Final Report for AOARD Grant FA2386-10-1-4041

"Some studies of slow-wave metamaterials and their tunability"

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Research goals

To study novel metamaterial structures for achieving slow waves. To study the applications based on slow wave components. Investigation on the tunability of the proposed structures.

Summary of research results

1. Classical analog of electromagnetically induced transparency

A classical effect of electromagnetically induced transparency (EIT) is demonstrated in a dielectric slab waveguide at visible frequencies. Two nano-sized elliptical silver particles are placed inside the waveguide core layer and their localized plasmonic resonances are utilized to obtain bright and dark states. The destructive interference between the two resonance paths leads to an EIT-like transmission spectrum of the waveguide.

2. Slow light ultra-broadband absorber

We have experimentally demonstrated a microwave ultra-broadband absorber consisting of a lattice array of quadrangular frustum pyramids with a metal film in the bottom layer to suppress the transmission.

3. Tunable Teraherz metamaterial absorber

Metamaterial absorbers can perfectly absorb an incident wave in a narrow frequency band. Here we use metamaterial absorbers to construct terahertz modulators. By controlling the carrier density in the n-doped semiconductor spacer between the patterned metallic superstructure and the homogeneous metallic substrate with different applied voltage bias, the absorption can vary sensitively, and the reflected wave amplitude (acting as the modulated signal) can be strongly

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14. ABSTRACT
This research investigates the properties of slow-wave metamaterials and tunability. Case studies reported include the demonstration of electromagnetically induced transparency demonstration in a dielectric slab waveguide, a slow-light ultra-broadband absorber at RF frequencies, and tunable THz modulators in n-type semiconductors.

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modulated.

4. **Other research results**

Research results in details

1. Electromagnetically induced transparency (EIT) observed in atomic media is a quantum coherent process. The transmission spectrum exhibits a narrow transparency window when a pumping light is present. The group velocity of a probing optical pulse may be greatly reduced (i.e., a slow wave) as a result of very steep dispersion. A slowing-down factor up to seven orders can be achieved by employing the EIT technique.

In this project, we have achieved an EIT-like phenomenon inside a single-mode dielectric slab waveguide in which the resonant elements (silver nanoparticles) are placed inside the core layer (see FIG. 1). In contrast to the previous EIT-scheme with a waveguide, resonators located inside the core layer can interact more strongly with the guided mode since most of the energy is confined inside the high-index core layer. Localized surface plasmon resonance ensures a strong response although the resonator is of subwavelength size. Compared with quantum EIT, the transparency window of this device can be easily tuned by adjusting the geometrical parameter of metallic particles inside the waveguide. The work has been accepted by Applied Physics Letters.

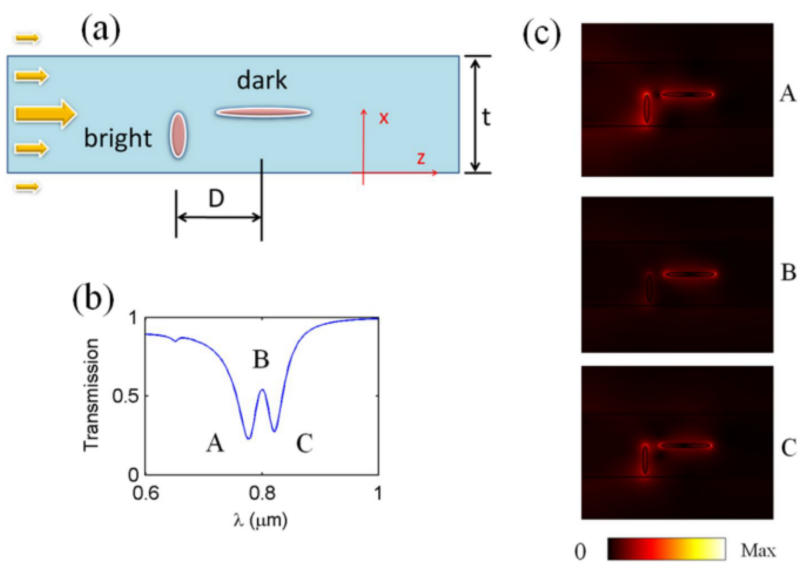

FIG. 1. (a) Configuration for achieving EIT. (b) Plasmon induced EIT transmitting spectrum of the waveguide. (c) Distributions of electric amplitude corresponding to the three wavelength values represented

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by A, B, and C in (b).

2. In our designed absorber structure, several closely positioned propagating modes are supported in the quadrangular frustum pyramid composed of alternating metallic and dielectric patches with taped widths. EM waves with an ultra-wide spectral band are slowed down or even stopped in the quadrangular frustum pyramid structure due to the spatial inhomogeneity of the dispersion curves, leading to ultra-broadband absorption. Fig. 2 shows the image of the designed and fabricated structure.

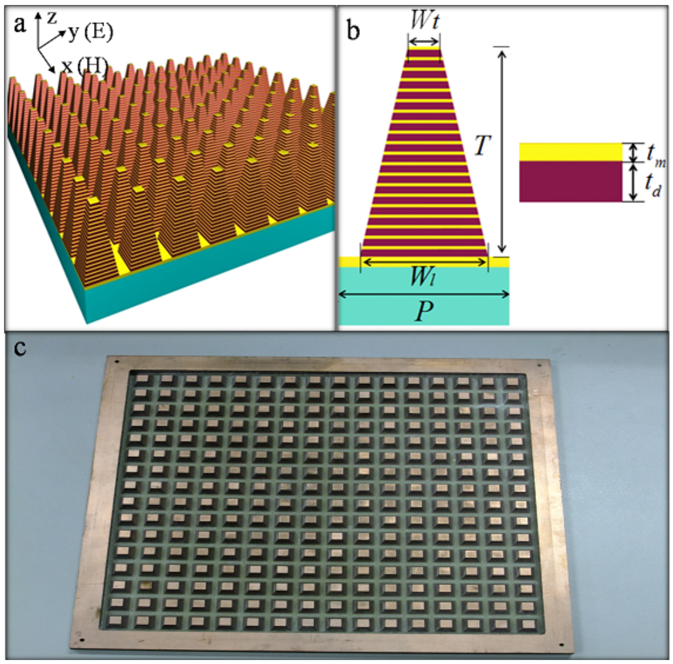
1. 

FIG. 2. Design and fabrication of the microwave ultra-broadband metamaterial absorber. The detailed dimensions are W_t=5, W_l=9, P=11, t_m=0.05, t_d=0.2, **and** T=5 **(all in millimeters).**

Especially, the absorption band can be tuned easily by change the grade of the qadrangular frustum pyramid widths. The bandwidth is more than 60% with respect to the central frequency, as shown in Fig. 3.

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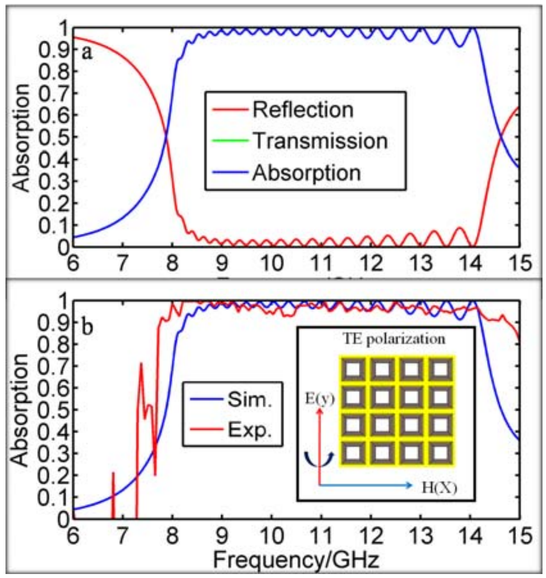

FIG. 3. Simulated and experimental performance of the microwave broadband metamaterial absorber. (a) Numerical simulations of the EM response: Reflection (red line), transmission (green line), and absorption (blue line). (b) A comparison between the experimental absorption (red line) and simulated absorption (blue line). Inset shows TE configuration.

The absorption band is nearly independent of the incident angle below 40°, and as the incident angle increases further the absorption band becomes narrow. Nevertheless, the absorbance still remains above 80% even at 60° (see Fig. 4).

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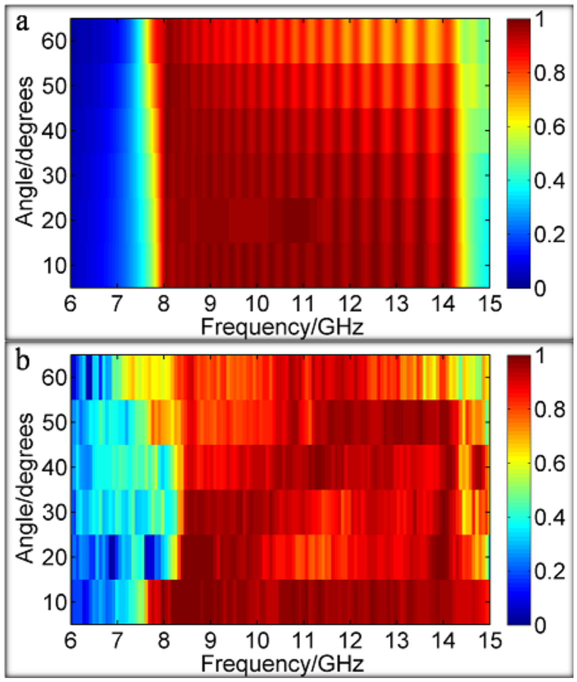

FIG. 4 The simulated (a) and experimental (b) angular dispersions of the absorbance peak for TE configuration.

3. We have investigated two types of tunable absorbers, one of which possesses a cross array as the superstructure, and the other has a complementary superstructure. By controlling the carrier density in the n-doped semiconductor spacer between the patterned metallic superstructure and the metallic ground with different applied voltage bias (see Fig. 5), the absorption can be sensitively varied, and the reflected wave amplitude acting as the modulated signal can be strongly modulated.

The cells fabricated on the top of n-doped GaAs are connected together with thin metallic wires to serve as a metallic gate (Schottky), and a voltage bias is applied between the Schottky and Ohmic contacts.

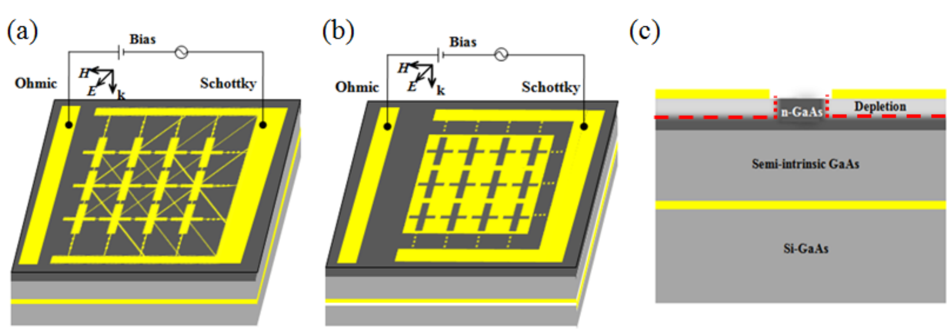

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Fig. 5. Modulators based on the cross absorber (a) and complementary absorber (b). (c) illustrates the depletion region near a gap, where the grey scale indicates the free charge carrier density. The gap may be the gap between neighboring metallic cross arms in (a), or a part of the gap crosses in (b).

Figure 6 shows the absorption spectrum as the increased voltage bias reduces gradually the conductivity in the depletion regions of the original and complementary modulators. For modulation, the absorption variation of the complementary modulator is more sensitive to the conductivity determined by the bias voltage than that of the original modulator. The work has been accepted by Progress in Electromagnetic Research.

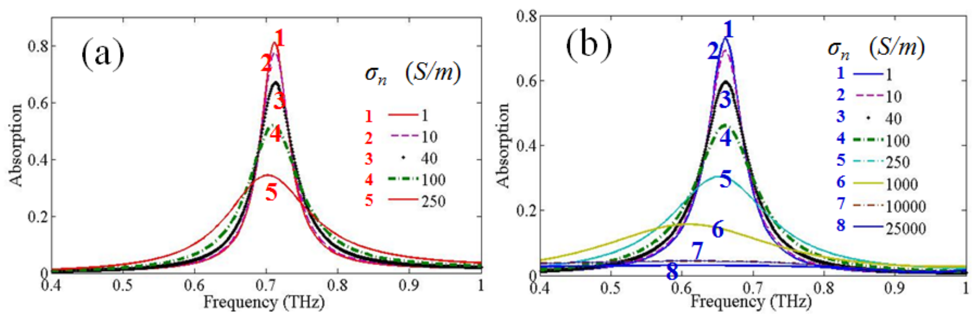

Fig. 6. Absorption as the conductivity in the depletion region is varied by the voltage bias. (a) is for the original modulator, and (b) for the complementary modulator. The conductivity increases from curve 1 as the insert shows.

4. We have also achieved the following results under the support of the present AOARD grant.

a) An electrically small frequency-reconfigurable antenna with a very wide tuning band is proposed. Three varactor diodes are used to achieve the tunable capacitance. With a modified feeding structure, the measured tuning range of the fabricated antenna reaches from 457.5 to 894.5 MHz, and the tuning band enhancement is also explained through an equivalent circuit. [Y. Yu, J. Xiong, H. Li, et al, IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, 10, 103-106 (2011).]

b) A novel ring structure is proposed for double negative NIMs at visible light spectrum with high FOM (e.g. about 11 at a wavelength of 583 nm) and low loss. To obtain special properties of a nearly zero-index metamaterial, it is very critical to reduce the loss (i.e., increase the FOM). Adapted from the original ring structure, two other types of structures, namely, disk and nanowire structures, are also given to further push double negative

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NIMs toward ultraviolet (UV) spectrum. [J. Tang, S. He, OPTICS EXPRESS, 18(24), 25256-25263, (2010).]

c) A simple and compact slot antenna with a very wide tuning range is proposed. A 25 mm open slot is etched at the edge of the ground. To achieve the tunability, only two lumped elements, namely, a PIN diode and a varactor diode are used in the structure. By switching the PIN diode placed at the open end of the slot, the slot antenna can resonate as a standard slot (when the switch is on) or a half slot (when the switch is off). Continuous tuning over a wide frequency range in those two modes can be achieved by adjusting the reverse bias (giving different capacitances) of the varactor diode loaded in the slot. [H. Li, J. Xiong, F. Yu, et al, IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, 58(11) 3725-3728, (2010).]

d) Carpet cloaking is proposed to hide an object on a dielectric half-space from electromagnetic (EM) detection. A two-dimensional conformal transformation specified by an analytic function is utilized for the design. Only one nonsingular material parameter distribution suffices for the characterization. The cloaking cover situates on the dielectric half-space, and consists of a lossless upper part for EM wave redirection and an absorbing bottom layer for inducing correct reflection coefficient and absorbing transmission. [P. Zhang, M. Lobet, S. He, OPTICS EXPRESS 18(17), 18158-18163 (2010)]

e) It is found that the electric field can be enhanced strongly inside a permittivity-near-zero object in free space, when the transverse cross section of the object is small and the length along the propagation direction of the incident wave is large enough as compared with the wavelength. The incident electromagnetic energy can only flow almost normally through the outer surface into or out of the permittivity-near-zero object, which leads to large energy stream density and then strong electric field inside the object. Meanwhile, the magnetic field inside the permittivity-near-zero object may be smaller than that of the incident wave, which is also helpful for enhancing the electric field. [Y. Jin, P. Zhang, S. He, PHYSICAL REVIEW B 82(7), 075118 (2010)]

f) We use both FEM (finite element method) and FDTD (finite difference time domain method) to simulate the field distribution in Maxwell's fish eye lens with one or more passive drains around the image point. Our simulation results indicate that if one uses an active coaxial cable as the object and set an array of passive drains around the image region, what one obtains is not an image of the object but only multiple spots resembling the array of passive drains. We also found that the subwavelength spot around the passive drain is due to the local field enhancement of the metal tip of the drain rather than the fish eye medium or the ability of the drain in extracting waves. [F. Sun, X.Ge, S. He, Progress In Electromagnetic Research, 110, 313-328, (2010).]

g) A new defected ground structure (DGS) is firstly proposed in this paper, which has better slow-wave effect than that of cross ordumbbell one. Using the model of transmission line, its equivalent parameters are extracted. With good omni-directional properties, the proposed DGS is then used in the design of a proximity coupled antenna for its miniaturization. The size of the developed antenna is about 68% smaller than that of the conventional one. Further, two artificial cells are added on the feed line to reduce the protrudent stub length from 26.9 mm to 18.94 mm. Such miniaturization in antenna size has little negative effect on its cross polarization, with both simulated and experimental results presented for comparison. [J. X. Liu; W. Y. Yin; S. L He, Progress In Electromagnetic Research, 107,115-128 (2010).]

List of published papers where the support of the AOARD grant has been acknowledged:

1) Y. He, H. Zhao, Y. Jin and S. He, “Plasmon Induced Transparency in Dielectric waveguide”, Appl. Phys. Lett. 2011 (accepted)

2) L. Qiang, D. Wang, et al, “Localized surface plasmon resonance enhanced organic solar cell with gold nanospheres”, APPLIED ENERGY, 88(3), 848-852, (2011).

3) Y. Yu, J. Xiong, H. Li, et al, “An Electrically Small Frequency Reconfigurable Antenna With a Wide Tuning Range”, IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, 10, 103-106 (2011).

4) J. Tang, S. He, “A novel structure for double negative NIMs towards UV spectrum with high FOM”, OPTICS EXPRESS, 18(24), 25256-25263, (2010).

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5) H. Li, J. Xiong, F. Yu, et al, "A Simple Compact Reconfigurable Slot Antenna With a Very Wide Tuning Range", IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, 58(11) 3725-3728, (2010).

6) B. Wang, M. A. Dundar, et al, "Photonic crystal slot nanobeam slow light waveguides for refractive index sensing", APPLIED PHYSICS LETTERS 97(15), 151105 (2010).

7) P. Zhang, M. Lobet, S. He, "Carpet cloaking on a dielectric half-space", OPTICS EXPRESS 18(17), 18158-18163 (2010)

8) Y. Jin, P. Zhang, S. He, "Abnormal enhancement of electric field inside a thin permittivity-near-zero object in free space", PHYSICAL REVIEW B 82(7), 075118 (2010)

9) F. Sun, X.Ge, S. He, "Can Maxwell's fish eye lens really give perfect imaging? Part II. The case with passive drains", Progress In Electromagnetic Research, 110, 313-328, (2010).

10) J. X. Liu; W. Y. Yin; S. L He, "A new defected ground structure and its application for miniaturized switchable antenna", Progress In Electromagnetic Research, 107,115-128 (2010).

A few other papers are in press.

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