Negative Index of Refraction Metamaterials in the Optical Frequency Range

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We present a set of relatively simple artificial structures which can exhibit a negative refraction index band up to 16% wide in a broad high-frequency range from infrared to the visible (blue) region. The structures are composed of two different kinds of materials, one made of a low-loss dielectric material, and other from a Drude-like material which may have plasma frequencies in the IR, visible, or in the UV. We are motivated by the fact that negative index of refraction metamaterials represent a new realm of phenomena in optics including superlensing, near-field imaging and amplification, cavity super-resonance, highly selective frequency filters, optical multiplexers, as well as frequency-tunable beam narrowing, focusing and expanding devices (V.G.Veselago, *Sov. Phys.-Usp., 10, 509, 1968,* J. Pendry, *Contemp. Phys.,* 45, 191, 2004). One possible realization of our structure is a simple cubic lattice of dielectric spheres embedded in a homogeneous Drude-like host medium. Another realization of the structure includes the same components where spherical inclusions are *randomly* distributed in a medium, rather than constituting a periodic structure. The resulting (effective) negative index of refraction structures are truly subwavelength structures with high host material wavelength-to-structure size ratio of up to 10:1.

Metamaterials based on periodic geometries have been proposed in many papers (see e.g. Vassilios Yannopapas, Alexander Moroz, *J. Phys.: Condens. Matter* 17, 3717-3734, 2005; K. C. Huang, M.L. Povinelly, and J.D. Joannopoulos, *Appl. Phys. Lett.*, 85, 543, 2004; Ch. L. Holloway, E. F. Kuester, J. Baker-Jarvis, and P. Kabos, *IEEE Trans. Antenna and Prop.*, 51, 2596, 2003; M. S. Wheeler, J. Stewart Aitchison and M. Mojahedi, *Nanophotonics Conference*, Sept. 12-14, 2005.). However, they were designed to operate in a non-visible range of frequencies where materials still can be magnetic with magnetic permeability values different from one. The principal distinctive features of our design are in the use of a Drude material as a host with relatively low losses operating below the plasma frequency but close to it. We show, that despite the principally non-magnetic nature of materials at high (optical) frequencies (L. D. Landau and E.M. Lifshitz, "*Electrodynamics of Continuous Media"*, Pergamon Press, 1960), there are still solutions corresponding to negative index of refraction behavior.

Our results are first explained in the context of the classical extended Maxwell-Garnett theory. Then, they are compared to the T-matrix multiple scattering theory and FDTD full wave simulations. The Maxwell-Garnett predictions agree well with the numerical results in terms of the resonant frequencies corresponding to the negative index of refraction behavior of the metamaterial. A sensitivity analysis of the resulting design in terms of the impact of the filling ratio and losses on the bandwidth of the negative index of refraction is also conducted. Furthermore, the theoretical results will be compared to experimental results.