Coherent Control of a Terahertz Metamaterial

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Abstract

We present the first coherent control experiments of a metamaterial. We fabricated a planar metamaterial showing two separated resonances at THz frequencies. It acts similar to an atomic system with two uncoupled excited states. Through temporal coherent control with broadband THz pulses we can excite both, none, or individual resonances.

1. Introduction

Coherent control experiments are performed since the late nineties to study and control light-matter interactions [1, 2, 3]. In combination with pulse shaping techniques, coherent control has proven to be a powerful tool for analysis as well as for manipulation of a variety of resonant systems. Here, we demonstrate the first coherent control experiments of a metamaterial. The often resonant response of metamaterials to incident electro-magnetic fields allows to use coherent control mechanisms to study and control that response in more detail. Due to the relatively short lifetime of the induced resonances of only a few oscillation periods, coherent control is very suitable for such a study. Performing these experiments at Terahertz (THz) frequencies has two main advantages: First, the necessary sub-wavelength sized metamaterial structures are relatively large and can be easily fabricated. Second, at THz frequencies experimental schemes exist that allow measuring the spatiotemporal distribution of the electric near- and far-field [4].

2. Experimental Scheme

Similar to an atomic system with two uncoupled excited states or a solid with two active phonon modes, we fabricated a planar split ring resonator (SRR) based metamaterial having two well separated resonance frequencies. Two different sized SRRs were used and, based on the Babinet's principle [5], we fabricated two different types of SRR materials having the same fundamental properties: First, a two dimensional array of metallic SRRs on an otherwise transparent substrate (positive structures). Second, an array of split ring shaped voids in a metallic sheet (negative structures). While the positive metamaterial is used to study the excitation of individual SRR by near-field measurements, the negative metamaterial allows for background free time domain spectroscopy where resonances appear as transmission peaks.

In our experiments the SRRs in the metamaterial are excited by broadband single cycle THz pulses. These are coherently generated and detected in a modified THz time-domain spectrometer in a pump/probe experimental scheme. It allows to directly measure amplitude, phase, and polarization of the electric field with sub 100 fs time resolution and and a spatial resolution better then $\lambda/50$. To achieve coherent control, shaping the generated THz pulses is essential. Techniques to do THz pulse shaping have been published earlier [6, 7]. Here, we realize temporal coherent control by applying a double pulse excitation to the metamaterial. Therefore, we placed a Michelson Interferometer in the optical pump beam path and by changing

ISBN 978-952-67611-2-1

the length of one of the interferometer arms we adjust the time delay between the two optical pump pulses which translates in two time delayed phase-locked THz pulses.

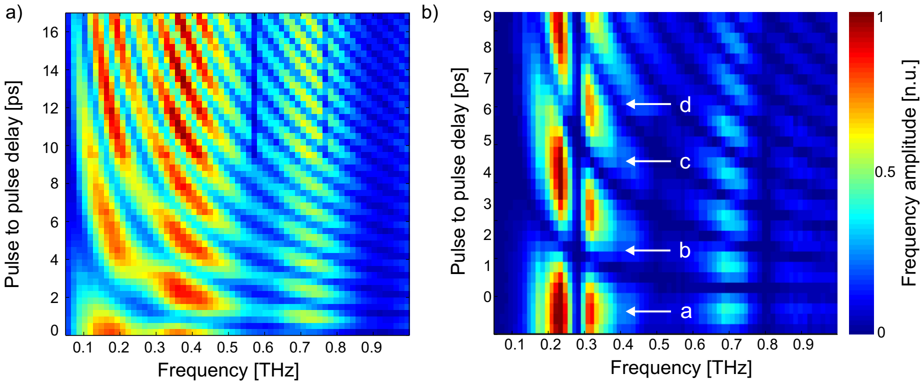

Fig. 1: a) Far-field spectra of the THz double pulses depending on the pulse to pulse time delay. b) Far-field transmission spectra through the metamaterial versus the THz pulse to pulse time delay. Marked with a) to d) are the four specific time delays where both, none, or an individual resonance is excited.

3. Results

Temporal coherent control as presented here, allows to suppress variable frequency components of the THz double pulse spectra, depending on the time delay between the two pulses. Varying the pulse to pulse delay results in a modulation of the amplitude of the frequency spectra as $f_{\text{osc}} = \frac{1}{\Delta t}$ where f_{osc} is the modulation frequency and Δt the time delay between the two pulses. The measured spectral modulation is shown in Fig. 1a). The color coded image shows the electric field amplitude as a function of the frequency and the time delay between the two THz pulses.

Applying the double pulse excitation to the metamaterial allows to transfer the coherence of the THz pulses to a coherence in the SRRs. Therefore, the variable modulation of the THz pulse spectrum allows to coherently control the individual excitation of the different types of SRRs. Figure 1b) shows the measured far-field spectra of the transmitted electric field depending on the pulse to pulse time delay. One can see the two distinct resonance frequencies of the SRRs at 0.22 THz and 0.31 THz as well as the amplitude modulation due to the varying time delay. Selecting a proper time delay allows to excite both, none, or an individual resonance and, thus, demonstrates coherent control. The four different excitation cases are marked with a)-d) in Fig. 1b).

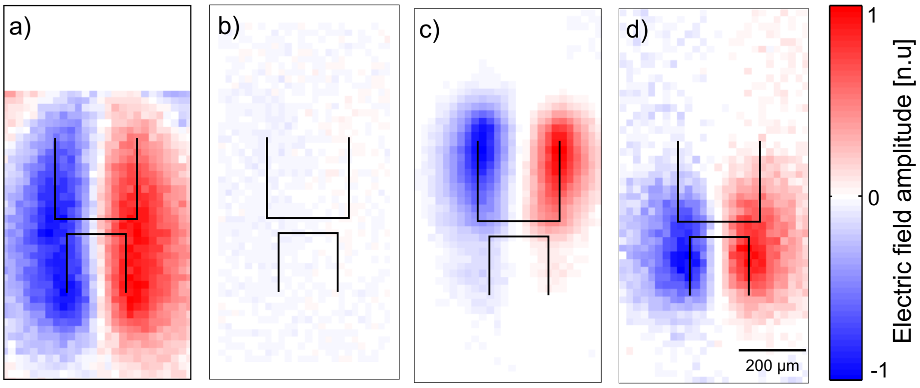

Fig. 2: Charge distribution on two positive SRR at a fixed time delay $t = 24$ ps after the double pulse excitation for the four possible excitation cases.

To understand in more detail the dynamics in the metamaterial we present near-field measurements of the time dependent charge distribution on the SRRs. The highly sub-wavelength spatial and ultrafast temporal resolution of our measurement setup allows to record movies of the excitation of individual SRRs and gives direct insight in the temporal coherence transfer from the THz field to the system, which in frequency domain may be understood since the time delay results in a suppression of individual frequency components. An example can be seen in Fig. 2 where the color code shows the out-of-plane electric field amplitude which is directly proportional to the charge distribution on the SRR. Figure 2 a)-d) show the charge distribution at a fixed time delay after the first excitation for the four cases where both, none, or one of the SRR is excited.

4. Conclusion

We presented coherent control of a planar SRR based metamaterial in the THz frequency range. A model system with two well separated resonances is studied by ultrafast measurement of the time dependent electric near- and far-field distribution to unravel the underlying coherence transfer.

References

[1] P. Brumer and M. Shapiro, Control of unimolecular reactions using coherent light, *Chem. Phys. Lett.*, vol. 126, no. 6, pp. 541-546, 1986.

[2] V. Blanchet, C. Nicole, M-A. Bouchene, and B. Girard, Temporal Coherent Control in Two-Photon Transitions:From Optical Intereferences to Quantum Interferences, *Phys. Rev. Lett.*, vol. 78, no. 14, pp. 2716-2719, 1997.

[3] P.Beaud, S.L. Johnson, A. Streun, R. Abela, D. Abramsohn, D. Grolimund, F. Krasniqi, T. Schmidt, V. Schlott, and G. Ingold, Spatiotemporal Stability of a Femtosecond Hard-X-Ray Undulator Source Studied by Control of Coherent Optical Phonons, *Phys. Rev. Lett.*, vol. 99, pp. 174801, 2007.

[4] A. Bitzer, H. Merbold, A. Thoman, T. Feurer, H. Helm, and M. Walther, Terahertz near-field imaging of electric and magnetic resonances of a planar metamaterial, *Opt. Exp.*, vol. 17, no. 5, pp. 3826-3834, 2009.

[5] A. Bitzer, A. Ortner, H. Merbold, T. Feurer, and M. Walther, Terahertz near-field microscopy of complementary planar metamaterials: Babinets Principle, *Opt. Exp.*, vol. 19, no. 3, pp. 2537-2545, 2011.

[6] T. Feurer, J.C. Vaughan, T. Hornung, and K.A. Nelson, Typesetting of terahertz waveforms *Opt. Lett.*, vol. 29, no. 15, pp. 1802-1804, 2004.

[7] L. De-Hua, M.A. Jian-Ju, Z. Wei, L. Sheng-Gang, Terahertz Waveforms Manupulation by Two Orthogonal-Polarized Femtosecond Pulses, *Chin. Phys. Lett.*, vol. 28, no. 6, pp. 064205, 2011.