Circular Displacement Current Induced Anomalous Magneto-Optical Effects in High Index Mie Resonators

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Dielectric Mie nanoresonators showing strong light–matter interaction at the nanoscale may enable new functionality in photonic devices, such as strong magneto-optical effects. However, most reports so far have been focused on the enhancement of conventional magneto-optical effects. Here, anomalous magneto-optical effects are observed in high-index-contrast Si/Co/YIG/YIG/SiO2 Mie resonators. In particular, giant modulation of light intensity in transverse magnetic configuration up to 6.4% under s-polarized incidence appears, which is non-existent in planar magneto-optical thin films. A large rotation of transmitted light polarization in longitudinal magnetic configuration is also observed, which is two orders of magnitude higher than for planar magneto-optical thin films. These phenomena are originated from the unique circular displacement current when exciting magnetic resonances in the Mie resonators, which change the electric field direction locally. This work indicates an uncharted territory of light polarization control based on complex modal profiles in all-dielectric magneto-optical Mie resonators and metasurfaces.

1. Introduction

Dielectric Mie resonators showing strong light–matter interaction at the subwavelength scale have attracted great research interest recently.[1–4] Compared to plasmonic devices in which metal nanostructures are used to confine electromagnetic fields at the nanoscale, all-dielectric Mie resonators show several important differences, including lower optical absorption loss, much larger field penetration into the dielectric nanostructures, and the existence of unique magnetic resonance modes.[5,6] These features make dielectric Mie resonators and metasurfaces a fertile playground to discover novel photonic phenomena. Observations such as magnetic mirror,[7,8] directional scattering,[9,10] enhanced optical nonlinear effects,[11,12] and photoluminescence[13] have been demonstrated, which are promising for future nanophotonic device applications.

Recently, enhancement of the magneto-optical effects has been reported in dielectric photonic nanostructures. Several theoretical works predict strong Faraday rotation enhancement in all-dielectric magneto-optical nanostructures,[14,15] as well as large Magneto-optical Kerr Effect (MOKE) enhancement in all-dielectric gratings.[16]
Figure 1. Device structure and mode analysis of the all-dielectric magneto-optical metasurface. a) Schematic diagram of the metasurface magnetized in Voigt configurations for s-polarized TMOKE and LMOKE-T measurements. The device consists of periodic silicon nanodisks on Ce:YIG/YIG bilayer thin films fabricated on a quartz substrate. The period, radius, and thickness of the Si pillars are \( P = 750 \text{ nm} \), \( R = 230 \text{ nm} \), and \( H = 170 \text{ nm} \), respectively. b) Top-view SEM image of a fabricated sample. The inset shows a zoom-in image of several Si nanodisks. c) Measured and simulated transmission spectra of the device under normal incidence and linear polarization. d,e) Simulated transmission spectra of the array with \( R = 230 \text{ nm} \) cylinder radius as a function of the wavelength and incident angles for s-polarized and p-polarized incidence respectively using rigorous coupled wave analysis (RCWA) method. The white dash lines indicate the dispersion of the WG modes in the metasurface calculated using the planar waveguide theory. f) Analytical multipole analysis of scattering spectra for an individual silicon nanodisk (height 170 nm, radius 230 nm) embedded into a low-index medium (\( n = 1.46 \)).

Experimentally, all-dielectric magneto-optical metasurfaces featuring quasi-waveguide modes have been fabricated.\(^{17,18}\) Transverse magneto-optical intensity effect is observed upon the excitation of waveguide modes.\(^{19,20}\) Meanwhile, silicon Mie resonators are reported to enhance the Faraday rotation and transverse magneto-optical intensity effect in a 5 nm thick metallic nickel film.\(^{21,22}\) Electric dipole resonance induced circular birefringence and dichroism are observed in a perpendicular magnetic anisotropic Pt/Co film.\(^{23}\) However, a high index contrast, all-dielectric magnetic metasurface exhibiting strong Mie resonance modes have not been considered in this respect. How the Mie resonance modes influence the magneto-optical effects remains largely unexplored.

Here, we observe the effect of the circular displacement current in the high index contrast Mie resonators on the magneto-optical activity. The effect is disclosed on the structure of Si nanodisks on a magneto-optical bilayer with Y\(_2\)Fe\(_5\)O\(_{12}\) (YIG) and Ce\(_2\)Y\(_2\)Fe\(_5\)O\(_{12}\) (Ce:YIG) films deposited on a quartz substrate (see Figure 1a). In the near infrared range Ce:YIG has a prominent magneto-optical activity much larger than that for YIG, therefore in this case most of the magneto-optical response comes from Ce:YIG. The YIG layer was deposited as a seed layer to promote crystallization of Ce concentration Ce:YIG films.\(^{24,25}\) Due to the large index contrast, the metasurface exhibits strong Mie resonance modes including the magnetic dipole (MD) mode, electric dipole (ED) mode, electric quadrupole (EQ) mode, magnetic quadrupole (MQ) mode, as well as waveguide (WG) modes. The highly confined electromagnetic field in Ce:YIG leads to strong light–matter interaction and circular displacement currents which induce anomalous magneto-optical effects in transversal and longitudinal magnetic configurations. It should be emphasized that these effects are absent or negligible in planar Ce:YIG thin films. These results indicate promising potential of controlling light propagation by utilizing the complex Mie resonance modes in all-dielectric magneto-optical Mie resonators and metasurfaces.

2. Results and Discussion

2.1. Optical Modes in the All-Dielectric Magneto-Optical Metasurface

The device consists of periodic Si (\( n = 3.17 \)) nanodisk metasurfaces on Ce:YIG (\( n = 2.30 \)) /YIG (\( n = 2.30 \)) bilayers fabricated on double side polished SiO\(_2\) (\( n = 1.46 \)) substrates (Figure 1a). The YIG (50 nm) and Ce:YIG (200 nm) thin films were
E and MD resonances show a tendency to couple with each (planar waveguide theory[18,19,28] (see white dashed lines in Figure 1d,e). These modes correspond to different diffraction orders of the Si nanodisk grating as labeled in the figures (see Supporting Information). However, other modes cannot be explained by waveguide modes, for example, the modes (transmission dips) at high incident angles labeled by black dashed lines for s-polarized incidence, whose wavelengths seem to be independent on the incident angle, and the full width at half maximum (FWHM) is quite broad. These modes can be attributed to different Mie resonance modes as indicated by multipole analysis results for normal incidence as shown in Figure 1f (see Supporting Information). The scattering cross-section is computed by considering an individual silicon nanodisk embedded into a low-index medium \((n = 1.46)\). The multipole analysis agrees with experimental observations despite of a blue shift of the Mie resonance wavelengths, which is due to the more complicated surrounding medium environment including multilayer YIG/GeYIG films, also the coupling effect between different nanodisks. For s-polarized incidence, the Mie resonance wavelengths are almost angle independent. As the incident angle increases, ED and MD resonances show a tendency to couple with each other, and the MD resonance becomes increasingly apparent. Characteristic circular displacement current distribution are observed in structure for MD and MQ resonances, as shown in Figure S5 (Supporting Information). For the p-polarized incidence, EQ and ED resonance wavelengths are almost angle independent for small incident angles. The mode at 1310 nm for the non-zero incident angles splits into two separate modes[29] and this dispersion relationship is consistent with the TM (1,0) WG modes.[31–34] Therefore, in the case of small incident angles, the Mie resonance and these WG modes couple with each other, which also explains why the resonance peaks of the modes in p-polarization is broader than that in s-polarization for small incident angles.[35] As the angle of incidence increases, the contribution of the WG modes dominates and the width of the resonance peak gradually narrows. The near-field distributions of these modes with s- and p-polarization under different incident angles are shown in details in Figures S5 and S6 (Supporting Information).

\[
\varepsilon_{MO} = \begin{bmatrix}
\varepsilon_{xx} & aM_x & aM_y \\
-aM_x & \varepsilon_{yy} & -aM_z \\
-aM_y & aM_z & \varepsilon_{zz}
\end{bmatrix}
\]  

(1)

where \(\varepsilon_{ij}\) and \(aM_i\) (\(i\) stands for \(x, y,\) or \(z\)) represent the diagonal and off diagonal permittivity tensor elements, respectively. Figure 1c shows the transmittance spectrum of the magneto-optical Mie resonators under normal incidence with linear polarized light along \(x\)-direction. Three resonance peaks at wavelengths of 1100, 1310, and 1420 nm are clearly seen. The experimental transmittance spectrum (red dotted line in Figure 1c) is in very good agreement with the simulation results (see details in Supporting Information). The small difference of transmission intensity and resonant wavelengths between the experiment and simulation may be attributed to the sample imperfections during the fabrication process, including slight size deviations, non-vertical sidewalls, etc. Simulated transmission spectra as a function of wavelengths and incident angles for s-polarized and p-polarized incident light (Figure 1d,e) demonstrate different dispersive behavior. To identify their character, we calculated the dispersion relation of the waveguide modes using the planar waveguide theory[18,19,28] (see white dashed lines in Figure 1d,e). These modes correspond to different diffraction orders of the Si nanodisk grating as labeled in the figures (see Supporting Information). However, other modes cannot be explained by waveguide modes, for example, the modes (transmission dips) at high incident angles labeled by black dashed lines for s-polarized incidence, whose wavelengths seem to be independent on the incident angle, and the full width at half maximum (FWHM) is quite broad. These modes can be attributed to different Mie resonance modes as indicated by multipole analysis results for normal incidence as shown in Figure 1f (see Supporting Information). The scattering cross-section is computed by considering an individual silicon nanodisk embedded into a low-index medium \((n = 1.46)\).[9] The multipole analysis agrees with experimental observations despite of a blue shift of the Mie resonance wavelengths, which is due to the more complicated surrounding medium environment including multilayer YIG/GeYIG films, also the coupling effect between different nanodisks. For s-polarized incidence, the Mie resonance wavelengths are almost angle independent.[29] As the incident angle increases, ED and MD resonances show a tendency to couple with each other, and the MD resonance becomes increasingly apparent.[30] Characteristic circular displacement current distribution are observed in structure for MD and MQ resonances, as shown in Figure S5 (Supporting Information). For the p-polarized incidence, EQ and ED resonance wavelengths are almost angle independent for small incident angles. The mode at 1310 nm for the non-zero incident angles splits into two separate modes[29] and this dispersion relationship is consistent with the TM (1,0) WG modes.[31–34] Therefore, in the case of small incident angles, the Mie resonance and these WG modes couple with each other, which also explains why the resonance peaks of the modes in p-polarization is broader than that in s-polarization for small incident angles.[35] As the angle of incidence increases, the contribution of the WG modes dominates and the width of the resonance peak gradually narrows. The near-field distributions of these modes with s- and p-polarization under different incident angles are shown in details in Figures S5 and S6 (Supporting Information).

2.2. S-Polarized Transverse Magneto-Optical Kerr Effect

In the planar magneto-optical thin films, it is well known that there is no transverse magneto-optical Kerr effect (TMOKE) under s-polarized incident light.[36,37] However, we observe large s-polarized TMOKE in the all-dielectric magneto-optical metasurface. We characterize the TMOKE spectra for s-polarized light incident at \(\theta = 45°\) for both the thin film and metasurface samples. The incidence plane is parallel to the (1,0) direction of the Si nanodisk grating. The schematic diagram of s-polarized TMOKE measurement is shown in Figure 2a. The value of TMOKE is defined as the relative change in reflectivity due to the magnetization switch along the incidence plane normal direction[38,39]:

\[
\delta = \frac{2R(+M) - R(-M)}{R(+M) + R(-M)}
\]  

(2)

According to Figure 1d, the reflection spectrum in Figure 2b (black curve) shows high reflectivity at 1100, 1250, and 1370 nm corresponding to the EQ, MQ, and MD modes, respectively. And a relatively weak resonance peak at 1420 nm wavelength is attributed to the ED mode. The electric and magnetic near-field distribution corresponding to these resonances are detailed in Figure S5 (Supporting Information). No TMOKE signal is observed on the bare Ce:YIG/YIG thin films as confirmed by the blue line in Figure 2b, which is zero within the measurement error. However, a large s-polarized TMOKE is observed in the magneto-optical Mie resonators, as shown by the red line in Figure 2b. Importantly, we observe high reflectivity up to 73% together with strong s-polarized TMOKE up to \(\delta = 2.7%\) at the MQ mode wavelength of 1250 nm. Stronger s-polarized TMOKE up to \(\delta = 6.4%\) at 1275 nm wavelength and \(\delta = -6.4%\) at 1170 nm wavelength are also observed around the MQ resonances, which are attributed to low reflectance (\(\approx 10%\), smaller value of the denominator in Equation (3)) induced enhancement of the TMOKE, namely the optical contribution.[40] A TMOKE peak of \(\delta = -1.4%\) also appears at 1375 nm wavelength with 61% reflectivity, corresponding to the MD mode. Note a sign change of the TMOKE is observed for both MQ and MD modes, which is caused by a sign change of the numerator in Equation (3). Meanwhile, the s-polarized TMOKE is also non-zero, but weaker at EQ and ED resonances. These measurement results agree very well with simulation using COMSOL as shown in Figure 2d (see details in Supporting Information).
To confirm our observation, we also measured the TMOKE hysteresis of the structure and film using a custom-built magneto-optical characterization set up (see Figure S8, Supporting Information), as shown in Figure 2c. A clear TMOKE hysteresis is observed for the metasurface sample with up to 3% intensity variation at 1230 nm, which is in drastic contrast with the thin film sample which showed no hysteresis at all. The hysteresis resembles the hysteresis of the Ce:YIG/YIG films with the in-plane magnetization.

It should be noted that these s-polarized TMOKE values are even higher than recently reported conventional p-polarized TMOKE in all-dielectric magneto-optical gratings.\cite{18, 19, 36} We also measured and simulated the TMOKE spectrum under conventional p-polarized incidence for the thin film and metasurface as discussed in Figure S7 (Supporting Information). Giant p-polarized TMOKE up to $\approx 20\%$ is also observed, which are attributed to waveguide mode induced TMOKE enhancement, as also discussed in previous publications.\cite{19}

### 2.3. Giant Longitudinal Magneto-Optical Kerr Effect in Transmission Mode

Next, we study the LMOKE effect in transmission mode with sample configuration shown in Figure 3a. The complex LMOKE-T angles $\phi_L$ can be expressed as:\cite{40}:

$$\phi_L = \psi + i\varphi = \arctan\left(\frac{t_{sp}}{t_{pp}}\right) \tag{3}$$

where $\psi$ and $\varphi$ are the LMOKE-T angle and ellipticity, respectively. And $t_{sp}$ and $t_{pp}$ represent Fresnel transmission coefficients for s-polarized and p-polarized light respectively for p-polarized incidence. For symmetry considerations, a non-trivial LMOKE-T can only be observed when $[k \times N] \neq 0$.\cite{36} We discuss the LMOKE-T of the bare Ce:YIG/YIG thin film is almost negligible ($<10^{-3}\%$). This value is smaller than our measurement noise, therefore it is only numerically simulated and shown by the blue line in Figure 3b. Interestingly, the LMOKE-T shows a giant enhancement when exciting the resonance modes. A large LMOKE-T angle up to $\psi = 0.086^\circ$ is observed at 1320 nm wavelength, which is about two orders higher compared to bare Ce:YIG/YIG films with same thicknesses of $\psi = 9 \times 10^{-4}\%$. Enhancement of LMOKE-T is also observed at 1250 and 1418 nm wavelength but with a lower amplitude, corresponding to the other waveguide mode and hybridized ED-WG mode respectively. This result can be better observed by comparing the LMOKE-T hysteresis loops between the metasurface and the film as shown in Figure 3c. A clear hysteresis resembling the in-plane magnetization hysteresis of the Ce:YIG thin film is observed. The LMOKE-T angle of 0.086° is even comparable to the Faraday rotation angle of a bare
Figure 3. Transmission spectra and giant LMOKE-T under p-polarized incidence. a) Schematic diagram of LMOKE-T characterization set-up. All measurements are obtained for p-polarized light and under $\theta = 3^\circ$ incidence angle. b) Measured LMOKE-T (red line with dots) and transmission spectra (black line) of the fabricated metasurfaces compared with bare Ce:YIG thin films (blue line). c) Measured LMOKE-T hysteresis loops for the metasurface with $R = 230 \text{ nm}$ and the bare MO film at 1320 nm wavelength. d) Simulated transmission and LMOKE-T spectra of the metasurface.

film at the same wavelength as shown in Figure S1b (Supporting Information). The simulated LMOKE-T spectrum is displayed in Figure 3d, which shows similar characteristics with experiment results, despite of sharper peaks and larger rotation angle values. This is because in the case of simulation, the transmittance at resonances is almost zero, leading to a much larger optical contribution. The difference of transmission intensity between experiment and simulation may be caused by sample imperfections originated from the fabrication process.

2.4. Mechanism of the Anomalous MO Effects

To understand the mechanism of the observed magneto-optical effects, we consider the electric and magnetic near-field distribution for different resonance modes as shown in Figure 4. Figure 4a,b shows the electric field profile under p-polarized incidence at $\theta = 3^\circ$ for the MD-WG and ED-WG mode wavelengths respectively (the LMOKE-T case). Figure 4c,d shows the modal profile under s-polarized incidence at $\theta = 45^\circ$ for the MQ and ED resonance wavelengths respectively (the TMOKE case). As shown in Figure 4a,c, for the MD/MQ modes, the resonances show characteristic circular electric field distribution. Thus the $E_z$ field is significantly enhanced, inducing circular displacement currents in Ce:YIG. Whereas for the ED resonances shown in Figure 4b,d, the electric dipole resonance induces mostly $E_x$ or $E_y$ fields in Ce:YIG due to the oscillated dipole resonance behavior. Considering the magneto-optical effect, only the electric field perpendicular to the applied magnetic field shows the magneto-optical effects, as indicated by the form of the permittivity tensors in Equation (1). Therefore, $E_z$ makes a main contribution for the near normal incident LMOKE-T and s-polarized TMOKE. We can quantitatively compare the $E_x$, $E_y$, $E_z$ field intensity by performing an area integral of $|E|$ inside the Ce:YIG layer. The integrated $E_z$ intensity is 1.34 times higher than $E_x$ at the MD-WG mode wavelength, whereas the intensity of $E_x$ is 4.6 times larger than $E_z$ at the ED-WG resonance mode for $\theta = 3^\circ$. For $\theta = 45^\circ$ incident angle of the s-polarized TMOKE configurations, the intensity of $E_z$ is comparable with $E_x$ at the MQ mode wavelength, whereas the intensity of $E_x$ is 1.87 times larger than $E_z$ at the ED resonance. Figure 4e,f shows the relationship between the incident wavevector, the electric field vector and the applied magnetic field directions. For the resonances dominated by MD/MQ, the p-polarized/s-polarized incident light generates $E_z$ component of the displacement current, leading to enhancement of Kerr effect when the magnetic field is along the $x$ (LMOKE-T configuration) or $y$ directions (TMOKE configuration). On the contrary, the electric field distribution for ED resonance modes is different. The electric fields remain mostly along $x$- or $y$-directions. Nevertheless, a small amount of $E_z$ field is also observed for these modes, therefore we do see TMOKE/LMOKE-T enhancement at around ED resonances but with a much lower amplitude compared to MD/MQ modes. These observations again highlight the important role of circular displacement currents to the observed anomalous magneto-optical effects.

The observed non-trivial s-polarized TMOKE invites speculation on the effective optical constants of the metamaterial. In fact, from a metamaterial perspective, s-polarized TMOKE indicates non-zero off-diagonal components of the effective permeability tensor.$^{[41–43]}$ We can treat the Si/Ce:YIG/YIG layers as a
metamaterial shown in Figure S9 (Supporting Information). Based on parameter retrieval and $4 \times 4$ transfer matrix methods, we calculated the diagonal effective permittivity tensor elements ($\varepsilon' + \varepsilon''$), diagonal effective permeability tensor elements ($\mu' + \mu''$) and off-diagonal permeability tensor elements ($\kappa' + j\kappa''$) for $s$-polarized incident light with incident angle $\theta = 45^\circ$, as shown in Figure S9 (Supporting Information). We see clear resonance peaks for the diagonal parts of $\varepsilon$ and $\mu$ at the Mie resonance wavelengths. We also observe resonance peaks for the off-diagonal elements of the permeability tensor. Large $\kappa'$ reaching $10^{-2}$ are observed at around $1275$ nm wavelength, consistent with the large $s$-polarized TMOKE. The numerically simulated and calculated reflectance and TMOKE spectra using the effective optical constants agree with each other, justifying the correctness of the effective optical constants.

The observation of several anomalous magneto-optical effects in high index contrast, all-dielectric magneto-optical metasurfaces in this work indicate unprecedented opportunity of using the complex modal profiles in high-index-contrast all-dielectric Mie resonators to control light propagation by magnetization and vice versa. Study on other dielectric resonance modes can be envisioned for future works, such as anapole modes, Fano resonance modes, supercavity modes as well as coupled Mie resonance modes. Ultra-high quality factor modes such as the bound states in the continuum modes can also be explored. Note the observed magneto-optical effects are rooted in localized Mie resonance modes, which is very different from several previous proposals of enhancing magneto-optical effects by propagating waveguide modes. This new mechanism offers a possibility to construct advanced magneto-optical materials by locally design the structure at the subwavelength scale, leading to a variety of possibilities to control the wave front by specifically designed magneto-optical Mie resonators and metasurfaces. By fabrication of high quality factor Mie resonators, the spectral selectivity and sensitivity of the magneto-optical resonances may be further enhanced, promising their applications in biosensing. On the other hand, the complex field profile also indicates rich physics of manipulating spin using femtosecond optical pulses, i.e., ultrafast optomagnetic effects in high index contrast Mie resonators. The low optical absorption, strong field localization, broad angular and frequency width and designable modal profiles may enable more efficient all-optical magnetization switch for future spintronic devices. The strong optical confinement in this resonant structure may also allow excitation of spin wave resonances in the magnetic system for opto-spintronic device applications. These possibilities make high index contrast, all-dielectric magneto-optical metasurfaces promising for a variety of applications including vectorial magnetic field sensing, free space non-reciprocal photonic devices, magneto-optical imaging and optomagnetic memories.

3. Conclusion

In summary, we observe anomalous magneto-optical effects including giant $s$-polarized TMOKE and LMOKE-T in high index contrast magneto-optical Mie resonators, which are not achievable in bulk or planar magneto-optical materials. These magneto-optical effects are originated from the unique circular displacement currents associated with MD or MQ modes in high index contrast all-dielectric Mie resonators. A giant $s$-polarized TMOKE up to $6.4\%$ and nearly two orders of magnitude enhancement of the LMOKE-T under near normal incidence conditions.
are observed experimentally. Our results indicate the possibility of utilizing the complex Mie resonance modes to realize novel magneto-optical effects, which will allow unprecedented opportunity to control light propagation with magnetization and vice versa. These new observations are promising for a variety of applications including vectorial magnetic field sensing, free space non-reciprocal photonic devices, magneto-optical imaging and optomagnetic memories.

4. Experimental Section

Sample Fabrication: The magnetic oxides were deposited on 10 mm × 10 mm double-polished quartz substrate by pulsed laser deposition (TSST PLD, Netherlands) equipped with 248 nm KrF excimer laser. A layer of 50 nm YIG was first deposited on SiO2 at room temperature with the oxygen pressure of 5 mTorr. Then a rapid thermal annealing process in oxygen atmosphere of 2 Torr at 900 °C for 480 s was performed to ensure crystallization. Subsequently, a 200 nm thick Ce:YIG layer was deposited at 750 °C with the oxygen pressure of 10 mTorr using 2.03 J cm⁻² power density. After deposition, the film was cooled down in the main chamber at the rate of 5 °C min⁻¹. The X-Ray Diffraction (XRD) pattern and magneto-optical response of the oxide film grown on quartz can be seen in Figure S1 (Supporting Information). The α-Si nanodisk arrays were fabricated by electron beam lithography (EBL, Raith). First, a layer of uniform amorphous silicon was deposited by plasma enhanced chemical vapor deposition (PECVD). Then the pillar-shaped patterns with an area of 200 μm × 200 μm was prepared by EBL using HSQ resist (XR-1541006) followed by deep reactive ion etching (DRIE). The etching gas and specific flow ratio applied in the experiment were CHF₃: SF₆: O₂ = 30: 30: 5.

Optical and Magneto-Optical Measurement: The transmittance spectra and LMOKE-T effects of the metasurfaces were measured by a custom-built characterization set-up as shown in Figure S8 (Supporting Information). The incident light was provided by a supercontinuum laser (NKT Photonics) connected with a spectrometer. Then the beam was incident on the sample surface through an aperture and a Glan–Taylor calcite polarizer to ensure linear polarization in the x direction. A pair of lenses of the same focal length were equipped on both sides of the sample to achieve confocal effect. The light spot can be focused into the size of 10 μm to meet the test requirements. LMOKE-T spectra were obtained with the applied magnetic field along x-direction. The magnetic field is generated by an electromagnet with the maximum magnetic field of 1 T. The reflection and TMOKE spectra were characterized on a spectroscopic ellipsometer (J.A.WoollamRC2). Thereflectance of the silicon wafer with a 25 nm silicon dioxide layer was firstly measured, then this was used as the baseline to obtain the reflection spectra of the structure at the 45° incident angle. The applied magnetic field of 3 Koe is along the in-plane y-direction, which was provided by a neodymium iron boron permanent magnet. By changing the position of the permanent magnet, the reflection spectra of the structure under the positive and negative magnetic field were measured, then the spectra of TMOKE were calculated according to Equation (3). As for the TMOKE hysteresis, it was also measured by the custom-built characterization set-up. The magnetic field generated by an electromagnet is applied in y-direction and the reflectivity of the sample changed with the applied magnetic field was measured. Then the hysteresis was obtained via using the equation $\theta = \frac{\theta_{\text{M}} - \theta_{\text{R}}}{\theta_{\text{R}}}$ [31] where R (0) is the reflectivity through the non-magnetized sample.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

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