APPLIED PHYSICS

The rise of near-zero-index technologies

Materials with designed electromagnetic response have a wide range of exotic applications

By **Iñigo Liberal**[1] *and* **Nader Engheta**[2]

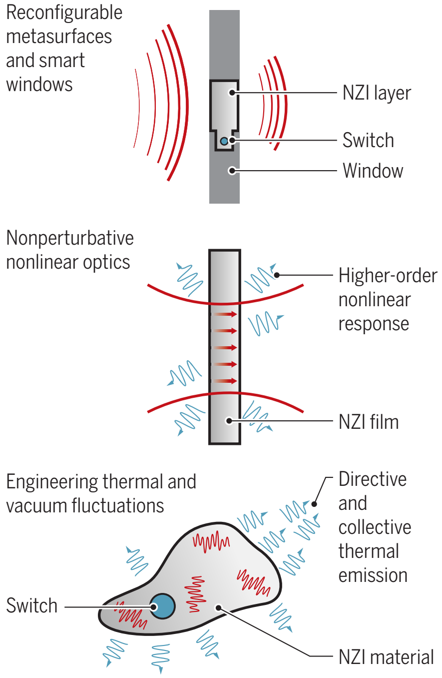
Since the beginning of metamaterial research, the electrodynamic properties of media with a refractive index near zero have attracted the interest of the scientific community because of the intriguing wave phenomena that they are expected to exhibit (*1*–*3*). As the refractive index approaches zero, the wavelength expands, and the spatial and temporal field variations effectively decouple (*1*, *3*). This gives access to a new regime of wave dynamics in which geometry-invariant wave phenomena can take place. For example, waves can tunnel through deformed waveguides (*2*), resonators can preserve their resonance frequency independently of the geometry of their external boundary (*4*), and light can be trapped in small three-dimensional (3D) regions, even if open to an unbounded environment (*5*, *6*). Recent experimental progress is also pushing forward the applied aspects of near-zero-index (NZI) media, leading to a generation of technologies with the potential to revolutionize different aspects of nanophotonics and other physical systems.

NZI technologies are built upon the basis of an extended collection of physical realizations of NZI media. For instance, the dispersive permittivity of different materials (such as polar dielectrics, transparent conducting oxides, and topological insulators) crosses zero at a specific frequency, whose value can range from terahertz to ultraviolet. Hence, around such frequencies, different materials may naturally behave as ϵ-near-zero (ENZ) media, a class of NZI media with near-zero permittivity. Alternatively, NZI media can be artificially realized with different structures or metamaterials, including waveguides near cutoff, wire media, multilayered structures, and all-dielectric implementations based on arrays of particles (*3*, *7*).

It turns out that NZI metamaterials are exotic constructs themselves, obeying different rules than those of conventional metamaterials. Typically, in metamaterials, a heterogeneous mixture is modeled as a homogenized medium, with effective material parameters (permittivity and permeability) with the use of effective medium theories (EMTs). However, some of the conventional constraints on the applicability of EMTs do not apply in NZI media (*8*). Instead of obeying the usual homogenization rules, rods immersed in a 2D ENZ medium behave as photonic analogs of electronic dopants, modifying the effective permeability of the entire structure in an additive manner, in-

Near-zero-index materials

Materials can now be fabricated to exhibit near-zero effective refractive index. A number of examples of near-zero-index (NZI) technologies can be expected to be realized by exploiting the properties of these materials.



dependently of the rods' position and while preserving the ENZ character of the host. This behavior, photonic doping (*8*), is qualitatively different from conventional EMTs. Homogenization is also possible, independent of the size and number of the particles. Even a 2D ENZ body containing a single particle can still be homogenized, leading to the intriguing concept of single-inclusion metamaterials. Moreover, this "dopant" particle does not need to be small and can be made resonant. This allows for the observation of extreme material parameters, such as ϵ-and-μ-near-zero (EMNZ) media, a medium with both effective permittivity and permeability near zero (*8*).

Photonic doping and single-inclusion metamaterials offer the possibility of controlling the scattering response of a large arbitrarily shaped body with a single and arbitrarily located actuator. This allows for a dynamic control of its scattering properties, with promising technological applications in developing flexible and reconfigurable metasurfaces (see the figure). Another aspect of NZI media favoring its applications in reconfigurable systems is that it lies at the transition between dielectric (transparent) and metal (opaque) regions. Therefore, small variations on its permittivity qualitatively modify its interaction with electromagnetic fields. This modulation can be finely controlled with voltage via field-effect modulation (*9*) or it can be made ultrafast (<1 picosecond) when carried out with a pump laser (*10*). A NZI-based dynamical phase grating has been demonstrated (*9*)—an important step forward toward the development of phased-array metasurfaces, with important implications in lidar and holography technologies. Together, the tuning and geometry-invariant properties of NZI media might bring closer the goal of flexible and/or reconfigurable metasurfaces, with control over all degrees of freedom in wavefront engineering.

The strong relative variations of the refractive index of NZI media can open up research on nonlinear optics (see the figure). When the linear part of the refractive index (and/or permittivity) of a medium is small, variations induced by nonlinear effects are no longer perturbative (*11*, *12*). This departs from conventional optical materials, in which nonlinear effects are considered a weak and perturbative effect. Therefore, NZI media might strengthen usual nonlinear processes as well as allow the exploration of higher-order nonlinear processes.

The impact of NZI media is also rapidly extending to other fields of physics, and one example of this is their ability to engineer vacuum and thermal fluctuations. In a similar manner to a photonic band-gap material, a NZI material can be used to "empty" the space of electromagnetic modes, inhibiting vacuum fluctuations in a given fre-

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quency band (*13*). At the same time, bound states can be induced by inserting dielectric particles (*5*, *6*), offering effects such as defect cavity modes. Thus, NZI media offer a control of quantum light-matter interactions analogous to photonic crystals, but with entirely different functionalities.

For example, bound eigenmodes may be possible in 3D open and arbitrarily shaped bodies (*3*), which can nevertheless be excited from the outside (*5*). Moreover, because the frequency of these bound states is not detuned by deforming the cavity, wave dynamics—qualitatively different from those of conventional quantum cavity setups—could be observed in flexible cavities and/or optomechanical systems (*13*). There is also a strong synergy between controlling vacuum fluctuations and then inducing ultrafast and nonperturbative variations of the refractive index. This combination could then be used to boost several vacuum amplification effects, including spontaneous photon production (*14*). In this manner, NZI media could provide an experimental platform for testing concepts of quantum field theory. Last, thermal fluctuations may be analogously controlled in NZI platforms, benefiting from an intrinsically enhanced spatial coherence facilitated by the enlargement of the wavelength near the NZI frequency and the distinct geometry-invariant effects and reconfigurability capabilities of such structures (see the figure). For example, a directive thermal beam could be dynamically enhanced and suppressed with only one switch, an arbitrarily located rod. Prospective applications for light sources, heat and energy management, chemistry, and bioengineering may be envisioned. ■

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PLANT BIOLOGY

The quest for durable resistance

A milestone for preventing the worldwide spread of wheat rusts has been reached

By **Matthew J. Moscou** *and* **H. Peter van Esse**

Agriculture transformed humans from hunter-gatherers into city dwellers. This was made possible through the domestication of crops, such as wheat and barley. Based on archaeological evidence (*1*), we know that our ancestors' crops were constantly plagued by disease, including rusts and mildews on cereals. During the 4th century BCE, Romans sacrificed red cattle, foxes, and dogs to the god Robigus in the belief that it would prevent epidemics of cereal rusts. Today, we understand that crop diseases are caused by plant pathogens. Cereal rusts are fungal pathogens that colonize foliar parts of the plant, such as the stem or leaf. The ability of these pathogens to infect a plant requires the suppression of the plant's immune system. The principal weapon used by pathogens to inhibit immunity are effectors, typically small secreted proteins. Plants recognize pathogens through immune receptors, including those that either directly or indirectly "perceive" pathogen effectors secreted into the plant (*2*). On pages 1604 and 1607 of this issue, Salcedo *et al.* (*3*) and Chen *et al.* (*4*), respectively, describe the identification of two effectors from the fungal pathogen *Puccinia graminis* f. sp. *tritici*, the causal agent of wheat stem rust. The discovery of these effectors represents a critical milestone for developing an approach to track and prevent the worldwide spread of the rusts of wheat (*5*) and improve our understanding of the biology of these devastating pathogens.

The ultimate goal of epidemiologists is to develop strategies to prevent disease. In crops, this is a challenge for reasons embedded in the nature of agriculture and human behavior: Large monocultures, poor agricultural practice, and the movement of contaminated seeds, plants, or soil facilitate the emergence of highly virulent pathogens. Plant breeders sought to overcome these challenges by introducing resistance from various sources of germ plasm (genetic material in germ cells) encompassing elite, landrace, and wild relatives. However, the introduction of these single resistance genes resulted in rapid and new outbreaks of disease (*6*). This loss of pathogen resistance occurred because of the strong selective pressure exerted on pathogens, a process that has strong parallels with antibiotic resistance in human pathogens (*7*). It became clear that to maintain durable disease resistance, modern epidemiology practices would need to be applied to agriculture. Critical first steps would involve robust international pathogen surveillance (*8*)

Leaf rust (*P. triticina*) infects a wheat crop in Kansas, USA.

and identification of plant immune receptors and the effectors they recognize. This would need to be combined with the development of dynamic breeding programs that can respond quickly to an ever-changing pathogen population (*5*). In wheat, three species of rust cause persistent losses: leaf rust (*P. triticina*), stripe rust (*P. striiformis* f. sp. *tritici*), and stem rust (*P. graminis* f. sp. *tritici*). All species infect leaves and reduce yield, but the most catastrophic is stem rust, which can compromise the in-

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