Temperature sensor based on PNR in Sagnac interferometer

Yuanhong Yang (杨远洪)

The 5th Research Division, Beijing University of Aeronautics & Astronautics, Beijing 100083

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A temperature sensor based on polarization non-reciprocity (PNR) in fiber-optic Sagnac interferometer (FSI) was proposed. The experimental study was made primarily and the results agree with theory well. Discussion shows that this kind of temperature sensor can achieve high precision and have great application potential.

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Fiber-optic Sagnac interferometer (FSI) has been used as fiber optic gyroscope (FOG) successfully. After more than 25 years development, almost all advantages and problems about FSI have been demonstrated and FOG has achieved very high performance. In recent years, the non-rotation applications of FSI, such as strain sensing and current sensing etc.[1,2], have become focus and some of them have been tried successfully in the field. It is the reciprocal configuration that makes FSI have excellent stability and very high phase detection capability (less than 10^{-7} rad) with special correlative detection technology. However, it is the reciprocal configuration too that makes it difficult for other physical information, except for rotation, to modulate the light propagating in fiber coil directly. Fortunately, there are many error factors in FOG that give us chance to modulate the parameters of light in fiber coil. The polarization non-reciprocity (PNR), which is due to birefringence and polarization mode coupling in fiber coil, is a very important error source that must be considered carefully in FOG and can be used to sense other physical information. In this paper, a special polarization coupling phenomenon in fiber coil, which can produce PNR, is demonstrated in detail and used to sense temperature by enhancing the PNR effect artificially.

Figure 1 shows the reciprocal configuration of FSI, this is an all polarization maintain (PM) configuration, where SLD is superluminescent diode, a polarizer is placed at the common reciprocal port, two PM fiber-optic couplers and the PM fiber coil are used, the fiber segment between P_1 and P_2 is temperature sense probe, it is PM fiber and the length is L, P_1 and P_2 are strong polarization mode coupling points which are formed by splice and their polarization axes have α and β angle offset to principle axis, respectively. The light from SLD became principle polarization mode after filtered by polarizer and divided at point J and directed into either end of the PM fiber coil. After travelling through the coil, the two light beams recombine at J and are directed to the detector. Because the fiber segment is a part of fiber coil, the output signal will contain the information of Sagnac phase and the effect of the fiber segment. To make the result simple, assume the polarizer and all PM fiber and components are ideal, namely the extinction of polarizer is zero and there are not polarization coupling in PM fiber. With the same analysis in Ref. [3], the output of this FSI can be

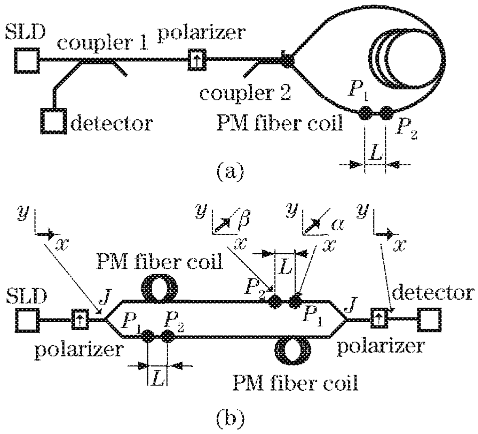

Fig. 1. Schematic diagram of FSI for temperature sensor. (a) Physical arrangement; (b) arrangement for analysis.

$$I = K|t_{xx}|^2[1 + \cos(\phi_\mathrm{S})], \tag{1}$$

where K is constant related to optical intensity inject to detector, t_{xx} is complex transformation along x axis, ϕ_S is phase due to Sagnac effect. At reset state, ϕ_S will be zero, t_{xx} can be determined with following analysis.

As shown in Fig. 1, when light travels from J to J along clockwise (cw) (or count clockwise (ccw)) direction, it will be filtered by polarizer at input and output ports. This configuration is same as the ordinary polarization light interferometer as shown in Fig. 2, where the PM fiber segment can be regarded as birefringence material, the principle axis of two polarizer is parallel to x axis. At two ends of PM fiber, P_2 and P_1, the angle offsets to x axis are β and α respectively. The Jones matrix is

$$T = \begin{pmatrix} t_{xx} & t_{xy} \\ t_{yx} & t_{yy} \end{pmatrix} =$$

$$\begin{pmatrix} \cos\beta\cos\alpha + \sin\beta\sin\alpha\cdot\mathrm{e}^{j\delta} & \sin\beta\cos\alpha - \cos\beta\sin\alpha\cdot\mathrm{e}^{j\delta} \\ \cos\beta\sin\alpha - \sin\beta\cos\alpha & \cos\beta\cos\alpha + \sin\beta\sin\alpha\cdot\mathrm{e}^{j\delta} \end{pmatrix},$$

so

$$t_{xx} = \cos\beta\cos\alpha + \sin\beta\sin\alpha\cdot\mathrm{e}^{j\delta}. \tag{2}$$

In PM fiber, δ is due to the propagation constant difference $\Delta\beta$ of two principle modes of PM fiber and can be described as

$$\delta = \Delta\beta\cdot L. \tag{3}$$

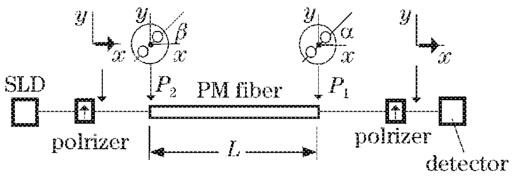

Fig. 2. Polarization light interferometer.

Combining Eqs. (1)−(3) and assuming $\phi_S = 0$, we have

$$I = 2K(\cos^2\beta\cos^2\alpha + \sin^2\beta\sin^2\alpha + 2\cos\beta\cos\alpha\sin\beta\sin\alpha\cdot\cos(\Delta\beta L)). \quad (4)$$

In FOG, if α and β are not zero, I may vary with $\Delta\beta$ or(and) L changing, this variety can be equivalent to drift due to polarization coupling, namely PNR[3].

Equation (4) represents a typical polarization interferometer phenomenon. Let $\alpha = \beta = 45°$, we can get the best fringe contrast. In this scheme, light source is broadband, the fringe contrast is modulated by contrast function $\gamma(\delta)$ of source too. So, Eq. (4) can be rewritten as

$$I_A = \gamma(\delta)\cdot K(1 + \cos(\Delta\beta L)). \quad (5)$$

PM fiber is based on linear birefringence induced by an additional stressing structure in the cladding and $\Delta\beta$ is inverse proportional to temperature within −200 − +400 °C and the coefficient is about negative 10^{-3} magnitude[4,5]. The fiber segment length L is well known to be linear with temperature and the coefficient is 10^{-6} magnitude. Assuming $\Delta\beta = \Delta\beta_0$ and $L = L_0$ at certain temperature T_0 and the temperature coefficients of $\Delta\beta$ and L are C_1 and C_2, respectively. neglecting small items, at temperature T, Eq. (3) can be rewritten as

$$\delta = \Delta\beta_0\cdot L_0\cdot(1 + C_1\cdot(T - T_0)) = B + AT, \quad (6)$$

where $B = \Delta\beta_0 L_0(1 - C_1 T_0)$, $A = \Delta\beta_0 L_0 C_1$. Equation (6) shows δ is proportional to temperature T. Then, the temperature sensed by fiber probe can be measured by detecting the phase δ.

Figure 3 shows the experimental setup of temperature sensor. A multifunction integrated optical circuit (MIOC), which is used in close-loop FOG and has the function of polarizer and coupler, was taken to replace the polarizer and coupler 2 in Fig. 1. TCB is temperature controlled box. The fiber coil is fabricated with about 500-m-long PM fiber. In the experimental setup, only the fiber segment L and its symmetrical segment are placed in TCB. The temperature in TCB is measured with a precise thermometer and the optical power is measured with a precision power meter (OPM). The temperature range is −60 − +90 °C and the values of temperature and optical power are recorded by a computer. The measured data have been normalized and are shown in Fig. 4. This curve is periodic and the amplitude increases with temperature increase. From Eq. (5), the amplitude changing represents the $\gamma(\delta)$ function because the sign of C_1 is negative and δ will decrease when temperature increases, the periodic response is due to $\cos(\delta)$. Assuming $\gamma(\delta)$ is linear within the measuring range, we can get the target function for fitting as

$$I = (a_1\cdot T + a_2)\cdot\cos(2\pi\cdot T/a_3 - a_4) - a_5. \quad (7)$$

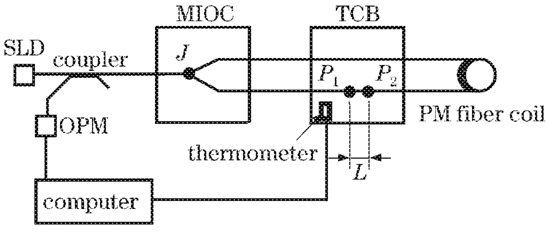

Fig. 3. Experimental setup of temperature sensor.

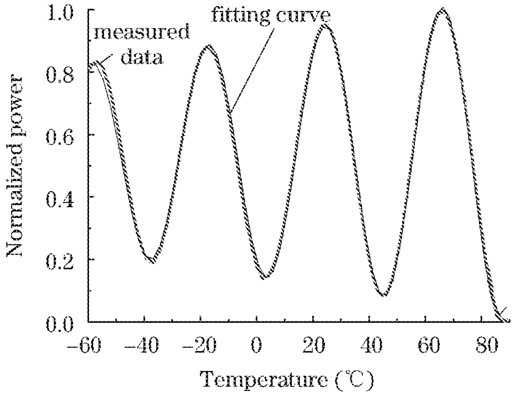

Fig. 4. Tested data and fitting curve.

Table 1. Fitting Result

Parameter	a_1	a_2	a_3	a_4	a_5
Value	0.00143	0.384	−41.537	−3.678	−0.530

The fitting curve is shown in Fig. 4 and the parameters obtained are listed in Table 1. The standard deviation between the measured value and the fitting value is less than 1%. This proves that Eqs. (5) and (6) are both satisfied. The temperature coefficient A, calculated with parameters in Table 1, is −0.15 rad/°C.

The beat length L_B of PM fiber used is about 2.2 mm and $\Delta\beta_0 = 2\pi/L_B$, the segment length is 50 mm, the operation wavelength is 1.3 μm, and C_1 is negative 10^{-3} magnitude. The temperature coefficient can be estimated with Eq. (6), A is about −0.143 rad/°C, it agrees with the fitting result well.

This temperature sensor can take the same configuration as FOG except for adding a sensor PM fiber segment to enhance PNR effect in fiber coil and the signal is similar with true FOG, this means that almost all technology used for FOG can be taken for this sensor. It is reasonable that this temperature sensor can achieve very good performance with mature FOG technology. Experimental results show that temperature changing from −60 to +90 °C produces more than 6π phase shift (as shown in Fig. 4), which means the temperature sensor can achieve high sensitivity and the sensitivity can be adjusted by changing the length L

easily according to Eq. (6).

Above analysis and study prove this temperature sensor is flexible and practical. Taking different configuration, parameters, and signal processing method, sensors with different performance, such as low precision and low cost, high precision, or very large measuring range, can be obtained. This scheme has combined the advantages of FSI and polarization light interferometer, which make it a stable, accurate, and flexible temperature sensor.

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