Magnetic field sensing using laser written birefringent scattering medium

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ABSTRACT

We demonstrate a polarization analyser based on processing of speckle patterns generated by a scattering medium. Each speckle pattern at a given wavelength and polarization state is unique and deterministic, and thus the polarization angle alters the speckle pattern motif. The polarization state of a given input light is obtained using reconstructive linear algebra methods. The system consists of a femtosecond laser written scattering chip and a CMOS sensor and contains no moving parts, making the proposed solution is low-cost and compact. The linear polarization angle was accurately reconstructed over a 0-20° test range, with 6 arcminutes (1/10°) standard error. To demonstrate an application as a polarimeter, we used the system to measure Faraday rotation in a SF59 lead silicate glass within an electromagnet. The magnetic field was successfully traced by determining the induced changes in the input beam's linear polarization angle in the range 0-80 mT with 10 mT standard error.

Keywords: Optical scattering, speckle pattern, polarization, Faraday rotation, magnetic field sensing

1. INTRODUCTION

Accurate analysis of light polarization is of fundamental and essential importance for a wide range of optical applications. Here, we demonstrate a technique for measuring the linear polarization state of light (either free space or from a fiber), based on a reconstructive approach utilizing polarization-dependent speckle patterns created by a scattering chip. The speckle pattern motifs are planar projections of multiple-scattered light and appear random and chaotic, but in fact, the opposite is true - these are highly reproducible and deterministic patterns, unique to the wavelength, polarization and environmental conditions (e.g. temperature, humidity).[1]

Previous reconstructive systems using scattering media as speckle generators include wavemeters, fiber Bragg grating interrogation, and strain measurement.[2,3] Such devices were first realized using multi-mode fibers (MMFs) producing interference patterns[4] for a high resolution wavemeter. However, a fundamental issue is instability due to the environmental conditions varying over time between system calibration and data measurement.[3]

To solve this challenge, our team developed a 3D silica scattering chip (Figure 1) for generating the speckles with high intrinsic stability (>7 days).[5] The scattering chip-based system benefits from no moving parts, low cost, straightforward manufacturing and applicability over a wide wavelength regime (as long as the sensor can detect the scattered light). Due to local stress-induced birefringence within the chip, the resulting speckles are also polarization dependent. Thus by calibrating the speckles with input light of known polarization angles, the polarization state of unknown input light can be recovered by analysing its speckle pattern against calibration data.

Furthermore, to demonstrate a practical application of the system, it was used as a magnetic field sensor, by tracing the Faraday polarization rotation induced by a glass sample inside an electromagnetic coil under different applied electrical currents.

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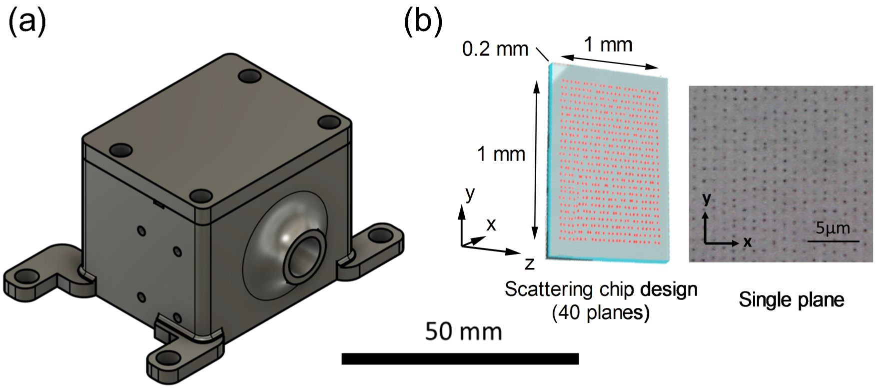

Figure 1. Scattering chip-based device: (a) sensor case, (b) scattering medium design with multiple void planes in silica and microscope image or a single plane of void scatterers.

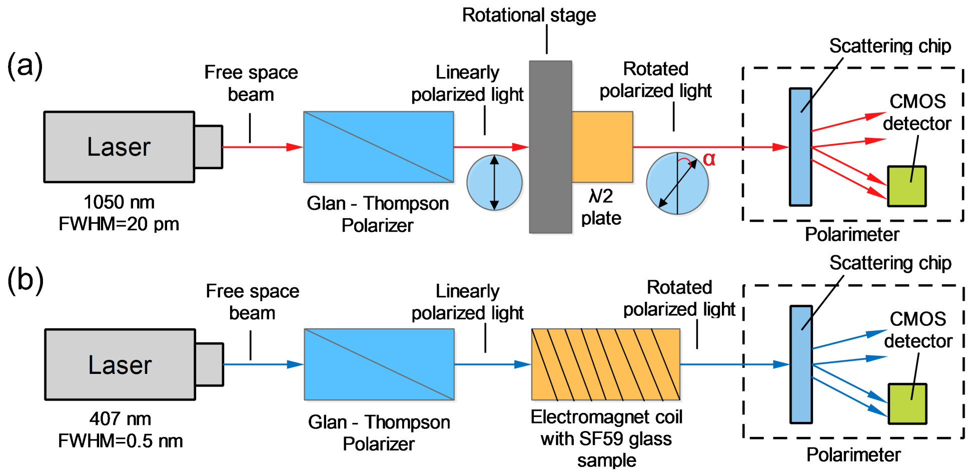

Figure 2. Experimental set up for: (a) polarization rotation sensing, (b) magnetic field sensing utilizing Faraday rotation effect via a SF59 glass sample inside an electromagnet coil.

2. DEVICE DESIGN AND FABRICATION

The scattering chip was fabricated in a fused silica substrate as 40 planes of pseudo-randomly displaced voids which act as scattering centres, with each void fabricated by a single femtosecond laser pulse (Fig. 1b). The pseudo-randomization enhances the scattering events and therefore produces more distinguishable (less correlated) speckles for neighbouring polarization angle states. Full details of the scattering medium design and fabrication are presented in our previous work.[5]

3. METHODS

3.1 Polarization angle detection

The presence of birefringence in the scattering chip introduced by local stress from laser writing allows for polarization-dependent speckles, so the device may function as a polarimeter and measure rotation angle α of the polarization plane. Angle measurement is obtained using singular value decomposition (SVD) and principal component analysis (PCA) as described elsewhere.[1,3,5–8]

Initially, the system was used to measure polarization rotation using a 1050 nm laser with 20 pm linewidth beam which was linearly polarized through a Glan-Thompson polarizer (Thorlabs, GTH10M) and a half waveplate (Thorlabs, WPHSM05-1064) (Fig. 2a). The beam was then incident directly on the scattering chip, after which the scattering interference speckle pattern was detected using a CMOS sensor (Sony, IMX219). Two experiments were performed: from 0 to 120 arcminutes (2°) with 10 minute increments (1/6°), and from 0 to

20° every 1°. For each increment, the speckle pattern was captured for calibration. Afterwards, a second dataset was collected over the same range for evaluating polarization reconstruction performance (Figs. 3 and 3b).

3.2 Magnetic field sensing

The magnetic field sensing test was based on an identical principle, but with the polarization rotation induced by applying an external magnetic field from an electromagnet coil, as shown in Fig. 2b. This rotation occurs as the beam passes through a SF59 lead silicate glass sample placed within the centre of the coil. The setup was similar to the polarisation rotation, except the waveplate and the rotational stage were replaced by an electromagnet coil (PHYWE) with SF59 glass mounted inside, and the laser source was changed to 407 nm with 0.5 nm linewidth (Thorlabs, PL205). Speckle patterns were captured every time the DC electric current applied to the coil was ramped up in range from 0 to 3.8 A with 0.1 A steps.

Since the generated magnetic field was proportional to the current applied, both the polarization rotation angle and the magnetic field can be calculated (Figs. 4a and 4b). The Faraday rotation angle is $\alpha = LVB$ and the magnetic field in the coil is $B = \mu_0\mu_r(N/L_{coil})I$, where $L = 2$ cm is the SF59 sample length, $V = 90$ rad/T/m the Verdet constant,[9] μ_0 the vacuum magnetic permeability, $\mu_r \approx 1$ the relative permeability of the SF59 sample, $N = 1200$ the number of coil turns, $L_{coil} = 7$ cm the coil length and I the coil current.

4. RESULTS

The reconstructed polarization angle rotation measurements (see Fig. 3), generally follow the linear ramping of the polarization angle and their standard error equals 6 arcmins in both cases, confirming the potential use of scattering chip-based system as an alternative polarimeter. Naturally, the linearity looks more consistent for the 1° increment, but the results prove the smallest measurable step of the system can indeed be as small as the calibration step of 10 arcmins (limited by the rotation stage precision), which suggests finer reconstruction resolution may be possible if calibrating using higher resolution.

Since such small changes in the polarisation can be traced, the magnetic field sensing results also follow a similar pattern, as shown in Fig. 4. However, the standard error equals 10 mT, which is larger than the sampling step (2 mT). The reason for this can be deduced from the trend of the results (Fig. 4a) - these are revealing noise in the reconstructed values, which is higher for higher magnetic fields. This can be explained by the coil heating due to the applied current. This rise in temperature affects alignment of the glass sample (SF59) and thus alters beam alignment relative to the scattering chip, thus affecting the speckle patterns. Hence at higher currents, higher deviation of the reconstructed results from the real value is observed.

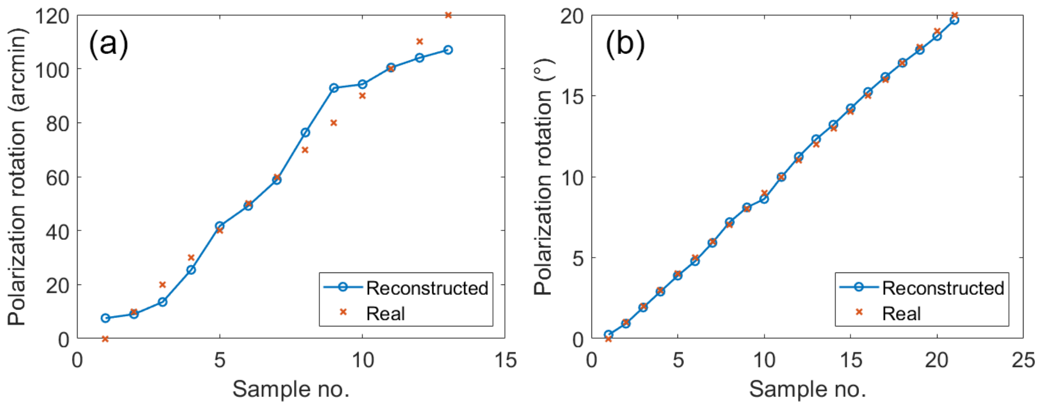

Figure 3. Polarization angle measurement of scattering chip-based device: (a) reconstruction of linear rotation in the range 0-2° every 10 arcminutes, (b) reconstruction of 0-20° rotation with 1° increments. In both cases the reconstructed data follows the real (reference) trend and standard reconstruction error is less than 6 arcminutes.

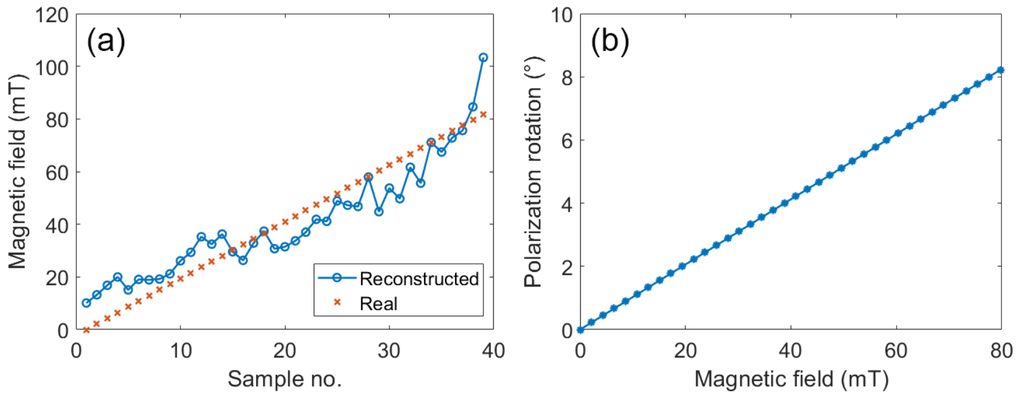

Figure 4. Magnetic field sensing experiment results, based on Faraday rotation: (a) reconstruction of the magnetic field while ramping the current (cross indicates real reference magnetic field values), (b) linear dependence between the magnetic field applied and the polarization rotation. Note the deviation of the reconstruction results from the reference at high magnetic field was due to instability from coil heating effects.

5. CONCLUSIONS

The realisation of a birefringent scattering medium-based reconstructive polarimeter and its application as a magnetic field sensor have been successfully demonstrated. The system was capable of distinguishing the linear polarisation angle with 6 arcminutes standard error, as well as recovering the magnetic field values in range 0-80 mT with 10 mT standard error. Although the scattering chip has high intrinsic stability, the increase in the temperature of the experimental set up, caused by the high currents applied to the electromagnet coil, induced instability and thus noise. Therefore, further work is required to investigate this phenomena and solve the potential challenge, which will allow practical exploitation of this system for magnetic field measurements.

ACKNOWLEDGMENTS

This work was supported by the EPSRC grant EP/S013776/1.

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