Generation of exceptional points in dye-infiltrated hyperbolic metamaterials in the strong-coupling regime

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We study the properties of active multilayer hyperbolic metamaterials with four-level dyes embedded inside the dielectric. In the strong-coupling regime, both emission and absorption lines cause a distortion of the plasmonic band due to Rabi splitting and a PT-symmetry broken phase with generation of exceptional points at the loss-gain compensation frequencies. We propose a semi-analytical model to describe these phenomena. This structure also overcomes the problem of light in-coupling by pumping the dyes from within the elliptic band inside the light-cone while emission occurs into the hyperbolic band outside the light-cone.

Introduction

Hyperbolic metamaterials (HMMs) are a particular class of metamaterials that presents multiple interesting properties such as a very large density of states [1], an extreme refractive index [2], and negative refraction [3]. However, because of the presence of metal in the structure, nanoplasmonic metamaterials such as HMMs suffer drastically from ohmic losses [4]. The inclusion of gain in the dielectric material offers a solution to compensate losses [5,6,7]. In this paper we present theoretical and numerical studies of the properties of active metal-dielectric multilayer HMMs infiltrated with four-level dyes (Figure 1a) inside the dielectric layers (Figure 1b).

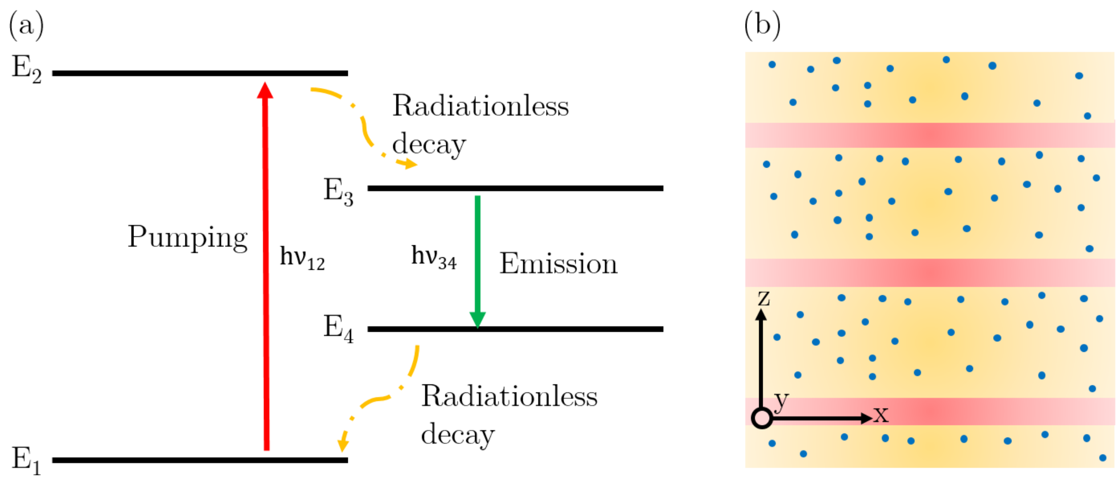

Figure 1: (a) Four-level dye scheme, with absorption line in red and emission line in green. (b) Structure under study: periodic multilayer of metal and dye-infiltrated dielectric.

Because we work in the visible regime, we use silver as metal (that we model with a Drude model $\varepsilon_m = 1 - \frac{\omega_P^2}{(\omega^2+i\omega\gamma_P)}$ with plasma frequency $\omega_P = 1.26\times 10^{16}$ rad/s and damping rate $5 \times 10^{13} s^{-1}$. A commonly used dye is Rhodamine 6G [8] with peak emission around 520 nm (0.288 ω_P) and peak absorption around 480 nm (0.313 ω_P), which we infiltrate inside the dielectric epoxy (n=1.6). In accordance with experimental data we assume linewidths of $\gamma = 0.005\ \omega_P$. To allow optical pumping the absorption line must be accessible from inside the light cone of the structure. For this reason, we choose the thickness of silver to be d_m = 5 nm and the thickness of epoxy d_d = 20 nm in each period, leading to an intersection point between the two plasmonic bands of the structure around 0.3 ω_P. In this configuration, the absorption line lies inside the light cone (Figure 2).

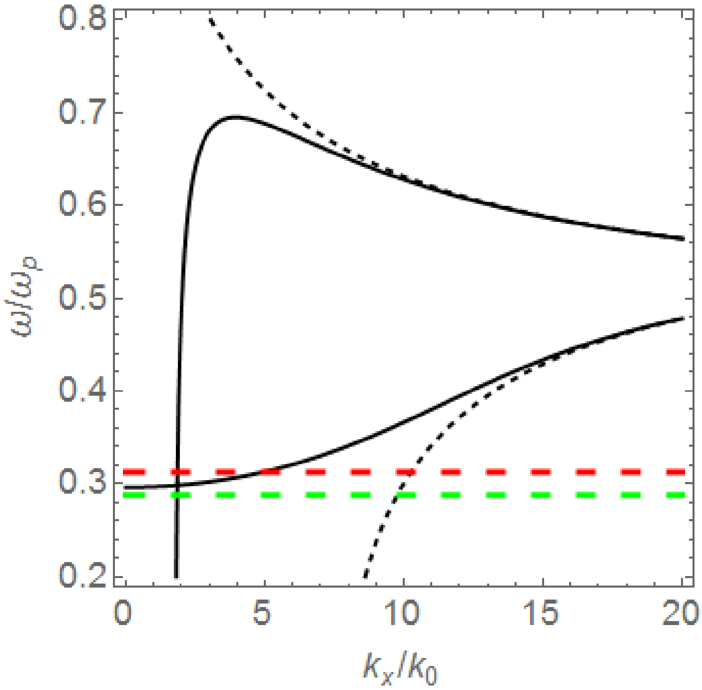

Figure 2: Dispersion of the multilayer of silver and epoxy with d_m = 5 nm and d_d = 20 nm. Black curves are the edges of the plasmonic band, red dashed curve is the absorption line and green curve is the emission line.

Semi-classical model

Because of the four-level nature of the dyes, both emission and absorption lines provide their own polarization and interact with the optical field. Using Maxwell-Bloch equations, we developed a semi-analytical model resulting in three coupled oscillator equations,

$$\partial_t \begin{pmatrix} E \\ P_a/\varepsilon_0 \\ P_e/\varepsilon_0 \end{pmatrix} = -i\tilde{\Omega} \begin{pmatrix} E \\ P_a/\varepsilon_0 \\ P_e/\varepsilon_0 \end{pmatrix} = \begin{pmatrix} -i\Omega_m & iA_m & iA_m \\ iK_a & -i\Omega_a & 0 \\ iK_m & 0 & -i\Omega_e \end{pmatrix} \begin{pmatrix} E \\ P_a/\varepsilon_0 \\ P_e/\varepsilon_0 \end{pmatrix}$$

where E is the modal field amplitude, and P_a and P_e are the polarizations for the absorption and emission line, respectively, Ω_a and Ω_e their complex frequency and $\tilde{\Omega}$ the eigenfrequency of the coupled system. Further, $A_m = \Omega_m \Gamma/2$, where Ω_m is the complex frequency of the optical mode of the unperturbed multilayer and Γ an overlap factor of the mode with the gain media, is a quantity related to the optical modes while $K_a = \sigma_a/\varepsilon_0$ and $K_e = \sigma_e/\varepsilon_0$ are quantities related to the absorption and emission lines. The cross-sections σ_a and σ_e of the excitonic transitions of absorption and emission, are related to the coupling strength of the oscillators via $\boldsymbol{g_{a,e} = \pi\sigma_{a,e}/\varepsilon_0}$. From the Maxwell-Bloch equations, we can show that $\boldsymbol{\sigma_a}$ and $\boldsymbol{\sigma_e}$ have opposite signs. Here we shall focus on the strong-coupling regime, providing exemplary results for $\boldsymbol{g_{a,e} = 10^{14}}$.

Results

We calculated the reflection of a finite 10-period multilayer (with parameters described previously) via transfer-matrix method for both the case without (Figure 3a) and with dyes infiltrated in the dielectric (Figure 3b), and compared the results with our semi-analytical model.

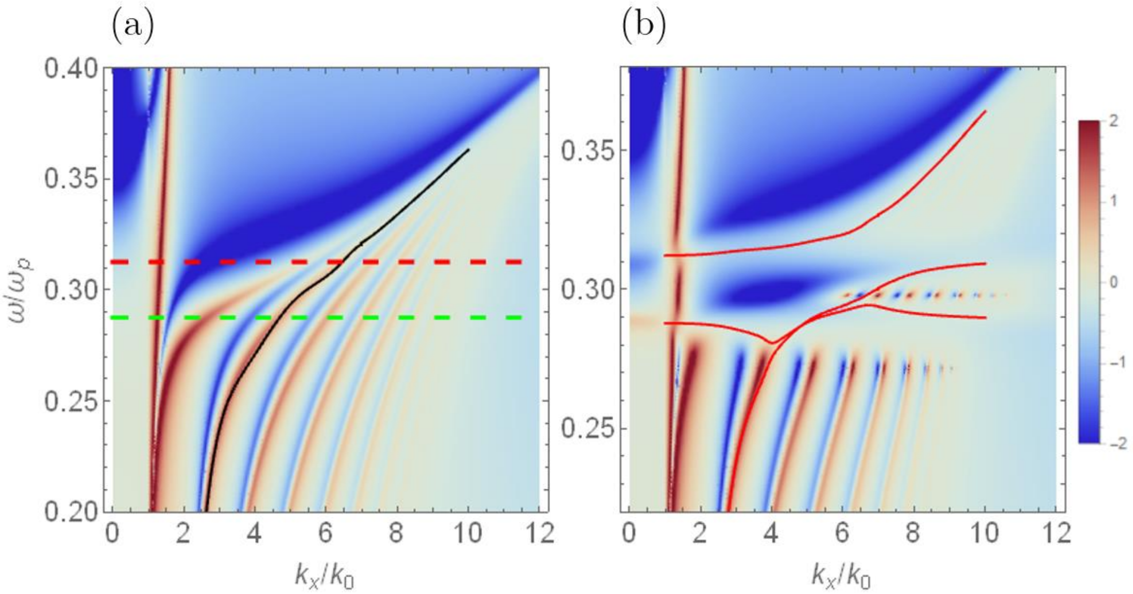

Figure 3: (a) Map of the logarithm of the reflectance for a 10-period multilayer without dyes incorporated in the dielectric. Black curve is the unperturbed optical mode we use for our model, red dashed curve is the excitonic line of absorption and green dashed curve is the excitonic line of emission of the dye. (b) Map of the logarithm of the reflectance for a 10-period multilayer with dyes incorporated in the dielectric, in the strong-coupling regime. Red curve is the dispersion obtained with our semi-analytical model.

We can observe two distinct type of behavior at the excitonic lines. At the absorption line, a typical strong-coupling splitting of the mode occurs and a gap opens. The gap widening is related to the Rabi splitting energy $h\Omega_{Rabi} \approx \sqrt{2K_aA_m}$. As we can see, the semi-analytical model provides an excellent fit to the numerical results. We also note, that our model only requires the parameters of the oscillators (complex frequency and coupling strength), while usual classical and quantum models need to introduce fitting parameters (usually the Rabi energy) to explain mode splitting behaviors [9].

At the emission line, the behavior is completely different as the sign of K_e is opposite to K_a, leading to a “fork-like” splitting of the modes, similar to the PT broken-phase symmetry regime with apparition of two exceptional points for each optical mode.

We can show that the exceptional points effectively appear in infinite multilayers. These exceptional points can be observed by calculating for example the group index in z-direction of the structure $n_{g,z}$ (Figure 4a), the presence of an exceptional point resulting in a divergence of this physical quantity (Figure 4b).

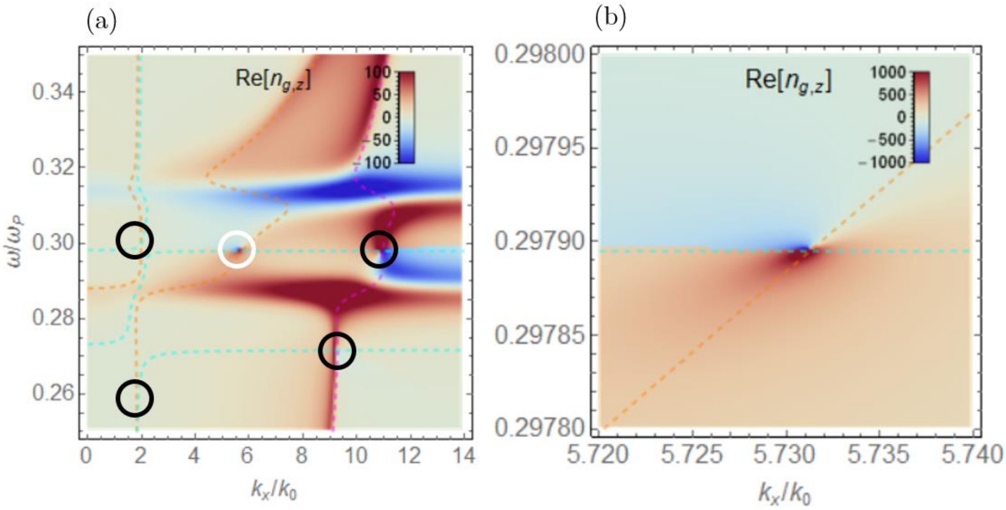

Figure 4: (a): group index in growth direction $n_{g,z}$ of the infinite multilayer. Orange curve is the plasmonic band edge at the center of Brillouin zone, purple curve is the plasmonic band edge at the edge of Brillouin zone and cyan curve shows the region where there is loss-compensation. Circles point out the presence of exceptional points. (b) Same as (a), zoom on the exceptional point delimited by the white circle.

These exceptional points appear exactly at the intersection of the plasmonic band edges (orange and purple curve in Figure 4) and the loss-compensation boundary (cyan curve in Figure 4) where the conditions for degenerate Bloch eigenvalues are met.

Conclusions

We have studied the properties of active multilayer HMMs infiltrated with four-level dyes. In the strong-coupling regime, both emission and absorption lines cause a distortion of the plasmonic band due to Rabi splitting and a PT-symmetry broken phase with generation of exceptional points at the loss-gain compensation frequencies. We developed a semi-analytical model to describe these phenomena and demonstrated that the model fits very well with the exact results obtained by the transfer-matrix method.

References

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