Magneto-optical properties of e-beam evaporated EuS films for room temperature applications

(Student paper)

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Traditionally, magneto-optical effects enable non-reciprocal optical response engineering in devices such as optical isolators. Unfortunately, conventionally used materials are bulky and hard to pattern, making scaling to integrated optics difficult. Here, we report on the Verdet-constant measurements between 600 – 800 nm at room temperature of e-beam evaporated EuS, which appears to be an order of magnitude higher than conventional TGG.

Keywords: *Farady effect, Magneto-optics, Light-matter interaction, Verdet constant, Room temperature, Polarization, Optical isolator, Nanofabrication, Europium Sulfide, Thin film, Refractive index*

INTRODUCTION

Light-matter interaction subjected to a magnetic field leads to a plethora of important physical effects that affect light polarization, including the Faraday effect [1]. The Faraday effect is exhibited as a rotation of the (linear) polarization vector when light propagates through a magneto-optical material parallel to the applied magnetic field. The rotation θ is proportional to the applied magnetic field strength B and the propagation distance travelled through the magneto-optical material L. Below the saturation magnetic field strength, the rotation can be well described by

$$\theta = VBL, \tag{1}$$

where the proportionally constant V is known as the Verdet constant. For paramagnetic materials, such as EuS at room temperature, the wavelength dispersion within the tail of a resonance is usually modelled as [2]

$$V = \frac{E}{\lambda^2-\lambda_0^2}, \tag{2}$$

where the proportionality constant E is dependent on the paramagnetic ion volume concentration, temperature, transition probability and Landé splitting factor, λ is the wavelength of interest, and λ_0 is the resonance transition wavelength of the paramagnetic ions.

Magneto-optical effects differ from the asymmetric power transmission associated with chiral media, because the orientation of the magnetic field determines the rotation direction of the polarization vector. Unlike approaches relying on nonlinear effects or time modulation, magneto-optical effects break the Lorentz reciprocity in a passive system [3]. Many optical devices have been realized using these effects, including magneto-optical modulators [4], circulators [5], and isolators [6]. One of the most widely used magneto-optical materials, terbium gallium garnet (TGG) crystal, has a moderate Verdet constant of ~10^3 deg T^{-1} m^{-1} for 600 – 800 nm wavelength [7]. Accordingly, a 45 deg rotation at 1 T field strength requires roughly a material length of several cm. Given a certain material, Eq. 1 suggests that scaling down to smaller lengths requires an increase in magnetic field strength. However, this requires strong magnetics and at some point the magnetic field will be saturated.

Therefore, a next step is to investigate materials with a higher Verdet constant and accompanied by fabrication simplicity that pave the way for the engineering of nanophotonic structures that enhance magneto-optical effects. Eu-chalcogenides such as EuS are known to have a remarkably high Verdet constant at cryogenic temperatures [8], but unlike other Eu-chalcogenides, the Verdet constant of EuS at room temperature has long been overlooked [9].

Recently, we published the first measurements of the magneto-optical properties of thin-film EuS at room temperature [10].

RESULTS

In this study, we measured the Verdet dispersion between 600 – 800 nm wavelength. Additionally, we measured the refractive index and extinction coefficient of EuS using ellipsometry. All EuS films used in this study are deposited by electron-beam evaporation, where the substrate was kept at room temperature. The base vacuum of the system was ~6 x 10^{-8} Torr whereas during electron-beam evaporation of EuS it was at ~2 x 10^{-6} Torr.

For the refractive index measurements, we prepared a half-inch silicon square substrate with a 100 nm thick film of EuS. We used a spectroscopic ellipsometer (J.A. Woollam V-VASE32) to measure the real and imaginary part of the refractive index of the EuS film inside and outside the visible spectral range. The ellipsometry fits for 400 – 1000 nm wavelength are presented in Fig. 1(a). In addition, we applied the Sellmeier model to the refractive index data between 650 – 800 nm. The Sellmeier model used is given by

$$n^2(\lambda) = 1 + \frac{A_1\lambda^2}{\lambda^2 - {B_1}^2}, \tag{3}$$

for which we found fitting parameters A_1 = 3.0117 and B_1 = 0.2527 um. The resulting fit is presented in Fig. 1(b).

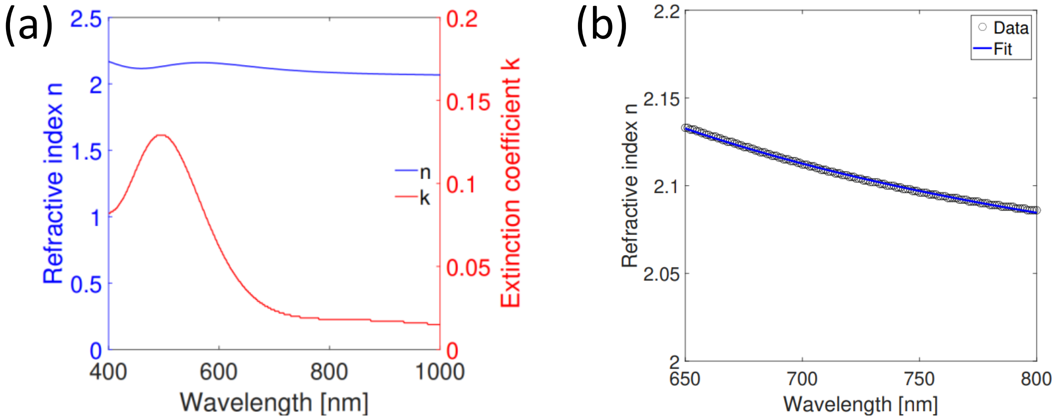

Fig. 1. Optical characterization of EuS. (a) The real (blue) and imaginary (red) part of the refractive index of EuS are extracted from ellipsometry measurements. (b) Sellmeier fit (Eq. 3) to the EuS refractive index data between 650 – 800 nm.

For the Verdet constant measurements, we prepared a 1 um thick EuS film on a 0.5 mm thick glass substrate. Our experimental setup is described in Ref. [10]. We used a home-built magnetic assembly that oscillated at 1 Hz and generated more than 1 T of magnetic field strength at the sample position. Our results are corrected for the Faraday rotation contribution of the glass substrate. The results of the Verdet constant measurements are presented in Fig. 2(a). The original Verdet constant measurements at 8 K temperature are presented in Fig. 2(b) [8].

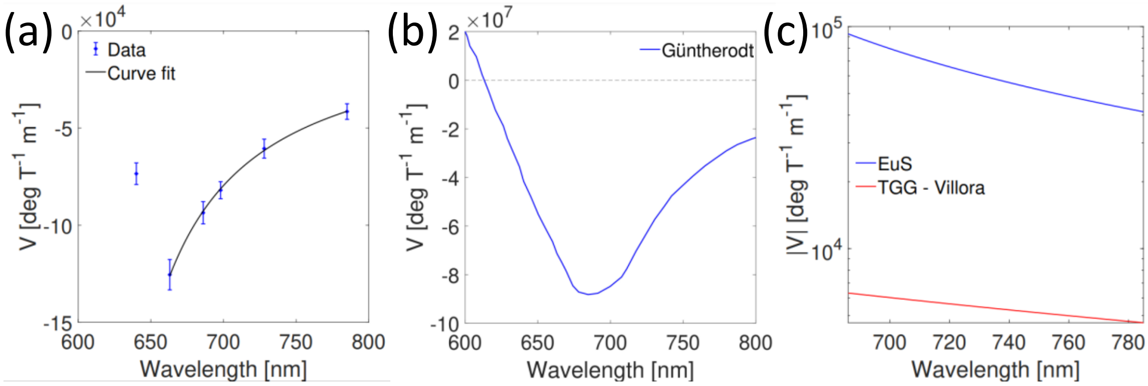

Fig. 2. Dispersion of the EuS Verdet constant. (a) Measured Verdet constant at room temperature and the fit to the data according Eq. 2. Error bars represent 95% confidence interval. (b) Verdet constant at 6 K [8]. Zero is indicated by the dashed line. Note the qualitative similar features of the resonance dip present in both graphs. (c) Verdet constant magnitude of EuS (blue) and TGG (red) [7] at room temperature. Note the order of magnitude difference.

We observe a similar qualitative behavior, therefore we omit the datapoint at 640 nm wavelength to fit the data with the model of Eq. 2. The extracted parameters are E = -10872 deg um^2 T^{-1} m^{-1} and λ_0 = 0.5944 um. The results for EuS are compared with the results of commonly used TGG in Fig. 2(c) [7]. We observe an order of magnitude higher Verdet constant for EuS.

DISCUSSION

We presented room temperature measurements of the Verdet constant, refractive index and extinction coefficient of thin-film EuS in the 600-800 nm wavelength range. In addition, we provided fitting parameters to commonly used dispersion models for the Verdet constant and refractive index. In recent years, nanophotonic devices have been proposed to enhance the magneto-optical response per unit length. Often these devices rely on patterning or depositing magneto-optical materials, making fabrication simplicity an important aspect. EuS can be easily deposited on top of patterned structures without losing its magneto-optical properties, making it an exciting material despite its moderate extinction coefficient. The fabrication simplicity of EuS thin films could potentially drive the realization of magneto-optical devices in integrated optics.

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