Diffractive coupling in metamaterial arrays studied by terahertz nearfield imaging

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Abstract

We experimentally study coupling in planar metamaterial systems consisting of periodically arranged split-ring resonators (SRRs) by terahertz (THz) near-field imaging. For appropriate lattice periodicities the SRRs couple via their diffracted fields leading to an avoided crossing in their transmission spectra. Our measured electric and magnetic field maps of the resonant modes in the SRR arrays reveal hybridization between the plasmonic resonance and the lattice mode in this diffractive coupling regime.

1. Introduction

Metamaterials typically consist of periodically arranged subwavelength structures, which show a strong resonant response to an incident electromagnetic field. While initially the individual sub-units have been treated as independent resonators, recent studies recognized the importance of inter-resonator coupling in metamaterials for a comprehensive understanding of its electromagnetic response, as well as representing a powerful possibility to tune strength, frequency and q-factors of its resonances [1, 2, 3]. In this paper we systematically study coupling between the constituents in planar SRR arrays by variation of their periodicities. While previous studies were mainly focussed on far-field properties of such arrays, i.e. their far-field transmission spectra, we are able to correlate these spectra with experimentally obtained maps of the electric and magnetic near-fields.

2. Plasmonic eigenmodes and lattice modes

In a SRR-based metamaterial an incident electromagnetic wave polarized perpendicular to the gap in the SRRs can excite odd plasmonic eigenmodes of the SRRs, which occur at frequencies that scale with the size of the structures. These resonance frequencies can be estimated to a good approximation by

$$\nu \approx n \cdot \frac{\tilde{c}}{2l}\ , \quad n = 1, 3, 5... \tag{1}$$

where l is the length of the unfolded SRR, corresponding to the resonator length, and $\tilde{c}$ the speed of light in the surrounding medium/substrate. Furthermore, in a rectangular array diffractive lattice modes are excited at frequencies which obey [3]

$$\nu^2 = i^2 \left(\frac{\tilde{c}}{g_x}\right)^2 + j^2 \left(\frac{\tilde{c}}{g_y}\right)^2\ , \tag{2}$$

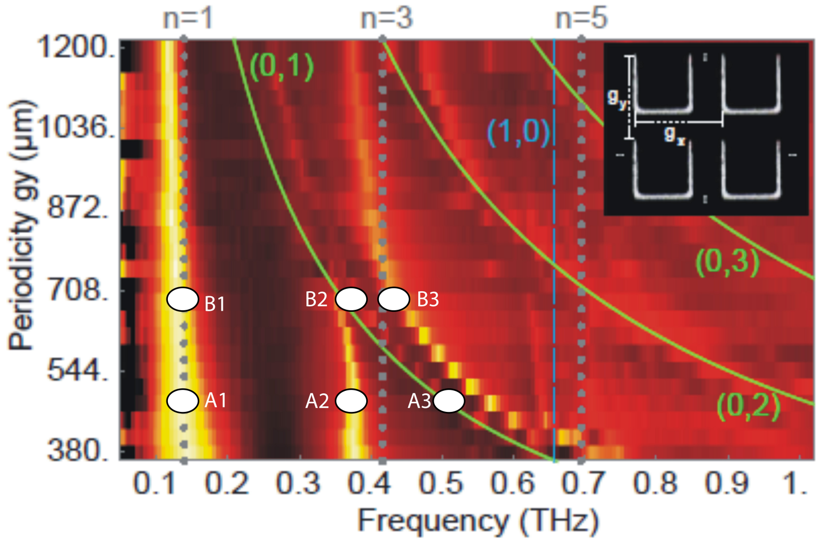

Fig. 1: Measured transmission spectra through arrays of SRRs with different lattice periodicities in y-direction ($g_y = 380 - 1200\mu$m) and constant $g_x = 380\mu$m.

where g_x and g_y are the lattice periods in x- and y-directions and (i, j) is a pair of integers counting the diffraction order.

Figure 1 shows transmission spectra of U-shaped SRR arrays, as shown in the inset, with different g_y periodicities. The vertical dotted lines mark the calculated frequencies of the eigenmodes of the SRRs according to Eq. (1), the green lines the different lattice modes determined from Eq. (2). By changing the lattice periodicity a lattice mode can be tuned to coincide with a SRR eigenmode, leading to enhanced radiative coupling indicated by an avoided crossing and a significant spectral line-narrowing [3]. In our example in Fig. 1 this occurs at the intersection between the third order plasmonic (n=3) and the (0,1)-lattice mode. In this diffractive coupling regime hybridization between both modes is expected [4].

3. THz near-field measurements

In order to verify hybridization of electromagnetic modes we measured the resonant near-fields of two different SRR arrays in the weak (A) and the strong (B) coupling regime, indicated by the white circles in Fig. 1. For our study we utilize THz near-field microscopy, which represents a novel and powerful tool for mapping electric and magnetic near-fields close to sub-wavelength resonator structures [5]. In Fig. 2 we show the measured electric (arrows) and magnetic field distribution (colors) of two different arrays of U-shaped SRRs with lattice periodicities $g_y = 487\mu$m (A) and $g_y = 700\mu$m (B); $g_x = 380\mu$m in both cases. Field maps are shown for three different frequencies at the marked spectral positions in Fig. 1. At 165 GHz the LC-resonance with a circulating current in each SRR associated with a magnetic dipole oscillating perpendicular to the sample plane is observed for both lattice periodicities (A1 and B1). At 390 GHz for the smaller lattice periodicity (A2), one can clearly identify the n=3 resonance as an electric quadrupole with corresponding four-fold magnetic field pattern, centered on each SRR [5]. The resonance at 450 GHz (A3) corresponds to the standing wave pattern of the (0,1)-lattice mode, showing almost no dependence on the resonator structure. This is also expressed in the 2D Fourier transforms of the magnetic field patterns shown in the insets, which reflect the modal patterns' spatial periodicity. While (A2) follows the periodicity of the SRRs, both in x- and y-directions, (A3) is only periodic along the y-axis ((0,1)-direction). Hence, (A2) and (A3) are basically uncoupled modes as expected in this weak coupling regime. On the other hand, the two corresponding modes in the strong coupling regime

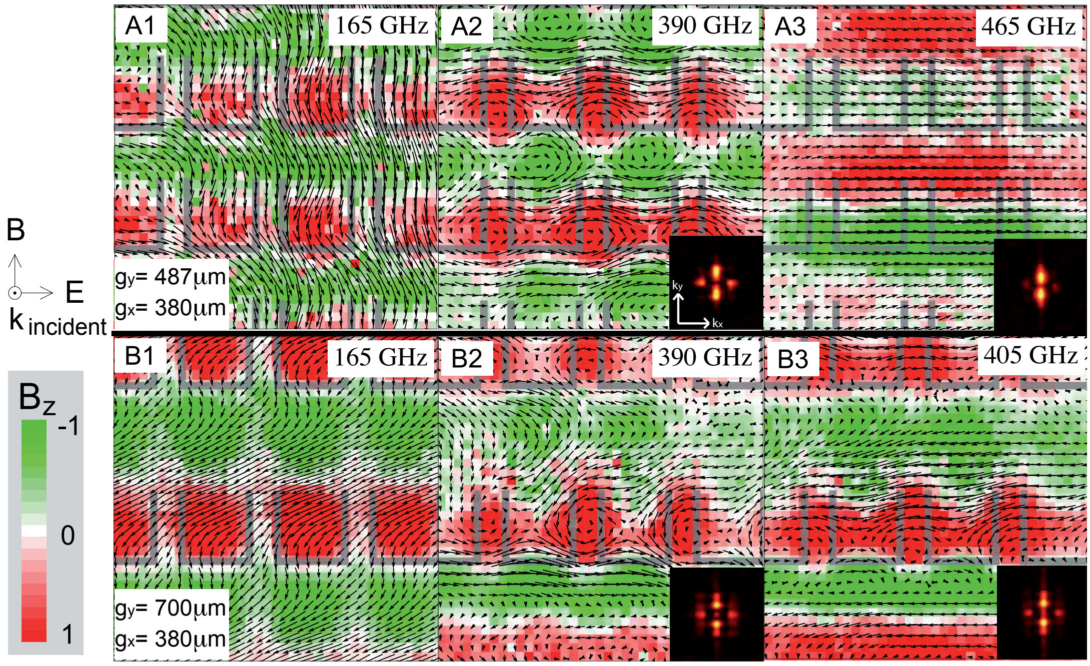

Fig. 2: Measured in-plane electric (vectors) and out-of-plane magnetic near-fields (colors) at the resonance frequencies of two SRR arrays with different lattice periodicities g_y. The insets show the corresponding spatial 2D Fourier-transforms of the magnetic field maps.

(B2) and (B3) are significantly mixed, as the result of mode hybridization. This can be clearly seen in their 2D Fourier transform plots which correspond in both cases to the superposition of the plasmonic (A2) and the lattice mode (A3).

4. Conclusion

In summary, we show here the existence of plasmonic/lattice hybrid modes in planar metamaterials by THz near-field microscopy. Our approach also allows to study next neighbour dipole-dipole coupling in densely packed SRR arrays, which will provide, in combination with the reported results, a comprehensive microscopic picture of coupling between meta-atoms.

References

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