Engineering resonances in THz metamaterials

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Abstract

We review our recent activities on THz metamaterials and disclose the measures that can be put in place in order to engineer the quality factor of their resonances. This leads to a systematic investigation on the impact of the intrinsic material properties but also, and most notably, on the impact of a long and short range interaction among the meta-atoms of the metamaterial; leading ultimately to such effects that bear analogies to electromagnetically induced transparency

1. Introduction

Metamaterials are usually described as an artificial media consisting of unit cells, called the meta-atoms, much smaller than the wavelength of the electromagnetic fields for which they are designed. Local effective properties can usually be assigned to the medium since only the scattering response of an external illumination at a particular point in the lattice causes a resonance response and contributes by such means to the overall properties of the metamaterial. The scattering response of the individual element is characterized by its resonance frequency, an oscillator amplitude and a damping parameter. The latter can be recast as to have various physical meanings, e.g. it may be understood as the line width of the resonance or, more generally, its quality factor. Generally speaking, the quality factor is measure to estimate how many optical cycles an excitation undergoes before it eventually dissipates. The quality-factor is usually dictated by losses which may be of radiative or non-radiative nature. Radiative losses tell us how good the excited state can couple to propagating modes of free space that carry the energy away from the particle; whereas non-radiative losses are dictated by the intrinsic absorption of light in any involved material. Starting from the resonance properties of this single element it can be usually safely concluded that the metamaterial itself will largely reflect the same resonance properties since it is presumed to be a local medium with no or only negligible interaction in the lattice.

Contrary to such argumentation, we outline here that the resonance properties of the metamaterial are not just the result of the scattering properties of the individual elements but it can be modified by various means. We outline strategies to lower the intrinsic absorption of light by relying on superconductive materials but we also show that the resonance properties of the entire metamaterial are strongly affected by the extraordinary interaction of the meta-atoms in the lattice. Such interaction

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may be far reaching; which nullifies the assumption on a local response and questions the feasibility of local effective properties. As we will show, the interaction may be of more obvious nature for closely spaced unit cells, where a strong near-field mediated interaction eventually causes effects that bear analogies to electromagnetically induced transparency. But we also disclose a far-field interaction which is strongly mediated by lattice modes.

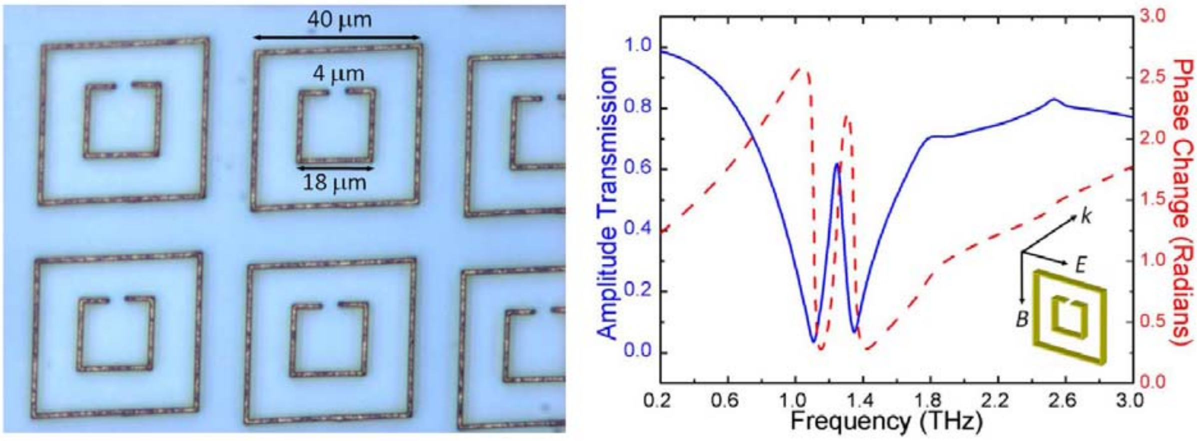

Fig. 1: Prototypical unit cell of a THz metamaterial to investigate effects that can be understood in analogy to electromagnetically induced transparency. The unit cell consists of two individual resonant elements, i.e. a split-ring resonator and a ring resonator. The sample is illuminated at normal incidence with the incident electric field being polarized parallel to the gap. The geometry of both constituents of the unit cell is carefully designed such that they possess their lowest order resonance at the same frequency, i.e. 1.2 THz. The ring resonator has an electric dipolar resonance which is fairly broad. The meta-atom is understood as to be the bright resonance since it couples well with free-space radiation. The split-ring resonator has a magnetic dipolar resonance (oriented normal to the surface) which is fairly narrow. The meta-atom is understood to be the dark mode since it couples less efficient with free space radiation. By quantifying the spectral response of both elements individually, the formation of a dip in transmission at the resonance frequency is witnessed. By combining the elements into a single unit cell, however, a largely enhanced transmission can be seen that lead to a narrow peak. This can be seen in the left of the figure. The large transmission is accompanied by a rapid variation of the transmitted phase; leading to huge group indices while damping of the propagating field is low.

2. Methods

Our work is performed at THz frequencies for two reasons. The first is of rather technical nature and is linked to the ability to fabricate metamaterials at THz frequencies with standard microfabrication technologies with an extraordinary precision. This is most notably beneficial while adjusting the very precise coupling conditions among adjacent entities. Moreover, spectral properties of metamaterials at THz frequencies can be measured conveniently in amplitude and phase; an ability less evolved at higher frequencies, e.g. in the visible. The second is of an application driven nature and is linked to the perspective use of THz metamaterials in sensing devices for various applications. There, most notably, high quality resonances are required to enhance the overall efficiency of the application.

Experimentally we fabricated most of the structures we present here with photolithographic techniques. Films made of various materials with a thickness that is usually in the order of a few hundreds of nanometers were deposited on n-type silicon substrates and the relevant meta-atoms were suitably inscribed. As unit cells we have been considering in most cases split-ring resonators. Such elements can be understood as sufficiently well characterized and the interpretation in the individual elements no more constitutes a major challenge. For the optical characterization of the samples in transmission we rely on a 8*f* confocal photoconductive switch based terahertz time domain spectroscopy system consisting of a terahertz transmitter, beam collecting and steering optics, and a terahertz receiver. The set-up allows to measure time resolved the transmission of an incident THz pulse through a sample. Fourier transforming the signal and normalizing it to the transmission through a plain substrate allows accessing the complex transmission. All experimental results are verified by numerical simulations which are usually performed with the Fourier Modal Method. Selected examples of the structures under investigation, along with experimental results from the characterization and a discussion of the effect we have been studying with these samples are shown in Fig. 1-2 [1-4].

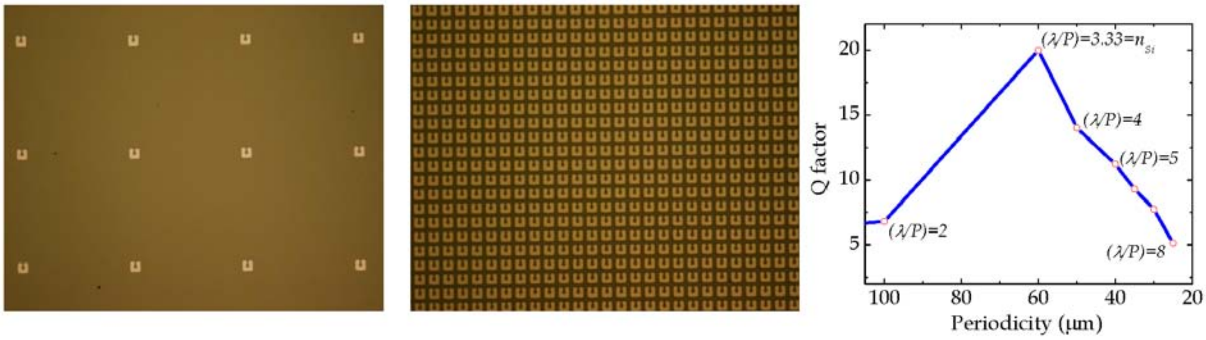

Fig. 2: A metamaterial to investigate the impact of the spacing of the individual meta-atoms on the quality factor of the resonance. In the left part of the figure two samples are shown which consist of nominally identical split-ring resonators but with a period that changes from 200 µm to 25 µm. The samples were spectrally characterized in transmission and the quality factor of the lowest order resonance was extracted from the measurements. Results are shown in right figure. It can be clearly seen, that the quality factor of the resonance strongly depends on the periodicity, i.e. the interparticle spacing. For particles placed in close proximity nearest-neighbour interaction enhances non-radiative losses and causes a decrease of the quality factor, whereas at more diluted objects the meta-atoms potentially couple well with free space radiation, leading equally to a low quality factor. For a particle spacing corresponding to the wavelength in the substrate medium, coherent interaction among neighbouring meta-atoms is strongly enhanced by virtue of excited lattice modes which sharpen the resonances extremely; leading to a high quality factor.

3. Conclusions

In conclusion, we will discuss in our contributions various mechanisms that affect the quality factor and the overall spectral appearance of resonances in THz metamaterials. We wish to stress most notably that the ensemble response from such metamaterials is not just dictated by the scattering response of the individual meta-atoms the metamaterial is made of, but that most notably the coherent response among the elements in the lattice and their near-field mediated coupling may cause a deviating response of the ensemble. The implications of such a collective response on the understanding of metamaterials and its effective properties are discussed.

Acknowledgments

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