Non-reciprocal diffraction in magnetoplasmonic gratings

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Abstract: Phase-matching conditions—used to bridge the wave vector mismatch between light and surface plasmon polaritons (SPPs)—have been exploited recently to enable nonreciprocal optical propagation and enhanced magneto-optic responses in magnetoplasmonic systems. Here we show that using diffraction in conjunction with plasmon excitations leads to a photonic system with a more versatile and flexible response. As a testbed, we analyzed diffracted magneto-optical effects in magnetoplasmonic gratings, where broken time-reversal symmetry induces frequency shifts in the energy and angular spectra of plasmon resonance. These result in exceptionally large responses in the diffracted magneto-optical effect. The concepts presented here can be used to develop non-reciprocal optical devices that exploit diffraction, in order to achieve tailored electromagnetic responses.

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1. Introduction

Surface plasmon resonances confine light into subwavelength dimensions which results in a corresponding increase in electric field intensities near plasmonic nanostructures [1]. This enables the use of surface plasmon resonances to enhance light matter interactions [2] and has prompted research into e.g. plasmon-assisted sensing [3–6], strong coupling [7–9] and lasing [10–12]. Beyond these properties, novel device concepts offer expanded functionalities by incorporating materials responsive to external stimuli. Particularly, magneto-optics is considered to have potential for, e.g., label-free detection using magnetoplasmonic sensors [13–15] or ultracompact nonreciprocal nanophotonic devices [16]. These new developments benefit from enhanced light-matter interaction made possible by exciting surface plasmon resonances in or in immediate vicinity of magnetic materials [17]. A wide range of nanophotonic devices that combine plasmonics with magneto-optics have been demonstrated, ranging from very simple, such as nanoparticles made of ferromagnetic metals [18–20], to more complicated, e.g. structures that incorporate noble metal nanoparticles with magneto-optically active materials in dimers or far-field coupled arrays [21,22].

Metallic diffraction gratings are one of the most common configurations to study surface plasmon polaritons (SPPs). They are also known as grating couplers due to their ability to couple light propagating in free space into SPPs and vice versa [23–25]. Nonreciprocal plasmon propagation and enhanced magneto-optical effects have been demonstrated in magnetoplasmonic gratings, fabricated of magnetic metals [26] or noble metals in contact with magneto-optical garnet materials [27–29]. Using such gratings, control over SPP excitation conditions by an external transverse magnetic fields was demonstrated [26,27,30]. Yet, all these previous studies focused on the excitation of plasmons and its consequences on the optical properties, but did not pay attention to a central property of a periodic grating: diffraction. Diffraction in magneto-optically active systems is an important phenomenon that is used, e.g., in diffracted magneto-optical effect (DMOKE) to probe magnetization reversal dynamics of submicron-sized magnetic patterns [31–35].
All things considered, we can say that up till now the mutual interplay of three important phenomena, i.e., plasmonics, magneto-optics and diffraction, has not been investigated in a single system. We show here that combining all the aforementioned properties provides new paths for flexible design of functional nanophotonic systems. To corroborate this point, we study the interplay of plasmon resonances and magneto-optics and their influence on diffraction properties of a simple diffraction grating. Despite its simplicity, it supports surface plasmon polaritons propagating both into backward and forward directions, enabling us to easily assess how breaking the time-reversal symmetry and presence of SPPs influences the diffracted beams.

2. Magnetoplasmonic gratings

To study how SPPs and magnetization influence diffraction, we fabricated magnetoplasmonic diffraction gratings by ion milling into cobalt/gold multilayer thin films. A multilayer of composition Cr (4nm)/Au (16 nm)/[Co (14 nm) / Au (16nm)]4/Co (14 nm)/Au (7 nm) was grown by e-beam evaporation on a commercial single crystal strontium titanate substrate (STO). The multilayer parameters were obtained by running an optimization script in a commercially available Lumerical FDTD software to find a multilayer configuration with good balance of plasmonic and magneto-optical properties. After metallic layer deposition an e-beam lithography process was performed to create an etch mask. The revealed part of the metallic layer was etched away by ion-milling, at the rate of 60 nm/minute, during 2.5 minutes. The final grating structure had a periodicity of 1000 nm, with grooves of 200 nm and a depth of 150 nm.

Figures 1(a) and 1(c) show, respectively, a schematic and a SEM micrograph of the grating. Light incident on the grating at an angle of \(\theta_0\) gives rise to diffraction maxima at \(\theta_m\), given by \(\sin \theta_m = \sin \theta_0 + m \lambda / nd\), where \(\lambda\) is the wavelength of the incident light, \(d\) the period of the grating, \(n\) the refractive index of the surrounding medium and \(m\) is an integer denoting the order of the diffraction maximum. The grating was immersed in index matching oil with \(n = 1.5\). The experimental setup used to study the optical and magneto-optical properties of the sample is presented in Fig. 1(b). A xenon lamp was used to provide a continuous white light source that was sent through a monochromator. The monochromatic beam was then polarized and collimated through an objective lens 10X N.A 0.4, which was placed over a movable platform, allowing modifications in the beam size. The collimated beam had a Gaussian profile. The incoming beam was reduced by moving the collimating objective so that the beam was limited to impinging angles between \(-5^\circ\) and \(5^\circ\), which resulted in a spot size of 10 \(\mu\text{m}\) of radius. The beam was then projected at the rear aperture of an oil immersion objective lens 63X, N.A 1.4, responsible for focusing and collecting the full angular spectrum of the reflected or diffracted light. All experiments were carried out at room temperature (20 C\(^\circ\)).
SPPs can be identified as sharp minima in the reflection spectrum of the grating. Similarly, diffraction efficiency is reduced by the SPP excitation [36,37] as the SPP excitation process competes with diffraction. Combinations of wavelengths and angles that allow for SPP excitation are given by the following equation [25]

\[ nk_0(\omega)\sin \theta_0 = \pm k_{\text{SPP}}(\omega) + \left( \frac{2\pi}{d} \right) \eta \]  

(1)

where \( k_0 \) is the magnitude of the wave vector of light in free space, \( \theta_0 \) the incidence angle and \( \eta \) an integer denoting the order of the SPP. The SPP wave vector \( k_{\text{SPP}} \) is given by \( k_{\text{SPP}} = k_0 \sqrt{\varepsilon_2 / (\varepsilon_1 + \varepsilon_2)} \), where \( \varepsilon_1 \) and \( \varepsilon_2 \) are the permittivities of the metal layer and the surrounding dielectric environment. We assume that due to the thickness of the gold/cobalt multilayer (120 nm), SPPs are excited only in the air/Au-Co multilayer interface. The permittivity of the gold/cobalt multilayer was measured by spectroscopic ellipsometry (Data File 1).

To explore how the magnetization influences the plasmon excitation condition in the gratings, we applied an external magnetic field to magnetize the grating in the direction parallel to its grooves, that we label the y-axis in Fig. 1(a). Conventionally, this geometry gives rise to transverse magneto-optical Kerr effect (TMOKE), where the presence of transverse magnetization \( M \) modifies the permittivity of the magnetic multilayer. In the case of magnetoplasmonic grating, this, in turn, modifies the wave vector \( k_{\text{SPP}} \) of the SPPs, which results in a magneto-optical effect that arises from the magnetic modulation of the SPP excitation condition. The change in \( k_{\text{SPP}} \) depends on the off-diagonal permittivity \( \varepsilon_{xy} \) of the metallic layer and is given for a smooth metallic/dielectric interface by \([26,38–40]\)
where \( \beta = \sqrt{\varepsilon_1 \varepsilon_2 (1 - \varepsilon_2^2 / \varepsilon_1^2)} \). In Eq. (2), the signs of the plasmon wave vector \( k_{SPP} \) and the magnetization \( M \) are determined by the symmetry of the system and can be understood as follows: The magnetization of the grating breaks the time-reversal symmetry of the system. Consequently, a reversal of the SPP propagation direction is equivalent to a reversal of the magnetization direction. As a consequence, the degeneracy between forward and backward propagating modes is lifted and the wave vectors for the forward and backward propagating modes, shown in red and blue in Fig. 1(a), become distinct, which results in changes in the diffracted light intensity as the function of magnetic field. To quantify these changes, the magnetization of the sample was cycled to record a hysteresis loop from which variation of the reflected and diffracted intensities as function of magnetization could be extracted. This is schematically illustrated in the diffracted beams in the lower part of Fig. 1(a). For magnetization in the positive y-direction (blue curves), the diffracted intensity is reduced for \( m > 0 \) diffracted orders, while it is increased for \( m < 0 \). The opposite is true when the magnetization is reversed (red curves). A more detailed description of the magneto-optical measurement procedure has been included in Appendix 1. However, before we can assess how the magnetization and SPPs influence the diffracted intensity, we first should examine how SPPs influence the diffraction characteristics of our array in the absence of magnetic fields, which is discussed in the following.

3. Results and discussion

Throughout most of the measured range of wavelengths, three emerging beams can be observed in our setup [Fig. 2(b)], corresponding to the zero-order specular reflection and the \( m = \pm 1 \) diffracted orders. At shorter wavelength range also the \( m = \pm 2 \) diffracted orders could be detected by our setup. Figure 2(a) shows the experimental results in the intensity of light scattered to a range of far-field angles throughout the visible wavelength regime. We used a normally incident Gaussian beam to probe the sample, and as a consequence, there is an angular spread in the emergent diffracted beams. As the SPP excitation is sensitive to the angle of incidence, the spread of angles facilitates assessment of the effects arising from SPPs. The SPP excitation angles calculated from Eq. (1) are superimposed on Fig. 2(a). We observe that in this far-field map the SPP excitation bands can be seen as distinctive cross-shaped minima, distinguished by a dip in reflectance in the angular spectrum of the light reflected or diffracted by the sample. A crossing of SPP bands occurs in the wavelength range of 700-850 nm, centred at 785 nm. A weaker SPP excitation can be also observed with crossing around 550 nm that also results in reduced diffraction efficiency. Figure 2(c) presents cross sections of the emitted intensity at selected wavelengths. We used Eq. (1) to calculate the angular position of the SPP excitations and indicate them in Fig. 2(c) as vertical dotted lines and arrows indicating the propagation direction of the SPP mode. The calculated SPP modes correspond with the observed dips in the emitted light intensity. We conclude that the excitation of SPPs travelling along forward/backward directions can be fingerprinted in the far-field angle-resolved reflectance scans, where at particular conditions of wavelengths and angles the intensity of diffractive beams is attenuated due to the transfer of energy and momentum to the propagating SPPs.
Fig. 2: Far field optical emission characteristics of the magnetoplasmonic grating. (a) Far field map of the diffracted beams emitted from the sample as the function of wavelength. The intensity of the specularly reflected beam (shaded region) was reduced by a factor of 5. The SPP bands calculated from Eq. (1) are superimposed on the figure. (b) Fourier space image of the 3 beams emerging from the grating at λ = 785 nm: on the sides the m = -1 and m = 1 diffracted orders with the specular reflection in the middle. (c) Far field profile of the reflected and diffracted beams at 3 different wavelengths. The presence of SPP excitation, indicated by dashed lines with the arrows indicating the direction of SPP propagation, results in conspicuous dips in the diffraction efficiency. The intensity in the shaded region has been reduced by a factor of 5.

Qualitatively, the effect of magnetism on the SPP excitation can be understood with Eq. (2), that predicts that the excitation condition for a forward propagating SPP ($k_{\text{spp}} > 0$) is modified by the presence of a transverse magnetization, so that depending on the direction of the magnetization the SPP band is either shifted to a lower ($M > 0$) or higher ($M < 0$) energy. For a backward propagating mode, on the other hand, the SPP excitation is instead shifted to a higher energy when $M > 0$ and to a lower energy when $M < 0$, behaving opposite to the forward propagating mode, i.e. the shifts in excitation energy for a fixed angle of incidence depend on the direction of the SPP propagation [27]. We will show that these effects result in changes in the reflective and diffractive properties of the magnetoplasmonic grating.

As a consequence of these changes in the plasmon resonance, there is a magnetization-dependent shift in the SPP reflection or diffraction minimum that can be observed when the reflection or diffraction spectrum of a magnetoplasmonic grating is measured at a fixed angle. The off-diagonal component that determines its magnitude is always relatively small and, thus, direct observation of the shift is rarely practical. Instead, the quantity measured in the experiments is the transverse magneto-optical Kerr effect (TMOKE) that manifests as a magnetization dependent change in the reflected intensity, or in the case of diffracted beams, the diffracted intensity. It is defined as $\text{TMOKE} = 2(I_+ - I_-)/(I_+ + I_-)$, where $I_+$ are the reflected or diffracted intensity at opposite saturation magnetizations. In the TMOKE spectrum near a forward propagating SPP we expect to observe a derivative line shape that originates from subtraction of two closely placed absorption features. As a result, the TMOKE signal crosses zero at the energy of the non-perturbed SPP. This lineshape can be clearly seen in the experimentally measured magneto-optical results, shown in Fig. 3, where it is easily discernible in Figs. 3(b) and 3(c). In Fig. 3(a), the TMOKE effect is presented as a function of wavelength and angle for the light beams reflected and diffracted by the grating. Our choice to use normal angle of incidence is motivated by our choice of magneto-optical geometry. In conventional magnetic materials, TMOKE is zero at normal incidence and increases monotonously with higher angles of incidence. Thus, illumination at zero angle of incidence is ideal for unravelling the contribution of SPPs to the magneto-optical activity, as the
ordinary TMOKE is minimized in this configuration. The procedure for extracting the TMOKE parameters from hysteresis loops has been illustrated in Fig. 4 in Appendix 1.

In Fig. 3(b) we highlight the spectral profile of the TMOKE activity for the part of the beam with positive incidence angles, where the magneto-optical activity is averaged at each wavelength. Namely, only the black dotted rectangular areas of Fig. 3(a) - corresponding to scattering to negative angles - have been considered, as summing over the whole range of angles would result in nulling the magneto-optical activity near the SPPs. A complementary plot for positive reflection angles is shown in Fig. 5. In the region between 700 and 850 nm we can observe a modulation of TMOKE around the plasmon resonance. As a consequence of this modulation, the magneto-optical activity abruptly increases, changing sign at the backward propagating SPP mode ($\eta = +1$, for $m = -1$ and $\eta = +3$, for $m = +1$) and again reversing at the forward propagating mode ($\eta = -3$, for $m = -1$ and $\eta = -1$, for $m = +1$). These modes are indicated by dotted lines in Fig. 3(b). We note that the signs of TMOKE are opposite for the specularly reflected ($m = 0$) and diffracted ($m = \pm 1$) beams. Hence, we can state that magnetoplasmonic gratings exhibit tuneable diffraction efficiency that can be either enhanced or reduced by choosing the magnetization state.

In order to have a broader view of the interplay between magnetism, plasmonics and diffraction, we present in Fig. 3(c) the far field profile of the magneto-optical activity for 3 different wavelengths around the surface plasmon resonance. The SPP excitation angles are indicated by vertical lines with arrows showing their propagation direction. Here, too, we can indeed observe the distinctive derivative line shape that results from magnetization shifting the SPP resonance condition, thus confirming that the magnetization doesn’t just shift the plasmon resonance in energy but also in the angular space. As pointed out earlier, Eq. (1) couples the incident angle with the wave vector of the SPP, hence these two quantities depend on each other and both can be adjusted by applying magnetic fields. As a consequence of the non-reciprocal nature of the MO effect, the sign of the MO effect is reversed by inversion of momentum $k \rightarrow -k$ (i.e., for reversal of the sign of the emission angle).

We make an additional observation on the specularly reflected beam in the center of Fig. 3(a). No magneto-optical effect is observed for strictly zero incidence/emission angle. For non-zero angles in the $m = 0$ beam, a weak TMOKE signal, similar to those in the diffracted beams, appears at the SPP crossing centred at $\lambda = 785$ nm. This can be contrasted with the $m = \pm 1$ and $\pm 2$ diffracted beams, plotted at the sides of Fig. 3(a) at their respective emission angles, where a noticeable TMOKE response is measured. This is due to the fact that the diffracted beams contain a longitudinal component that gives rise to ordinary diffracted magneto-optical Kerr effects (DMOKE) even in the absence of SPP excitations. In the wavelength range where SPP resonances are not present, this results in a magneto-optical effect whose sign is determined by the far-field angle of the diffracted beam. We have chosen the sign convention of the magnetization of the sample $M$ so that the sign of this “ordinary DMOKE” is positive for positive angles of emission and negative for negative angles of emission. This effect is more pronounced for the $m = \pm 2$ diffracted orders, only present in shorter wavelengths at high angles, because of the larger angle at which these beams are diffracted to [Fig. 3(a)].
Finally, we point out that the maximum of the TMOKE effect occurs at an angle where the incident light is not resonant with the SPP, but close to it [27]. This property, which is due to the derivative line shape of the TMOKE spectrum, is easy to infer from the middle panels of Figs. 2(c) and 3(c) where the diffracted intensity and TMOKE at wavelength of 785 nm are shown. There we see that the angular range where SPP excitations enhance magneto-optical activity extends beyond the zone of the SPP minimum. As a consequence, the maximum of magneto-optical activity is actually observed close to the maximum of diffracted intensity, not the minimum.

4. Conclusions

We have explored how magnetization can be used to modulate the plasmon excitation conditions so that, in combination with diffractive properties, they can be used as a powerful pathway towards flexible design of magnetoplasmonic systems. Our study makes obvious some consequences of magnetically induced shift of the SPP resonance. Firstly, we emphasize that the presence of magnetization not only shifts the SPP excitation conditions in the energy space [26,27], but also induces shifts in the angular space. They are explicitly demonstrated in derivative TMOKE line-shapes seen at SPP resonances in Fig. 3(c). The result is easily understood from Eq. (1): modifying the SPP wave vector $k_{SPP}$ necessarily changes the excitation angle.

As a second observation, we call the attention to the fact that the presence of SPPs results in significant changes in the magneto-optical activity in the diffracted beam. Even though the origin of the plasmon-enhanced magneto-optical activity in the diffracted beams is the same as in the specularly reflected beam, they support much higher magneto-optical activity, which can be assessed in Fig. 3(c). With zero angle of incidence, a maximum of 3% intensity change between the opposite magnetization states in diffraction is observed. This can be considered a large magnitude for TMOKE. In conventional magneto-optical geometries, the intensity modulation in transverse magneto-optical Kerr effect is usually less than 0.1% while for magnetoplasmonic systems higher numbers have been reported [26,41,42], up to 2% in magnetoplasmonic gratings [43]. In transmission geometry magnetoplasmonic systems have
been shown to support even higher modulation, though accompanied with a large losses [27,44].

There is still a third consideration, regarding the exploitation of optical absorption—which always appears at plasmon resonances—for nonreciprocal propagation. By using magnetic fields, we were able to nudge the absorption maximum both in the energy and angular space. Effectively, we have demonstrated how magnetic field modulation of excitation of SPPs can be used to tune diffraction efficiency for a given wavelength and angle. As many recent advances in nanoscale optics, such as metalenses [45] rely on sub-wavelength arrangement of diffraction elements, it is interesting to consider how active properties could be integrated to such elements. Here we have explored a magnetoplasmonic grating and shown how it can be switched between a more diffractive “on” and less diffractive “off” state using an external magnetic field. Given the non-reciprocal nature of the diffraction in magnetoplasmonic gratings, this kind of grating could act as an isolator or an active grating coupler, where external magnetic fields could be used to tune coupling efficiency. Additional applications for magneto-optically active plasmonic devices could be found in bio-sensing, where ultrasensitive magnetoplasmonic sensors have been explored recently [14,15].

Our experiments were performed with a simple metallic grating in order to highlight the interaction between the three phenomena under investigation: plasmons, magneto-optics and diffraction. However, we anticipate that our results can be generalized and used to design more complex diffractive elements, such as many plasmonic metasurfaces, where they could find use in designing non-reciprocal, isolating devices.

Appendix 1

To extract the TMOKE parameters at one wavelength and reflected/diffracted angle, multiple far-field optical emission images of the grating were recorded while the magnetization was cycled from positive to negative saturation and back, enabling us to record a complete magneto-optical hysteresis loop. Two such hysteresis loops are shown in Fig. 4(a) and 4(b). As is evident from their shape, they correspond to areas with negative and positive TMOKE, respectively. TMOKE is calculated from the hysteresis loops by averaging over the data points in positive ($I_+$) and negative ($I_-$) saturation and subtracting them from each other. The intensity change is then normalized to obtain the relative change in emitted intensity that is described by the definition $\text{TMOKE} = 2(I_+ - I_-)/(I_+ + I_-)$. Here, the pre-factor of two accounts for the averaging of the positive and negative saturation intensities. Repeating this procedure for each measured emission angle over a range of wavelengths from 550 to 865 nm with 5 nm steps, resulted in a composite image that is shown in Fig. 3(a).
Fig. 4. (a) and (b) Hysteresis loops recorded in areas with negative (a) and positive (b) TMOKE response. (c) A highlight from the data shown in Fig. 3(a) where the areas from where (a) and (b) were obtained are shown by black rectangles.

Appendix 2

Figure 5 shows the spectral profile of the TMOKE activity for the part of the beam with negative incidence angles, where the magneto-optical activity is averaged at each wavelength. Namely, only areas complementary to the black dotted rectangular areas of Fig. 3(a) that correspond to scattering to positive angles are considered.

Fig. 5. Average magneto-optical activity in the reflected and diffracted beams as function of wavelength for positive (0 to ~5°) reflection angles.
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References

1. G. W. Bryant, F. J. García de Abajo, and J. Aizpurua, “Mapping the plasmon resonances of metallic nanoantennas,” Nano Lett. 8(2), 631–636 (2008).
2. J. A. Schuller, E. S. Barnard, W. Cai, Y. C. Jun, J. S. White, and M. L. Brongersma, “Plasmonics for extreme light concentration and manipulation,” Nat. Mater. 9(3), 193–204 (2010).
3. J. Homola, S. S. Yee, and G. Gauglitz, “Surface plasmon resonance sensors: review,” Sens. Actuators B Chem. 54(1-2), 3–15 (1999).
4. J. Melendez, R. Carr, D. U. Bartholomew, K. Kukanski s, J. Elkind, S. Yee, C. Furlong, and R. Woodbury, “A commercial solution for surface plasmon sensing,” Sens. Actuators B Chem. 35(1-3), 212–216 (1996).
5. K. A. Willets and R. P. Van Duyne, “Localized surface plasmon resonance spectroscopy and sensing,” Annu. Rev. Phys. Chem. 58(1), 267–297 (2007).
6. A. Tao, F. Kim, C. Hess, J. Goldberger, R. He, Y. Sun, Y. Xia, and P. Yang, “Langmuir–Blodgett Silver nanowire monolayers for molecular sensing using surface-enhanced Raman spectroscopy,” Nano Lett. 3(9), 1229–1233 (2003).
7. J. Dintinger, S. Klein, F. Bustos, W. L. Barnes, and T. W. Ebbesen, “Strong coupling between surface plasmon-polaritons and organic molecules in subwavelength hole arrays,” Phys. Rev. B Condens. Matter Mater. Phys. 71(3), 035424 (2005).
8. C. Van Vlack, P. T. Kristensen, and S. Hughes, “Spontaneous emission spectra and quantum light-matter interactions from a strongly coupled quantum dot metal-nanoparticle system,” Phys. Rev. B Condens. Matter Mater. Phys. 85(7), 075303 (2012).
9. A. I. Väkeväinen, R. J. Moerland, H. T. Rekola, A.-P. Eskelinen, J.-P. Martikainen, D.-H. Kim, and P. Törnä, “Plasmonic surface lattice resonances at the strong coupling regime,” Nano Lett. 14(4), 1721–1727 (2014).
10. P. Berini and I. De Leon, “Surface plasmon–polariton amplifiers and lasers,” Nat. Photonics 6(1), 16–24 (2012).
11. F. van Beijnum, P. J. van Veldhoven, E. J. Geluk, M. J. A. de Doed, G. W. ’t Hooft, and M. P. van Exter, “Surface plasmon lasing observed in metal nanoparticle arrays,” Phys. Rev. Lett. 110(20), 206802 (2013).
12. T. K. Hakala, H. T. Rekola, A. I. Väkeväinen, J.-P. Martikainen, M. Nečáš, A. J. Moilanen, and P. Törnä, “Lasing in dark and bright modes of a finite-sized plasmonic lattice,” Nat. Commun. 8, 13687 (2017).
13. B. Sepúlveda, A. Calle, L. M. Lechuga, and G. Armelles, “Highly sensitive detection of biomolecules with the magneto-optic surface-plasmon-resonance sensor,” Opt. Lett. 31(8), 1085–1086 (2006).
14. N. Maccaferri, K. E. Gregorczyk, T. V. A. G. de Oliveira, M. Kataja, S. van Dijken, Z. Pirzadeh, A. Dmitriev, J. Åkerman, M. Knez, and P. Vavassori, “Ultrasensitive and label-free molecular-level detection enabled by light phase control in magnetoplasmic nanoantennas,” Nat. Commun. 6(1), 6150 (2015).
15. S. Pourjamal, M. Kataja, N. Maccaferri, P. Vavassori, and S. van Dijken, “Hybrid Ni/SiO2/Au dimer arrays for high-resolution refractive index sensing,” Nanophotonics 7(5), 905–912 (2018).
16. Z. Yu, G. Veronis, Z. Wang, and S. Fan, “One-way electromagnetic waveguide formed at the interface between a plasmonic metal under a static magnetic field and a photonic crystal,” Phys. Rev. Lett. 100(2), 023902 (2008).
17. G. Armelles and A. Dmitriev, “Focus on magnetoptplasmonics,” New J. Phys. 16(4), 045012 (2014).
18. V. Bonanni, S. Bonetti, T. Pakizeh, Z. Pirzadeh, J. Chen, J. Nogués, P. Vavassori, R. Hillenbrand, J. Åkerman, and A. Dmitriev, “Designer magnetoptplasmonics with nickel nanoferrromagnets,” Nano Lett. 11(12), 5333–5338 (2011).
19. N. Maccaferri, A. Berger, S. Bonetti, V. Bonanni, M. Kataja, Q. H. Qin, S. van Dijken, Z. Pirzadeh, A. Dmitriev, J. Nogués, J. Åkerman, and P. Vavassori, “Tuning the magneto-optical response of nanosize ferromagnetic Ni disks using the phase of localized plasmons,” Phys. Rev. Lett. 111(16), 167401 (2013).
20. M. Kataja, T. K. Hakala, A. Julku, M. J. Huttunen, S. van Dijken, and P. Törnä, “Surface lattice resonances and magneto-optical response in magnetic nanoparticle arrays,” Nat. Commun. 6(1), 7072 (2015).
21. J. C. Banthi, D. Meneses-Rodríguez, F. García, M. U. González, A. García-Martín, A. Cebollada, and G. Armelles, “High magneto-optical activity and low optical losses in metal-dielectric Au/Co/Au-SiO2 magnetoptplasmonic nanodisks,” Adv. Mater. 24(10), OP36–OP41 (2012).
22. M. Kataja, S. Pourjamal, N. Maccalferri, P. Vavassori, T. K. Hakala, M. J. Huttunen, P. Törmä, and S. van Dijken, “Hybrid plasmonic lattices with tunable magneto-optical activity,” Opt. Express 24(4), 3652–3662 (2016).
23. R. H. Ritchie, E. T. Arakawa, J. J. Cowan, and R. N. Hamm, “Surface-plasmon resonance effect in grating diffraction,” Phys. Rev. Lett. 21(22), 1530–1533 (1968).
24. G. Vecchi, V. Giannini, and J. Gómez Rivas, “Surface modes in plasmonic crystals induced by diffractive coupling of nanoantennas,” Phys. Rev. B Condens. Matter Mater. Phys. 80(20), 201401 (2009).
25. D. Maystre, “Chapter 2 Theory of Wood’s Anomalies,” in Plasmonics, Springer Series in Optical Sciences No. 167 (Springer-Verlag, 2012).
26. A. Chetvertukhin, A. A. Grunin, A. V. Baryshev, T. V. Dolgova, H. Uchida, M. Inoue, and A. A. Fedyanin, “Magneto-optical Kerr effect enhancement at the Wood’s anomaly in magnetoplasmonic crystals,” J. Magn. Magn. Mater. 324(21), 3516–3518 (2012).
27. V. I. Belotelov, I. A. Akimov, D. A. Bykov, S. Kasture, A. S. Vengurlekar, A. V. Gopal, D. R. Yakovlev, A. K. Zvezdin, and M. Bayer, “Enhanced magneto-optical effects in magnetoplasmonic crystals,” Nat. Nanotechnol. 6(6), 370–376 (2011).
28. V. I. Belotelov, L. E. Kreilkamp, I. A. Akimov, A. N. Kalish, D. A. Bykov, S. Kasture, V. J. Yallapragada, A. V. Gopal, A. M. Grishin, S. I. Khartsev, M. Nur-E-Alam, M. Vasiliev, L. L. Doskolovich, D. R. Yakovlev, K. Alameh, A. K. Zvezdin, and M. Bayer, “Plasmon-mediated magneto-optical transparency,” Nat. Commun. 4(1), 2128 (2013).
29. G. A. Wurtz, W. Hendren, R. Pollard, R. Atkinson, L. L. Guyader, A. Kirilyuk, T. Rasing, I. I. Smolyaninov, and A. V. Zayats, “Controlling optical transmission through magneto-plasmonic crystals with an external magnetic field,” New J. Phys. 10(10), 105012 (2008).
30. V. I. Belotelov, L. E. Kreilkamp, A. N. Kalish, I. A. Akimov, D. A. Bykov, S. Kasture, V. J. Yallapragada, A. V. Gopal, A. M. Grishin, S. I. Khartsev, M. Nur-E-Alam, M. Vasiliev, L. L. Doskolovich, D. R. Yakovlev, K. Alameh, A. K. Zvezdin, and M. Bayer, “Magneto-photonic intensity effects in hybrid metal-dielectric structures,” Phys. Rev. B Condens. Matter Mater. Phys. 89(4), 045118 (2014).
31. Y. Souche, M. Schlenker, and A. D. Santos, “Non-specular magneto-optical Kerr effect,” J. Magn. Magn. Mater. 140–144, 2178–2180 (1995).
32. S. Gadetsky, T. Suzuki, M. Ruane, I. Syrgabai, J. K. Erwin, and M. Mansuripur, “Measurements of the magneto-optic Kerr effect and the extraordinary Hall effect on grooveless glass substrates coated with amorphous TbFeCo,” J. Opt. Soc. Am. A 13(2), 314–318 (1996).
33. V. Eremenko, V. Novosad, V. Pishko, O. Geoffroy, Y. Souche, and B. Pannetier, “Diffractional enhancement of the Kerr magnetooptic effect,” JETP Lett. 66(7), 494–497 (1997).
34. V. Novosad, Y. Souche, V. Pishko, T. Crozes, Y. Otani, and K. Fukamichi, “Magneto-optical Kerr effect in conical diffraction geometry of micron-size Fe3Si wire array,” IEEE Trans. Magn. 35(5), 3145–3147 (1999).
35. M. Grimsditch and P. Vavassori, “The diffracted magneto-optic Kerr effect: what does it tell you?” J. Phys. Condens. Matter 16(9), R275–R294 (2004).
36. H. Raether, “Surface plasmons on gratings,” in Surface Plasmons on Smooth and Rough Surfaces and on Gratings, Springer Tracts in Modern Physics (Springer, 1988), pp. 91–116.
37. A. A. Maradudin, I. Simonsen, J. Polanco, and R. M. Fitzgerald, “Rayleigh and Wood anomalies in the diffraction of light from a perfectly conducting reflection grating,” J. Opt. 18(2), 024004 (2016).
38. J. J. Brion, R. F. Wallis, A. Hartstein, and E. Burstein, “Theory of surface magnetoplasmons in semiconductors,” Phys. Rev. Lett. 28(22), 1455–1458 (1972).
39. M. S. Kushwaha and P. Halevi, “Magnetoplasmons in thin films in the Voigt configurations,” Phys. Rev. B Condens. Matter 36(11), 5960–5967 (1987).
40. V. I. Belotelov, I. A. Akimov, M. Pohl, A. N. Kalish, S. Kasture, A. S. Vengurlekar, A. V. Gopal, D. Yakovlev, A. K. Zvezdin, and M. Bayer, “Intensity magnetooptical effect in magnetoplasmonic crystals,” J. Phys. Conf. Ser. 303(1), 012038 (2011).
41. A. V. Chetvertukhin, A. A. Grunin, T. V. Dolgova, M. Inoue, and A. A. Fedyanin, “Transversal magneto-optical Kerr effect in two-dimensional nickel magnetoplasmonic crystals,” J. Appl. Phys. 113(17), 17A942 (2013).
42. J. N. Hayek, A. A. Herreño-Fierro, and E. J. Patiño, “Enhancement of the transversal magnetic optic Kerr effect: Lock-in vs. hysteresis method,” Rev. Sci. Instrum. 87(10), 103113 (2016).
43. M. Pohl, L. E. Kreilkamp, V. I. Belotelov, I. A. Akimov, A. N. Kalish, N. E. Khochkov, V. J. Yallapragada, A. V. Gopal, M. Nur-E-Alam, M. Vasiliev, D. R. Yakovlev, K. Alameh, A. K. Zvezdin, and M. Bayer, “Tuning of the transverse magneto-optical Kerr effect in magneto-plasmonic crystals,” New J. Phys. 15(7), 075024 (2013).
44. L. E. Kreilkamp, V. I. Belotelov, J. Y. Chin, S. Neutzner, D. Dregely, T. Wehls, I. A. Akimov, M. Bayer, B. Stritzker, and H. Giessen, “Waveguide-plasmon polaritons enhance transverse magneto-optical Kerr effect,” Phys. Rev. X 3(3), 041019 (2013).
45. M. Khorasaniejad, W. T. Chen, R. C. Devlin, J. Oh, A. Y. Zhu, and F. Capasso, “Metalenses at visible wavelengths: Diffraction-limited focusing and subwavelength resolution imaging,” Science 352(6290), 1190–1194 (2016).