

Low-Loss Metamaterials Based on Classical Electromagnetically Induced Transparency

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We demonstrate theoretically that electromagnetically induced transparency can be achieved in metamaterials, in which electromagnetic radiation is interacting resonantly with mesoscopic oscillators rather than with atoms. We describe novel metamaterial designs that can support a full dark resonant state upon interaction with an electromagnetic beam and we present results of its frequency-dependent effective permeability and permittivity. These results, showing a transparency window with extremely low absorption and strong dispersion, are confirmed by accurate simulations of the electromagnetic field propagation in the metamaterial.

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Electromagnetically induced transparency (EIT) is a coherent process observed in three-level atomic media, whose optical response to a laser beam is modified by a second beam with a well-determined detuning [1,2]. EIT has been explained in terms of a dark superposition state [3,4] or, alternatively, by destructive quantum interference between different excitation pathways of the excited state [5]. Because of this process, a small transparency window with significantly enhanced absorption length can be observed in the frequency response of an otherwise opaque medium. At the resonance frequency, the anomalous dispersion profile normally observed for a two-level resonance is transformed into extremely steep normal dispersion. This may slow down light pulses by 7 orders of magnitude [6,7]. More advanced techniques based on EIT even allow for the storage of optical data in matter [8]. For a recent review, the reader can consult, e.g., Ref. [9].

EIT has been demonstrated for media consisting of an ensemble of noninteracting atomic systems. The first and many recent experiments have been conducted with metal atoms in the gas phase [5,10]. Later experimental work was also performed on doped solid-state materials [11,12] and on quantum dot based systems [13]. The experimental handling of these setups is rather hard, since EIT is extremely sensitive to inhomogeneous broadening, e.g., due to the Doppler effect or quantum dot size dispersion; the setups must typically be cooled down to liquid helium temperatures and/or magnetic fields must be applied [14]. Recently, a classical equivalent of EIT was introduced by using coupled optical resonators [15] and coupled fish-scale patterns [16].

In this Letter, we demonstrate theoretically that EIT can be achieved in metamaterials, i.e., artificially fabricated materials made up of mesoscopic structured units significantly smaller than the wavelength of the interacting radiation. This allows us to characterize their electromagnetic properties by an effective permittivity and per-

meability [17]. Metamaterials combining negative permittivity and permeability, i.e., negative index materials (NIMs), can be obtained [18], and metamaterials also underlie the recently proposed optical invisibility cloaks [19]. The main obstacle in realizing NIMs in the visible is dissipation due to Ohmic losses; reducing these losses is the real challenge of the metamaterials field. EIT in metamaterials, and its associated low absorption, may provide a way to overcome this obstacle. In this Letter, we shall deal with EIT in the metamaterial's magnetic and electric response.

It is known that EIT-like effects are in general not restricted to systems supporting quantum mechanical states and can in principle be observed in classical systems such as plasmas [20] and coupled microresonators [21]. The design proposed here is based on the observation that a simple mechanical system [see Fig. 1(a)], consisting of a driven mass-spring oscillator linearly coupled to another oscillator with different dissipation factor, can reproduce an EIT-like absorption dip in its power spectrum [22]. This has been attributed to destructive interference between the normal modes of the mechanical system at the resonance

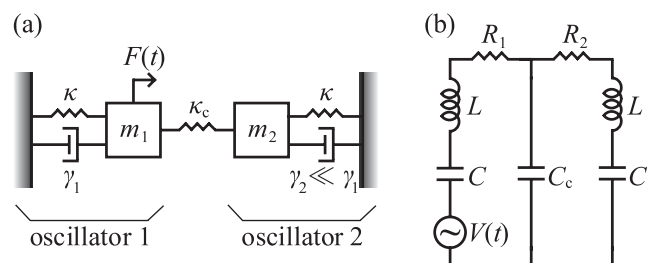


FIG. 1. (a) A driven mechanical system—consisting of two damped mass-spring resonators with mass $m_1 = m_2$ and spring constant κ linearly coupled by a third spring κ_c —that exhibits an EIT-like response in its power spectrum. (b) Its electrical analogue.

frequency. We start by converting this mechanical model to its equivalent electrical circuit [Fig. 1(b)]: a double RLC circuit with inductance L and capacitance C coupled by a shared capacitor C_c . The two circuits have a different resistance, respectively, R_1 and R_2 . The power delivered by a sinusoidal voltage source of magnitude V to the circuit equals

$$P = \text{Re} \frac{i\omega \frac{V^2}{2} (L\omega^2 - iR_2\omega - \frac{1}{C_{\parallel}})}{\frac{1}{C_c^2} - (L\omega^2 - iR_2\omega - \frac{1}{C_{\parallel}})(L\omega^2 - iR_1\omega - \frac{1}{C_{\parallel}})},$$

with $C_{\parallel} = (1/C + 1/C_c)^{-1}$. The above power spectrum exhibits an EIT-like response. The dissipation minimum, which occurs approximately at the resonance frequency, can be approximated by $P \approx (C_c^2/C_{\parallel}L)(R_2V^2/2)$ if it is assumed that the losses are small ($R_1R_2 < LC_{\parallel}/C_c^2$). It will thus suffice to make the second current loop with low enough resistance to obtain a pronounced dissipation minimum in the power spectrum of the circuit.

A possible implementation of the double RLC circuit of Fig. 1(b) for use in a metamaterial consists of two coupled split-ring resonators (SRR) as depicted in Fig. 2(a). For perpendicular propagation, the electromagnetic wave couples only to the one-gap SRR (right part), which we will therefore designate below as the “radiative” resonator. The two-gap SRR on the left is not directly coupled to the external field, so this is the “dark” resonator. The coupling between the dark and the radiative resonators is mainly capacitive (and inductive, to some extent). In contrast to atomic EIT, where the coupling between the energy states is realized by a pump beam, the coupling between the radiative and the dark SRRs in the EIT metamaterial is determined by their spatial separation; the coupling strength can thus be tuned by changing the distance between the two SRRs. The numerical simulations were carried out using the finite integration technique package CST MICROWAVE STUDIO. In these simulations, we have included the losses that are typically associated with the resonant behavior of metamaterials in the dielectric materials and the metals were taken as perfect electric conductors. This choice greatly facilitates the numerical calculations without changing the results significantly, at least for the frequencies used in this work and for low metallic losses. We will see below that the resulting quality factors of the individual elements are rather low (order of magnitude of 100 or smaller), as appropriate for metamaterials.

For the chosen geometry of Fig. 2(a), the resonance frequencies of the isolated SRRs are equal and around 42.9 THz. The quality factor for the dark SRR alone is equal to 120 and the corresponding value of Q for the radiative SRR alone equals 10. The quality factor of the dark SRR is thus an order of magnitude larger than that of the radiative SRR. The quality factor of the radiative (dark) resonator was obtained by removing the dark (radiative) element from the structure and simulating the reflection

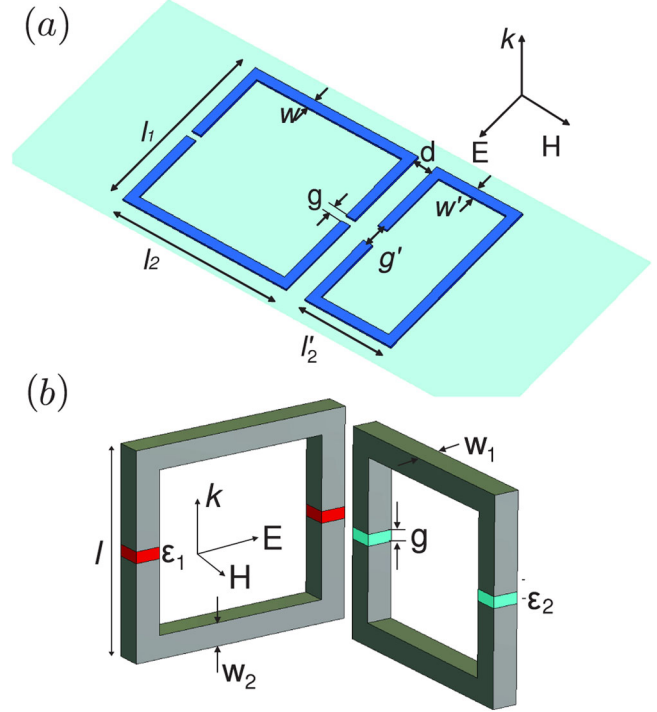


FIG. 2 (color online). (a) Design with electric coupling. The propagation direction of the incident wave and the directions of the electric and magnetic fields are shown. For this configuration, the resonance of the single-gap SRR is excited electrically by the incident wave, whereas the double-gap SRR is not coupled to the external field. The dimensions are $l_1 = l_2 = 0.9 \mu\text{m}$, $w = 0.1 \mu\text{m}$, $g = 0.0035 \mu\text{m}$ for the left SRR, and $l'_1 = 0.9 \mu\text{m}$, $l'_2 = 0.47 \mu\text{m}$, $w' = 0.1 \mu\text{m}$, $g' = 0.01 \mu\text{m}$ for the right SRR. The distance between the two SRRs is chosen $d = 0.08 \mu\text{m}$ and $d = 0.8 \mu\text{m}$ in two different simulations. (b) Design with magnetic excitation of the resonance. The propagation direction of the incident wave is shown. For this propagation direction, only the left SRR is excited by the magnetic field of the incident radiation. The dimensions of the SRR are $l = 0.9 \mu\text{m}$, $w_1 = w_2 = 0.1 \mu\text{m}$, and $g = 0.05 \mu\text{m}$. The dielectric constants are $\epsilon_1 = 10$ with loss tangent of $\tan\delta_1 = 0.01$ and $\epsilon_2 = 10$ with $\tan\delta_2 = 0.001$. The distance along the H axis between the two SRRs is chosen $d = 0.2 \mu\text{m}$ and $d = 0.6 \mu\text{m}$. In both structures, the SRRs are taken to be perfect metals and the losses are coming from the dielectric filling in or below the gaps of the SRRs.

and transmission; the quality factor was then calculated from the resulting Lorentzian-like absorption curve by $Q = \omega_0/\Delta\omega$, where ω_0 is the resonance frequency and $\Delta\omega$ is the full width at half maximum bandwidth. Note that for the calculation of the quality factor of the dark resonator, we have rotated the dark SRR over 90° in order to excite its resonance; this can be done because the quality factor of a linear system is independent of the manner of excitation.

In Figs. 3(a) and 3(b), we present results for the transmission and absorption versus frequency for weak and strong coupling. One can clearly see a dip in the absorption

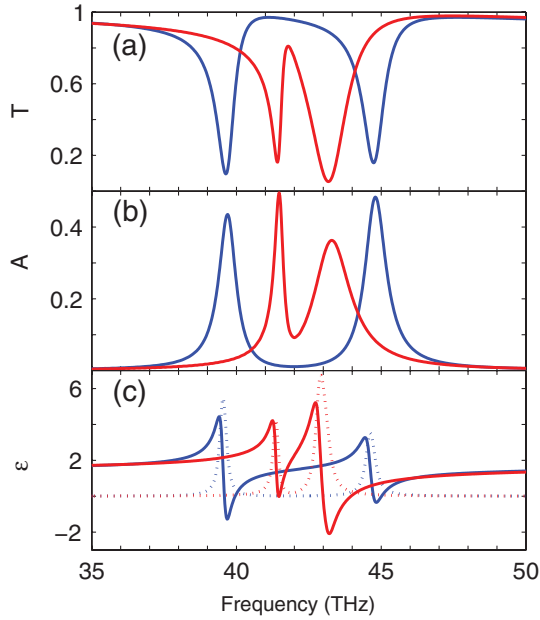


FIG. 3 (color online). (a) Transmission, and (b) Absorption spectra for the metamaterial design in Fig. 2(a) for two different separations, $d = 0.08 \mu\text{m}$ (blue line, strong coupling) and $d = 0.8 \mu\text{m}$ (red line, weak coupling). (c) The real (solid line) and imaginary part (dashed line) of $\varepsilon(\omega)$ for the two coupling strengths.

due to classical EIT. In Fig. 3(c), we present the retrieval results [17,23] for the effective dielectric permittivity, $\varepsilon(\omega)$, for weak and strong coupling, which clearly shows a dip in the imaginary part of ε , and one can see the really strong dispersion of $\varepsilon(\omega)$. This strong dispersion with simultaneously low absorption can be used to slow down light for a variety of potential applications.

Figure 2(b) describes another metamaterial design that responds magnetically and also provides classical EIT. This design is more difficult to fabricate experimentally, especially at terahertz and optical frequencies, since it is necessarily three dimensional. The left SRR of Fig. 2(b), directly excited by the incident magnetic field, provides here the radiative resonator. The right SRR is the dark resonator and can only be excited due to its coupling to the radiative SRR. The resonance frequencies of the isolated SRRs in Fig. 2(b) are equal and around 42.5 THz. The quality factor of the dark SRR alone is equal to 61 as calculated from the frequency dependency of its absorption peak. The corresponding value of Q for the radiative SRR alone is 42. The coupling between the two SRRs is predominantly capacitive (because of the proximity of the gaps) and can be tuned by adjusting the distance between the two SRRs. This coupling induces a frequency splitting of the degenerate resonances associated with the dark and the radiative resonators. In Figs. 4(a) and 4(b), we show the simulated transmission and absorption spectra for this structure. At large separation between the SRRs, i.e.,

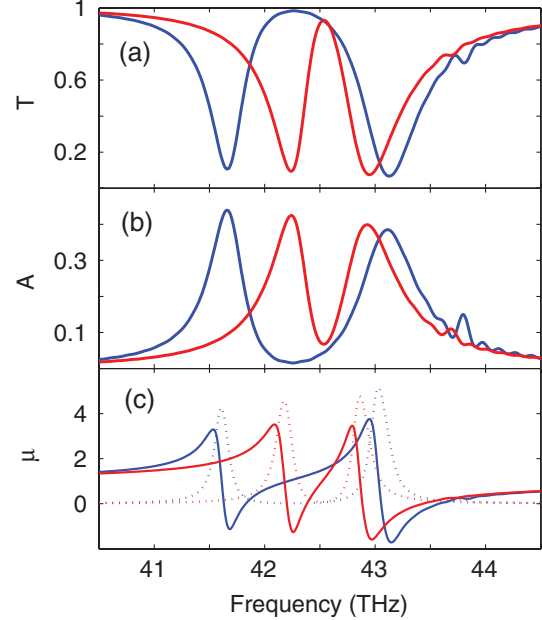


FIG. 4 (color online). (a) Transmission, and (b) absorption spectra for the metamaterial design in Fig. 2(b) for two different separations, $d = 0.2 \mu\text{m}$ (blue line, strong coupling) and $d = 0.6 \mu\text{m}$ (red line, weak coupling). (c) The real (solid line) and imaginary part (dashed line) of $\mu(\omega)$ for the two coupling strengths.

weak coupling, the splitting of the two resonance frequencies is small and the dispersion in between them is very steep. Simultaneously, a strong dip in the absorption spectrum appears. With increasing coupling between the two SRRs, the dip in the absorption spectrum widens and becomes deeper and, at the same time, the dispersion becomes more flat.

In Fig. 4(c), we show the retrieved real and imaginary parts of the effective magnetic permeability for the coupled system of SRRs as shown in Fig. 2(b). One clearly sees the classical EIT effect. The imaginary part of μ has a very low value at 42.5 THz, signifying small loss, which occurs simultaneously with steep dispersion in the real part of μ . This strong dispersion gives a very large group index of the order of 100 (see Fig. 5), which can slow down light for many applications.

In Fig. 5, we plot the real part of the group index, $n_g = n + \omega dn/d\omega$, versus frequency for the weakly coupled magnetic EIT system shown in Fig. 2(b). Note that n_g becomes really large (of the order of 500) at about 42.2 and 43.0 THz; the losses at these points are also tremendous as one can see from Fig. 5. However, the imaginary part of the index of refraction becomes very small in the frequency band from 42.4 to 42.8 THz. In this region, $n_g \approx 100$ and $\text{Im}(n)$ is less than 0.03. Our classical EIT metamaterial, shown in Fig. 2(b), can thus reduce the group velocity of light by a factor of 100 with low loss. A similar reduction of the group velocity can be obtained

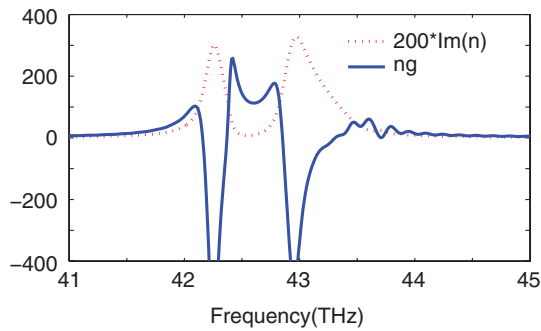


FIG. 5 (color online). Real part of the group index (solid line) in comparison to the imaginary part of the index of refraction (dotted line, multiplied by a factor of 200) for the magnetic EIT system shown in Fig. 2(b) for weak coupling.

with the design shown in Fig. 2(a). An important figure of merit for slow light applications is the delay bandwidth product, which equals approximately 8% for a single layer of our metamaterial.

In conclusion, we have presented designs of novel metamaterials consisting of coupled split-ring resonators. We have shown that these materials can support a dark state leading to a phenomena similar to electromagnetically induced transparency: the metamaterial exhibits a transmission window with extremely low absorption and steep dispersion. No quantum mechanical atomic states are required in this metamaterial to observe EIT. We demonstrate the effect for the electric as well as for the magnetic response. The proposed metamaterial could lead to slow light applications from the microwave up to the terahertz regime, where the structures can be most easily fabricated. Furthermore, our classical EIT structures show that a strong resonance in the effective parameters is not always associated with high loss at the same frequency. Therefore, more complex designs—possibly taking advantage of knowledge from quantum optics—could provide a new way to solve the problem of losses in metamaterials. Our structures already achieve a figure of merit $FOM \approx 60$ in the transparency window for both the electric permittivity ($\epsilon \approx 1$) and the magnetic permeability ($\mu \approx 1$), which should be compared with a $FOM \approx 10$ for state-of-the-art left-handed materials.

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