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TITLE: MEASUREMENT OF FARADAY ROTATION IN TWISTED OPTICAL FIBER USING ROTATING POLARIZATION AND ANALOG PHASE DETECTION

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Measurement of Faraday rotation in twisted optical fiber using rotating polarization and analog phase detection

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Abstract

We have demonstrated phase modulation of rotating linearly polarized light by current-induced Faraday rotation in a single mode optical fiber and used the technique to measure the current in ZT-40M, a Reversed-Field Pinch. We have also demonstrated the practicality of using twisted sensing fiber to overcome the problems associated with linear birefringence.

Introduction

We and others have previously reported[1-3] measurements of electric current by monitoring the Faraday rotation of linearly polarized light in an optical fiber that made one or more loops about the current. These measurements were based on direct polarimetry. We have proposed, developed, and demonstrated heterodyne polarimetry, the measurement of the shift in phase of rotating linearly polarized light in the Faraday current probe. The amount of the phase shift is numerically the same as the angle determined by direct polarimetry, which is twice the Faraday rotation of a linearly polarized beam. The new technique offers greater sensitivity, improved noise immunity, and simplified data reduction.

We have demonstrated heterodyne polarimetry in conjunction with tests of a twisted fiber that was developed at our request by a fiber manufacturer.

Method

Figure 1 shows linearly polarized light from a Helium-Neon laser being split by a Bragg cell that is modulated at 40 MHz. One of the beams passes through a half-wave plate that is used to rotate the plane of polarization by $\pi/2$. The beams are at this point orthogonally polarized and have a frequency difference of 40 MHz. They are recombined in a calcite prism that is oriented so that the ordinary and extraordinary axes line up with the appropriately polarized incident beams. The spatial separation is adjusted so that the output beams are collinear; they are then incident upon a quarter-wave plate that converts each to circular polarization. The resultant, the sum of oppositely circularly polarized beams of different frequencies, is equivalent to a linearly polarized beam that rotates at one-half the difference frequency.

The beam is injected into a single mode optical fiber that makes one or more loops about an electrical current. Upon leaving the fiber the light passes through a polarization analyzer and is detected by a photodiode. The photocurrent is a 40 MHz sinusoid that is modulated by the Faraday rotation.

Referring to Fig. 2, the low-level photocurrent drives a 40 MHz IF amplifier the output of which is applied to the RF input of a phase comparator. The LO input to the comparator is derived from the Bragg cell modulation voltage. The comparator outputs are the the sine and cosine of the phase difference between the two input signals. The outputs are digitized and recorded for analysis.

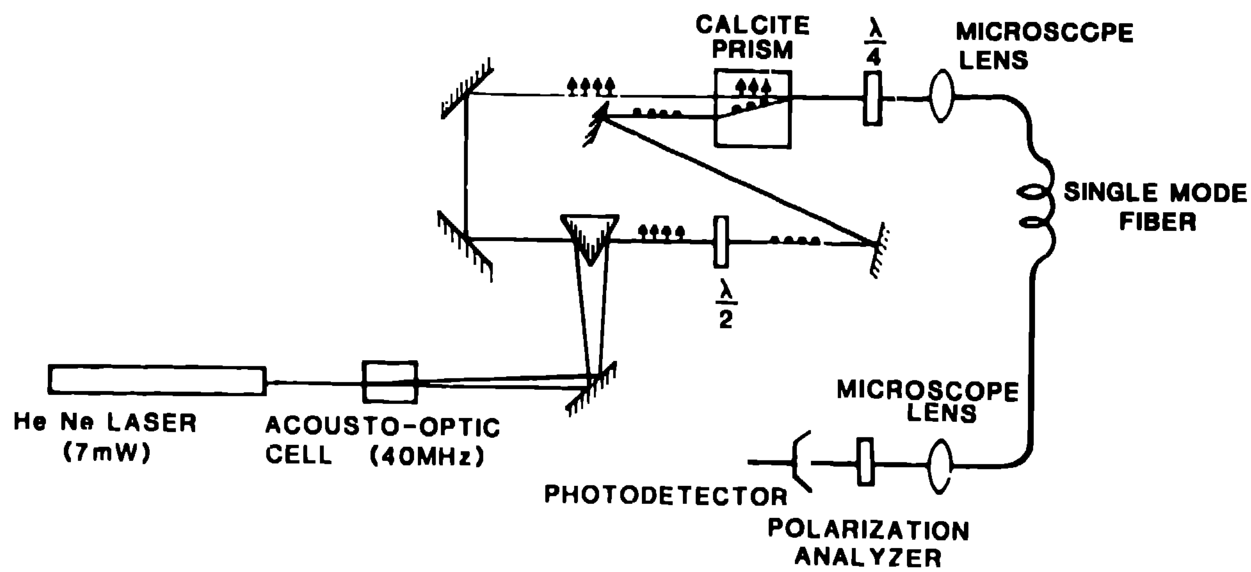

Figure 1. Optical apparatus.

A computer program that was written for the analysis of interferometer data from the Reversed Field Pinch fusion experiment, ZT-40M, was used to calculate the current. The algorithm computes the equivalent of a Lissajous pattern from two inputs, locates the centroid of the pattern, and then plots the phase angle, scaled to the current, as a function of time.

Analysis

The response of the system was analyzed using the Jones matrix method of Tabor and Chen.[4] The fiber was modeled as a single 2 x 2 matrix containing linear birefringence b and circular birefringence 2F caused by Faraday rotation (circular birefringence caused by twisting can be included by adding an additional term to F). The matrix formulation is

$$\begin{pmatrix} E_x \\ 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} A & -B \\ B & A^* \end{pmatrix} \begin{pmatrix} \cos(\omega t/2) \\ \sin(\omega t/2) \end{pmatrix}$$

Output Electric Field Vector	Matrix of Polarizer	Matrix of Fiber	Input Electric Field Vector

where $A = \cos(\phi/2) - i\cos(\chi)\sin(\phi/2)$

$B = \sin(\chi)\sin(\phi/2)$

$\phi = (4F^2 + b^2)^{1/2}$

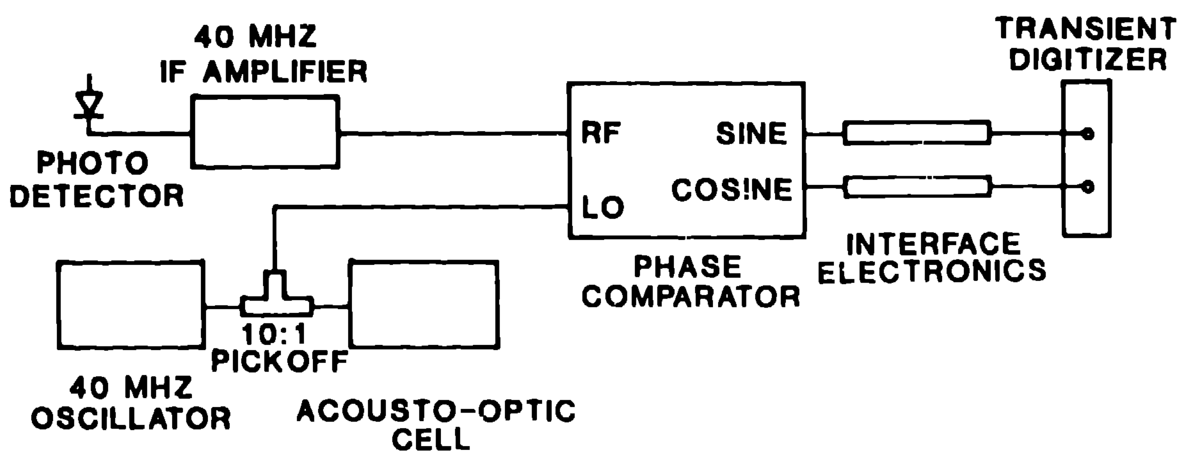

Figure 2. Electrical schematic.

$$\chi = \tan^{-1}(2F/b)$$

$$F = n_1 n_2 VI$$

$n_1 n_2$ is the product of the number of turns of fiber and the number of turns of current-carrying conductor, V is the Verdet constant, 4.68×10^{-6} rad/amp for silica at 633nm, and I is the current in amperes.

The first matrix on the right side represents the analyzer, set with its axis parallel to the x direction, the second represents the fiber, and the 2 x 1 vector on the right is the rotating linearly polarized input. The square law detector produces an output proportional to $E_x^* E_x$. It can be shown that the phasing of the intensity modulation $|E_x|^2 \exp i(\omega t - \Psi')$ is given by

$$\Psi' = \tan^{-1}\left(\frac{2\cos(\frac{\phi}{2})\sin(\frac{\phi}{2})\sin\chi}{\cos^2(\frac{\phi}{2}) - \sin^2(\frac{\phi}{2})}\right) \qquad (2)$$

When the linear birefringence b is small or zero, $\Psi' \to \Psi = 2F$. The outputs of the phase comparator are $\sin\Psi'$ and $\cos\Psi'$ and can be used to compute Ψ' directly for comparison with Eq. (2). The ratio, $\Psi'/2F$, can be used as a figure of merit for the system as a current sensor: the precision with which the phase can be directly scaled to the current is better, the nearer $\Psi'/2F$ is to unity. Figure 3 plots this ratio against 2F/b for three different values of b.

From Fig. 3 it is apparent that the quality of a measurement will be dependent upon the Faraday rotation exceeding the linear birefringence by a factor that is dependent upon the total value of the linear birefringence. Current measurements will increase in precision with the amount of current measured and the reduction of linear birefringence.

If the linear birefringence is irreducible, or the current is small, it is possible to add circular birefringence by twisting the fiber and by so doing to improve the figure of merit. In this case the Faraday rotation F is replaced by the sum F + T, where T is the induced circular birefringence.[5,6] Unless T>>F, the fiber winding direction must be in the sense for which T adds to F.

The foregoing analysis rests on the assumption that the birefringence properties, including the Faraday rotation, are uniformly distributed along the length of the fiber. It also assumes that the input is linearly polarized, but a small amount of elliptization of the rotating input only decreases the intensity modulation and to zero order does not reduce the perceived phase shift. Furthermore, the results are affected only very slightly if the fiber and polarizer matrices are referenced to different axes.

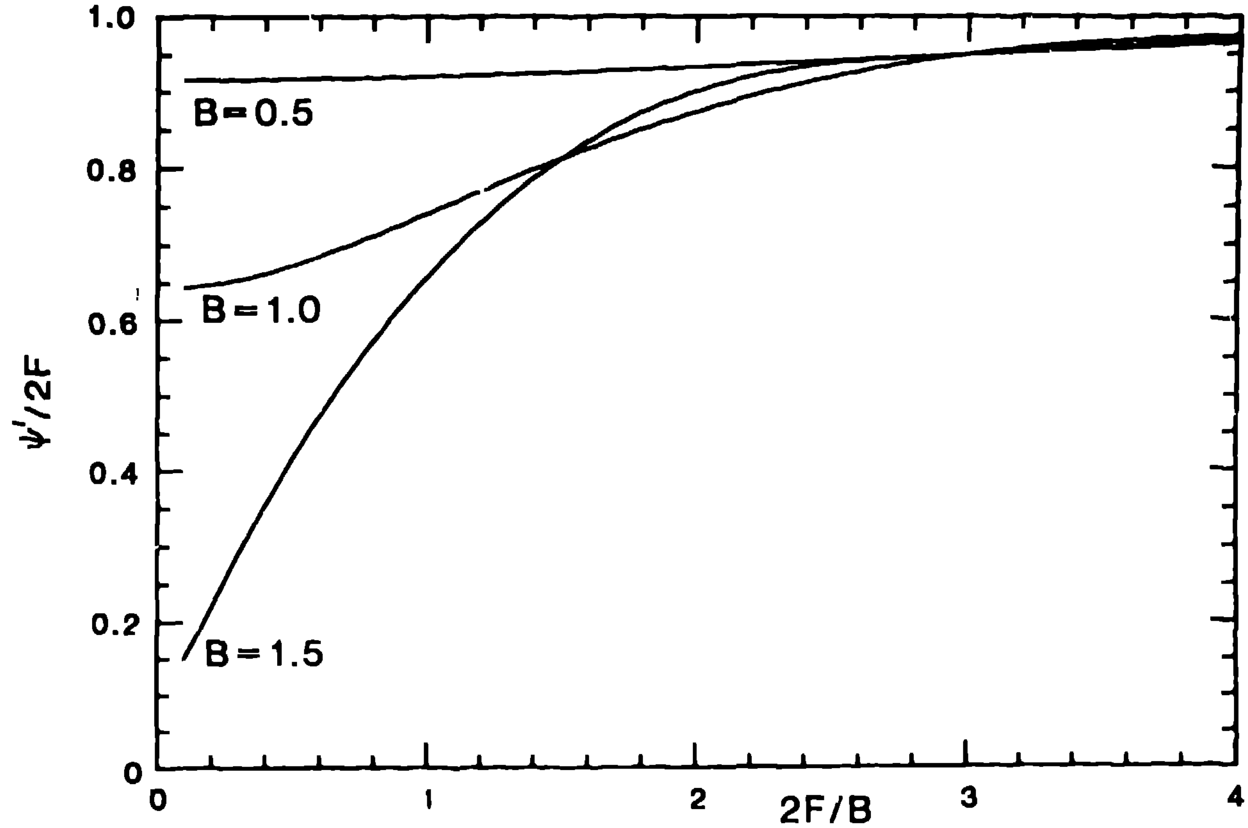

Figure 3. Plots of figure-of-merit as a function of ratio of Faraday rotation to linear birefringence, with total linear birefringence as a parameter.

Experiments

ZT-40M is a toroidal, reversed-field-pinch, magnetic fusion experiment at Los Alamos National Laboratory that produces currents as high as 400 kA for periods of 1 to 30 milliseconds. We installed two single-mode optical fibers by wrapping each six times poloidally around the torus (the short way around). The fibers were made by EOTec[7] and are single-mode at 633 nm. One of the fibers had been twisted 15 turns per meter and the twist locked in by re-coating. The coils were approximately 398 mm in diameter and were fusion spliced to leads 26 meters long made from very low linear birefringence single mode fiber that was manufactured by another company.

Although approximately 300 μW of light power was injected, only 3 to 6 μW was available at the photodetector. This was apparently caused by poor splices and bending losses incurred because of the tortuous route the fiber followed through the insulation surrounding the torus. This resulted in a poor signal-to-noise ratio. A source of low frequency noise, or drift, was fluctuations in the optical paths traversed by the two beams before recombination on the calcite crystal. These fluctuations produced phase shifts that were indistinguishable from those caused by Faraday rotation. This inadvertent interferometer was used to inject phase shifts for testing the system by tapping on the mounting plate.

The fiber was optimized for mechanical strength so that it could survive the twisting process. As a result it has high internal stresses and a slightly elliptical core and can be expected to display a high intrinsic linear birefringence. In addition, the routing of the fiber and its leads induces birefringence because of stresses in the fiber. Although we do not have the equipment to measure the total birefringence, we consider this experiment to have been a test of current measurement under conditions of high linear birefringence.

Figure 4 is a plot of the current computed from the Faraday rotation apparatus with the twisted fiber in place (dashed,noisy line) and a plot of the current calculated from the Rogowski coil that is the standard current diagnostic on ZT-40M. The failure of the Faraday current trace to return to zero at the end of the current waveform can be attributed to drift caused by the path fluctuations described above, driven by air currents or vibrations of the mounting plate. This baseline drift could have been reduced if the current sensitivity had been increased by a larger number of turns up to the extent permitted by Fig. 3.

The second fiber, identical but not twisted, produced no detectable response to the current, although the optical path fluctuations were detected during the "tap test", and drift was observed during the period of current flow.

The same apparatus was used to make current measurements on a laboratory source that produces an approximately 20 kA peak-to-peak, 40 μs period, damped sinusoidal current. This source was used to drive a ten turn coil, through which had been threaded four turns of single-mode optical fiber. This fiber was

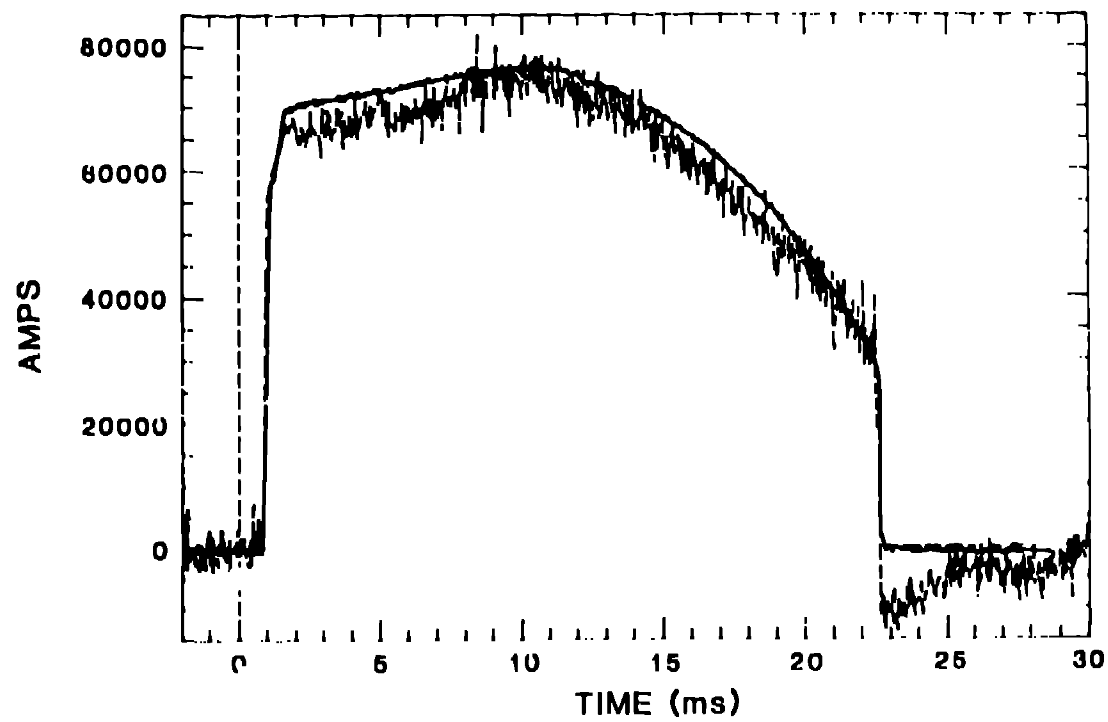

Figure . Solid line: ZT40M Rogowski current transformer. Dashed line: Faraday current diagnostic.

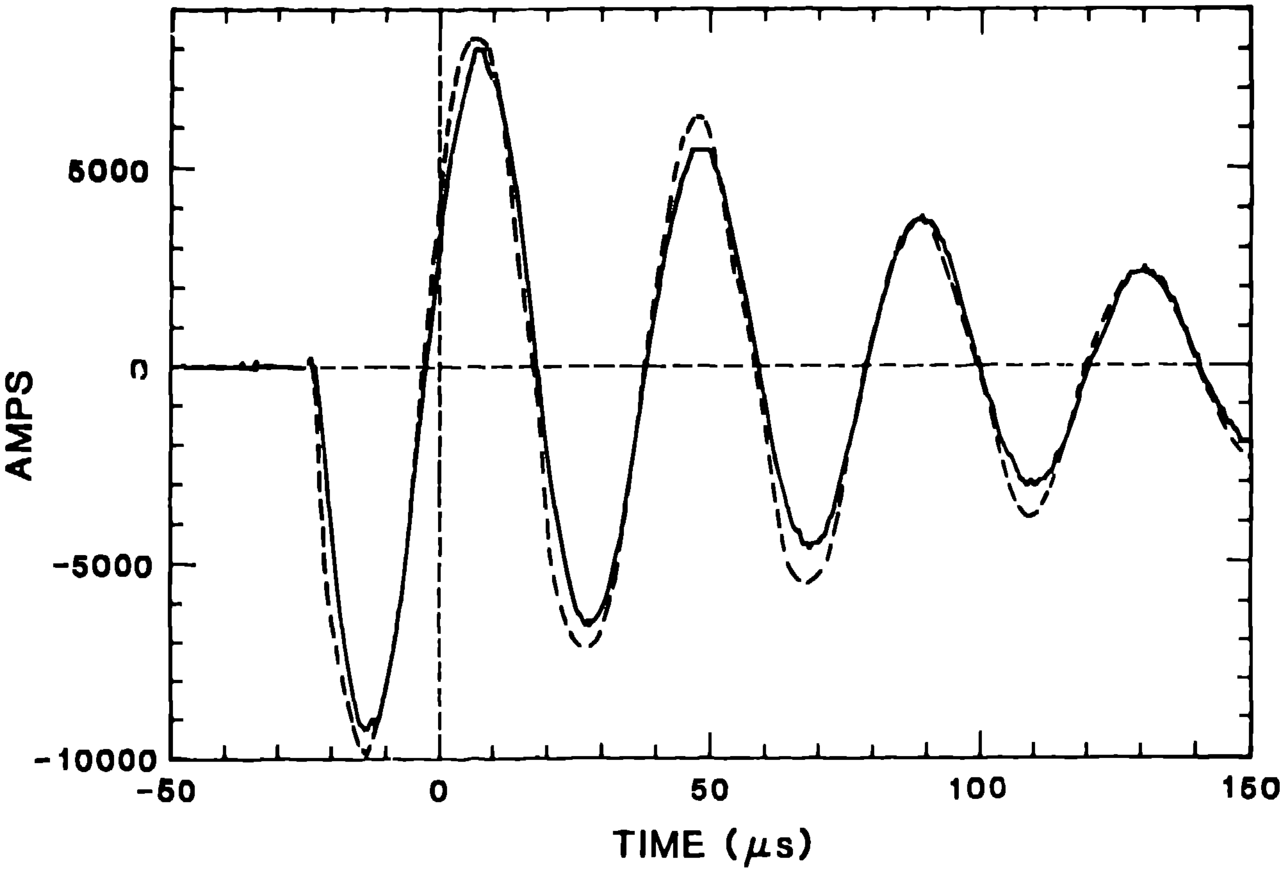

Figure 5. Solid line: Sinusoidal source Rogowski current transformer. Dashed line: Faraday current diagnostic.

not twisted and was manufactured by Lightwave Technologies, Inc.[8] The leads were much shorter, there were no splices, the fiber has much less intrinsic birefringence, and therefore the total birefringence can be expected to be much less. Also the signal level at the photodetector was approximately 300 μW, which resulted in an improved signal-to-noise ratio.

Figure 5 displays plots of the Faraday current measurement (dashed line) and the output of a current transformer.

The currents from the Faraday rotation experiments in both Figs. 4 and 5 were scaled from the Verdet constant and the number of turns, that is as Ψ, not as Ψ'. No corrections of any kind were applied.

Future work

The drift caused by fluctuations in the optical path generated by vibrations or air currents can be eliminated or reduced in several ways. One is to split off a part of the input signal and use it to drive a feedback mechanism, for example a piezoelectrically operated mirror.[9] Another is to avoid having divided optical paths by using an electro-optic cell with two electrode pairs driven in quadrature to produce the rotating linear polarization.[10] A third method is to measure the drift by using the front reflection off the fiber input to drive a second set of electronic phase shift analyzers and subtracting the result from the current signal.

Conclusions

We have demonstrated heterodyne polarimetry for current measurements by Faraday rotation in single-mode optical fibers. The technique overcomes many of the drawbacks of conventional polarimetry. We have also shown that it is feasible to use twisted fiber to eliminate the problems caused by birefringence.

Acknowledgements

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