Study of fiber-optic current sensing based on degree of polarization measurement

Feng Liu (刘 峰), Qing Ye (叶 青), Jianxin Geng (耿健新), Ronghui Qu (瞿荣辉), and Zujie Fang (方祖捷)

Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800

Received December 4, 2006

A novel fiber-optic current sensing scheme is proposed by converting the Faraday rotation to the optical signal's degree of polarization (DOP) change. In this scheme, the lightwave passes through a fiber resonant cavity multiply and experiences Faraday rotation simultaneously. Its main merit is immunity from the environment disturbance to the fiber used in ordinary Faraday rotation sensor. Brief theoretical analysis and simulation are given to show its basic characteristics. Experimental results are demonstrated and the feasibility of the proposed method is also shown.

OCIS codes: 060.2370, 230.2240, 260.5430.

Fiber-optic current sensors (FOCS) based on the Faraday effect are very attractive for the monitoring of high power delivery systems for their advantages, such as good electric isolation, insensitivity to electromagnetic interference, and a large dynamic range[1]. A lot of efforts have been devoted to the employment of fiber-optic sensors, such as using polarization multiplexing technique and reciprocal reflection interferometers[2−4], but the instability of signal polarization state in fiber between the sensor at high voltage and the apparatus at ground is still a major problem which limits the performance of FOCS. The polarization maintaining fiber (PMF) and other special fibers are effective to avoid the polarization coupling in single mode fiber (SMF)[1−3], however, FOCS composed by ordinary SMF is still an attractive device for its low cost[5].

Degree of polarization (DOP) degradation of optical signal induced by polarization mode dispersion (PMD) has been extensively studied, and used as a convenient feedback signal in PMD compensation systems[6]. In the FOCS, the polarization of lightwave is rotated by Faraday effect, but its DOP will usually keep un-changed when the lightwave passes through the detected magnetic field. In this letter, a new FOCS scheme based on DOP measurement is proposed and demonstrated experimentally, which uses a fiber-optic cavity to make the lightwave pass through the magnetic field multiply and to cause the DOP changed with the intensity of the field. The sensors by using fiber cavity have shown successful in recent years[7,8], and it will also show very useful for Faraday current sensor in this letter, especially immune from fluctuation of the polarization in the SMF. Moreover, the issues for further improvement are also discussed in the letter.

Figure 1 describes the sensor structure schematically. The fiber cavity consists of a 2 × 2 coupler and two Faraday rotation mirrors (FRMs). The fiber is coiled along the current lead and the lightwave travels back-and-forward in the cavity by reflection of two FRMs. In our scheme, the lightwave will experience a polarization rotation when it passes the fiber cavity every time. Meantime, it goes out partly every time from the cavity backward to the input fiber and output to the DOP analyzer by a circulator. Light waves reflected at different times induce different polarization rotation angles and the Faraday polarization rotation will accumulate for multiple reflections. So the whole output signal polarization state becomes a sum of different polarization states. The polarization states after passing through the cavity, twice, three times and so on, are shown schematically in a Poincare sphere in Fig. 2. If the laser beam has a definite line-width and its coherent length is shorter than the fiber length of the cavity, it will be depolarized after the multiple passes, and its DOP will decrease with

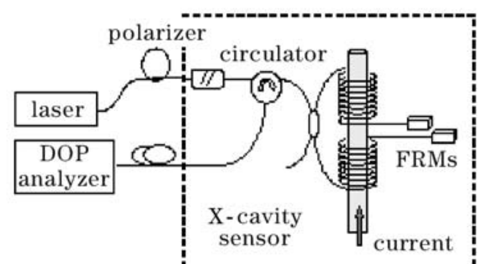

Fig. 1. Layout of the FOCS with X-shape fiber cavity.

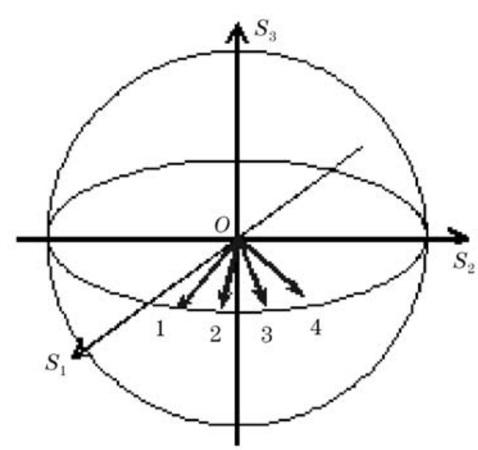

Fig. 2. Evolution of DOP by accumulated Faraday rotation in the cavity.

1671-7694/2007/050267-03

increasing the current in the wire. In the structure, a polarizer is used to make the propagating light linearly be polarized, and two FRMs are used to mitigate the background birefringence in the fiber cavity[3]. The DOP is not as vulnerable as the polarization direction to environmental fluctuation in the fiber, and then commercial SMF can be used to fabricate the sensor.

To analyze the polarization state evolution, some assumptions are taken to show a brief physical description. Under the ideal condition, the FRM can be assumed to compensate the reciprocal birefringence of the fiber cavity completely, and the loss in the cavity is ignored for a conceptual discussion. A linear polarized light is taken into consideration for clarity, and thus the Stokes component $S_3 = 0$. Since a low coherence light source is used, optical power summation is applied in the theoretical analysis instead of amplitude summation. By denoting the power split ratio of the coupler as K, and the Faraday rotation angle for every time as $\theta = 2VNI$, where V is the Verdet constant of fiber, and N is the number of turns in the fiber coil wound around the current, we deduced the expressions of output light wave's Stokes components S_1, S_2, and DOP as

$$S_0 = P_{\text{out}} = P_{\text{in}}(1-K)^2 \sum_{n=1}^{\infty} K^{2n} = P_{\text{in}} K^2 (1-K)/(1+K), \quad (1)$$

$$S_1 = P_{\text{in}}(1-K)^2 \sum_{n=1}^{\infty} K^{2n} \cos n\theta = P_{\text{in}} \frac{(1-K^2)(K^2+\cos\theta)}{1-2K^2\cos\theta+K^4}, \quad (2)$$

$$S_2 = P_{\text{in}}(1-K)^2 \sum_{n=1}^{\infty} K^{2n} \sin n\theta = P_{\text{in}} \frac{(1-K^2)\sin\theta}{1-2K^2\cos\theta+K^4}, \quad (3)$$

$$\text{DOP} = \frac{\sqrt{S_1^2+S_2^2+S_3^2}}{S_0} = \frac{1-K^2}{\sqrt{1-2K^2\cos\theta+K^4}}. \quad (4)$$

It is shown in Eq. (4) that DOP is a function of Faraday rotation; and in the range of θ smaller than $\pi/2$, the DOP decreases monotonously with the increase of θ. And the sensitivity increases with split ratio K. This analysis is reasonable because the light will keep longer inside the cavity and travel more times in case of larger K, though a larger K means also a smaller signal power obtained from the reflection port of the cavity. If $K = 0.99$ is used, the leakage loss will reach 23 dB. Figure 3 shows a curve of DOP versus Faraday rotation calculated with $K = 0.99$. Figure 4 shows calculated sensitivity varied with K calculated for $\theta = 0.02$, indicating that a trade-off between loss and sensitivity has to be considered in design of the sensor.

The proposed current sensor scheme was verified experimentally by using a cavity composed of a coupler with split ratio of 0.99, a 6000-turn coil made of 3-km commercial SMF fiber on a drum with diameter of 15 cm, and a wire passing through at its inner hole, as shown in Fig. 5. The total loss of sensor head is 38 dB. Figure 6

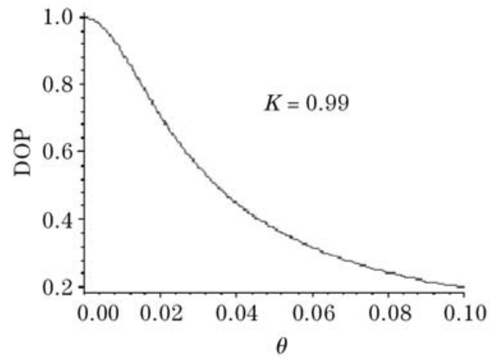

Fig. 3. Theoretically calculated curve of DOP versus Faraday rotation.

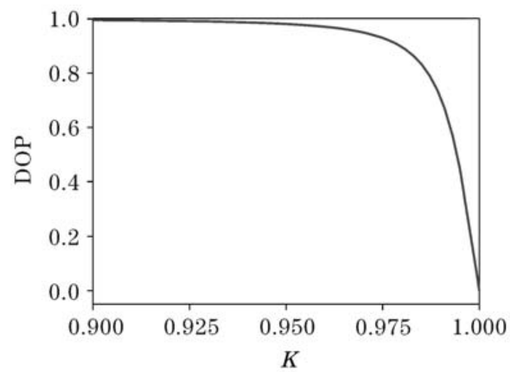

Fig. 4. Sensitivity with split ratio K of the coupler.

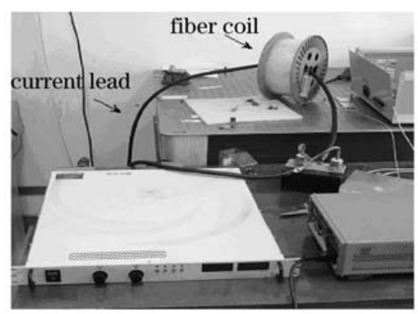

Fig. 5. Photograph of experimental device.

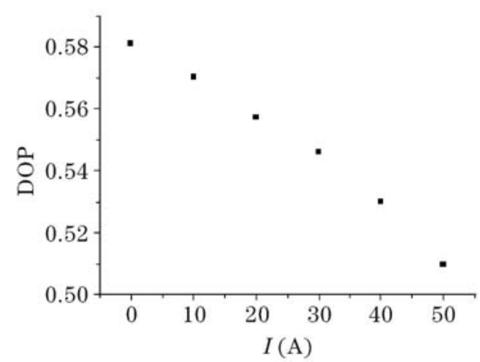

Fig. 6. Experimental result.

shows the measured DOP varied with the detected current which was changed from 0 to 50 A. With the rising of current, the DOP of feedback signal decreases form 0.58 to 0.51. The experimental result indicates that DOP measurement can be used as a parameter for high current sensor.

In the experiment, the DOP value at zero current was not measured to be 1 as expected in Fig. 3. It may be attributed to some following factors: there existed inevitably background birefringence caused by fiber twist, bend and so on in the cavity, which would cause the DOP decreased for a light with definite linewidth, similar to the effect of PMD; the used two FRMs did not compensate the fiber residual birefringence completely; and the fiber used in the experiment might be too long. In practical applications the measured current may be much higher than that in experiment; and the system design is expected to be optimized.

In conclusion, we have proposed and demonstrated a novel fiber cavity sensor scheme for FOCS based on DOP measurement. Theoretical analysis indicates that the Faraday rotation can be accumulated in a fiber cavity, and causes the DOP degreased with the current increase. There are two intrinsic merits of this scheme: 1) The error due to environment disturbances in usual FOCS method based on polarization rotation measurement can be avoided; 2) DOP measurement method is immune from the power fluctuation of light source. Detailed theoretical analyses, careful system design and optimization have to be studied further.

Q. Ye is the author to whom the correspondence should be addressed, his e-mail address is yeqing@mail.siom.ac.cn.

References

1. G. Frosio and R. Dandliker, Appl. Opt. **33,** 6111 (1994).
2. Z. B. Ren and Ph. Robert, Opt. Lett. **14,** 1228 (1989).
3. H. Lin, W.-W. Lin, and M.-H. Chen, Appl. Opt. **38,** 2760 (1999).
4. K. Bohnert, P. Gabus, J. Nehring, and H. Brändle, J. Lightwave Technol. **20,** 262 (2002).
5. A. Ben-Kish, M. Tur, and E. Shafir, Opt. Lett. **16,** 687 (1991).
6. N. Kikuchi, J. Lightwave Technol. **19,** 480 (2001).
7. Yu. O. Barmenkov, A. Ortigosa-Blanch, A. Diez, J. L. Cruz, and M. V. Andrés, Opt. Lett. **29,** 2461 (2004).
8. C. Wang and S. T. Scherrer, Opt. Lett. **29,** 352 (2004).