Wide-angle and polarization insensitive and plasmonically induced transparency by planar metamaterial in the infrared regime

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ABSTRACT

We present the design, characterization and experimental demonstration of a polarization insensitive and wide-angle plasmonically induced transparency (PIT) planar metamaterial (MM) in the near infrared regime. The experimental results show qualitative agreement with the simulated results. It proves that localized asymmetry leading to the plasmon-assisted interaction is the key to produce the PIT phenomenon in MMs, but it does not mean that the PIT phenomenon must depend on the polarization and the angle of incident waves. This kind of PIT planar MMs will help to overcome some of the limitations of customary designs demonstrated so far. Our work will offer a further step forward to the capability of optical modulation.

Keywords: plasmonically induced transparency, polarization insensitive, wide-angle

1 INTRODUCTION

Plasmonically induced transparency (PIT) in metamaterials (MMs) is a fascinating phenomenon of making the otherwise opaque metamaterial transparent, which mimics quantum interference effect of electromagnetic induced transparency (EIT) in laser-driven atomic systems [1-4]. As the inherent limitations of EIT in application, PIT has received much attention due to the prominent advantages of room temperature manipulability, artificially controlling spectral response and the ability to integrate with nanoplasmonic circuits.

In spite of many obvious advantages, the previous designed PIT devices principally have an inherent disadvantage. They strongly depend on the polarization and the angle of incident waves as the asymmetry of the structures. Most studies demonstrate that introducing a broken symmetry to the spatial arrangement of the bright and dark resonators is a prerequisite for PIT, since the asymmetry permits the excitation of the otherwise forbidden dark mode. The degree of asymmetry determines the coupling strength of the bright and dark modes. Therefore, the previous devices also strongly depend on the incident angle.

In this paper, we present the design, characterization and experimental demonstration of a PIT planar MM in the near infrared regime. We demonstrate that the PIT phenomenon can be realized by symmetrical planar MMs.

2 STRUCTURE DESIGN AND SIMULATIONS

The proposed PIT planar MM fabricated on a quartz substrate, in which the top metallic layer consists of four rotationally aligned “=” pairs, as shown in Fig. 1. The optimized structure was achieved by using the finite element method (FEM) based commercial software COMSOL Multiphysics [5]. The three-dimensional simulations were performed with a plane wave source incident in the *z* direction. Periodic boundary conditions were used for *x-y* plane, and waveguide ports boundary conditions were used on the other boundaries. The refractive index of quartz substrate is 1.5. The optical constants of bulk gold in the infrared spectral regime are described by the Drude model with the plasma frequency $\omega_p = 2\pi \times 2.175 \times 10^{15}\ \mathrm{s}^{-1}$ and the damping constant and

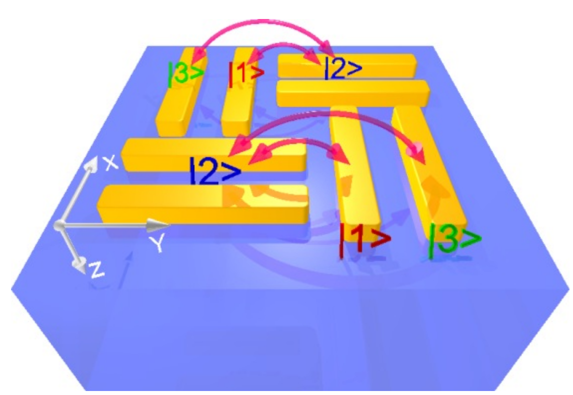

Figure 1: Perspective view of a unit cell of the PIT planar MM. The pink arrows indicate the near-field coupling between meta-atoms.

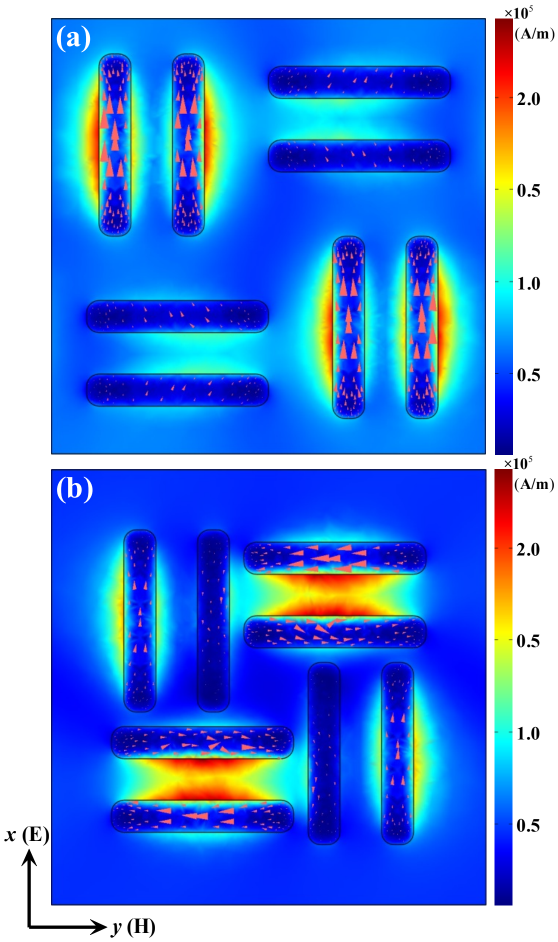

Figure 2: Colormaps and pink arrows respectively represent the distributions of the amplitude of the magnetic fields and induced surface current densities of the top metallic elements at 2.85 μm wavelength for (a) S = 300 nm and (b) S = 60 nm.

the damping constant $\omega_c = 2\pi \times 6.5 \times 10^{12}\ \mathrm{s}^{-1}$ [6]. Owing to the surface scattering and grain boundary effects in the thin gold film, we used a three times higher damping constant than bulk.

We calculated the surface current density distribution and the magnetic field amplitude distribution of the top metallic layer for x-polarized TEM wave at 2.85 μm wavelength, as shown in Fig. 2. The "=" pairs parallel to y-axis, which may function as a magnetic quadrupole antenna, can serve as the dark mode. The "=" pairs parallel to x-axis, which may function as two similar optical dipole antennas, can serve as the bright mode and additional mode. With the maximum interspace S = 300 nm (nearly without coupling to the dark mode), the bright mode and additional mode are strongly excited by the incident beam with strong magnetic field and high surface current densities (as shown in Fig. 2(a)). By decreasing the interspace to S = 60 nm (with strong coupling to the dark mode), the magnetic field and surface current is coupled back to the dark mode (as shown in Fig. 2(b)).

The PIT mode of the designed structure can work over a wide range of incident angles. Figures 3(a) gives the simulated angular dispersion of the transmission spectra for TE polarization in the case of S = 60 nm. For the TE case, the PIT mode is nearly independent of incident angle, since the electric field can effectively provide the strong electric resonance at all incident angles. The polarization insensitive performance and the wide-angle incident beams are important in practical applications. In order to demonstrate the polarization insensitive behavior of the designed PIT planar MM, we plot the transmission spectra as a function of polarization angle for S = 60 nm in Fig. 3(b). Results

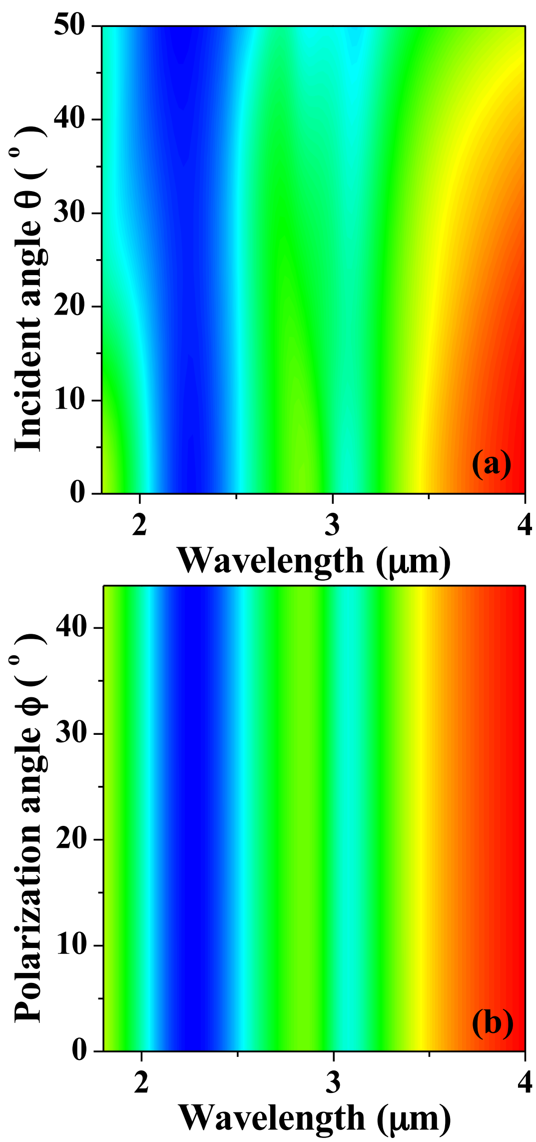

Figure 3: (a) Simulated angular dispersion of the transmission spectra for TE polarization in the case of S = 60 nm. (b) Simulated transmission spectra as a function of wavelength and the polarization angle for S = 60 nm.

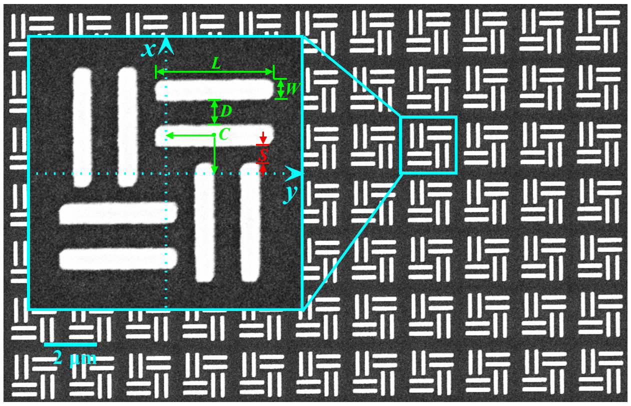

Figure 4: SEM of the sample with S = 140 nm. Inset: The amplified figure of the unit cell, showing the definitions of the geometrical parameters: L = 900 nm, W = 150 nm, D = 200 nm, respectively.

show that the transmission spectra of the designed PIT planar MM are polarization insensitive.

3 EXPERIMENTS

A series of samples were fabricated by standard E-beam deposition and E-beam lithography technique. First, a layer of ITO material (100 nm) was deposited on a 0.5 mm thick quartz substrate by RF magnetic sputtering system. The top patterned layer was defined by electron beam lithography. Then Cr (5 nm)/Au (100 nm) were deposited by electron beam evaporator, and the pattern transfer was completed by lift-off in acetone. Both samples have a total area of 300 μm×300 μm. Figure 4 shows the scanning electron microscopy (SEM) image of the fabricated PIT planar MM. It has a repeat period of 2.1 μm in both the x and y directions.

To study the PIT tuning mode of the designed PIT planar MM, we give the simulated and experimental transmission spectra in dependence of the interspace S in Fig. 5. The PIT mode can be apparently observed from the transmission spectra. The simulated transmission spectra obtained by FEM are show in Fig. 5(a). There is a broad transmission dip in the case of maximum interspace S = 300 nm. Then, a tiny transmission peak emerges within the broad transmission dip with the decreasing of the interspace S. Finally, the transmission peak can reach $T(\omega)$ = 51.2% at 2.85 μm in the case of minimum interspace S = 60 nm.

The transmission spectra are measured at room temperature with a Fourier-transform infrared spectrometer (Bruker VERTEX 70, tungsten lamp) combined with an infrared microscope (36× magnification objective, liquid N_2-cooled MCT 77K detector). The transmission of the sample was recorded by averaging measured data over 64 measurements in order to improve the signal-to-noise ratio. Before measuring the PIT sample, the transmission was calibrated with a blank structure without gold bars.

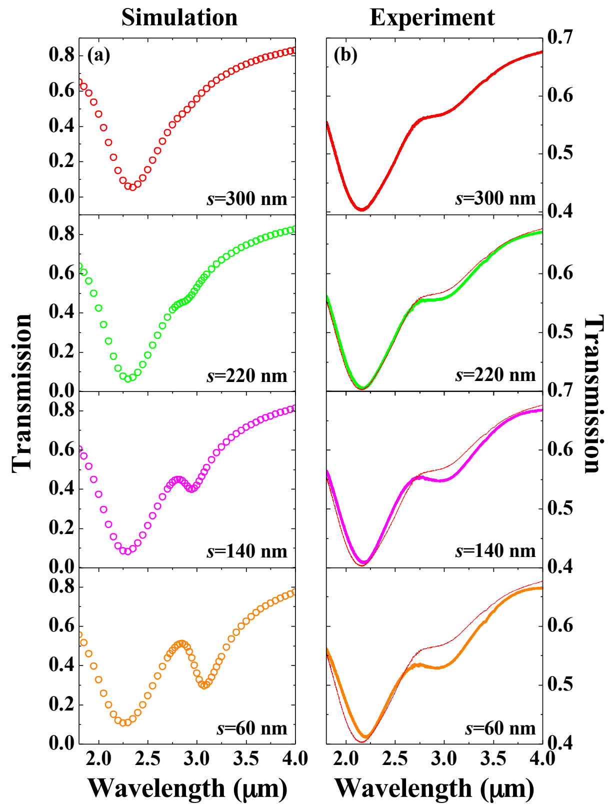

Figure 5: (a) Simulated transmission spectra achieved by FEM for different interspaces S. (b) Corresponding experimental transmission spectra. The transmission spectrum of S = 300 nm is shown in every graph by a fine red-solid line to guide the eyes.

Corresponding experimental transmission spectra in Fig. 5(b) show qualitative agreement with the simulation. These discrepancies between experiment and simulation are likely due to the fabrication tolerances such as the inhomogeneity of the interspace S.

4 CONCLUSIONS

In conclusion, we have numerically and experimentally demonstrated a novel PIT planar MM based on coupled meta-atoms. It proves that localized asymmetry leading to the plasmon-assisted interaction is the key to produce the PIT phenomenon in MMs, but it does not mean that the PIT phenomenon must depend on the polarization and the angle of incident waves. Our work will offer a further step forward to the capability of optical modulation.

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