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Nonlinear effects in left-handed metamaterials and related structures

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We describe a number of nonlinear effects associated with the concept of left-handed metamaterials–composite materials with simultaneously negative dielectric permittivity and magnetic permeability. First, we study transmission of electromagnetic waves through a slab of left-handed metamaterial with a hysteresis-like nonlinear response and describe two types of nonlinear effects: (i) nonlinearity-induced suppression of the wave transmission when an initially transparent left-handed material becomes opaque with the growth of the input wave amplitude, and (ii) nonlinearity-induced transparency of the slab when an initially opaque composite material becomes left-handed (and, therefore, transparent) when the input wave amplitude is increased. We demonstrate, with the help of the finite-difference time-domain numerical simulations, that the nonlinearity-induced wave transmission through an opaque slab is accompanied by the development of modulational instability and the generation of spatiotemporal solitons. Next, we analyze the structure of guided waves supported by a left-handed slab, and the wave transmission through periodic structures made of transparent negative-index (or left-handed) and conventional layers. In addition, we demonstrate novel unique properties of the electromagnetic crystals that include the layers of left-handed metamaterial. In particular, in a sharp contrast with all known results in the theory of wave propagation in periodic media, we demonstrate that a one-dimensional periodic structure with left-handed layers can possess, under certain conditions, a full two-and even three-dimensional spectral gap for the TE- or TM-polarized waves. In this case, the Green function characterizing radiation of a point source becomes exponentially localized in all directions because the electromagnetic radiation cannot propagate through the one-dimensional structure at any angle in the plane.