Nanoscale

Cite this: *Nanoscale*, 2012, **4**, 874

www.rsc.org/nanoscale

PAPER

More electromagnetic energy converged by the assembly of magnetic resonator and antennas

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Received 8th September 2011, Accepted 16th November 2011
DOI: 10.1039/c1nr11268f

The interaction of magnetic resonators connected by nano-antennas is studied for the first time. Compared to a simple magnetic resonator, the absorptance can be obviously much enhanced and more electromagnetic energy can be converged by the assembled magnetic resonator and nano-antennas (nano-strip). The nano-strip plays the role of both nano-antenna and phase tuner for propagating surface plasmon polaritons (SPPs). The interaction of localized surface plasmon resonance and propagating SPPs can remarkably be tuned by simply changing the width of nano-strips. When lattice coherence happens at the magnetic resonance, maximum enhancements of local field are achieved. This approach paves a new way for the design of a metamaterial based on magnetic resonators.

Introduction

Metamaterials are manufactured materials that exhibit properties not found in nature. Electromagnetic metamaterials affect electromagnetic waves by having structural features smaller than the wavelength of light.[1,2] They enable unprecedented properties such as negative index,[3,4] superlensing effect,[5,6] invisible cloak[7,8] and metamaterial antennas.[9,10] It is not only possible to design a metamaterial for a required purpose, but also to implement further adjustment capabilities at the level of assembly.[11] Especially the latter can lead to novel configurations and open a new way to manipulate light. For example, a left-handed material was successfully produced by combining the split-ring resonator with thin wire conducting posts.[3]

In this paper, a quasi-one dimensional structure of the metamaterial is designed by combining the magnetic resonator with nano-antennas (nano-strips) to enhance the local electromagnetic field while not changing the resonance wavelength. A magnetic resonator at the resonance wavelength can act as a local field concentrator focusing the electromagnetic energy. So there are two purposes for employment of nano-antennas connecting the magnetic resonators. One is to help collect more electromagnetic energy and transmit electromagnetic energy to magnetic resonator. Another is to work as a phase tuner. As the Bloch wave SPPs propagate through the artificial atoms and couple to localized surface plasmon (LSP) resonance of magnetic resonator, Bloch's theorem has to be obeyed. The strategy is to tune the width of nano-antennas which can change not only the lattice period but also the phase of Bloch wave SPPs between the neighboring atoms. The local magnetic and electrical field within the magnetic resonator is expected to be enhanced after the assembly of magnetic resonator and nano-antennas compared with a simple magnetic resonator.

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Structure

The structures of magnetic resonator and nano-antennas with detailed sizes are shown in Fig. 1a and 1b, respectively. The bottom of the magnetic resonator is a groove and the top is a nano-strip which is supported by a PMMA nano-strip. There is a gap between the top nano-strip and bottom groove. The quasi-one dimensional structure of the assembled metamaterial is

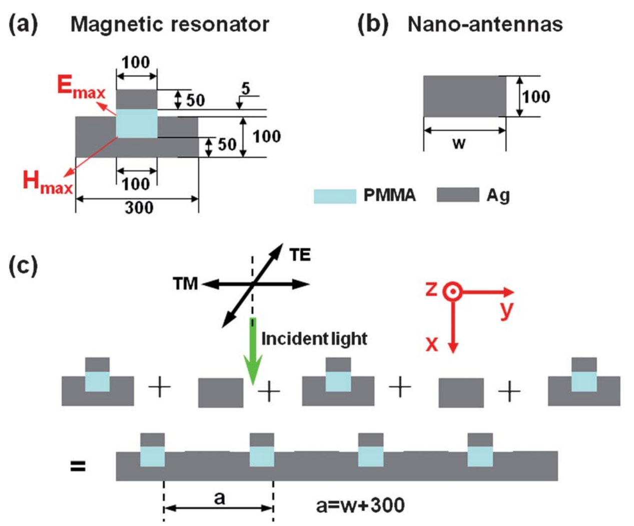

Fig. 1 (a) Cross-section view of a single magnetic resonator scaled in nm. (b) Cross-section view of nano-antennas scaled in nm. (c) Cross-section view of quasi-one dimensional nanostructure of the assembled metamaterial.

shown in Fig. 1c. The magnetic resonators are connected by nano-strips of different width w. The period is a ($a = w + 300$ nm). The laser is incident perpendicularly as shown in Fig. 1 and the transverse magnetic (TM) and electrical (TE) waves indicate that the laser polarization direction is vertical and parallel to the nano-strips of units respectively. Similar to the split-ring resonator,[12] the magnetic component of the TM wave induces the faradic current in the magnetic resonator which can counteract the external magnetic field, while the electric-field component of TM wave also induces the current due to the electric-field component normal to the plates of the capacitors (two side-faces of nano-strips, two inner and two outer side-faces of grooves), either giving rise to a magnetic dipole.[12] So the resonance arises from localized geometric plasmon resonance.

Calculated results and discussion

The high structure symmetry in the view of polarized incident plane wave reduces the dimensionality of the electromagnetic problem from 3D to 2D. The finite element method using commercial software (COMSOL Multiphysics) was used to simulate the spatial distribution of the electromagnetic fields in the cross section of the quasi-one dimensional metamaterial for normal-incidence illumination, and thus to compute the reflectance R and transmittance T. The absorptance A is equal to 1-R-T. The simulations with the element size less than 1 nm are performed by modeling the quasi-one dimensional metamaterial using periodic boundary conditions and a single resonator using perfectly matched boundary condition, respectively. The dielectric constant of PMMA is 2.226 and the wavelength-dependent complex dielectric constants of Ag are based on the experimental data of ref. 13.

For the single magnetic resonator, there is a broadband peak of absorptance at 1.282 μm for TM mode (Fig.2a, red curve labeled by M) caused by the resonance of magnetic resonator, while no absorptance peak and no magnetic resonance appear for the TE mode.[14] The model of standing-wave plasmonic resonances provides the relationship[15] $L = m\lambda_m/(2n)$, where L represents the entire length of the split-ring resonator, λ_m denotes the wavelength of the resonance mode m, and n is the refractive index of the surrounding medium. The structure of magnetic resonator is similar to the split-ring resonator, so we use the same formula to estimate the resonance wavelength. Since $m = 1$ is for a dipolar resonance, $n = 1.49$ for PMMA and $L \approx 0.45$ μm for the structure, the resonance wavelength is $\lambda_m \approx 1.34$μm for the magnetic resonator, which is in good agreement with simulated value $\lambda_m = 1.282$ μm. The magnetic dipole results in the huge local electric field appearing at the gap[16] between the top nano-strip and bottom groove while the huge local magnetic field enhancement appears within the groove. The magnetic field enhancement ($|H_Z|/|H_0|$) at the bottom inner corner of the groove (where the maximum magnetic field is; shown in Fig. 1a), and the electrical field enhancement ($|E|/|E_0|$) at 1 nm above the upper and inner edge of the groove (where the electric field is very near to the maximum; shown in Fig. 1a) at 1.282 μm for TM mode are 18.2 and 139.5, respectively (Fig. 2b and 2c, red curve labeled by M).

For the periodic structure, when the period is 1.0 μm, Fig. 2 also shows the wavelength dependence of absorptance, the magnetic field enhancement ($|H_Z|/|H_0|$) at the bottom corner of the groove and the electrical field enhancement ($|E|/|E_0|$) at 1 nm above the upper and inner edge of the groove at normal incidence for TM waves, respectively. The black curve is for the assembled nanostructure of resonator and antennas labeled by M + S, and red curve for the single magnetic resonator labeled by M. The absorptance peak corresponds to the magnetic resonance which leads to much enhancement of the local magnetic and electrical field and the absorbed energy provides the ohmic loss in the metal. So, $|E|/|E_0|$, $|H_Z|/|H_0|$ and absorptance have a broad peak at the same wavelength of 1.271 μm and 1.282 μm for black and red curves, respectively. After adding the nano-strips of width 0.7 μm, $|E|/|E_0|$ is 99% higher and $|H_Z|/|H_0|$ is 89% higher although the resonance wavelength has a small shift less than 1%. In all three black curves, $|E|/|E_0|$, $|H_Z|/|H_0|$ and absorptance, have a cusp at 1.0 μm except the big peak at about 1.271μm. The cusp at 1.0 μm is caused by the standing wave related to plasmon coherence caused by the periodic structure, *i.e.* Woods–Rayleigh anomaly (WA). For normal incident light, the free-space wavelength λ_{WA} that satisfies the WA condition is given by

$$\lambda_{WA} = ia\varepsilon_d^{1/2}$$

where i is the integer corresponding to the specific order of WA mode, a is the lattice constant and ε_d is the relative permittivity of the surrounding dielectric. Here ε_d is 1 for air and the order $i = 1$. So simply $\lambda_{WA} = a$.

Fig. 3 shows the magnetic field enhancement ($|H_Z|/|H_0|$), electric field enhancement ($|E|/|E_0|$) and power flow enhancement ($|S|/|S_0|$) in the cross section for normal-incidence illumination at

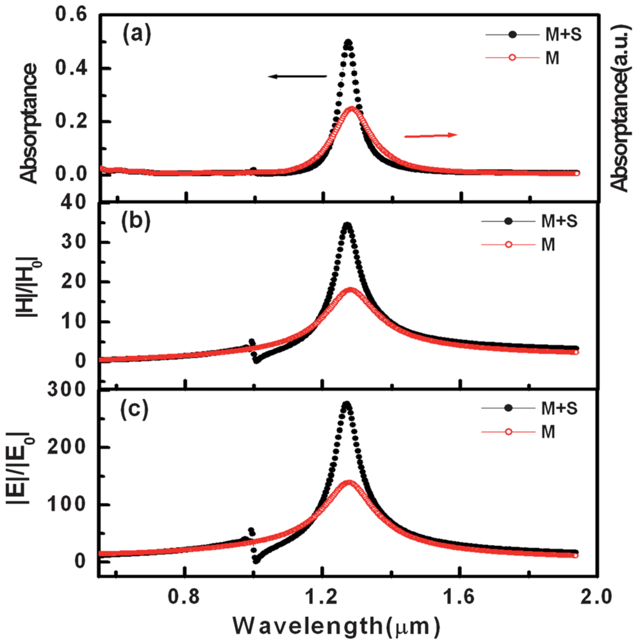

Fig. 2 The wavelength dependence of (a) absorptance, (b) magnetic field enhancement ($|H_Z|/|H_0|$) at the bottom corner of the groove and (c) electric field enhancement ($|E|/|E_0|$) at 1 nm above the upper and inner edge of the groove at normal incidence for TM waves when the period is 1.0 μm. M + S represents the assembled nanostructure of magnetic resonator and nano-strip, and M represents the single magnetic resonator.

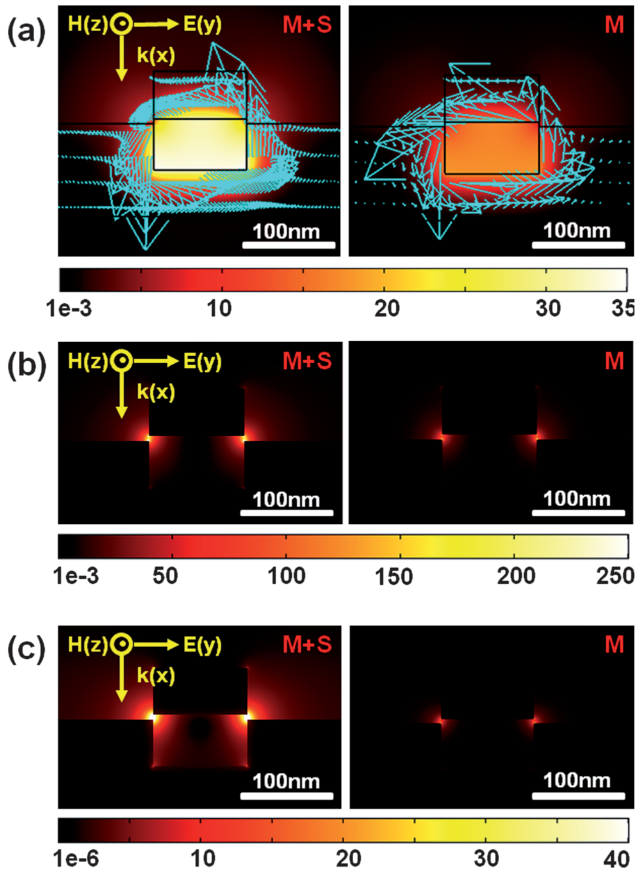

Fig. 3 (a) Magnetic field enhancement ($|H_Z|/|H_0|$), (b) electric field enhancement ($|E|/|E_0|$), (c) power flow enhancement ($|S|/|S_0|$) in the cross section for normal-incidence illumination at the TM mode at the resonance wavelength of 1.271 μm for the assembled nanostructure (left) with a period of 1.0 μm and 1.282 μm for the single magnetic resonator (right).

the TM mode at the resonance wavelength of 1.271 μm for the assembled nanostructure with a period of 1.0 μm (left) and 1.282 μm for the single magnetic resonator (right). The power flow is given by the time-average Poynting vector which depends on the product of electric and magnetic fields. Compared with the enhancement of electric field which is up to 280 in Fig. 3b, the maximum enhancement of the magnetic field is only 35 in Fig. 3a. Therefore, the power flow in Fig. 3c looks similar to the electric field enhancement in Fig. 3b. A huge enhancement of power flow appears at the gap and the power flowing through the gap into the groove is converged by the magnetic resonator, leading to the huge enhancement of the local magnetic and electrical field. It can be directly observed that more magnetic (Fig. 3a) and electric (Fig. 3b) energy is converged by magnetic resonance in the assembled nanostructure than the single magnetic resonator. The arrows in Fig. 3a are proportional to the current density J within the metal structure.

The simulation also shows that the optical property can be tuned by period. Fig. 4 shows the relative shift of absorptance peak $(\lambda_r - \lambda_{r0})/\lambda_{r0}$ (where λ_{r0} = 1.282 μm is the resonance wavelength of a single magnetic resonator), the maximum of absorptance, the maximum of $|H_Z|/|H_0|$ and the maximum of $|E|/|E_0|$ *versus* period for the assembled nanostructures, respectively. The wavelength of the absorptance peak corresponding to

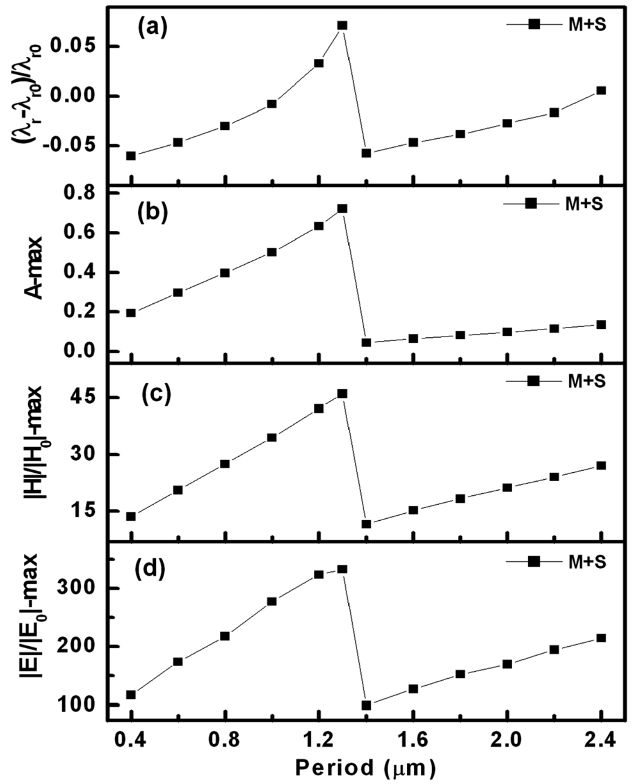

Fig. 4 (a) The relative shift of absorptance peak, (b) the maximum of absorptance, (c) the maximum of $|H_Z|/|H_0|$ and (d) the maximum of $|E|/|E_0|$ *versus* period, respectively.

the magnetic resonance is not very sensitive to the period and only has a moderate shift while the maximum of absorptance, the maximum of $|E|/|E_0|$ and the maximum of $|H_Z|/|H_0|$ can remarkably be tuned by period. They reach the maxima when the period is equal to or near to the resonance wavelength of the magnetic resonator, *i.e.* when plasmon coherence and resonance of magnetic resonator happen together. This assembled nanostructure takes full advantage of two types of surface plasmons, propagating surface plasmon polaritons and non-propagating LSPs. The oscillation relationship suggests that the interaction of the magnetic resonators through nano-antennas is sensitive to the phase due to the interaction of magnetic resonance and Bloch wave surface plasmon polaritons.

Two effects are observed after adding metal nano-strips between magnetic resonators. First the absorptance, $|E|/|E_0|$ and $|H_Z|/|H_0|$ are enhanced at the resonance wavelength, which indicates that the nano-strip as nano-antennas helps to collect and transport more electromagnetic energy to magnetic resonator. Secondly, the enhancement effect is more obvious when the period is increased near to the resonance wavelength of magnetic resonator. The periodic structure excites Bloch wave surface plasmon polaritons that can couple with local surface plasmons of the magnetic resonator, leading to the multiplicative enhancements and the energy enhancement factor $\beta = \beta_{Bloch}\beta_{LSP}$, where β_{Bloch} and β_{LSP} are enhancement factors associated with Bloch wave surface plasmon polaritons and localized surface plasmons of single magnetic resonator, respectively. It is well known that the wave vector of SPPs k_{spp} is given by

$$k_{\mathrm{spp}} = \frac{\omega}{\mathrm{c}}\left(\frac{\varepsilon_{\mathrm{d}}\varepsilon_{\mathrm{m}}}{\varepsilon_{\mathrm{d}}+\varepsilon_{\mathrm{m}}}\right)^{1/2}$$

where ε_{d} and ε_{m} are the relative permittivities of the surrounding dielectric and metal, respectively. For metal Ag, when the wavelength λ is within 1.0–2.0 μm and $\varepsilon_{\mathrm{d}} = 1$ for air, k_{spp} is within 1.010–1.003(ω/c), *i.e.* $k_{\mathrm{spp}} \approx k_{\mathrm{incident}} = k$. For a period structure, such as photonic crystal, the magnetic vector field $\vec{H}(\vec{r},t)$ satisfies the relationship by Bloch theorem,[17]

$$\vec{H}(\vec{r}+\vec{R}) = \vec{H}(\vec{r})\mathrm{e}^{\mathrm{i}\vec{k}\cdot\vec{R}}$$

where $\vec{R}$ is the lattice vector. The factor for nearest neighbor of the 1D lattice is e^{ika}. When lattice coherence happens at the resonance *i.e.* $a = 2\pi n/k = n\lambda_{\mathrm{resonance}}$, then $\mathrm{e}^{ika} = 1$ and no Bloch phase factor exists between the magnetic resonators. Thus all the resonators are coherent and the absorptance, $|E|/|E_0|$ and $|H_Z|/|H_0|$ reach the maxima. But near the maximum, there is a jump due to WA. As can be seen from Fig. 2, the line shape corresponding to absorptance, $|E/E_0|$ and $|H/H_0|$ of the narrow-band surface wave excitation (WA) arising from the periodicity of structure is asymmetric. The spectral overlapping of band LSP resonance of individual magnetic resonator and narrow-band WA leads to not only huge field enhancement but also asymmetric shapes of absorptance and field enhancement *versus* period, as shown in Fig. 4.

Our structure (strips on top of grooves) looks similar to the structure of Christ A (strips on top of a flat metal film).[18] But the optical properties are very different from each other due to the strong structure dependence of optical properties. The enhancement of electric field is very important for practical application of SERS (surface-enhanced Raman spectroscopy) and biosensors. The electric field enhancement that appears at the gap can be applied for SERS in our structure while the electric field of Christ's structure is enhanced between the strip and film which cannot be applied for SERS. In addition, in terms of physical function, our structure is an assembled structure of magnetic resonators and nano-antennas rather than the coupled structure of top nano-strips and bottom period grooves since the shift of resonance wavelength is small when connected with nano-antennas. As we know, magnetic resonance can be interpreted in terms of an inductor-capacitor (LC) circuit. Magnetic resonance leads to a low energy state which is similar to a low-energy plasmon well. The surrounding plasmons in the nano-antennas tend to fall in the well. So the magnetic resonator, which works as the local concentrator focusing the electromagnetic energy and nano-antennas connecting the magnetic resonators, not only help collect and transmit electromagnetic energy to the magnetic resonator but can also tune the phase of Bloch wave SPPs. The resonance, whether weakened or enhanced, depends upon the phase of Bloch wave SPPs which is tuned by changing the width of the antennas and the antennas can be called a phase tuner. Therefore, our structure is very different from Christ's structure and the other previous structures.

We didn't change the geometrical parameters of magnetic resonator, such as the width of the top nano-strip, since the magnetic resonance wavelength strongly depends on the width of top nano-strip (it is 100 nm in our structure, as shown in Fig. 1a). We only change the width of antennas W (shown in Fig. 1b) which leads to the change of the period since period = 300 nm + W (shown in Fig. 1c) and the corresponding results are shown in Fig. 4. The focus of this paper is to give a way to enhance the magnetic/electric field while keep the resonance wavelength almost unchanged since it is very important for structure design for practical application. As we know, it often happens in structure design that when some geometrical parameter changes, the field is enhanced but the corresponding resonance wavelength is also unexpectedly much changed.

The fabrication of this structure is not complicated and three steps are needed. (1) The substrate is coated by Ag film. (2) PMMA gratings are prepared by EBL (electron beam lithography) on the top of the Ag film. (3) After coating with a suitably thick Ag film (the thickness of Ag film must be less than the thickness of PMMA), the structure is obtained and its parameters are controlled by the geometrical parameters of PMMA gratings and the thickness of Ag film.

The practical function of nano-antennas is very obvious. Here, by tuning the width of nano-strips, such as from 100 nm to 900 nm, *i.e.* the period changing from 400 nm to 1200 nm, the maximum of absorptance, the maximum of $|E|/|E_0|$ and the maximum of $|H_Z|/|H_0|$ can be enhanced more than three times while the absolute shift of magnetic resonance wavelength is less than 6% compared with the single magnetic resonator. As we know, in practical applications, such as SERS and biosensors, the strategy is attractive and useful if the absorption and the magnetic/electric field are enhanced while keeping the resonance wavelength almost unchanged. Our results show that it is an effective method to use nano-antennas to help a magnetic resonator collect more electromagnetic energy. The assembly of magnetic resonator and antennas paves a new way for the design of metamaterials based on magnetic resonators, in particular, which is very attractive for the highly demanded local field enhancement, such as SERS. The SERS enhancement factor due to electromagnetic contribution, to a first approximate, is proportional to $|E|^4/|E_0|^4$.[19] For this assembled structure, the maximum electrical field enhancement at the "hot line" can reach more than 330 when the period is 1300 nm. Therefore, the SERS enhancement factor is more than 10^{10}. It is very attractive to the practical design for extremely sensitive and reproducible substrates of SERS. This complex structure is very different from the conventional structures for SERS, which pay much attention to the small structures with small gaps such as metal colloids whose limited stability and reproducibility often limit their practical application.[20,21]

Conclusions

A quasi-one dimensional metamaterial assembled by magnetic resonator and nano-antennas is designed. The interaction of magnetic resonators can be tuned through Bloch wave SPPs by changing the period or the width of nano-strips. Although the resonance wavelength isn't very sensitive to the period, the local electrical and magnetic field focused by magnetic resonance can remarkably be tuned by the period. They reach the maxima when plasmon coherence and resonance of magnetic resonator happen together. It suggests that the interaction of the magnetic resonators is sensitive to the phase due to the interaction of magnetic resonance and Bloch wave SPPs. Significantly more electromagnetic energy can be converged by adding nano-strips while the nano-strips play the roles of both nano-antennas and phase tuner. This approach paves a new way for the design of metamaterial based on magnetic resonators and development of its application.

Acknowledgements

This work was supported by National Science Foundation of China (Grant No.61178047).

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