Optical Fiber Technology 41 (2018) 69–73

Contents lists available at ScienceDirect

Optical Fiber Technology

journal homepage: www.elsevier.com/locate/yofte

Regular Articles

A novel polarization demodulation method using polarization beam splitter (PBS) for dynamic pressure sensor

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A R T I C L E I N F O

Keywords:
Fiber optics sensors
Birefringence
Pressure sensor
Polarization

A B S T R A C T

In this paper we propose a new design to demodulate polarization properties induced by pressure using a PBS (polarization beam splitter), which is different with traditional polarimeter based on the 4-detector polarization measurement approach. The theoretical model is established by Muller matrix method. Experimental results confirm the validity of our analysis. Proportional relationships and linear fit are found between output signal and applied pressure. A maximum sensitivity of 0.092182 mv/mv is experimentally achieved and the frequency response exhibits a < 0.14 dB variation across the measurement bandwidth. The sensitivity dependence on incident SOP (state of polarization) is investigated. The simple and all-fiber configuration, low-cost and high speed potential make it promising for fiber-based dynamic pressure sensing.

1. Introduction

Fiber optic sensors have been demonstrated to extremely attractive for various areas of biomedicine, automotive industries and environmental monitoring [1–6]. They provide significant advantages such as small size, geometric flexibility and distributed sensing possibilities [7,8]. Among them, optical fiber pressure sensors are of great interests owing to their various applications.

Polarization dependent effects are becoming a major topic for fiber sensing [9]. The fiber birefringence is one of the basic polarization effects which contribute to the well-known PMD (polarization mode dispersion), meanwhile it is an important physical parameter for many fiber-based sensing applications such as pressure sensors, temperature sensors, and etc [10]. Ref. [10] proposed a convenient approach to analyze the stress distribution in SMFs. The Mueller matrix of loaded fiber are get by polarization state measuring using Polarimeter. The birefringence $B = 0.2779P$ rad/m for wavelength $\lambda = 1550$ nm was get. Then a static pressure vector sensing based on ~ 2 km SMF with the validity analyzed was performed.

Polarization-dependent properties induced by birefringence in fiber Bragg gratings (FBGs) such as polarization-dependent loss (PDL) and differential group delay (DGD) can also be used for transverse force measurement [11–13]. In these reports, the evolutions of the PDL or DGD peak amplitudes increase monotonically with applied force in dynamic range. Thus, by measuring PDL or DGD peak amplitudes the amount of applied force is determined. This design requires a complex measuring system to determine the peak values. Large amounts of data points over a wide range of spectrum must be continually analyzed in high resolution, resulting in a rather slow processing speed.

Pressure sensors can be applied in many domains such as structural health monitoring of composite materials [14–15] or for biomedical applications [16–17]. Therefore it is necessary to do research for real-time sensing and prove its practical use. We have demonstrated a compact real-time transverse-force sensing system through Stokes parameters measurement at single wavelength [18]. The measuring system used in the experiment was an in-line polarimeter (General Photonics's POD-001) which measured the Stokes parameters at a certain wavelength, enabling real-time transverse force monitoring.

However the principle of these methods to obtain polarization dependent properties is based on the 4-detector polarization measurement approach [18]. Each photo detector measures the optical signal intensity of a particular polarization state. Stokes vector components are a linear combination of these measured intensities. Commonly three polarizers and a 1/4 wave plate should be used in traditional design. In technology it is very demanding to gain compact size for practical use. Therefore the in-line polarimeter used in Ref. [19] is relatively expensive. In addition its bandwidth is limited because it is an un-termination type polarimeter. So it is not suitable for high frequency dynamic pressure measurement.

In this paper we proposed a simple designed, low-cost and high speed method based on a polarization beam splitter (PBS) to demodulate the polarization information induced by pressure. There is no need to employ 1/4 wave plate and polarizers, no need to calibrate, enable possible for all fiber configuration. And there is no need to obtain the

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https://doi.org/10.1016/j.yofte.2017.12.015
Received 17 November 2017; Received in revised form 19 December 2017; Accepted 19 December 2017

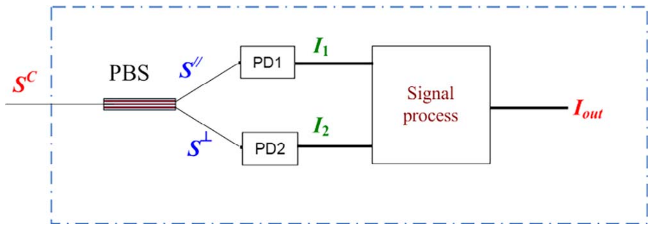

Fig. 1. The demodulated scheme using PBS.

values of Stokes parameters. A proportional relationship and linear fit are observed between the applied pressure and the output signal. Therefore it can greatly reduce the cost in practical use and it has potential for high frequency dynamic pressure sensing due to its all fiber inline configuration and simple demodulation method.

2. Principle and simulations

The birefringence induced by pressure is proportional to the applied pressure, as

$$\Delta\ \mathrm{n}= (\Delta n_{eff})_x - (\Delta n_{eff})_y = K\frac{F}{L\cdot D}, \tag{1}$$

Where D is the fiber diameter, F is the applied force, and L is the length of the region under stress. Using the parameters provided by Refs. [20–22], we can get $K = 9.0431 \times 10^{-12}/\mathrm{pa}$.

The birefringence contributes to the variation of SOP. The analytical expression and experiments [23] demonstrated that the Stokes vectors have cosine relationship with applied pressure. Hence the linear part can be used for sensing.

Next we will put emphasis on the method to demodulate the applied pressure using a PBS from SOP of light. The scheme is illustrated in Fig. 1. The light from sensor head is directed into a PBS. The light is spitted into two beams which are mutually orthogonal. Both of the beams contain information about F. Using photo detectors (PD) the light signals will be converted to electric signal. And the information about F can be demodulated by signal processing.

The SOP of light from sensor head is denoted as S^C and it can be described as,

$$S^C = (S_0^C, S_1^C, S_2^C, S_3^C)^T \tag{2}$$

Then the normalized Stokes parameters can be computed using:

$$s_1^c = \frac{S_1^C}{S_0^C};\ s_2^c = \frac{S_2^C}{S_0^C};\ s_3^c = \frac{S_3^C}{S_0^C}; \tag{3}$$

These three parameters change with pressure. By adjusting the SOP of incident light the variations of normalized Stokes parameters can be linear with F, as

$$s_1^c = k_1F + b_1;\ s_2^c = k_2F + b_2;\ s_3^c = k_3F + b_3 \tag{4}$$

Where k_1, k_2 and k_3 represent sensitivity for s_1, s_2 and s_3, respectively, F is applied transversal force.

The directions of two in-line polarizers of PBS are denoted as $\parallel$ direction and $\perp$ direction. The angle between $\parallel$ direction and x-axis is assumed to be α, and therefore the angle between $\perp$ direction and x-axis is $\alpha + 90°$. So the Muller matrix of the two polarizers are described as Eq. (5-a) and (5-b), respectively.

$$M_{\parallel} = \frac{1}{2}\begin{bmatrix} 1 & \cos(2\alpha) & \sin(2\alpha) & 0 \\ \cos(2\alpha) & \cos^2(2\alpha) & \cos(2\alpha)\sin(2\alpha) & 0 \\ \sin(2\alpha) & \cos(2\alpha)\sin(2\alpha) & \sin^2(2\alpha) & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{5-a}$$

$$M_{\perp} = \frac{1}{2}\begin{bmatrix} 1 & -\cos(2\alpha) & -\sin(2\alpha) & 0 \\ -\cos(2\alpha) & \cos^2(2\alpha) & \cos(2\alpha)\sin(2\alpha) & 0 \\ -\sin(2\alpha) & \cos(2\alpha)\sin(2\alpha) & \sin^2(2\alpha) & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{5-b}$$

The SOPs of the two outputs are calculated by Eq. (6-a) and (6-b), respectively.

$$S^{\parallel} = M_{\parallel}\cdot S^C \tag{6-a}$$

$$S^{\perp} = M_{\perp}\cdot S^C \tag{6-b}$$

The photo detector detects the power of light, which is related to the first Stokes parameter. There are,

$$S_0^{\parallel} = \frac{1}{2}(S_0^c + S_1^c\cos2\alpha + S_2^c\sin2\alpha) \tag{7-a}$$

$$S_0^{\perp} = \frac{1}{2}(S_0^c - S_1^c\cos2\alpha - S_2^c\sin2\alpha) \tag{7-b}$$

And the corresponding photocurrent can be represented as,

$$I_1 = R_1\cdot S_0^{\parallel} = \frac{1}{2}R_1\cdot(S_0^c + S_1^c\cos2\alpha + S_2^c\sin2\alpha) \tag{8-a}$$

$$I_2 = R_2\cdot S_0^{\perp} = \frac{1}{2}R_2\cdot(S_0^c + S_1^c\cos2\alpha + S_2^c\sin2\alpha) \tag{8-b}$$

Where R_1 and R_2 are constants related to the responsibility of two detectors, respectively. Substituting Eq. (4) into Eq. (8-a) and (8-b), respectively, we can get,

$$I_1 = \frac{1}{2}R_1S_0^c(1 + b_1\cos2\alpha + b_2\sin2\alpha) + \frac{1}{2}R_1S_0^c(k_1\cos2\alpha + k_2\sin2\alpha)\cdot F \tag{9-a}$$

$$I_2 = \frac{1}{2}R_2S_0^c(1 + b_1\cos2\alpha - b_2\sin2\alpha) - \frac{1}{2}R_2S_0^c(k_1\cos2\alpha + k_2\sin2\alpha)\cdot F \tag{9-b}$$

Getting rid of the DC part, we get,

$$I_1' = \frac{1}{2}R_1S_0^c(k_1\cos2\alpha + k_2\sin2\alpha)\cdot F = A\cdot F \tag{10-a}$$

$$I_2' = -\frac{1}{2}R_2S_0^c(k_1\cos2\alpha + k_2\sin2\alpha)\cdot F = -\frac{R_2}{R_1}A\cdot F \tag{10-b}$$

Where $A = \frac{1}{2}R_1S_0^c(k_1\cos2\alpha + k_2\sin2\alpha)$. It can be seen that the amplitude values of the two outputs are opposite. Therefore the sensitivity can be improved by subtracting as Eq. (11),

$$I_{out} = I_1' - I_2' = A\left(1 + \frac{R_2}{R_1}\right)\cdot F \tag{11}$$

And corresponding voltage is,

$$V_{out} = rA\left(1 + \frac{R_2}{R_1}\right)\cdot F \tag{12}$$

Where r is the convert coefficient from current to voltage.

3. Experiment and discussion

We will now describe our experimental set-up and present some experimental results that we have obtained. Our experimental setup is shown schematically in Fig. 2. The input light from a tunable laser source (Agilent 8163B lightwave Multimeter) was launched into a standard single-mode fiber. A 3-circles fiber polarization controller (PC) was used to adjust the polarization state of the light. In the PZT-based squeezing device, the signal generator produced signals with tunable amplitude and frequency which was amplified by the driver to drive the PZT. Therefore dynamic pressure can be produced and applied to the fiber. The transmitted signal from sensing head was directed into a PBS. The digital sampling oscilloscope records the intensities measured by the photodiodes. During the measurements, the fiber connectors were