Editor's Note: Issues similar to those made in the following two Comments were also raised in a paper by N. Garcia and M. Nieto-Vesperinas, Madrid, Spain.

Comment on "Negative Refraction Makes a Perfect Lens"

The very high spatial frequencies of an optical image are carried by waves with a wave vector larger than ω/c, i.e., highly damped, evanescent waves. These waves do not contribute to the far field; therefore, one is restricted to near-field optics for image formation below the diffraction limit. To remedy the damping of evanescent waves Pendry [1] has recently proposed to employ negative refractive index materials to create a perfect lens giving rise to subwavelength resolution in the far field. As shown by the author a slab of such a material with simultaneously negative dielectric constant ϵ and negative magnetic permeability μ [2] has a transmission coefficient for evanescent waves that is exponentially large; i.e., it counterbalances the damping in the surrounding normal medium. The purpose of this Comment is to show that Pendry uses incorrect arguments to arrive at his, otherwise, correct conclusions.

The flow of the argumentation in Ref. [1] is as follows: Consider a wave carrying high lateral (in the x, y direction) spatial information. In free space such a wave decays exponentially in the positive z direction; its wave vector $k_z = i\alpha$ is imaginary, with $\alpha > 0$. On the basis of causality Pendry argues that the wave vector $k_z^l = i\alpha'$ of the evanescent wave inside the negative-index material has the same sign. Consequently, the electric field is exponentially decaying in the positive z direction both inside and outside the slab.

This line of argument leads to the following inconsistencies: First, the causality argument is completely at odds with the result of Veselago [2] that the component of the wave vector perpendicular to the interface changes sign, when going from left-handed to right-handed material or vice versa. Second, the author shows that the amplitude transmission coefficient of the slab is exponentially increased [Eq. (21) of Ref. [1]], completely inconsistent with the exponential decay of the electric field component across the slab. Third, the summation over the various terms in the geometrical series does not converge, since for $\mu = -1$ and $k_z^l = k_z$ the transmission Fresnel coefficient as well as the reflection Fresnel coefficient is infinitely large.

To avoid the aforementioned issues it suffices to realize that the problem in essence is two dimensional, so that the Maxwell equations split up into two separate sets (see, e.g., Ref. [3]): a set for E polarization and a set for H polarization. Consider the set of E polarization (s-polarized light) with the electric field vector pointing along the y axis. Since there is no spatial dependence on y, the continuity of H_x is the same as continuity of $\partial E_y/\mu\partial z$. Since μ is changing sign at every interface and downstream from the slab we must have an exponentially decaying amplitude, it follows that inside the slab the amplitude of the wave must exponentially *increase* and upstream of the slab it must exponentially decrease, implying that $k_z^l = -k_z$ for both propagating and evanescent waves. Applying the continuity of E_y as well as of $\partial E_y/\mu\partial z$, the amplitude of the electric field at the exit face of the slab can be expressed in the amplitude at the entrance face of the slab. One obtains an amplitude *increase* of a factor $\exp(-ik_z d)$. Not only the overall transmission coefficient has increased but also the amplitude of the electric field vector, as it should. Note that there is no backreflected wave at the faces of the slab since the amplitude Fresnel coefficients for reflection are equal to zero and those for transmission equal to unity.

The consequence of this is that for a macroscopic thickness of the slab and atomic size point sources the amplitude of the electric field can *easily reach values beyond the breakdown of any material* as the exponent $-ik_z d$ can easily reach a value of the order of 10^8. This surprising result is not at all evident from Ref. [1].

With the kind of evanescent waves described above, which are at each point in space either exponentially decreasing or increasing, there is no energy transport. These solutions are clearly not applicable when a source is turned on, i.e., when the fields are building up, or in the presence of absorbers, e.g., a detector in the focal plane. To find the proper solutions for those practical situations, including the buildup of the field to unphysically large values at the exit face of the slab, is a far from trivial task. For instance, the total electrical field at each point in space integrated over all possible wave vectors must be calculated in order to find the energy density. For the solutions as given in Ref. [1] this integral diverges at locations in the slab downstream from the image point for sources with sharp boundaries.

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[1] J. B. Pendry, Phys. Rev. Lett. **85**, 3966 (2000).
[2] V. G. Veselago, Sov. Phys. Usp. **10**, 509 (1968).
[3] Max Born and Emil Wolf, *Principles of Optics* (Pergamon Press, Oxford, 1999), Sec. 11.4.1.

