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TITLE: MEASUREMENT OF MEGAMPERE CURRENTS WITH OPTICAL FIBERS

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MEASUREMENT OF MEGAMPERE CURRENTS WITH OPTICAL FIBERS

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Abstract

We have used fiber optic sensors routinely to measure multi-megampere currents. The sensors are low noise, absolutely calibrated, and electrically decoupled from the pulsed power source. Polarized light from a HeNe laser is guided past the current carrier by a single-mode, low-birefringence fiber. The magnetic field from the current causes a Faraday rotation of the light polarization which is detected by a polarization analyzer and photodiode at the end of the fiber. We observe a rotation of about 250°/MA ± 5%, slightly less than the Verdet constant for non-birefringent silica glass. We find that highly birefringent (polarization preserving) optical fibers do not work in this application. We are now trying to ruggedize the sensor for field use with high-explosive-driven current sources by using a diode laser and single mode fiber couplers to replace the laboratory system of lenses and spatial filters.

Introduction

Traditionally, a large, fast current pulse, I, is measured with a Rogowski loop, a wire in which the magnetic flux surrounding the current induces a secondary current proportional to the rate of change in I with time, dI/dt. Although such loops have been used satisfactorily for currents up to a megampere or more, they begin to distort in the large fields present near higher currents and become less accurate. An alternative method for measuring both large currents and high magnetic fields (> 100 T) involves a probe based on the Faraday effect.[1,2] Recent advances in the fabrication of single mode fiber optics has made it possible to build a Faraday effect sensor having almost no intrusion on the system being measured.

Faraday Rotation

The Faraday effect appears as a rotation of the polarization plane of a light wave traversing a medium when there is a magnetic field along the direction of propagation. This rotation arises because the magnetic field induces a circular birefringence, a difference in the refractive indices for the left and right circularly polarized components of the light wave, and the rotation angle is $\phi = V' \int_0^L \vec{B} \cdot d\vec{x}$ where B is the magnetic field, L is the path length in the field and V' is a constant that depends on the medium and the wavelength of the light. For a closed path with current I flowing through the area it bounds, the rotation is $\phi = VI$, $V = V'/\mu_0$, by Ampere's law. For silica glass of the type used in making single mode fibers, the constant V, known as the Verdet constant, is about 260°/MA at a wavelength of 633 nm.[3]

The circular, field-induced birefringence does not combine in a simple way with the linear birefringence caused by internal stresses in the glass and external stresses from clamping, bending, or otherwise applying pressure to the fiber.[3] If either the circular or the linear birefringence is much larger than the other, its effects dominate. Hence we used very low internal birefringence fiber; high-birefringence, polarization-preserving fibers do not work at all in this application. In the laboratory we found that the linear birefringence caused a rotation of < 30° in 5 m of fiber. We believe that most of this rotation occurred where the ends were held. In the field we used about 10 m for each sensor, and there was a tight (30 mm diam) loop in the fiber which caused an estimated 120° of rotation.[4] The effect of this much birefringence on the first polarization peak (in the direction perpendicular to the zero-field fiber output polarization) is to lower the peak about 30% and to make it occur near 70° field-induced rotation instead of at 90°, but there is relatively little effect on the subsequent peaks at higher fields. Thus for currents of 1 MA or more the calibration is nearly independent of the stress-induced birefringence.

Details of the Sensor

Figure 1 shows a schematic diagram of the Faraday rotation sensor. We inserted polarized light from a HeNe laser into the 4 μm fiber core using a 10X microscope objective lens. A similar lens collimated the fiber output into a Wollaston prism which separated the two polarization components and directed them to the two detectors. One detector was a Devar type 539 photodiode and operational amplifier with a bandwidth of 4 MHz, and the other was an EG&G type FOD-100 photodiode with a Los Alamos transimpedance amplifier having 100 MHz bandwidth. Presently we run the detectors and laser in a screen room to minimize noise pickup.

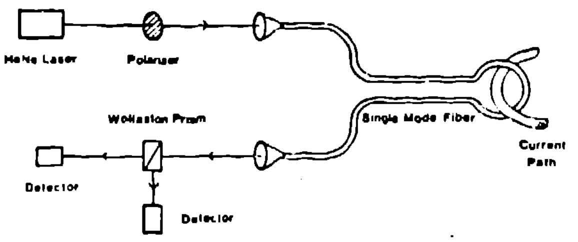

Fig. 1. A schematic diagram of the fiber optic sensor. Polarized light from a HeNe laser proceeds down the fiber, around the current carrier, and back to a Wollaston prism which separates the two linear polarization components, directing one component to each detector. When current flows, it rotates the polarization plane and changes the relative detector signals.

We used type F1506C single mode fiber purchased from Lightwave Technologies, Inc. The important features of this fiber are its low internal birefringence and the glass jacket, which has a higher index of refraction than the cladding, to mode-strip out of the fiber any light being transmitted by the cladding. (Similar fibers are manufactured by several other companies.) Since we use short pieces, the fiber attenuation is of relatively little importance to us. For most of our measurements we used a single loop of fiber wound around the current carrier.

We calibrated the sensor to ± 5% on a capacitor bank with about 1 MA output current by comparing with a Rogowski loop of known geometry. The calibration acuracy was limited by our ability to determine the rotation angle, but we will repeat this calibration with a sensor having a large number of fiber loops to get an accurate calibration.

Our early measurements showed a great deal of detector noise from light that coupled into the fiber core. We eliminated most of this with filters in front of the detectors and black paint sprayed on the part of the fiber inside vacuum chamber. Some EMI noise remains on the detector signals, particularly for the Devar detector, but by paying careful attention to shielding and fabrication details, EG&C was able to reduce the noise on the newer detector to a satisfactory level.

Results

Figure 2 shows oscillograms of signals from two detectors measuring the orthogonal light intensities from a fiber encircling a capacitor bank load four times. The lower trace is from the higher bandwidth EG&G detector. Each on-off cycle represents a 180° rotation of the polarization plane, or about 0.17 MA change in the load current. The current rose to a peak of 5 MA in 6 μs and then began to drop, at which time the polarization rotation reversed. At 18 μs the current reversed again. The 2-μs-wide peak at 14 μs in the lower trace is a fiducial timing marker.

Figure 3 shows a current measurement. The points were read from the peaks and dips of the oscilloscope trace for a single-turn sensor, and the curve is a sine wave with a 23.2 μs period and an amplitude normalized to fit the measurements. After about 9 μs, the current begins to deviate from the sine function because of resistive damping in the LC circuit. Comparisons between the Faraday rotation sensor and Rogowski loop detectors also show excellent agreement.

Figure 4 shows the geometry of a more interesting bank load, a coaxial opening switch for megampere currents. The current flows down the center conductor, through an aluminum foil about 1 mm thick, and back the outer conductor. The $\vec{I} \times \vec{B}$ force on the foil accelerates it down the channel, much as in a rail gun, and a fiber in the slot measures the current rise as the foil jumps the slot (Fig. 4b). The detector signals are shown in Fig. 5, along with the signal from a fiber farther upstream measuring the input current. The 2.3 MA current pulse enters the load with a risetime of 6 μs, and later nearly half of it is switched into the slot with a risetime of 0.5 μs. Figure 6 shows the measured currents in the two fibers.

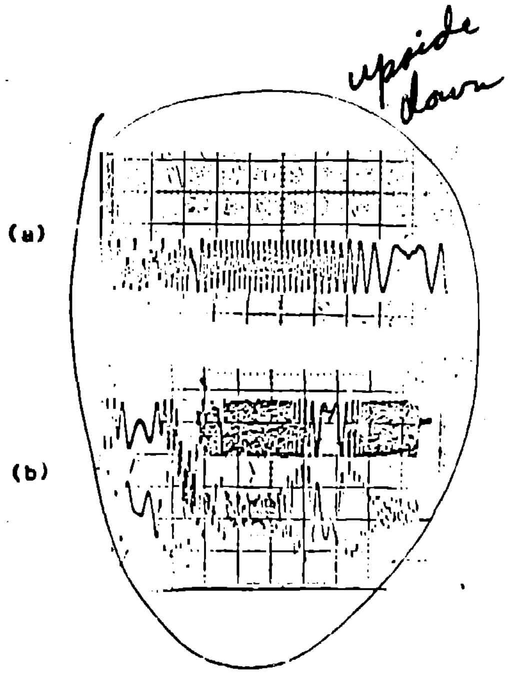

Fig. 2. Photodiode signals (2 μs/div) of the two polarization components of light emerging from an optical fiber looped four times around the current load. The upper trace is from the earliest detector type we fielded, and the lower trace is from a newer EG&G detector with a faster response time and less noise. In part (b), the center portion of the EG&G detector signal is shown on a 1 μs/div oscilloscope sweep.

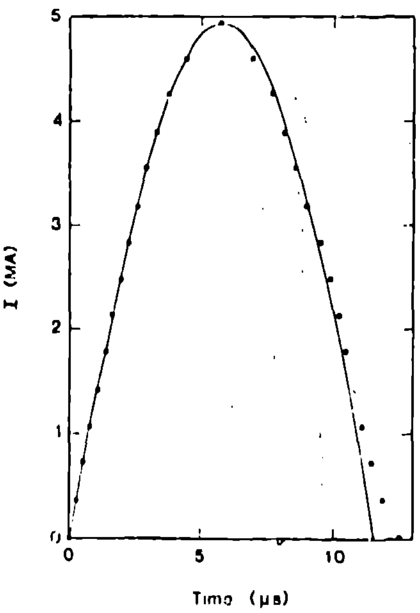

Fig. 3. Measured current from detector signals similar to those of Fig. 2. The curve is a sine wave (arbitrary amplitude normalization). The measured points deviate from the sine function at late times because of resistive damping in the capacitor bank load circuit.

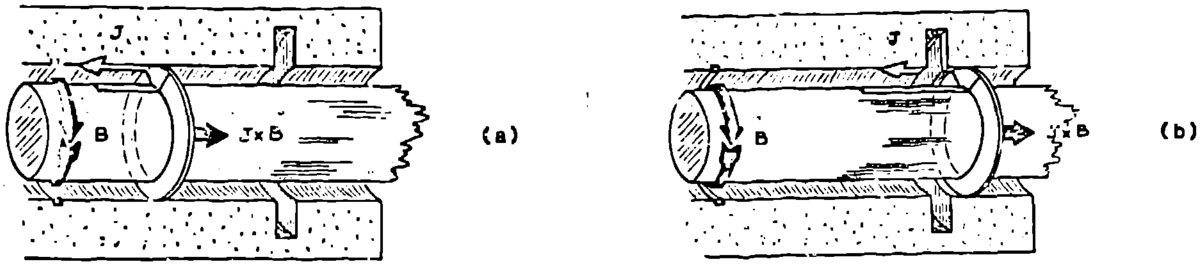

Fig. 4. (a) Geometry of the bank load being tested as an opening switch. Megampere currents, J, flow along the surface of the center conductor, radially outward through the 1-mm-thick aluminum foil, and back along the inner surface of the outer conductor. Optical fibers measure the current on each side of the foil. The magnetic field, B, in the gap accelerates the foil in the direction of $\vec{J} \times \vec{B}$. Part (b) shows the foil position after the peak of the current pulse has discharged into the load and the foil has moved down the gap and past the slot.

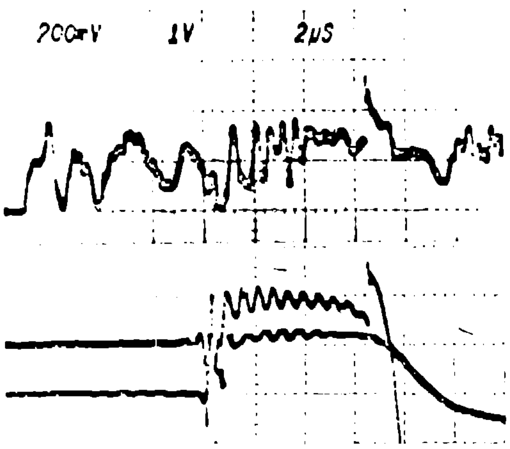

Fig. 5. Detector signals for the two fibers illustrated in Fig. 4. The upper trace is for the left fiber. Noise on the trace makes this signal difficult to interpret and different from the sine wave we measured with the Rogowski loop. The lower traces are for the fiber in the slot. The noise problem was less severe for this fiber because it was better protected. No current was recorded until the foil passed the slot. The measured current rise time can be calculated from the foil thickness and the measured velocity. The small oscillations appearing after the current rise are from shock stress on the fiber, and the peak between 14 and 16 μs (also in the upper trace) is a fiducial marker.

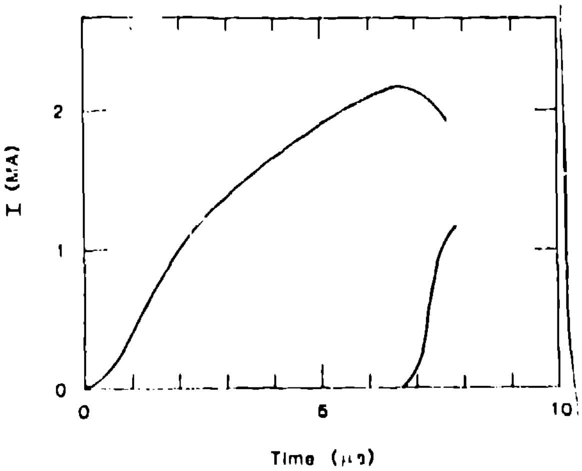

Fig. 6. Current measurements. The upper curve is from the upper trace of Fig. 5. The time at which the polarization reversed and the current began to drop was determined from another (Rogowski) current probe because of the noise on this signal. The lower curve is from the lower trace of Fig. 5 and is for the fiber in the large slot of Fig. 4.

Future Improvements

We plan to change from HeNe lasers to 830 nm laser diodes as soon as possible. With laser diodes we will eliminate the tedious alignment procedure that we must now follow with up to four sensors for each experiment, and we hope to increase our signal-to-noise ratio by increasing the amount of polarized light in the fiber. We intend to upgrade the detectors to the faster FOD-100 type because of their increased bandwidth and lower noise levels (see Fig. 2), and we will then repeat the switching experiments to get more accurate results.

We have ordered a piece of polarizing fiber from York V.S.O.P.; it is advertized that this fiber transmits one polarization mode while guiding the other mode into the cladding and out of the fiber, so that in 1 or 2 m of fiber unpolarized light becomes polarized. It offers the possibility of fabricating an all fiber sensor consisting of a laser diode, the low-birefringence fiber in the magnetic field, a short piece of polarizing fiber to analyze the polarization, and a detector. If necessary, a long piece of fiber could be spliced to the polarization analyzer to carry the modulated light to a distant detector, and polarizing fiber just past the source would permit use of a light-emitting diode or an unpolarized laser diode for more flexibility.

To eliminate fiber stress as a factor in the measurements, we would like to build a fiber optic Sagnac interferometer, shown schematically in its simplest form in Fig. 7. The laser input light enters a coupler which sends half of the light in each direction around the closed fiber path. Were there no polarization rotation in the fiber, the light having traversed the closed loop and returning to the coupler would interfere constructively with the light that went the opposite direction, giving a signal in the detector (and feedback to the laser). Stress-induced birefringence has identical effects on the light in both paths, and therefore its effects cancel except for possible time-dependent stresses which could affect the different paths at different times, but magnetic field-induced birefringence changes the index of refraction in opposite directions depending on which direction the light passes through the field. Consequently, the detector will see a field-dependent intensity which, for large fields, becomes a series of intereference fringes similar to those shown in Figs. 2 and 5.

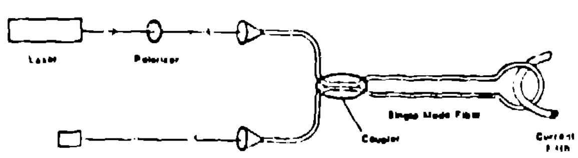

Fig. 7. Schematic diagram of a simple Sagnac fiber interferometer proposed for measuring large currents or magnetic fields with less noise than the sensor we have been using.

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