Ballistic metamaterials

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Metamaterials are artificial composites structured on a subwavelength scale, where the effect of the subwavelength pattern controls the average electromagnetic response of the medium, leading to many properties that are not readily available in natural materials. On the microscopic level, this behavior generally originates from the plasmon resonance in subwavelength metallic elements incorporated in the unit cell of the composite.

In the theoretical description of metamaterials, electromagnetic response of the metallic inclusions is generally treated using the formalism of the local dielectric permittivity, that corresponds to the material at the given spatial position. While adequate for bound electrons, this approach however neglects the inherent mobility of the free charge carriers. Furthermore, the actual free electron dynamics in the metallic constituents, may be qualitatively different – from the diffusive behavior to ballistic regime. Although in the diffusive and in the quantum regimes, the standard description in terms of the local dielectric permittivity may be adequate, the ballistic case shows qualitatively different behavior, with the resonant response due to the interplay of the electromagnetic field period and the ballistic round-trip time.

As we show in the present work, when the round-trip time of the electron motion is equal to the period of the electric field, the resulting electromagnetic response is enhanced, leading to the negative effective permittivity in the direction normal to the metal-dielectric interface, even above the plasma frequency. As the in-plane permittivity component in this regime remains positive, the composite shows the hyperbolic behavior, with its many exciting manifestation - from the negative refraction and diffraction-free propagation to the enhanced quantum and nonlinear effects due to the density of states singularity in hyeprbolic media.

Hyperbolic response of the planar metal-dielectric metamaterials well above the plasma frequency of its “metallic” component, shows the potential of ballistic metamaterials to extend the applications of the existing material platforms: e.g. the use of the high-quality doped semiconductors originally introduced as “designer metals” for mid- and far-infrared frequencies, can now be extended well into the near-IR range.