Metallic Metamaterials with a High Index of Refraction

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There is great interest in exploiting subwavelength resonances in metallic structures to create artificial materials with unusual effective electromagnetic responses. The most notable example is the creation of negative refractive index metamaterials.[1] Recently, we described a method for designing metamaterials that feature arbitrary high, positive indices.[2] Such a capability is potentially important for miniaturizing optical or electromagnetic devices, improving imaging resolution and slowing down light.

In our design, the effective index is controlled by geometry. Since refractive index is commonly regarded as an intrinsic material property directly related to the underlying electronic states, this work carries fundamental implications as well. In particular, it adds evidence to the important potential of replacing electronic states with subwavelength electromagnetic resonances—which could open up a new world of possibilities in optical physics.

We showed that a metallic film with a periodic arrangement of cut-through slits can be regarded as a dielectric slab with a frequency-independent effective refractive index. The key to creating the desired effective index behavior lies in the existence of subwavelength propagating modes. In slits, regardless of how small their width is, there always exists a propagating transverse electromagnetic mode (electric field perpendicular to the slits).

We showed that the properties of a perfect metal film for transverse-magnetic (TM, magnetic field parallel to the slits) polarization—i.e., transmission *and* waveguiding—asymptotically approach those of a dielectric slab with a uniquely defined refractive index $n = d/a$ and a width L/n, where L is film thickness, d is periodicity and a is slit width. In the figure, (a) and (b) depict the fundamental waveguide modes in the metal film and the corresponding effective dielectric slab. Identical spatial periodicity, indicated by arrows, clearly demonstrates the equivalence of the two systems.

The surprising waveguiding properties are directly applicable from microwave to far-infrared wavelengths, where loss and plasmonic effects in metals can be largely neglected. In the optical wavelength range, however, the presence of the plasmonic response leads to additional subwavelength propagating modes, which may also be exploited in creating novel optical materials. In fact, we confirmed the presence of two distinct types of TM guided modes propagating in a direction perpendicular to the slits. In the figure, (c) shows the band diagram for those guided modes at optical frequencies. The first type is a well-known surface plasmon mode [red curves and inset (i)].

The second type originates from a subwavelength electromagnetic state supported by the slits and gives rise to guided modes [blue curves and inset (ii)], which closely resemble waveguide modes in a dielectric slab.[3] This finding indicates the possibility of extending our method for designing high-index metamaterials all the way into the optical regime.

Since the structure considered is two-dimensional, its behavior is strongly polarization dependent. However, the mechanism of creating effective high refractive index dielectric structures is not restricted to two dimensions. Subwavelength propagating modes exist in many geometries and may be used to create high-index materials in three dimensions. ▲

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References

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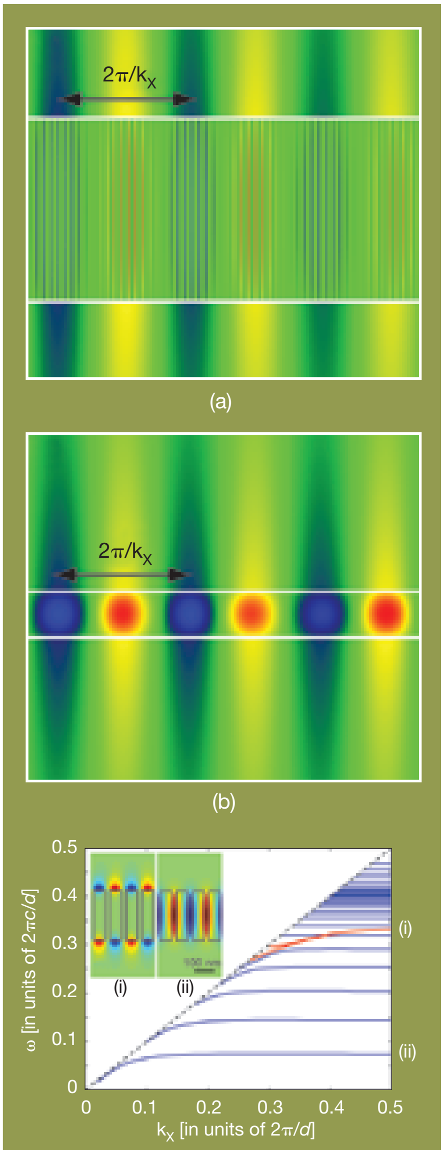

(a)

(b)

(c)

Magnetic field distributions for the fundamental waveguide modes of (a), a perfect metal film, and (b) the corresponding effective dielectric slab for $n = d/a = 4$, $L/d = 25/4$, and $\omega = d/\lambda = 0.0516$. Red and blue indicate positive and negative amplitude, respectively. White lines outline the film in (a) and the slab in (b). Arrows indicate the identical periodicity of the fields. (c) Guided-mode band diagram for a metal film at optical frequencies (TM polarization, first Brillouin zone) when $L = 256$ nm, $d = 80$ nm, $a = 20$ nm. Shown are two degenerate surface modes (red curves) and a series of effective dielectric slab modes (blue curves). The dashed line is the light line in vacuum. Insets show magnetic field distributions for (i) one of the degenerate surface modes and (ii) the fundamental effective dielectric slab mode.