Fano resonance engineering in a slanted hyperbolic metamaterial cavity

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We present the possibility to engineer Fano resonances in multilayered hyperbolic metamaterials based on a central slanted section. The key concept is interference between a propagating and a rarely analyzed evanescent mode inside the slanted section that allows for highly tunable resonances. The propagating mode can reach extremely high effective indices, making the realization of deeply subwavelength cavities as small as 5 nm possible. These phenomena cannot be described using effective medium theory. The developed resonances are very sensitive to any structural changes and could be useful for sensing applications.

Introduction

Control of light is a major research direction over the last decades. Thanks to the progress in nanofabrication, metamaterials and their subwavelength features have generated a large scientific interest for their abilities to govern electromagnetic fields [1, 2, 3]. Among these materials, hyperbolic metamaterials (HMMs), obtained classically with a periodic stack of subwavelength metal and dielectric layers, present multiple interesting properties such as a very large density of states [4], an extreme refractive index and negative refraction [5].

Various designs of cavities based on HMMs have been studied [5, 6]. The purpose of this paper is to present the possibility to create Fano resonances inside very compact cavities based on slanted multilayer HMMs.

Fano resonances are asymmetrically shaped resonant phenomena that arise from the interference between a slowly varying background and a narrow resonant process [7]. Stemming from the interplay between two distinct mechanisms, the resonances are very sensitive to small changes, rendering them in particular interesting for sensing applications [8].

Through rigorous numerical simulations and a thorough modal analysis, we show the origin of these Fano resonances is the simultaneous excitation of a propagating and a rarely exploited evanescent mode inside the cavity.

Geometries and optical parameters of the structures

We numerically study the transmission and reflection of light for normal incidence along the x direction (so $k_y = 0$) of a HMM with a finite section of tilted layers in the center (Fig. 1). The parameters describing the central tilted section are the vertical offset A, the horizontal offset B, the parallel length L and the tilt angle θ.

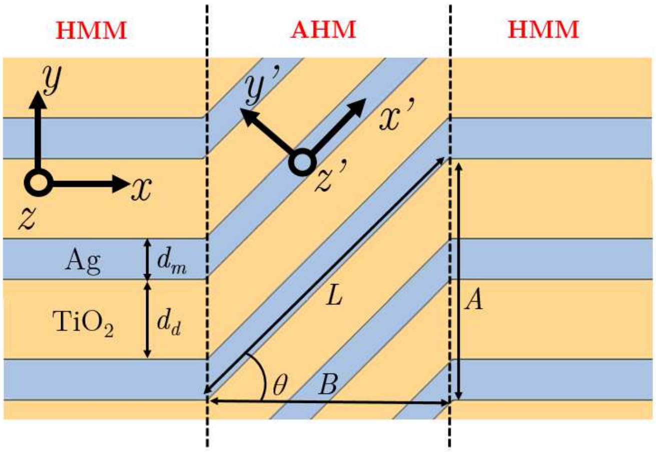


Figure 1: Described geometry. The modes are excited from the left. The structure is divided in three parts along the x direction: Two identical HMMs on the left and right and an asymmetrical HMM (or AHM) in the center.

We use silver (Ag) as the metal that we model with a lossless Drude model $\varepsilon_{\mathrm{Ag}} = 1 - \frac{\omega_p^2}{\omega^2}$ (with $\omega_p = 1.26 \times 10^{16}$ Hz the plasma frequency) and a dispersionless TiO$_2$ as dielectric ($n_{\mathrm{TiO}_2} = 2.7$).

Working with wavelength larger than 600 nm, only one propagating Bloch mode exists in the HMM. We excite the structure from Fig. 1 with this propagating mode at normal incidence ($k_y = 0$) from the left and calculate the reflectance and transmittance for different geometric parameters. The conservation of the momentum in the transverse direction ($k_y = 0$) imposes in the tilted coordinates (x', y'):

$$k_y = k'_x \sin\theta + k'_y \cos\theta = 0 \tag{1}$$

so

$$k'_x \sin\theta = -k'_y \cos\theta \tag{2}$$

Rigorous calculations and analysis

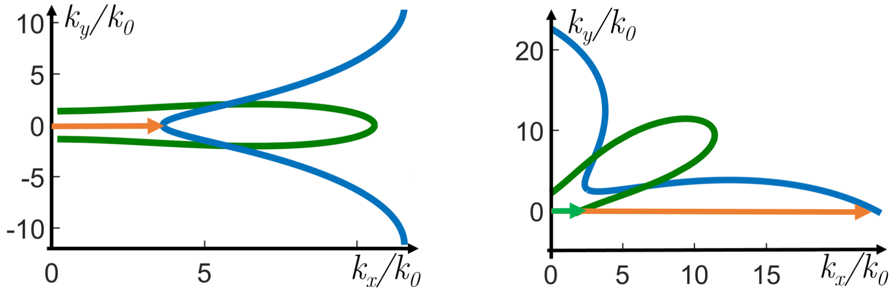
The exact dispersion relation of the HMM is obtained from solving Maxwell's equations and applying Bloch's theorem [9, 10] leading to:

$$\cos(k_y D) = \frac{(\kappa_d \varepsilon_m + \kappa_m \varepsilon_d)^2}{4\kappa_d \kappa_m \varepsilon_d \varepsilon_m} \cosh(\kappa_d d_d + \kappa_m d_m) - \frac{(\kappa_d \varepsilon_m - \kappa_m \varepsilon_d)^2}{4\kappa_d \kappa_m \varepsilon_d \varepsilon_m} \cosh(\kappa_d d_d - \kappa_m d_m) \tag{3}$$

with $D = d_m + d_d$ the period, $\kappa_{d,m} = \sqrt{k_x^2 - k_0^2 \varepsilon_{d,m}}$ the decay coefficients in the dielectric and metallic layers, respectively. Eq. 3 is also valid in the AHM, by replacing (k_x, k_y) with (k'_x, k'_y), $d_{d,m}$ with $d'_{d,m} = d_{d,m} \cos\theta$ and D with $D' = D\cos\theta$.

Two modes satisfy simultaneously this equation and the momentum conservation (Eq. 2) inside the AHM cavity for all tilt angles θ: an evanescent one and a propagating one (Fig. 2).

The orange arrow in Fig. 2a shows the incident momentum inside the HMM. In Fig. 2b, two horizontal arrows are needed to represent the momentum of the two excited modes inside the AHM. The orange arrow represents the momentum of the propagating mode and the green arrow represents the momentum of the evanescent mode.



(a) HMM (b) AHM

Figure 2: Isofrequency contours (a) in the HMM and (b) in the AHM for a tilt angle of 45° in the first Brillouin zone for $\lambda_0 = 700$ nm. Blue curves correspond to propagating waves, green curves correspond to evanescent waves. Conservation of the transverse wavevector is illustrated by the orange and green arrows.

The interferences between these two modes inside the AHM cavity are responsible for the asymmetric Fano resonances appearing in Fig. 3 (blue solid curve). Indeed, Fano resonances can be described as arising from the interference between the slowly varying background from the evanescent wave (green solid curve in Fig. 3) and the narrow Fabry-Perot oscillations of the propagating mode (red dashed curve in Fig. 3).

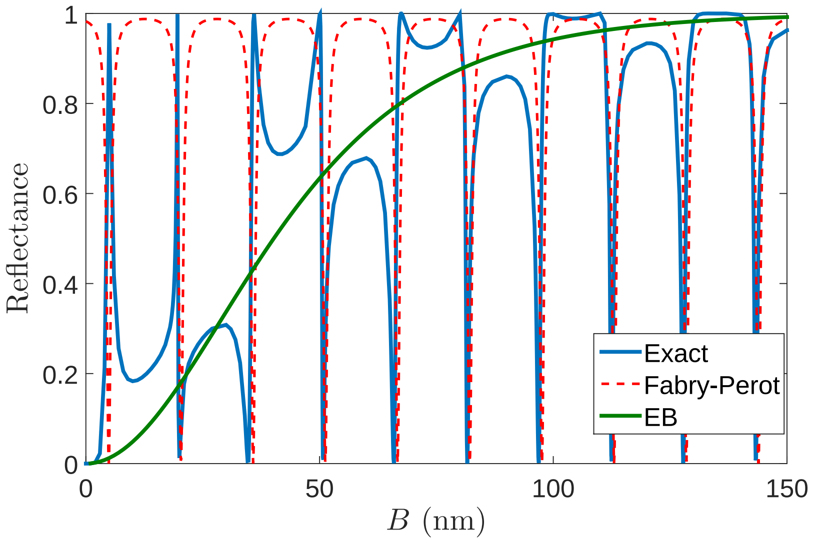


Figure 3: Comparison between the exact reflectance of the structure (blue solid curve) and the background of the evanescent mode (green solid curve, EB) and the Fabry-Perot oscillations of the propagating mode (red dashed curve) for $\theta = 45°$ at $\lambda_0 = 700$ nm.

The very high value of the effective index of the propagating mode inside the cavity leads to the possibility to create very compact cavities, on the order of 5 nm width for $\theta = 45°$ (first peak in Fig. 3). From Eqs 3 and 2, we can show that the effective index of the propagating mode increases with the tilt angle, making the cavity smaller and the resonance peaks narrower.

Conclusion

We show Fano resonances inside cavity made of a tilted multilayer structure under normal incidence. Inside this cavity, a propagating mode and an evanescent mode are always excited simultaneously. The propagating mode is responsible for Fabry-Perot oscillations, while the evanescent mode to a slowly varying background.

Fano resonances arise from the interference between these two modes and their characteristic can be tailored, either presenting total transmittance or total reflectance at resonance, or an asymmetric spectrum.

One should note that effective medium theory cannot explain the existence of these resonances because it only predicts one mode at a time, either propagating or evanescent.

Taking into account metal losses, these Fano resonances still exist [11]. The underlying interference mechanism thus offers new practical possibilities, for instance in the domain of sensing applications.

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