Optical magnetic response in three-dimensional metamaterial of upright plasmonic meta-molecules

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Abstract

Fabrication of 375×375 vertical U-shape nano gold rings (110 nm x 60 nm x 40 nm) on a fused silica substrate has been successfully implemented by a novel e-beam lithography double exposure process. Plasmonic resonance modes of such particles are investigated by finite-element simulations and optical measurements, which are in excellent agreement with each other. Results show magnetic field solely depends on the resonance mode showing either enhanced between two prongs of vertical U-shape nano ring or enhanced around two prongs of vertical U-shape gold ring.

1. Introduction

Metamaterials composited with sub-wavelength split ring resonators (SRRs) have attracted many attention because of a number of extraordinary properties, such as optical chirality [1] and negative refraction index [2], optical spectrum manipulation [3]. However, due to the challenges in fabrications, so far most U-shape SRRs were fabricated as planar or multi-layered structures. In this paper, we successfully fabricated vertical U-shape SRRs and studied their optical properties by both experiments and numerical simulations. A unique characteristic of our structure is that its magnetic resonance can be excited by normally incident light. We found such vertical SRRs to exhibit rich plasmonic resonances different from planar SRRs, showing unique magnetism responses related to the magnetic field of incident light.

2. Fabrication, measure and simulation

Using electron beam lithography, we fabricated 375×375 vertical U-shape three-dimensional gold resonance rings on fused silica substrate, covering a total area of ~75×75μm^2. The three dimensional gold resonance rings are made by e-beam double exposure process. For the precision alignment of e-beam double exposure process, two golden cross alignment marks (size 9×150 μm) with a thickness 100 nm are fabricated and used. First, The bottoms of resonance rings are defined in positive resist (495k PMMA) after first e-beam exposure and lift-off process. Subsequently, the two prongs of reso-

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nance ring are made by second e-beam exposure and lift-off process. The detail of fabrication process is similar with our prior work. Figure 1(a) shows the schematic diagram of the vertical resonant nano-rings. The size of each unit-cell is 110 nm length and 60 nm height, and the periodicity is 200 nm. The resonant rings are illuminated at normal incidence using x- and y-polarized light. Figure 1(b) shows an SEM micrograph of the fabricated pattern. The inset of Fig. 1(b) shows a magnified view of four vertical U-shape three-dimensional resonance rings with the bottom length (L_1) 110 nm.

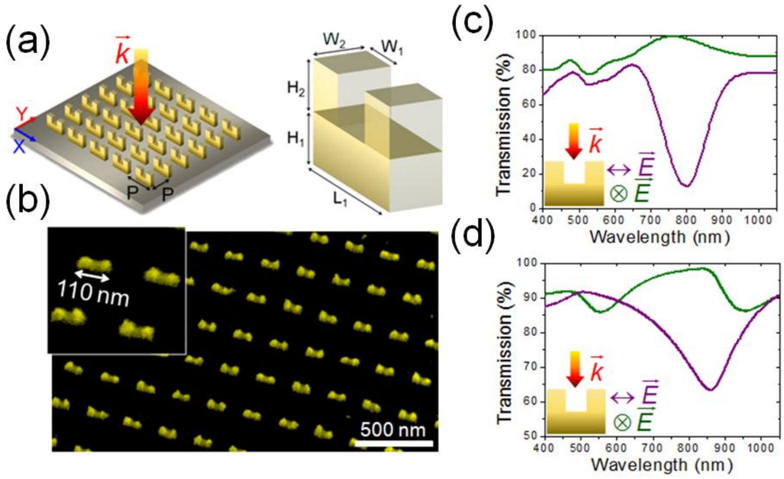

Fig. 1. (a) Schematic diagram showing the feature size of vertical U-shape three-dimensional resonance ring, L_1= 110 nm, H_1= 30 nm, H_2= 30 nm, W_2= 40 nm, W_1= 40 nm, P= 200 nm, respectively. (b) SEM image of a small region from the fabricated sample. (c) Finite-element simulation transmission spectra for x-polarized illumination (the purple curve) and y-polarized illumination (the green curve). (d) Experimental transmission spectra for x-polarized illumination (the purple curve) and y-polarized illumination (the green curve). The inset in both frames (c) and (d) show the propagating direction as well as polarization state of incident light.

Figure 1(c) and 1(d) show the measured and simulated transmission spectra through the sample as described in Fig. 1(a), illuminated by normal-incidence lights polarized along x and y directions. The transmission spectra are normalized by the transmissivity of an un-patterned region of the fused silica wafer. The simulation spectra are obtained with the finite-element method (commercial software, Comsol Multiphysics).

3. Results

As expected, when illuminated by a y-polarized light, the magnetic resonance of the 3D nano-rings cannot be excited so that the transmission spectra (the green curves in Figs. 1(c) and 2(d)) are nearly flat in both experiment and simulation. On the contrary, our structures show significant optical response to an x-polarized incident light, resulting in a pronounced dip in the transmission spectrum at the wavelength (λ) of 850 nm (the purple curves in Figs. 1(a) and 2(b)). This resonant mode results from a ring-like current flowing on the surface of the vertical nano-ring which has been demonstrated by FDTD simulation, and is a magnetic resonance which can only be excited by external lights with a y component of magnetic field.

To gain a deeper understanding on the resonance mode, we varied the structural details of the nano-rings and then performed simulations to study the transmission spectra. Figure 2(a) shows the simulated spectra for nano-rings with H_2 (length of prong) kept as a constant and L_1 (length of the bottom bar) changed from 110 nm to 150 nm. Obviously, the fundamental resonance mode shifts to longer wavelength as L_1 increases, which is understandable noting that the current flows on the longer path. Figure 2(b) shows the evolution of transmission spectra as H_2 increases. Again, we found a red shift of the resonance mode similar to Fig. 2(a). Intriguingly, we found another resonance at a higher frequency being excited by the x-polarized normal-incident light as H_2 increases. Magnetic field pattern and field line are shown in Figs. 2(c) and Fig. 2(d) to illustrate the resonance response of the vertical

U-shape nano gold ring. The plane is chosen as the root plane of its two prongs. We can find that, the low order resonance mode, so called mode I, shows strong response to external magnetic field of incidence light in the gap of standing U-shape ring. Contrarily, the higher order mode, so called mode II, shows to push its magnetic field line outside its two standing prongs. In the case of mode I, the enhanced magnetic field happened between the prongs of the nano U-shape ring resulted from clockwise and anticlockwise surface current oscillation on the surface of gold ring structures (shown at the inset of Fig. 2(c)), which exhibits parallel response to the magnetic field of incident light. In the case of mode II, a pair of anti-phase current along two prongs of the U-shape ring (shown at the inset of Fig. 2(d)) and the flowing current along the bottom of the U-shape resonance ring gives destructive (constructive) magnetic response at the inside (outer) wings of the resonance U-shape gold nano ring. The currents distributions at the surface of rings can perfectly explain the field pattern illustrated here.

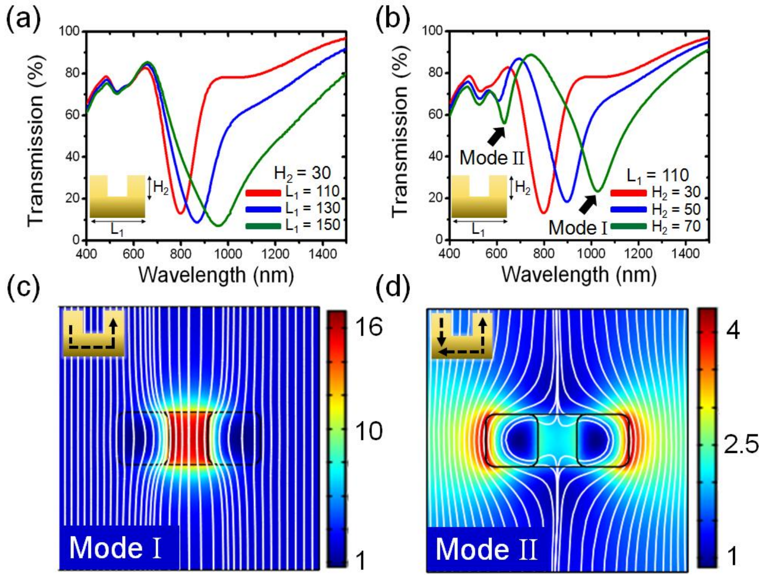

Fig. 2. Evolution of the finite-element simulation transmission spectra for x-polarized illumination upon varying the bottom length L_1 (a) and the prong length H_2 (b) of vertical U-shape three-dimensional gold ring. Simulation magnetic field in arbitrary units (color-coded) and field line of magnetic field (white line) for mode I (c) and mode II (d) of Fig. 2(b). The inset of Figs. 2(c) and 2(d) show the direction of flowing surface current.

4. Conclusion

Plasmonic resonances modes of *vertical* U-shape three-dimensional nano gold rings are found from the experimental transmission spectra and finite-element simulations. Results show the low order resonance mode shifts to longer wavelength as the bottom of the vertical U-shape gold ring increased. When the length of prongs of the vertical U-shape nano gold ring grows, a higher resonance mode can be excited by x-polarized illumination at normal incidence. The low order resonance mode is related to the U-shape surface current of resonance gold ring, and the higher order resonance mode is associated to a pair of anti-phase current along two prongs of the U-shape gold nano ring. The distribution of the magnetic field is either squeezed between two prongs, or compelled and enhanced around two prongs of vertical U-shape gold ring for low order and high order plasmonic resonance mode, respectively.

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