Subwavelength Optics with Hyperbolic Metamaterials: Waveguides, Scattering, and Optical Topological Transitions

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ABSTRACT

Hyperbolic metamaterials possess unique optical properties owing to their hyperbolic dispersion. As hyperbolic metamaterials can be constructed just from periodic multilayers of metals and dielectrics, they have attracted considerable attention in the nanophotonics community. Here, we review some of our recent works and demonstrate the benefits of using hyperbolic metamaterials in plasmonic waveguides and light scattering. We also discuss nonlocal topological transitions in the hyperbolic metamaterials that effectively induce a zero refractive index.

Keywords: hyperbolic metamaterial, plasmonic waveguide, light scattering, optical topological transition, zero refractive index.

1. INTRODUCTION

In optics, while metals are used to reflect light, loss-less dielectrics are used as transparent windows or substrates. Consider periodic metal-dielectric multilayers whose periodicity is much smaller than the wavelength of interest, as shown in Fig. 1. In this case, the optical properties of the multilayer structure are completely different from both the dielectric and metal, and thus becomes extremely anisotropic. This is the simplest metamaterial, called the hyperbolic metamaterial (HMM) [1-3]. With regard to anisotropic materials, some of them are often used in optics such as calcite and liquid crystals. They are uniaxial and both of the permittivity components (ε_o and ε_e) are positive ($0 < \varepsilon_o, \varepsilon_e$). For the case of an HMM, it is uniaxial but the two components have opposite signs, such that $\varepsilon_o\varepsilon_e < 0$ ($\varepsilon_o < 0 < \varepsilon_e$ or $\varepsilon_e < 0 < \varepsilon_o$). This defines the extreme anisotropy of the HMMs.

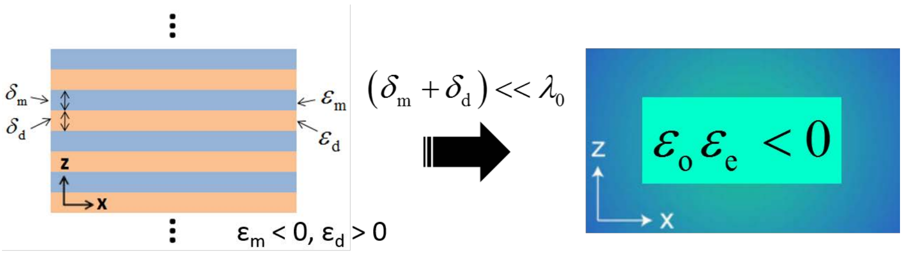

Figure 1. Schematic of a hyperbolic metamaterial (HMM) and its effective dielectric property.

Plotting an iso-frequency curve that shows the available wavevector (k) in k-space at a fixed frequency is an effective way to visualize the optical properties of an HMM. The iso-frequency curve of the HMM is hyperbola, which allows an unbounded wavevector such that the amplitude of the wavevector can be infinitely large in the ideal situation. As a result, in real space an HMM can support wavelengths that are shorter than the diffraction limit.

In the following, we review our recent works using the HMM as the cladding of plasmonic waveguides and as light scatterers in the form of nanoparticles. We also discuss optical topological transitions of the HMMs induced by nonlocality.

2. PLASMONIC WAVEGUIDE CLADDED WITH HYPERBOLIC METAMATERIALS

In this section, the extreme anisotropy of the HMM is applied to modify the mode profile of the plasmonic waveguides [4-6]. Here, we consider the plasmonic waveguides in which symmetric HMMs clad the dielectric core, as shown in Fig. 2(a). In waveguides, it is desirable to have longer propagation lengths and smaller mode sizes. Thus, in our study, we defined a figure of merit as, FoM = (propagation length)/(mode size), and plot the FoMs of the HMM-insulator HMM (HIH) waveguides in addition to two conventional plasmonic waveguides: metal-insulator-metal (MIM) and insulator-metal-insulator (IMI) waveguides. The calculated results are shown in Fig. 2(b). Although the IMI waveguide demonstrated superior performance to other waveguides for wavelengths shorter than 1450 nm, the HIH waveguide starts to outperform in a range longer than 1450 nm.

Plasmonic waveguides are one of the key components for on-chip optical devices because the wavelengths of surface plasmon polaritons can be shorter than those of light propagating in free space. With the MIM waveguides, the mode sizes are subwavelength; however, the propagation lengths are limited. For the IMI waveguides, the propagation lengths can be a few millimeters, but the mode sizes are also on the order of millimeters. The HIH waveguides combine the best features, having small mode sizes as well as long propagation lengths. Such properties are a consequence of the extreme anisotropy of the HMMs.

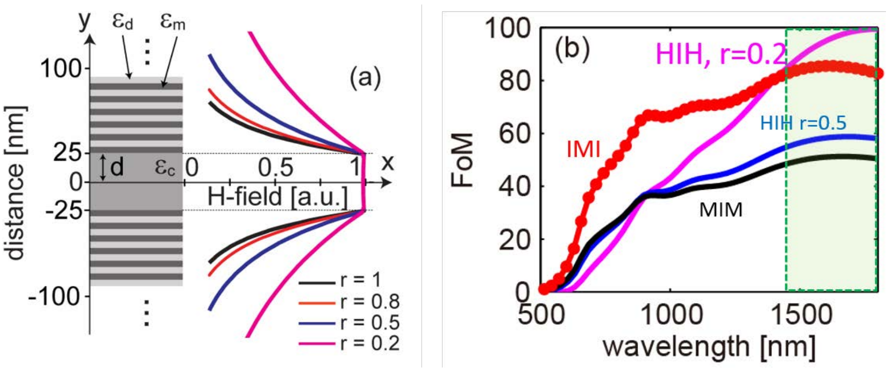

Figure 2: (a) Schematic cross section of an HIH waveguide with different mode profiles. Parameter r defines the volume ratio of the metal in each HMM. When r = 1, an HIH waveguide is equivalent to an MIM waveguide; (b) Figure of merit (FoM) of HIH, IMI, and MIM plasmonic waveguides. In the wavelength range longer than 1450 nm, the HIH waveguide (r = 0.2) outperforms conventional MIM and IMI waveguides.

3. SCATTERING OF LIGHT BY HYPERBOLIC METAMATERIAL PARTICLES

The extreme anisotropy of HMM causes electromagnetic waves to propagate in a certain direction defined by the ratio of ε_o and ε_e. Such beam-like propagation enables hyperlens [7, 8] and subwavelength interference inside the HMMs [9]. In this section, we numerically demonstrate that the extreme anisotropy also affects electromagnetic waves scattered by the HMM in far field.

For this, we consider a spherical HMM nanoparticle in air and study the far-field scattering patterns [10, 11]. The effective permittivity of the HMM is obtained from the periodic silver-silicon multilayers using the effective medium theory (EMT). When the radius is 60 nm, the HMM nanoparticle exhibits a strong resonance at 1564 nm, when the incident angle is parallel to the optical axis, as shown in Fig. 3(a).

Then, we studied the incident angle dependence of the far-field scattering pattern from the HMM nanoparticles at resonance wavelength. In this study, two different incident angles were defined: θ and ϕ are the angles with respect to the optical axis of the HMM for TM- and TE-polarized light, respectively [see Fig. 3(b)].

The incident angle dependences of the far fields are plotted in Fig. 3(c–f). Surprisingly, regardless of the incident angle, the maximum far-field amplitudes always appear at 0 and 180 degrees along the optical axis. The electromagnetic field at the resonance inside the HMM nanoparticles is always along the optical axis because of the extreme anisotropy of the HMM. The incident-angle-independent far-field patterns can be advantageous for optical sensing and light extraction from high-refractive-index materials.

4. NONLOCAL TOPOLOGICAL TRANSITIONS IN HYPERBOLIC METAMATERIALS

So far, the optical properties of the HMM have been discussed by considering the effective permittivities derived from EMT. Although EMT is a simple yet relatively accurate method to estimate the effective permittivities of the HMMs, recent studies have shown that nonlocality in the HMM cannot be negligible for certain conditions [12, 13]. As EMT treats the HMM as homogenous, spatial dispersion, which originates from finite periodicity, is completely ignored. Hence, detailed analysis on the nonlocality of the HMMs is critical to fully understand their optical properties.

In our study, we analytically solved the exact dispersion equations for the HMM without any approximation and elucidated a hidden state (critical state) that is not predicted by the EMT [14]. As the frequency increases, the originally single-sheet connected iso-frequency surface transforms into a conical surface, called the critical state at ω_c. After the critical state, the iso-frequency surface transforms to disconnected hyperboloids.

The evolution of the iso-frequency surfaces in 3D and their cross sections in 2D space are plotted in Fig. 4(a–c). Figure 4(d) illustrates the evolution of the iso-frequency curve with respect to frequency.

In particular, at the critical state, the iso-frequency surface crosses the origin, and thus, the HMMs are a new type of zero-refractive index material. The conical iso-frequency surface also results in conical diffraction. As the topology of the iso-frequency surface determines the optical properties of the HMM, we anticipate that further research on nonlocal optical topological transitions will impact other optical properties such as scattering and nonlinear optics.

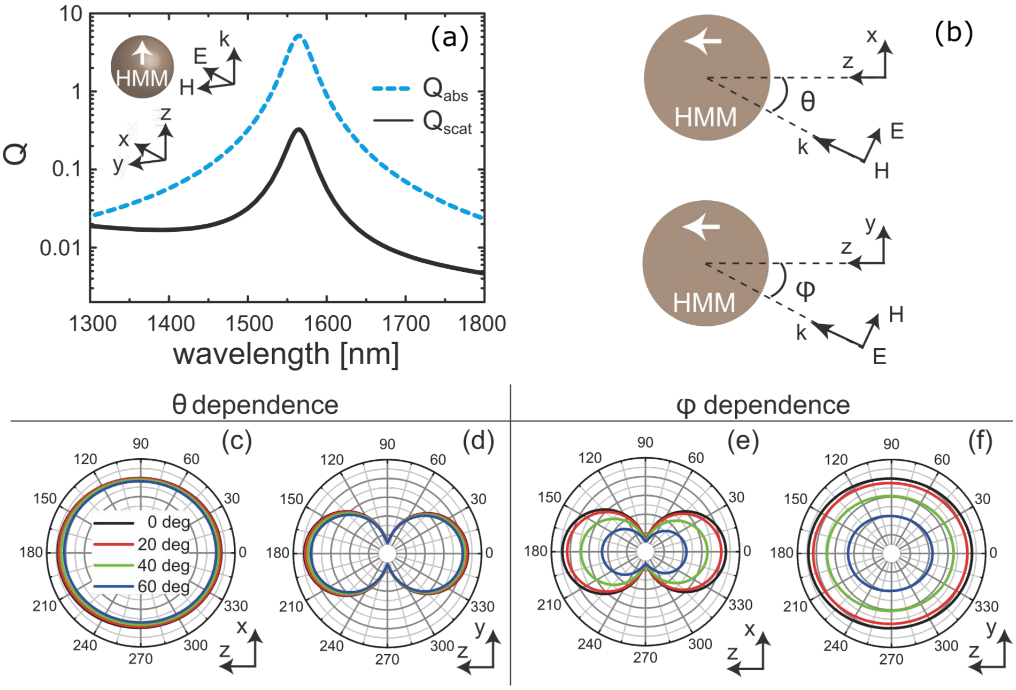

Figure 3: (a) Wavelength dependences of the absorption efficiency (Q_{abs}) and scattering efficiency (Q_{scat}) for an HMM nanoparticle 60-nm in radius; (b) Definition of the incident angles θ and ϕ; (c–f) Incident angle dependences of the far-field scattering patterns at the resonance wavelength.

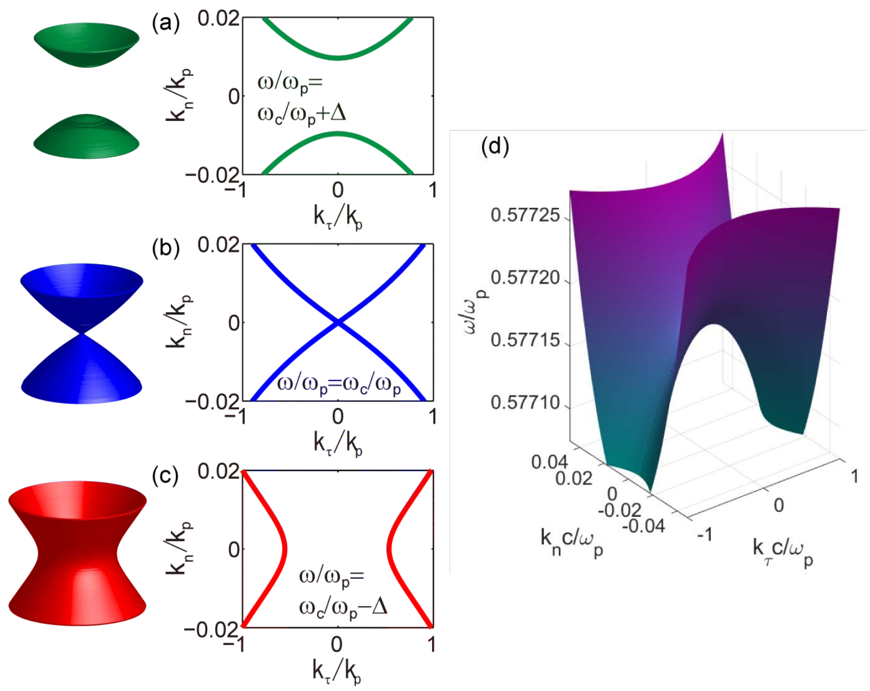

Figure 4: (a–c) Iso-frequency curves of the multilayer HMM in 3D space and in their cross sections in 2D space at $\omega/\omega_p = \omega_c/\omega_p + \Delta$ (a), $\omega/\omega_p = \omega_c/\omega_p$ (b) and $\omega/\omega_p = \omega_c/\omega_p - \Delta$ (c); (d) Evolution of iso-frequency curve with respect to frequency from $\omega/\omega_p = \omega_c/\omega_p - \Delta$ to $\omega/\omega_p = \omega_c/\omega_p + \Delta$. In the entire plots, ω_p represents the plasma frequency of the metal and $\Delta = 2.5 \times 10^{-5}$.

5. CONCLUSIONS

To conclude, multilayer HMMs open wide possibilities in subwavelength optics despite their simple structures. Among several applications so far, we reviewed our recent works focusing on the HMM-clad plasmonic waveguides, light scattering by the HMM nanoparticles, and nonlocal optical topological transitions in the HMMs.

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