Realizing Giant Spin-Selective Reflection based on a Chiral Meta-structure Operating in the Visible-Infrared Regime

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\textbf{Abstract}— The spin-selective reflection to introduce chirality which can have a lot of applications in real life such as spectroscopy, optical setups, media industry etc. In this paper, a reflection based metasurface proposed to introduce the giant chiroptical effects at broadband visible and infrared (IR) regimes. The optimization and results of basic unit also termed as nanostructure are demonstrated here. The reflectance at the optimal parameters for the proposed nanostructure shows the inclusion of multiband giant chiroptical effects in reflection mode. The results show that this metasurface can elicit large spin-selective reflection coefficients with moderate chirality covering the broadband wavelength. The circular dichroism in the visible and IR regime shows its potential applicability for a lot of applications in our daily life. This work also provides a new approach to achieve giant Spin Hall Effect at broadband wavelength ranges with low loss.

\textbf{Keywords—}CD; reflection parameters; spin-orbit interaction (SOI); optical sensing

I. INTRODUCTION

The past two decades have seen a lot of interest in artificial materials that can manipulate electromagnetic waves in novel ways, not possible with natural materials [1-5]. In particular, the engineered metasurfaces have demonstrated the ability to control the reflection and scattering of incident waves with subwavelength spatial resolution. This capability has led to a range of new applications such as lasing, cloaking, and imaging at the nanoscale [6-10]. Chirality is a property of objects that are not identical to their mirror images. An object can be chiral if it cannot be superposed on its mirror image. This occurs due to the lack of a plane of symmetry in the object. A chiral object and its mirror image are called enantiomers. The nature of light interaction with chiral objects is quite different from that of achiral objects [11-13]. When light interacts with a chiral object, it can be left-handed or right-handed depending on the object's handedness. The handedness of an object is determined by its chirality. Chirality in a nano-structure introduces the chiroptical effects such as optical activity (OA), asymmetric transmission (AT) and circular dichroism (CD) [14-18].

Circular dichroism (CD) is a type of optical activity that occurs when light interacts with chiral molecules. CD defined as the difference between the absorption for the left handed and right handed circularly polarized light. This phenomenon can be used to probe the structure and function of chiral molecules [19-20]. CD spectroscopy is a powerful tool for studying the conformational structure of proteins and other biomolecules. CD spectroscopy can be used to measure the strength of chiral interactions, as well as the handedness of chiral molecules [21-23]. CD spectroscopy can also be used to study the dynamics of chiral molecules, such as how they rotate and vibrate. Recent work has shown that metasurfaces can also be used to generate significant spin-orbit interactions (SOI) in visible frequency ranges [24-27]. The ability to generate such strong SOI with metasurfaces opens up the possibility of creating compact devices for a variety of applications such as spin-based optoelectronics and spintronics. In particular, metasurfaces offer a promising platform for achieving the giant Spin Hall Effect (SHE) [28-31].

Metal nanostructures may also be chiral, and their optical activity is typically greater than that of their molecular counterparts. The revelation that small clusters have a chiral response when coordinated with chiral ligands was one of the early achievements in this field [32-33]. During the initial years of chirality using metamaterials, metallic nanostructures were reported, Zhancheng et al proposed a chiral mirror using aluminium nanostructures for the manipulation of the optical waves and having the range of 1200 nm to 1600 nm [34]. Hentschel et al. used theoretical and experimental verification to show that a single layer chiral metamaterial with subwavelength thickness may produce significant variations in the transmittances of LCP and RCP. An interference mechanism causes the powerful chiroptical effect without compromising the reciprocity and mirror symmetry. As a result of this action, we may be able to manipulate light in a chiral fashion and create chiral optical devices using plasmonic materials [35,3]. Irrespective of chiral devices metals have been used to design a lot of optical devices such as amplifiers, absorbers, reflectors, resonators etc. [36-44].

Our work provides a new approach to achieve spin-switching giant chiroptical effects in visible and IR wavelengths. The metasurface studied in this work can elicit large spin-selective reflection coefficients with moderate chirality. The unit atom based on a partial ring structure is engineered in
such a way to introduce spin-switching chirality at the broadband wavelengths in visible and IR regime. In visible regime, the proposed chiral structure provides maximum reflectance for cross-polarized parameter of RCP incident light whereas minimum reflectance for cross-polarized parameter of LCP illumination. In contrast, for IR regime maximum reflectance obtained for cross-polarized parameter of LCP incident light whereas minimum reflectance for cross-polarized parameter of RCP illumination. This makes it an attractive platform for applications such as spin-based optoelectronics and spintronics.

II. DESIGN METHODOLOGY

The chirality, circular dichroism and giant reflection parameters can be used to design a metasurface that reflects left-handed or right-handed circularly polarized light. The parameters can also be used to control the degree of reflection and the handedness of the reflected light. The reflectance parameters of a chiral metasurface optimized for the required optical responses using the finite-difference time-domain (FDTD) method [45-46]. In this method, the metasurface is discretized into a three-dimensional grid, and the electromagnetic fields are evolved in time using the FDTD equations. The reflection coefficients of the metasurface are then obtained from the time-averaged values of the electromagnetic fields. The FDTD method is well suited for the design of reflection parameters, as it can take into account the effect of both the electric and magnetic fields on the metasurface. In addition, the FDTD method can be easily parallelized, making it possible to design large metasurfaces with a reasonable amount of computational resources. In Figure 1, nanostructure has been designed of dimensions $r_1 = 100\ nm$, $r_2 = 130\ nm$, $P_x = 900$ and $P_y = 900$.

![Figure 1: The proposed meta-atom schematic illustration to design chiral metasurface](image)

The proposed nanostructure optimized for the giant CD and the obtained results are presented and discussed in this section. It is shown that the reflectance parameters used to control the amplitude and the polarization of reflected circularly polarized (CP) light. The results may find applications in designing novel optical devices. For visible wavelengths, the right-hand circularly polarized (RCP) light is reflected by the metasurface with a positive reflectance, while the left-hand circularly polarized (LCP) light is reflected with a negative reflectance. The simulated results of the reflectance parameters $R_{LR}$ and $R_{RL}$ are plotted in Figure 2. In addition for IR wavelengths, left-hand circularly polarized (LCP) light is reflected by the metasurface with a positive reflectance whereas the right-hand circularly polarized (RCP) light is reflected with a negative reflectance. It can be seen that the unit atom have different optical responses to RCP and LCP light, which is in good agreement with the designed chirality.

Based on unit atom, the metasurface is designed to have an average reflectivity of 88% for right-handed circularly polarized light and 12% for left-handed circularly polarized light at visible wavelengths. However, for IR wavelengths, the metasurface exhibits a high degree of reflection for left-handed circularly polarized light and a low degree of reflection for right-handed circularly polarized light. The reflectivity of the chiral metasurface can be further increased by increasing the number of layers in the metasurface. For example, by increasing the number of layers from two to four, the reflectivity for right-handed circularly polarized light can be increased upto 100%.

![Figure 2: Reflectivity of the chiral metasurface for right-handed and right-handed circularly polarized light](image)

The circular dichroism for the designed nanostructure is presented in Figure 3. The phenomenon of circular dichroism is the differential absorption of left and right-handed CP light whereas optical activity is defined as the rotation of the plane of polarization of incident linearly polarized light. These CDs are crucial in agricultural, pharmacological, and biomedical research [47-51]. This phenomenon also used in CD spectroscopy to detect the differential absorption of an enantiomer irradiated with right circularly polarized light and left-circularly polarized (RCP/LCP) light. The circular dichroism spectroscopy (CDS) can both determine chiral
compounds' structure as well as the purity of a chiral solution [52]. Figure 3 depicts the average circular dichroism (CD) of ≈ 73%. The metasurfaces has the ability to be designed for on-chip nanophotonics using VLSI or deep learning techniques [53-57].

![Circular Dichroism (CD) spectra of the designed meta-structure](image1)

**Figure 3:** Circular Dichroism (CD) spectra of the designed meta-structure

![Dependency of absorption spectra on incident angles](image2)

**Figure 4:** Dependency of absorption spectra on incident angles

For oblique incident analysis, the dependency of the incident angle has been described in Figure 4. By varying the incident angle from 0 to 80 degrees the absorption has been observed.

**IV. CONCLUSION**

In this work, the chiral metasurface designed exhibits reflection parameters with giant chirality across all frequency bands in visible and IR regimes. The average circular dichroism (CD) obtained is of ≈ 73%. Moreover, the dependence on incident angle describe that no change in absorption has been observed. The circular dichroism parameter with high efficiency indicating that the proposed structure can be used to create optical filters with high selectivity. Overall, the designed chiral metasurface provides a versatile platform for manipulating light at different wavelengths. This makes the design well-suited for applications that require high levels of reflectivity, such as solar energy collection, light harvesting, and optical sensing.

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