Plasmon coupling in vertical split-ring resonator magnetic metamolecules

P.C. Wu[1], W.L. Hsu[1], M. K. Chen[1*], W. T. Chen[1], Y.W. Huang[1], C. Y. Liao[1], A. Q. Liu[2], N. I. Zheludev[3], G. S.[4] and D. P. Tsai[1,5]

[1]Department of Physics, National Taiwan University, Taipei 10617, Taiwan
[2]School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore
[3]Optoelectronics Research Centre and Centre for Photonic Metamaterials, University of Southampton, Southampton SO17 1BJ, UK
[4]Department of Physics, University of Massachusetts Boston, Boston, Massachusetts 02125, U.S.A.
[5]Research Center for Applied Sciences, Academia Sinica, Taipei 11529, Taiwan

*E-mail address: cmksmart@gmail.com

Abstract

Vertical split-ring resonators (VSRRs) were fabricated which behave as magnetic metamolecules sensitive to both incident electric and magnetic fields with the stronger induced magnetic dipole moments upon excitation in comparison to planar SRRs. Using these metamolecules with different spacing in VSRR dimers, we investigate the hybridization of the magnetic plasmon modes associated with each constituent VSRRs. We found that plasmon coupling can be precisely controlled by varying the gap separation between VSRRs. The resulting wide tuning range of these hybrid modes offers the possibility of developing frequency selective functional devices such as sensors and filters based on plasmon coupling with high sensitivity.

Introduction

Past decade has seen a number of interesting designs proposed and implemented to generate artificial magnetism at optical frequencies using plasmonic metamaterials, but owing to the planar configurations of typically fabricated metamolecules that make up the metamaterials, the magnetic response is mainly driven by the electric field of incident electromagnetic wave. This work investigate the resonance tuning of coupled VSRRs by fabricating a series of dimer samples with different spacing as shown schematically in Fig. 1(A) with the expectation to reveal the strong magnetic dipole coupling in vertical dimers because VSRRs can be placed much closer to each other. The simulation and measurement of resonance energy separation $\Delta\omega = \omega_{a+b} - \omega_{a-b}$ of the "anti-bonding" and "bonding" for the four samples with VSRR spacing from 40 to 90 nm under normal illumination shown in Figure 1(B) . The coupled resonance separation $\Delta\omega$ is consistently greater than the resonance energy difference (~20 THz) obtained from the transmission measurement of the isolated VSRRs of same two different sizes

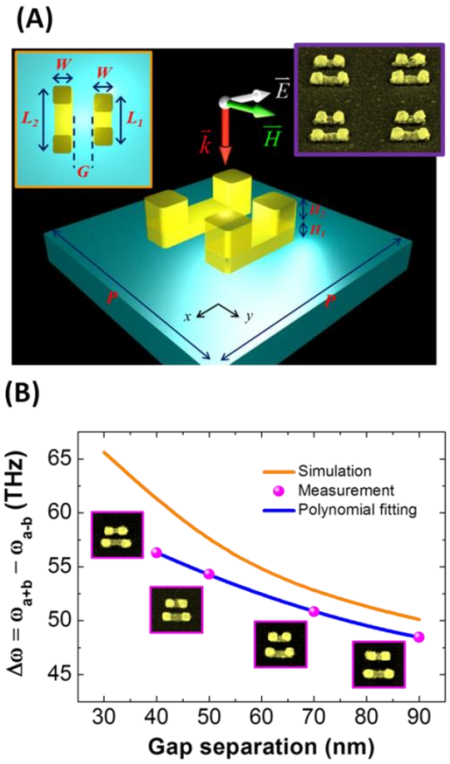

Fig1. (A) Schematic diagrams of VSRR dimer unit cell with designed parameters and the 45° SEM micrograph with the zoom-in view (inset) for the sample with G = 50 nm. Scale bar: 500 nm.(B) The bonding and anti-bonding splitting vs. the gap in a VSRR dimer.

Fabrication

VSRR structures with different feature sizes are fabricated using electron beam lithography with high precision alignment technology. A 200 nm-thick 495K PMMA (polymethyl methacrylate) layer was spin-coated at 4000 rpm on cover glass and then baked for 3 min at 180 ℃. The conductive polymer Espacer is then spin-coated at 1500 rpm

over the PMMA layer to avoid the charging problem during the e-beam exposure process. An ELS-7000 electron beam lithography system (Elionix Inc., Tokyo, Japan) is used for exposure with 100 keV acceleration voltage and 30-pA current. The position of the VSRR base rod was defined on the PMMA resist relative to the two 100-nm-thick gold cross alignment marks which were first fabricated on the substrate for precise alignment during e-beam exposure process. After exposure, the sample was rinsed with de-ionized water to remove Espacer, then developed in solution of methyl isobutyl ketone (MIBK) and isopropyl alcohol (IPA) of MIBK:IPA = 1:3 for 60 seconds, rinsed again, this time with IPA, for 20 seconds, and blow-dried with nitrogen gas. Once the development of the resist was completed, a gold film with designed thickness was thermally deposited on the sample, and the un-patterned regions were removed using a lift-off process. Subsequently, the two VSRR prongs were fabricated in a similar fashion by the second e-beam exposure and lift-off process. The area of each fabricated structure is 75 × 75 μm2 on a cover glass substrate.

Measurement and simulation

The spectra were measured by a self-assembled micro-spectrometer, and an inverted Olympus microscope IX-70 (10× IR objective with numerical aperture NA = 0.3, long working distance condenser with NA = 0.3, visible to near-infrared polarizer U68-750 from Edmoud Optics and 100W halogen light source) equipped with two spectrometer (BTC111E for λ = 400 nm to λ = 1000 nm with ~0.5 nm resolution and BTC261E for λ = 900 nm to λ = 1700 nm with ~5 nm resolution) from B&W Tek, Inc. All transmittance spectra were normalized by an un-patterned region of the cover glass substrate.

All simulation results were performed with the commercial software COMSOL Multiphysics by solving 3D Maxwell equations. Both isolated and coupled VSRR dimers are simulated with periodic boundary conditions under x-polarized light illumination. The refractive index of cover glass substrate is fixed at 1.51. The permittivity of gold in the near infrared regime is described by the Drude-Lorentz model with plasmon frequency ωp = 8.997 eV and damping constant Γp = 0.14 eV, which is two times larger than that of the bulk value because of the surface scattering and grain effects.

Summary

we have fabricated a series of metamolecules consisting of either isolated VSRRs or their coupled dimers with different SRR spacing using e-beam lithography with high precision alignment technique. These VSRR metamolecules have the advantage of direct coupling to both the electric and magnetic components of the normal incident wave in comparison to their planar counterpart that only interacts with the electric field, resulting in stronger magnetic response. By conducting simulation and measurement of the optical transmittance, we have observed hybridization between the magnetic plasmon modes associated with constituent VSRRs in a metamolecule where bonding and anti-bonding modes emerged. We have found that the energy separation between the bonding and anti-bonding modes in a metamolecule depends on the gap separation in VSRR dimers. The tuning capability enabled by the magnetic plasmon mode coupling can be explored for developing frequency selective functional devices.

References

[1] Maier, S. A.; Brongersma, M. L.; Kik, P. G.; Meltzer, S.; Requicha, A. A. G.; Atwater, H. A. Adv. Mater. 2001, 13, 1501-1505.
[2] Zheludev, N. I. Science 2010, 328, 582-583.
[3] Lin, J.; Mueller, J. P. B.; Wang, Q.; Yuan, G.; Antoniou, N.; Yuan, X.-C.; Capasso, F. Science 2013, 340, 331-334.
[4] Chen, W. T.; Yang, K.-Y.; Wang, C.-M.; Huang, Y.-W.; Sun, G.; Chiang, I. D.; Liao, C. Y.; Hsu, W.-L.; Lin, H. T.; Sun, S.; Zhou, L.; Liu, A. Q.; Tsai, D. P. Nano Lett. 2013, 14, 225-230.