Nanophotonics lab-on-a-chip sculpted by focused-ion-beam milling: direct characterization of negative-index metamaterials operating in the visible

H. J. Lezec[1], K. J. Chau[1], J. A. Dionne[2], H. A. Atwater[2]

[1]Center for Nanoscale Science and Technology, NIST, Gaithersburg MD.
[2]T.J. Watson Laboratory of Applied Physics, California Institute of Technology, Pasadena, CA.

Advances in nanofabrication technology offer new opportunities for creating photonic materials with artificially tailored bulk optical characteristics, otherwise known as "metamaterials". We have recently shown [1] that visible-frequency electromagnetic modes propagating in a metal-insulator-metal waveguide with deep-subwavelength thickness can be harnessed to yield a two-dimensional (2D) metamaterial with a unique optical property: a negative index of refraction. In such a material, light travels as a "backwards" wave with anti-parallel phase and energy velocities.

As early as 1967, it was theoretically proposed that a negative-index material would enable a number of exotic electromagnetic phenomena when interfaced with a standard positive-index medium [2]. It was predicted that light incident at an angle upon the boundary between two such media would be refracted to the same side of the normal, i.e. undergo negative refraction. It was also suggested that an illuminated negative-index medium would experience a negative radiation pressure, i.e. a pull instead of a push.

A negative-index metamaterial was first demonstrated at microwave frequencies, via direct visualization of the negative refraction of light emerging into free space from a centimeter-scale, wedge-shaped assembly of circuit-boards patterned with millimeter-scale split-ring resonators and wires [3]. However, the direct observation of negative-refraction and related phenomena at visible frequencies presents unique challenges due to the submicron dimensions intrinsically involved in the design of the structures.
.
Here we describe how focused-ion-beam (FIB) milling was used to fabricate an optics "lab-on-a-chip" integrating 2D regions of both positive and negative index, as well as structures for launching light and detecting the refracted component. We show how such a system was used to achieve the first direct geometric visualization of negative refraction in the visible. Finally, we describe current efforts towards implementing a monolithic fiber-based "optical bench" for visible-frequency characterization of a novel volumetric (3D) negative-index metamaterial, which we have designed using finite-difference-time-domain simulations.

1. H. J. Lezec, J. A. Dionne, and H. A. Atwater, *Science* **316**, 440 (2007).
2. V.G. Veselago, *Sov. Phys. Usp.* **10**, 509 (1968).
3. R. A. Shelby, D. R. Smith, and S. Schultz, *Science* **292**, 77 (2001).