# Influence of angle misalignment on detection polarization coupling in white light interferometer

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## ABSTRACT

A white light interferometer is designed to measure the distributed polarization coupling (DPC) in polarization-maintaining fiber (PMF). By using a Michelson interferometer to compensate the optical path difference induced by the modal birefringence of PMF, both the coupling strength and position of the coupling point can be acquired. The two reflective mirrors on the fixed and scanning arms should be vertical to each other. But in practice, the movable reflective mirror can't be vertically aligned exactly to the fixed mirror, which would lead to angle misalignment. The angle misalignment would induce the variance of the optical path difference (OPD), which would reduce the fringe visibility. Finally, the angle error would lead to a decrease on the signal noise ratio (SNR) and miscalculation of the polarization coupling intensity. The angle misalignment and diameter of the incident light beam both have an effect on the fringe visibility. The simulation results show that the requirement of angle error becomes stricter with the increasing of the light beam diameter. To decrease the angle misalignment, the two plane reflective mirrors should be replaced with the corner cube prisms. A revised coupling strength calculation equation was proposed to minimize the influence of angle misalignment.

**Key words**: white light interferometer, polarization-maintaining fiber (PMF), distributed polarization coupling (DPC), Michelson interferometer, angle misalignment

## 1.INTRODUCTION

High-birefringence polarization-maintaining fibers (PMFs) can preserve a linear polarization state over a long fiber length and have widely employed in interferometric fiber-optic sensors, polarization sensitive optical devices[1]. But even in PMFs, due to some internal and external perturbations, such as intrinsic structure imperfections, transverse stresses and twists, one polarization mode will be coupled into another orthogonal one, which is called polarization coupling[2,3]. Polarization coupling will reduce polarization conservation ability and affect system performance. So it is crucial to detect the location and coupling intensity of the coupling point in polarization fiber manufacturing, installation and

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application[4,5]. Because the coupling intensity has a definite relationship with the external transverse forces, distributed stress and location sensing can be realized with polarization coupling system[6-8]. There are several methods to measure the distributed polarization coupling (DPC), including polarization optical time domain reflectometry[9], white light interferometry (WLI)[10,11], frequency modulated continuous wave, optical Kerr effect and synthesis of optical coherence function.

WLI has been widely used due to absolute measurement and high spatial resolution. A traditional white light interferometric measurement system consists of a sensing interferometer and a processing interferometer. The former is used to convert the measurand into a variation of the optical path difference (OPD). The latter compensates the OPD in the orthogonal axes and creates the interference fringe pattern. The Michelson interferometer is adopted with a scanning arm driven by a stepping motor and a fixed arm. The two reflective mirrors on the scanning and fixed arms should be vertical to each other. But in practice, the movable reflective mirror on the scanning arm can't be vertically aligned exactly to the fixed mirror. The influence of the angle misalignment between the two mirrors is evaluated theoretically. Based on the analysis, the solution will be proposed to decrease the influence of angle error

## 2.MEASUREMENT PRINCIPLE OF THE DPC DETECTION SYSTEM

The working principle of the distributed polarization coupling detection system is shown in Fig.1. The polarized light is coupling into the PMFs with only one polarization mode excited. When there is one polarization coupling point, a little fraction of light is coupled into the orthogonal axis. Because of the modal birefringence $\Delta n_b(\lambda)$ of the PMF, two polarization modes propagate through the fiber with different group velocities. At the output end of the fiber, an optical path difference (OPD) $\Delta n_b(\lambda)\times l$ is produced between two orthogonally polarized modes, where $l$ is the fiber length between the coupling point and the output end of the fiber, $l$ also represents the coupling point position. L is the total fiber length, also represents the maximum measurement range. Because of the OPD in the two orthogonal directions, there is no interference fringe pattern. Using an analyzer, the two modes are projected to the same polarization direction. The sensing interferometer consists the light source, the PMF and the analyzer, which converts the polarization coupling measurand into the OPD. The Michelson interferometer is adopted as the processing interferometer, which compensates the OPD induced by the polarization coupling point and creates the interference fringe pattern.

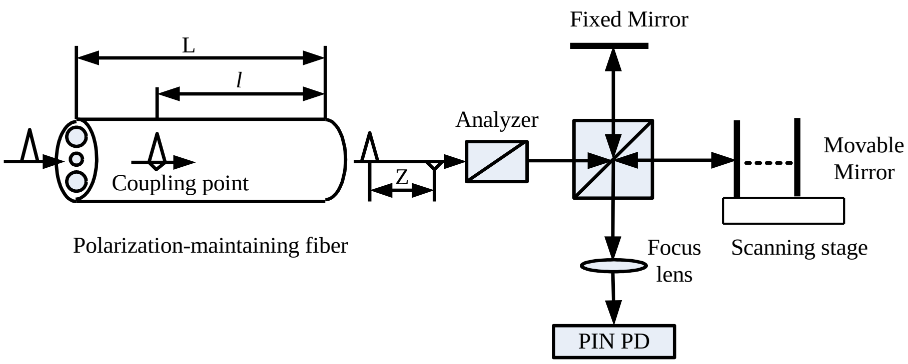


Fig.1 Principle of polarization coupling detection system

The superluminescent diode (SLD) is adopted to act as the broadband light source and the light ejected from the SLD is converted to linear-polarization light. It is assumed the x-directional polarized light is coupled into the PMF, the light wave vector will be written as

$$E_{x0} = A exp(i\phi_0) \tag{1}$$

Where A is the amplitude of the electric field. From the polarization coupling point, light propagates through an *l* fiber length and phase latency is produced. Then light wave vector is described by

$$E_{x1} = A exp\left(i(\phi_0 + \phi_1)\right) \tag{2}$$

In the polarization coupling point, the x-directional light is coupled into orthogonal y-directional polarization axis. Because the perturbed fiber length is limited, the phase change caused by the beat variance is neglectful. The light wave vectors on the x- and y-directional are described by

$$E_{xc} = \sqrt{1-h} A exp\left(i(\phi_0 + \phi_1)\right) \tag{3}$$

$$E_{yc} = \sqrt{h} A exp\left(i(\phi_0 + \phi_1)\right) \tag{4}$$

Where h is the coupling strength parameter. The polarization-maintaining fiber birefringent is $n_x - n_y = \Delta n_b$, and the light wave vector on the ouput end of fiber is rewritten as

$$E_x = \sqrt{1-h} A exp\left(i(\phi_0 + \phi_1 + kn_x l)\right) = \sqrt{1-h} A exp\left(i(\phi + k\Delta n_b l)\right) \tag{5}$$

$$E_y = \sqrt{h} A exp\left(i(\phi_0 + \phi_1 + kn_y l)\right) = \sqrt{h} A exp(i\phi) \tag{6}$$

Where k=2π/λ is the wave number in vacuum. The two orthogonal polarization modes are projected on the same polarization direction using the analyzer and the projection proportion is both $1/\sqrt{2}$. The light wave vector in the projection axis is described by

$$E = \sqrt{(1-h)/2} A exp\left(i(\phi + k\Delta n_b l)\right) + \sqrt{h/2} A exp(i\phi) \tag{7}$$

The light power in the projection axis is coupled into the Michelson interferometer. The OPD between the scanning arm and the fixed arm is ΔZ, and the electric field vector on the two arms is defined by

$$E_1 = (\sqrt{1-h}/2) A exp\left(i(\phi + k\Delta n_b l + k\Delta Z)\right) + (\sqrt{h}/2) A exp\left(i(\phi + k\Delta Z)\right) \tag{8}$$

$$E_2 = (\sqrt{1-h}/2) A exp\left(i(\phi + k\Delta n_b l)\right) + (\sqrt{h}/2) A exp(i\phi) \tag{9}$$

The light reflected from the scanning arm will interfere with that reflected from the fixed arm. The interference intensity is calculated by

$$I = A^2 / 4 \begin{Bmatrix} 1 + \gamma(\Delta Z) cos(k\Delta Z) \\ + \sqrt{h(1-h)}\gamma(\Delta Z \text{ - } \Delta n_b l) cos(k(\Delta Z \text{ - } \Delta n_b l)) \\ + 2\sqrt{h(1-h)}\gamma(\Delta n_b l) cos(k\Delta n_b l) \\ + \sqrt{h(1-h)}\gamma(\Delta Z + \Delta n_b l) cos(k(\Delta Z + \Delta n_b l)) \end{Bmatrix} \tag{10}$$

Where γ(x) is the optical coherence function of the light source. It is assumed that γ(x) function distribution agrees with Gauss function distribution. $\gamma(\Delta x) = exp(-(2\Delta x / L_c)^2)$, where Δx is the optical path difference and Lc is the coherence length of the light source. From the equation (9), there will be interference only on the two cases.

$$I = A^2 / 4[1 + \gamma(\Delta Z) cos(k\Delta Z)] \qquad |\Delta Z| < L_c \tag{11a}$$

$$I = A^2 / 4\left[1 + \sqrt{h(1-h)}\gamma(\Delta Z \text{ - } \Delta n_b l) cosk(\Delta Z \text{ - } \Delta n_b l)\right] \qquad |\Delta Z - \Delta n_b l| < L_c \tag{11b}$$

Equation (11a) indicates the interference when OPD in the two arms is zero. Equation (11b) indicates that the interference occurs when the OPD compensates the OPD caused by PMF. Using the interferograms, the coupling point position and strength can be calculated by

$$h(dB) = 20\log\left(I_{coupling} / I_{main}\right) \tag{12}$$

$$l = \Delta Z / \Delta n_b \tag{13}$$

where $I_{main}$ is the amplitude of interference fringe when the OPD is zero, $I_{coupling}$ is the amplitude of zero-order fringe in the interference packet, as shown in Fig.2. Under ideal condition, the fringe contrast will be constant and the value is 1.So $I_{main}$ will be equal to $I_0$, where $I_0$ is the DC component of the inference. Finally, the coupling strength will be calculated by

$$h(dB) = 20\log\left(I_{coupling} / I_0\right) \tag{14}$$

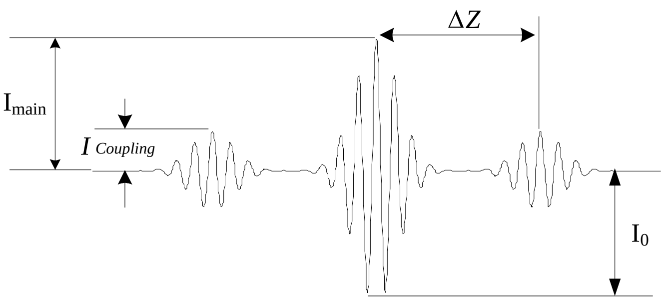


Fig.2 Read out interferograms with one coupling point

## 3.INFLUENCE OF ANGLE MISALIGNMENT

In Michelson interferometer, it is usually considered that the movable mirror is vertical to the fixed reflected mirror. The ray transmits through the cube beam splitter, some is reflected to the fixed mirror while the other transmits the beam splitter and entered the movable mirror. But in practice, the two mirrors are not strictly vertical each other[12], so the ray reflected from the mirror will not have the same OPD. Because the incident parallel ray is not single ray, the collimated extended light diameter usually reaches to several millimeters. The OPD between the two arms will be not constant, which will change within the diameter. As shown in Fig.3, the OPD will increase or decrease when the angle misalignment varies. The OPD variance will affect the interferogram, which will deduce miscalculation of coupling position and strength.

In Fig.(3), x coordinate is set as shown. Owing to the angle misalignment, the OPD in the ray section between two arms is defined by

$$\delta Z = 2(Z + x \cdot \tan\alpha) \tag{15}$$

where z is the length difference of the two arms. $\alpha$ is the angle misalignment between the two arms. The light wave vector is described by

$$E_1 = A \cdot S \cdot exp(ikZ_1)\,, \qquad E_2 = B \cdot S \cdot exp(ikZ_2) \tag{16}$$

Where A and B are the amplitude of light waves respectively on the fixed and movable mirror. S is the area of the parallel incident light beam. $Z_2$ is dependent on the x coordinate. It is assumed that the incident light beam is a circle, the interference intensity is described by

$$\begin{aligned} I &= \int_{-d/2}^{d/2} \left(A^2 + B^2 + 2AB\gamma\left(2z + 2x \cdot \tan\alpha\right)\cos k\left(2z + 2x \cdot \tan\alpha\right)\right) dx \int_{-\sqrt{d^2/4 - x^2}}^{\sqrt{d^2/4 - x^2}} dy \\ &= (A^2 + B^2)S + 2AB\int_{-d/2}^{d/2} \gamma\left(2z + 2x \cdot \tan\alpha\right)\cos k\left(2z + 2x \cdot \tan\alpha\right)\sqrt{d^2 - 4x^2}\, dx \end{aligned} \tag{17}$$

Where $\gamma(\ )$ is the coherent function of the light source. It is shown that when there is no angle misalignment, the interferograms contrast will be dependent on the light wave amplitude A, B and the coherent function $\gamma(\ )$.But when the $\alpha$ is not zero, that is to say, there exits angle error, the interferogram contrast variance will be independent of the value of A,B ,which will be determined by the integration in the Equation 16.

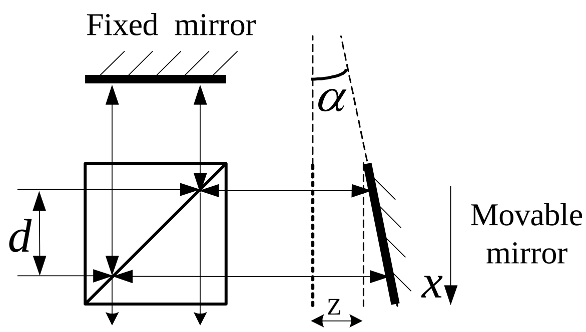


Fig.3 Angle misalignment in Michelson interferometer

Because the Equation 16 is complicated, it is very difficult to solve the solutions through the integration. The analytical solution is adopted to analysis the influence of angle misalignment. It is assumed that A is equal to B, the central wavelength of light source is $\lambda$=1300 nanometers, the coherent length of light source is Lc=30μm, and the diameter of parallel ray is 1 mm. It is shown that the normalized interference power will change with the OPD, when the angle misalignment is 0˚、0.03˚ and 0.05˚ respectively. When the OPD varied around the zero, the interference intensity will decrease with the increasing the angle misalignment. When the angle error reaches to 0.5˚, the interference power will drop half of original value. The interference intensity fall will drop the signal noise ratio (SNR).

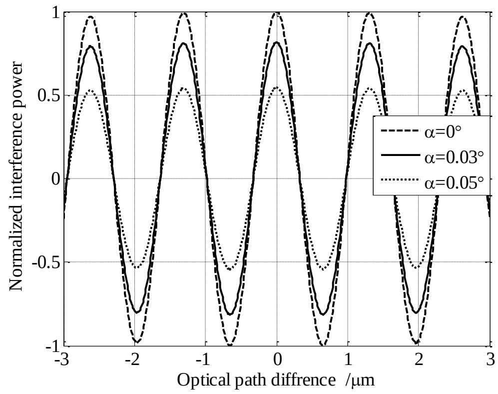


Fig.4 Interference power change with the angle $\alpha$

As the same situation to Fig.4, the interference fringe contrast will change with the angle misalignment when the light diameter is 0.5mm、1mm and 2mm respectively, which is shown in Fig.5. When the angle error varies from 0˚ to 1˚, the fringe contrast will overall drop. The drop amplitude will become quickly when the light diameter is increasing. When the diameter is 1mm and the angle error is larger than 0.03˚, the fringe contrast will drop to 80 percent of original value and the contrast will drop to 1.5 percent of original value when the angle error $\alpha$ is 0.5˚. The requirement to angle misalignment will be raised exponentially with the increasing the light diameter.

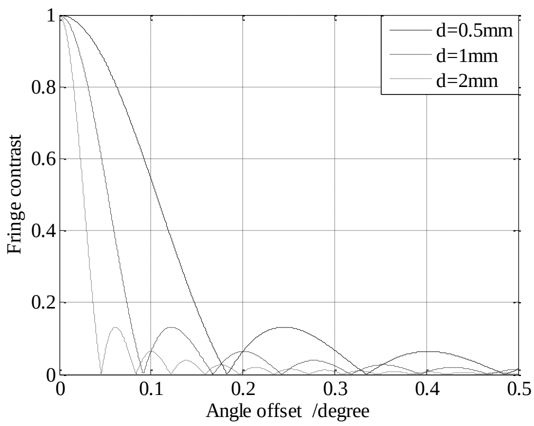


Fig.5 Interferogram contrast change with the angle misalignment $\alpha$

At the same angle misalignment, the fringe contrast will change with the light diameter, which is shown in Fig.6.The fringe contrast will drop with the increasing the light diameter. When the angle error is 0.01° and the light diameter is

3mm, the fringe contrast will fall to 80 percent of original value. So the large light diameter will raise the requirement to two reflected mirror perpendicularity.

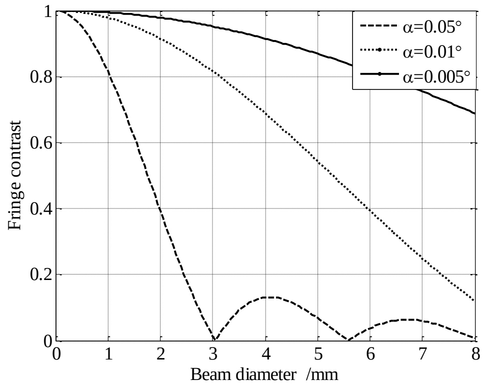

Fig.6 Fringe contrast change with the light diameter d

## 4.DISSCUSSION

From above analysis, the angle misalignment of the two mirrors will have an effect on the interference intensity, which will reduce fringe contrast. The reduced fringe contrast will cause the decline of SNR, which will finally determine the result miscalculation. So we should consider the method to reduce the angle misalignment. First, we consider that the corner cube prism should take the place of the plane reflective mirror. Although the corner cube prism demands the complicated installation mechanical structure, it can provide the smaller angle misalignment after proper installation. Of course, the corner cube prisms or the plane mirrors with the high surface-quality should be selected first. Because the above analysis is based on the angle misalignment of nonvertical to each other, the influence takes not account of the self-quality error of the mirrors. At the same time, the smaller light diameter should be considered priority.

But in practice, it is avoidless there exits the angle misalignment. The angle error will lead to the decline the fringe contrast, which will cause $I_{main}$ no longer equal to $I_0$. Furthermore during the scanning process, the light power fluctuant will cause the low frequency fluctuant in DC component in the interference. Both will lead to the interference situation caused $I_{main}$ is not the same as that caused $I_0$, we should consider to revise the calculation method of coupling strength.

From the Equation 17, if the angle misalignment no longer changes during the interference process, the equally decline proportion of fringe contrast will have the same effect on the interference packet. So the Equation 14 can be revised by

$$h(dB) = 20\log\left(I_{coupling} \big/ (k \cdot I_0)\right) \tag{18}$$

Where k is the fringe contrast when the two arms is balanceable, that is the OPD is zero in the Michelson interferometer. In practice, the coefficient k is first measured through the interference fringe. The equation 18 would a certain extent overcome the influence of angle misalignment.

## 5.CONCLUSION

The influence of angle misalignment on the two-arm reflective mirrors on the distributed polarization coupling detection system was investigated theoretically. The angle misalignment and the incident light diameter together had an effect on the interferograms. Decreasing the interference power and declining the fringe contrast were found in the interference scanning process, which would further lead to reduce the SNR and miscalculate the coupling strength. The corner cube prism should take place of the plane mirror, which would lead to smaller angle error. Based on the error analysis, a revised coupling strength calculation equation was put forward to a certain extent minimize the influence of angle misalignment.

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