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A New Path

Ultralow-index metamaterials present new possibilities for controlling light propagation.

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In many photonic structures composed of two or more dielectrics, the absolute value of the refractive index contrast is critical to performance. Increasing the index contrast would therefore be extremely useful. Recent work on ultralow-refractive-index metamaterials (ULIMs) suggests a path toward this goal.

Metamaterials, an extension of the concept of artificial dielectrics, typically consist of periodic structures of a guest material embedded in a host material. While homogeneous dielectrics derive their optical properties from the subnanometer-scale structure of their atoms, metamaterials derive their properties from the subwavelength-scale structure of their component materials. When the wavelength of the field interacting with the structure is much longer than the feature sizes and unit cell, the metamaterial can be treated as a homogeneous dielectric with macroscopic parameters like effective refractive index n_{eff}. The proper choice of component materials and geometries can yield metamaterials with novel optical properties, which allow the metamaterials to control light in unconventional ways with potential applications in photonic integration.

Properties of ULIMs

Traditional methods of deriving an effective refractive index apply in the long-wavelength limit.[1] We have demonstrated that metamaterials consisting of thin wires can behave like low-loss dielectrics at wavelengths much longer than the wire thickness, but barely longer than twice the unit cell (see figure 1).[2] Photonic crystals also have been assigned an effective refractive index based on their band structure at wavelengths only slightly longer than the features and unit cells.[3–4]

Research on ultralow-refractive-index metamaterials focuses on achieving an effective refractive index of less than unity at optical frequencies. For example, a metamaterial composed of a 2-D square array of thin silver wires that is embedded in an air host medium behaves on refraction, reflection, and transmission as a low-loss dielectric with the real part of the effective index below unity ($0 < \mathrm{Re}(n_{eff}) < 1$). This property has been verified at visible and near-IR (NIR) wavelengths.

Such a material has some interesting implications. A beam incident on a planar interface between air ($n = 1$) and a ULIM would be refracted away from the normal, instead of refracted toward the normal as with most optical materials. If one were to build a plano-concave lens with a ULIM, the result would be a converging device (see figure 2). Unfortunately, such a lens would be hard to fabricate for optical frequencies and would have limited applicability because of inherent losses.

Another intriguing property involves the superluminal character of the phase velocity inside ULIMs. Because the effective index of refraction (real part) can be lower than unity, the phase velocity can exceed the velocity of light in a vacuum. Note that this behavior is in complete agreement with fundamental physical laws because the material is both dispersive and lossy; thus, the energy velocity is not superluminal.

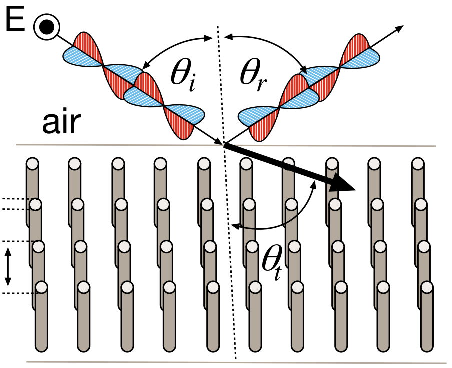

Figure 1 Light reflects off the normal to the air-metamaterial interface and the refracted waves are inhomogeneous. The metamaterial consists of a square array (period *a)* of silver wires of width *r.*

A subwavelength structure with a given effective refractive index should refract light like a homogeneous structure with the corresponding refractive index. If features of the structure are small enough compared to the unit cell and wavelength, it should refract an incident plane wave as a plane wave, and the wavelength inside the material should be $\lambda = \lambda_0 / n_{\text{eff}}$, where λ_0 is the free-space wavelength. This leads to one of the available methods to calculate the effective index. By computing the fields inside the metamaterial and extracting their wavelengths by fitting them to plane waves, we can define the effective refractive index by the ratio of the free-space wavelength to the refracted wavelength. By this method, a metamaterial consisting of silver wires of diameter $r = 30$ nm in a 200-nm square array has an effective refractive index of $n_{\text{eff}} = 0.62 + 0.024i$ at $\lambda_0 = 1$ µm.

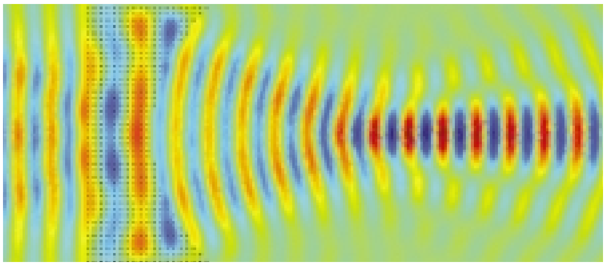

Figure 2 A plano-concave lens made of ultralow-refractive-index metamaterials would focus light just as a conventional plano-convex lens does. This simulation shows $\lambda_0 = 1$ µm light incident on a lens with a 5-µm radius of curvature.

Likewise, a subwavelength structure with an effective refractive index should have the same reflective properties as a homogeneous structure with the same refractive index. While normal-incidence reflection and transmission coefficients have been used to define the complex refractive index of heterogeneous structures, we have used the Fresnel formulae to find the complex refractive index of a homogeneous dielectric slab whose angle-dependent reflectivity, $R(\lambda)$, best matches that of the metamaterial.[5] Compared to the single-angle method, this multiple-angle method is more robust because the computed n_{eff} depends on reflectivity at many angles. In the single-angle method, the computed n_{eff} is based on only one angle, and hence, it does not account for anisotropy. The effective refractive index computed with the multiple-angle method agrees with that derived from normal-incidence refraction.

Total External Reflection

Ultralow-refractive-index metamaterials exhibit an interesting new optical property at visible wavelengths: total external reflection (TER). TER occurs when light propagating in a vacuum is incident on a medium with a refractive index of less than unity at an angle exceeding the critical angle as defined by Snell's law. For angles exceeding the critical angle, as defined for the lossless case, the refracted waves are evanescent and the reflectivity is very close to unity. This effect is very well known for x-rays incident on planar interfaces at grazing angles. In the x-ray regime, though, the index of refraction is just slightly less than one and is expressed as $n = 1 - \lambda$, where $\lambda \approx 0.01$. In contrast, metamaterials can be engineered to exhibit TER at visible wavelengths with the real part of the refractive index well below unity and very-low-loss components as compared to bulk metals.

Conventional waveguides operate by total internal reflection, where the index of the core material is greater than that of the cladding. ULIMs open up the possibility of hollow waveguides based on TER. Recent numerical designs show that slab waveguides with hollow cores and metamaterial cladding are feasible for visible and NIR wavelengths. The guiding is produced by TER because the cladding refractive index (real part) is smaller than the core refractive index. Numerical simulations have shown that ULIM waveguides can propagate visible ($\lambda_0 = 500$ nm) light more than 60 wavelengths, which compares favorably with current plasmonic waveguides for applications in photonic-integrated devices.[6] The design's limitation is the inherent loss of metamaterials with ultralow index. In the mode profile of such a waveguide, both the mode profile and the attenuation agree with analytical predictions based on the effective index.

Unlike photonic-crystal waveguides, which require a photonic bandgap to confine light, metamaterial cladding waveguides guide light by TER and do not require a bandgap. Similar to photonic-crystal waveguides, ULIM waveguides can guide light along sharp turns with low loss, although this remains to be demonstrated. Insertion losses should, moreover, be lower for ULIM waveguides because the modes decay into the cladding as they do in conventional dielectric waveguides, which reduces the mode-matching problem.

Currently, our research group is working to fabricate ULIMs with scalable processes. The required feature sizes are feasible with current lithographic techniques, but new approaches such as self-assembly and holographic lithography are more promising for 3-D scalable fabrication. Silver is the best metal candidate at visible wavelengths because both the real and imaginary parts of its refractive index are small. The refractive index of silver clusters smaller than approximately 15 nm diverges from the bulk value for the material, though, which could make the silver clusters unsuitable for certain ULIM designs.[7] Metamaterials with both square and hexagonal lattices, and wires with both square and circular cross-sections, have negligible effects on the structure's effective refractive index. Tolerances in metamaterial periodicity should change the effective index only slightly.

We can design metamaterials with a wide range of effective refractive index values, opening up new opportunities for device applications. Since the materials behave similarly to their equivalent homogeneous materials, designers can optimize device performance with analytical and numerical models based on homogeneous materials. Full numerical simulations of the subwavelength features can be reserved for final design stages. **oe**

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