Experimental Demonstration of Primordial Metamaterials

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Abstract: We experimentally demonstrate primordial metamaterials - composite media supporting essentially nonlocal wave propagation, grown with molecular beam epitaxy. Our transmission measurements confirm the theoretically predicted spectral signature of coupling to nonlocal modes.

In the majority of materials science, optics, electro-optics, and sensing applications, materials are considered to be local, i.e. the response of a material at a given point is driven by the field at that same point [1]. Nonlocal corrections to materials have been demonstrated in room-temperature plasmonic and quantum nanostructures as well as in single-crystal ultra-low-temperature systems [2–4]. In the former case, nonlocality appears as a quantitative correction to the electromagnetic response. In the latter case, nonlocality fundamentally alters the optical properties of the materials, leading to the excitation of additional waves; unfortunately, raising the operating temperature of or introducing defects to these materials exponentially suppresses these additional modes. Metamaterials can, under some circumstances, mimic nonlocal electromagnetism by engineering light coupling to plasmonic modes [5–7]; however, such "effective" nonlocality still relies on local material components. A recent theoretical proposal [8] suggests that the structuring of materials at the scale of their "suppressed" nonlocality can provide a mechanism for engineering new classes of macroscopic media that are inherently nonlocal, at both micro- and macro-scales. These *primordial metamaterials* open new dimensions in understanding and controlling light matter interaction. Here we report the first realization of a primordial metamaterial in an all-semiconductor "designer metal" material platform.

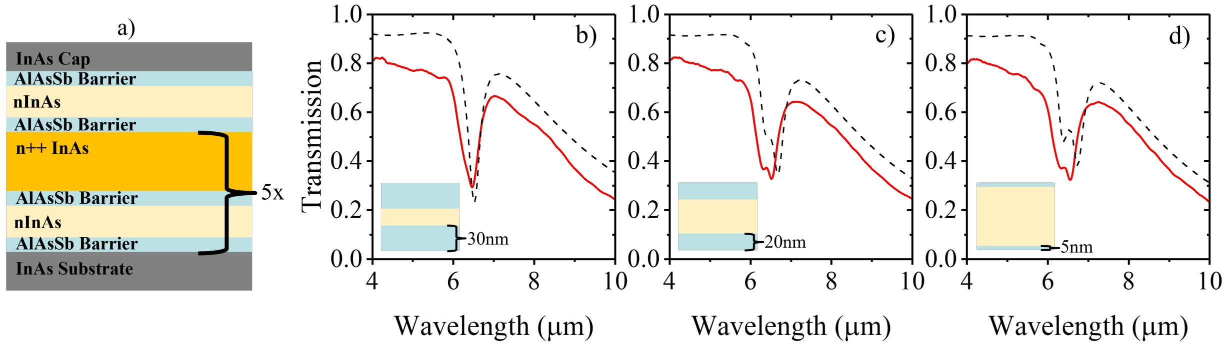

Fig. 1. (a) Dimensionless layer stack of the hyperbolic metamaterials (HMMs) studied in this work. TM-polarized transmission taken at 60° plotted in red is compared to nonlocal transfer matrix calculations of primordial modes plotted in black for HMMs of varying barrier thickness with total dielectric thickness held constant [8]. Our HMM system is comprised of the periodic semiconductor material stack AlAsSb/nInAs/AlAsSb/n^{++}InAs: (b) 30nm/20nm/30nm/80nm, (c) 20nm/40nm/20nm/80nm, and (d) 5nm/70nm/5nm/80nm.

The metamaterials used in this study are comprised of periodic multi-layered semiconductor structures. Previously, similar material platforms have been utilized to demonstrate anisotropic and hyperbolic metamaterials by periodically arranging ~ 50 nm thick undoped AlAsSb and highly doped InAs layers [9, 10]. While the optical response of highly doped plasmonic media is known to be weakly nonlocal (with typical nonlocality scale $\sim v_F/\omega \sim 50nm$), the nonlocality scale of the undoped barrier layers are significantly shorter, effectively suppressing the nonlocal response of the composite as a whole. To analyze the emergence of primordial nonlocal behavior, we replace the undoped layers of the original HMM with a three-layer structure comprised of a low-doped nInAs well and AlAsSb barriers; the doping of the InAs well is chosen such that the permittivity of this plasmonic media is equal to the permittivity of AlAsSb barriers at the target wavelength of $\sim$ 7um.

These samples were grown by molecular beam epitaxy and consist of 5 periods of a degenerately doped (n^{++}) InAs layer (the optical metal) and an AlAsSb/nInAs/AlAsSb quantum well structure (the dielectric layer) as shown in Fig. 1a. Multiple samples were grown and characterized using infrared reflection and transmission spectroscopy. First, we performed a study of HMMs with varying nInAs well and AlAsSb barrier layer thicknesses while the overall dielectric thickness was held constant. For barrier layers of 30nm thickness, the nonlocal response is suppressed, and the response of the composite mimics that of the previously-studied HMMs: the transmission spectrum is dominated by a single angle-dependent minimum corresponding to the epsilon-near-zero (ENZ) transition of the metamaterial [10]. However, as the size of the barrier is reduced, the transmission spectrum reveals additional minima in the vicinity of ENZ. Theoretical modeling links these new minima to the excitation of additional nonlocal waves in the metamaterial. By changing the period of the structure (while keeping the barrier size constant) we can control the dispersion - and therefor - the operating frequency of these new modes (Fig. 2). Such control demonstrates a clear advantage of primordial metamaterials over their homogeneous low-temperature nonlocal counterparts (whose nonlocal corrections are typically pinned to the ENZ frequency [1]).

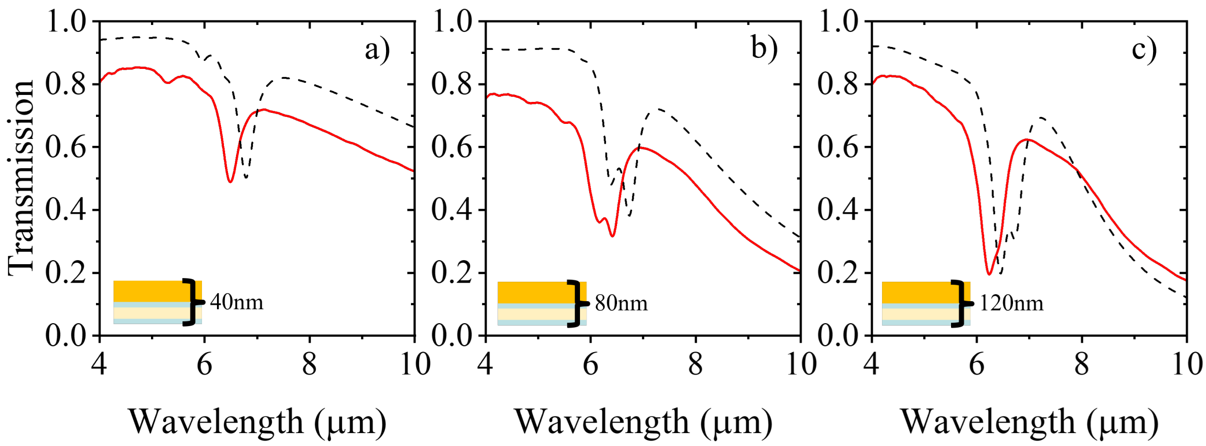

Fig. 2. TM-polarized transmission taken at 60° plotted in red is compared to nonlocal transfer matrix calculations of primordial modes plotted in black for HHMs of varying period with barrier thickness held constant [8]. AlAsSb/nInAs/AlAsSb/n^{++}InAs: (a) 5nm/40nm/5nm/40nm, (b) 5nm/80nm/5nm/90nm, and (c) 5nm/120nm/5nm/130nm.

We have demonstrated anomalous coupling to primordial modes using MBE-grown InAs/AlAsSb hyperbolic metamaterials. Transmission measurements of HMMs of varying barrier thicknesses and periods show good agreement with analytical modeling of these modes, opening the door for design and engineering of nonlocal electro-optical interactions in the mid-infrared.

The authors acknowledge funding from the National Science Foundation DMREF program (Award No. 2119302, 2119157, and 2118787).

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