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Leaky modes in low-damping ε-near-zero slabs

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Abstract: We present a complex-mode analysis of an ε-near-zero metamaterial slab made of chains of core-shell nanocylinders. The mesoscopic nature of the slab induces narrowband, strong, effective nonlocal response mediated by leaky modes.

OCIS codes: (160.3918) Metamaterials; (250.5403) Plasmonics; (350.4238) Nanophotonics and photonic crystals

1. Introduction

Materials with ε-near zero (ENZ) have the ability to enhance antenna directivity [1-3], channel light into sub-wavelength regions [4] and boost local fields [5, 6]. In Ref. [3] the enhancement of highly-directional radiation was explained as due to the excitation of a leaky mode in the ENZ slab. Some examples of systems that exhibit an electric, plasma-like response are: guided modes at cutoff, two- and three-dimensional arrangements of metallic rods, and dipole resonances in arrays of nanoparticles. The use of either low-loss plasmonic materials [7] or damping compensation mechanisms [8, 9] lowers the real and imaginary parts of the effective permittivity at the same chosen frequency. As a result weak optical phenomena can be strongly magnified in low-damping ENZ slabs [10, 11]. Examples are characteristically small bulk or surface nonlinearities, and *intrinsic* nonlocal perturbations due to the free-electron gas pressure in metal. This property makes these materials excellent platforms to enhance optical harmonic generation, optical multistability and switching at low-irradiance levels [10]. In addition, low-damping ENZ slabs also support strong, *effective* nonlocal behavior associated with leaky modes. Here we discuss the nature of these modes by means of a complex Bloch mode analysis, and the role slab thickness plays on the number and parity of available modes with low attenuation constant. These modes alter transmission, reflection and absorption spectra via phase-matching with TM-polarized, homogeneous plane waves at oblique incidence.

2. Complex Bloch mode analysis of arrays of core-shell nanocylinders

The system under investigation is a metamaterial slab with finite thickness made of chains of core-shell nanocylinders immersed in silica. The core of each nanocylinder is made of a mixture of an active, gain medium (Rhodamine 800) and silica (dielectric permittivity taken from [9]), whereas the shell is made of silver (permittivity taken from [12]). The period is a = 114 nm, the internal radius is r_1 = 25 nm, and shell thickness is 5 nm, i.e., the external radius is r_2 = 30 nm. The slab thickness d is defined by the number of arrays stacked along the z-direction (as schematically represented for Array II in Fig. 1).

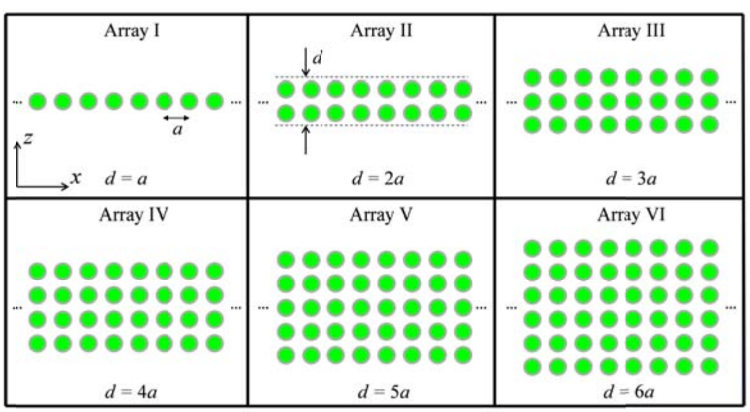

Fig. 1. Schematics of the metamaterial slabs under investigation. We analyze the complex Bloch modes supported by each of these arrays.

Fields and structure are invariant along the y direction. We analyze the modes, with magnetic field polarized along y, supported by slabs with several thicknesses, namely: $d = a$, $d = 2a$, $d = 3a$, $d = 4a$, and $d = 5a$, as illustrated in Fig. 1. We find the complex modes with Bloch wave vector $\mathbf{k}_B = k_x \hat{\mathbf{x}} = (\beta_x + i\alpha_x)\hat{\mathbf{x}}$ propagating in the x direction for each of the array slabs shown in Fig. 1 by using an eigenvalue solver based on the finite element method [10, 13]. In Fig. 2 the modes of the six arrays I-VI are represented in the complex k_x / k_h plane in the frequency range 420-424 THz, where k_h is the wave number in silica (different colors depict multiple modes).

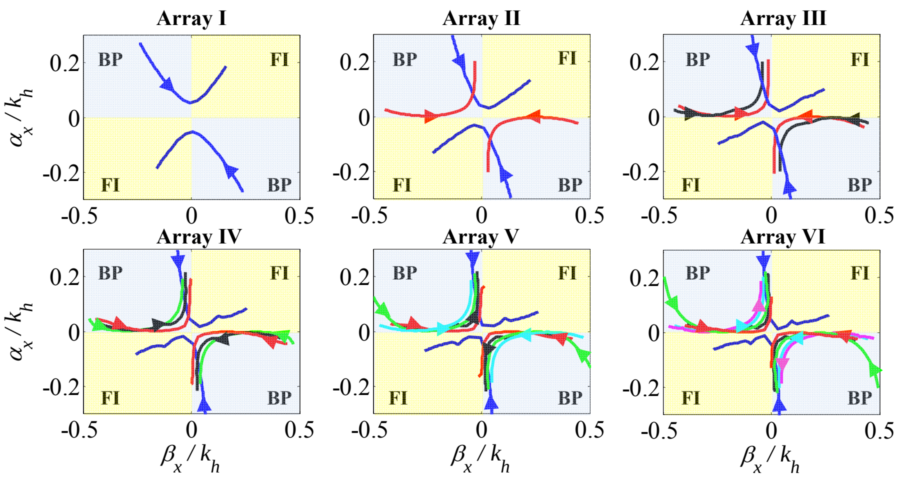

Fig. 2. Bloch modes of the Arrays I-VI (illustrated in Fig.1) in the complex k_x plane for the frequency range 420-424 THz (arrows indicate the direction of increasing frequencies).

As a general rule, we find that increasing the thickness *d* of the slab by one row of nanoparticles adds one mode with complex wavenumber in the complex k_x plane. The mode represented with a blue curve, which we refer to as pseudo-Brewster mode [10], exists regardless of the slab thickness, even for a single row of nanoparticles ($d = a$). This mode, which is the only one that crosses the imaginary axis hence switching from backward proper (BP) to forward improper (FI), according to the classification done in [14], is responsible for the ENZ behavior of the bulk array (i.e., infinite periods in both *x* and *z* directions). We find that the other leaky modes supported by the slab are equally important in this frequency range, since they can interact with incident TM-polarized plane waves. This interaction with propagating waves occurs by phase-matching, i.e., a forced excitation, and it is stronger when the imaginary part of the modes' wavenumber, α_x, is very low when compared to k_h. We will show that this interaction generates extremely narrow resonant features in the angular and frequency spectra, which open new windows of opportunity for the design of low-power, all-optical devices.

4. References

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