Low Loss Volume Modes in a Slab of Lamellar Hyperbolic Metamaterial

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Abstract. We have studied, theoretically and experimentally, coupling to propagating volume modes in a lamellar metal/dielectric metamaterial with hyperbolic dispersion. Highly efficient light penetration though tens of metamaterial's layers suggests reasonably low propagation loss.

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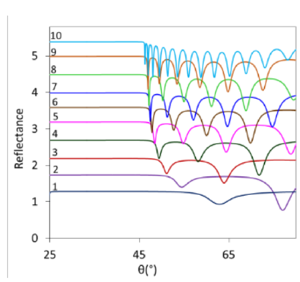
Metamaterials with hyperbolic dispersion (or hyperbolic metamaterials, HMMs), whose dielectric permittivities in orthogonal directions have opposite signs, have generated a lot of interest in the research community because they can propagate electromagnetic waves with nominally infinite wave-vectors and possess a broadband singularity of the photonic density of states [1]. Slabs of lamellar metal-dielectric metamaterials with hyperbolic dispersion were shown to have the waveguide modes, termed volume plasmons or bulk plasmons [1,2], supported by the whole volume of a metamaterial [1,2]. These modes are of potential importance for signal propagation in photonic circuits operating at optical frequencies and stimulated emission at the nanoscale [3,4].

In this work, we have studied, theoretically and experimentally, coupling to the HMMs' volume modes in the Kretschmann geometry and shown that light can penetrate through tens of metallic and dielectric layers without substantial loss. In our studies, lamellar stacks of Ag and MgF_2 layers have been deposited on the 90^o ZnSe prism. The targeted thicknesses of the Ag and MgF_2 films were 25 nm and 35 nm, respectively. Such metamaterial has hyperbolic dispersion at λ>374 nm [5]. The index of refraction of ZnSe (at the λ=860 nm wavelength used in our experiments) was equal to 2.5.

For this experimental configuration, the angular dependent reflectance, $R(\theta)$, and the electric field distribution across the layers, $E_{\text{norm}} = \sqrt{\overrightarrow{E_x}\cdot\overrightarrow{E_x}+\overrightarrow{E_y}\cdot\overrightarrow{E_y}+\overrightarrow{E_z}\cdot\overrightarrow{E_z}}$ were calculated at p polarization using the commercial finite-element-method (FEM) solver, COMSOL Multiphysics. We have found that:

(1) The number of dips in the angular reflectance profile, $R(\theta)$, increased with increase of the number of layers and the overall thickness of the metamaterial stack (Fig. 1).

(2) At the angular position of the first reflectance dip (measured from the normal to the ZnSe / HMM interface) the field distribution, calculated across the metamaterial stack, was characteristic of the $\lambda/2$ standing wave resonance. That at the position of the second dip corresponded to the λ standing wave. The field distribution at the third dip was typical of the $3\lambda/2$ resonance, etc.



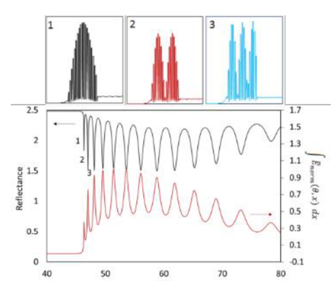


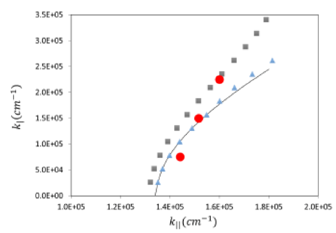
Fig. 1 (left). Angular reflectance profiles $R(\theta)$ $R(\theta)$calculated for 2 pairs of Ag and MgF_2 layers (1), 3 pairs (2), 4 pairs (3), 5 pairs (4), 6 pairs (5), 7 pairs (6), 8 pairs (7), 9 pairs (8), 10 pairs (9) and 20 pairs (10).

Fig. 2 (right). Angular reflectance profile $R(\theta)$ and profile of the electric field E_{norm} at the back metamaterial wall, calculated for the metamaterial slab consisting of 20 pairs of Ag and MgF_2 layers. Upper insets: field intensities calculated across the thickness of the metamaterial slab calculated at angular positions of three first dips in the reflectance profile.

(3) The standing wave resonances above determined y component of the wavevector, k_y (perpendicular to the layers). The x component, k_x (along the layers), was calculated for the angular position of each reflectance dip, θ, knowing the

wavelength, λ, and the refractive index of ZnSe, n. When k_y values were plotted *versus* k_x values, the points were very close to the isofrequency parabolic dispersion curve, which can be calculated for the hyperbolic metamaterial using effective media parameters, Fig. 3.
(4) When the lamellar metal/dielectric stack was replaced with the slab of the effective medium metamaterial of the same thickness, the angular reflectance profile, $R(\theta)$, and the standing wave field distributions were nearly the same as those calculated for the lamellar metamaterial, Fig. 3.
(5) When we calculated the angular distribution of $E_{norm}(\theta)$, measured at the back wall of the metamaterial slab, the maxima of this function corresponded to the angular positions of the dips in the reflectance profile, $R(\theta)$. Thus, the standing wave resonance enhanced the electric field in the volume of the metamaterial slab, which was manifested by increase of the field intensity at its back wall – the quantity, which can be measured experimentally.
(6) Intriguingly, the intensity of the standing wave did not decrease with increase of the thickness of the metamaterial slab up to 10 pairs of metallic and dielectric layers (250 nm of Ag) and showed the sign of reduction only when the number of pairs was increased to 20 (500 nm of Ag). This low loss penetration through the thickness of the metamaterial slab is promising for waveguiding applications, compensation of loss by gain, and stimulated emission in active metamaterial structures.

Experimentally, we deposited ten pairs of Ag/MgF_2 layers onto ZnSe prism and studied the angular reflectance profile, $R(\theta)$, in p polarization at λ=860 nm. The incidence angles (measured from the normal to the ZnSe / metamaterial interface), which could be accessed in our setup, spanned from 40° to 65°. In this angular range, we have observed three dips in the reflectance spectrum, Fig. 4. This experimental angular profile has a fair agreement with that calculated for seven pairs of layers, Fig. 1. Likewise, the experimental and the calculated dispersion curves have the best match at the assumption of seven pairs of layers, Fig. 3. After the first series of measurements, another ten pairs of Ag/MgF_2 layers have been added to the same sample. Surprisingly and in contrary to the theoretical predictions, the reflectance profile of the twice larger sample changed only very little, by ~1°. We infer that the disagreement between the model and the experiment was caused by imperfections of the metamaterial sample.



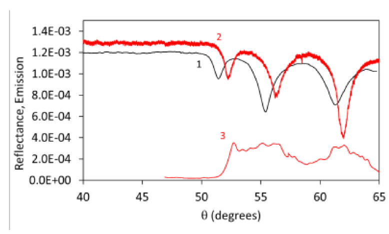


Fig. 3 (left). Isofrequency dispersion curves obtained by plotting the positions of the minima in the angular reflectance profile calculated for the lamellar metamaterial slab (squares); same for the effective medium metamaterial slab (triangles); calculated in the effective medium approximation (solid line); and obtained from the experimental reflectance profile, assuming that the metamaterial slab consists of 7 pairs of Ag and MgF_2 layers (large circles).

Fig. 4 (right). Experimental angular reflectance profiles R (traces 1 and 2) and corresponding profile I of the 'back spot' intensity (3). Trace 1 – 10 pairs of Ag and MgF_2 layers, traces 2 and 3 – 20 pairs of Ag and MgF_2 layers.

As the first dip in the reflectance profile, $R(\theta)$, was observed during the angular scan, the bright spot has emerged on the back of the metamaterial slab. When the CCD camera was set to monitor the back of the slab during the scan, we were able to record the angular profile of the 'back spot' intensity, $I(\theta)$, along with the angular profile of reflectance, $R(\theta)$, Fig. 4. The two profiles approximately corresponded to each other (the maxima in the $I(\theta)$ profile were fairly aligned with the minima in the $R(\theta)$ profile), in accord with the theoretical predictions, see the calculated profiles $R(\theta)$ and $E_{norm}(\theta)$ in Fig. 2. Although difficult to quantify, the back spot was bright and easy to observe, in agreement with the model prediction of efficient penetration of light through multiple metamaterial layers. For comparison, no penetration of light is possible through Ag film of equivalent thickness (≥200 nm).

To summarize, we have studied coupling to propagating volume modes in a lamellar metal/dielectric hyperbolic metamaterial. Highly efficient light penetration though tens of metamaterial's layers suggests that the modes have reasonably low loss and can be of importance for photonic circuits and stimulated emission at the nanoscale.

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