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High Current Sensing Through Faraday Rotation of Polarized Light of Varying Wavelengths in Fibers III

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Abstract

Traditionally, large-amplitude, fast rise tiOI1 electrical currents and magnetic fields have been measured with electromagnetic probes such as Rogowski coils or B-dot probes. These measurements can be problematic if made near high voltage electrodes with insufficient probe isolation. An alternative method for measuring electrical current and magnetic fields involves using the Faraday effect on linearly polarized light propagating in optical fibers. OI2

Faraday effect probes have been used to measure magnetic field strength for many years. In this application, the fiber probe is subject to a magnetic field, the propagating polarized light will rotate within the fiber. For strong magnetic fields, the rotation angle may exceed many hundreds of degrees with the resultant probe receiver output exhibiting a sinusoidal response. Each sinusoidal period represents a phase shift = 180 degrees (one "fringe"), and for simple cases, the magnetic field strength can be determined simply by counting the fringes. The fiberoptic signal line can pass light long distance with minimal attenuation and because the optical fiber is a dielectric material its able to be used near high voltage electrodes. Furthermore, the response of these probes is based solely on the material properties of the sense fiber, thereby making any calibration, in situ or otherwise, unnecessary. Due to technical advances in the telecommunication industry, a robust compact Faraday effect optical assembly is now available at low cost.

This paper builds on the authors previous work (Ref 6 & 7) and summarizes recent experimental data taken with the Mykonos Linear Transformer Driver (LTD) at Sandia National Laboratories and attempts to calculate the Verdet constant for four fiber type propagating four different wavelength's of light. The Mykonos LTD was operated to discharge ~ 550 Kilo-amps into a coaxial load region containing our four (4) probe sensor assembly. The discharge current 10/90 % risetime equals ~ 72 ns OI3 and current peaks ~ 115 nsec after the discharge current begins. A summary of our results using this four probe sensor, optimized at wavelengths 450 nm, 532 nm, 632 nm and 850 nm is presented.

Introduction

One fundamental measurement requirement for most pulsed power researchers is the ability to measure the pulsed discharge current output from the devices they utilize. Ref 1 discusses many approaches for this to include: 1) measuring the voltage from a probe monitoring the time rate of change of the magnetic field ("B-dots and Rogowski coils") and 2) measuring the voltage induced by the discharge current across a low impedance resistor ("current viewing resistors and current shunts").

These measurement techniques work well for many situations, however we want to examine other techniques that are more electrically isolated from the experimental device and electrically immune from the experimental EMI generated when the device fires. One such alternative method for measuring these large currents involves the Faraday effect on linearly polarized light(LPL) propagating within single mode fibers (ref 2-thru 7).

Briefly, the Faraday effect results in the rotation of the LPL within the fiber due to the fibers core behavior within the magnetic field (ref 2). The amount of LPL rotation is given by

$$\theta = V' \int_0^L B \cdot dx \quad (1)$$

For a fiber wrapped N times around a conductor this becomes: (2)

$$\theta = V' \, 2\, pi \, N \, B$$

Using Ampere's law for a closed path we can obtain:

$$I = \frac{\theta}{\mu_o N V'} \quad (3)$$

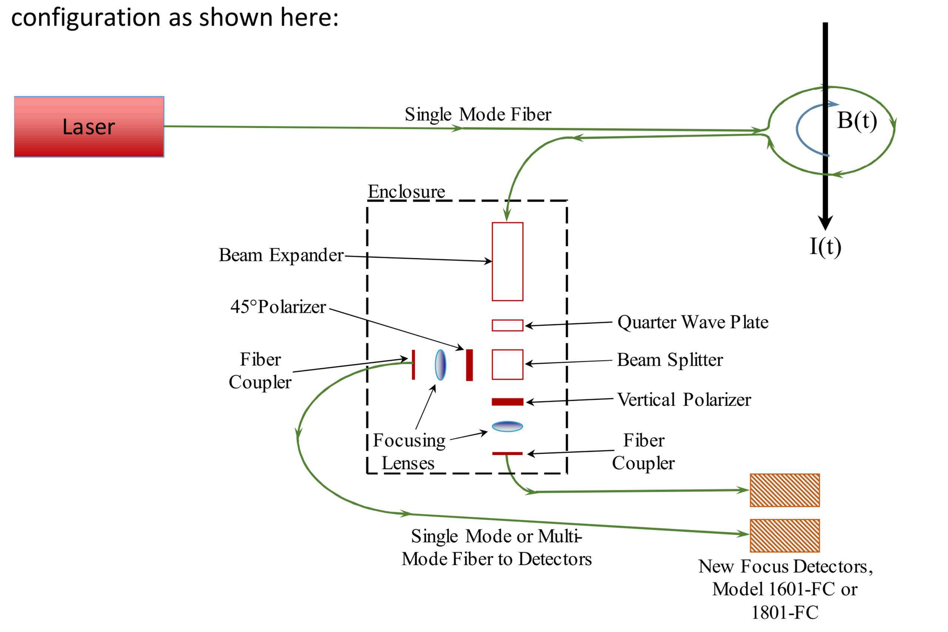
Where: V' = fiber Verdet constant

N = number of turns around conductor

Thus if we can measure the LPL rotation within the sensor fiber probe, using equation 3 we can then calculate the current.

Faraday Rotation Probe Design

The majority of the optical components were built by Oz Optics with the probe configuration as shown here:



We purchased four sets of systems to include the laser, beam splitter assembly and enclosure and a pair of photo-detectors for each operating wavelength of 450nm, 520nm, 635nm, and 850nm.

The laser and beam splitter contain rotatable optics allowing the user a means to manually rotate the LPL while simultaneously observing the photodetector signal outputs. By displaying these signals as a Lissajous curve the user can optimize initial polarization angle(s). Monitoring of the photodetector signals also provides direct feedback to user of required digitizer vertical sensitivity for this probe. OI5 OI4

Calculate Verdet constant

For each fiber probe there are two photo-detectors. When the fiber probe is subject to a strong magnetic field the linearly polarized light (LPL) within is rotated and each photo-detector (p-d) signal output will exhibit a sinusoidal type behavior. A p-d signal output maximum occurs when the LPL aligns with the polarization angle of the beam splitter (see diagram) and a signal minimum occurs when the LPL has rotated 90 degrees from the maximum. For a continuously increasing magnetic field, one peak-to-peak span of the p-d signal output represents a rotation angle change of the LPL light equal to 180 degrees and is sometimes referred to as a "fringe".

To subject our probe to the magnetic field of Mykonos, we install the probe assembly between the coaxial anode/cathode conductors within the Mykonos vacuum load region. To calculate the Verdet constant we rearranging equation (3) and solve for V' to obtain:

$$V'' = \frac{\theta}{NI} \quad (4)$$

Where: V'' = fiber Verdet constant (radians / (Mega-amp – turn))

N = number of turns

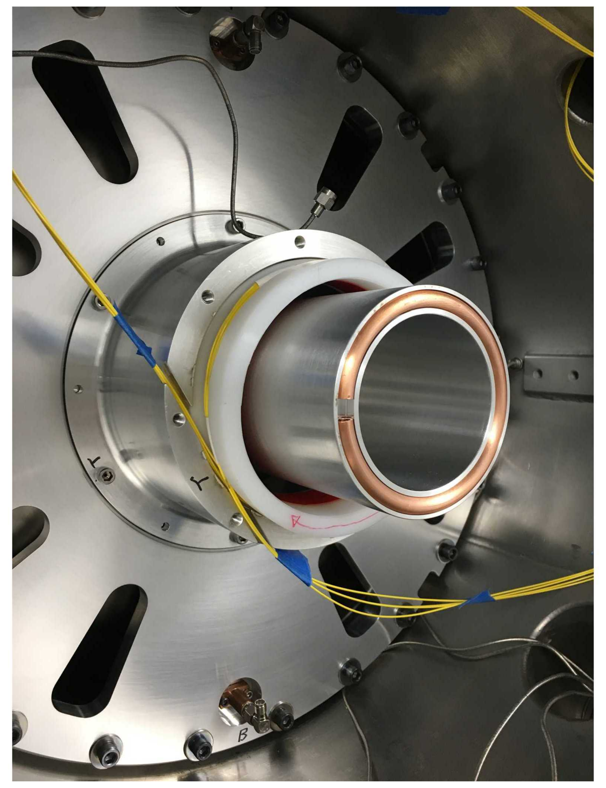
theta = rotation angle till first discharge current peak amplitude (radians)

I = discharge current peak amplitude (Mega-amps)

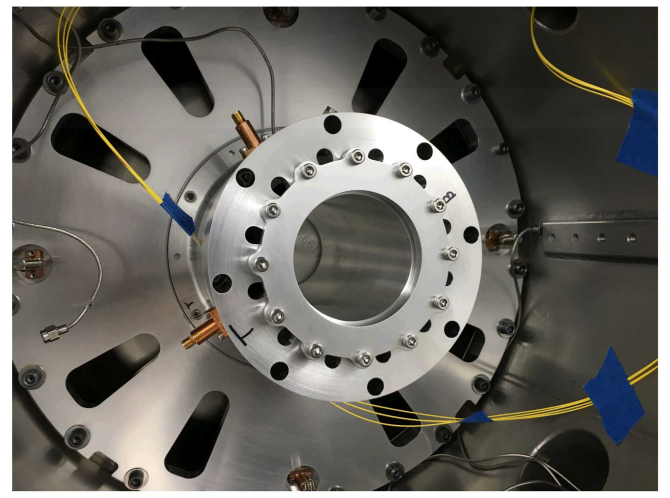
For example, on Mykonos shot 10138, we measure 13.4 fringes from photo-detector signal "Faraday_1A" up to a time equal to the first current peak amplitude of 558 Kilo-amps. This represents a rotation angle = 2412 degrees or 42.1 radians. Thus, for our 9 turn coil, we calculate a Verdet constant = 8.38 (radians/(Mega-amp-turn)).

Experimental Probe Setup on Mykonos

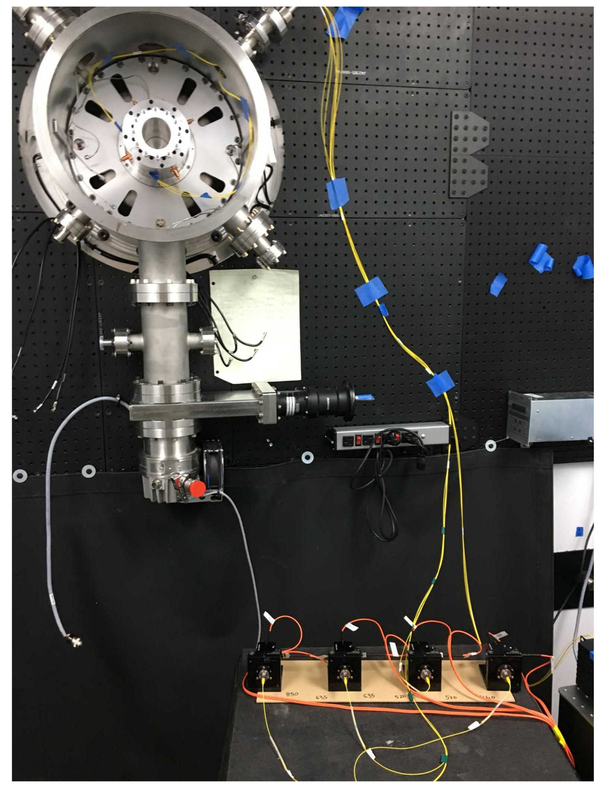
View of ~ 4" ID 9 turn coil



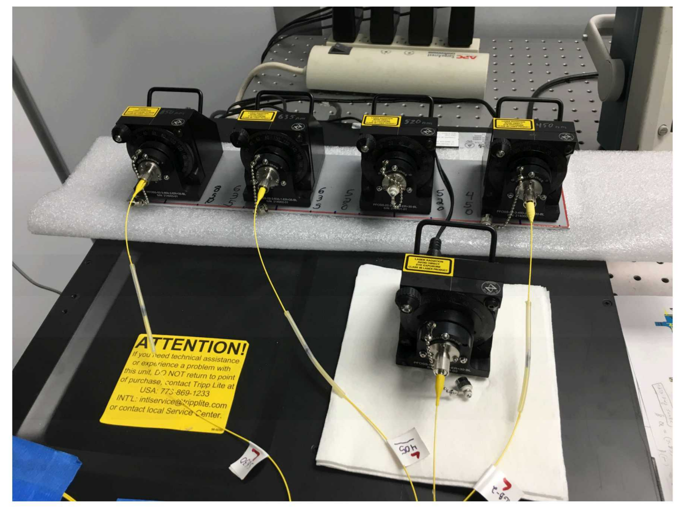
Assembled load



Mykonos / fiber assembly

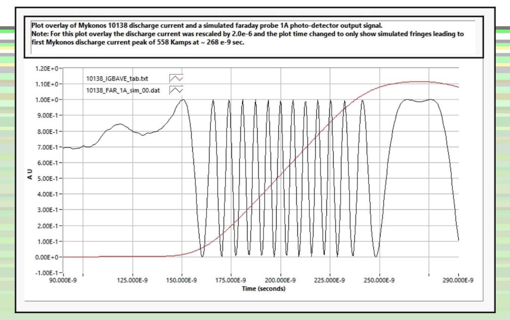


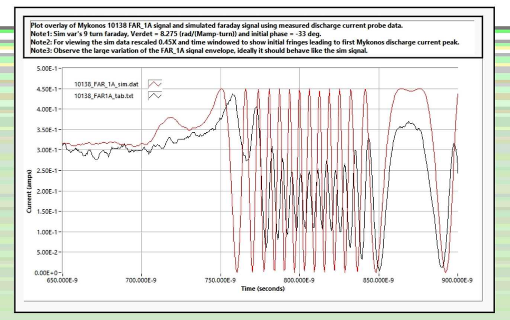
Four (4) fiber output polarized laser transmitters



Experimental results OI6

Immediately upon shooting the Mykonos pulser we observed some distortion of the signal envelope of photo-detector signal outputs from our fiber probes. The concern is that the output signal maximum and minimum amplitudes are not consistent during the shot time frame. For reference, a plot overlay of the Mykonos (shot 10138) discharge current and a simulated fiber probe signal is shown below (left side) whereas the plot on the right is an overlay of this simulated data plotted with the photo-detector signal from Mykonos probe "FAR_1A" during shot 10138.





Notice that the plot on the left (simulated photo-detector) has signal fringe maximum and minimum that are uniform over the time window but the plot on the right (Mykonos probe "10138_FAR_1A") shows signal maximum and minimums that are varying through out the plot window. This is indicative of a problematic probe monitoring system.

This problematic behavior can be caused by a laser transmitter power issue due to shot noise pickup or a fiber probe assembly problem or both. Though Mykonos shot noise is very small, our lasers were powered from a battery powered invertor to address shot noise issues and we believe the transmitter power source was not faulty. The author has seen similar abnormal fiber probe signal behavior and previously the source of the problem was that the fibers were physically over-strained leading us to believe something similar occurred.

Calculated Verdet constants

Though we experienced problems with the photo-detector signal upper and lower signal envelopes we were able to process some of the data sets. Some data was seriously "challenged" due to maximum and minimum signal distortions causing some fringes to be lost entirely. We present the calculated Verdet constants in the table below for the latest data taken as well as the Verdet constants presented last year (Ref 7).

Fiber type	850 nm Verdet (rad/(Mamp-turn))	635 nm Verdet (rad/(Mamp-turn))	520 nm Verdet (rad/(Mamp-turn))	450 nm Verdet (rad/(Mamp-turn))
Corning HI780 >780 nm	??? / 2.68	N/A / 3.61	6.6 / 6.32	5.9 / 10.7
Corning RGB 450-700 nm	??? / 2.57	4.6 / 4.72	N/A / 7.16	8.7 / 10.3
Thor Labs S630 630-860 nm	??? / 2.57	4.6 / 4.61	5.9 / 6.89	N/A / 7.63
Thor Labs SP405 400-680 nm	N/A / ???	??? / 4.66	6.1 / 6.65	8.3 / 9.91

From the above table, for Thor Labs fiber type S630 at 635 nm wavelength, we calculated a Verdet constant = 4.61 vs a Verdet = 4.61 calculated previously. Similarly, for fiber type SP405 at 450 nm wavelength we calculated a Verdet = 8.3 vs a Verdet = 9.91 calculated and presented previously. Clearly, our fiber probe operation is problematic and adversely OI7 affecting our latest calculations. For the cases where the Verdet constants = "???" or "N/A" either the signal data was to noisy to work or we ran out of time and had to stop testing.

Discussions

1) The authors have recently acquired instruments to measure and quantify the profile of laser beams within both the visible and IR wavelength range. We want to examine and quantify beam profiles exiting our probe fibers under various levels of strain.

2) Our shot series on Mykonos was undertaken only a month before this conference so we were not able to repeat and present our measurements using fiber probes assembled with less strain. We want to repeat these measurements with new fibers after we have quantified the laser beam profiles as mentioned in 1).

3) Monitor the laser power source for shot noise or measure the stability of the laser output during shots.

4) Compare calculated Verdet values with published values.

Acknowledgement

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Slide 1

OI1	rise time Owens, Israel, 6/18/2019
OI2	optical fibers Owens, Israel, 6/18/2019
OI3	ns Owens, Israel, 6/18/2019
OI4	hwp will rotate linear polarization and qwp will circularize the polarization Owens, Israel, 6/18/2019
OI5	instead of a 50/50 beam splitter with a vertical and 45 degree polarizer, would a PBS work? Owens, Israel, 6/18/2019
OI6	This section is a bit confusing. I think we should clearly spell out the figures of merit for calculated or expected result versus the measurements in the expeirment. Owens, Israel, 6/18/2019
OI7	Explain... Owens, Israel, 6/18/2019