The Enhanced Optical Chirality Induced by Surface Plasmons in Achiral Magnetoplasmonic Nanostructures

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Received: 2 August 2022 / Accepted: 27 September 2022 / Published online: 10 October 2022
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Abstract
We show theoretically that the enhanced optical chirality in the achiral magnetoplasmonic nanostructures including dual-metallic grating (DMG) structure and single-metallic grating (SMG) structure under linearly polarized light can be achieved. The simulated results, based on the extended finite difference time domain (EFDTD) method, show that the designed structures possess the enhanced optical chirality in the visible and near-infrared wavelengths. More importantly, although the magnetoplasmonic nanostructure with DMG structure possesses an easy fabrication process, its performance of optical chirality is superior to that of the SMG structure. The physical origin of the enhanced optical chirality is deeply researched in detail. We also show that the optical chirality can be adjusted by the external magnetic field, which denotes that the magnetoplasmonic nanostructures will be used to develop a new chiro-optical device.

Keywords Optical chirality · Magneto-optical effects · Surface plasmon polariton · Magnetoplasmonic nanostructures

Introduction
Chirality, which is a geometrical asymmetry in that an object is not superimposable with its mirror image by any rotation and translation, exists everywhere in nature, for instance, DNA, amino acids, sugars, and so on [1]. Generally, a chiral object and its opposite chirality (i.e., enantiomer) possess most of the physical properties and chemical constructions except for handedness. Nevertheless, they may exhibit complete differences in biological activities [2]. Therefore, discriminating and separating the enantiomers have already become a research hotspot in the fields of biology, chemistry, medicine, and so on [3–5]. As a significantly and widely used spectral analysis technique for analyzing chiral molecules, chirality-sensitive circular dichroism (CD) still remains very limited to effectively distinguish the chirality because of the most enantiomers’ inherently weak chiro-optical reactivity to the incident light [6]. Moreover, the resonant response of CD of most chiral enantiomers is focused on the ultraviolet wavelength band, which cannot be detected by the traditional visible-light spectrometer [7]. Therefore, enhancing the resonant response of CD of the chiral molecules, particularly in the visible range, is still an intense research hotspot.

To date, most of the research has focused on the nanostructures with intrinsic chiral or achiral geometry under illumination of circularly polarized light (CPL), whereas little literature about the enhancement of optical chirality by linearly polarized light has been sprung up [8]. This is because that the structures that can give rise to the enhanced optical chirality under illumination of linearly polarized light are usually complicated, for instance, intertwined helix, gammazon, “shuriken” structures, or even more complex structures, whose fabrication is very challenging [6, 9–11]. Fortunately, Tian et al. achieved the enhanced chiral fields in their system under illumination of linearly polarized light and their study results demonstrated that the sign of the optical chirality can be altered by the polarization of the incident light. Nevertheless, the chiral fields with different handedness often appear simultaneously outside the resonant fields, which will undoubtedly discount the performance of enhanced CD response [12]. Furthermore, Yao et al. obtained a sign-uniform chiral field inside the proposed structure alone with the enhancement of optical chirality under linearly polarized illumination, but the direction of polarization of incident light is off the groove [7, 13]. Obviously, the chiral and achiral...
structures mentioned above only consist of non-magnetic material, which cannot produce the magneto-optical (MO) effects. It is the most wonderful thing that the enhanced optical chirality and magneto-optical properties can be achieved simultaneously in the present magnetoplasmonic nanostructures whose properties can be controlled by the external magnetic field.

In this paper, we propose two one-dimensional periodic magnetoplasmonic nanostructures including a uniform magnetic dielectric layer, which can give rise to the MO effects induced by the external magnetic field. Based on the EFDTD method, the optical chirality of the proposed structures is investigated. As expected, the sign-uniform chiral fields accompanied by large optical chirality emerge in the magnetoplasmonic structures when the gratings are illuminated by the linearly polarized light with the electric or magnetic field polarized perpendicular to the grating. Meanwhile, the optical chirality performance of DMG structure is superior to that of the SMG structure.

**Fundamental Principle of the Optical Chirality**

To obtain the enhanced CD response, it is important to enhance the near-field with chirality of the designed structure. The chiral field is in nature represented by the optical chirality, which can be defined as [14]

\[
\chi = -\frac{\omega}{2c^2} \cdot \text{Im}(\mathbf{E}^* \cdot \mathbf{H})
\]

(1)

where \(\omega\) and \(c\) represent the angular frequency and the speed of light under vacuum, respectively, and \(\mathbf{E}\) and \(\mathbf{H}\) are the electric and magnetic field vectors, respectively. From the definition of Eq. (1), it can be found that the optical chirality has a positive or negative value, which means that it possesses two different handedness. It can be seen that only the parallel components of electric field vector and magnetic field vector can give rise to the non-zero optical chirality. Consequently, if only the TM polarized light or TE polarized light is incident on the achiral structure, the optical chirality will not appear, because the electric field vector \(\mathbf{E}\) and the magnetic field vector \(\mathbf{H}\) are always orthogonal to each other, so as to their dot product is always equal to zero. Contrastively, if both TM and TE polarized light appear simultaneously, the electric field vector \(\mathbf{E}\) coincides with magnetic field vector \(\mathbf{H}\) partly in the same direction, so the chiral field with the enhanced optical chirality certainly appears. Whereupon, we construct an achiral magnetoplasmonic grating structure including the uniform magnetic dielectric layer. The magnetic dielectric layer plays a very important role in the conversion between TM mode and TE mode. When the TM polarized light or the TE polarized light is impinged on the achiral magnetoplasmonic grating structure, even though the direction of polarization of incident light is perpendicular to the grating, the transmission light travels through the magnetic dielectric layer, because of the coupling with the magnetization \(\mathbf{M}\) of the magnetic material, another component of electric field \(E_y\) (i.e., TE polarized mode) or magnetic field \(H_y\) (TM polarized mode) will be produced. This will cause that both TM and TE polarized modes appear simultaneously, so that the electric field vector \(\mathbf{E}\) coincides with the magnetic field vector \(\mathbf{H}\) partly in the same direction, the enhanced optical chirality and MO effects will be simultaneously produced.

**Results and Discussion**

Schematic diagrams of the magnetoplasmonic nanostructures including the DMG and SMG are shown in Fig. 1. The DMG structure is composed of a dielectric (photore sist) grating sandwiched by the upper and lower gold gratings on a glass substrate, meanwhile the SMG structure only includes the lower metallic grating. Both structures are deposited on a nonmagnetic dielectric layer with a thickness of \(h_1\), whose main function is to increase the electromagnetic field of the uniform magnetic dielectric layer (Bi-substituted yttrium iron garnet (Bi:YIG)) with a thickness of \(h_2\), which will enhance the interaction between the
incident light and the magnetic dielectric layer. This leads to the enhancement of the MO effects and optical chirality of the magnetoplasmonic nanostructures. In the experimental fabrication process, the SMG structure can be obtained from the DMG structure, in which a lift-off technique is needed to remove the deposited metal on top of the photoresist [15]. Then, the DMG structure has an advantage over the SMG structure in the sample manufacture, which involves only photoresist patterning and metal deposition, therefore its fabrication is much simpler and cheaper than that of the SMG structure. Despite the easy fabrication process, the DMG structure has been proved that it has much better optical chirality performance than that of SMG structure in the following. The other geometrical parameters of two structures are period $P$, photoresist height $h$, photoresist width $w$, and metal thickness $t$. In order to achieve the enhanced optical chirality, we completely optimize the geometrical parameters of the designed structures by using the EFDTD method. The optimum geometrical parameters are $h = 150 \text{ nm}$, $h_1 = 20 \text{ nm}$, $h_2 = 100 \text{ nm}$, $t = 70 \text{ nm}$, $w = 250 \text{ nm}$, $P = 500 \text{ nm}$, respectively [16]. The TM polarized incident light, with the magnetic field parallel to the $y$ axis, is incident upon the grating along the negative $x$ direction with an incident angle $\theta$ (shown in Fig. 1).

In both designed structures, we consider the Bi:YIG dielectric layer uniformly magnetized parallel to the $z$ axis, and the permittivity of the Bi:YIG is given by $\epsilon_{ij} = \epsilon_0 - i\epsilon_{ijk} g_k$, where $\epsilon_{ijk}$ is the Levi–Civita tensor, and $i, j, k = x, y, z$, and $g_k$ is related to the magnetization. Since in a selected visible region the permittivity of Bi:YIG is slightly dispersive, the average value of the tensor with $\epsilon_{xx} = \epsilon_{yy} = \epsilon_{zz} = 5.5 + i0.0025$, $g_x = g_y = 0$, $g_z = (1 - i0.15) \times 10^{-2}$ is adopted [17]. The frequency-dependent dielectric function of Au film is obtained from [18], and the refractive indices of photoresist, dielectric layer, and glass substrate are fixed at 1.61, 1.4, and 1.46, respectively [16].

When the TM polarized incident light is obliquely incident on the designed structures, it can not only produce the localized surface plasmon resonance (LSPR) [19] but also the surface plasmon polaritons (SPPs) [20]. At the same time, inside the magnetic dielectric layer, the TM and TE waveguide (WG) modes appear simultaneously which are produced by TM polarized light and TE polarized light, respectively [21]. Furthermore, for the DMG structure, the Fabry–Perot (F-P) resonance is generated by the coupling between the upper and lower gold gratings [22]. Hence, the coupling of these resonant modes can greatly enhance the electric field and magnetic field inside the DMG structure, which undoubtedly increases the optical chirality.

Figures 2a and b demonstrate the diagrams of optical chirality of two magnetoplasmonic structures for TM polarized light with different incident wavelengths and angles. At the same time, the curve diagrams as a function of the wavelength at incident angles $\theta = 5^\circ$ and $10^\circ$ are presented in Fig. 2c and d, in order to more clearly demonstrate the relations between the optical chirality and incident wavelengths. As it can be observed in Fig. 2a, the optical chirality spectrum of the DMG structure mainly has a broad resonant peak in the vicinity of 700 nm and two resonant dips (i.e., negative maxima) in the near-infrared wavelengths. With the incident angle increasing, the region of the resonant peak will become smaller, while the region of resonant dip is almost invariable. For the SMG structure (as shown in Fig. 2b), there also exist two resonant dips at the same wavelengths; however, their resonant amplitudes of optical chirality are weaker than that of the DMG structure (shown in Fig. 2c and d). At the same time, a series of resonant peaks appear in the region that is from 820 to 840 nm of the incident wavelengths and the incident angles ranging from $1^\circ$ to $5^\circ$. Based on Eq. 1, we can undoubtedly conclude that the enhancement of observed positive and negative optical chirality only depends on the increase of the parallel components of electric field vector and magnetic field vector, and the positive and negative optical chirality rest with the phase of transverse electric and magnetic fields. In addition, according to the study results of our previous works [16, 23], we can draw a conclusion that the first resonant peak of optical chirality mainly results from the transverse magnetic fields, because the transverse electric fields that are converted from the TM-mode fields are weak, that is, the MO effects are rather weak. Nevertheless, the two resonant dips of optical chirality are attributed to the emergence of TM polarized mode and TE polarized mode simultaneously, which results in the enhancement of the MO effects and optical chirality, simultaneously [16, 23].

To further elaborate the mechanism of the enhancement of optical chirality, we take the first resonant dip of the two designed structures at $\lambda = 819 \text{ nm}$ and $\theta = 5^\circ$ as an example and provide the spatial distributions of the electromagnetic field intensity, as demonstrated in Fig. 3. Figures 3a and c denote the spatial distribution of the electromagnetic field intensity, meanwhile, Figs. 3b and d demonstrate the spatial distribution of the $\left| H_y \right|$ for the DMG and SMG structures, respectively. As expected, the TE mode and TM mode in the two designed structures are really produced simultaneously. As already mentioned above, the emergence of the electric and magnetic fields in the same direction leads to the enhancement of optical chirality. In addition, the TE-polarized light only produces the pure WG mode (Fig. 3a and c), whereas for the TM polarized light, the WG and SPP modes are also excited simultaneously in the DMG structure, but in the SMG structure, only the WG mode produces (Fig. 3b and d). Furthermore, compared with two structures, the resonant intensity of the
LSPR mode of the DMG structure is stronger than that of the SMG structure [23]. Consequently, the strong coupling of these resonant modes above leads to much stronger intensities of the electric and magnetic field in the same direction inside the magnetic dielectric layer than that of the SMG structure (Fig. 3a, b and c, d), which will lead to a bigger enhancement of the optical chirality of DMG structure than that of the SMG structure.

Finally, the change of the optical chirality in dependence of the period of two designed structures is also discussed to deeply explain the physical phenomenon observed above, as plotted in Fig. 4. Study results show that the optical chirality has almost the same behavior for two designed structures with different periods, as the reverse of optical chirality can be achieved in the interesting wavelengths. Meanwhile, it is demonstrated that the resonant positions of the optical chirality for two designed structures produce the red-shifts with the period increasing. It is because that the resonant positions of SPP mode and WG mode are closely correlated with the period, which will produce an obvious red-shifts with the period increasing [20, 21]. This further verifies that the enhanced optical chirality is ascribed to the production of SPP mode and WG mode. Furthermore, the amplitude of the optical chirality will accordingly vary with the period of our designed structures. This denotes that the optical chirality performance of the DMG and SMG structures can be easily adjusted by the period.
Conclusions

The optical chirality of two different magnetoplasmonic nanostructures with DMG and SMG has been theoretically investigated in this paper. The enhancement of optical chirality in the visible and near-infrared wavelengths can be achieved both in two magnetoplasmonic nanostructures. More importantly, although the DMG structure possesses an easy fabrication process, its performance of optical chirality is superior to that of the SMG structure. The physical origin of the enhancement of optical chirality is deeply researched in detail. It is shown that the stronger enhancement of optical chirality of the DMG structure results from the strong coupling between the modes of LSPR, SPP, WG, and F-P resonance. Furthermore, the optical chirality can be easily adjusted by the incident angle, the geometric parameters such as the period of achiral magnetoplasmonic nanostructures.

Fig. 3 Color online. Spatial distribution of electric and magnetic field intensities of two designed structures at $\lambda = 819$ nm, $\theta = 5^\circ$. a, b and c, d correspond to the DMG structure and SMG structure, respectively.

Fig. 4 Color online. Curve diagrams of optical chirality spectra of the DMG structure (a) and SMG structure (b) with different periods in dependence of the wavelength and at incident angle $\theta = 5^\circ$. 
Author Contribution All authors contributed to the study’s conception and design. The numerical simulations were performed by Wang Xi and Mengjiao Zhu. The first draft of the manuscript was written by Chengxin Lei. Figures 1, 2, 3, and 4 were prepared by Shenggui Fu, Zhongsheng Man, and Xiaolu Ge. All authors discussed the results. All authors read and approved the final manuscript.

Funding This study was supported by the Natural Science Foundation of Shandong Province of China (Grant No. ZR2019MA046) and the National Natural Science Foundation of China (Grant Nos. 12074224, 11704226).

Data Availability All data included in this paper are available from the corresponding author upon reasonable request.

Declarations

Ethics Approval The authors assure that this material is the authors’ own original work, which has not been previously published elsewhere. The paper is not currently being considered for publication elsewhere.

Competing Interests The authors declare no competing interests.

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