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CURRENT MEASUREMENTS BY FARADAY ROTATION IN SINGLE MODE OPTICAL FIBERS

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Abstract

Development of techniques for measuring magnetic fields and currents by Faraday rotation in single-mode optical fibers has continued. We summarize the results of attempts to measure the toroidal plasma current in the ZT-40 Reversed-Field-Pinch using multi-turn fiber coils. The fiber response is reproducible and in accord with theory, but the amount and distribution of the stress-induced birefringence in this case are such that prediction of the sensor response at low currents is difficult if not impossible. The low-current difficulty can be overcome by twisting the fiber to induce a circular birefringence bias. We report the results of auxiliary experiments with a fiber that has been twisted with 15 turns per meter and then re-coated to lock the twist in place.

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INTRODUCTION

The Faraday effect results in the rotation of the plane of polarization of linearly polarized light propagating in a medium along a magnetic field. The rotation is given by

$$F = V \int \underline{H} \cdot d\underline{l}, \quad (1)$$

where $\underline{H}$ is the magnetic field, and V is the Verdet constant of the medium. With optical fibers it is easy to make one or more closed loops around a current I so that by Ampere's law the rotation is

$$F = V \oint \underline{H} \cdot d\underline{l} = NVI \quad (2)$$

where N is the number of current linkages. This effect has been observed in single-mode optical fibers¹⁻⁵, most of which exhibit Verdet constants typical of fused silica: $V = 4.68 \times 10^{-6}$ rad/Amp (1.28×10^{-2} min/Oe-cm) at a wavelength of 633 nm.

The Faraday effect is a field-induced circular birefringence, that is, an induced difference in the indices of refraction for left- and right-circularly polarized light. Optical fibers also possess linear birefringence caused by asymmetries frozen in during manufacture and by externally applied stresses such as bending and clamping. The analysis of sensor response requires the treatment of the fiber as a polarization element; the Jones calculus is useful because many fiber properties are nearly ideal: we often measure extinction ratios on single-mode fibers in the range of 1000:1, and attenuation by lengths under 100 meters is negligible unless some extreme environmental conditions occur. Multi-mode fibers are not useful, except possibly in very short lengths, because of the scrambling of polarization. An excellent review of the polarization properties of optical fibers is given in reference 6.

Some advantages of optical fiber-based current and field sensors are: they respond directly to the magnetic field; the fundamental limitation on the response time is the transit time of light in the sensor region; the fiber is a dielectric component that eliminates the need for isolation in many high voltage applications; and many of the electromagnetic interference problems associated with conductive wire sensors are removed.

I. INSTRUMENTATION

Figure 1 is a sketch of the Faraday rotation apparatus first described and analyzed by Smith¹ and adapted to our purposes. Linearly polarized light from a He-Ne laser is incident on the end of a single-mode optical fiber; an intervening half-wave plate is used to rotate the plane of polarization to coincide with one of the axes of linear birefringence of the fiber. After passing through the fiber the light is analyzed by a Thompson beam-splitter that separates orthogonal linear polarization states; photodiodes produce photocurrents I_1 and I_2 that are proportional to the intensities of those states. We define the quantity

$$T = (I_1 - I_2)/(I_1 + I_2). \quad (3)$$

In reference 1 the analysis is carried through for the analyzer axes oriented at $\frac{\pi}{4}$ to the fiber axes, and T is found to be a complicated function of the linear birefringence of the sensor section, δ_1 , the output lead section, δ_2 , and the Faraday rotation F from (2), that is,

$$T = T(F, \delta_1, \delta_2). \quad (4)$$

When δ_1 and δ_2 are small compared to F the relation simplifies to

$$T \approx -\sin 2F. \quad (5)$$

In (4), the effect of linear birefringence is to modulate the simple response of the non-birefringent case represented by (5), by suppressing the amplitude or

delaying the phase of the first few cycles. See Figure 2. In the analysis by Smith, orienting the input polarization with a fiber axis eliminated the birefringence δ_0 of the fiber between the source and the sensor. We have noted that orienting the analyzer axes parallel to the output fiber axes, rather than at $\frac{\pi}{4}$, also eliminates the effects of the birefringence δ_2 between the sensor and the output. In most applications the fiber is in the form of a coil, and the bending-induced birefringence is important, so that these source and detector orientations do not eliminate the problem of the linear birefringence, δ_1 , in the sensor section itself. Additional circular birefringence, which would appear in (4) and (5) as an addition to F, can be induced in a fiber by twisting; with enough twist it should be possible to bias the sensor at some point on a curve such as those shown in Figure 2 beyond which the response is essentially sinusoidal with increasing F. This also explains the success in applications where very high currents have been measured^{3,5}: the sensor behaves in accordance with (5) as the current increases beyond the first one or two cycles.

II. SUMMARY OF EXPERIMENTS ON ZT-40

We have previously reported⁵ the results from 50-, 10-, and 7-turn coils wound around the ZT-40 torus in various configurations. ZT-40 is a Reversed-Field-Pinch that produces toroidal plasma currents in the range 80 - 400 kA. We found that the results were consistent with (4), and that at higher currents we could use (5) to estimate the current with an error around 5%. See Figure 3. The effects of linear birefringence made the estimation difficult at low currents, because it is not possible to accurately measure the amount and distribution of the birefringence. We also found that it is necessary to isolate the fiber from mechanical vibrations that occur during the current

pulse. Finally, the fiber is intolerant of sharp bends that can be created in bringing the leads out through the layers of insulation between the shell and the liner; such bends cause light losses that reduce the signal-to-noise ratio, and add to the birefringence in the leads.

III. TWISTED FIBER

When a fiber is twisted a circular birefringence is induced that is proportional to the twist,

$$\alpha = g\tau, \quad (6)$$

where α = circular birefringence, τ = twist, and g is a constant that is related to the elastooptic constants, and has been reported⁷ to be in the range of 0.12 to 0.16. We initiated the development⁸ of a fiber that, after having been drawn and coated, was twisted at 15 turns per meter and re-coated to lock in the twist. Locking the twist in place is important to retain the ease of installation, another important advantage of fibers over conductive sensors. The fiber was installed in an apparatus similar to the one shown in Figure 1. The current source is an ignitron-switched 14.2 μ F capacitor charged to 6.5 kV and driving a ten-turn load coil. The current is a damped sine wave with an initial peak of 16.0 kA. The fiber is looped twice through the coil; the peak value of NI is thus $2 \times 10 \times 16\text{kA} = 320 \text{ kA-turns}$.

The results we obtained are illustrated in Figure 4. The top trace is the current waveform. The second trace shows T for a low linear birefringence control fiber from Lightwave Technologies, Inc.(LTI)⁹. Obviously the value of $2F$ at peak current just exceeds $\frac{\pi}{2}$; finding the current at which T peaks allows the calculation of the Verdet constant: $V = 4.91 \times 10^{-6} \text{ rad/Amp}$, about 5% higher than the accepted value for fused silica. The third trace was taken with an untwisted length of EOTec fiber. No response is apparent above the noise from

the source, because the fiber is highly birefringent due to an elliptical core. The fourth trace shows the response of the twisted EOTec fiber. Clearly the twisting has overcome the lack of response of the untwisted fiber; using the technique described above one calculates that $V = 4.09 \times 10^{-6}$ rad/Amp, about 13% lower than the fused silica value. The twisted fiber is not as good as the untwisted LTI fiber; possible explanations are being explored: the residual linear birefringence may not have been sufficiently depressed for the first cycle; also the fiber core was slightly larger than single-mode. Another fiber is being produced. There has not yet been an opportunity to install the twisted fiber on ZT-40.

One remarkable feature of the fourth trace in Figure 4 is its asymmetry about the horizontal axis. A qualitative explanation of this can be given with the aid of Figures 2 and 5. Figure 2 shows two plots of (4) for different, arbitrary amounts of birefringence, and a plot of (5) for reference. This illustrates the variability of the response at low currents because of birefringence, and the regularity that ensues at higher values of current. One of the curves from Figure 2 is plotted in Figure 5 as a transfer function for a sinusoidal input; the distortion introduced in the output as a result of the asymmetry is apparent. Note that this asymmetry would also persist for a perfectly sinusoidal response function if the zero current bias phase point were displaced from a zero crossing.

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Figure Captions

Figure 1. Optical fiber Faraday rotation current sensor.

Figure 2. Two plots of equation (4) for different, arbitrary values of linear birefringence, and a plot of equation (5) for reference.

Figure 3. ZT-40 current from the Faraday rotation current sensor (points) and from a Rogowski coil (line).

Figure 4. Test of the effects of twisting a fiber:

- (a) Current in load coil.
- (b) T for the control case of low linear birefringence fiber.
- (c) T for the untwisted high linear birefringence fiber.
- (d) T for the fiber of (c) with 15 twists/meter.

Figure 5. Using T from equation (4) and Figure 2 as a transfer function to demonstrate an interpretation of the asymmetric output in Figure 4(d).

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FIGURE 1

FIGURE 2

FIGURE 3

10 μ s/div.

FIGURE 4

"delta-2 delta-1"
 Acc150
 Acc140

FIGURE 5