by the experiment setup. The length of the fiber is 3.016 m. The testing result is shown in Fig.7.

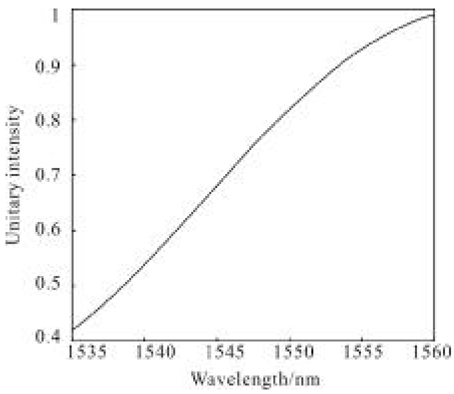

Fig.7 Ordinary single-mode fiber beat-length testing experiment

Use curve fitting to calculate the beat-length. The fitting equation was $A+B\cos(C/x+D)$.

Four parameters were set. Of which $C=2\pi LB$, so the beat-length was:

$$L_b=2\pi L\lambda/C \quad (16)$$

The result was 13.97 cm. In the experiment the error in fiber length was 0.1 mm, the error of wavelength was 0.01nm, the error of the fitting was less than 30. So the error of the beat-length was 0.3%. **C** would decrease when beat-length became longer.

To the devices in this test, when the beat-length is less than 20 m, the error is less than 1.2%.

6 Conclusion

In this study a best-length measurement fitting for low birefringence fiber is shown. It is based on polarized light interference. When the beat-length of measured fiber is shorter than 20 m, the testing precision can reach 1%. There is no special limit on fiber length and structure for measured fiber. The request for polarizer is not very strict. The beat-length testing range is longer than 100 m in theory. In farther study, a positive compensate method can be applied to improve the reality precision.

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