Polarization multiplexing applied to a fiber current sensor

Z. B. Ren and Ph. Robert

Laboratoire de Mêtrologie, Swiss Federal Institute of Technology of Lausanne, CH-1015 Lausanne, Switzerland

Received May 4, 1989; accepted August 25, 1989

The measurement of Faraday rotation can be made insensitive to linear birefringence by time multiplexing of different states of polarization at the input of the fiber. This offers a new possibility of overcoming the linear birefringence effect in fiber current sensors. Experimental results and the measurement accuracy versus the quality of the optical components used are presented.

The performance of the optical fiber Faraday current sensor is limited by the presence of linear birefringence in the fiber.[1] The major problem is that the linear birefringence sums up vectorially with the Faraday rotation in the fiber, and it is physically impossible to separate them at the output. This leads the sensor sensibility to be dependent on the linear birefringence. In the worst case, the Faraday rotation is completely quenched by the linear birefringence and the current measurement becomes impossible. Several possibilities of compensation of the linear birefringence have been proposed.[2–6] The use of an ultralow-birefringence spun fiber[2] can eliminate the intrinsic linear birefringence in the fiber. But this fiber is not resistant to external effects; in particular, the bend-induced birefringence cannot be avoided if the sensor is based on the use of a sensing fiber surrounding the electrical conductor. The introduction of a large circular birefringence by twisting the fiber mechanically can limit the linear birefringence effect to some extent,[3] but the twist-induced birefringence is temperature dependent.[7] Furthermore, the required degree of twist is so great that the fiber often reaches its fracture limit. The development of a circular-polarization-preserving fiber[5,6] might by a promising solution. However, such a fiber is not yet commercially available.

Here we propose a new technique for a direct Faraday rotation measurement in the presence of linear birefringence. By time multiplexing of two different states of polarization at the input of the fiber and short signal processing at the output, the Faraday rotation can be deduced directly from the obtained signals. In this case the linear birefringence need not be compensated physically. This theory is supported by an experimental prototype of the current sensor. The accuracy of the results is discussed, taking into account the performances of the optical components commercially available.

The conventional Faraday current sensor is based on a polarimetric measurement of linearly polarized light. The propagation of the light through the sensing fiber exhibiting both linear and circular birefringence can be described by the Jones calculus[1,8]:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix}_{\mathrm{out}} = \begin{bmatrix} A & -B \\ B & A^* \end{bmatrix} \begin{bmatrix} E_x \\ E_y \end{bmatrix}_{\mathrm{in}}, \quad (1)$$

where

$$A = \cos(\alpha/2) + j \sin(\alpha/2)\cos\chi, \quad (2)$$

$$B = \sin(\alpha/2)\sin\chi, \quad (3)$$

$$\alpha = [\delta^2 + (2F)^2]^{1/2}, \quad (4)$$

$$\tan\chi = (2F)/\delta, \quad (5)$$

F is the Faraday rotation, and δ represents the total linear birefringence in the fiber.

The output polarized light is generally analyzed by a Wollaston prism oriented at 45° with respect to the fiber linear birefringence axes. For a linearly polarized input light, the intensities I_1 and I_2 of the two orthogonally polarized modes separated by the Wollaston prism are given by

$$I_1 = 1/2(1 + \sin\chi \sin\alpha), \quad (6)$$

$$I_2 = 1/2(1 - \sin\chi \sin\alpha). \quad (7)$$

Then the sensor output S_1 becomes

$$S_1 = \frac{I_1 - I_2}{I_1 + I_2} = 2F \frac{\sin\alpha}{\alpha}. \quad (8)$$

When $2F \gg \delta$, $S = \sin(2F)$, the measurement of Faraday rotation is relatively easy. If $2F \ll \delta$, $S = (2F)(\sin\delta/\delta)$, the sensor sensitivity is dominated by the linear birefringence by a factor of $(\sin\delta/\delta)$.

In the absence of linear birefringence the system shows, according to Eq. (8), the maximum possible sensitivity to Faraday rotation for linearly polarized input light. Conversely, in the absence of Faraday rotation, if a circularly polarized input light is used, the system exhibits the maximum possible sensitivity to linear birefringence.[9] These facts suggest the alternate use of two different states of polarization of the input light, in order to separate better the effects of Faraday rotation and linear birefringence. When a circularly polarized light is launched into the fiber the output signal is given by

0146-9592/89/211228-03$2.00/0

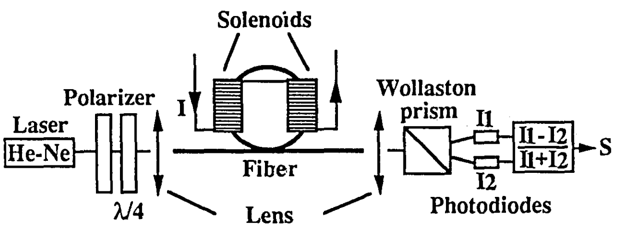

Fig. 1. Experimental setup for the Faraday rotation measurement by polarization multiplexing at the input of the fiber.

Table 1. Parameters of the York LB-600 Fiber

Diameter (μm)	Core Diameter (μm)	Cutoff Wavelength (nm)	Attenuation (dB/km)	Verdet Constant (deg/A)
115	3.5	562	6.5	10^{-4}

$$S_c = \frac{I_1 - I_2}{I_1 + I_2} = \delta \frac{\sin \alpha}{\alpha}, \tag{9}$$

where the index c is for circularly polarized input light.

By successively eliminating δ and F from Eqs. (8) and (9), it follows that the Faraday rotation is given by

$$F = \frac{\arcsin(S_1^2 + S_c^2)^{1/2}}{2[1 + (S_c/S_1)^2]^{1/2}}. \tag{10}$$

In the same way the linear birefringence may be written in the form

$$\delta = \frac{\arcsin(S_1^2 + S_c^2)^{1/2}}{[1 + (S_1/S_c)^2]^{1/2}}. \tag{11}$$

Accordingly, the Faraday rotation can be distinguished from the linear birefringence in the fiber simply by using an input-light polarization multiplexing.

Our experimental setup for Faraday rotation measurement with the polarization-multiplexing technique is shown in Fig. 1. The linear and circular polarization-multiplexing system is made of a polarizer and a quarter-wave (λ/4) plate. The axes of the polarizer can be rotated with respect to the axes of the λ/4 plate. When the transmission axis of the polarizer is parallel to one of the axes of the λ/4 plate, linearly polarized light is launched into the fiber. When the polarizer is rotated at 45° with respect to the axes of the λ/4 plate, circularly polarized light is obtained. A microcomputer is used for the storage of the corresponding signals S_1 and S_c as well as for the calculus of F given by Eq. (10). A York VSOP LB-600 ultralow-birefringence fiber is used as the sensing element. The relevant parameters of the fiber are summarized in Table 1. Seven turns of the fiber are wound in a 20-cm-diameter groove carved into a polyvinyl chloride plate. A current of approximately 8 kA across the fiber loops is simulated by two 800-turn solenoids in series. A typical result of the measured Faraday rotation with respect to the applied current in the solenoids is given in Fig. 2. The linear regression of the measurements yields $dF/dI = 3.12$ deg/A, corresponding to a Verdet constant of 2.78×10^{-4} deg/A.

By using an ultralow-birefringence fiber and by carefully winding the fiber in the groove, only the bend-induced birefringence remains. The measured value of this birefringence was found to be 103° by Eq. (11), which is in agreement with the value of 100° calculated according to the theory developed in Ref. 10. The bend-induced birefringence does not depend on the current applied to the solenoid. In Fig. 3 the steadiness of δ measured [Eq. (11)] for various currents demonstrates the efficiency of the separation between F and δ obtained in practice.

Equations (10) and (11) are valid only if the input linear and circular polarizations are perfect. In practice, every real optical element exhibits certain imperfections. Thus it is never possible to obtain a perfect linear or circular polarization. The key elements used in the proposed system are the polarizer, the λ/4 plate, and the Wollaston prism. The errors introduced by the imperfections of a high-grade polarizer and a Wollaston prism can be neglected.[9] This means that the accuracy of the measurement with linearly polarized input light is not affected by the imperfections of the optical elements. Conversely the errors introduced by an imperfect circular input polarization may be not negligible, even if a high-quality λ/4 plate is used. This means that measured S_1 induces no error on F given by Eq. (10). The difference between the measured F and the exact value of F is then due only to S_c.

The deviation of the input light from an ideal circu-

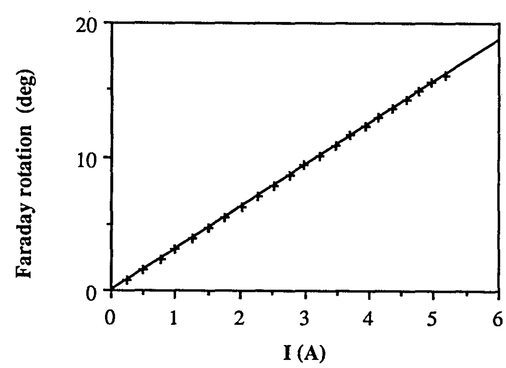

Fig. 2. Measured Faraday rotation versus the current applied to the solenoids.

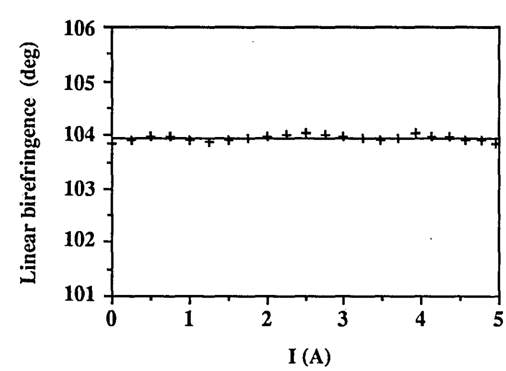

Fig. 3. Invariability of the measured linear birefringence.

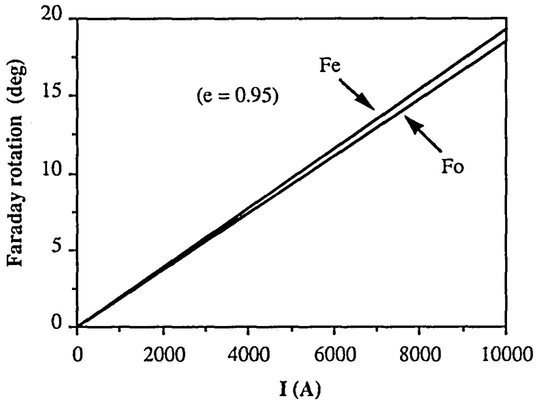

Fig. 4. Computed Faraday rotation for circular and elliptical input polarization.

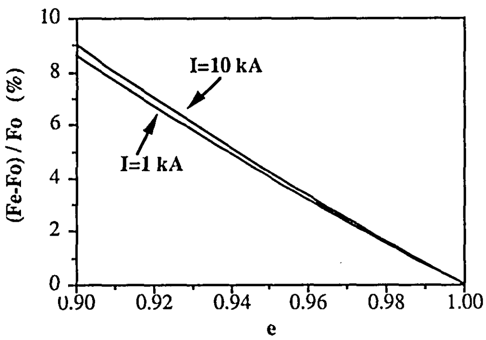

Fig. 5. Relative error of the measured Faraday rotation versus the ellipticity of the input light.

lar polarization can be considered as arising only from the retardation tolerance Δ of the $\lambda/4$ plate. This deviation is measured here by the ellipticity of the input circular polarization, which is defined as the ratio of the semiminor to the semimajor axes of the polarization ellipse. The $\lambda/4$ plates commercially available exhibit values of Δ ranging from $\lambda/20$ to $\lambda/500$, corresponding to ellipticities ranging from 0.73 to 0.99. Now the question is what is the accuracy of the method when a slightly elliptically polarized light is launched into the fiber instead of a perfectly circularly polarized one. For an input elliptical polarization with an ellipticity of e, a modified value of S_c, termed S_{ce}, can be derived:

$$S_{ce} = \frac{1}{1+e^2}\left[(1-e^2)\cos\alpha + 2e\sin\alpha\cos\chi\right]. \quad (12)$$

It can easily be verified that S_{ce} converges toward S_c given by Eq. (9) where $e \rightarrow 1$. In practice, S_{ce} is substituted for S_c in Eq. (10). The effect of the quality of the $\lambda/4$ plate on the accuracy of the measured Faraday rotation is illustrated in Figs. 4 and 5. Figure 4 shows a numerical plot of Faraday rotation against the equivalent current I through the fiber loops. F_o is the value of Faraday rotation obtained by Eq. (10) in the case of perfect circularly polarized input light; F_e refers to the case of an elliptically polarized input light characterized by $e = 0.95$. Figure 5 shows the effect of the ellipticity of the input light on the relative error $[(F_e - F_o)/F_o]$ for different values of I.

One can see from Fig. 4 that a residual ellipticity in the input light corresponds to an increase of the apparent Verdet constant. Indeed, dF_e/dI leads to $V = 2.76 \times 10^{-4}$ deg/A instead of the 2.65×10^{-4} deg/A given by dF_o/dI. This explains the difference of approximately 5% between the measured Verdet constant in Fig. 2 and the value of 2.65×10^{-4} deg/A measured in a straight portion of the same fiber. The ellipticity of the input polarization in the experiment corresponding to Fig. 2 was 0.95.

The imperfection of the input circular polarization causes a systematic error to appear. This error can be limited if a high-quality $\lambda/4$ plate is used. In any case, this error can be known, *a priori*, and compensated for. Another possibility is to use a birefringence compensator and thus obtain a quasi-circular polarization.

In conclusion, a direct Faraday rotation measurement in the presence of linear birefringence can be carried out by polarization multiplexing at the input of the fiber. The measurement procedure is relatively simple. The first experiment yields results in agreement with theory. It can be used for the measurement of a steady or slowly varying current because the rotation of the polarizer is controlled by a step motor. A new device, which operates in the kilohertz range, is under development. The accuracy of the method depends on the quality of the input circular polarization. High accuracy can be obtained provided that high-grade optical components are used.

This research is supported by the Swiss National Science Foundation.

References

1. A. M. Smith, Appl. Opt. **17,** 52 (1978).
2. A. J. Barlow, D. N. Payne, M. R. Hadley, and R. J. Mansfield, Electron. Lett. **17,** 725 (1981).
3. S. C. Rashleigh and R. Ulrich, Appl. Phys. Lett. **34,** 768 (1979).
4. G. W. Day and S. M. Etzel, in *Proceedings of 11th European Conference on Optical Communications* (Istituto Internazionale delle Comunicazioni, Genova, 1985), p. 871.
5. M. P. Varnham, R. D. Birch, and D. N. Payne, in *Proceedings of 11th European Conference on Optical Communications* (Istituto Internazionale delle Comunicazioni, Genova, 1985), p. 135.
6. R. I. Laming, D. N. Payne, and L. Li, Proc. Soc. Photo-Opt. Instrum. Eng. **798,** 283 (1987).
7. Z. B. Ren, Ph. Robert, and P.-A. Paratte, Opt. Lett. **13,** 62 (1988).
8. R. C. Jones, J. Opt. Soc. Am. **31,** 488 (1941).
9. Z. B. Ren, Ph. Robert, and P.-A. Paratte, J. Phys. E **18,** 859 (1985).
10. R. Ulrich, S. C. Rashleigh, and W. Eickhoff, Opt. Lett. **5,** 273 (1980).