Radiative Coupling in Planar Metamaterials Studied by THz Time-Domain Spectroscopy

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Abstract: We employ near- and far-field measurements of single-cycle THz pulses and numerical simulations to investigate the influence of diffraction in metamaterial arrays. We find that radiative coupling leads to substantial modifications of the spectral response.

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1. Introduction

Metamaterials have been a topic of considerable interest in recent years due to previously unanticipated electromagnetic phenomena such as negative refractive indices [1], perfect lensing [2], or invisibility cloaking [3]. These man-made structures typically consist of periodically arranged metallic elements with sub-wavelength dimensions which show resonant electric and magnetic responses to an incoming light field. One of the most prominent examples is an array of metallic rings with a gap, so called split-ring resonators (SRRs) [4]. These SRRs exhibit several resonances of increasing order where a combination of charge accumulations and current flows are excited on the structure [5]. The periodic arrangement of the elements may effectively act as a grating so that diffraction effects [6] play a crucial role for the understanding of the metamaterial's spectral response.

Here we study these effects in detail using two different experimental approaches. In the first part using THz time-domain spectroscopy (THz TDS) [7] and numerical simulations we show that coupling between the grating and the split-ring modes leads to a pronounced anti-crossing behavior resulting in a remarkable increase of the resonances' quality factors. Choosing appropriate geometries therefore allows one to control the spectral position, line width, and mode character of the resonances and thus customize the metamaterial. In the second part we employ a THz polaritonic approach [8] to directly visualize the interaction of the lattice modes with the SRR arrays. The waveforms can be measured with sub-wavelength and sub-picosecond precision within a volume around the metamaterial that is several tens of wavelengths in size, thus, allowing us to directly monitor the spatiotemporal near- to far-field transition. Our results show that single-cycle THz pulses transmitted through or reflected from the SRR arrays feature periodic modulations which are assigned to near-field interference of the different diffraction orders.

2. Coupling between split-ring and lattice modes

We fabricated sets of U-shaped SRR arrays as shown in the inset to Fig. 1(a). Whereas the periodicity along the *x* direction was kept constant the periodicity along the *y* direction was changed in steps.

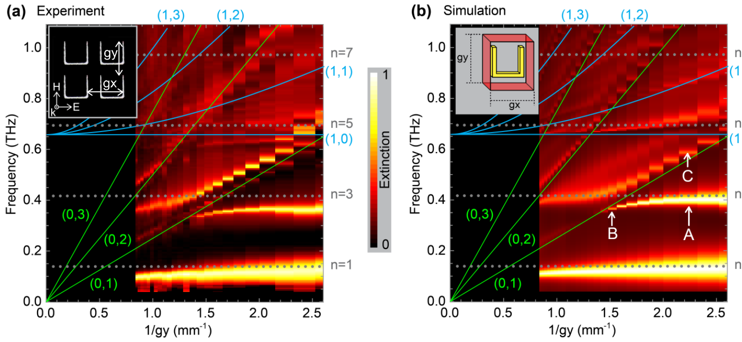

Fig. 1. Dispersion diagram obtained from (a) measurement and (b) simulation. The lattice constant gy is varied in steps while gx is kept constant. The dotted grey lines mark the resonances of the SRRs and green and blue lines indicated the lattice modes. Points A and C mark a pure split-ring and a pure lattice mode while point B marks the strong coupling regime.

The transmission through the samples has been analyzed using fs laser based THz TDS and the spectral evolution is shown in Fig. 1(a) as a function of the reciprocal *y* lattice constant. In these dispersion diagrams the dotted horizontal lines mark the resonance frequencies of the split-ring structures obtained from a simple antenna model stating that resonances occur when odd multiples of half the wavelength match the wire length of the unfolded

SRR. The solid green and blue lines indicate the various lattice modes which correspond to transmission minima due to Wood anomalies [9] where certain frequency components are diffracted into the sample plane. At those regions where the split-ring and lattice modes meet we observe a pronounced anti-crossing accompanied by a remarkable sharpening of the SRR modes. This is explained through strong radiative coupling between the elements mediated by the lattice modes. Our experimental observations are confirmed by finite element simulations [10] as shown in Fig. 1(b).

3. Near- to far-field transition of THz pulses propagating through planar metamaterial arrays

Using a THz polaritonic approach [8] based on an amplified fs laser system we are able to monitor the spatio-temporal evolution of broadband THz pulses interacting with metamaterial arrays. A typical image of a THz waveform recorded approximately 25ps after the reflection from a SRR array is shown in Fig. 2(a).

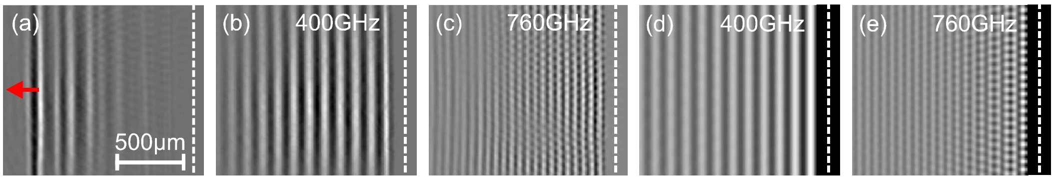

Fig. 2. (a) Broadband measurement of a THz wave after being reflected from a SRR array (dashed line). The arrow marks the propagation direction. Spatial distribution of the 400 GHz and 760 GHz frequency components obtained from the measured datasets (b),(c) and from a calculation assuming a linear array of 30 point sources positioned on the dashed line (d),(e).

The waveform consists of a main oscillation cycle followed by a slowly decaying temporal ringing which is a direct signature of the SRRs' resonant response to the incident field. The reflected signal also features inclined periodic modulations with wavelengths much shorter than the estimated length of the main oscillation cycle. Since our datasets are composed of two spatial and one temporal dimension we can apply a Fourier transformation for each spatial pixel to obtain the electric field distribution at exclusive frequency components as shown in Fig. 2(b) and (c). Whereas at 400GHz the field distribution corresponds to a rather plane wave it exhibits a more complex pattern at 760GHz featuring periodic modulations. We have additionally calculated the electric field distribution resulting from a linear array of 30 point sources as shown in Fig. 2(d) and (e) and obtain excellent agreement with the measurement. For the given periodicity and a frequency of 400 GHz the effective grating supports only the 0th diffraction order. For 760 GHz, however, the observed field distribution corresponds to the near-field interference pattern of the 0th and ±1st diffraction orders. One can see that the further the THz wave propagates to the left, the more it evolves into a plane wave since the diffracted components leave the image region. The near- to far-field transition is therefore dominated by the interference of the different diffraction orders at higher frequencies.

4. References

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