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Research Article

Magnetic Plasmon Sensing in Twisted Split-Ring Resonators

J. X. Cao, H. Liu, S. M. Wang, Y. J. Zheng, C. Zhu, Y. Wang, and S. N. Zhu

Department of Physics and National Laboratory of Solid State Microstructures, Nanjing University, Nanjing 210093, China

Correspondence should be addressed to H. Liu, liuhui@nju.edu.cn and S. N. Zhu, zhusn@nju.edu.cn

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We studied the sensing properties of stereo-SRRs metamaterials composed from two twisted split-ring resonators (SRRs). Due to the strong hybridization effect in the system, the polarization state of the transmitted wave is greatly changed at resonances. Since the stereo-SRRs structure is strongly coupled to the surrounding medium, the polarization change of the transmitted waves is quite sensitive to the refractive index change of the environment medium. The polarization ratio $\mathrm{PR}_{\mathrm{tran}} = T_y/T_x$ is used as sensing parameter and its figure of merit can reach 22.3 at the hybridized magnetic plasmon resonance. The results showed that the stereo-SRRs metamaterial can be applied to optical sensors an or other related field.

1. Introduction

Recently, a new concept in nanophotonics named as stereometamaterial was proposed [1]. This indicated that the electromagnetic properties of plasmonic metamaterials are determined not only by the geometry structure of elements but also by the spatial arrangement of these elements. Up to now, some different stereometamaterials are reported, such as gammadions [2], spirals [3], crosses [4], and stacked wires [5]. Among them, the twisted-SRRs system, also named as stereo-SRRs, is an interesting example for investigation. According to the previous studies, the electromagnetic responses could be tuned through changing the orientation angle of the SRRs [6]; a Lagrange model was introduced to demonstrate the chiral optical properties [7] and give a good description for the polarization change of the electromagnetic wave passing through the twisted-SRRs metamaterials [8, 9].

As is well known, surface plasmon resonance and localized surface plasmon resonance based on metal structures can be used as optical sensors because the resonance modes shift with the refractive index change of the surrounding medium [10, 11]. Since the magnetic plasmon resonance had a stronger field localization and narrower response linewidth, it could also be used as sensors [12, 13]. In this work, we will show that polarization change induced by magnetic plasmon resonances in the stereo-SRRs could be strongly coupled to the environment and is sensitive to the refractive index fluctuation of the surrounding medium. Stereo-SRRs structure could possibly work as a new kind of optical sensor.

2. Design of Numerical Models

Figure 1 presents one unit cell of the stereo-SRRs metamaterial with its geometry parameters. The structure is composed of two stacked SRRs, between which there is a twisted angle 90°. The period of the unit cell is $p = 700$ nm. The incident electromagnetic wave propagates in the z direction. Periodic boundary condition is used in the x and y direction, and the open boundary condition is used in the z direction. The substrate and the middle layer between the two SRRs are MgF_2, whose permittivity is taken as $\varepsilon = 1.9$.

To study the electromagnetic response of the twisted-SRRs metamaterial, a commercial software package CST Microwave Studio (Computer Simulation Technology GmbH, Darmstadt, Germany) is employed to investigate the transmission properties. The permittivity of metal is defined by the Drude model, $\varepsilon(\omega) = 1 - \omega_p^2/(\omega^2 + i\omega_\tau\omega)$, where ω_p and ω_τ are the bulk plasma frequency and the relaxation rate, respectively. For gold, the characteristic frequencies fitted to experimental data are $\omega_p = 2\pi \times 2.175 \times 10^{15}\ \mathrm{s}^{-1}$ and $\omega_\tau = 2\pi \times 6.5 \times 10^{12}\ \mathrm{s}^{-1}$ [14].

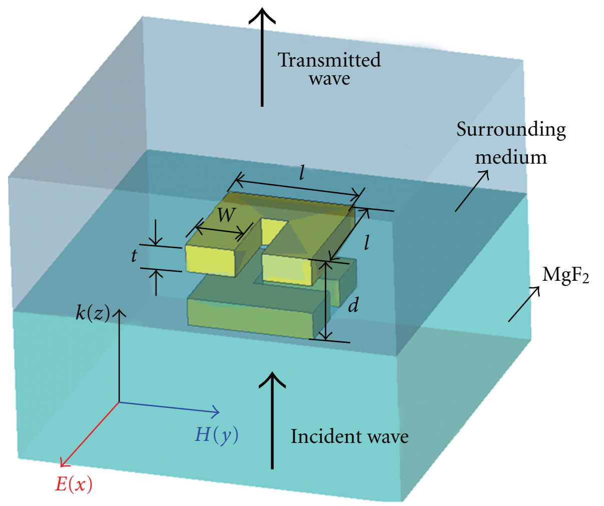

Figure 1: Schematics of unit cell of the stereo-SRRs metamaterial, together with the direction of the incident wave. The geometry parameters were $l = 230\,\text{nm}$, $w = 90\,\text{nm}$, $t = 50\,\text{nm}$, and $d = 50\,\text{nm}$. The periods in both of the x and y directions were $p = 700\,\text{nm}$.

3. Results and Discussions

In the simulations, the incident linearly polarized plane wave shined on the structure along the z direction with its electric field in the x direction (see Figure 1). As reported in [6–9], there are two magnetic plasmon modes induced in the twisted-SRRs system due to the hybridization effect. For the mode at the shorter resonance wavelength, the magnetic fields in two SRRs are in the opposite direction along the z axis (this mode is named as mode 1); while for the mode at the longer resonance wavelength, the magnetic fields in two SRRs are in the same direction along the z axis (this mode is named as mode 2). Like the electromagnetic properties of localized surface plasmon resonance, the electromagnetic field is strongly localized around the twisted SRRs at these two resonance wavelengths. This makes the structure couple with the environment strongly. The fluctuation of the refractive index of the surrounding medium will change the magnetic plasmon resonances of the structure greatly. Thus, the two hybrid magnetic plasmon modes could also be possibly applied in sensing.

Due to the chirality of this structure, the polarization state of the transmission wave will be changed at two resonance wavelengths [7]. Generally, the transmitted wave is not linearly x-polarized state. It includes the electric field components in both the x and y direction: E_x^{tran} and E_y^{tran}. Figures 2(a) and 2(b) give the transmitted energy of the two electric components $T_x = |E_x^{\text{tran}}|^2/|E_x^{\text{in}}|^2$ and $T_y = |E_y^{\text{tran}}|^2/|E_x^{\text{in}}|^2$ of the transmitted wave through the twisted-SRRs metamaterials. Here, the input signal of the excited plane wave is normalized. The two hybridized magnetic plasmon modes correspond to two absorption ditches in the transmission curves of T_x, while for the transmission curves of T_y, they correspond to two peaks. This means that part of the energy of the incident wave E_x^{in} is transferred into the transmitted wave E_y^{tran}. Here, we could define the polarization ratio (PR) $\text{PR} = T_y/T_x$ to characterize the polarization change between the incident wave and the transmitted one. Obviously, for the x polarized incident wave, $\text{PR}_{\text{in}} = 0$. For the transmitted wave, PR_{tran} results can be determined through the simulation data, which are given in Figure 2(c). Compared with the curves of T_x, and T_y, it can be obviously found that the PR_{tran} curves have narrower linewidth. This makes PR_{tran} a better sensing parameter.

In order to investigate the sensing properties of the twisted-SRRs system, we change the refractive index of the surrounding medium to see what happens to the magnetic plasmon response of the structure. In our simulations, when the refractive index of the surrounding medium is increased from 1.312 to 1.352 with step being 0.01, different transmission curves are obtained, and the resonance wavelengths will shift to longer wavelengths (see Figure 2). For mode 1, the resonance wavelength changes from 1.859 μm to 1.877 μm. For mode 2, the resonance wavelength changes from 2.083 μm to 2.107 μm. Under the different refractive indices of the surrounding medium, the resonance wavelengths of the two magnetic plasmon modes show good linear relationship. As is well known to all, the slope of the wavelength shift via the refractive index change represents the sensitivity as sensing element. That is to say, the sensitivity m here is defined as the wavelength shift over one refractive index unit change of the surrounding medium. So, for the case of our proposed twisted-SRRs system, the sensitivities for mode 1 and mode 2 are equal to 461 nm/RIU (refractive index unit) and 581 nm/RIU, respectively.

To understand the sensing performance of the two hybridized magnetic plasmon modes in the twisted-SRRs metamaterials, the general concept "figure of merit" (FOM) is introduced as follows [15]:

$$\text{FOM} = \frac{m\,(\text{nm/RIU})}{\text{FWHM}\,(\text{nm})}. \tag{1}$$

Here, m and FWHM are the sensitivity of the two hybridized magnetic plasmon modes and the full width at half maximum of the obtained curves (T_x, T_y, or PR_{tran}). Due to including the information of the sensitivity m and the linewidth of the signals, the parameter FOM represents the overall sensing performance of the twisted-SRRs metamaterials. Table 1 shows the calculated linewidth and FOM at the two resonance modes. In Table 1, when T_x is chosen as the sensing parameter, the FOM for mode 1 and mode 2 is 9.1 and 12.5, respectively, both of which are larger than that of the single-SRR structures being 8.73. While T_y is used for the sensing parameter, the FOM for mode 1 and mode 2 is 8.0 and 10.6. Obviously, T_x is better than T_y. For the PR_{tran} curves, it can be clearly found that the FOM parameters for mode 1 and mode 2 are 14.0 and 22.3, respectively. Both of them are larger not only than the FOM of the single SRR structures, but also than T_x and T_y of the stereo-SRRs system. Especially, the FOM at mode 2 is even much larger than mode 1. Thus, PR_{tran} is the best choice of sensing parameter.

As we reported before, when two SRRs compose one magnetic dimer, the coupling between the two SRRs leads to

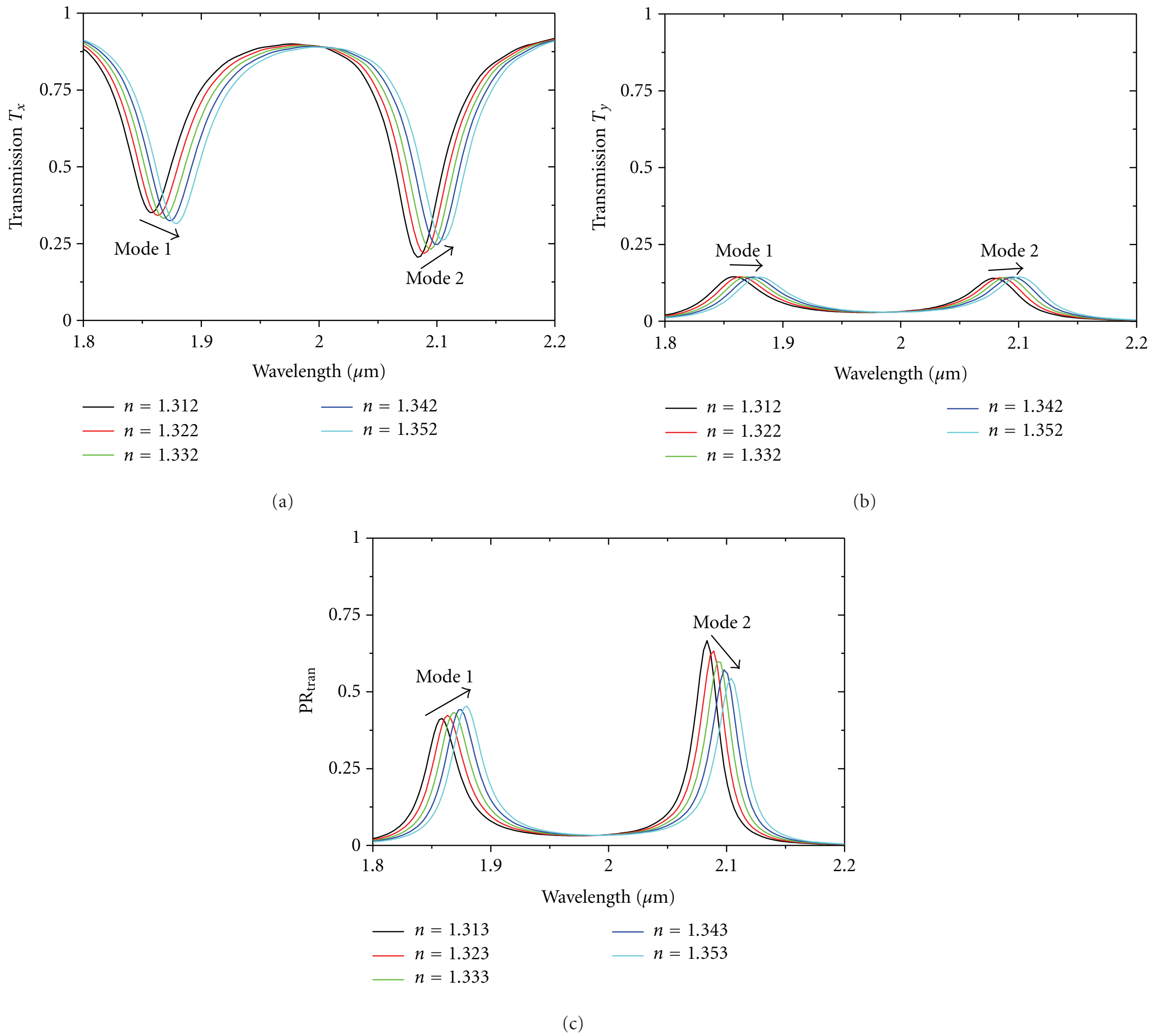

Figure 2: The calculated transmission spectrums for (a) T_x, (b) T_y, together with (c) PR_{tran} curves obtained by the simulated transmission data. The arrows in Figure 2 denoted that the resonance wavelengths shifted to longer wavelength when the refractive index of the surrounding medium was increased from 1.312 to 1.352.

Table 1: The FOM for the two hybridized magnetic plasmon modes of the stereo-SRRs metamaterials, and the parameters FWHM. Obviously, when the PR_{tran} result was used as sensing signal, the sensing performance of the two modes was best.

Eigenmode	FWHM (nm)	FOM
Mode 1 (T_x)	50.7	9.1
Mode 2 (T_x)	46.3	12.5
Mode 1 (T_y)	57.8	8.0
Mode 2 (T_y)	54.6	10.6
Mode 1 (PR_{tran})	33.0	14.0
Mode 2 (PR_{tran})	26.0	22.3

the hybridization of the magnetic response in the magnetic dimer, and two magnetic plasmon modes could be excited [8, 9, 16]. That is to say, the two magnetic plasmon resonance modes of the twisted SRRs come from the coupling between the two SRRs. Then their sensing properties are dependent on the coupling process. In the simulation, we change coupling strength through changing the distance between two SRRs. The dependence of sensitivity m, FWHM, and FOM of PR_{tran} at the two modes on the distance between two SRRs is calculated and given in Figures 3–5. The results show that, for both two modes, when the distance between two SRRs is reduced, the sensitivity m is increased (see Figure 3). Simultaneously, their FWHM is decreased (see Figure 4). As a result, FOM of the two modes will be increased when the distance between the two SRRs is decreased (see Figure 5). This means that stronger coupling will improve the sensing performance.

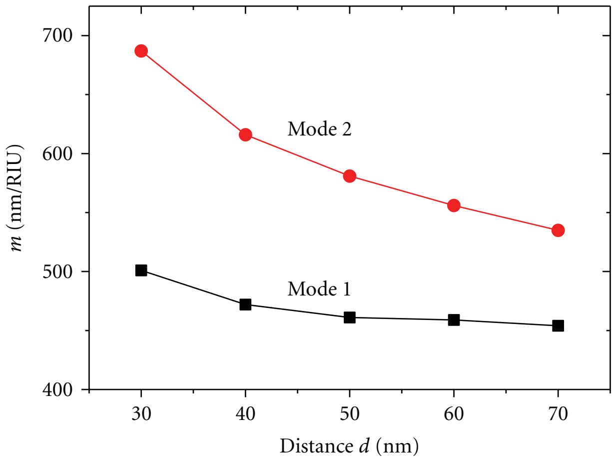

Figure 3: Sensitivity m for the two magnetic plasmon modes with different distances of the two SRRs when choosing the PR_{tran} curves as sensing signal.

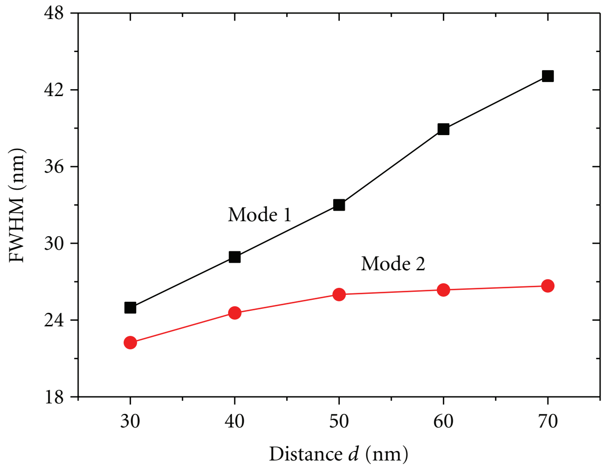

Figure 4: FWHM for the two magnetic plasmon modes with different distances of the two SRRs when choosing the PR_{tran} curves as sensing signal.

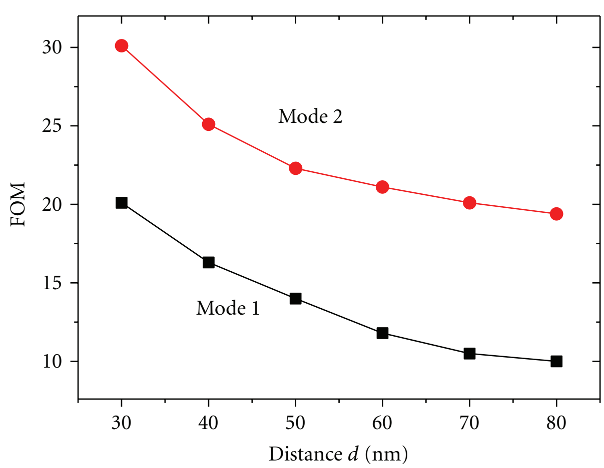

Figure 5: FOM for the two magnetic plasmon modes with different distances of the two SRRs when choosing the PR_{tran} curves as sensing signal.

According to our former work, the chirality of stereo-SRRs metamaterial comes from the magnetic coupling between two SRRs. Due to this coupling effect, the part of energy of the x-component of the incident wave can be converted to the y-component of the transmitted wave. The polarization conversion efficiency is determined by the coupling process. When we decrease the distance between two SRRs, the coupling effect becomes stronger. Then we can obtain larger FOM and better sensing performance.

4. Conclusion

In conclusion, the sensing properties of the stereo-SRRs metamaterials are investigated in this work. Based on the hybridization effect of the twisted SRRs, the polarization state of the transmitted wave is changed and great polarization ratio PR_{tran} is obtained at resonances. Compared with the transmission curves of T_x and T_y, PR_{tran} has narrower linewidth and larger FOM and is a better sensing parameter. Our work shows that stereo-SRRs metamaterials can be possibly applied in optical sensors and other related techniques.

Acknowledgments

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