Ultra-transparent Media: Metamaterials with a Wide Range of Brewster Angles

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Transparent media are the foundation of almost all optical instruments. However, perfect transparency has never been realized in natural transparent solid materials such as glass because of the impedance mismatch with free space or air. Non-reflection only occurs at a particular incident angle for a specific polarization, which is known as the Brewster angle. As a consequence, there generally exist unwanted reflected waves at the surface of a glass slab, as illustrated in Fig. 1(a). It would be interesting and it would be highly valuable for practical applications to extend the Brewster angle from a particular one to a wide range of - or even all - angles, so that there would be no reflection for all incidences.

Moreover, the virtual image formed by a glass slab placed in air is usually blurred to a certain extent [Fig. 1(a)]. Such a blur indicates the aberration of virtual images, and is caused by the mismatch of equal frequency contours between air (grey lines) and the glass (blue lines).

Profs. Zhi Hong Hang and Yun Lai from Soochow University and colleagues explore the possibility to realize ultimate transparency by artificial optical structures [1]. They pursue the realization of transparent media with the extreme property of omnidirectional impedance matching and the ability to form aberration-free virtual images, which are hereby denoted as ultra-transparent media. They propose that ultra-transparent media can be realized by using pure dielectric photonic crystals. Photonic crystals [2], known as the periodic arrangement of dielectrics, is more commonly known for the photonic band gaps introduced. The blockade of light propagation of photonic band gapped materials is the opposite of ultra-transparency. Their proposal also extends the understanding of transformation optics by utilizing effective medium with nonlocal parameters, i.e. permittivity and permeability that are dependent on the incident angle. The equal frequency contour of the ultra-transparent photonic crystal can be tuned to be a shifted ellipse (red lines) with the same height of that of air (grey lines). By using ray optics, such an equal frequency contour can be proved to endow the valuable ability of forming aberration-free virtual images, as presented in Fig. 1(b).

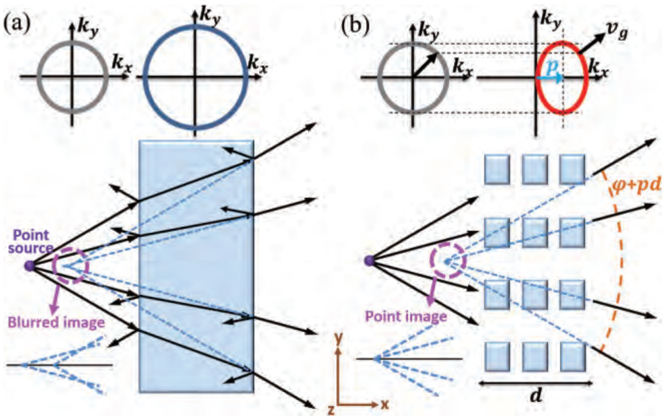

Fig. 1: Illustration of ultra-transparent media with spatial dispersion. The figure is adapted from Ref. [1].

An extreme example with almost complete transparency (T>99%) for nearly all incident angles (-89°, 89°) is demonstrated. The ultra-transparent photonic crystal is composed of a rectangular array of dielectric rods in free space, with the unit cell shown in Fig. 2(a). With transverse electric polarization, at the working frequency, the equal frequency contour is a shifted ellipse (red dashed curve) with the same height as that in free space (grey dashed curve), as shown in Fig. 2(b). The transmittance through such a photonic crystal slab is always near unity (>99%) for nearly all incident angles (<89°), and is almost irrespective of the layer number *N*.

Ultra-transparent media can, in principle, be designed using transformation optics with local effective medium parameters [3]. However, the complex subwavelength metallic components of metamaterials make the realization of perfect transparency extremely difficult, if not impossible. By introducing spatial dispersion to the effective medium, the extra degree of freedom relaxes the stringent requirement to realize local effective medium parameters. The shift of the equal frequency contour completely retains the refractive behavior for light incident on the surface perpendicular to the "shift" direction. Thus, photonic crystals can be good candidates to be explored because the photonic band dispersion manipulation techniques can be utilized to help the design of ultra-transparent media. Nonlocal effective parameters (i.e. spatially dispersive) can be obtained. Moreover, the ultra-transparent media also enable additional phase modulation *pd*, where *p* is the shift magnitude and *d* is the slab thickness [Fig. 1(b)], which is absent in the traditional transformation optics.

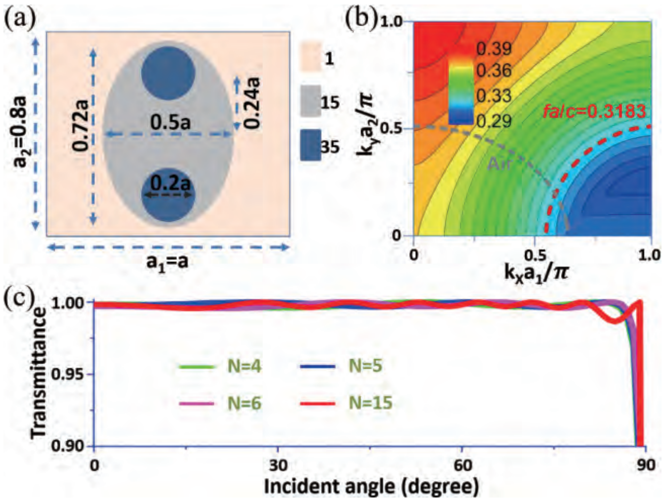

Fig. 2: Illustration of ultra-transparent media with spatial dispersion. (a) The unit cell of ultra-transparent photonic crystal. Colors indicate permittivities of materials adopted. (b) Equal frequency contour of the photonic crystal. (c) Transmittance through the photonic crystal slab with (*N*=4, 5, 6, 15) layers of unit cells as functions of the incident angle. The figure is adapted from Ref. [1].

In order to prove the theory, proof-of-principle microwave experiments were performed by utilizing a simplified photonic crystal consisting of rectangular alumina bars in a square lattice, as shown in Fig. 3(a). Similar shifted dispersion can be obtained from such a simplified design and a wide-angle impedance matching effect can be visualized. An incident microwave beam (from bottom left, as in Fig. 3) transmits through the photonic crystal slab at a wide range of angles with barely noticeable reflection.

The concept and theory of ultra-transparency gives a guideline for realizing the ultimate transparency which would be broadband, omnidirectional and polarization-insensitive. Though the demonstration is at the microwave regime, as dielectrics with reasonable permittivity are adopted, ultra-transparent solid optical materials may be optimized and bring unprecedented levels of transparency to optical frequencies. The introduction of spatial dispersion to transformation optics may also contribute to the future design of low-loss transformation optics devices, and provide a new way of controlling the optical phase beyond its original framework.

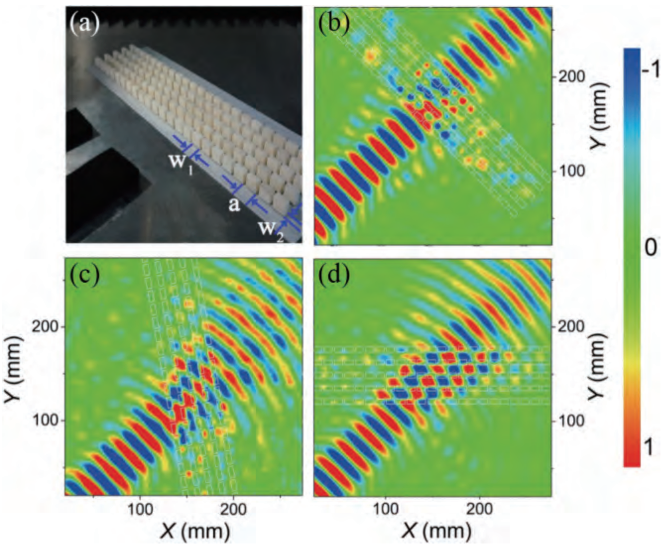

Fig. 3: Experimental demonstration of reflectionless transmission at a wide range of angles (15 degree (b), 30 degree (c) and 45 degree (d)) through an array of photonic crystals made of alumina blocks. The figure is adapted from Ref. [1]. The picture of the experimental setup is shown in (a).

References

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