Multi-Spectral Plasmon Induced Transparency in Coupled Meta-Atoms

Supporting Information

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1. Electric Field Distributions and Enhancements at Plasmon Induced Reflection Peaks

At the plasmon induced reflection peaks fairly high field enhancement values are obtained. Enhanced fields are in the vicinity of the quadrupolar slot antennas as was shown with the cross-sectional charge distributions. For the multi-spectral case, high field enhancement values are observed at the same spatial locations at multiple frequency bands, enabling enhanced light-matter interaction. The cross-sectional absolute electric field distributions for both EIT-like peaks are given in FigS1. Both quadrupolar and dipolar antenna field patterns are included and all field distributions are normalized with a same maximum of 1100 V/m. The shown results are calculated using FDTD with the same structural parameters as shown in Fig1(a). Higher field enhancements can be acquired by utilizing a thinner dielectric layer which will increase the near-field interaction between the constituent metamaterial layers. Also a non-linear medium (such as AlGaAs) can be used as the dielectric support to use the structure in multi-spectral plasmon assisted non-linear applications.

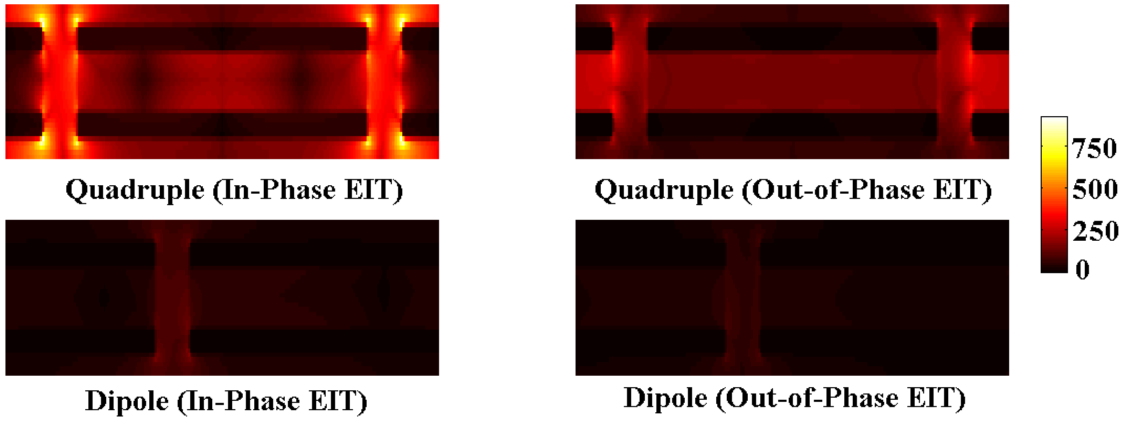

Fig.S1. *Absolute electric field distributions of the hybrid quadrupolar and dipolar modes at in-phase and out-of-phase EIT-like resonance frequencies are shown. Quadrupolar modes are excited in major in both modes compared to dipolar modes. Spatial distribution of the electric field is similar for both EIT-like peaks.*

2. Multi-Spectral Plasmon Induced Transparency with Nanoparticles

To stress the fact that discussed method of multi-spectral EIT-like phenomena is kept general and can be extended to different geometries, we investigate a multi-layered version of the nanoparticle based *dolmen* structures [6]. This structure is comprised of a plasmonic quadrupolar and a dipolar nanorod antenna. A small distance in between the multiple layers is needed to acquire the plasmon hybridization effect that forms the basis of our analysis. Therefore an inter-layer distance of 60 nm is utilized. The geometry of the analyzed multi-layered structure is shown in FigS2(a). The particle sizes are kept exactly the same in both layers and the dipolar antenna has a length of 130 nm and a width of 50 nm, quadrupolar antenna is comprised of two identical nanorods with a length of 100 nm and a width of 30 nm. Thicknesses of both antennas are designed to be 20 nm, and the material is chosen to be Ag. These structural parameters enable an efficient spectral overlap between the quadrupolar and dipolar resonances. The distance between the quadrupolar and dipolar antennas is 60 nm in each layer.

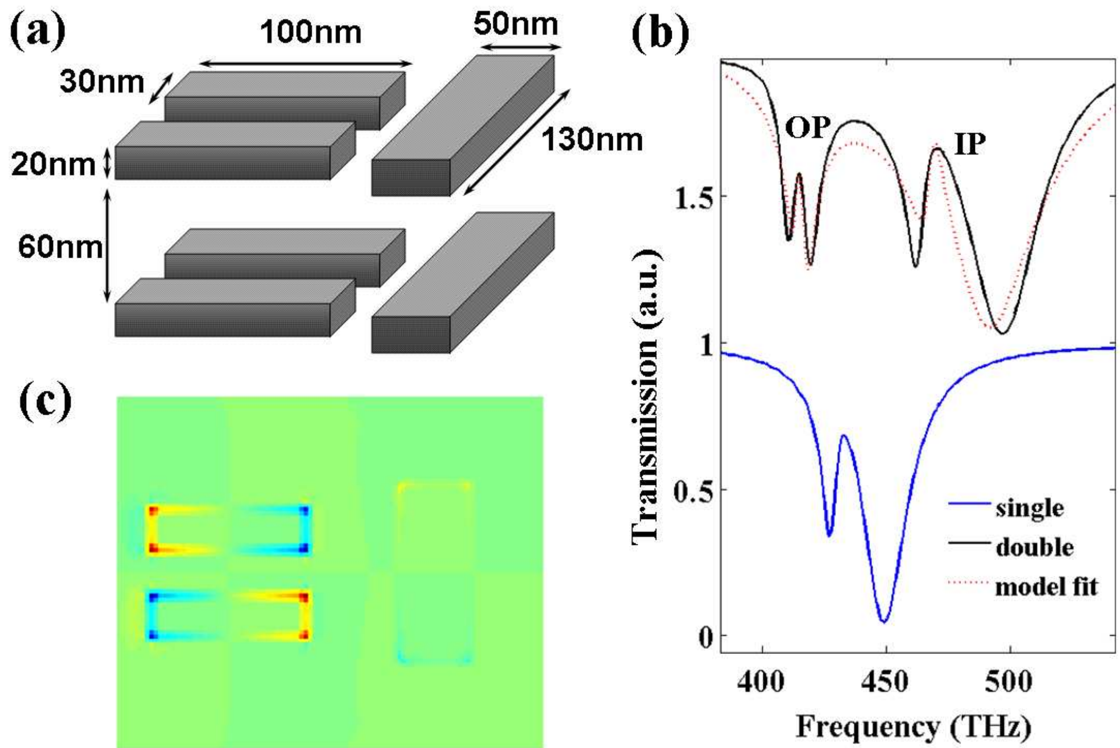

Fig.S2. *(a) Geometry of the multi-layered particle based dolmen structure. The structural parameters are shown, where the inter-layer distance is kept at 60nm. (b) Transmission spectra obtained from a single-layered and a double-layered dolmen structure. Multi-spectral EIT-like behavior (IP and OP) is very clearly observed and a model fit based on coupled Lorentzian oscillators are provided. The extracted parameter are,* κ^+ / κ^- *=28/10 THz,* ω_+ / ω_- = 489/416 THz, δ_+ / δ_- = 20.61/1.42 THz, γ_Q^+ / γ_Q^- = 10/5.61 THz, γ_D^+ / γ_D^- = 72.3/15.6 THz. *(c) Charge distribution of the single-*

layered dolmen structure at the EIT peak. Strong excitation of the quadrupolar mode is evident where there is almost no charge in the dipole antenna.

Once illuminated with a plane wave that is linearly polarized along the long-axis of the dipolar nanorods antenna, *single-layered* nanoparticle based dolmen structure shows a single EIT-like peak in the transmission spectrum (at near infra-red / visible regime) as shown in FigS2(b). This structural design is inherently asymmetric and therefore there is no need to define a geometrical parameter *s*. Amplitude of the EIT-like peak is therefore solely dependent on the distance between the dipolar and quadrupolar antennas. At the EIT-like peak, the major excitation of the quadrupolar mode is seen in FigS2(c), whereas there's almost no charge in the dipolar mode, as expected.

With the addition of the second layer, following the introduced formalism based on the Hamiltonian description and coupled Lorentzian oscillators, we can see that the in-phase and out-of-phase hybridized modes of the multi-layered structure gives rise to the in-phase and out-of-phase EIT-like peaks as shown in FigS2(b). An investigation of the charge distributions for the multi-layered structure as shown in FigS3 demonstrates the expected hybrid mode behavior.

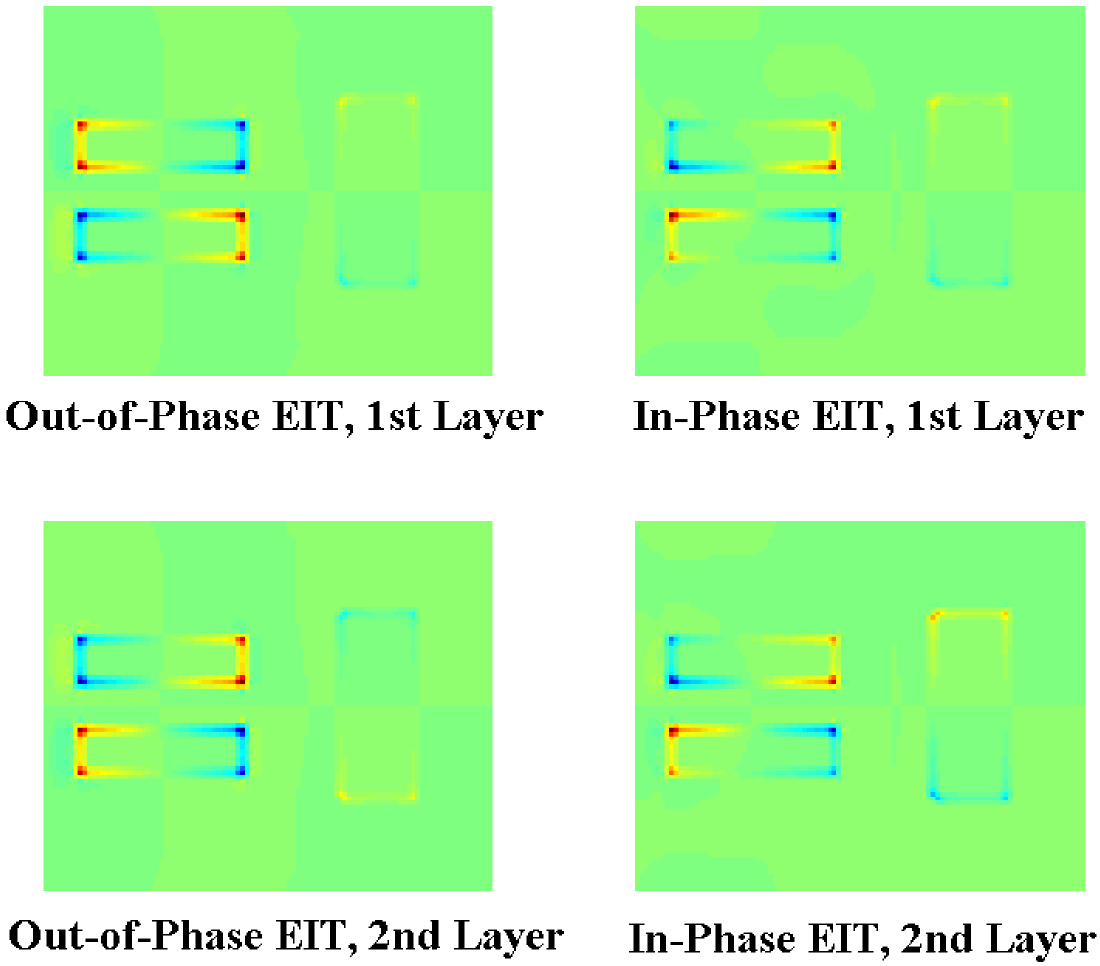

Fig.S3. *Charge Distributions obtained from both layers of the multi-layered dolmen structure at both EIT-like peaks. In-phase and out-of-phase behavior predicted by our model is clearly observed, where in both cases quadrupolar modes are excited in major with very small charge accumulation in the dipolar antenna.*