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Original research article

Accurate regulation of circular dichroism signal in double-layer nanostructure

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ABSTRACT

Chiral plasmonic systems have been shown to exhibit stronger circular dichroism (CD) because of strong interaction between light and noble metals. In this study, we utilize double-layer chiral plasmonic nanostructures composed of achiral nanoplate and two achiral nanodisks to produce a chiroptical response. The chiroptical response is due to the twisted electric dipoles and the phase between them. In addition, the CD signal of the plasmonic nanostructure can be accurately regulated when plasmonic nanostructure parameters are tuned. Overall, results will allow further tuning of the optical responses in plasmonic systems to tailor chiral light–matter interaction.

1. Introduction

Chiral structures are those that cannot be superposed with their mirror images [1–4]. Chiral metamaterials have revealed several novel electromagnetic phenomena, such as negative refraction [5,6], asymmetric transmission effect [7–10], linear or/to circular polarization conversion [11,12], circular dichroism (CD) effect [13–16] and others. In particular, the CD of circularly polarized light through chiral metamaterials has attracted significant attention in recent years. This effect is due to different transmission intensities between the left circularly polarized light (LCP) and right circularly polarized light (RCP). Chiral structures with CD are always related to circular polarizers for optoelectronic conversion [17,18], polarization conversion [19,20], and molecular analysis [21–24].

In recent years, the CD effect of nanoscale plasmonic systems was widely studied. The nanoscale plasmonic systems have shown significantly enhanced CD because of the strong interaction between light and noble metals [25,26]. These significant interactions between electric and magnetic resonance cause large CD signals in 3D helix or helix-like chiral plasmonic nanostructures [27–32]. Thus, a layer-by-layer chiral nanostructure is designed considering that the helix-like chiral structure is complex and not easy to tune. In addition, the layer-by-layer chiral plasmonic nanostructure can generate larger CD signals because of the coupling between two layers [33–41]. Various approaches have been used to create plasmonic nanostructures and tune chiroptical responses. Changing parameters are often applied to tune the magnitude of a CD signal or shift the wavelength of the aforementioned chiral structures; however, the CD signals cannot be regulated individually. This phenomenon provides a hint to design nanoscale plasmonic systems to accurately regulate optical response without affecting another response.

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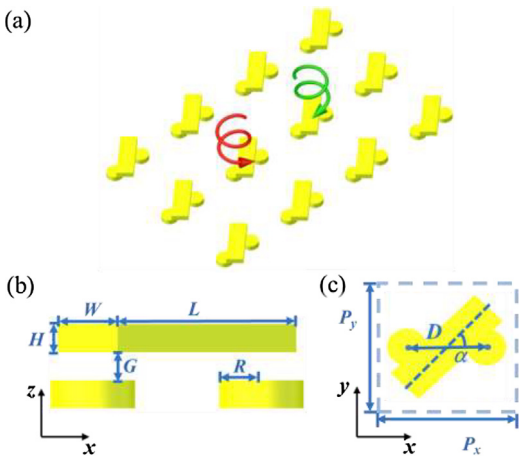

Fig. 1. (a) The schematic of nanostructure arrays, and structure parameters of the unit cell in (b) *x*-*z* plane and (c) *x*-*y* plane.

In this study, a double-layer chiral mental nanostructure that consists of an achiral nanoplate and two achiral nanodisks were designed to generate a CD effect. The results show that the double-layer chiral mental nanostructure generates two CD signals, and one CD signal can be tuned by varying the parameter without affecting the other CD signal. This process enables investigating plasmonic analog and studying optical response when the resonances of the constituents are intentionally tuned. In addition, the Born–Kuhn model has been used to analytically interpret the observed CD spectrum, providing insight into the underlying coupling mechanisms. This study can guide the design to accurately tune chiroptical response for practical application in biosensing.

2. Structure and computational method

Fig. 1(a) shows the proposed nanostructure arrays, and each unit is composed of two layers. The bottom layer is two nanodisks and the top layer is a nanoplate. The rotational symmetry centers of the two nanodisks coincide with the center of the nanoplate in the *z*-direction. The period is $P_x = 300$ nm and $P_y = 300$ nm in the *x* and *y* direction, respectively. Fig. 1(b) depicts the cell of nanostructure in *x*-*z* plane. The radius of nanodisk is labeled as *R*. The nanoplate has a length of *L*. The width and height of nanoplates are indicated as $W = 60$ nm and $H = 20$ nm, respectively. The gap between two layers is *G*. Fig. 1(c) shows the cell of nanostructure in *x*-*y* plane. And the twist angle between the line of center of two nanodisks is α in the *x*-*y* plane. The distance between the centers of the two nanodisks is $D = 120$ nm.

The 3D finite-element method software COMSOL Multiphysics is used to calculate the transmittance of nanostructure arrays. The refractive index of gold is taken from Ref. [42]. The excitation sources are RCP light and LCP light along the $-z$ direction and the magnitude of the incident electric field is set at 1 V/m. Transmittance was defined as $T = P_{out}/P_{in}$, which is the ratio of output power to incident power. The transmittance spectrum of RCP light and LCP light are represented by T_{++} and T_{--}, respectively. Therefore, the chirality of structures is represented by $CD = T_{++} - T_{--}$.

3. Results and discussion

Fig. 2(a) shows the transmission spectra of plasmonic arrays under RCP and LCP light illuminations. The structure parameters of the arrays are $L = 180$ nm, $R = 30$ nm, $\alpha = 45^\circ$, and $G = 20$ nm. Two evident resonant modes, namely, modes I and II of approximately 860 and 550 nm, respectively, are observed in the transmission spectra. Fig. 2(b) is the CD spectra of the nanostructure arrays. One CD peak and valley appear at the resonance wavelengths. In mode I, the transmittance under LCP illumination is larger than those under RCP illumination. In mode II, the transmittance under RCP illumination is larger than those under LCP illumination. Around the resonance wavelengths, the spectra of T_{++} and T_{--} correspondingly present different responses, thereby leading to a large CD effect.

The charge distributions were examined to investigate the transmission mechanism of the nanostructure arrays under circular illumination. Fig. 3 shows the top view of the normalized charge distributions of the nanodisk and nanoplate, where red and blue indicate positive and negative charges, respectively. Fig. 3(a) and (b) shows the normalized charge distributions of the nanoplate at modes I and II, respectively. The green arrows represent the equivalent electric dipole moments of nanoplate (upper layer). Fig. 3(c) and (d) shows the normalized charge distributions of the nanodisks at modes I and II, respectively. The light-blue arrows represent the equivalent electric dipole moments of the nanodisk (lower layer).

At $\lambda_I = 860$ nm, the equivalent electric dipole moment of the nanoplate along the long axis direction is presented. The effective dipoles $P_{I\text{-}D1}$ and $P_{I\text{-}D2}$ constitute $P_{I\text{-}D}$. In Fig. 3(e), $P_{I\text{-}D}$ and $P_{I\text{-}U}$ form a bonding mode in the Born–Kuhn oscillator model [43,44]. At $\lambda_I = 550$ nm, the effective dipole $P_{I\text{-}U}$ represents the equivalent electric dipole moment of the nanoplate along the short axis direction. $P_{II\text{-}D1}$ and $P_{II\text{-}D2}$ represent the equivalent electric dipole moments of nanodisks and can also