Classical to Quantum Transitions in Multilayer Plasmonic Metamaterials

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Abstract: We demonstrate that classical-to-quantum transition of free electron plasma can be used to as a doping-independent parameter controlling optical topology of metamaterials and present a comprehensive description of this phenomenon.

Highly doped semiconductor-based designer metals have emerged as a reliable platform to bring plasmonics to the mid-IR frequency range [1]. Over the years, the designer metal platform has been used to realize selective thermal emitters, high performance absorbers, optical filters, as well as anisotropic (hyperbolic) metamaterials that comprise multiple optically thin designer metal layers separated by undoped semiconductor spacers[1-2]. Hyperbolic metamaterials promise to enable deep subwavelength light manipulation and strong enhancement of optical density of states, two cornerstones that can spur further development mid-IR nano-photonics [3]. Granularity of metamaterials is one of the main limitations of their performance [4]. However, as components of the metamaterials become increasingly thin, their optical response is expected to deviate from bulk values due to quantum confinement effects. In this work we analyze, analytically, numerically, and experimentally, the optical response of semiconductor hyperbolic metamaterials whose designer metal layer undergo the classical-to-quantum transition. We develop an analytical and numerical description of this transition and demonstrate that electron quantization can be used as a doping-independent control mechanism to engineer the optical topology of multilayer metamaterials.

From a homogenized perspective, the two-component multilayer metamaterial, schematically shown in Fig.1(a), represents a uniaxial anisotropic medium whose electromagnetic response can be described by a diagonal permittivity tensor whose components can be related to permittivity of the individual layers via [4]:

$$\epsilon_{xx} = \epsilon_{yy} = \epsilon_{\parallel} = \frac{d_1\epsilon_{1,\parallel} + d_2\epsilon_2}{d_1 + d_2}; \quad \epsilon_{zz} = \frac{(d_1 + d_2)\epsilon_{1,\perp}\epsilon_2}{d_1\epsilon_2 + d_2\epsilon_{1,\perp}}$$

where d_j describe layer thickness ($j = 1$ represents doped "designer metals" and $j = 2$ represent undoped semiconductors), ϵ_1 describes permittivity of doped layers and ϵ_2 represents the permittivity of the undoped dielectric layers. We assume that the in-plane response of the free electrons is adequately described by Drude model [5],

$$\epsilon_{1,\parallel}(\omega) = \epsilon_\infty \left\{1 - \frac{\omega_p^2}{\omega(\omega + i\tau^{-1})}\right\}$$

To characterize the permittivity of the designer metals excited by the field polarized perpendicular to the layers, we assume that their permittivity is related to the interband transitions in the finite-height quantum wells [6],

$$\epsilon_{1,\perp}(\omega) = \epsilon_\infty \left\{1 + \sum_{n=1}^{N} \frac{f_n\omega_{p,n}^2}{\omega_n^2 - \omega^2 - i\omega\tau_n^{-1}}\right\}$$

where ϵ_∞ is the background permittivity, ω_n, τ_n, f_n are the frequency, decay rate, and is the oscillator strength of a given quantum transition [6], and $\omega_{p,n}^2 = Ne^2/m^*\epsilon_0\epsilon_\infty$. Our calculations incorporate the non-parabolicity of effective mass as well as the lateral motion of the electrons.

Fig. 1(b) illustrates the permittivity $\epsilon_{1,\perp}$ for four different confinement scales (layer thicknesses) with other parameters (doping, material structure, etc) being constant. It is seen that for the samples with thicker layers, HMM1 (80 nm) and HMM2 (33 nm), the approach proposed here largely recovers conventional Drude model. The onset of deviation from the bulk Drude response can be quantitatively described by a semi-classical analytical model. However, as the confinement scale decreases to HMM3 (9.5 nm) and HMM4 (5.5 nm) the response of the dopants significantly deviates from bulk Drude predictions and eventually transitions to that of a single-oscillator.

Naturally, modulation of the permittivity of one of the layers of metamaterials yields changes in the effective medium response of the metamaterial as a whole. This process is illustrated in Fig.1(c). Importantly, the confinement scale plays the role of a control parameter (in addition to doping and effective mass) that can be used to engineer the electromagnetic response of a metamaterial. In particular, metamaterials with 9.5-nm and 33-nm thicknesses have drastically different optical topologies (for example, at $6\mu m$ HMM3 is hyperbolic while HMM1 is elliptic).

Four metamaterials with identical total thickness were fabricated with Molecular Beam Epitaxy, according to specifications of HMM1…HMM4, described above. The optical response of these samples was characterized by angle and polarization dependent FTIR reflection and transmission spectroscopy and was calculated theoretically using transfer-matrix formalism that incorporates effective medium approach, as described above. The comparison between numerical calculations and experimental data is shown in Fig.1(d…g). It is clearly seen that modulation of the thickness of individual component of the composite yields strong modulation of optical response of the composite as a whole. It is also seen that our theoretical techniques adequately describe the observed transition, demonstrating quantum-induced control of optical topology.

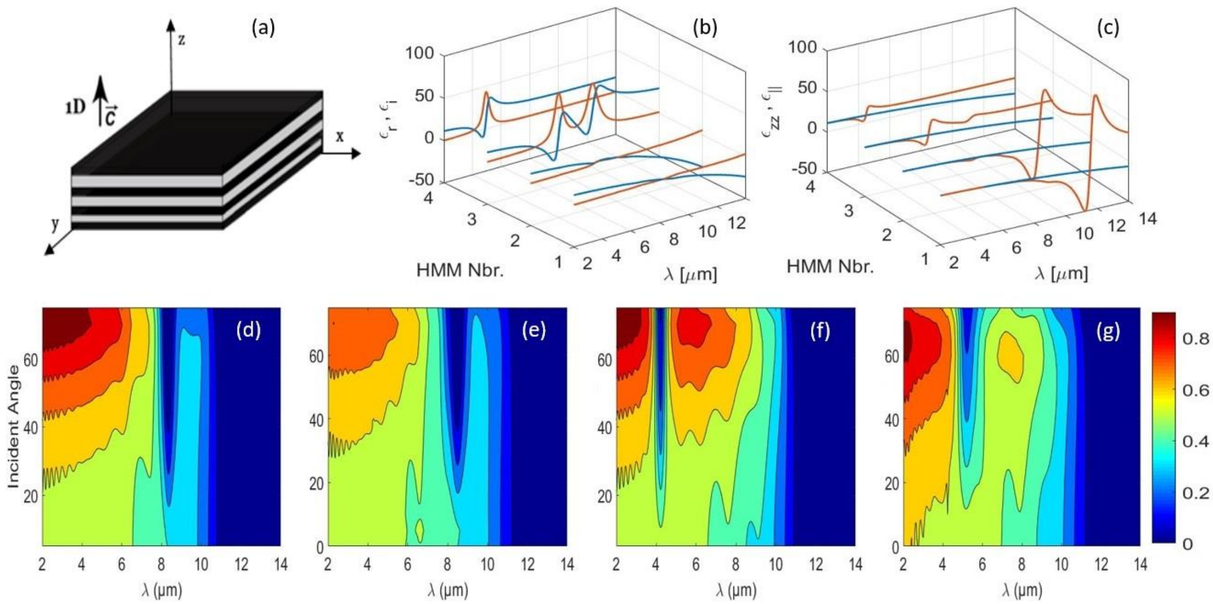

Figure 1: (a) Layered metamaterial with optical axis aligned with azimuthal direction. (b) The real (blue lines) and imaginary (orange lines) components of the parameter $\epsilon_{1,\perp}$. (c) real parts of effective-medium permittivity ($\epsilon_{||}$) (blue lines) and (ϵ_{zz}) (orange lines) different samples. (d…g) wavelength- and angle-dependent transmission of metamaterials HMM1 (d,e) and HMM4(f,g) obtained theoretically (d,f) and experimentally (e,g).

The quantum-confinement-driven change in optical topology is expected to affect density of optical states, and thus will have implications in the design of future detectors, emitters, and other optical components by offering an additional control parameter to alter the optical response of a selected material system.

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