Electromagnetically induced transparency in metamaterials at near-infrared frequency

Jingjing Zhang[1], Sanshui Xiao[1], Claus Jeppesen[2], Anders Kristensen[2] and Niels Asger Mortensen[1*]

[1] *DTU Fotonik - Department of Photonics Engineering, Technical University of Denmark, DK-2800 Kongens Lyngby, Denmark.*
[2] *DTU Nanotech - Department of Micro and Nanotechnology, Technical University of Denmark, DK-2800 Kongens Lyngby, Denmark.*
**asger@mailaps.org*

Abstract: We employ a planar metamaterial structure composed of a split-ring-resonator (SRR) and paired nano-rods to experimentally realize a spectral response at near-infrared frequencies resembling that of electromagnetically induced transparency. A narrow transparency window associated with low loss is produced, and the magnetic field enhancement at the center of the SRR is dramatically changed, due to the interference between the resonances with significantly different linewidths. The variation of the spectral response in terms of relative position of the bright and dark elements is evaluated with numerical simulations.

OCIS codes: (260.2110) Electromagnetic optics; (160.3918) Metamaterials; (000.4930)

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#130525 - $15.00 USD Received 22 Jun 2010; revised 21 Jul 2010; accepted 21 Jul 2010; published 28 Jul 2010

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1. Introduction

Electromagnetic induced transparency (EIT) is an appealing phenomenon where an atomic medium is rendered transparent to a probe laser beam by a second, coupling beam. The importance of EIT stems from the fact that it gives rise to greatly enhanced nonlinear susceptibility in the spectral region of induced transparency and is associated with steep dispersion [1], allowing for many potential applications in a wide range of fields. The dramatic modification of the refractive properties also results in very slow group velocities [2], which can be applied in signal processing and optical data storage [3,4]. In addition, the narrow transparency resonance in the absorption spectrum is potentially highly desirable for sensing applications [5,6]. Recently, increasing attention has been paid to the fact that EIT-like effects are not restricted to systems supporting quantum mechanical states and can occur in classical oscillator systems. Several methods have been considered, including an LC resonance electric circuit [7], coupled micro-resonators [8], drop-filter cavity-waveguide systems [9], and a hybridized plasmonic-waveguide system [10]. In particular, it is demonstrated theoretically that EIT can be mimicked with metamaterials [11–13], and experimentally realization of metamaterial analogue of EIT at microwave [14], terahertz [15,16], and optical frequencies [17,18] have also been reported. With judiciously designed metamterial structures, transparency can be excited without quantum mechanical atomic states. This may greatly reduce the difficulty in the experimental realization of EIT, and in particular, will hence bring us closer to its exciting applications in bio-sensing, signal processing, etc.

In this paper, we study the EIT-like property of a split-ring-resonator (SRR) [19,20] combined with a pair of metallic nano-rods [11,21]. The SRR acts as the bright element which couples strongly to the excitation field, while the metallic rods behave as the dark element whose resonance can only be excited by its electromagnetic coupling to the SRR. The EIT-like feature dramatically changes the magnetic field enhancement at the center of SRR, which may hold the promise of sensing applications. The EIT-like behavior is verified experimentally at near-infrared frequency with gold nano-structures. With numerical simulation, we demonstrate that this EIT-like feature is based on the response of each individual unit structure, rather than on a collective effect. It is also shown that the coupling strength between the bright and the dark element can be tuned by varying their relative position.

2. Metamaterial geometry and numerical modeling

Figure 1 illustrates the geometry of the metamaterial structure composed of a SRR and a pair of rods. The light is incident perpendicularly to the plane of the structure with the electric field along the gap of the SRR. Therefore, the SRR couples strongly to the incident light, supporting the bright mode. The paired nano-rods, which do not couple to the radiation field, support the dark mode. The magnetic field induced by the resonance of the bright element will excite the anti-parallel current modes on the paired nano-rods, resulting in the EIT-like effect.

#130525 - $15.00 USD Received 22 Jun 2010; revised 21 Jul 2010; accepted 21 Jul 2010; published 28 Jul 2010

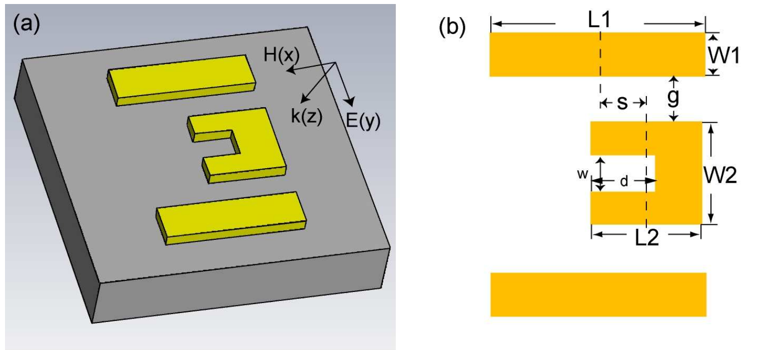

Fig. 1. Schematic of the metamaterial geometry and the incident light polarization. Here $L1$ = 360nm, $W1$ = 95nm, $W2$ = L2 = 200nm, w = 80nm, d = 100nm.

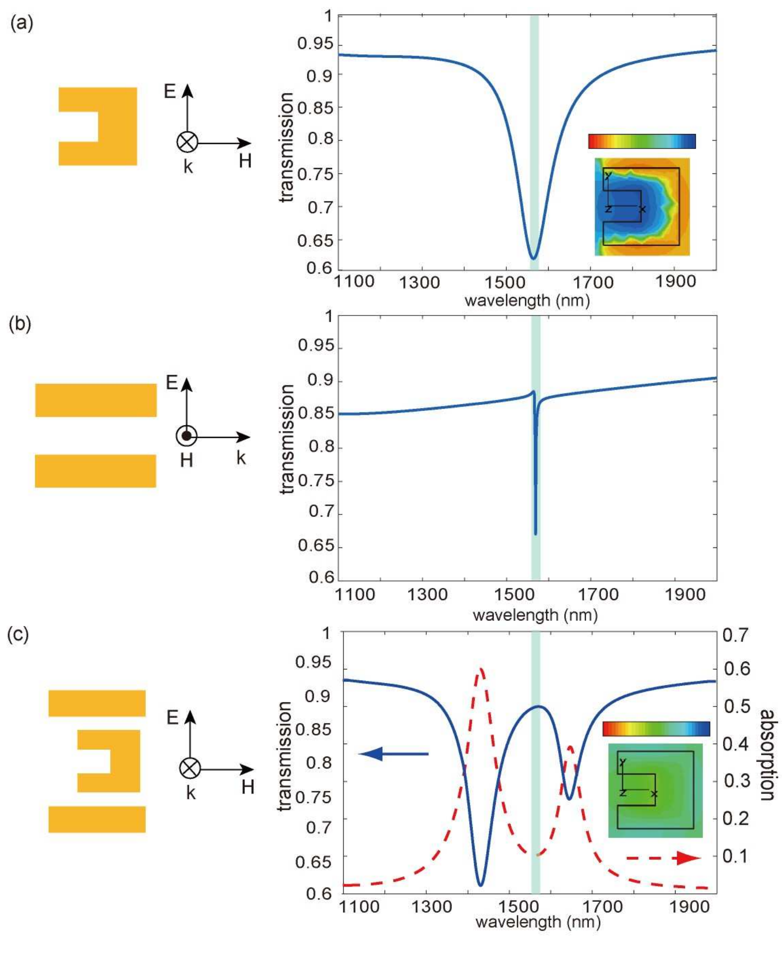

Fig. 2. Simulated transmission spectra of (a) SRR (b) paired rods (c) the combination of SRR and paired rods. The insets show H_z for SRRs at 1560nm.

We use a commercially available finite integration method solver package (CST Studio Suite 2010) to simulate the spectral response of the separated elements, as shown in Fig. 2. In the simulation configuration, periodic boundary conditions are applied in the x and y

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directions to simulate the real experimentally studied sample. The 800nm × 800nm unit cell is composed of a 30nm-thick gold nano-structure on a 200nm thick glass substrate. The permittivity values of gold at the simulated frequencies are taken from experimental data [22] and the permittivity of glass is taken as 2.245.

According to simulations (Fig. 2(a)), an isolated SRR structure exhibits an LC resonance at 1560nm due to the external excitation. As shown in the inset, the magnetic field at the center of SRR is greatly enhanced at the resonance frequency due to the induced circular surface currents. The real fields that would be induced by the bright element at the resonance spectrum are indicated in Fig. 2(b). Here, we should mention that since periodic boundary condition is used, we have to rotate the wave vector k by a small angle in the k-H plane in the simulation. In this case the magnetic field still has the component perpendicular to the plane of the paired rods, which causes anti-parallel currents in the two rods, thereby causing the magnetic response of the system. By choosing appropriate parameters, a resonance also centered at 1560nm can be achieved. It should be noted that the dark mode has a much smaller linewidth (high quality factor) than that exhibited by the bright mode, which is a requirement for exciting and observing EIT. Next, the SRR and the paired rods are placed in proximity and the polarization of the electric field is chosen to be parallel to the gap of the SRR, which only allows excitation of the eigenmode in SRR in the spectrum of interest. A transmission peak is shown to appear at 1560nm, associated with an absorption dip in the spectral domain caused by the overlap of the two hybridized resonances' envelopes, as indicated in panel (c). The interference between the bright and dark modes gives rise to the suppression of field at the center of SRR, as shown in the inset of panel (c). This dramatic change of field at a very small region is potentially valuable in sensing applications.

3. Experimental realization

The proposed structure is fabricated, and Fig. 3(a) shows the scanning electron microscope image of the fabricated sample. In the fabrication, a 100nm thick layer of positive EBL resist, ZEP520A is first spin-coated onto a 1mm fused silica substrate. A 15nm aluminum layer is thermally deposited on top of the ZEP layer to prevent charge accumulation during EBL. The EBL exposure is performed with a 100 kV JEOL JBXa9300FS EBL tool. The aluminum layer is then removed in MF-322 and the resist is developed in ZED-N50 developer. Afterwards 5nm titanium and 30nm gold are deposited by electron beam deposition, covering an area of 2.4mm × 2.4mm. Finally, a lift-off process is performed with Remover 1165 in an ultrasound bath.

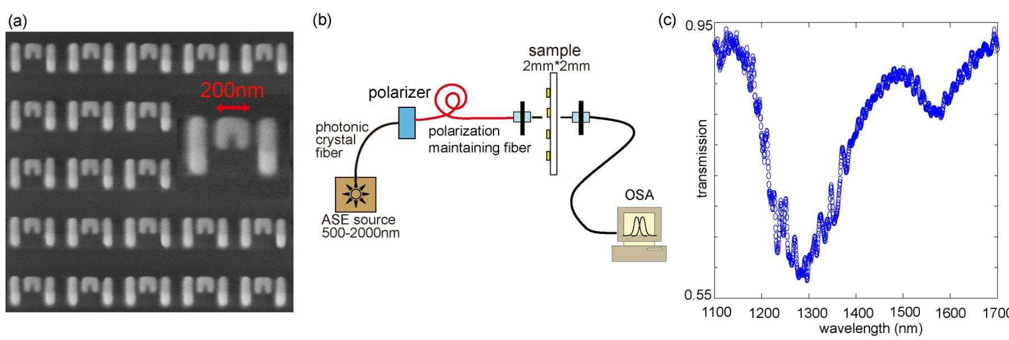

Fig. 3. Panel (a) shows a micrograph of a SRR array with pitch = 800 nm. The inset gives an enlarged view of the structures. Panel (b) illustrates the measurement setup. Panel (c) shows the measured spectral transmission.

The measurement setup is shown in Fig. 3(b). The light from a broadband optical source (500-2000nm) is transmitted through a photonic crystal fiber to a polarizer, which provides the linear polarization as desired. A polarization maintaining fiber is used to keep the required polarization of the light. Since the end of the fiber is very close to the surface of the sample, the emitted overall Gaussian beam, with a spot size of about 80μm, can be taken as a plane

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wave. An ensemble of around 10^4 unit cells is illuminated by the spot at the same time. The optical properties of the samples at normal incidence were recorded with an optical spectrum analyzer Ando AQ-6315E, and the normalized transmission spectrum is shown in panel (c). The measurement result agrees with the calculated transmission property, and variations of the frequency of the transparency window and depth of the dip are attributed to the tiny size differences and the blunt edges of the structures in the fabricated sample, as well as the introduction of 5 nm titanium as an adhesion layer (In the simulation, we didn't consider this titanium layer).

4. Discussion

Like in the quantum state system, an EIT-like response in a metamaterial should ideally depend only on the bright and dark elements in each single cell. To demonstrate this point we simulate the spectral response of the structures comprising a single cell. Figure 4 shows a comparison of the simulated transmission properties for periodic structures (blue solid line) and a single unit structure (red dashed line). Good agreement of the two curves indicates that the EIT-like phenomenon we observe is indeed the intrinsic property of the elements in every unit cell, rather than a complicated integrated effect caused by the massive arrayed structures.

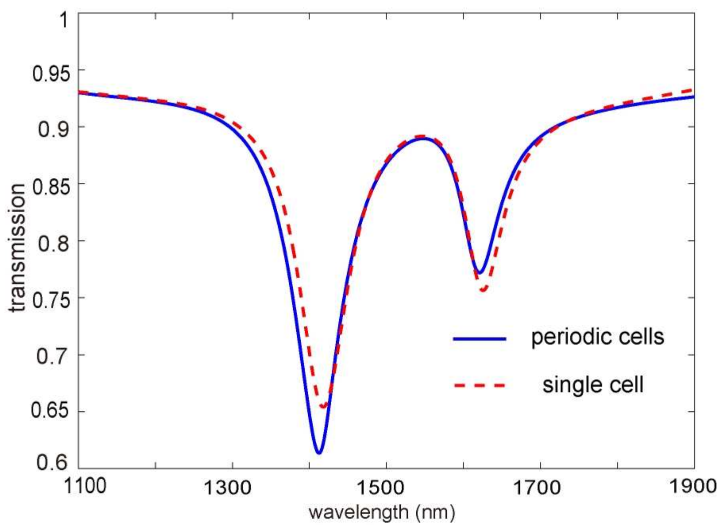

Fig. 4. Simulated transmission spectra (a) for periodically aligned cells (b) for a single cell.

In order to further understand the factors that affect the EIT-like feature, we calculate the transmission property in terms of the lateral displacement *s* of the SRR relative to the geometrical center of the nano-rod and the gap *g* [see Fig. 1(b)] between the SRR and the nano-rod, as shown in Fig. 5. Structures with blunt edges are used in the modeling in order to make the simulation better resemble that of the real structure, as shown in the insets of Fig. 4. First the gap is fixed as g = 80nm and the lateral shift *s* is changed from 20nm to 95nm. It is shown that as *s* increases, the transmission peak gets more pronounced, indicating a stronger coupling induced by the structural asymmetry. This phenomenon arises because the broken symmetry of the system allows excitation of the dark state. Next the displacement *s* is fixed while the gap *g* is varied. As expected, when the two parts get closer, a stronger interaction is observed and the transmission gets higher at the peak. A lower absorption, associated with a wider resonance spectrum is also observed at the same time when *g* decreases.

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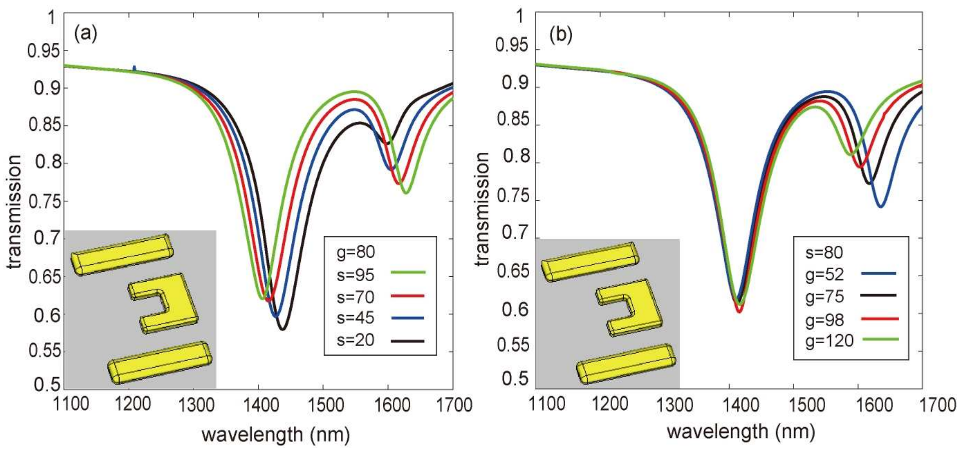

Fig. 5. Transmission spectra (a) for different lateral displacement s calculated at g = 80nm (b) for different gap g calculated at s = 80m. The insets show the structure used in the simulation.

5. Summary

A metamaterial structure composed of the SRR and paired rods is proposed and fabricated at near-infrared frequencies to mimic the electromagnetically induced transparency. The coupling of the SRR and paired rods gives rise to a transparency window in the absorption band. The coupling strength can be tuned by changing the lateral displacement or the distance between the bright and dark elements. This experiment opens up a way to study quantum mechanical phenomena with metamaterials that can be readily fabricated with the aid of state-of-the-art electron-beam lithography.

Acknowledgments

The authors acknowledge Radu Malureanu and Peixiong Shi for technical assistance. The work is supported by a Hans Christian Ørsted postdoctoral fellowship as well as by the Danish Research Council for Technology and Production Sciences (FTP grant #274-07-0080 and 274-07-0379).