Plasmonic Metamaterials with Low Spatial Symmetry and Their Applications

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Abstract

Low Spatial Symmetry (LSP) plasmonic structures is a novel building block of optical metamaterials. In this talk I will discuss the potential of LSP metamaterials as platforms for optical devices designed to produce broad-band slow light, transform light polarization, enhance nonlinear effects, and enable highly-sensitive infrared bio-sensing. Fano resonances in LSP metamaterials will be discussed, and experimental results presented. Both metal and dielectric-based metamaterials will be discussed. The results of optical characterization of ordered and disordered arrays will also be presented.

As the sophistication of electromagnetic metamaterials is increasing, there is a growing number of quantum-mechanical phenomena that can be effectively emulated by these new emerging structures. One such phenomenon is the Fano Resonance that was originally observed in atomic systems and later in the solid state. In the context of metamaterials, Fano resonances provide an effective method of radiation lifetime engineering that enables ultra-sharp spectral lines and extremely high electromagnetic field enhancements. The other related phenomenon is the so-called Electromagnetically Induced Transparency. Both phenomena are observed in complex metamaterials supporting several resonances with vastly different radiative lifetimes. This talk will describe a new class of plasmonic multi-resonant metamaterials that exhibit Fano resonances: Low Spatial Symmetry Metamaterials (LSSM). An example of

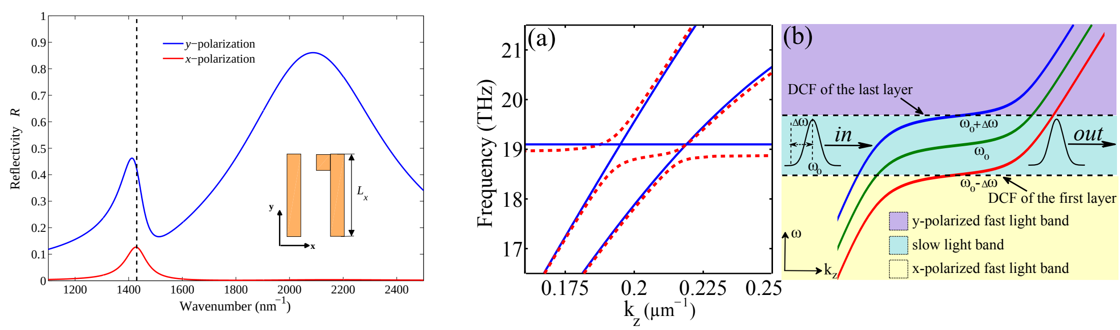

Fig. 1: (Left) Reflectivity spectra of the LSSM Blue and red lines: x- and y-polarized spectra. Dashed vertical line: spectral position Ω_Q of the "dark" (quadrupolar) resonance. (Center) Photonic band structure of a stacked array of LSSMs. Different line styles correspond to the reduction of the spatial symmetry of a metamaterial: from two mirror-symmetry planes (solid) to none (dashed).(Right) Broadband slow light: the medium is comprised of multiple layers of DCF metamaterials with spatially-varying resonance frequency Ω_Q in the $\omega_0 - \Delta\omega < \Omega_Q < \omega_0 + \Delta\omega$ range. The incoming light undergoes polarization transformation and is slowed down.

the unit cell of such metamaterial is shown as an inset in Fig. 1(left). The unit cell possesses no mirror symmetries whatsoever.

Plasmonic LSSMs is a novel and exciting recent development in the area of electromagnetic metamaterials because they truly represent building blocks unavailable in Nature. Specifically, while most molecules and atoms possess at least some degree of spatial symmetry (e.g., a finite number of inversion planes), LSSMs can be designed to have none. This opens us exciting opportunities for making new optical devices that are based on both single-layer and multi-layers. For example, LSPM can be used for efficient polarization manipulation. Three-dimensional LSPM whose properties slowly vary along the direction of light propagation can be used for making slow-light devices [1], as illustrated in Fig. 1(middle) by the dashed line representing the dispersion relation ω versus k. The dispersion curve contains a flat spectral region imbedded inside a spectrally-broad continuum of states. LSSMs can be used for engineering the

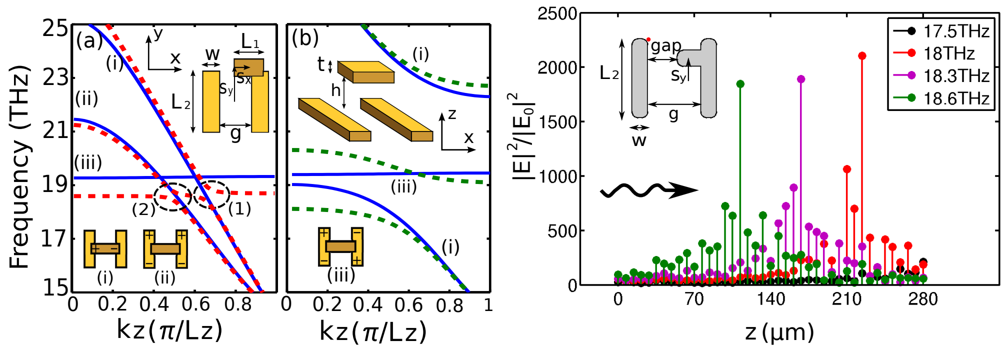

Fig. 2: Photonic Band Structure for slow-light metamaterials based on the DCF resonance (a) and on the EIT (b). The insets show the geometry and dimensions of the unit cell and the three supported resonances: (i) horizontal dipole, (ii) vertical dipole, and (iii) the quadrupole. Solid lines: band diagram computed for a unit cell without symmetry breaking ($s_x = 0$ and $s_y = 0$). (a) Propagation bands for DCF-based metamaterial (dashed lines): $s_x = 700$ nm, $s_y = 2$ μm, $L_1 = 2$ μm. The avoided crossings marked (1) and (2) are caused by $s_y \neq 0$ and $s_x \neq 0$, respectively. Flat portion of the spectrally-extended middle band: slow-light. (b) Propagation bands for the EIT-based metamaterials (dashed lines) with partial symmetry breaking ($s_x = 0$ nm, $s_y = 500$ nm, $L_1 = 3.8$ μm): emergence of slow light for the spectrally-narrow middle band. For (a) and (b): t =400 nm, h =400 nm, L_2 =4 μm, w =800 nm, $g = 2.2$ μm. (Right) Field enhancements of four different frequency components propagating in an adiabatically varying DCF-based metamaterial. Inset: single-layer unit cell. Spectral position of the slow light is adiabatically varied by changing $L_2[\mu m] = 3.75 + z/700$. Field intensity is calculated at the red spot shown in the inset. Other parameters: $s_y = L_2/4$, $w = t = 0.8$ μm, $g = 2.7$ μm, and $gap = 1.7$ μm.

radiative lifetimes of metamaterials because they can be designed to support both ”bright” (radiant) and ”dark” (sub-radiant) resonances. The interference between the two results in the so-called Fano resonance. One attractive feature of LSSMs is that, depending on the light polarization, the same resonance can give rise a Fano-like or Lorentzian line shapes. Such example is shown in Fig. 1(left), where the reflection spectrum of the $y-$polarized radiation has a characteristic Fano shape (blue line), whereas the reflection spectrum of the $x-$polarized radiation has a characteristic Lorentzian shape (red line).

In the talk I will describe the fundamental theory explaining these resonant shapes and present experimental results for the pi-shaped plasmonic antennas. It will be shown that the polarization state of the LSSM is described by a set of simple equations for the dipole-dominant and quadrupole-dominant components characterized by their respective strengths D and Q:

$$\frac{dQ}{dt} = j\omega_Q Q - \left(\frac{1}{\tau_Q^{Oh}} + \frac{1}{\tau_{Qx}} + \frac{1}{\tau_{Qy}}\right) Q + \kappa_{Qx} E_x^{in} + \kappa_{Qy} E_y^{in}, \quad (1)$$

$$\frac{dD}{dt} = j\omega_D D - \left(\frac{1}{\tau_D^{Oh}} + \frac{1}{\tau_{Dx}} + \frac{1}{\tau_{Dy}}\right) D + \kappa_{Dx} E_x^{in} + \kappa_{Dy} E_y^{in}, \quad (2)$$

where variables Q and D characterize excitation intensity in terms of the quadrupolar and dipolar eigenmodes of the meta-molecule with their eigenfrequencies ω_Q and ω_D , respectively, and different contribution to the eigenmodes lifetime were written explicitly. Polarization amplitudes D and Q can be used to obtain the Fano-shaped complex reflectivity spectra:

$$r_{\alpha\beta} = \frac{\kappa_{Q\alpha}\kappa_{Q\beta}}{j(\omega - \omega_Q) + 1/\tau_Q} + \frac{\kappa_{D\alpha}\kappa_{D\beta}}{j(\omega - \omega_D) + 1/\tau_D}, \quad (3)$$

where Greek indexes indicate the polarization (x or y, respectively), and τ_Q and τ_D are total lifetimes of modes. Reflectivity coefficients $|r_{xx}|^2$ and $|r_{yy}|^2$ are shown in Fig. 1(a).

The conceptual difference between Fano resonance (discrete resonance embedded inside the continuum of electromagnetic states) and Electromagnetically Induced Transparency (bright and dark resonances close to each other) will be explained as illustrated in Fig. 2. Slow-light devices based on EIT and the double-continuum Fano (DCF) structures will be compared. Field enhancement predicted by the simulations will be used to evaluate the potential of LSPM-based devices for nonlinear applications. Examples of such enhancements are shown in Fig. 2(right).

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References

[1] Chihui Wu, A. Khanikaev, and G. Shvets, Phys. Rev. Lett. **106,** 107403 (2011).

