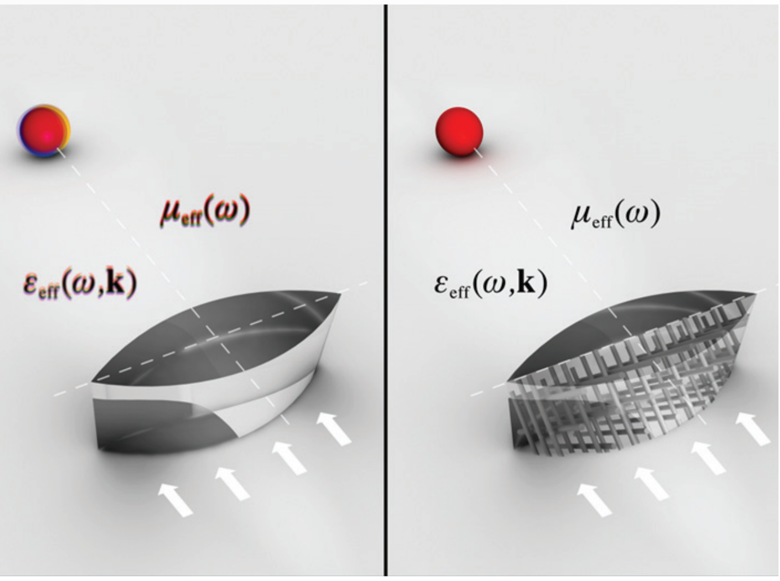
Nonlocal Metamaterials and Applications

One of the intriguing potentials of novel functional structured materials – metamaterials – is the possibility to realize a nonlocal electromagnetic reaction, such that the effective medium response at a given point is fundamentally entangled with the macroscopic field distribution at long distances. Here, it is demonstrated that nonlocality can have interesting physical implications, and enable reversing rainbows and correcting the chromatic aberrations of optical systems.



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Two Main Publications

M. G. Silveirinha, **"Anomalous dispersion of light colors by a metamaterial prism"**, Phys. Rev. Lett., 102, 193903, 2009.

J. T. Costa, M. G. Silveirinha, **"Achromatic Lens Based on a Nanowire Material with Anomalous Dispersion"**, Optics Express, 20, 13915, 2012.

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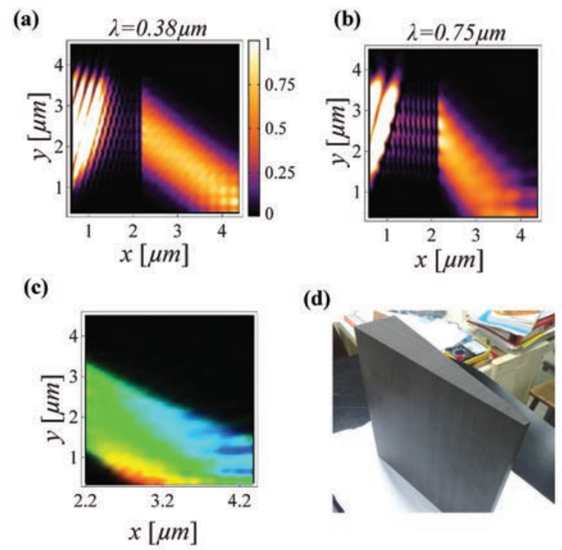

Fig. 1 A nonlocal metamaterial prism refracts long wavelengths more than short wavelengths (panels a–b), producing a reversed rainbow (panel c). Panel (d) shows a prototype of the metamaterial prism used to experimentally demonstrate this effect at microwaves.

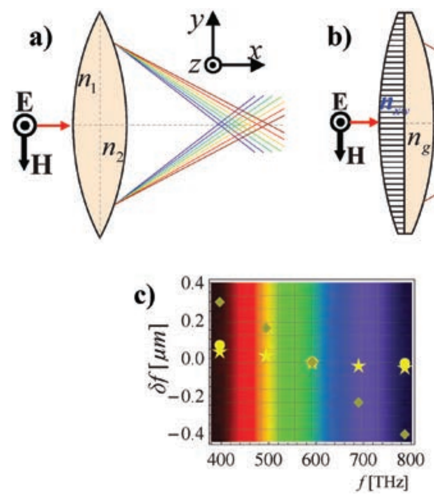

Fig. 2 (a) Illustration of the chromatic aberration of a conventional glass lens. (b) Biconvex optical metamaterial lens that corrects the chromatic aberration for all the colors of light. (c) Yellow stars/circles: focal curve for the compensated metamaterial lens. Diamond symbols: focal curve for a conventional single-material lens.

Structured functional materials with extended electromagnetic responses have been on the spotlight in recent years. These metamaterials consist of periodic arrangements of metallic or dielectric particles embedded in a host medium. One of the intriguing potentials of metamaterials is the possibility to realize a nonlocal response. A nonlocal material is characterized by the fact that the polarization vector at a given point of space does not depend exclusively of the macroscopic electric field in a small neighborhood of that point, but ultimately may depend on the electric field distribution in the whole crystal. Most of the conventional (solid-state) materials behave, to a good approximation, as local materials. The electrodynamics of nonlocal materials is fundamentally different and much richer than the electrodynamics of conventional local materials, and this may open new opportunities for fundamental science research and applications. Our main goal was to study the physics of novel nonlocal metamaterials, and to prove that such metamaterials may have unique features such as low loss broadband anomalous dispersion in the visible domain, which may permit correcting the chromatic aberrations of optical lenses.

The dazzling profusion of colors observed in rainbows is among the most remarkable optical phenomena. This beautiful effect stems from the dispersion of the refraction index of the water droplets, which, from a fundamental causality argument, must invariably decrease with the wavelength of light for any conventional material with low loss. This is the reason why the palette of colors refracted by a glass prism must follow a fixed pattern, showing "red" as the least refracted color and "violet" as the most refracted color. In this research, we demonstrated that, surprisingly, by breaking the locality of the material response, it is possible to have a broadband anomalous dispersion regime with negligible loss such that the refractive index increases with the wavelength of light. A consequence of this property is that a prism of such metamaterial will reverse the palette of refracted colors!

To have a strong nonlocality the metamaterial topology needs to be fundamentally different from that characteristic of natural crystalline materials, wherein the atoms lie isolated at the lattice points. The trick is to interconnect all the structural unities of the metamaterial such that the response of each individual meta-atom becomes fundamentally entangled with that of other meta-atoms located at large distances, giving rise to a strong nonlocal response. Our design is based on crossed metallic nanowires that span many unit cells of the material. Thus, the polarization acquired by each meta-atom (formed by segments of the metallic nanowires) strongly depends on the macroscopic electric field in neighboring cells.

One of the interesting possibilities made possible by anomalous material dispersion is the correction of chromatic aberrations. It is well-known that conventional single-material glass lenses are unable to focus all the spectral components of light into the same convergence point, even in ideal circumstances where the effects of diffraction are negligible. The reason for this limitation is the glass material dispersion, which causes wavelengths associated with different colors to be refracted differently. Hence the image produced by a glass lens may have distortions, and in such a case the optical system is said to suffer from chromatic aberrations. In this research, we have shown that by capping a conventional glass lens with normal material dispersion with a suitably designed metamaterial with anomalous dispersion it may be possible to suppress the effects of material dispersion, and eliminate the chromatic aberrations for all light wavelengths, providing an exciting route for improved optical instruments insensitive to chromatic aberrations. Other promising applications of these nonlocal metamaterials include ultra-subwavelength waveguiding and focusing with planar lenses based on negative refraction.