Resonant metal-semiconductor nanostructures as building blocks of low-loss negative- and zero-index metamaterials

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Abstract

Artificial materials showing electromagnetic properties not attainable in naturally occurring media, the so called metamaterials, are among the most active fields of research in optical and material physics. One of the major challenges found is to obtain truly bulk isotropic negative index metamaterials (NIM) at optical frequencies [1]. Recently, we reported [2] the possibility to use a certain class of core-shell (CS) nanospheres as building blocks of 3D isotropic NIMs, operating in the near infrared. These CS, made of a metallic core and a high permittivity shell, are doubly-resonant (see Fig. 1), allowing for a spectral overlap of their first electric and magnetic dipolar resonances. Since the responses do not depend on the interaction between constituents, no particular arrangement is needed to build the metamaterial, which is, moreover, broadly isotropic, though polarization dependent. Nonetheless, such 3D NIMs exhibit moderate losses, and their fabrication is somewhat challenging.

Therefore, we have extended our study to metallo-dielectric core-shell nanowires (NWs), revealing similar properties when incident light wavevector and polarization are both normal to the nanowire axis (see Fig. 2). We show that, for certain geometrical parameters and filling fractions, metamaterials composed by such CS-NWs can have simultaneously negative permittivity and permeability between 1.2-1.5 mm [3]. The resulting metamaterial, at the expense of reduced dimensionality and fixed polarization, then behaves as a 2D isotropic NIM (see Fig. 3) with extremely low losses [3] (f.o.m. up to 200, about one order of magnitude better than previously proposed designs).

Also, the same metamaterials design is shown to yield either negligible dielectric permittivity (ENZ) or negligible magnetic permeability (MNZ), thus leading to a negligible refractive index, manifest fascinating optical properties [4]; specially interesting is the case of zero-index metamaterials (ZIM) with similarly small dielectric permittivity and magnetic susceptibility (impedance Z~1) for obvious reasons. Strictly speaking, unlike for NIMs, no strong resonances are required to achieve such effective ZIM parameters, the only condition being an overlap of the tails of both resonances. Thus we will show [5] that simpler nanostructures, such as solid dielectric cylinders with relatively large refractive index, can actually satisfy such condition in order to behave as a ZIM (see Fig. 4). Moreover, broad spectral regions are also found where the effective index nearly vanishes, while matching vacuum impedance; such zero-index metamaterials are shown to beautifully exhibit the rich phenomenology formally expected.

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References

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Figures

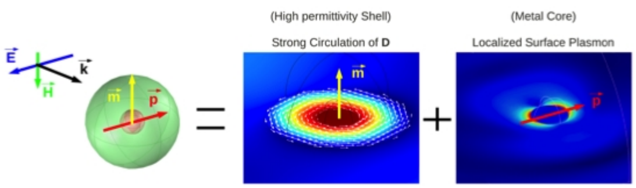

Figure 1: Illustration of the double (electric and magnetic) resonance in core-shell nanospheres [3].

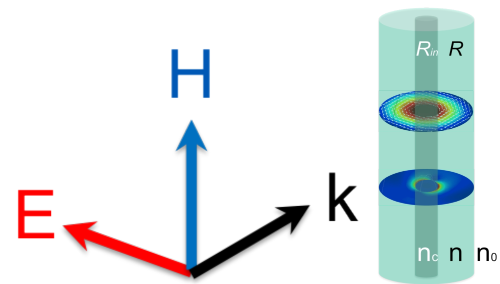

Figure 2: Illustration of the scattering geometry (TE polarization) for a doubly-resonant, single (Ag@Si) core-shell nanowire.

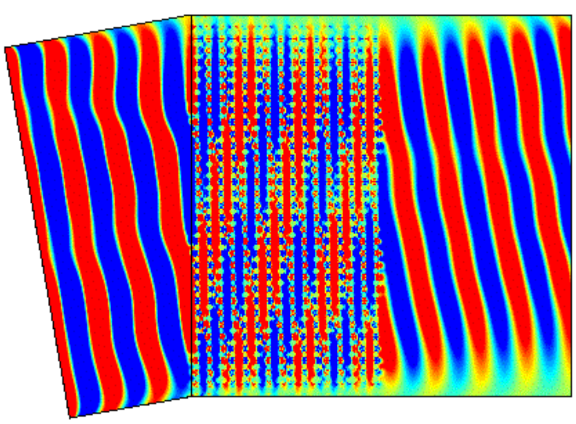

Figure 3: Negative-refraction-index slab made of core-shell (Ag@Si) NWs operating at λ=1.35 μm (TE polarization).

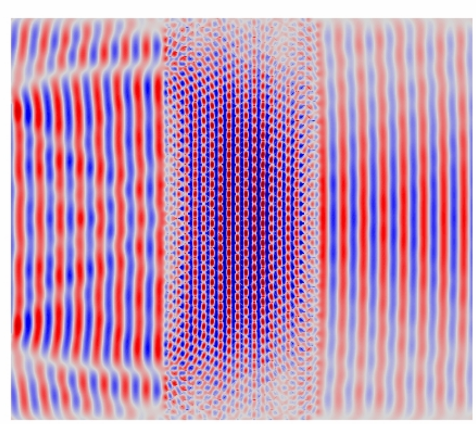

Figure 4: Nearly-zero refraction-index slab made of TiO_2 NWs operating at λ=780 nm (TE polarization).