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Negative Refraction in Metamaterials and Surface Plasmonics[1]

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In this talk, we explore general requirements on negative-refraction metamaterials imposed by the fundamental principle of causality [1]. We show that the causality imposes lower limit on optical losses at and near the observation frequency. We also discuss specific, exactly solvable models of nanoplasmonic materials that possess the negative refraction [2] and compare them with the predictions of the exact theory based on the dispersion relations. From the requirements of causality, we derive the dispersion relation for squared refraction index $n^2(\omega)$ of a metamaterial (optically-linear refraction is considered). Using this relation, we derive a rigorous criterion of the negative refraction with a low optical loss at observation frequency ω as

$$\frac{2}{\pi}\int_0^\infty \frac{\varepsilon''(\omega)\mu'(\omega)+\mu''(\omega)\varepsilon'(\omega)}{\left(\omega_1^2-\omega^2\right)^2}\omega_1^3 d\omega_1 \leq -1,$$

where $\varepsilon'(\omega)$ and $\mu'(\omega)$ are the real parts of the permittivity and permeability, and $\varepsilon''(\omega)$ and $\mu''(\omega)$ are their imaginary parts describing the electric and magnetic losses. This criterion imposes the lower limits on the electric and magnetic losses in the region of the negative refraction. If these losses are eliminated or significantly reduced by any means, including the compensation by active (gain) media, then this criterion is violated and the negative refraction will disappear. This criterion can be particularly useful in designing new left-handed materials: testing the expected polarizabilities of a medium against this criterion would check the compliance with the causality and verify the design feasibility. As examples of this general criterion, we consider negative refraction of surface plasmon polaritons in three exactly-solvable nanoplasmonic systems: metal nanolayer in dielectric, dielectric nanolayer in metal, and a dielectric nanolayer on metal surface. In all these three cases, the regions of negative refraction are also those of very strong absorption where extinction of the optical wave occurs on a distance on order of the wavelength. This is in accord with the obtained criterion. **References** 1. M. I. Stockman, *Does Nature Allow Negative Refraction with Low Losses in Optical Region?*, cond-mat/0611350 (2006). 2. M. I. Stockman, *Slow Propagation, Anomalous Absorption, and Total External Reflection of Surface Plasmon Polaritons in Nanolayer Systems*, Nano Lett. **6**, 2604-2608 (2006).

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