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Stabilization of the Sagnac optical fiber current sensor with automatic active-twist control

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We present a novel method for the stabilization of the Sagnac current sensor with active twist control. The sensor output was improved more than 8 times by employing the proposed stabilization method. Stability within ±1.7% was demonstrated between 36^oC and 62^oC.

I. INTRODUCTION

Recently, there has been much interest in optical fiber current sensors with Sagnac configurations[1,2]. But, the bending-induced linear birefringence existing in a Sagnac loop reduces the long-term stability of Sagnac current sensors. The stability of the Sagnac current sensors is also affected by vibration, stress and temperature change. It is well known that the stability of the Sagnac optical fiber current sensors can be improved by twisting fibers[3,4] or using spun birefringent fibers[5]. A mirrored Faraday rotator in conjunction with highly twisted low-birefringence fibers[6] was also used to stabilize the Sagnac current sensors. But these methods use mostly expensive specialty fibers and/or rather complicated signal processing, meaning that they are less practical.

We have already reported[7] some preliminary results on a simple method of stabilizing a Sagnac optical fiber current sensor(SOFCS). It is characterized by simply creating an appropriate amount of twist-induced circular birefringence into the Sagnac loop to eliminate the linear birefringent effects. Provided that the twist-induced circular birefringence remains constant, the technique could be a good stabilization method. But, the twist-induced circular birefringence in single-mode fiber is generally temperature dependent[8], hence the output of the sensor drifts with temperature. To remove this drift problem, the twist-induced circular birefringence needs to be readjusted as temperature changes.

In this paper, we present a novel method for the stabilization of the Sagnac current sensor. The method is realized by actively readjusting the twist-induced rotation angle to the maximum visibility point as the environmental condition changes. The theory leading to the stabilization technique is outlined. The SOFCS employing the method is constructed with all-standard single-mode fiber and tested to see the effectiveness of the method.

II. THEORY

Fig. 1 shows a Sagnac current sensor possessing a linear and a circular birefringence. For a general input polarization of the light entering, the Jones matrix E_0 is given by $E_0 = \begin{bmatrix} cos(\beta) \\ sin(\beta)e^{-i\gamma} \end{bmatrix}$, and the Jones matrix $B_L(\delta)$ for a linear birefringence whose fast axis is parallel to the laboratory x axis, and the Jones matrix for a circular birefringence B_C in the fiber coil are given by, $B_L = \begin{bmatrix} e^{\frac{i\delta}{2}} & 0 \\ 0 & e^{-\frac{i\delta}{2}} \end{bmatrix}$ and $B_C = \begin{bmatrix} cos\alpha & -sin\alpha \\ sin\alpha & cos\alpha \end{bmatrix} = F(\alpha)$. Here, $\delta(=B_L k_0 l)$ is

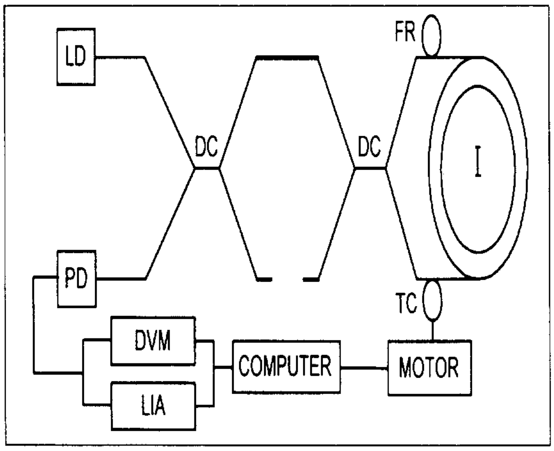

FIG. 1. The schematic of the experimental setup for a Sagnac optical fiber current sensor:LD, laser diode:DC, fiber directional coupler; PD, photodetector; TC,twist controller; FR,Faraday rotator.

the average phase retardation between the slow and the fast waves and $\alpha(=B_C k_0 l)$ is the average rotation angle induced by the circular birefringence. For a Faraday rotation θ the Jones matrix for clockwise propagation is $F_{cw}(\theta)$ and for counterclockwise propagation $F_{ccw}(-\theta) = F_{cw}(\theta)$.

It is often convenient to follow the Jones calculus to see roughly the performance of the SOFCS under the assumption that the Faraday rotation, the circular birefringence-induced rotation and the phase retardation due to the linear birefringence occur in series. The output irradiance $P_{1,2} = P_0(1 + V_0 cos2\theta)$ where the P_0 and the visibility V_0 are

$$P_0 = \frac{1}{16}[2 + cos(2\alpha) - cos(2\alpha)cos\delta], \qquad (1)$$

$$V_0 = \frac{1 + cos\delta}{2 + cos(2\alpha) - cos(2\alpha)cos\delta}. \qquad (2)$$

This indicates that the visibility of the Sagnac varies with the phase retardation δ, and the rotation angle α, but is independent of the input polarization state. Note that the visibility remains always unity regardless of the linear birefringence at the circular birefringence-induced rotation angle $\alpha = (m + 1/2)\pi$, where m is an integer. Thus, we can maintain the SOFCS stable as long as the circular birefringence in the Sagnac is properly adjusted.

Twisting a single-mode fiber(SMF) with length l at a twist rate ξ yields the circular birefringence $g\xi$, whose corresponding rotation angle $\alpha_c = g\xi l/2$ (g= proportionality). In general, some amount of circular birefringence α_i exists in the Sagnac fiber loop wound around the conductor. So, the total circular birefringence-induced rotation angle is given by $\alpha = \alpha_c + \alpha_i$. Then, the maximum visibility condition is expressed by $\alpha_c = [(m + 1/2)\pi] - \alpha_i$.

Therefore, if α_i varies with temperature T, α_c needs to be readjusted for maximum visibility as the temperature changes. In this way temperature stability of the SOFCS can be achieved. When an electric current $I_1 sin\omega_s t$ is applied to the conductor and a 45-degree Faraday rotator is inserted for optical biasing between the second directional coupler and the single-mode fiber coil with the Verdet constant V and the number of turns N, the output intensity P becomes

$$P = P_0[1 - 2V_0 J_1(2VNI_1) sin\omega_s t + \cdots]. \qquad (3)$$

Then, the ratio M of the amplitude of the ω_s-component P_{ω_s} to the amplitude of the dc-component P_{dc} becomes M= $2V_0 VNI_1 = 2\theta$, which explains that the current I_1 can be determined if the ratio M is measured and V_0 is set to the maximum, preferably 1.

III. EXPERIMENT

The sensor configuration shown in Fig. 1 is used for testing the stability of the SOFCS. The light source is a laser diode(wavelength=1300nm) and the fiber is a SMF at 1300nm. A conductor with diameter 13cm was wound with 78m of the fiber. The twist controller(TC) was used for controlling the twist rate of the optical fiber to change the twist-induced rotation angle α_c. The proportionality g of a 1m-long fiber in the TC was measured as 0.15, which gives a twist-induced rotation angle α_c of 360° at 13.5 turns. We attached a motor to the TC to control α_c for the maximum visibility automatically. P_{ω_s} and P_{dc} were measured by a

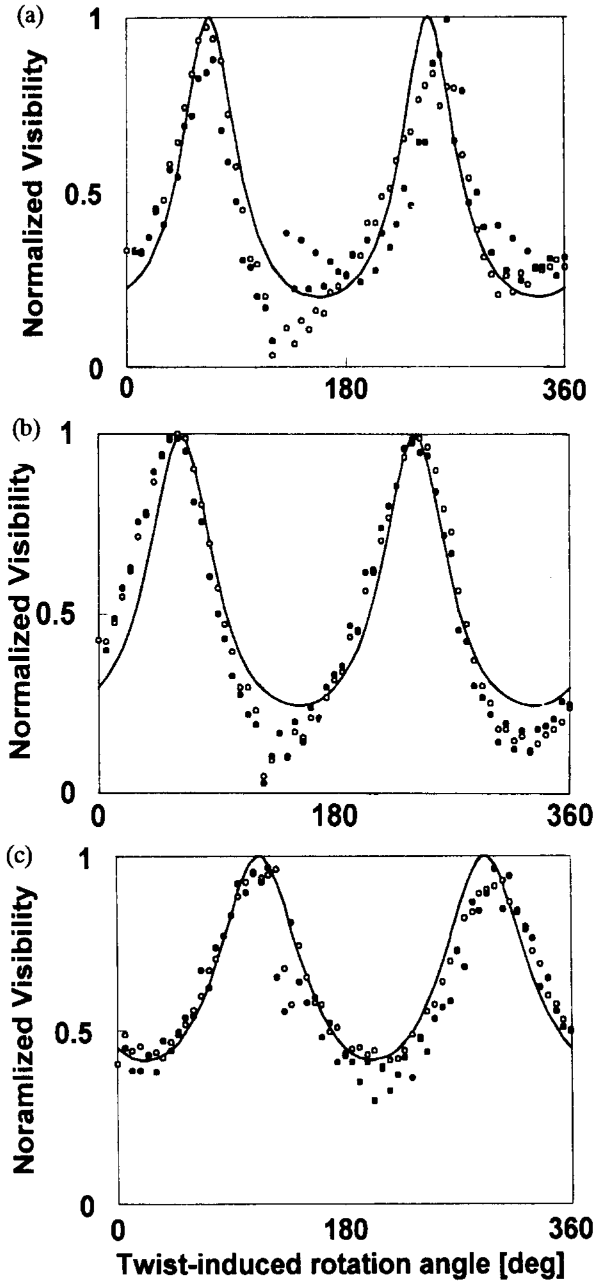

FIG. 2. The visibility of the Sagnac current sensor measured at different twist-induced rotation angles α_c for three different temperatures (a)T=30°C, I_1=200Arms (b)T=50°C, I_1=600Arms (c)T=70°C, I_1=800Arms.

digital multimeter(DVM) and a lock-in amplifier(LIA), respectively. Therefore, M and the sensor output were obtained.

Fig. 2 shows the visibility of the SOFCS measured at different twist-induced rotation angles for the three different conductor temperatures $30°C$, $50°C$ and $70°C$. The temperatures of $30°C$, $50°C$ and $70°C$ were achieved by flowing ac currents of 200Arms, 600Arms and 800Arms, respectively. The visibility measurements at each temperature were made continuously in order while changing the twisting rate. The dots are data measured while increasing the twisting rate and the open circles are measured while decreasing the twisting rate. The experimental data fit well to the Eq.(2) and the best fit curves are displayed by solid lines in Fig. 2.

A number of experimental results including those in Fig. 2 indicate that the visibility of the SOFCS varies periodically with α_c as expected from Eq.(2). From Fig. 2 and Eq.(2), it is also not difficult to realize that α_i remains roughly constant between $30°C$ and $50°C$ but increases by about $40°$ at $70°C$. For the maximum visibility when the circular birefringence in the Sagnac loop varies with temperature, the twist-induced circular birefringence needs to be readjusted by the same amount as the shift in the temperature-dependent circular birefringence. The adjustment was performed automatically in this work.

Next, we set α_c to the maximum visibility point, then heated slowly only one side of the Sagnac fiber loop with two halogen lamps from $36°C$ to $65°C$. During the heating, P_{ω_s}, P_{dc} and M were simultaneously measured over 35 minutes, and are plotted in Fig. 3. Note that P_{ω_s} and P_{dc} fluctuate more than $\pm 14\%$ but shows a similar trend over the temperature range. As a result, the ratio M (i.e., the sensor output) remains stable within $\pm 1.2\%$ for 30 minutes. However, at temperatures above $60°C$ the stability of the sensor starts to get worse (Fig. 4(a)). This is because α_i increases

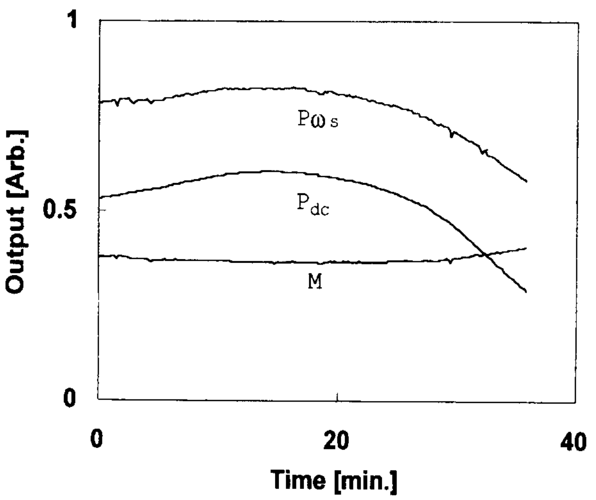

FIG. 3. The output fluctuation of P_{ω_s}, P_{dc} and M in the Sagnac current sensor (at f_s= 60Hz, 300Arms). Temperature was raised slowly from $36°C$ to $65°C$ during the measurement.

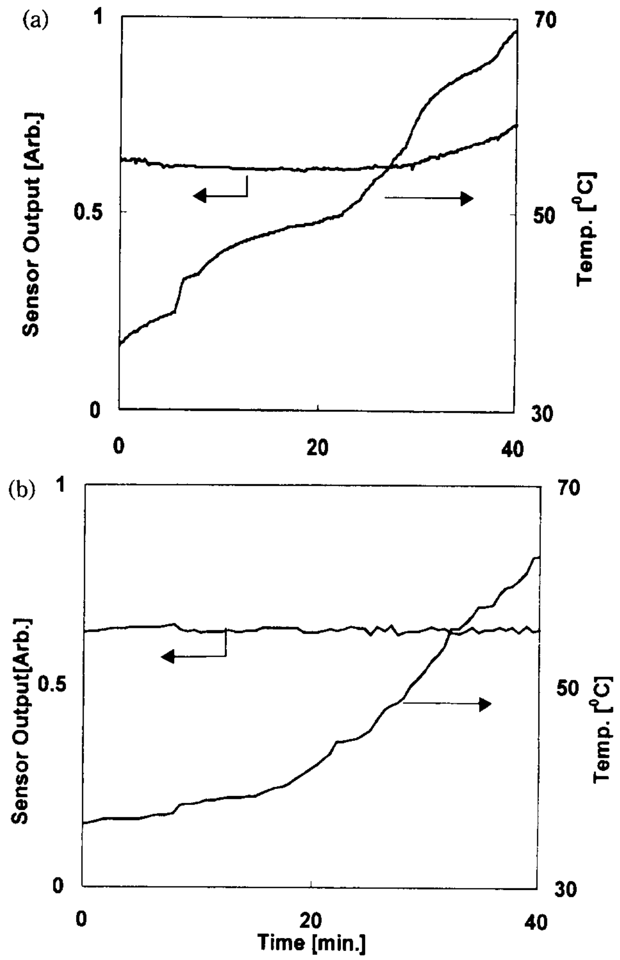

FIG. 4. The output variations of the Sagnac current sensor (at f_s=60Hz, 300Arms) without and with the active twist control during the temperature transient (a)without (b)with the active twist control.

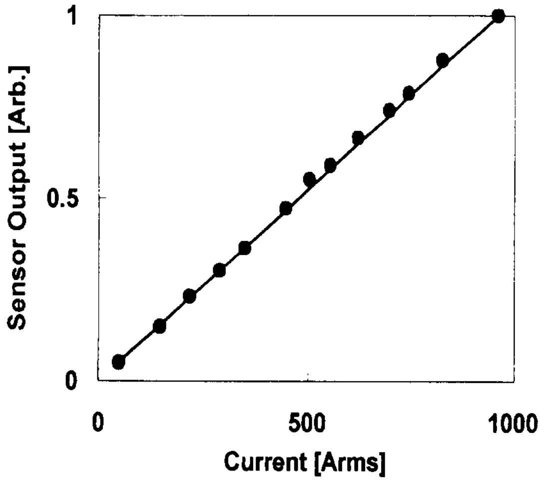

FIG. 5. Sensor output versus ac current (f_s=60Hz).

significantly at high temperature as shown in Fig. 2.

The output variations of the SOFCS without and with the active twist control during the heating are compared in Fig. 4. Here, α_c was initially set to the maximum visibility point by the TC. The sensor output looks very stable even without the active twist control over part of the temperature range, but in the temperature range of 50^oC - 69^oC the sensor output varies as much as ±9%. However, the sensor output with the active twist control fluctuates less than ±1.7% in the same temperature range (see Fig. 4(b)). This means that the SOFCS should be stabilized with the active twist control when α_i drifts. Small fluctuation of the sensor output appearing in Fig. 4(b) is due to the incompleteness of the automatic-feedback twist control system(Fig. 1). Fig. 5 shows a good linearity over the current range of 50Arms - 960Arms.

IV. CONCLUSION

We present a novel method for the stabilization of the SOFCS. The method is characterized by adjusting an appropriate amount of the twist-induced circular birefringence in the Sagnac loop. Preliminary experimental results indicate that this technique with the active twist control works well even for the Sagnac in which severe bias drift arises. Employing the proposed method, the stability of the SOFCS was demonstrated to be within ±1.7% even under the harsh temperature condition for which only one side of the Sagnac loop was heated between 36^oC and 62^oC during the stability test.

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