Newsroom

10.1117/2.1201112.003839

Optical magnetic response of upright plasmonic molecules in 3D metamaterial

Wei Ting Chen, Pin Chieh Wu, Chen Jung Chen, Shulin Sun, Lei Zhou, Guang-Yu Guo, Chih Ting Hsiao, Kuang-Yu Yang, Nikolay I. Zheludev, and Din Ping Tsai

An array of fabricated U-shaped split-ring resonators shows a profound response to the magnetic field of light incident normal to the sample.

Metamaterials are defined as an array of artificial subwavelength structures that frequently show unique optical behavior not found in nature.[1,2] Composites of these materials made with split-ring resonators (SRRs) have attracted wide attention owing to a number of extraordinary properties, including optical chirality,[3] negative index of refraction,[4] and optical spectrum manipulability.[5] Metamaterials have application as nanorulers,[6] luminescence enhancement,[7] and ultrafast optical switches.[8] The ability of SRRs to induce negative refraction was first studied in the microwave region in 2000.[9] Since 2005, interest in them has extended to the optical frequency region to make the technology more broadly applicable.[10]

Despite their obvious appeal, fabrication of these structures in 3D presents significant challenges because of their limited spatial resolution. Consequently, to date most U-shaped SRRs (a configuration conducive to magnetic plasmon resonance) have been made in planar or multilayered form, some of which are 3D but on the scale of microns. One way to excite the magnetic plasmon resonance of planar SRRs requires applying off-normal incident light possessing the required magnetic vector field component.

To overcome these issues, we successfully constructed a photonic metamaterial by e-beam lithography using a precise alignment technique (under 10nm misalignment). The metamaterial consisted of an array of vertical (3D) U-shaped gold SRRs on the nanometer scale (nanorings). We then studied their optical properties both experimentally and using numerical simulations (see Figure 1).[11,12] A special feature of our structures is that their magnetic plasmon resonance can be excited simultaneously by the electric and magnetic fields of normally incident light, providing a rich response. Electromagnetic resonance modes in 3D SRR structures have been little studied to date. Consequently, we focused our investigations on both the magnetic and bi-anisotropic magneto-electric susceptibilities of our built structures.

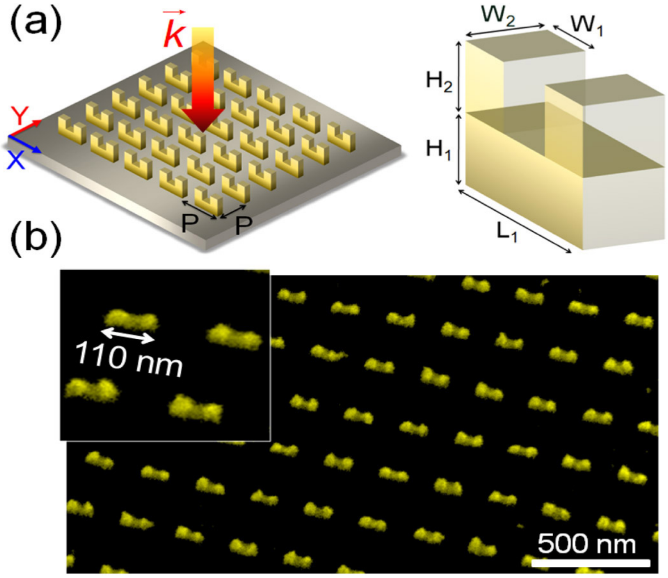

Figure 1. *(a) Schematic diagram showing the feature size of the split-ring resonator (SRR) structure.* $L_1 = 110nm$, $H_1 = 30nm$, $H_2 = 30nm$, $W_2 = 40nm$, $W_1 = 40nm$, $P = 200nm$, *respectively. The period P is 200nm in both the x and y directions. The vector* $\vec{k}$ *denotes the direction of incident light. (b) Scanning electron microscope image of a small region of the fabricated sample. L: Length. W: Width. H: Height.*

Figure 2 shows measured and simulated transmission spectra through the sample described in Figure 1. As expected, when illuminated by y-polarized light, the magnetic plasmon resonance

Continued on next page

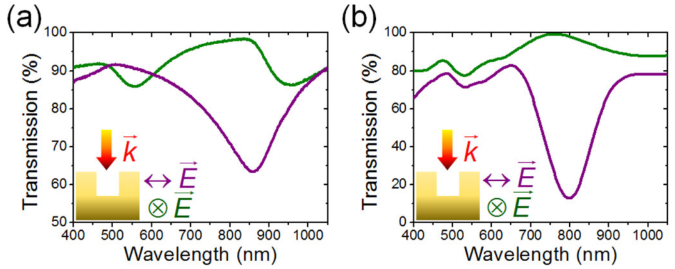

Figure 2. *Experimental (a) and finite-element simulation (b) transmission spectra for x-polarized illumination (the purple curve) and y-polarized illumination (the green curve).* $\vec{E}$*: Direction of the electric field.*

of the 3D nanorings cannot be excited, and experiments as well as simulations show the transmission spectra to be nearly flat. In contrast, the nanorings exhibit significant optical response to *x*-polarized incident light, resulting in a pronounced dip in the transmission spectrum at a wavelength of 850nm. This resonant mode results from a ringlike current flowing on the surface of the 3D nanoring shown by finite-element simulation. The mode represents magnetic plasmon resonance with a magnetic dipole response that is excited by external light.

We then varied the structural details of the nanorings and carried out simulations to study their transmission spectra. Figure 3(a) shows the simulated spectra for nanorings with L_1 (length of the bottom bar) changed from 110 to 150nm. The resonance mode (denoted as mode I) shifts to longer wavelengths as L_1 increases, as predicted by the standing wave model. Figure 3(b) shows the evolution of transmission spectra as H_2 (height of the prong) increases. Again, we found a redshift of the resonance mode similar to that in Figure 3(a). We found another resonance at a higher frequency (denoted as mode II) excited by *x*-polarized normal-incident light.

Resonance modes I and II show distinct responses to the magnetic field of incident light: see Figure 3(c) and (d). Mode I exhibits an enhanced magnetic field in the hollow of the off-plane U-shaped ring. In contrast, in mode II the magnetic field line is pushed outside the two standing prongs and enhanced around their center. The magnetic fields of modes I and II show parallel and anti-parallel responses to the magnetic field of incident light, respectively. The current distribution at the surface of the rings—see Figure 3(c) and (d), insets—perfectly explains the magnetic field patterns illustrated here. For example, in the case of mode II, a pair of anti-phase currents along the two prongs of the U-shaped ring—see Figure 3(d), inset—and the flowing current along the bottom result in a destructive magnetic response at the ring's center.

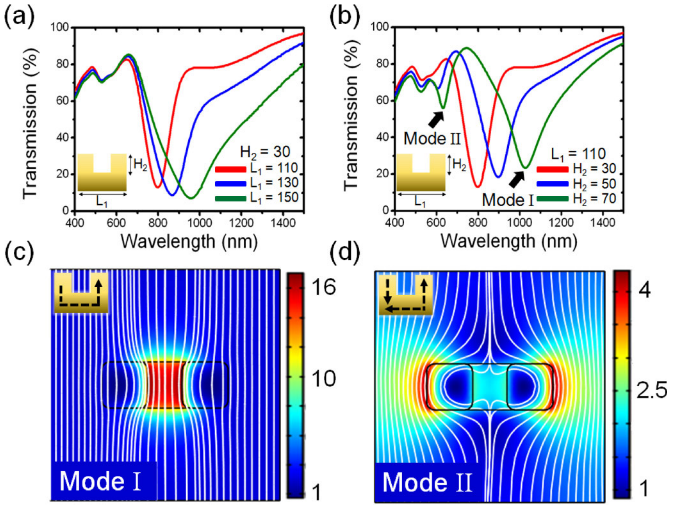

Figure 3. *Evolution of finite-element simulation transmission spectra for x-polarized illumination on varying the bottom length* L_1 *(a) and the prong length* H_2 *(b) of the SRR structure. Simulated magnetic fields in arbitrary units (color-coded) and magnetic field lines (white) for mode I (c) and mode II (d) of (b). The insets of (c) and (d) show a side view of the direction of the flowing surface current.*

In summary, we fabricated an array of 3D U-shaped SRRs. Compared with other methods of making such structures, our approach provides both smaller size and improved resolution. However, the height of our devices is limited by the thickness of the resist. We showed that the magnetic response of 3D SRRs can be excited simultaneously by electric and magnetic fields under normal incident illumination. In future work, we will investigate the coupling between two or more upright SRRs to generate complex and functionally dense 3D metamolecules with toroidal or so-called Fano resonance.

Author Information

Wei Ting Chen, Pin Chieh Wu, Chen Jung Chen,
Chih Ting Hsiao, and Kuang-Yu Yang
Department of Physics
National Taiwan University
Taipei, Taiwan

Continued on next page

Shulin Sun
National Center for Theoretical Sciences at Taipei
Physics Division
and
Department of Physics
National Taiwan University
Taipei, Taiwan

Lei Zhou
State Key Laboratory of Surface Physics
and
Key laboratory of Micro and Nano Photonic Structures
Fudan University
Shanghai, China

Guang-Yu Guo
Department of Physics
National Taiwan University
Taipei, Taiwan
and
Graduate Institute of Applied Physics
National Chengchi University
Taipei, Taiwan

Nikolay I. Zheludev
Optoelectronics Research Center
and
Centre for Photonic Metamaterials
University of Southampton
Southampton, United Kingdom

Din Ping Tsai
Department of Physics
National Taiwan University
Taipei, Taiwan
and
Instrument Technology Research Center
National Applied Research Laboratory
Hsinchu, Taiwan

References

1. T. Kaelberer, V. A. Fedotov, N. Papasimakis, D. P. Tsai, and N. I. Zheludev, *Toroidal dipolar response in a metamaterial*, **Science 330**, pp. 1510–1512, 2010.
2. W. T. Chen, P. C. Wu, C. J. Chen, H. Y. Chung, Y. F. Chau, C. H. Kuan, and D. P. Tsai, *Electromagnetic energy vortex associated with sub-wavelength plasmonic Taiji marks*, **Opt. Express 18**, pp. 19665–19671, 2010.
3. E. Plum, X. X. Liu, V. A. Fedotov, Y. Chen, D. P. Tsai, and N. I. Zheludev, *Metamaterials: optical activity without chirality*, **Phys. Rev. Lett. 102**, p. 113902, 2009.
4. V. M. Shalaev, *Optical negative-index metamaterials*, **Nat. Photon. 1**, pp. 41–48, 2007.
5. E. Plum, K. Tanaka, W. T. Chen, V. A. Fedotov, D. P. Tsai, and N. I. Zheludev, *A combinatorial approach to metamaterials discovery*, **J. Opt. 13**, p. 055102, 2011.
6. N. Liu, M. Hentschel, T. Weiss, A. P. Alivisatos, and H. Giessen, *Toroidal dipolar response in a metamaterial*, **Science 330**, pp. 1510–1512, 2010.
7. T. Kaelberer, E. Plum, J. Y. Ou, T. Uchino, and N. I. Zheludev, *Multifold enhancement of quantum dot luminescence in plasmonic metamaterials*, **Phys. Rev. Lett. 105**, p. 227403, 2005.
8. M. Ren, B. Jia, J. Y. Ou, E. Plum, J. Zhang, K. F. MacDonald, A. E. Nikolaenko, J. Xu, M. Gu, and N. I. Zheludev, *Nanostructured plasmonic medium for terahertz bandwidth all-optical switching*, **Adv. Mater.**, 2011. Published online 24 October
9. D. R. Smith, Willie J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, *Composite medium with simultaneously negative permeability and permittivity*, **Phys. Rev. Lett. 84**, p. 4184, 2000.
10. J. Zhou, T. Koschny, M. Kafesaki, E. N. Economou, J. B. Pendry, and C. M. Soukoulis, *Saturation of the magnetic response of split-ring resonators at optical frequencies*, **Phys. Rev. Lett. 95**, p. 223902, 2005.
11. W. T. Chen, C. J. Chen, P. C. Wu, S. Sun, L. Zhou, G.-Y. Guo, C. T. Hsiao, K.-Y. Yang, N. I. Zheludev, and D. P. Tsai, *Optical magnetic response in three-dimensional metamaterial of upright plasmonic meta-molecules*, **Opt. Express 19**, p. 12837, 2011.
12. W. T. Chen, C. J. Chen, P. C. Wu, S. Sun, L. Zhou, G.-Y. Guo, C. T. Hsiao, K.-Y. Yang, N. I. Zheludev, and D. P. Tsai, *Optical magnetic response in three-dimensional metamaterial of upright plasmonic meta-molecules*, **Int'l Conf. Mater. Adv. Technol.**, 2011.