Infrared Plasmon-Polariton Modes in Hyperbolic Metamaterials Based on III-V Semiconductors

E.D. Caudill,[1] M.A. Lloyd,[2] K.E. Arledge,[1] T.D. Mishima,[1] C.G. Cailide,[1]
J.A. Nolde,[2] C.T. Ellis,[2] P. Weerasinghe,[3] T.D. Golding,[3]
J.P. Murphy,[2] M.B. Santos,[1] and J.G. Tischler[1]

[1] *The University of Oklahoma, Norman, OK, 73019, USA*
[2] *U.S. Naval Research Laboratory, Washington, DC, 20375, USA*
[3] *Amethyst Research Incorporated, Norman, OK, 73069, USA*

msantos@ou.edu

The iso-frequency *k*-space surface of an electromagnetic wave in a hyperbolic material is a hyperboloid, in contrast to the spherical or elliptical surface for an ordinary dielectric material. This unusual property arises when one principal component of the dielectric tensor has the opposite sign to the other two principal components. Hyperbolic materials are expected to exhibit a range of distinctive behaviors, including negative refraction and enhanced superlensing effects [1]. Ionic crystals with anisotropic optical-phonon frequencies provide natural low-loss infrared hyperbolic resonances through the excitation of phonon polaritons. However, the operational bandwidth of these materials is limited to a few hundred wavenumbers (cm^{-1}) or tens of millielectronvolts. A promising route to a wider infrared bandwidth is the excitation of plasmon polaritons in homoepitaxial material engineered to have alternating layers of high- and low-carrier concentration [2,3].

In this work, we implement a low-loss Type-II hyperbolic metamaterial covering a wide spectral bandwidth of 2000 cm^{-1} for wavelengths above 5.3 μm. We produced the hyperbolic metamaterial with a stack of intercalated heavily-doped InAs and undoped InAs epilayers grown by molecular beam epitaxy. Electron concentrations of 7×10^{19} cm^{-3} were obtained by Tellurium doping of InAs epilayers and the optical properties of this stack were measured by infrared ellipsometry. These materials were then dry etched to form one-dimensional square gratings (with periods from 2 to 10 μm) and modeled by finite-element electromagnetic calculations (COMSOL). The models agree with measurements, showing the formation of hyperbolic plasmon polaritons at the same frequencies where experimental features were observed. Additionally, we have identified an Epsilon Near Zero mode associated with long-range surface plasmon polaritons contained in the dielectric layers. This work demonstrates that highly subdiffractional light confinement can be achieved with a III-V metamaterial that can be integrated with III-V semiconductor infrared devices such as photodetectors and emitters at a large scale.

This material is based upon work supported by the Office of the Undersecretary of Defense for Research and Engineering Basic Research Office STTR under Contract No. W911NF-21-P-0024. Disclaimer: The content of the information does not necessarily reflect the position or the policy of the Government, and no official endorsement should be inferred.

1. A. Poddubny et al., *Nature Photonics* **7**, 948 (2013).
2. D. Wei et al., *Optics Express* **24**, 8735 (2016).
3. Angela J. Cleri et al., *Advanced Optical Materials* **11**, 2202137 (2023).