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Applications Based on Zero-index Materials: Hybrid Skin Cloaks and Coherent Perfect Absorption

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The beauty of Maxwell's Equation relies on the fact that the propagation of an electromagnetic wave within a material is well determined by a certain spatial distribution of permittivity and permeability. By engineering metamaterials, which are artificial resonating subwavelength structures with unprecedented permittivities and permeabilities, the long-held dream to control the flow of light has become possible. In the past two decades, various intriguing applications have been triggered with the help of metamaterial designs, including negative refractions, super resolution imaging and "Harry Porter's" invisibility cloak. In principle, by designing subwavelength electromagnetic structures, any value of permittivity and permeability is possible.

There is one peculiar group of metamaterials, with zero refractive index. As the refractive index of a material can be obtained by taking the square root of the multiplication of its permittivity and permeability, a zero-index material (ZIM) is possible with either zero permittivity, zero permeability or zero permittivity and permeability [1]. Special properties of electromagnetic waves exist in a ZIM. First, a zero refractive index indicates that the wavelength inside such a medium is infinitely long. Or in other words, the field inside a ZIM shall be homogenous. No matter what the length of a waveguide filled with ZIMs can be, an electromagnetic wave propagating inside it will have no phase accumulation. People may also wonder if the speed of light in a zero refractive index medium can be infinite, which is seemingly impossible. However, for a dispersive medium with only one frequency to have a zero-index property, a phase velocity exceeding the speed of light is perfectly fine and it can be proved that its group velocity is still governed by causality.

The reflection and refraction when incident to a ZIM from vacuum can be well obtained based on Snell's Law. Total reflection will occur if a light beam impinges obliquely. Even with normal incidence, the coupling from vacuum to ZIM is not easy. The reflection at normal incidence is determined not by the refractive index but by impedance, which is the square root of the permeability divided by the permittivity. For a ZIM with zero permittivity (permeability), the impedance will be infinite (zero) if with a finite value of permeability (permittivity). To couple perfectly with an incident plane wave, an impedance matching to vacuum is needed: a ZIM with permit-

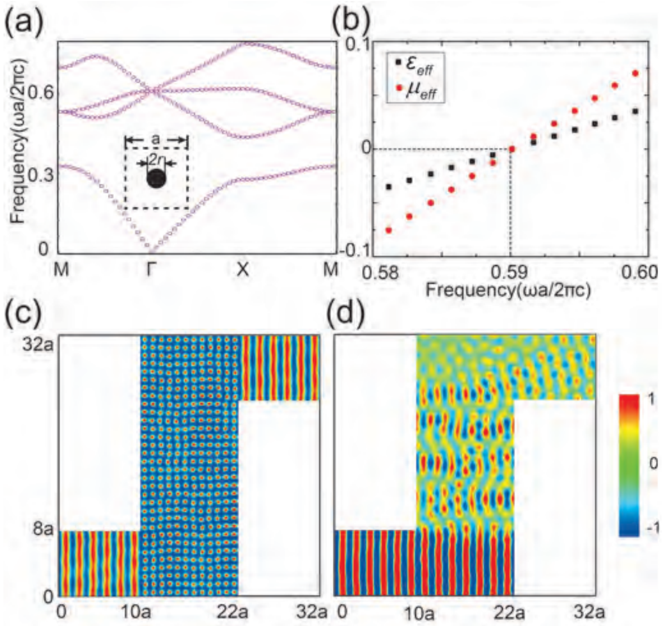

Fig. 1: The design principle of DZI PC. (a) 2D photonic band diagram for a square lattice alumina (ε= 8.5) PC. A Dirac cone appears at Γ point. (b) The retrieved effective permittivity (blue) and permeability (red) for DZI PC. (c) Wave tunneling effect of a waveguide filled with DZI PC. (d) The wave tunneling effect is absent if the DZI PC is removed.

tivity and permeability approaching zero simultaneously is preferred and is referred to as a double zero index (DZI) material.

A complex metamaterial design to achieve DZI property is very difficult if not impossible. In 2011, Huang et al. [2] discovered that by inducing an accidental degeneracy of the photonic band diagram of a two-dimensional (2D) dielectric photonic crystal (PC), a triply-degenerate Dirac cone dispersion appears at the Brillion zone center (Γ point). The polarization under consideration is with the electric field parallel to the dielectric cylinders. Dispersive effective permittivity and permeability close to the Dirac frequency can be numerically obtained (as shown in Fig. 1(b)) and both permittivity and permeability are zero at the Dirac frequency. Constructed using pure dielectrics, DZI PC is low in loss and can be readily prepared at optical frequencies to contribute to optical device designs.

The wave tunneling effect inside a ZIM is seen in numerical simulations as shown in Fig. 1(c). If a plane wave is incident from the left-bottom port to a straight waveguide filled with DZI PC, its wavefront will recover completely from the upright port. It can be easily recognized that the electric field inside the waveguide is nearly homogenous, which is direct proof of its zero-index property.

Researchers may wonder how an electromagnetic wave can propagate inside a ZIM again, given that with a zero-refractive-index, the Poynting vector is not well defined. This can be explained by the Dirac cone dispersion that occurs in conjunction with a DZI property. In a manner similar to the electrons in graphene, an electromagnetic wave propagates pseudo-diffusively at the presence of Dirac cone dispersion [3]. Electromagnetic waves diffuse inside DZI PC and thus it is more appropriate to refer their propagation as tunneling.

Since the discovery of DZI PC, applications related to their zero-index property have been developed and two recent examples will be discussed as follows.

Hybrid Skin Cloak

"Harry Porter's" invisibility cloak is one of the most essential stimulated applications for metamaterials. As shown in Fig. 2(a), transformation optics [4] provided a strategy to realize invisibility; with the help of the graded permittivity and permeability arrangement in the cloak shell, light is guided to bypass the to-be-hidden object. However, the complex design hindered the development of optical applications. Profs. Z. H. Hang and Y. Lai from Soochow University and Profs. S. L. Sun and L. Zhou from Fudan University developed a new scheme: the hybrid skin cloak [5]. The cloak shell is constructed of two layers: one layer of a transparent metasurface to manipulate the incident/exit electromagnetic waves and one layer of a ZIM to tunnel electromagnetic energy. When a plane wave impinges on our cloaking shell from the left, the left outer metasurface layer (rainbow-colored thin shell, shown in Fig. 2(b)) will bend the transmitted wave to be normally incident to the ZIM (in orange). Then the incident light can couple and squeeze through the ZIM. As the tunneling property of the ZIM layer is independent to its geometry, the to-be-hidden object has no size or shape limit. After the tunneling, the electromagnetic wave leaves the ZIM layer at a direction perpendicular to its surface. The metasurface layer on the right side will then bend the exit wavefront to be identical to what the incident wave would be without the hybrid cloak. Based on this principle, a unidirectional hybrid skin cloak of arbitrary shape and size is achievable.

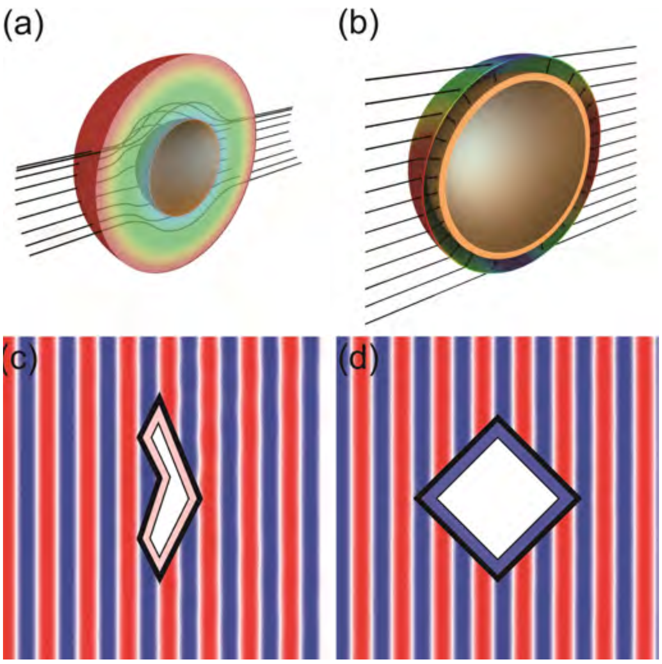

Fig. 2: Principle of the hybrid skin cloak. The figure is adapted from Ref. [6]. (a): Schematic for "Harry Porter's" invisibility cloak. Light is guided by inhomogeneous distribution of metamaterials. (b): Schematic for the hybrid skin cloak. (c) & (d): Simulations of arbitrary shaped objects being cloaked.

Microwave demonstration experiments were carried out. By arranging metasurface units locally with a different transmitted phase Φ, the transmitted beam could be bent from an incident angle θ_i to a direction with a transmitted angle θ_t:

$$(\sin \theta_t - \sin \theta_i)\, k_0 = d\Phi/dy, \tag{1}$$

k_0 is the wavenumber at the working frequency. The transparent metasurface design can be found in Fig. 3(a). High transmission and the required transmitted phase are obtained. The working frequency is at 10.2 GHz. In simulation (Fig. 3(b)), they show the successful bending of an incident wave by 45 degrees, which is key to a rhombus-shaped cloak.

The adopted DZI PC's photonic band diagram is shown in Fig. 1(a). The scaling invariance of Maxwell's Equation guarantees that as long as we keep the ratio between the lattice constant a and radius r of the alumina cylinders, the DZI property can be configured to different frequencies. At the lattice constant a=17.46 mm, a DZI PC also working at 10.2 GHz was constructed (white cylinders in Fig. 3(c)). As shown in Fig. 3(d), an experimentally measured exit plane wavefront was obtained, which verifies the cloaking effect.

With a completely different cloak scheme and a much easier fabrication method, the hybrid skin cloak could provide a promising route to the creation of an optical cloak.

Coherent Perfect Absorption

What about a time-reversed process of a laser? If two coherent light beams impinge to a lossy deep subwavelength film, these two light beams will be totally absorbed [6]. This so called Coherent Perfect Absorption (CPA) effect has attracted intensive research attention because of its huge potential for application. However, coherent head-to-head light incidence casts a strong constraint. Profs. Z. H. Hang and Y. Lai from Soochow University provided a routine to release the geometrical constraint and more tunability to CPA by introducing a ZIM [7]. Because of the inhomogeneous field inside a ZIM, no matter where the incident ports and the embedded absorber are, the incident beams shall always be coherent. The CPA effect can be easily tuned by simply changing the embedded lossy defect and a new configuration scheme is also possible as more incident beams can be introduced. A microwave experiment successfully demonstrated the CPA effect using again the DZI alumina PC (Fig. 4).

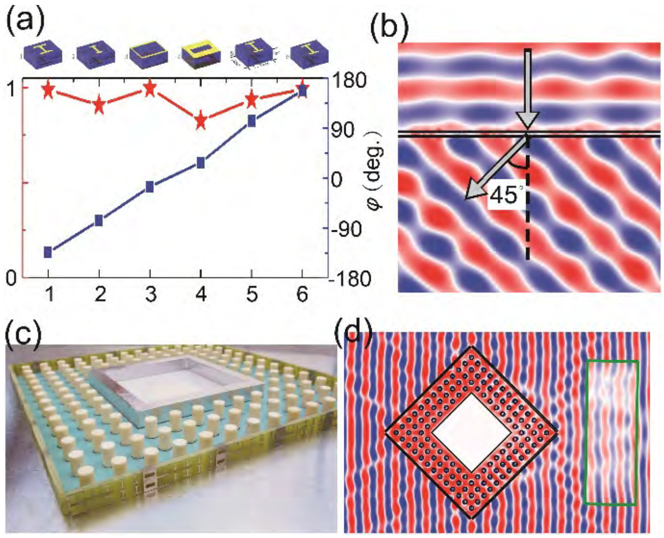

Fig. 3: Hybrid skin cloak. (a) & (b): Transparent metasurface for beam manipulations. (c) & (d): In microwave experiments, the plane wavefront after propagating through the hybrid cloak can be recovered. This figure is adapted from Ref. [5].

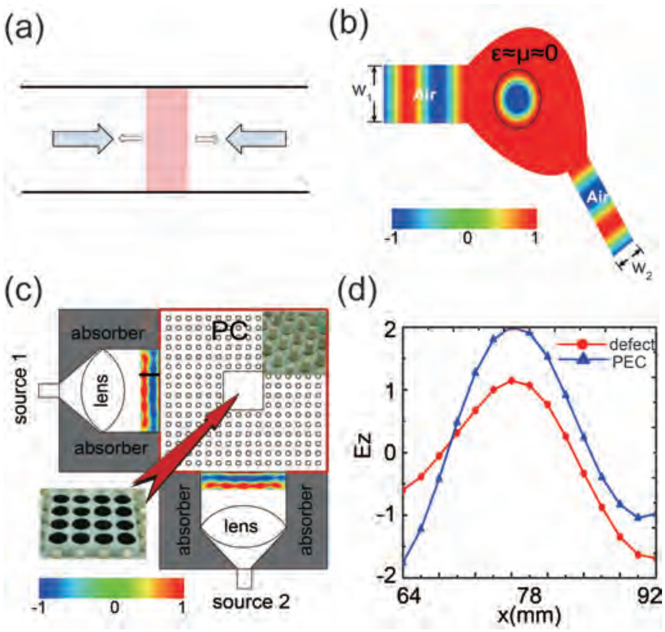

Fig. 4: CPA using DZI PC. The figure is adapted from Ref. [7].

With a slightly smaller lattice constant (a = 16.2 mm), the working frequency is now at 11.17 GHz.

As only low loss dielectric structures are needed to construct an impedance matched DZI material, DZI PC will serve as a good platform in the innovation of more optical applications.

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