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Dependence of transmittance and group index on the coupling strength between constituents of a metamaterial

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Abstract
Recent studies on the coupling effects between constituent elements of metamaterials have opened up a new gateway to many fascinating electromagnetic properties and functionalities that cannot be explained by the uncoupled point of view. In this work, we numerically investigated, in a THz regime, the coupling between a cut wire and a split-ring resonator, which gives rise to an interesting phenomenon—the so-called electromagnetically induced transparency-like effect. The trade-off between the maximum transmittance of the transmission window and the group index, which depends on the coupling strength between constituent elements, was systematically studied. Furthermore, by characterizing this trade-off by the transmittance-delay product (figure of merit), a criterion for slow-light applications was provided.

Keywords: metamaterial, electromagnetically induced transparency, coupling, slows light

Classification number: 5.17

1. Introduction

Metamaterials (MMs) are artificial structures consisting of sub-wavelength elements that exhibit superior properties not found in nature and not observed in the constituent materials [1]. The fascination of metamaterials lies in the fact that they enable unprecedented control of the electromagnetic field and provide a wide range of applications, such as left-handed materials [2], superlenses [3], cloaking [4] and electromagnetically induced transparency (EIT) [5–11]. Recently, studies on coupling effects have opened up a new avenue for MM research since they can play the role as an efficient degree of freedom, providing many interesting physics and applications that do not exist in uncoupled ones. An understanding of neighboring interactions and coupling effects, beyond the average effect, turns out to be very important in tailoring and manipulating the properties of MMs at will [12]. Owing to the coupling interaction, resonances can be shifted, reshaped, or even split into multiple modes, leading to a significant modification in the resonant and spectral responses of coupled structures.

Among a variety of researches on coupling phenomena, the MM analog of EIT has received a great deal of attention. This phenomenon not only links a coherent quantum process to its classical version with an interesting underlying physics but also promises a future for the real applications in slow light and sensing [5–9]. In quantum optics, EIT is achieved from the destructive interference between two pathways, rendering an absorptive medium transparent to a resonant probe field in a narrow frequency range [13]. These quantum phenomena are excellent media for fundamental investigation but limited for practical application since they are observable only in cold gases and Bose–Einstein condensates. The discovery of EIT-like effect in MMs with flexible and rather simple

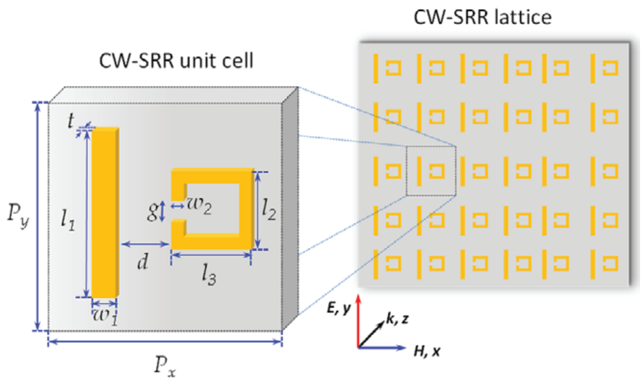

Figure 1. Schematic of the unit cell (left) and lattice (right) of CW–SRR structure. The yellow regions indicate gold and the grey regions illustrate the supporting substrate. The CW has dimensions of $l_1 = 600$ nm and $w_1 = 120$ nm, and the SRR has dimensions of $l_2 = l_3 = 350$ nm, $g = 140$ nm and $w_2 = 80$ nm. The separation d represents the coupling strength between two elements to be in the range from 50 to 350 nm.

experimental setups has, therefore, brought many advantages to applications. Different from quantum EIT, the MM analog of EIT offers room-temperature slow light with a wide operating bandwidth, and the possibility of integration with a nanophotonic circuit.

So far, the EIT-like effect in MMs has been extensively studied for many proposed designs. The approaches for the realization of those effects can be summarized in three main categories: trapped-mode resonance [5], bright and dark mode coupling [6, 7], and bright and quasi-dark mode coupling [8]. For each approach, the analogy and the electromagnetic mechanism have been discussed in detail. However, the trade-off between transmittance and group index, which is of great importance for slow-light applications, and the flexible range of those structures still need more attention to bring those interesting phenomena to real applications. In this paper, we present a detailed numerical study of the trade-off between transmittance and group index in a planar MM consisting of a cut-wire (CW) and a split-ring resonator (SRR) in a THz regime. This trade-off between transmittance and group index is characterized by a figure of merit, namely the transmittance-delay product (TDP), suggesting a criterion for the optimization of structure for slow-light purposes.

2. Model and numerical setup

The schematic and geometrical parameters of our MM structure are presented in figure 1. This consists of one CW and one SRR, facing each other through the SRR gap and the CW side (CW–SRR structure) [8, 9]. The periodicities in the x and y directions are fixed to be $P_x = P_y = 900$ nm. The dimensions of the CW are $l_1 = 600$ nm and $w_1 = 120$ nm, and those of the SRR are $l_2 = l_3 = 350$ nm, $g = 140$ nm and $w_2 = 80$ nm. They are made of gold and have the same thickness of $t = 20$ nm. In our simulation, we apply the Drude model for gold with plasma and collision frequencies of $\omega_p = 1.367 \times 10^{16}\ \mathrm{s}^{-1}$ and $\omega_c = 1.22 \times 10^{14}\ \mathrm{s}^{-1}$, respectively [14]. For simplicity, we remove the substrate in the simulation setup. This treatment results in a small shift in the resonant frequency but does not affect the results considerably. The numerical simulation was performed using the commercial software CST Microwave Studio. The normally incident light with the E-field polarized along the y-axis and the H-field along the x-axis was employed. To mimic the periodic arrangement of CWs and SRRs, we used the unit-cell boundary condition along the x and y axes. The group delay of light through the structure is defined as the negative rate of phase change with frequency $\tau_g = -\partial\varphi/\partial\omega$. The group index n_g is then calculated from $\tau_g c/L_{\mathrm{eff}}$ [9], where L_{eff} is the effective thickness of the MM along the direction of light propagation [15].

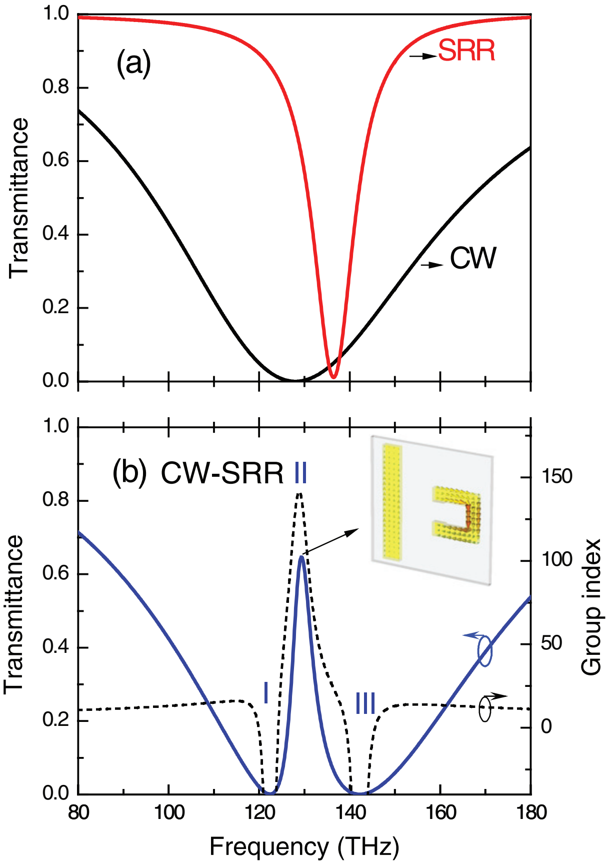

Figure 2. (a) Transmission of CW and SRR structures. (b) Transmission and calculated group index of the CW-SRR MM. The inset shows the characteristic current density at the transmission window (II).

3. Results and discussion

The simulated transmission spectra of structures with only CW and with only SRR are presented in figure 2(a). The CW has a typical broad transmission dip with a low Q-factor of 2.1. The SRR, in contrast, shows a narrow transmission dip with a much higher Q-factor of 13.2. The resonance frequency of the CW is at 130 THz and that of the SRR is slightly higher at 136 THz. It has been demonstrated that the difference in Q-factor of the constituents is important in order to access a very narrow and dispersive transmission of the MM structures [6–9].

Figure 2(b) presents the transmission spectrum and the corresponding group index of the CW–SRR structure with a separation $d = 250$ nm. As expected, a narrow and very

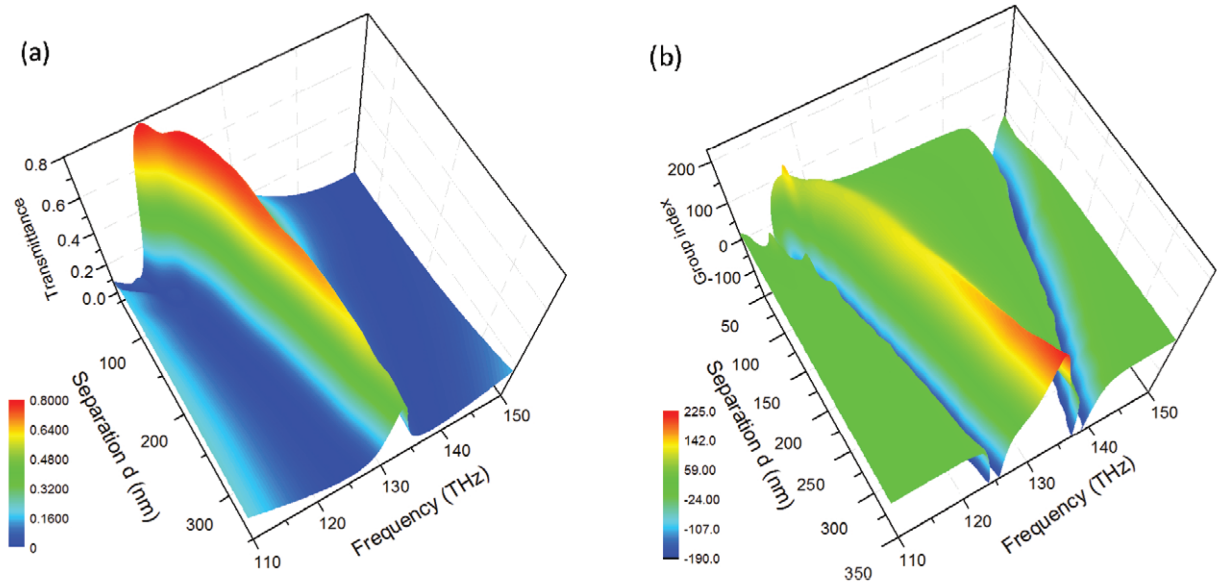

Figure 3. Dependence of (a) transmittance and (b) group index on the coupling separation *d*.

dispersive transmission is observed at a frequency where the transmission gaps of the structures with only CW and with only SRR take place. Accompanied by this sharp transparency is a positive group index of about 150. This means that if a packet of light at the frequencies of the transmission window passes through the effective thickness of the MM, it will experience a reduction in group velocity by a factor of 150. This interesting phenomenon can be explained in terms of the plasmonic hybridization between the CW and the SRR, which leads to the splitting of resonances [9]. Between two new resonances there exists a narrow frequency region where a transmission window takes place. A more intuitive explanation is given by using the equivalent-circuit model, showing that the transmission window is formed by the destructive interference between the strongly radiative current in the CW and the less-radiative current in the SRR [8]. The evidence for this claim can be seen in the current density shown in the inset of figure 2(b).

In the following, we will investigate the dependences of the transmittance and the group index on the coupling strength between the CWs and SRRs, which are presented as three-dimensional graphs in figure 3. The maximum values and the bandwidth of the transmittance window as well as the corresponding group index versus separation *d* are also plotted in figure 4. We can clearly see that the intensity of the transmission window gradually decreases from 0.8 to 0.44 when we vary *d* from 50 to 300 nm. It is important to emphasize here that, for many slow-light applications, high transparency, large group index and broad bandwidth are all desirable. However, as far as the group delay is concerned, the higher group index will come at a price of much lower transparency of the medium and much narrower operating frequency band, and vice versa. In other words, there always exists an inevitable trade-off between the amount of light passing through the media, and the ability to slow down the group velocity as well as the operating bandwidth. Understanding this trade-off plays a central role in controlling and optimizing the structure for slow-light purposes.

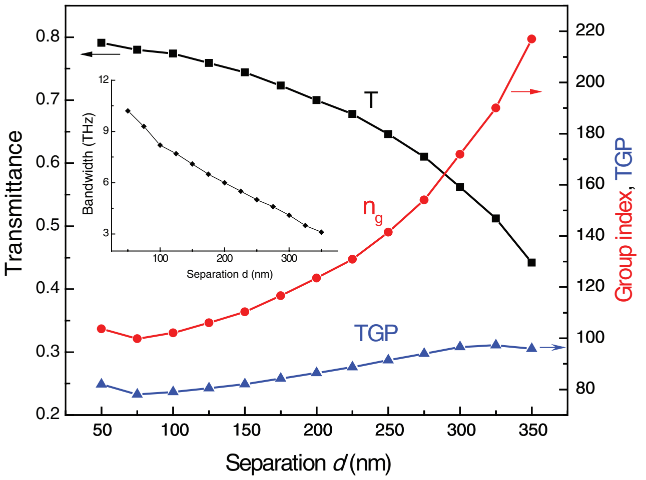

Figure 4. Dependence of the transmittance-group index product on the coupling strength between the CW and the SRR. The inset shows the corresponding bandwidth of the transmission window.

For slow-light applications, two major drawbacks are dispersion and loss. A strong dispersion requires a narrow bandwidth and therefore limits the operation frequency range; losses set the limitation for storage time and interaction length [16]. In some instances, such as optical nonlinearities or quantum optics, the enhancement of light energy density and the storage of the quantum state of light for a sufficiently long time to enable quantum operations are of significant importance. Therefore, beside the well-known delay-bandwidth product, which characterizes the possible range of the trade-off between group index and bandwidth [16], we introduce here another figure of merit (FOM), namely transmittance-group index product ($\mathrm{TGP} = T \times n_g$). This FOM, characterized by the amount of light passing through the effective medium (T) and the light-slowing factor (n_g), tells us how much enhancement of energy density of light the structure can attain. The change in TGP with respect to coupling distance *d* is presented in figure 4. Initially, TGP increases when *d* increases from 75 nm, attaining the maximum value at 325 nm and then decreases for larger values of d. This means that the enhancement of the energy density of the propagating light is most efficiently facilitated at $d = 325$ nm for this specific structure. This FOM, therefore, provides a very useful criterion for the optimization of other MM structures for the aforementioned slow-light applications.

Additionally, we can observe the gradual change in frequency of the transmission peak from 120 to 132 THz when d increases from 50 to 350 nm. This strong shift cannot be explained if we consider the CW and SRR as equivalent nanocircuits with the fixed values of lumped elements [8]. This is because when the CW and SRR are brought to the strong local field of each other, their intrinsic eigenmodes are also strongly modified. On the other hand, that behavior might come from the effect of higher-order electric multipoles, which become more pronounced when the CW and SRR are brought closer [17]. The detailed explanation of such a complicated phenomenon, however, needs more elaborate studies and goes beyond the scope of this paper.

4. Conclusions

We have studied the coupling between a CW and a SRR, which gives rise to an interesting phenomenon—the so-called EIT-like effect in MMs in a THz regime. Based on the platform of that structure, the trade-off between the maximum transmittance of the transmission window and the corresponding group index, depending on the coupling strength between constituent elements, was elaborately studied. Moreover, by introducing the transmittance-delay product as a FOM, we have provided a criterion for MM-based slow-light applications.

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References

[1] Engheta N and Ziolkowski R W 2006 *Metamaterials: Physics and Engineering Explorations* (Hoboken, NJ: Wiley)
[2] Smith D R and Kroll N 2000 *Phys. Rev. Lett.* **85** 2933
[3] Pendry J 2000 *Phys. Rev. Lett.* **85** 3966
[4] Fang N, Lee H, Sun C and Zhang X 2005 *Science* **308** 534
[5] Papasimakis N, Fedotov V A, Zheludev N I and Prosvirnin S L 2008 *Phys. Rev. Lett.* **101** 253903
[6] Zhang S, Genov D A, Wang Y, Liu M and Zhang X 2008 *Phys. Rev. Lett.* **101** 047401
[7] Tassin P, Zhang L, Koschny Th, Economou E N and Soukoulis C M 2009 *Phys. Rev. Lett.* **102** 053901
[8] Thuy V T T, Tung N T, Park J W, Lam V D, Lee Y P and Rhee J Y 2010 *J. Opt.* **12** 115102
[9] Bai Q, Liu C, Chen J, Cheng C, Kang M and Wang H T 2010 *J. Appl. Phys.* **107** 093104
[10] Lu Y, Jin X, Lee S, Rhee J Y, Jang W H and Lee Y P 2010 *Adv. Nat. Sci.: Nanosci. Nanotechnol.* **1** 045004
[11] Vu D L, Pham V T, Do T V, Nguyen T T, Thuy Vu T T, Le V H and Lee Y P 2010 *Adv. Nat. Sci.: Nanosci. Nanotechnol.* **1** 045016
[12] Liu H, Liu Y M, Li T, Wang S M, Zhu S N and Zhang X 2009 *Phys. Status Solidi* b **246** 1397
[13] Haris S E 1997 *Phys. Today* **50** 36
[14] Ordal M A, Long L L, Bell R J, Bell S E, Bell R R, Alexander R W and Ward C A 1983 *Appl. Opt.* **22** 1099
[15] Chen X, Grzegorczyk T M, Wu B, Pacheco J and Kong J A 2004 *Phys. Rev.* E **70** 016608
[16] Krauss Th F 2008 *Nature Photon.* **2** 448
[17] Liu N, Liu H, Zhu S and Giessen H 2009 *Nature Photon.* **3** 157