# Multilayer Cladding with Hyperbolic Dispersion for Plasmonic Waveguides

**Viktoriia E. Babicheva,[1,2] Mikhail Y. Shalaginov,[1] Satoshi Ishii,[1,3]**
**Alexandra Boltasseva,[1,4] and Alexander V. Kildishev[1,*]**
*[1]School of Electrical and Computer Engineering and Birck Nanotechnology Center, Purdue University, 1205 West State Street, West Lafayette, IN 47907-2057, USA*
*[2]ITMO University, Kronverkskiy, 49, St. Petersburg 197101, Russia*
*[3]International Center for Materials Nanoarchitectonics (MANA), National Institute for Materials Science (NIMS), Tsukuba, Ibaraki 305-0044, Japan*
*[4]DTU Fotonik, Technical University of Denmark, Oersteds Plads 343, Kgs. Lyngby 2800, Denmark*
**kildishev@purdue.edu*

**Abstract:** We study the properties of plasmonic waveguides with a dielectric core and multilayer metal-dielectric claddings that possess hyperbolic dispersion. The waveguides hyperbolic multilayer claddings show better performance in comparison to conventional plasmonic waveguides.

**OCIS codes:** (130.3120) Integrated optics devices; (230.7370) Waveguides; (250.5403) Plasmonics

## 1. Introduction

Engineering plasmonic metamaterials with anisotropic optical properties enables us to tune the waveguide properties [1,2]. One possible approach to achieve the highest mode localization and the lowest propagation losses is to use a hyperbolic material as a guiding medium [3,4]. Recently, properties of plasmonic waveguides with a dielectric core and multilayer metal-dielectric claddings with hyperbolic dispersion (HIH waveguides) were studied (Fig. 1(a)) [5]. It was shown that utilizing a nanostructure with hyperbolic dispersion as a cladding can provide more advantages in comparison to standard metal-insulator-metal (MIM) and insulator-metal-insulator (IMI) plasmonic waveguides, especially in terms of propagation length and mode confinement. Furthermore, the validity of effective medium theory (EMT, Fig. 1(b)) for multilayer homogenization was demonstrated and applicability of EMT when the number of periods is more than ten was proved. By means of rigorous calculations applied to the thinner cladding, eigenmodes inside the cladding of the HIH waveguides of finite width were determined [6]. By finding the eigenmodes of the cladding layers, it was found that their corresponding propagation constants match the dispersion anomalies of the finite-width HIH waveguides. Henceforth, to avoid excitation of these anomalous modes leading to unfavorable regimes, the waveguide cladding should be properly designed.

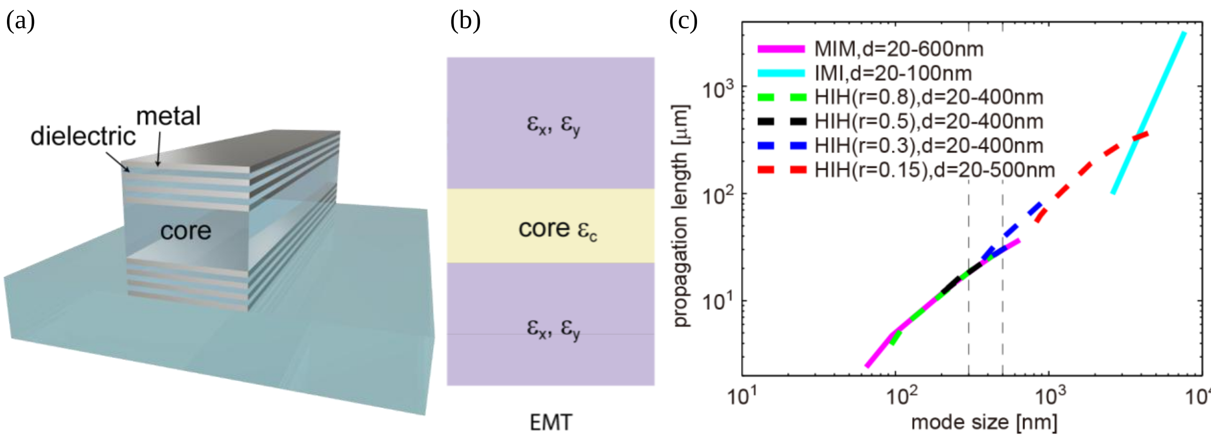


Fig. 1. (a) Schematic of the HIH waveguide. Dielectric core is cladded by lamellar structures consisting of alternating metal and dielectric layers; (b) a waveguide with semi-infinite anisotropic effective medium claddings ($\varepsilon_x$, $\varepsilon_y$) that correspond to the lamellar structure (a); (c) characteristics of the HIH waveguides and their comparison with MIM and IMI waveguides at the wavelength of 1.55 μm.

## 2. Comparison with MIM and IMI waveguides

To show advantages of HIH waveguide, we compare their characteristics with two other conventional plasmonic waveguides: MIM and IMI. Thus, we varied filling ratio *r* and thickness of the core *d* and plotted propagation length and effective mode size for the different structures as shown in Fig. 1(c). To analyze the structure, we studied the case of telecom wavelength 1.55 μm and two materials, i.e. gold and silica. The vertical dotted lines show mode size which approximately corresponds to the size of conventional photonic waveguide, so this region is of particular interest. Thus, for low filling ratio $r < 0.3$, HIH waveguides can have properties which are not achievable with MIM or IMI waveguides. In particular, HIH waveguides can have a higher propagation length (> 650 μm) while maintaining a smaller mode size (< 2 μm).

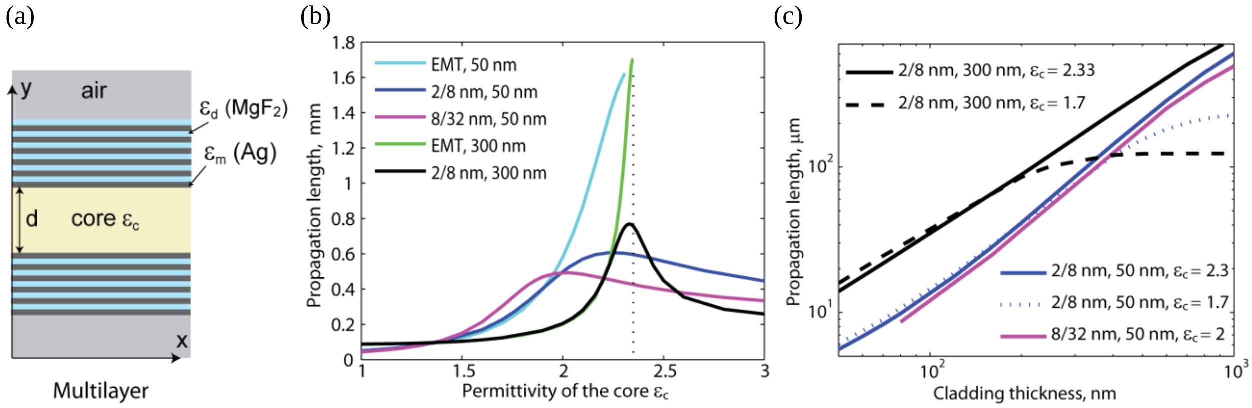


Fig. 2. (a) Schematic of the HIH waveguide with finite-number of metal/dielectric layers, and varied permittivity of the waveguide core $\varepsilon_c$. (b) Propagation length in the HIH waveguides in the case of effective medium approximation and multilayer cladding with different layer thickness . Cladding thickness is fixed to 1 μm. Core thickness is 50 or 300 nm according to notations in the plot. (c) The dependence of propagation length on cladding thickness for HIH waveguide with specified parameters. The core permittivity is fixed and corresponds to the maximum of propagation length shown in (b).

## 3. Optimal parameters of the core

To study the dependence of HIH waveguide properties on dielectric core, we varied permittivity of the core and calculated propagation length for the both EMT approximations and multilayer structure with either 2/8-nm-thick metal/dielectric layers or 8/32-nm ones. In all cases filling ratio $r = 0.2$. Figure 2(b) shows that the propagation length is drastically increased at $\varepsilon_c = 2.35$, which corresponds to $\varepsilon_y$ of the HMM layer. In this case, surface plasmon polaritons (SPPs) of each layer are strongly coupled and exhibit properties similar to long-range SPPs of a single layer. Finite thickness of the cladding limits propagation length (Fig. 2(c)), which is also consistent with behavior of long-range SPPs.

## 4. Conclusions

We study the guiding properties of plasmonic waveguides where the isotropic dielectric cores are cladded by multilayer metal-dielectric structures possessing the hyperbolic dispersion. Working with hyperbolic metamaterials enables us to tune the properties of the waveguides with existing materials. We showed that for filling ratio $r < 0.3$, HIH waveguide can have a higher propagation length and smaller mode size than conventional MIM and IMI plasmonic waveguides. We also showed an existence of long-range propagation regime for the case of $\varepsilon_c$ approximately equal to $\varepsilon_y$ of the HMM layer and possibility to achieve propagation length up to 800 μm.

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