Waveguide stopped light mediated by hyperbolic to standard mode transition

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Hyperbolic metamaterials (HMMs) are uniaxial materials that have hyperbolic dispersion curves. There are two types of hyperbolic metamaterials, type I that has described by a permittivity tensor with $\varepsilon_{||} > 0$ and $\varepsilon_{\perp} < 0$, and type II that has $\varepsilon_{||} < 0$ and $\varepsilon_{\perp} > 0$. Planar waveguides with hyperbolic materials has been studied with propagation direction along the principal axis of the dielectric tensor only. They showed that the modes features anomalous ordering in such a way that cut-off appears for lower order modes as light frequency increases. Interestingly, stopped light featuring null group velocity at specific wavelengths for modes near cut-off has been predicted in type II HMMs planar waveguides for optical axis (OA) oriented along the propagation direction [1]. Here, we theoretically study light propagation in type II HMMs planar waveguides for any orientation ϕ of the OA contained in a plane parallel to the waveguides interfaces. The results shows that a change in the wavelength only changes the OA direction ϕ at which stopped light exist. The process is a consequence of the lack of mode cut-off and it is caused by a mode spectroscopy transition from hyperbolic modes, with anomalous order propagating along the OA (ϕ = 0º), to standard guided modes, with normal order, propagating orthogonal to the OA (ϕ = 90º).

We study a three layer system, as it can be seen in Fig. 1a, in which the film and the cladding are the same isotropic material, and the layer in between is a type II HMM. The optical axis of the waveguide is parallel to the interfaces forming an arbitrary angle with the propagation direction. Guided modes of this geometry are obtained using a Berreman method for different wavelengths.

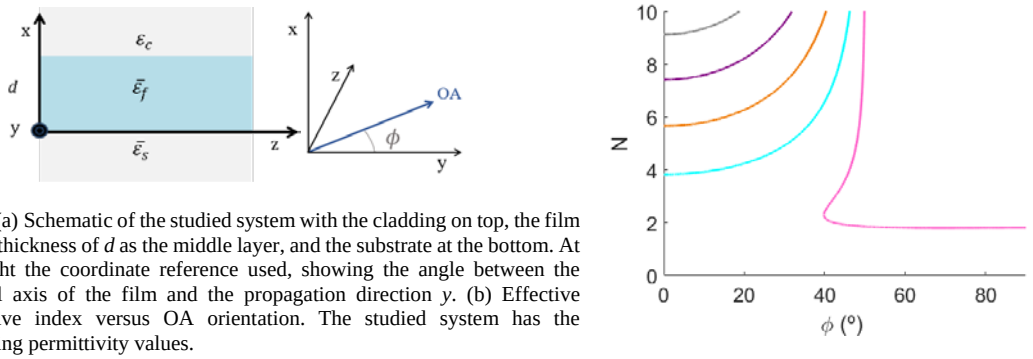

Fig. 1 (a) Schematic of the studied system with the cladding on top, the film with a thickness of *d* as the middle layer, and the substrate at the bottom. At the right the coordinate reference used, showing the angle between the Optical axis of the film and the propagation direction *y*. (b) Effective refractive index versus OA orientation. The studied system has the following permittivity values.

At long wavelength, above a wavelength threshold ($\lambda > 17.5\ d$ in our system), guided modes feature one sheet hyperboloid dispersion surfaces, existing as an infinite set of TM-dominant modes propagating along the OA with anomalous ordering (the fundamental mode shows the lower effective index) [1], while at OA orientation orthogonal to the propagation direction, only TM plasmon-like modes exist. As the wavelength decreases, lower order modes stop existing at propagation directions parallel to the optical axis and they start to transit to propagation directions orthogonal to the optical axis (ϕ = 90º). In this process, the modes exists as a two sheet hyperboloid at intermediated propagation angles, resulting in stopped light at propagation directions where there is the turning point of the two sheet hyperboloid (Fig. 1b). Linked to this phenomenon, backward and forward propagation is observed for the lower and upper branches, respectively [1]. In addition, the TM-dominat, anomalous ordered modes that existed at ϕ = 90º, transform into a lower order TE dominant modes with standard order (the fundamental mode shows the higher effective index). For example, in Fig. 1b, the dominant TM_1 mode in the vicinity of ϕ = 0º transforms into the fundamental dominant TE_0 mode at ϕ = 90º.

As a result, our work shows that hyperbolic waveguide are structures with an infinite number of modes that lack cut-off. Instead, mode transits from a parallel to orthogonal propagation direction with respect to the OA, and from an infinite set of anomalous ordered modes to a finite set of standard ordered modes, resulting in stopped light during the transition. These results can by significant in light trapping, low mode filtering and polarization/order mode conversion in integrated circuits.

References

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