K-Space Signatures of Negative-Index Metamaterials

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It has been shown that a hypothetical medium with simultaneously negative values of ϵ and μ can sustain a left-handed plane wave with anti-parallel phase and energy velocity for all directions of propagation. In other words, the equifrequency contour (EFC) of such a medium is a sphere whose frequency gradient points inward everywhere on the sphere's surface. This property can be completely characterized by a three-dimensionally isotropic negative refractive index and has been predicted to result in many interesting phenomena such as negative refraction, flat lensing, sub-diffraction imaging, and invisibility cloaking.

In order to achieve these effects in experiment, a variety of artificial structures known as metamaterials have been built and tested at various frequencies across the electromagnetic spectrum. These sub-wavelength periodic structures have been shown to support propagating backward Bloch modes in which the fundamental Floquet-Bloch wave vectors trace circular or spherical EFCs in the spatial frequency domain (k space) with antiparallel time-and-space-averaged Poynting vectors. By modeling these backward Bloch modes by a single left-handed plane wave, metamaterials have often been characterized by an effective negative refractive index, a characterization that is consistent with experimental observations of negatively refracting electromagnetic beams. Although such simplifications can be useful, they can also hide valuable information regarding the spatial variation of electromagnetic fields as well as the origins of backward power in different structures.

It has been shown that decomposing a Bloch mode to its complete spatial frequency harmonics and mapping the power flow to k space can illustrate how the fundamental harmonic can have a non-significant contribution to the total power flow. These k-space maps of power flow provide a complete description of the relationship between phase and power flow that cannot be obtained from either effective medium theory or dispersion diagrams. In this paper, we show that backwards Bloch modes cannot be completely modeled by a single left-handed plane wave with a corresponding negative effective index. Although metamaterials have been shown to exhibit circular or spherical EFCs resembling isotropic left-handed homogeneous media, the origin of backward power in these structures is not always the same. In fact, here we show that k-space mappings can be used as signatures for categorizing different metamaterial structures according to their backward wave mechanism, regardless of operating frequency. We show that backward power arises from higher-order right-handed harmonics in structures such as photonic crystals, magnetodielectric crystals, and coupled-plasmonic-waveguide metamaterials (for out-of-plane propagation). By contrast, backward power is shown to by dominated by pairs of left-handed waveguide modes in split-ring resonator and wire composites, plasmonic crystals, fishnet structures, and coupled-plasmonic-waveguides metamaterials (for in-plane propagation). It has also been shown that k-space maps can be used to determine the refractive behavior of phase and power at the interface between two media, as well as enhance the coupling efficiency across an interface by matching the incident waves to the dominant harmonics.