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High-sensitivity and real-time displacement sensor based on polarization properties in fiber

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ABSTRACT

A novel displacement sensor based on polarization properties in fiber is demonstrated in this paper. The cantilever beam is used as a transducer to convert the displacement into a transverse force onto the fiber which results in the fiber birefringence and hence the amplitude of the Stokes parameters in fiber. The sensitivity and linear range of the sensor depends on incident state of polarization (SOP) and the mechanical and geometric parameters of the cantilever beam. The highest sensitivity of 4.0045/mm has been achieved in the experiments.

1. Introduction

Fiber optic sensors have been demonstrated to extremely attractive for various areas of biomedicine, automotive industries and environmental monitoring [1–4]. Among them, optical fiber displacement sensors are of great interests owing to their great multiplexing capability, compact size, immunity to electromagnetic interference and easy signal detection. So far, various optical fiber configurations for displacement measurement have been reported. The main type is based on RIM-FOS (reflective intensity modulated fiber optics sensor) [5,6]. Other type such as the displacement sensor based on a dual polarization DBR fiber laser was proposed in [7]. Recently it is more and more demanding for high sensitivity, high resolution, easy detection, and real-time characteristic for displacement sensor, especially in small range measurement areas. Therefore it is necessary to do research for new method and prove its practical use.

Polarization dependent effects are becoming a major topic for fiber sensing [8]. 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 [9]. Ref. [9] 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 obtained. Then a static pressure vector sensing based on ~2 km SMF with the validity analyzed was performed.

We have demonstrated a compact real-time transverse-force pressure sensing system through Stokes parameters measurement at single wavelength [10,11]. Based on that principle, in this letter, we demonstrate a high-sensitivity and real-time displacement sensor incorporated with a cantilever beam. The cantilever beam converts the displacement into a transverse force onto the fiber which results in a change in the fiber birefringence and hence in the Stokes parameters. The sensitivity, dynamic range, repeatability, and the sensitivity dependence on the parameters of the transducer are investigated.

2. Principle

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

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

where D is the fiber diameter, F is the applied force, and L is the length of the region under pressure. Using the parameters provided by Ref. [12–14], we can get $K = 9.0431 \times 10^{-12}/\text{pa}$. This birefringence causes phase difference δ and changes SOP of the light in fiber.

In Stokes space, optical components or devices can be described by a Mueller matrix. For the fiber region under pressure, the input Stokes vector $S_{in} = (S_0, S_1, S_2, S_3)'_{in}$ and output Stokes vector $S_{out} = (S_0, S_1, S_2, S_3)'_{out}$ are related by

$$S_{out} = J \cdot S_{in} \quad (2)$$

where J is Mueller matrix of the fiber under pressure.

In the coordinate system based on polarimeter, when pressure azimuth is θ with respect to x axis, J can be described as

$$J(\theta, \delta) = R(\theta)W(\delta)R(-\theta) \quad (3)$$

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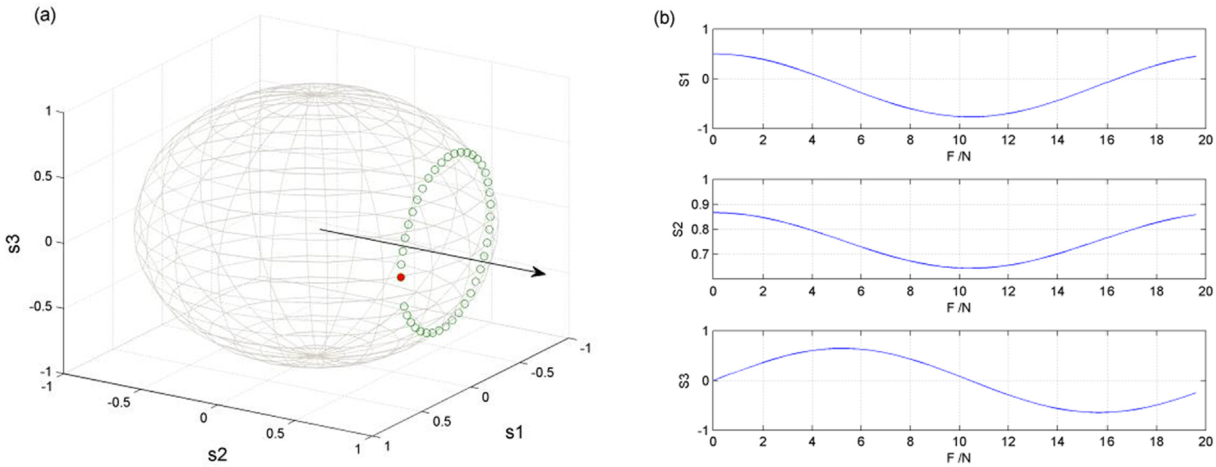

Fig. 1. (a) Simulated traces of output SOP and (b) amplitude of Stokes parameters related to applied pressure.

Where $W(\delta) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos(\delta) & \sin(\delta) \\ 0 & 0 & \sin(-\delta) & \cos(\delta) \end{bmatrix}$ $R(\theta) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\theta) & \sin(2\theta) & 0 \\ 0 & \sin(-2\theta) & \cos(2\delta) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

Then the output Stokes vector S_{out} rotates around an axis and forms a circle on Poincaré sphere as pressure alters. Theoretically this axis will be s_1 axis when pressure azimuth θ is 0° or 90°. While in practice, the rotation axis may not be s_1 axis or s_2 axis. Actually the rotation axis is calculated using a set of polarization state trace [a circle] since the axis is on the normal of the plane[15]. The practical axis can be called eigen rotation axis. As shown in Fig. 1(a) as an example.

The trace of the circle depends on the initial SOP and eigen rotation axis. The corresponding Stokes vectors (s_1, s_2 and s_3) have cosine relationship with applied pressure as shown in Fig. 1(b) as an example. Hence the linear part can be used for sensing. The Muller matrix *PleaseCheck*is determined as squeezing structure fixed. Hence the incident SOP S_{in} will be the most important factor to adjust the characteristics of the sensor, such as sensitivity and linear range. The experimental results show the great influences of incident SOP on the pressure sensitivity [10,11]. Hence a polarization controller (PC) can be used to optimize the sensitivity and linear zone of the displacement sensor.

A cantilever beam can be used as a transducer. When the free end of the cantilever beam is subjected to a vertical displacement, the fiber experiences a transversal force. That changes the fiber birefringence as Eq. (1), therefore, the Stokes parameters of the transmitted light in fiber. The relationship between the displacement and the induced transverse force is [7],

$$F = \frac{E_b b h^3}{8 l^3}\left(\frac{3l}{x} - 1\right) y_b \tag{4}$$

where E_b is the Young's modulus of the cantilever beam, b, h, and l are the width, thickness, and length of the cantilever beam, x is the location of the fiber laser relative to the fixed end of the cantilever beam, and y_b is the displacement at the free end. It is demonstrated the linear function between the displacement at the free end of the cantilever beam and produced force. Hence Stokes parameters also have cosine relationship with displacement.

3. Experiments

We will now describe our experimental set-up and present some experimental results that we have obtained. Fig. 2 shows the measurement set-up for this experiment. A tunable laser source (Agilent 8163B lightwave Multimeter) was used as the laser beam for launching into the fiber. A polarization controller (PC) was used to modify the state of polarization (SOP) of the light. The transmitted signal was directed into a polarimeter (General Photonics's in-line polarimeter POD-15-SS-02) which measured the Stokes parameters at a certain wavelength. After A/D conversion and signal process the experimental

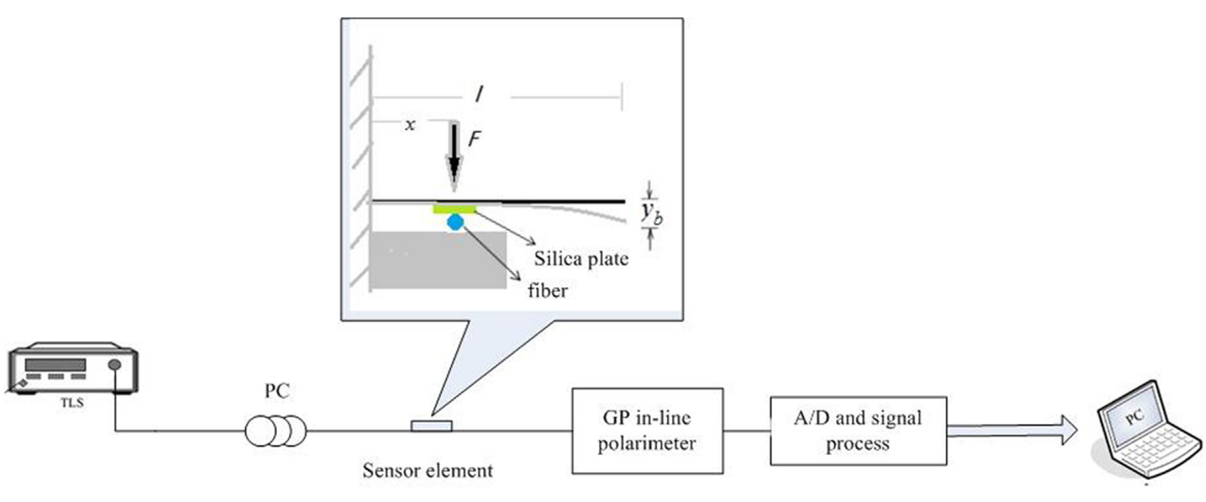

Fig. 2. Schematic diagram of the proposed displacement sensor based on Stokes parameters.