A magneto-optic probe for magnetic fluctuation measurements

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Results from a proof-of-principle experiment are presented that demonstrate it is possible to construct a completely optical, robust, and compact probe capable of spatially resolved measurements of magnetic field fluctuations smaller than 1 G over a frequency range of 1 Hz–8 MHz in a plasma. In contrast to conventional coil probes, the signal strength is independent of fluctuation frequency and the measurement technique is immune to electrostatic pickup. The probe consists of a high Verdet constant crystal, two polarizers, optical fibers, and a photodetector. © *2009 American Institute of Physics.* [doi:10.1063/1.3238509]

I. INTRODUCTION

For several decades, the standard method of performing localized measurements of magnetic fluctuations in plasmas has been through the use of pickup coils, also known as *B*-dot probes.[1] The voltage induced across *n* turns of a conducting wire provides a measure of the time-varying magnetic flux through the coil. Other magnetic fluctuation measurement techniques, such as laser polarimetry, have been successfully employed in large-scale magnetic fusion plasma experiments, but with considerable cost and infrastructure requirements.[2]

A fundamental problem with conventional *B*-dot probes is their susceptibility to capacitive pickup, especially in rf generated plasmas where large electrostatic fluctuations, on the order of 100 V, are typical.[3] A variety of electrostatic pickup compensation methods have been developed.[4] However, even the best compensation technique does not entirely eliminate electrostatic pickup. Another limitation of conventional *B*-dot probes is that they have a limited frequency range. Some are useful only in low frequency applications up to a few tens of kilohertz,[5] while others are more appropriate for higher frequencies.[6] Because the signal amplitude of a *B*-dot probe is proportional to the fluctuation frequency, the dynamic range of *B*-dot probe amplifiers also plays an important role in the probe frequency range.

A compact probe that employs measurements of the Faraday rotation of propagating laser light in a small crystal would be immune to electrostatic pickup effects; have a signal amplitude independent of the fluctuation frequency; and, through the use of multiplexed or wide-band amplifiers, have a frequency response ranging from a few hertz up to many gigahertz. The essential physics of the probe is the same as that employed in polarimetry systems for magnetic fusion experiments, but a probe provides spatially resolved magnetic fluctuation measurements at a much lower cost than a line-integrated polarimetry system.[1] Magneto-optic probes are routinely used for measurements of very high frequency currents in microwave circuits[7] and a prototype probe based on a ZnSe crystal, with a sensitivity of 40 G, was recently employed in a high magnetic field (~10 000 G) pulsed plasma experiment.[8] A key result of the pulsed plasma experiment was that the ZnSe electro-optic properties were not altered by the intense x-ray emission associated with the plasma pulse. That probe employed three optical fibers. Light injected into the ZnSe crystal through one fiber was split into two paths for polarization analysis and conveyed through a pair of optical fibers that extended beyond the magnetically active region.

This work extends the previous work to much weaker magnetic fields (<1.0 G) by selecting polarizer angles that maximize the modulation of the transmitted light and by focusing on measurements of the magnetic fluctuation spectrum instead of absolute measurements of the magnetic flucutation amplitude. The design of the apparatus reduces the required number of optical fibers and polarizers from three to two (by demonstrating that magnetic fluctuation spectrum measurements can be obtained directly from the modulation of the light transmitted through the detector assembly) and the measurements demonstrate that the signal amplitude is independent of the modulation frequency. The measured sensitivity and frequency range are sufficient for the probe to be used for magnetic fluctuation measurements in Alfvén wave propagation experiments (in which the driven wave fields have amplitudes on the order of 0.1 G).

II. EXPERIMENTAL APPARATUS

As discovered by Faraday, certain materials exhibit circular birefringence when their optical axis is aligned with the direction of an applied magnetic field.[9] For linearly polarized light propagating along the optical axis, the plane of polarization rotates an amount proportional to the path length of the light in the material[10]

$$\Phi_F = V\oint B \bullet dl, \tag{1}$$

where *V* is the Verdet constant, *B* is the magnetic field, and the integral over *l* is the length of the crystal. The Verdet constant is given by[11]

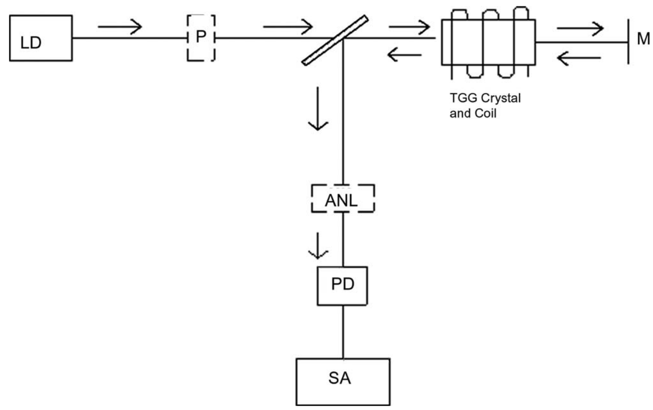

FIG. 1. Schematic of materials testing apparatus. (LD: diode laser; P: polarizer; M: mirror; ANL: analyzer; PD: photodiode; SA: spectrum analyzer).

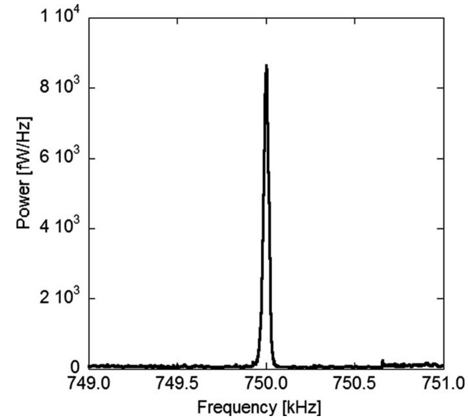

FIG. 2. Power spectrum of the photodiode signal for a 10 G, 750 kHz applied magnetic field fluctuation.

$$V = \frac{\pi\gamma}{\lambda n}, \qquad (2)$$

where γ is a constant dependent on the material (the magnetic gyration coefficient), λ is the free space wavelength of the light, and n is the index of refraction.

For initial materials testing, a 25-mm-long terbium gallium garnet (TGG) crystal was placed inside a tight-fitting electromagnet constructed from 20 turns of enamel-coated copper wire (see Fig. 1). The electromagnet was driven with an Agilent 3322OA function generator amplified with an RF Power Laboratories Inc. FK30-50 wideband rf amplifier. A 1 Ω shunt resistor in series with the electromagnet was used to monitor the current through the electromagnet.

At 532 nm, the Verdet constant of TGG is 0.2 min/G/cm. TGG is not the highest Verdet constant material available, e.g., the Verdet constant of ZnSe is almost twice as large. It was selected for these preliminary experiments for its moderate cost and immediate availability. Considerably higher Verdet constant materials exist, such as cadmium manganese telluride (CdMnTe) with $V=5.6$ min/G cm. Since, as will be shown, the 25-mm-long TGG crystal provides adequate signal, the thickness of the active crystal could be reduced to less than 1 mm provided CdMnTe is used. At a thickness of less than 1 mm, a single CdMnTe crystal of the appropriate diameter costs some tens of dollars.

During the materials testing, a polarizer (Edmund Optics NT47-216) and a beam splitter (Newport Optics 10B20) were placed between the TGG crystal and the 532 laser diode (an inexpensive laser pointer with a power of less than 5 mW). Since an inexpensive laser pointer was used as the light source, the first polarizer was used to establish a highly polarized incident beam. After passing through the TGG crystal, the laser beam was reflected from a mirror and passed back through the TGG crystal. After exiting the TGG crystal, a portion of the laser beam was directed toward another polarizer and then into an unamplified avalanche photodiode (OSI PIN-10D) by the beam splitter. The frequency spectrum of the fluctuations in transmitted light intensity recorded by the photodiode was measured with a Hewlett–Packard 3585A rf spectrum analyzer.

For a magnetic field that is parallel to the laser beam path and uniform over the length L of the crystal, Eq. (1) reduces to $\Phi_F = VBL$. Since the magnitude of Faraday rotation depends only on the magnitude of the magnetic field and the angle between the laser beam and the crystal's optical axis, the two passes through the TGG crystal double the total rotation of the plane of polarization of the laser beam.[12] Therefore, as long as the transit time through the crystal is much shorter than the fluctuation period of interest, any ambient magnetic field fluctuation will produce double the polarization rotation predicted by Eq. (1). To maximize the change in the transmitted light intensity as a function of polarization shift, the angular difference between the axes of the two polarizers was fixed at 45°. To first order, fluctuations in the transmitted intensity are linearly proportional to the strength of the ambient magnetic field fluctuation

$$I(\tilde{B}) \cong \frac{I_o}{2}(1 + 2V\tilde{B}L), \qquad (3)$$

i.e., the measured intensity variations are a direct measure of the strength of the magnetic field fluctuation amplitude.

The frequency spectrum of the transmitted light for an electromagnet modulation frequency of 750 kHz during materials testing is shown in Fig. 2. The total polarization axis rotation, expected to be 8.2 min for an electromagnet current of 1 A and two passes through the 25-mm-long TGG crystal, was confirmed by scanning the angle of the second polarizer and fitting the resultant intensity versus relative polarizer angle to Malus' law, $I(\theta)=I_o \sin^2(\theta-\theta_o)$, where θ_o is the shift in the laser polarization axis from the 90° separation of the two polarizer axes. The signal-to-noise ratio (SNR) for a 10 G fluctuating magnetic field at 750 kHz, as shown in Fig. 2, is 800:1.

Shown in Fig. 3 is the experimental geometry used to demonstrate that this measurement technique can be incorporated into a compact probe that can be inserted into a plasma experiment. Laser light was coupled into a 200 μm core, multimode, optical fiber. Since the multimode optical fiber does not preserve the laser light polarization, light exiting the fiber was linearly polarized with a 1/4 in. diameter polarizer (Edmund Optics) sandwiched between the end of the fiber and the TGG crystal. The analyzing polarizer (polarization axis at 45° relative to the first polarizer) was placed on the other side of the crystal and the single-pass transmitted light

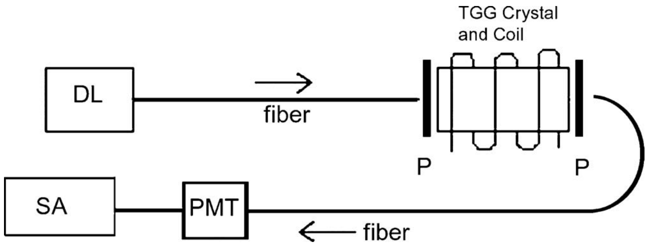

FIG. 3. Dye laser light at 611 nm is coupled into a 200 μm core optical fiber, polarized, and passed through the TGG crystal. Upon exiting the crystal, the light passes through another 1/4 in. diameter polarizer oriented at 45° relative to the first and is coupled into a second fiber that conveys the light to a 10 MHz bandwidth PMT detector whose output is monitored with the spectrum analyzer. (DL: dye laser; P: polarizer; SA: spectrum analyzer).

coupled into a second optical fiber. Similar fiber geometries inside a probe have been implemented in previous experiments in our laboratory.[13] In actual implementation, unsheathed optical fibers would be used and the entire probe assembly diameter could be as small as 1 mm.

III. EXPERIMENTAL RESULTS

The light coupled into the collection fiber shown in Fig. 3 is coupled into a 10 MHz bandwidth Hamamatsu photomultiplier detector and the signal monitored with the spectrum analyzer. A typical signal is shown in Fig. 4(a) for a magnetic field modulation frequency of 600 kHz. The measured signal versus modulation frequency is shown in Fig. 4(b) for the probe configuration. With the photomultiplier tube (PMT) detector and its integrated transimpedance amplifier, the signal is nearly constant over the entire modulation frequency range investigated. The decrease in signal amplitude at frequencies ~10 MHz is due to the high frequency cutoff of the PMT amplifier.

The signal (averaged over five sweeps of the spectrum analyzer) signal for a magnetic field fluctuation amplitude of 2.0 G at a frequency of 1.2 MHz yields a SNR of greater than 10:1 (see Fig. 5). At field strengths smaller than 2 G, the calibration magnet was unstable. Based on the measurements at 2.0 G, we conservatively estimate that the magnetic field fluctuation sensitivity achievable with this diagnostic method is <0.1 G.

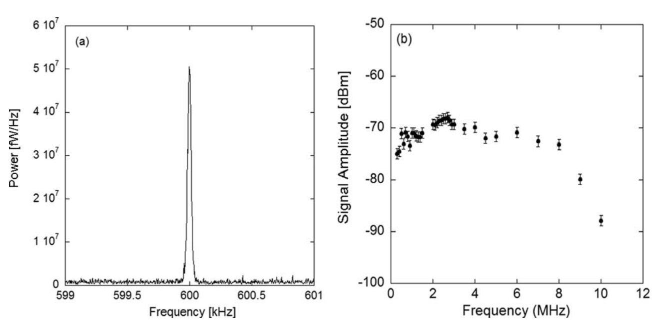

FIG. 4. (a) Typical power spectrum obtained with the fiber coupled, "probe" experimental configuration for a 10 G, 600 kHz modulated magnetic field. (b) Measured signal for a magnetic fluctuation amplitude of 40 G vs modulation frequency.

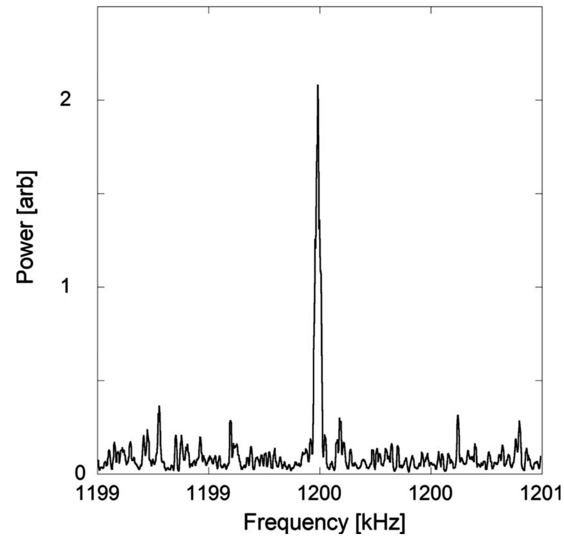

FIG. 5. Power spectrum obtained with the fiber coupled, probe experimental configuration for a 2 G, 1200 kHz modulated magnetic field.

IV. DISCUSSION

Based on these experiments and the previous work by other researchers, it appears possible to construct a low-cost, all-optical probe for the measurement of the fluctuation spectrum of small amplitude magnetic fluctuations in plasmas while avoiding the limitations of conventional probes. In addition to being immune to capacitive pickup, the frequency range of such a probe easily spans from 1 Hz up to many megahertz; a frequency range significantly wider than most magnetic fluctuation probes in use today. With improved detection electronics and a wider bandwidth detector, the frequency range could be extended up to many tens of megahertz. Improved sensitivity is achievable with higher quality polarizers, lower noise electronics, and higher Verdet constant materials (while still maintaining the approximately 1 mm spatial resolution transverse to the axis of the measured field that these experiments demonstrate is achievable). The spatial resolution along the measured field is determined by the length of the crystal and with the higher Verdet constant materials, the length of the crystal can be reduced to 1 mm without compromising SNR. In fact, the SNR is likely to increase significantly because the loss of light due to beam divergence in the crystal would be reduced in a shorter crystal. Thus, a probe such as that depicted in Fig. 3 can be used as a direct replacement for existing magnetic fluctuation probes.

ACKNOWLEDGMENTS

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