Negative refraction in outer space?

In the 1960s, when the Russian physicist Victor Veselago first speculated upon the properties of a hypothetical isotropic material which simultaneously exhibits negative relative permittivity ε_r and negative relative permeability μ_r, the explosion of interest that was to follow almost three decades later could scarcely have been foreseen. Amongst the many intriguing implications arising from $\varepsilon_r < 0$ and $\mu_r < 0$, it is the prospect of negative refraction which has in the past few years captured the imagination of the optics and electromagnetics research communities and inspired much lively debate[1].

At that time, Veselago's ideas concerning $\varepsilon_r < 0$ and $\mu_r < 0$ were not widely followed up since no materials – naturally-occurring or otherwise – conforming to $\varepsilon_r < 0$ and $\mu_r < 0$ were known to exist. It was not until the dawn of the twenty-first century that interest in this topic was dramatically rekindled, following the first reported experimental observation of negative refraction by researchers at the University of California, San Diego (UCSD)[2]. The UCSD group tracked the propagation of a microwave beam across the interface between air and a composite metamaterial consisting of conducting wire and ring inclusions embedded periodically on printed circuit boards. Further independent experimental reports have emerged recently, which confirm the existence of microwave negative refraction in metamaterials[3,4].

While $\varepsilon_r < 0$ and $\mu_r < 0$ is a sufficient condition for negative refraction, it is in fact not a necessary condition nor is it strictly applicable to real materials. In reality, materials – which are in essence collections of charged particles – cannot respond instantaneously to an applied electromagnetic field. Accordingly, all real materials are dissipative to some degree and their constitutive parameters are complex-valued quantities whose imaginary parts arise from dissipation. It is readily demonstrated that the key criterion for the negative refraction of plane waves in real materials is that the phase velocity be oppositely directed to the direction of energy flow[5]. Materials supporting such planewave propagation are called negative phase-velocity (NPV) materials to distinguish them from conventional positive phase-velocity (PPV) materials in which the phase velocity and rate of energy flow are co-directional. In the quest for negative refraction, it is significant that NPV propagation may be predicted for materials when only one of ε_r and μ_r has a real part which is negative-valued.

With negative refraction in the microwave regime now appearing to be well-established, current efforts are directed towards higher frequencies[6], with optical negative refraction being the ultimate goal. The scope for achieving NPV propagation and thereby negative refraction is considerably broadened by considering anisotropic and bianisotropic materials. For example, through the homogenization of an isotropic chiral material with a magnetically biased ferrite, both of which are PPV materials, a bianisotropic NPV homogenized composite may be conceptualized[7].

In the context of homogeneous materials, we recently reported on the exciting prospects for NPV propagation and negative refraction which arise from the Lorentz covariance of the basic laws of electromagnetics[8]. Suppose, from the perspective of an inertial reference frame Σ, we have a PPV isotropic dielectric-magnetic material M. As viewed from the perspective of another inertial frame Σ' which translates at a constant velocity v with respect to Σ, the material M is not an isotropic dielectric-magnetic material at all. Instead, M considered from Σ' is a non-isotropic complex material whose electromagnetic constitutive properties depend upon both the orientation and magnitude of v. Crucially, it has been found that the material M can support NPV propagation, provided that the inertial frame Σ' from which it is observed is translating with sufficiently high velocity. Moreover, the converse applies too: if we have material M which is an isotropic dielectric-medium supporting NPV propagation in an inertial frame Σ, then it may be considered from the perspective of an inertial frame Σ' as a non-isotropic, electromagnetically complex PPV material provided that Σ' translates with sufficiently high velocity with respect to Σ.

Commonplace terrestrial velocities are likely to be too low to give rise to NPV propagation in a material which supports PPV propagation when viewed at rest. However, one may envisage relativistic negative refraction being exploited in astronomical scenarios such as, for example, in the remote sensing of planetary and asteroidal surfaces from space stations. Although current research activities relating to negative refraction are largely directed towards the nanoscale, it may possibly be the case that space telemetry technologies will be the first to reap the benefits of negative refraction. Furthermore, it is possible that many unusual phenomena would be discovered and/or explained by the application of the idea of relativistic negative refraction to interpret data collected via telescopes. Perhaps, many more planets, hitherto hidden, would be thereby lit up on our space maps.

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