Analog of electromagnetically induced transparency in a hybrid metamaterial

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Abstract

We present a theoretical and experimental study on coherent coupling between a split ring resonator (SRR) metamaterial and dielectric substances. The resulting optical properties of the coupled system are similar to those observed for electromagnetically induced transparency or plasmonic induced transparency. We describe the local field interaction between the metamaterial and the dielectric by analytic and numerical means and evidence the validity of our model by measuring the terahertz transmission spectrum of α-lactose-monohydrate coupled to an SRR metamaterial.

1. Introduction

Electromagnetically induced transparency (EIT) is a comprehensively investigated quantum interference effect, where a narrow-width transmission window is induced by destructive interference between a broadband bright mode and a narrow-width dark mode. In consequence, this leads to a minimum of absorption for light at frequencies close to the resonance frequency of the dark mode[1]. Adjacent to a high transmission, high dispersion can be observed near the resonance frequency enabling slow light applications. Recently the underlying concept of EIT has been applied to metamaterials (MM) and lead to an analog that was termed plasmon induced transparency (PIT)[2, 3]. Here the bright and dark modes were excited in plasmonic structures that acted as an electric dipole and an electric quadrupole. The concept of PIT is a beneficial approach for overcoming the high losses in MM at optical frequencies and paved the way for a new generation of sensors and slow light applications [2, 3]. Here, we combine the approaches of EIT and PIT in a hybrid structure by coherently coupling the broadband absorption mode of a plasmonic metamaterial to the narrow-band absorption mode of a dielectric. For this purpose we utilized an SRR structure that provides strong local fields in the capacitance gap and thus allows one to efficiently couple the enhanced electric fields to the narrow absorption line of a dielectric. We theoretically determined the mutual interaction between the plasmonic and dielectric resonance by an analytic model that described both the SRRs and the dielectric as two-level systems. Furthermore, we evidenced the theoretical model in a proof-of-principle experiment by measuring the hybrid coupling between an SRR metamaterial and α-Lactose-monohydrate in the THz-regime.

2. Theory

As discussed above, the strong enhancement of the electric field in the gap of the SRRs can be exploited to efficiently couple the local fields between the MM and the two-level system (2LS). To quantify the mutual interaction we followed a model developed in references [4, 5]. In this model, the coupling is

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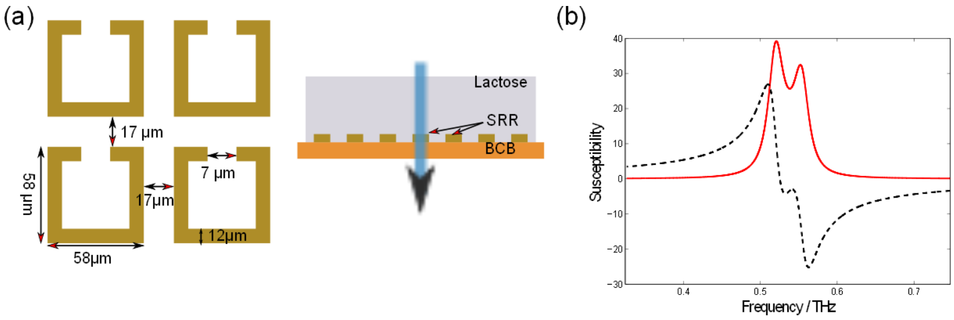

Fig. 1: a) Sample structure and profile with indicated SRR-dimensions. b) Analytic calculation of the experimental parameters of the real part (black dashed line) and the imaginary part (red solid line) of the susceptibility.

described by an empirical coupling constant $\mathcal{L}$. Following this approach, we obtained for the local fields [4, 5] of the 2LS $E_L^{(1)} = E_{\text{ext}} + \mathcal{L}P_{\text{MM}}$ and $E_L^{(2)} = E_{\text{ext}} + \mathcal{L}P_{12}$ for the MM, respectively. Hereby, P_{MM} and P_{12} are the macroscopic polarizations of the coupled MM and 2LS respectively, which are related to the coherence ρ, the particle densities $N_{\text{MM},12}$ and the dipole transition moments $\mu_{\text{MM},12}$ by $P_{\text{MM},12} = N_{\text{MM},12} \cdot \mu_{\text{MM},12} \cdot \rho_{\text{MM},12}$. The behavior of an ensemble of 2LS in the ground state can be described employing the Maxwell-Bloch equations [4, 5]. Since the SRRs can be described as an ensemble of bosons we can derive similar expressions for both systems [4, 5]:

$$\dot{\rho}_{12} = -i(\Delta_{12} - i\gamma_{12})\rho_{12} - i\frac{\mu_{12}}{\hbar}E_L^{(1)} \tag{1}$$

$$\dot{\rho}_{\text{MM}} = -i(\Delta_{\text{MM}} - i\gamma_{\text{MM}})\rho_{\text{MM}} + i\frac{\mu_{\text{MM}}}{\hbar}E_L^{(2)} \tag{2}$$

Hereby, $\Delta_{12,\text{MM}} = \omega - \omega_{12,\text{MM}}$ are the detunings, $\gamma_{\text{ab,MM}}$ are the dampings of the 2LS and the MM, respectively. The susceptibility χ of the combined MM-2LS shown in Fig. 1 (b) can be obtained by these formulas as described in Ref. [4, 5]. The imaginary part , which describes the absorbance of the hybrid system at the resonance frequency $\omega_{12} = \omega_{\text{MM}}$ can be approximated to:

$$\chi'' \approx \frac{N_{MM}\mu_{MM}}{\gamma_{MM}}\left(1 - \frac{(\mathcal{L}\mu_{12}\mu_{MM}/\hbar)^2 N_{ab}N_{MM}}{(\mathcal{L}\mu_{12}\mu_{MM}/\hbar)^2 N_{12}N_{MM} + \gamma_{12}\gamma_{MM}}\right) \quad . \tag{3}$$

The value of χ'' is inverse proportional to γ_{MM}. On the other hand, we observe that a strong coupling, represented by $\mathcal{L}$, and a low damping γ_{12} results in a low absorption at the resonant frequency since the second term in the brackets approaches one. In consequence, a high $\mathcal{L}$ and the condition $\gamma_{12} << \gamma_{\text{MM}}$ induce a pronounced minimum for χ'' and hence a maximum for the transmission.

3. Analytic, numerical and experimental results

To demonstrate the effect of resonant coupling between the MM and the 2LS, we investigated a system of SRRs and α-Lactose monohydrate (Lactose) on a bencocyclobutene (BCB) substrate as depicted in Fig. 1(a). α-Lactose monohydrate possesses a narrow absorption line at a frequency of $\nu_{12} = 0.53\,\text{THz}$ due to molecular vibrations. To investigate the physical behavior of the hybrid structure, we performed numerical calculations with CST Microwave Studio. We modeled BCB as lossy dielectric and the gold SRRs as lossy metal. For the description of lactose we assumed a Lorentz model with parameters derived from the geometric and physical properties of the experimental samples. We fabricated the samples by photolithography. To grow a thin lactose film we performed a quick crystallization process from a supersaturated lactose solution. We measured the spectral transmission of the SRR metamaterial without

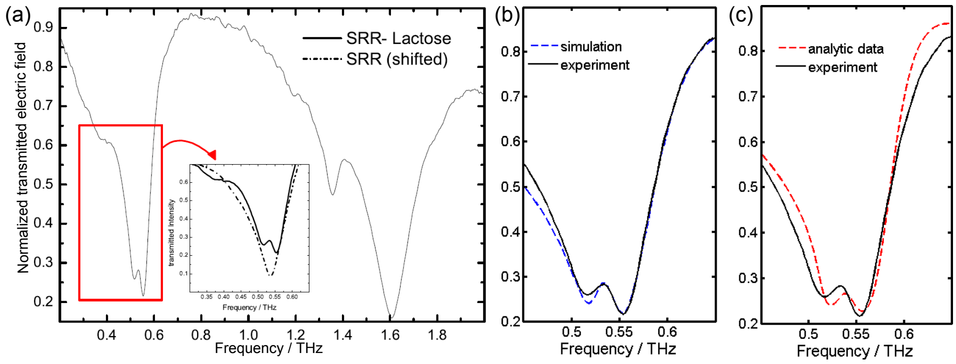

Fig. 2: Spectral transmission of the metamaterial with lactose (solid line) and without lactose (dashed line). (a) experiment, (b) numerical calculations and (c) analytic results.

lactose and with lactose by using a standard THz time domain system. The electric field was polarized parallel to the gaps of the SRRs. Fig. 2(a) shows the spectral transmission of the SRR metamaterial with lactose (solid line) and without lactose (dashed line). The sample with lactose reveals a Mie-resonance of the SRRs at $1.6\,\mathrm{THz}$ and a vibrational resonance of the lactose at $1.37\,\mathrm{THz}$, which indicate the existence of two constituent parts on the sample. Furthermore, we observed that the SRR resonance frequency approximately matched the Lactose absorption resonance at $\omega_{\mathrm{MM}} \approx \omega_{12} = 2\pi \cdot 0.53\,\mathrm{THz}$. Due to the coherent coupling between the SRR resonance and the absorption resonance of lactose we observed a characteristic EIT-like transmission at a frequency of $0.53\,\mathrm{THz}$. This is evidenced by a discrete increase of transmission within the broadband resonance of the SRRs. The narrowband transmission peak exactly occurred at the resonant frequency of the lactose absorption. As a further confirmation of the EIT-like effect, Figs. 2(b) and 2(c) show excellent agreement between the experimental data and the numerical and analytic results, respectively and prove the observation of coherent coupling.

4. Conclusion

We experimentally demonstrated resonant coupling between the broadband absorptive excitation mode of a plasmonic SRR metamaterial and the narrow-band absorption mode of a dielectric (α-lactose-monohydrate). We found that coherent coupling between the two modes leads to the hybrid analog of electromagnetically induced transparency (EIT). We supported the experimental observations by numerical simulations and developed an analytic model that described the mutual interaction between the metamaterial and the dielectric. Both, the numerical and analytic data showed excellent agreement with the experimental results.

References

[1] M. Fleischhauer, A. Imamoglu and J. P. Marangos, Electromagnetically induced transparency: Optics in coherent media, *Reviews of modern physics,* vol. 77, p. 633, 2005.
[2] S. Zhang, D. A. Genov, Y. Wang, M. Liu and X. Zhang, Plasmon-Induced Transparency in Metamaterials, *Physical Review Letters,* vol. 101, p. 047401, 2008.
[3] N. Liu, L. Langguth, T. Weiss, J. Kästel, M. Fleischhauer, T. Pfau and H. Giessen, Plasmonic analogue of electromagnetically induced transparency at the Drude damping limit, *Nature Materials,* vol. 8, p. 758, 2009.
[4] Martin W., J. L. Garcia-Pomar, C. M. Soukoulis, N. Meinzer, M. Ruther and S. Linden, Toy model for plasmonic metamaterial resonances coupled to two-level system gain, *Optics Express,* vol. 16, p. 19785, 2008.
[5] J. L. Garcia-Pomar, R. Beigang, M. Rahm, Nonlinearity and optical bistability caused by local field effects in the interaction between a two level atomic system and a metamaterial, *arXiv:1102.4262v1,* 2011.