Transition metamaterials for local-field enhancement

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Nearly all forms of light-matter interaction are mediated by the electric field. Therefore, these effects can be dramatically amplified through local enhancement of the applied field within a small volume. The ability to achieve significant local-field enhancement has applications in sensing, nonlinear optics, and quantum optics. Such local-field enhancement is typically achieved using free-space optics such as lenses or Fabry–Pérot etalons, or at the microscale using dielectric resonators or plasmonics. However, the field enhancement factor of these mechanisms is restricted by the focusing limit of lenses, or large mode volumes of dielectric resonators, or heating and parasitic losses of plasmonics in the optical regime. These drawbacks limit the strength of light-matter interactions and restrict applications.

Here, we present a mechanism to achieve strong local-field enhancement within a graded-index slab, where the refractive index varies from positive to negative. Electromagnetic waves entering this material at oblique angles refract as they propagate through the slab, which can be modeled as a series of interfaces between materials with increasingly negative index. The normal component of the electric displacement field must be continuous across each interface, causing the electric field to increase in proportion to the decrease in permittivity. If the index decreases gradually, the reflections at each interface can be minimized, and the incident wave can be transmitted through the metamaterial slab. As the wave penetrates into the slab, the electric field continues to grow until it diverges at the middle of the slab where the index reaches zero (N. M. Litchinitser *et al.*, Opt. Lett, 33, 2350-2352, 2008).

We design a transition metamaterial based on 2D Dirac-cone metamaterials, consisting of a square array of dielectric pillars (Y. Li *et al.*, Nature Photon., 9, 738-742, 2015). By adjusting the radius and separation of the pillars, we obtain an effective refractive index equal to zero in the optical regime, while maintaining finite impedance. This design is easily extended to positive (negative) index by increasing (decreasing) the separation and radius of the pillars. A graded-index transition metamaterial can be created by continuously varying the dimensions of the unit cell across the width of the array. In order to characterize the performance of transition metamaterial, we use numerical simulations to compute the enhancement of the electric field as a function of the incident angle and slab length. Here the Dirac-cone metamaterial consists of silicon pillars, designed for an operating wavelength λ = 1550 nm. The field enhancement is maximized for a narrow range of incident angles, which depends on the length of the metamaterial slab. This is caused by a "forbidden" region near the middle of the slab, which does not support propagating waves. Instead, the electromagnetic field tunnels across this barrier as an evanescent wave. Longer slabs require smaller incidence angles in order to minimize the width of the "forbidden" region near zero index, while thinner slabs can tolerate relatively wider forbidden regions. Thus, we can control the optimal angle for field enhancement by adjusting the length of the slab. For optimized incident angles, the tangential component of the electric field is enhanced by a factor of more than 400 due to the zero-index transition.

We plan to fabricate the transition metamaterial based on well-established Dirac-cone metamaterial platform. Furthermore, we will experimentally characterize the field enhancement of the transition metamaterial through near-field scanning optical microscopy. We will measure the intensity of the light that scatters from each position to map the electric field distribution over the metamaterial.

In conclusion, we demonstrate a new physical mechanism—optical transition metamaterials—to accomplish local-field enhancement in the optical regime, opening the door for novel applications in nonlinear optics, lasers, sensing, and quantum optics.