Nonlinear and Active Hyperbolic Metamaterials

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Hyperbolic metamaterials hold great promise to enable a family of novel, metamaterial-inspired electromagnetic devices that can become essential components of future microwave, infrared and optical circuits. These devices may realize lenses overcoming the diffraction limit, exhibit negative refraction, achieve perfect absorption and obtain broadband super-Planckian thermal emission in different frequency ranges.

Negative refraction is achieved due to the hyperbolic dispersion of these structures, which may ideally allow infinite number of evanescent high spatial harmonics to be converted to propagating modes. As a result, subwavelength imaging can be achieved, even at optical frequencies. Note that these media exhibit broadband negative refraction without a negative *index* of refraction and, as a result, they can have more broadband performance combined with much lower sensitivity to material losses, compared to double-negative metamaterials.

We analytically and numerically analyze a structure composed of alternative layers of dielectric and plasmonic material. This geometry was found to achieve hyperbolic dispersion and, as a result, imaging with subwavelength resolution (P. A. Belov, and Y. Hao, *Phys. Rev. B* 73, 113110, 2006). In our presentation, we will discuss in detail the bandwidth performance of the device's negative refraction operation, with an efficient analytical technique based on transmission-line theory. We connect the negative refraction operation to the condition for which the slope of the phase of the transmission coefficient is negative with respect to the angle of incidence, which allows efficiently analyzing the parameter space for optimal performance. We will demonstrate that several bands of high transmission can exist in different frequency ranges, where negative refraction for a broad range of incidence angles is dominant.

In addition, we discuss the introduction of interesting anomalous effects when considering third-order optical nonlinear effects and optically active materials in the alternating layers of the hyperbolic metamaterial. We will demonstrate that it is possible to achieve abrupt changes between positive and negative refraction response of the proposed nonlinear hyperbolic metamaterial structure, when it is illuminated by low-power lasers. We will also discuss all-optical switching among no transmission, positive refraction and negative refraction with relative low input intensities. We will finally discuss loss compensation with gain materials to achieve broadband hyperbolic dispersion with low loss. We envision that the presented work will lead to the design of novel nonlinear electromagnetic devices, with exciting applications, such as nanomemories, all-optical switches and tunable subwavelength imaging systems.