Coupling effects in low-symmetry planar split-ring resonator arrays

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We introduce a particular low-symmetry (point group of unit cell C_1) planar periodic arrangement of magnetic split-ring resonators that acts as an effective optical wave plate. We show that this behavior specifically results from the in-plane interactions among the individual split-ring resonators. Measured normal-incidence transmittance and conversion spectra of gold-based samples fabricated via electron-beam lithography show fundamental resonances at around 235 THz frequency (1275 nm wavelength) that are in good agreement with theory. © 2009 Optical Society of America

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Metallic split-ring resonators (SRRs) [1] can be viewed as resonant subwavelength electromagnets. They may, e.g., serve as magnetic dipoles oscillating at optical frequencies in magnetic and/or in negative-index photonic metamaterials [2–4]. In this context, as a first approximation, it is often reasonable to assume that the SRRs in a periodic array experience only little interaction with their neighbors. However, previous theoretical work [5] as well as experiments [6–8] at optical frequencies has already shown that the mutual interaction, e.g., brought about by a magnetoinductive coupling [5] among the SRRs, can be a significant correction.

In this Letter, we introduce a particular low-symmetry planar periodic arrangement of SRRs that is distinct from usual periodic SRR arrays. We show that the resulting polarization behavior is that of an effective wave plate. We also show that this effect specifically stems from the in-plane SRR interactions.

Figure 1(a) shows a usual periodic square lattice of equally oriented magnetic SRRs [9]. The unit cell contains a single SRR and has onefold rotational symmetry and one vertical mirror plane. Hence, the corresponding point group is C_{1v}. For horizontal polarization of the incident light, the fundamental magnetic mode of the SRR can be excited [9]. The arrangement shown in Fig. 1(b) is different from (a) and is the subject of this Letter. Clearly, this structure (b) with four SRRs in its unit cell has only one onefold rotational axis and no vertical mirror planes. The point group of the unit cell is C_1.

What optical response do we expect? For the sake of gedankenexperiment, we assume strictly zero interaction among the SRRs. In this case, the unit cell composed of four individual SRRs shown in Fig. 1(b) can easily be decomposed into two different parts (with two equally oriented SRRs each) that are indicated by red and blue. By symmetry, the optical response of the "blue" part for horizontal (vertical) incident polarization is identical to that of the "red" part for vertical (horizontal) polarization. We can conclude that (without interaction), for the combined structure with four SRRs in one unit cell, the optical response will be strictly identical for horizontal and vertical polarizations. Furthermore, the linear polarization will be strictly maintained upon transmission for both polarizations. In particular, the combined structure will clearly *not* act as a wave plate for either horizontal or vertical incident polarization of light in the absence of SRR interactions.

Next, we show that our experiments reveal a completely different behavior. An electron micrograph of a typical part of one of the investigated samples is shown in Fig. 2(a). All samples are made on glass substrate coated with a 5 nm thin film of indium tin oxide (ITO) using standard electron-beam lithography, electron-beam evaporation of the gold film, and a subsequent lift-off procedure. The gold thickness is 50 nm, the unit cells are arranged in a square lattice with lattice constant $a=480$ nm, and the sample footprint is 80 μm $\times$ 80 μm. For the dimensions of Fig. 2(a), the fundamental magnetic resonance of the SRR lies at around 235 THz frequency, as determined

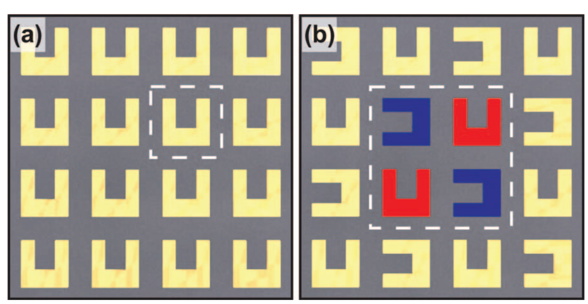

Fig. 1. Scheme of (a) a usual SRR array, (b) the particular low-symmetry arrangement discussed in this Letter. The dashed white lines highlight one unit cell. The decomposition of (b) into the blue and red parts illustrates that by symmetry—without SRR interactions—the array has identical optical properties for horizontal and vertical incident polarizations, respectively. No polarization conversion is expected under these conditions.

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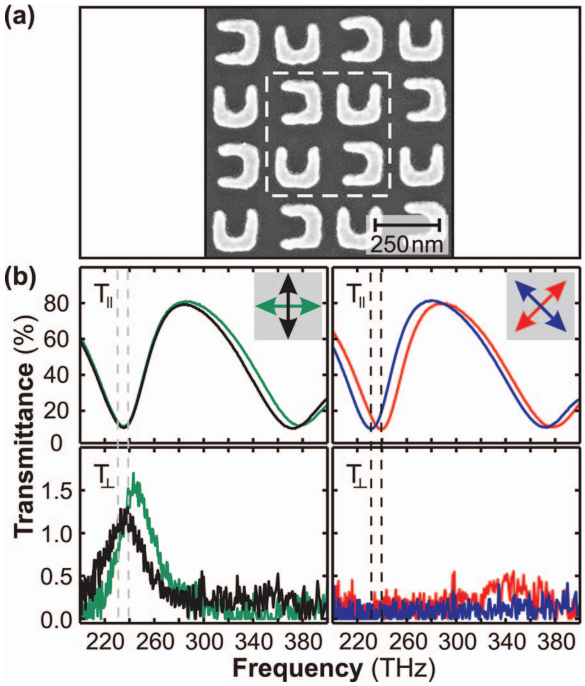

Fig. 2. (a) Electron micrograph of a representative region of one of the samples investigated. (b) Measured normal-incidence transmittance spectra T. $T_{\perp}$ (conversion) and $T_{\parallel}$ refer to detecting the component perpendicular and parallel to the incident linear polarization behind the sample, respectively. The four different linear incident polarizations along the horizontal (green), the vertical (black), and the two diagonals (red and blue) are shown.

from independent spectroscopic measurements on usual SRR arrays (not shown) [9]. Figure 2(b) shows normal-incidence transmittance spectra for four different linear incident polarizations: along the horizontal, the vertical, and along the two diagonals. An additional polarizer behind the sample allows for measuring the components parallel ($T_{\parallel}$) and perpendicular ($T_{\perp}$) to the incident linear polarization, respectively. It becomes obvious that horizontal or vertical linear incident polarization leads to very substantial polarization conversions (i.e., $T_{\perp} \neq 0$). In contrast, no significant conversion is found at all for incident polarization along either one of the two diagonals. The noise floor is identical for the case without any metamaterial sample. Yet, the resonance positions are different for the two diagonals [see the two dashed black vertical lines in Fig. 2(b), right-hand side]. This behavior is clearly that of a wave plate with its two different principal axes along the two diagonals. As argued in the above gedanken-experiment, however, such behavior is *not* expected for noninteracting SRRs. We can conclude that the observed behavior originates specifically from the SRR interactions.

One might argue that the experimental result could be an artifact of sample imperfections. To rule out such artifact and to further support our interpretation of the experimental data, we have performed additional numerical calculations. We use a commercial finite-element program package (COMSOL Multiphysics) and choose the geometrical parameters as illustrated in Fig. 3(a). As usual, the gold permittivity is described by the Drude model plus a background dielectric constant of $\epsilon_b = 9.07$. We choose a plasma frequency of $\omega_{\text{pl}} = 2\pi \times 2108$ THz and a collision frequency of $\omega_{\text{col}} = 2\pi \times 24$ THz. The refractive index of the glass substrate is taken as $n_{\text{SiO}_2} = 1.45$; the thin ITO film is neglected. The calculated normal-incidence transmittance spectra depicted in Fig. 3(b) nicely reproduce the experiments [Fig. 2(b)]. In particular, both the spectral resonance positions as well as the conversion behavior are reproduced, indicating an intrinsic effect indeed. We note that the parameter set used in Fig. 3 is not critical at all. In particular, the center-to-center SRR spacing in relation to the SRR size—which mainly determines the strength of the SRR interaction—is rather quite typical for photonic metamaterials (see, e.g., [2–4,9]).

To further support our interpretation in terms of the SRR interactions, Fig. 4 shows snapshots of the calculated axial component of the magnetic field B_z in the plane cutting through the middle of the gold SRRs as false-color plots. The parameters correspond to those of Fig. 3. For the two diagonal incident polarizations (the two principal axes as argued above), this behavior leads to two different eigenmodes: a high-frequency symmetric mode in which all four SRRs in the unit cell oscillate in phase and a low-frequency antisymmetric mode for which one pair of SRRs oscillates with 180° phase shift with respect to the other pair in the unit cell. A snapshot of the latter mode resembles an antiferromagnetic behavior. The frequency splitting between these two modes (8 THz) is a measure of the coupling among the SRRs. The

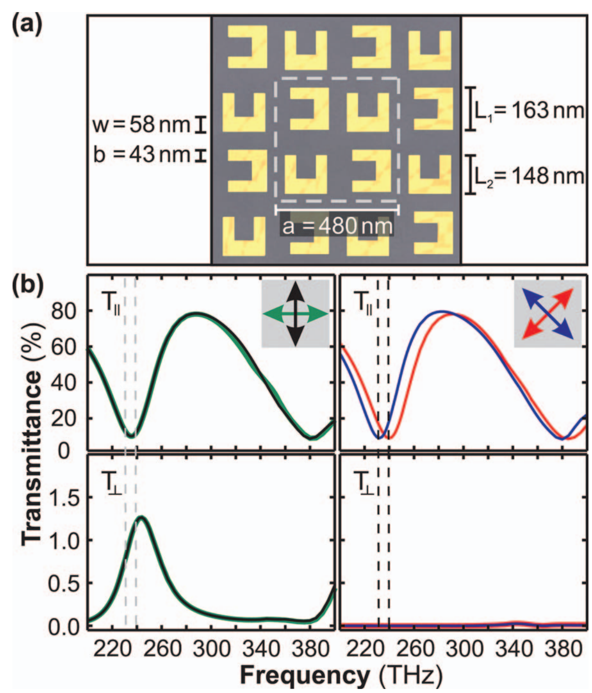

Fig. 3. (a) Definition of the geometry assumed in our numerical calculations [compare with experiment in Fig. 2(a)]. Gold thickness is 50 nm. (b) Calculated normal-incidence transmittance spectra that can directly be compared with the experiment in Fig. 2(b). The dashed vertical lines indicate the two frequencies for which Fig. 4 shows field distributions.

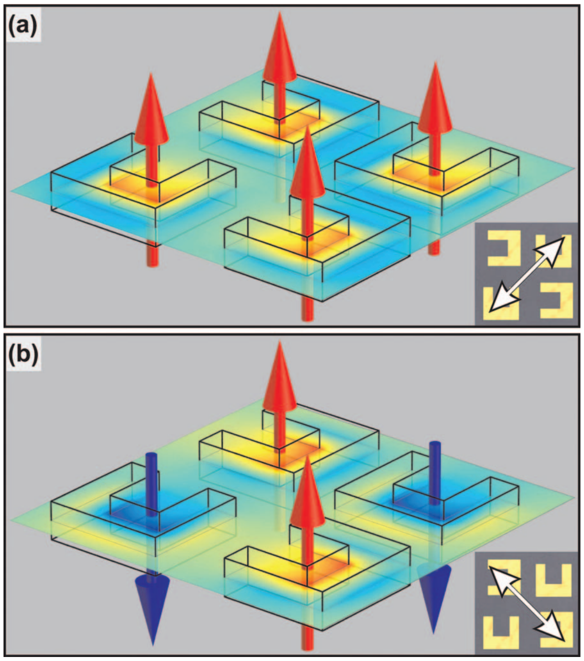

Fig. 4. Snapshots of the axial magnetic component B_z in an xy plane cutting through the middle of the SRRs (red = positive, green = zero, blue = negative). The incident polarization is along either of the two diagonals (see white arrows). (a) 240 and (b) 232 THz frequencies [these two frequencies are highlighted by the two dashed black vertical lines in Fig. 3(b)]. Parameters are as in Fig. 3.

splitting is about 3.4% of the mean center frequency of 236 THz, indicative of fairly strong coupling.

One mirror plane in our structures has clearly been omitted by the presence of the glass substrate. In additional calculations without any substrate (not shown) we find a similar overall behavior, yet shifted in frequency owing to the different dielectric environment.

Finally, one might be tempted to believe that the SRR interaction is short range and restricted to nearest neighbors. In contrast, recent work on pairs of spherical gold nanoparticles [10] indicates a long-range and retarded interaction.

In conclusion, we have fabricated particular low-symmetry periodic arrays of SRRs. The measured optical spectra are those of a wavelength-dependent optical wave plate. We have argued by symmetry that this behavior is not expected at all in the absence of SRR interactions. Thus, this behavior specifically arises from the interactions among SRRs. Numerical calculations agree well with experiment and support our reasoning.

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References

1. J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, IEEE Trans. Microwave Theory Tech. **47**, 2075 (1999).
2. V. M. Shalaev, Nat. Photonics **1**, 41 (2007).
3. C. M. Soukoulis, S. Linden, and M. Wegener, Science **315**, 47 (2007).
4. K. Busch, G. von Freymann, S. Linden, S. F. Mingaleev, L. Tkeshelashvili, and M. Wegener, Phys. Rep. **444**, 101 (2007).
5. E. Shamonina and L. Solymar, J. Magn. Magn. Mater. **300**, 38 (2006).
6. G. Dolling, M. Wegener, A. Schädle, S. Burger, and S. Linden, Appl. Phys. Lett. **89**, 231118 (2006).
7. N. Liu, H. Guo, L. Fu, S. Kaiser, H. Schweizer, and H. Giessen, Nature Mater. **7**, 31 (2008).
8. N. Liu, S. Kaiser, and H. Giessen, Adv. Mater. **20**, 4521 (2008).
9. C. Enkrich, M. Wegener, S. Linden, S. Burger, L. Zschiedrich, F. Schmidt, J. Zhou, T. Koschny, and C. M. Soukoulis, Phys. Rev. Lett. **95**, 203901 (2005).
10. P. Olk, J. Renger, M. T. Wenzel, and L. M. Eng, Nano Lett. **8**, 1174 (2008).