Faraday-rotation fiber-optic current sensor: Response to different locations of the conductor

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ABSTRACT

The linear birefringence exhibited by the wound fiber in a Faraday rotation current sensor is shown to be responsible for a significant dependence of the output signal on the location of the conductor within the fiber loop, and for non-zero outputs for conductors outside the loop. Numerical calculations show a signal variation of up to \( \approx 10\% \) as the conductor is moved around the circumference of the loop.

1. INTRODUCTION

Faraday-rotation fiber-optic current sensors were demonstrated\(^1\) to have some unique advantages over conventional technologies in high electrical current measurements. In these devices the linear polarisation of the light rotates as it propagates along the fiber loops which encircle the current carrying conductor. This polarisation rotation can in turn be evaluated at the fiber output, thereby giving a measure of the current flowing in the conductor. The ability of these devices to measure directly the current (rather than its time derivative), their natural high bandwidth and high dynamic range, as well as their inherent EMI (Electro-Magnetic Interference) immunity and lack of saturation effects, render them very good candidates for next generation high current sensors.

It has long been realised that the linear birefringence exhibited by the sensing fiber, mainly due to the bending it undergoes in forming the sensor loop, may cause severe degradation of the performance of these devices. The major effect of this birefringence is to decrease the magnitude of the device scale factor, and thus its sensitivity. In addition, the scale-factor, being dependent on this birefringence, becomes quite sensitive to a variety of environmental effects. Many schemes have been proposed to overcome these difficulties, including twisting the fiber, using a spun highly birefringent fiber, annealing the fiber after the winding process and using special winding geometries\(^1\)\(^–\)\(^3\).

Here we claim that this birefringence is responsible for still another effect. It may introduce a dependence of the device output on the location of the conductor within the loop and may generate non-zero signals for currents flowing outside the loop.

2. SIGNIFICANCE OF CONDUCTOR LOCATION

It follows from Faraday and Ampere laws that in the ideal (birefringence free) closed-loop device the total rotation angle depends only on the encircled current, \( I \):

\[
\theta = \int_C d\phi = \int_C VH dl = V \int_C H dl = NV I,
\]

where \( \theta \) and \( d\phi \) (\( VH dl \)) are the total and incremental polarisation rotation angles, \( V \) is the Verdet constant (which depends on the core composition and wavelength), \( H \) is the local magnetic induction field and the integration is carried out along the \( N \geq 1 \) fiber loop(s). The rightmost equality (Ampere's law) states that the total rotation angle depends only on the total current flowing in the loop and not on its detailed spatial distribution. Also, for conductors outside the loops we expect zero rotation. But these conclusions are valid only when the current does not change much while light is travelling through the device (from the input port to the output port). Indeed, for fast enough currents it has been demonstrated that the output signal does depend on the conductor location\(^4\). However, for small sensors and for currents whose bandwidth does not exceed a few megahertz, this phenomenon can be neglected. Recently, in a study of
Quantitatively, we measure this dependence by $D(I, r, \Omega)$

$$D(I, r < R, \Omega) = \frac{P'_{\text{center}}(I) - P'(I, r < R, \Omega)}{P'_{\text{center}}(I)} \times 100\%.$$  \hspace{1cm} (4)

which is the normalised deviation of the reading for a conductor at $(r, \Omega)$ from the reading when the conductor, carrying the same current, is centered $(r = 0)$. Naturally, for external conductors $(r > R)$, the definition of the normalised deviation has a slightly different form:

$$D(I, r > R, \Omega) = \frac{P'(I, r > R, \Omega)}{P'_{\text{center}}(I)} \times 100\%.$$  \hspace{1cm} (5)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2a.png}
\caption{(a) Conductor lies inside the loop ($D(I, r < R, \Omega)$, Eq. (4)); (b) External conductor ($D(I, r > R, \Omega)$, Eq. (5)).}
\end{figure}
a current sensor using a highly twisted fiber\textsuperscript{a}, the authors theoretically checked whether the presence of linear birefringence generated any location-dependent errors even for slowly varying currents. The effect was found to be negligible, mainly because the fiber linear birefringence was swamped by the very high circular birefringence introduced by the twist-induced circular birefringence. Also, they simplified their analysis to the extent that it applies only to relatively low currents.

We will show below that bend-induced birefringence in an otherwise low birefringence fiber, may give rise to a few percents spatial variations of the scale factor.

3. THE CURRENT SENSOR

Of the large variety of available designs, we shall study here a 3-turn, 150mm diameter Faraday effect current sensor, which was previously constructed\textsuperscript{b} from a low-birefringence 125mm fiber with input and output polarizers, respectively aligned parallel and at 45 degrees to the bend induced birefringence axes, see Fig. 1 (Only one turn is shown for simplicity). Careful design and subsequent measurements resulted in a value of 0.47\(\pi\) radian for the accumulated linear birefringence along the three turns of the sensor.

![Figure 1: Schematics of a Faraday effect fiber-optic current sensor. The input and output polarizers, \(P_{in}\) and \(P_{out}\), are, respectively, perpendicular and at 45\(^\circ\) with respect to the loop plane.](image)

4. NUMERICAL STUDY

In the presence of both linear birefringence and Faraday rotation, the differential rotation accumulated along a given differential length is no longer proportional to the magnetic field and Eq. (1) cannot be used. Instead, the Jones calculus\textsuperscript{1} is invoked, and when both the linear and Faraday induced circular birefringences are uniform along the optical path, one can analytically arrive at a single Jones matrix describing the propagation throughout the device. For non-centered conductors the total fiber length must be divided into many \((M)\) segments, assuming uniform birefringence in each, and describing the total polarization evolution by the product of these \((M)\) matrices. \(M\) is made large enough to ensure proper convergence of the results. When measuring currents, the quantity of interest is

\[
P'(I) = P(I) - P(I = 0),
\]

which measures the optical power change induced by the electrical current, \(I\). For noncentered conductors, we want to investigate the dependence of \(P'\) on the location of the conductor within the loop (see Fig. 1).
5. RESULTS AND DISCUSSION

Typical results of these numerical investigations, using the parameters of our sensor and assuming a current of 60KAmp, are presented in Fig. 2 for conductors inside and outside the loop. The input polarization was assumed to be perpendicular to the loop plane. $D(I, r, \Omega)$, the normalized deviation from the reading with centered conductor, is plotted against $\Omega$ for various distances of the conductor from the loop center ($r/R$). For conductors inside the loop (Fig. 2a), the deviations increase as the conductor approaches the inner circumference of the loop, and saturate at about $\approx 13\%$ as $r/R \rightarrow 1$. Of more concern is Fig. 2b which shows that outside conductors can significantly affect the readings of the sensor. For example, an outside conductor carrying 1MAmp at $r/R = 1.5$ may generate approximately the same (but erroneous) response as a central 100KAmp conductor, so that lower central currents may be completely masked by outside current carrying conductors. An interesting feature common to both parts of Fig. 2 is the bipolarity of the deviations with zero values at $\Omega = 0$.

Further calculations indicate that the results for $I (|I| < 100KAmp)$. Obviously, the results depend on the integrated linear birefringence and the number of turns. Since the scale factor of such sensors is proportional to $\sin[\text{integrated linear birefringence}]/[\text{linear birefringence per turn}]$, proper design calls for an integrated linear birefringence close to $\pi/2$. Subject to this constraint, the deviations do grow with the magnitude of the linear birefringence. The loop radius affects the deviations only through its effect on the birefringence.

6. CONCLUSIONS

We have numerically shown that the response of Faraday-rotation fiber optic current sensors may depend on the location of the conductor, even for slowly varying and DC currents. Bend-induced birefringence is responsible for these variations which can exceed 10%. These are only preliminary results. Their significance, though, warrants further experimental and theoretical studies of this type of error in Faraday-effect fiber-optic current sensors, including other architectures as well.

7. ACKNOWLEDGMENTS

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8. REFERENCES


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