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Vertical split-ring resonators for plasmon coupling, sensing and metasurface

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ABSTRACT

Split-ring resonator (SRR), one kind of building block of metamaterials, attracts wide attentions due to the resonance excitation of electric and magnetic dipolar response. The fundamental plasmonic properties and potential applications in novel three dimensional vertical split-ring resonators (VSRRs) are designed and investigated. The resonant properties arose from the electric and magnetic interactions between the VSRR and light are theoretically and experimentally studied. Tuning the configuration of VSRR unit cells is able to generate various novel coupling phenomena in VSRRs, such as plasmon hybridization and Fano resonance. The magnetic resonance plays a key role in plasmon coupling in VSRRs. The VSRR-based refractive-index sensor is demonstrated. Due to the unique structural configuration, the enhanced plasmon fields localized in VSRR gaps can be lifted off from the dielectric substrate, allowing for the increase of sensing volume and enhancing the sensitivity. We perform a VSRR based metasurface for light manipulation in optical communication frequency. By changing the prong heights, the 2π phase modulation can be achieved in VSRR for the design of metasurface which can be used for high areal density integration of metal nanostructures and optoelectronic devices.

Keywords: Plasmonic metamaterials, vertical split-ring resonators, plasmon coupling, plasmon hybridization, metasurface

INTRODUCTION

Metamaterials are the artificial structures in sub-wavelength scale which perform promising novel and exotic electromagnetic phenomena not found in nature, such as negative refraction [1-3], cloaking [4, 5] and super-resolution [6, 7]. These "unusual" phenomena are intrinsically connected to the localized surface plasmon resonances (LSPR) [8] arising from the collective oscillations of free electrons which is able to induce strong electromagnetic fields adjacent to the artificial sub-wavelength metallic elements in the metamaterials. A lot of near-field coupling based on plasmon interaction in metamaterials are also promising for applications in optics, such as the Fano resonance [9, 10], toroidal dipolar response [11, 12] and sensor [13-16]. These works reveal that the plasmonic coupling is very important for the development on plasmonic circuit devices and antenna applications [17, 18]. Split ring resonators (SRRs), commonly constructed building blocks of plasmonic metamaterials, have been proposed to produce electric as well as magnetic dipolar response [19-23]. Up to now, most of the metamaterials are design in two dimensions, which causes fraction of the plasmon field diffused into substrates. We recently fabricated vertical split-ring resonators (VSRRs) which exhibits the ability of phase and reflection modulation by controlling the geometric size along z (vertical) direction. On the other hand, the VSRR structure standing up vertically on a substrate which reducing the fraction of the plasmon field diffused into substrates and increase the coupling with incident light. In this investigation, we experimentally and numerically demonstrate the plasmonic hybridization in VSRR dimers. We also verify the VSRR structure is benefitting for sensor, metasurface and light manipulation.

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RESULTS AND DISCUSSIONS

To study the plasmonic hybridization between two magnetic metamolecules, the VSRR dimers with different gap between two VSRR with different geometric sizes will be investigated [24]. The schematic diagram of VSRR dimer is shown in Fig. 1(a). Two transmittance dips are observed in both simulation and measurement transmittance spectra, which is resulting from the plasmonic hybridization in VSRRs. The dominance of the electric coupling indicates which resonance is corresponding to the high-order (low-order) response and locates at higher (lower) frequency. The “bonding” mode exhibits out-of-phase electric dipoles, resulting in an out-of-phase magnetic dipole moment oscillation. On the other hand, the “anti-bonding” mode which located at lower frequency has in-phase electric and magnetic dipoles. The resonance frequency separation of the “anti-bonding” and “bonding” for four different gaps from 40 to 90 nm under normal illumination shows that the coupled resonance separation increases rapidly with the decreasing the gap.

Figure 1. Schematic diagram for VSRR dimer.

A magnetic plasmon induced Fano resonance is investigated based on VSRR structures [25]. The geometries of a three-dimensional plasmonic metamolecule are shown in Fig. 2 in which the incident electric is along y axis. The metamolecule consists of a pair of horizontal SRR (H-SRR) on the side and one along the vertical direction (V-SRR) in the middle. The lateral displacement between the central axes of V-SRR and H-SRR pair is defined as D . Under this condition, the symmetry of this metamolecule could be destroyed by shifting D . In the case of $D = 0$ (symmetry), a single transmittance dip can be observed caused by the plasmonic resonance of the V-SRR at the middle of the metamolecule. A transmittance peak appears by introducing structural asymmetry with D , which is caused by the magnetic field induced by the plasmonic resonance of V-SRR to pass through the gap of H-SRRs. The intensity of Fano resonance is increased as D increased.

Figure 2. Schematic diagram of Fano resonance VSRR metamolecule unit cell.

Figure 3 shows the idea of VSRR based plasmonic sensor. The VSRR structure stands up vertically on a SiO_2 substrate which increases the sensing volume and also enhances the field entirely in the free space away from the dielectric substrate [26]. A strong electromagnetic field confines within the gap as the magnetic plasmon is excited. The resonance dip of measured spectrum is shifted from 1058 nm to 1236 nm and 1254 nm, as the refractive index of the environment is changed from air to 1.32 and 1.33, respectively. The simulation result also shows a good agreement with the measurement. Using a linear fit, the simulation has predicted a sensitivity of about $\delta\lambda/\delta n = 797 \text{ nm/RIU}$, while our measurement has produced a less value of 603 nm/RIU. It shows that VSRR sensor is much sensitive to the change of the environment.

Figure 3. Illustration of the VSRR based plasmonic sensor. Inset: SEM images of the fabricated structure.

A high density metasurface works at telecommunication wavelength $\lambda = 1548$ nm can also be approached by using VSRR [27]. Figure 4 shows the illustration of the VSRR-based metasurface beam steering device. Based on generalized Snell's law [17], 2π phase modulation with a constant phase gradient is a very important factor for the design of metasurface. We choose six equally spaced phase modulation points separated by 60° corresponding to prong heights of $H_2 = 30, 60, 90, 120, 150$, and 0 nm for the metasurface design. The scattered field intensity at 1548 nm under various incident angles ($0^\circ, 5^\circ, 10^\circ, 15^\circ$, and 20°) is calculated by FDTD. The reflection angle increases from 45° to 77° as the incident angle varied from 0° to 15° . Small amount of scattered light can be observed within the region of $\theta_r < 40^\circ$ which is the result of unmodulated. In the case of normal incidence, FWHM angle is 2.9° of reflection angle of 45° is obtained and the intensity of reflection at 45° is 31 times stronger than that of unmodulated reflection. It indicates that the VSRR-based metasurface is capable of steering light with a high extinction ratio. In comparison with beam steering in Au nano-rods nanostructures, the requirement of footprint for VSRRs based metasurface is much smaller to perform the same functionalities. It can be established that the footprint of the VSRR unit cell is roughly half of that of nano-rods unit cell, allowing for implementation of high density configuration for a range of metasurface-based applications.

Figure 4. Illustration of the VSRR-based metasurface beam steering.

CONCLUSIONS

In summary, the fundamental plasmonic resonance and plasmonic coupling in VSRRs have been investigated. The magnetic resonance plays an important role in plasmon coupling in VSRRs rather than the electric one. By tuning the configuration of VSRR unit cells, we are able to control the optical phenomena in VSRRs, such as Fano resonance and plasmon hybridization. Compared with planar SRR, plasmonic resonance of VSRR has stronger magnetic energy density under the same dimensions and environment. Moreover, the VSRR reduces the fraction of the plasmon field diffusing into substrate, which could increase the sensing volume and the sensitivity. By varying the prong heights, the 2π phase modulation can be achieved in VSRR for the design of metasurface. Compared with traditional rod-based metasurface, VSRR-based metasurface allow for implementation of high density configuration with high extinction ratio property. Because of the specific vertical geometry, the VSRR open an avenue for the development on plasmonic devices such as opto-electronic devices and so on.

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