MAR09-2008-020181

Abstract for an Invited Paper
for the MAR09 Meeting of
the American Physical Society

Left-handed metamaterials operating in the visible: negative refraction and negative radiation pressure

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Forty years ago, V. Veselago derived the electromagnetic properties of a hypothetical material having simultaneously-negative values of electric permittivity and magnetic permeability [1]. Such a material, denominated "left-handed", was predicted to exhibit a negative index of refraction, as well as a number of other counter-intuitive optical properties. For example, it was hypothesized that a perfect mirror illuminated with a plane wave would experience a negative radiation pressure (pull) when immersed in a left-handed medium, as opposed to the usual positive radiation pressure experienced when facing a dielectric medium such as air or glass. Since left-handed materials are not available in nature, considerable efforts are currently under way to implement them under the form of artificial "metamaterials" – composite media with tailored bulk optical characteristics resulting from constituent structures which are smaller in both size and density than the effective wavelength in the medium. Here we show how surface-plasmon modes propagating in a stacked array of metal-insulator-metal (MIM) waveguides can be harnessed to yield a volumetric left-handed metamaterial characterized by an in-plane-isotropic negative index of refraction over a broad frequency range spanning the blue and green. By sculpting this material with a focused-ion beam we realize prisms and micro-cantilevers which we use to demonstrate, for the first time, (a) in-plane isotropic negative-refraction at optical frequencies, and (b) negative radiation pressure. We predict and experimentally verify a negative "superpressure", the magnitude of which exceeds the photon pressure experienced by a perfect mirror by more than a factor of two. 1) V. Veselago, *Sov. Phys. Usp.* 10, p.509 (1968).