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Magneto-Optical Measurement of High Magnetic Fields for Pulsed Power Systems

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Abstract: Electrical currents and magnetic field generated in high energy pulsed power accelerators are key operating parameters. However, to date, accurate and precise magnetic field and electrical current measurements on these high energy pulsed power accelerators have proven to be very difficult. This difficulty in performing the measurements is partly due to the fact that traditional metallic-probe field sensors require electrical impedance matching and are prone to noise that interferes with the desired signal. A non-metallic method for sensing magnetic fields is accomplished by utilizing the Faraday effect. We report on a magneto-optical approach based on the Faraday effect that uses a rare earth element crystal to measure magnetic fields and requires no interfering metallic probes or components to disturb the measured field. Here we focus on device theory, operating parameters and a benchtop laboratory experiment that illustrates the principles of operation on a high energy pulsed power accelerator.

Introduction and Motivation

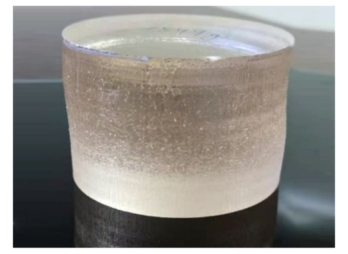
- Magneto-optical sensors (MOSs) are ideally suited for noninvasive pulse power diagnostics because they do not suffer from many of the issues of conventional diagnostics.
- Galvanic isolation is important as metallic elements will bring noise back to the readout electronics, and improper electrical impedance matching conditions hamper desired signals with unwanted reflections.
- Magneto-optical sensors do not require any integration factors because there exists a direct linear relationship between the magnetic field and the measured optical signal.
- Paucity of literature on the use of magneto-optical sensors to measure magnetic field and voltage. In particular, sensing fast, high current magnetic field pulses is the most thinly represented.
- For accurate and precise measurement of the magnetic field strength of a high energy puled power machine, it is important to consider both the high magnetic field strength itself and fast timing requirements.

Theory and Materials

- Physically, the Faraday effect is a magneto-optical effect whereby the plane of polarization of light passing through the media is rotated, and the amount of rotation (θ) depends upon the properties of the magnetized media, the wavelength of light propagating, the intensity of the magnetic field (**B**), and the path length (d) of the light in the media.
- The material property that describes the strength of the Faraday rotation is referred to as the Verdet constant (v). The Verdet constant of a material is the wavelength and temperature dependent. Even though the Faraday effect only has a weak temperature dependence, the Verdet constant is strongly wavelength dependent. Even so, the Verdet constant is relatively small for common magneto-optical sensor materials such as those commonly found in the core of optical fiber.

$$\theta = v(\lambda, T)\mathbf{B}d$$

- There are a total of 17 types of rare earth elements on the earth, but the Faraday effect is strongest in materials that contain paramagnetic ions such as terbium.
- Terbium gallium garnet (TGG) and yttrium iron garnet (YIG) are the specific materials we selected for this project. In TGG, the Faraday effect is inversely proportional to the wavelength of the light. For YIG, the Verdet constant increases above 1300 nm and extends through to the 1550 nm range.



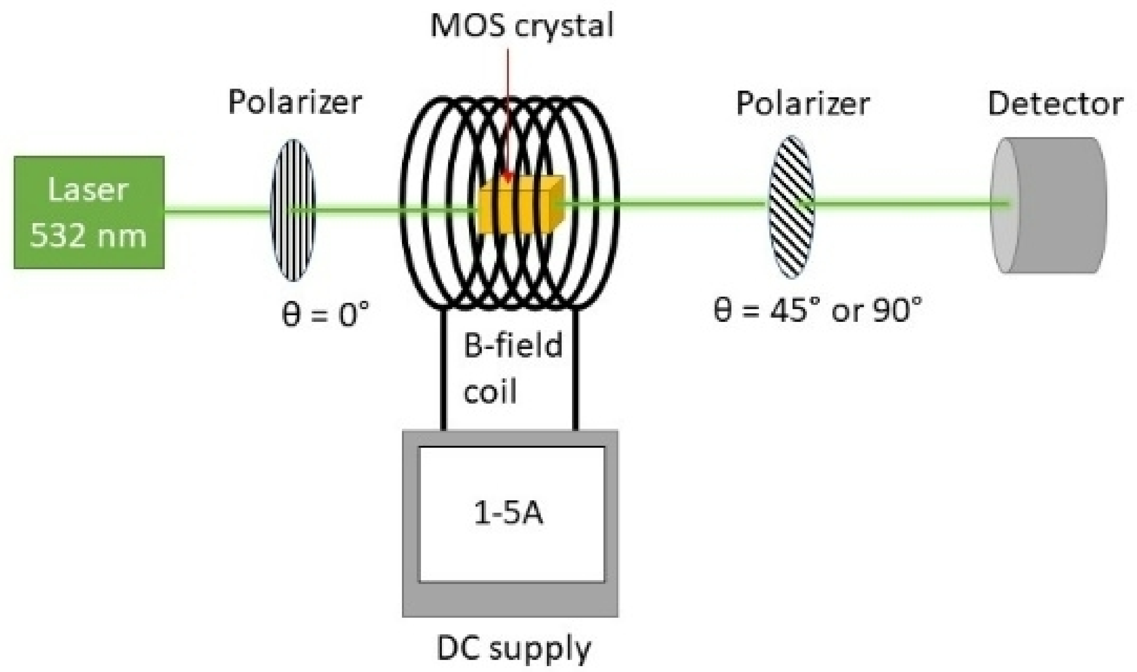
TGG

YIG

Verdet Constant Measurement

- The main components of the benchtop Verdet constant measurement consisted of a 250 mW continuous wave single-mode, low-noise 532-nm fiber-coupled laser, 1-5A DC supply, 50 mT magnetic field reference coil, a 10 mm x 6 mm x 6mm TGG crystal, polarizers and a detector to measure the light intensity level .
- Using the expression for Faraday rotation, we can calculate the Verdet constant based on a rotation angle Δθ that represents the required rotation for a reference magnetic field applied that minimizes the detector intensity level relative to the starting position at 45° or 90°. By applying a series of electrical current values between 1-5A DC, we determined the Verdet constant of the TGG crystal at 532 nm to be **190 RadT^{-1}m^{-1}**.

$$v(\lambda, T) = \Delta\theta / \mathbf{B}d$$



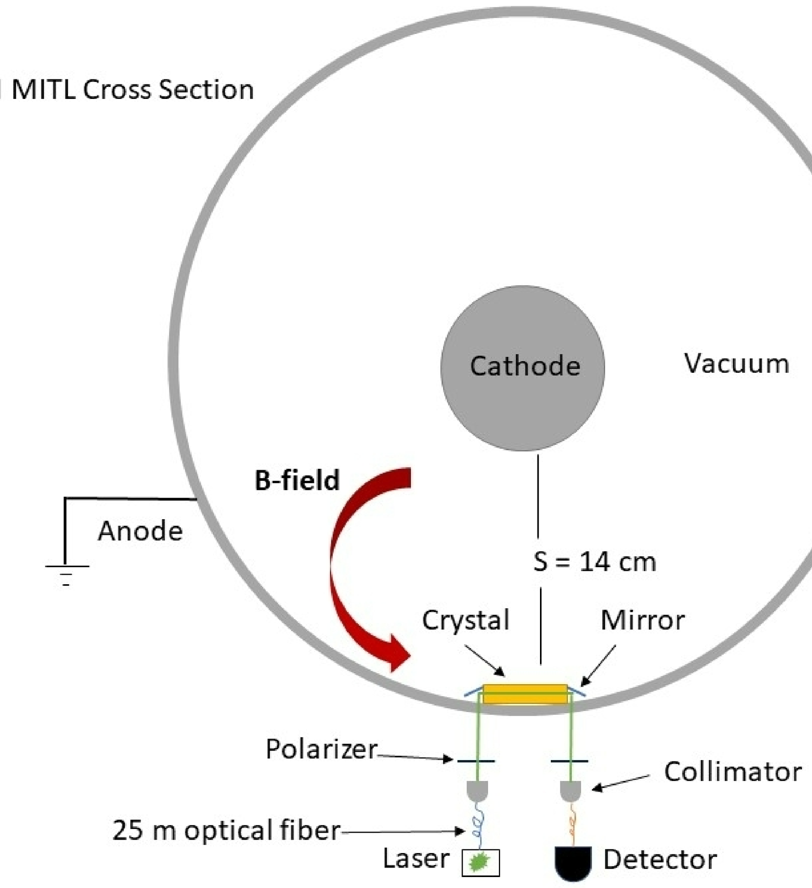
MOS on HERMES III Pulsed Power Accelerator

- HERMES III (HIII) is a high energy pulsed power accelerator that produces up to a 20 MV at 550 kA with 30 ns FWHM pulses.
- To show feasibility of our concept, we consider a TGG crystal illuminated at 532 nm, and we model the magnetic field of the HIII magnetically insulated transmission line (MITL) as generated by a current carrying wire (**B** = $\mu_o I/2\pi r$) along the MITL axis to determine the expected Faraday rotation angle, system modulation voltage, magnetic field sensitivity and resolution.
- With a 550 kA current, and a .14 m radial gap from the cathode to anode, the magnetic field is approximately **1T** across the TGG crystal. Using the expression for the Faraday rotation, a 10-mm-long crystal of TGG, 190 RadT^{-1}m^{-1} this results in a linear polarization rotation of **90°**.
- With 100 mW of 532 laser light, a photodetector responsivity of 9.5 A/W (into 50Ω), 10% light transmission through the optical system, and a $\cos^2(\theta)$ dependence of the Faraday rotation angle to light output intensity, we'd expect approximately **1-volt** signal on an oscilloscope. At a system background noise level of 1 mV, the sensitivity is in the **20 µV/A** range.
- A series of six shots on HIII were fired with the MOS device to ascertain whether or not we'd see a signal of magneto-optical origin. Preliminary results look promising, and we noted the MOS system was not damaged in the high energy environment. Further experimentation on HIII is planned to obtain a larger data set for more detailed analysis of the MOS system response.

Conclusion

- MOS shows promise as a noninvasive approach for measuring magnetic fields as it does not suffer from many of the issues of conventional diagnostics.
- System operating wavelengths (532 nm and 1550 nm) and crystal sensing materials (TGG and YIG) were selected due to their robustness in the operating environment and sensitivity to magnetic fields.
- The Verdet constant of TGG at 532 nm was measured in the laboratory, and a calculation to show feasibility of measuring a magneto-optical signal in the MITL of HIII accelerator was demonstrated.
- Initial experiments performed on HIII look promising in terms of ascertaining the magneto-optical origin of the system response, and ensuring the sensor is not damaged in the high energy environment.
- Future interest includes exploring how different sensing crystal materials, operating (laser) wavelength (e.g. 1550 nm), and range of magnetic field strengths affect the magneto-optical electric field sensing.

We plan to perform an additional series of experiments on HERMES III to better understand the nature of the magneto-optical response in a high energy environment filled with sources of electrical and optical noise.



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