We experimentally and theoretically demonstrate an approach enabling construction of a scalable multi-layered metamaterial media supporting multispectral plasmon induced transparency. A perturbative model incorporating hybridization and mode coupling is introduced to explain the observed novel spectral features.

Multi-Spectral Plasmon Induced Transparency with Hybridized Metamaterials

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Abstract

In this paper, we introduce an approach enabling construction of a scalable metamaterial media supporting multispectral plasmon induced transparency. The composite multilayered media consist of coupled meta-atoms with radiant and subradiant hybridized plasmonic modes interacting through the structural asymmetry. A perturbative model incorporating hybridization and mode coupling is introduced to explain the observed novel spectral features. The proposed scheme is demonstrated experimentally by developing a lift-off-free fabrication scheme that can automatically register multiple metamaterial layers in the transverse plane. This metamaterial which can simultaneously enhance nonlinear processes at multiple frequency domains could open up new possibilities in optical information processing.

1. Introduction

Electromagnetically induced transparency (EIT) is an effect observed in atomic physics, where a destructive interference between excitation pathways results in a transparency window in a broad absorption regime. This transparency window is accompanied with an extreme dispersion, hence EIT has been utilized in many different applications ranging from slowing of light pulses to orders of magnitude enhancements in non-linear phenomena. However, demanding experimental constraints restricted a wide utilization of EIT in real-life applications. Classical analogues of EIT observed in photonic and plasmonic systems overcome these experimental constraints [1,2].With these analogues, artificial photonic or plasmonic atoms are constructed which mimic the characteristics of their atomic physics counterparts. However, much of the research effort so far focused on isolated meta-atoms (either plasmonic or photonic) showing EIT-like effects at a single resonant frequency. Instead, creating an artificial complex media that can simultaneously enhance non-linear processes at multiple frequency domains could open up new possibilities.

In this work [3], we are proposing an approach to carry the plasmon induced transparency effect to multiple-spectral positions by extending the structure design into the third dimension and tailoring the near-field interactions within the multi-layered structure. In the 3D structure, multiple hybrid modes of different characters (subradiant and radiant) will be formed at different frequencies and an introduced near-field coupling between these modes will give rise to the observed multi-spectral plasmon induced transparency effect. We are utilizing a recently proposed slot-antenna based planar design and also pi-shaped particle antennas (also known as dolmen structures) as examples [4], however the results are kept general and can be easily applied to a diversity of geometries. Experimental demonstration is il-

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lustrated with a double layer slot-antenna structure. To achieve such 3D structures, we introduce a lift-off free fabrication scheme that can simultaneously register multiple metamaterial layers.

2. Discussion

An illustration of the proposed structure is shown in Fig1(a). Resonant frequencies of the dipole and quadruple antennas are designed to be spectrally overlapping, where quadrupolar antenna's resonance is dark due to its vanishing net dipole moment. An introduced asymmetry (s≠0) in the single-layered structure results in a near-field coupling between the antennas. This is observed as a narrow peak in the simulated reflection spectrum as shown in Fig1(b) (blue curve). For the multi-layered structure, we can see two EIT-like effects at different spectral positions (Fig1(b), black curve). Once stacked in a multi-layered structure, presence of strong near-field coupling between the meta-atoms causes splitting of the EIT resonances and leads to multi-spectral EIT-like behavior. The underlying physical principles can be explained by plasmon hybridization effects [5] and by near-field coupling between dark and bright hybrid modes of the total system.

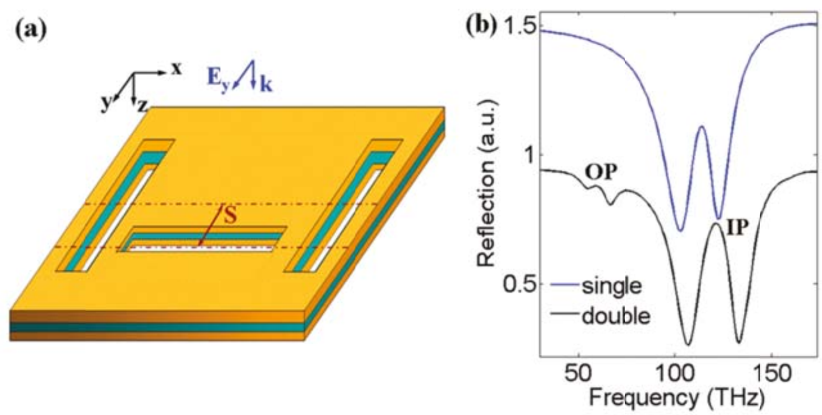

Fig. 1: (a) Geometry of the multilayered metamaterial. Structure consists of two Au layers (30 nm thickness) that are separated by a dielectric (SiNx) layer (70 nmthickness). Each layer has a dipole and a quadrupole slot antenna (all slot antennas have 700 nm length, 100 nm width). The small in-plane separation between the dipolar and quadrupolar antennas is 50 nm on both sides and periods are 1200 nmon both x and y directions. Parameter s is defined as the offset of the dipolar antenna from the geometrical center of the structure. Blue arrows show the configuration of the incident light. (b) Simulated reflection spectra for asymmetric (s≠0) single- and doublelayered structures are shown (with an offset for clarity). Multispectral EIT-like response (in-phase and out-of-phase) is observable with double-layered metamaterial.

The symmetric multi-layered structure's reflection spectrum is shown in Fig2(a) (blue curve). As it is seen, there are two dips corresponding to the in-phase and out-of-phase dipolar hybridized modes. Lack of asymmetry in this case prevents the excitation of quadrupolar modes, which are not directly accessible by the external continuum. Once an asymmetry is induced to the system (s≠ 0), hybridized quadrupolar modes (which are in spectral overlap with hybridized dipolar modes) get excited (Fig2(a) - black curve). This near-field excitation of the dark modes introduces the plasmon analogue of the EIT effect at multiple spectral positions simultaneously. Inset to Fig2(a) shows that at these frequencies the quadrupolar mode is getting excited in major. In-phase and out-of-phase character of the modes is clearly observed in the cross-section charge distributions (Fig2(b)). This effect can be modeled by superposition of multiple coupled Lorentzian oscillators by utilizing the hybrid eigenstates of the total system as the building blocks. A model fit is included in Fig2(a) (red-dashed curve), that traces the calculated spectra near-perfectly. Through this model coupling efficiencies between the hybridized states can be extracted.

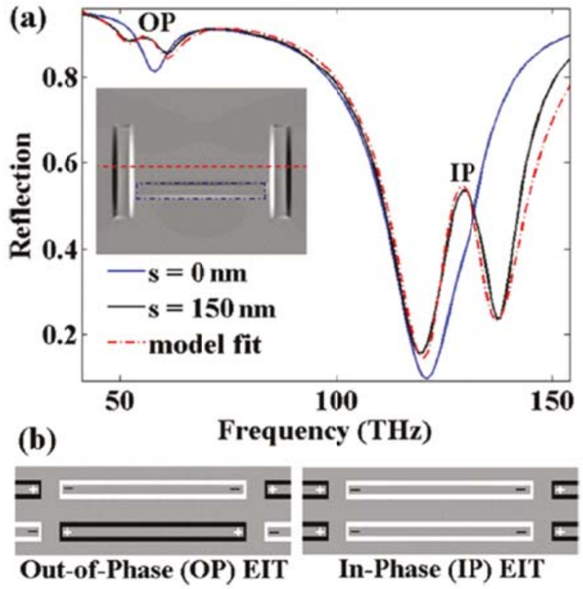

Fig. 2: (a) Asymmetric (s = 150 nm) and symmetric (s = 0 nm) double-layer EIT-like spectra. Two dips seen in the symmetric structure's spectrum corresponds to hybrid dipolar modes. Asymmetric structure shows two EIT-like peaks at different spectral positions. A model fit based on Lorentzian harmonic oscillators is shown for the double layered structure (red dashed curve), which traces the calculated spectra very well. Calculated group indices for the in-phase and out-of-phase modes are n_g= 16 and n_g = 9.3, respectively. Inset shows the top view charge distribution at the air/metal interface for the out-of-phase EIT peak (in-phase EIT peak also shows the same distribution). Stronger excitation of the quadrupolar mode is shown. (b) Cross-sectional charge distributions of the quadrupolar antennas at a position marked with the red dashed line in the inset.

Experimental results demonstrating the multi-spectral plasmon induced transparency effect will also be presented. To achieve the final multi-layered structure, we developed a lift-off free fabrication scheme, where patterning of freestanding dielectric (SiNx) membranes are used as the building blocks. Subsequent metal depositions on the patterned membrane result in the multi-layered structures, which are automatically registered with respect to each other. Very good agreement between the experimental measurements, numerical modeling and analytical calculations will be demonstrated, which also confirms the physical origin of this proposed multi-spectral EIT-like behavior.

3. Conclusion

In conclusion, we present a scheme to extend the EIT-like phenomena to multiple-spectral positions by tailoring the near-field interactions in a multi-layered structure. This effect can be important for a variety of applications ranging from biosensing to optical communication systems. Also it can be a useful tool for certain fundamental research to investigate the interaction between multiple EIT-like responses to increase the efficiency of non-linear phenomena.

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