넓은 파장대역에서 매우 높은 굴절율을 가지는 삼차원 메타물질

Three-dimensional metamaterials with an ultra-high effective refractive index over broad bandwidth

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One of the motivations for developing metamaterials is to achieve relative electric permittivity ε_r and magnetic permeability μ_r, in the ranges not readily accessible using naturally occurring materials[(1)]. In particular, creating an arbitrarily high refractive index ($n = \sqrt{\varepsilon_r \mu_r}$) is of interest for imaging, lithography[(2)], and broadband slow light for delay lines[(3)] or interferometers[(4)]. Here, we design three-dimensional metamaterials with an index of refraction that is arbitrarily high, over a broad frequency range extending down to near-zero frequencies.

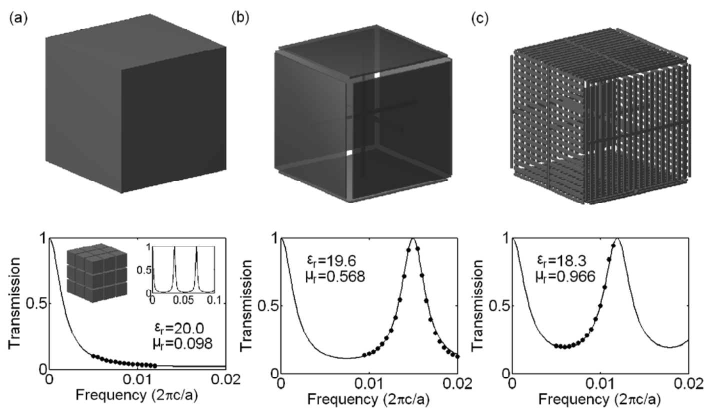

Figure 1. Electromagnetic responses of metamaterials. In (a)-(c), the top panels show the metallic inclusion in each unit cell and the bottom panels are the corresponding transmission spectra of ten-unit-cell-thick slabs of such media. Dots: numerical simulation results; Solid lines: effective medium fitting.

Previous approaches[(5-7)] of index manipulation utilized resonances and were inherently narrowband. Even though it was also known that the use of an array of subwavelength capacitors could lead to the frequency-independent and broadband enhancement of the relative electric permittivity[(8-10)], these structures exhibited strong diamagnetic behavior[(10-12)]. Hence, in all previous systems, the capability of increasing the refractive index was very limited.

The key idea to overcome previous limitations is to generate a large electric dipole response, while simultaneously preventing the formation of large-area current loops. This can be achieved with proper structural design of the metallic inclusions of a metamaterial. We begin with a simple cubic array structure of metal cubes [Fig. 1(a)]. Transmission spectra were calculated using finite difference time domain (FDTD) schemes[13]. Accurate values of effective ε_r and μ_r can be extracted from such transmission spectra and the permittivity and permeability are found to be ε_r=20.0 and μ_r=0.098, yielding n=1.4, when $b=19a/20$, where a and b are the size of the unit cell and the metal cube, respectively. With successive structural changes [Figs. 1(b) and 1(c)], it is possible to increase μ_r, without affecting ε_r much. As a result, the effective index increases from 1.4 to 3.34 (ε_r=19.6; μ_r= 0.568) to 4.2 (ε_r=18.3 and μ_r=0.966)[14].

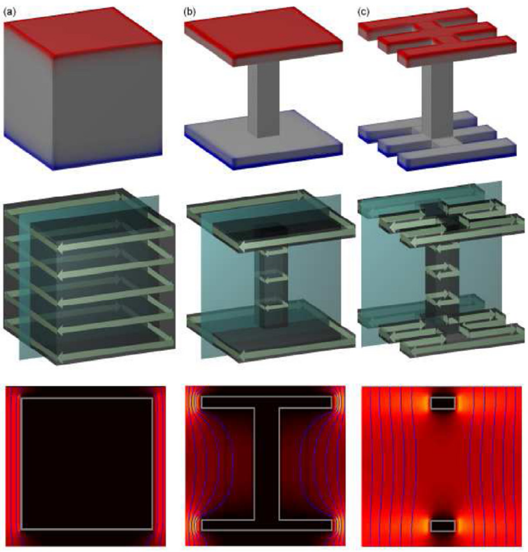

Figure 2. Electromagnetic response of simplified metallic objects. The top panels show the object and the occurrence of charge concentration at the top and bottom surfaces when electric fields are applied. The middle panels show the current distribution induced by external magnetic fields. Bottom panels show magnetic fields on the slice plane indicated in the middle panels.

The fact that the effective permittivities of these structures are similar but the effective permeabilities are drastically different is readily understood if we look at the simpler, but related structures in Fig. 2. When external electric fields are applied in the vertical direction, the charge accumulation on top and bottom surfaces are similar in all structures as long as the slits in Fig. 2(c) are of a deep-subwavelength size. On the other hand, the average area of induced current loops when external magnetic fields are applied is greatly affected by such structural differences.

Even further enhancement of the index can be achieved in two ways. The effective index is inversely proportional to the square root of the distance between adjacent metallic inclusions[14]. Also, if the air region of the metamaterial is filled with a dielectric medium, the effective index is multiplied by the index of the filling medium[14].

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