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Bending, splitting, compressing and expanding of electromagnetic waves in infinitely anisotropic media

Youming Zhang¹, Baile Zhang^{1, 2, *}

¹*Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 637371, Singapore*

²*Centre for Disruptive Photonic Technologies, Nanyang Technological University, Singapore 637371, Singapore*

**E-mail: blzhang@ntu.edu.sg*

Abstract

High-efficiency diffraction-free manipulations of electromagnetic waves is fundamentally difficult to realize, though reflectionless wave bending or sub-diffraction-limited imaging has been realized separately in previous demonstrations. Recent advances in epsilon-near-zero and anisotropic epsilon-near-infinity metamaterials have provided unique possibilities to achieve reflectionless diffraction-free electromagnetic wave manipulations. Here we propose bending, splitting, compressing and expanding of electromagnetic waves with infinitely anisotropic media that can be achieved without diffraction or reflection. The results are verified by numerical simulations. This work furthers the study of infinitely anisotropic media, and might find applications in high-efficiency interconnection of subwavelength photonic information.

Manipulating electromagnetic (EM) waves without reflection or diffraction is fundamentally difficult to realize due to the wave nature of EM waves. Previously, reflectionless manipulation of EM waves can be achieved by transformation optics [1, 2] techniques which maps a virtual space into the physical space so that EM waves can be controlled at will without reflection. A typical example of reflectionless EM wave manipulation with transformation optics is the invisibility cloak which guides EM waves around a certain cloaking region and makes the EM waves preserve their original trajectory and phase after they propagate through the cloak [1]. However, the invisibility cloak designs suffer from the complex parameters that require to be implemented with complicated metamaterials [3-7] or photonic structures [8-10]. Besides invisibility cloaks that are often based on continuous coordinate transformations, finite embedded coordinate transformations [11], which means the transformation-optical medium and the surrounding media are not continuous at the boundary, have been applied to design many photonic devices, such as beam bends, splitters and expanders [12-15] etc. Nevertheless, these designs cannot overcome the diffraction of EM waves since the virtual space that the transformation starts from is not free of diffraction.

Another approach to realize reflectionless EM wave manipulation is to use epsilon-near-zero (ENZ) media. It has been proposed and demonstrated that EM waves can be highly compressed and tunnel through a narrow ENZ-media-filled waveguide channel without reflection regardless of the specific geometry of the channel [16-18]. This property of ENZ media has been applied to realize EM wave bending and nonlinear effects boosting [19, 20] etc. However, the realizations of ENZ metamaterial fundamentally suffer from narrow bandwidth. Besides, subwavelength information cannot be preserved in ENZ media if no anisotropy is introduced.

Recently, metamaterials with extreme anisotropy has been proposed to achieve reflectionless diffraction-free EM wave routing [21]. This interesting phenomenon has been further experimentally demonstrated using metallic-plate-stacking structures over a broad bandwidth at microwave frequencies [22]. Here, we propose to use media with extreme anisotropy to realize

reflectionless diffraction-free EM wave bending, splitting, compressing and expanding. The results are verified by numerical simulations with COMSOL Multiphysics. This work furthers the study of infinitely anisotropic metamaterials and can be useful for manipulation and interconnection of subwavelength photonic information.

We firstly discuss the diffraction-free property in infinitely anisotropic media. The general three-dimensional (3D) cases have been discussed in Ref. [22] Here we discuss the two-dimensional (2D) cases. We start from the dispersion relations in infinitely anisotropic media. Assume the permittivity tensor of an infinitely anisotropic medium is $\text{diag}\{\varepsilon_{\parallel}, \varepsilon_{\perp}, \varepsilon_{\perp}\}$, where $\varepsilon_{\parallel}$ is finite and $\varepsilon_{\perp}$ is near infinite (we regard the direction of the finite component as that of the optical axis). The isofrequency contour of the ordinary waves (in 2D scenario, ordinary waves are transverse-electric polarized) is a circle with an infinite radius. Thus, ordinary waves are suppressed. The dispersion of the extraordinary waves (in 2D scenario, extraordinary waves are transverse-magnetic (TM) polarized) is:

$$\frac{k_{\perp 1}^2}{\varepsilon_{\parallel}} = \omega^2 \varepsilon_0 \mu_0 \quad (1)$$

where $k_{\perp 1}$ denotes the wave vector component perpendicular to the optical axis. The isofrequency contour of the extraordinary waves is a pair of parallel lines oriented along the direction of the optical axes. Due to the flat shape of the isofrequency contour of the extraordinary waves, real infinite values of transverse wave vectors are supported and meanwhile a same phase accumulation is guaranteed when extraordinary waves propagate, thus wave diffraction is suppressed in the direction of the optical axis [21].

Fig. 1 shows the comparison between wave propagations in free space and an infinitely anisotropic medium in a 2D scenario. Fig. 1 (a) and (d) show the 2D isofrequency contours of free space and infinitely anisotropic media, respectively. As can be seen that the isofrequency contour

of free space is a circle which supports power flow in arbitrary directions with a uniform wave number of k_0 . Thus, when a TM polarized (the magnetic field is in the out of plane direction) Gaussian beam (with a waist size of 0.6 wavelength), which is an integral of plane waves with different wave vectors, propagates in free space, the beam soon diffracts as shown in Fig. 1(b). When the TM polarized Gaussian beam hits a perfect conducting obstacle with a random shape and a size of approximate one wavelength, the beam gets scattered into the whole space due to diffraction. The geometrical details of the obstacle can hardly be retrieved from the scattered waves. However, isofrequency contour of an infinitely anisotropic medium is a pair of parallel straight lines that supports arbitrary wave number but power flow only in the directions perpendicular to the isofrequency lines. Therefore, a TM polarized Gaussian beam with the same feature of that in Fig. 1(b) propagates in an infinitely anisotropic medium, as shown in Fig. 1(e), the Gaussian profile of the beam is maintained, which implies the diffraction-free property of infinitely anisotropic media. Even when the TM polarized Gaussian beam hits a perfect conducting obstacle (features the same with that in Fig. 1(c)), no wave can bypass the obstacle to propagate in the shadow region, as shown in Fig. 1(f), and the width of the shadow is exactly the same with the vertical dimension (perpendicular to the incident direction of the beam) of the obstacle. Moreover, it can be found that the geometrical details of the obstacle shined by the beam can be retrieved from the reflected waves directly, showing a unique imaging property of infinitely anisotropic media.

Now we discuss the transmission between two infinitely anisotropic media. Assume two pieces of infinitely anisotropic media are connected along y - z plane. The optical axes of medium 1 and medium 2 are O_1 and O_2 in x - y plane, making angles of θ_1 and θ_2 with the interface, respectively. The finite permittivity components of medium 1 and medium 2 are ε_1 and ε_2 . An EM plane wave with an arbitrary extraordinary wave vector is incident from medium 1 to medium 2. By matching boundary conditions, we can obtain the reflectance and transmittance, from which the general reflectionless transmission condition in 2D scenario can be obtained [21, 22].

$$\sqrt{\varepsilon_1} \cos(\theta_2) = \sqrt{\varepsilon_2} \cos(\theta_1) \quad (2)$$

The detailed derivation can be found in Ref. [21] and [22]. Under the reflectionless transmission condition, if the magnetic field of the incident wave is $\bar{H}_i = \hat{z}e^{i\bar{k}_i\bar{r}}$, the electric field of the incident wave can be calculated as $\bar{E}_i = \hat{o}_1\sqrt{\varepsilon_1}e^{i\bar{k}_i\bar{r}}$, and the magnetic field and electric field of the transmitted wave can be written as $\bar{H}_t = \hat{z}e^{i\bar{k}_t\bar{r}}$ and $\bar{E}_t = \hat{o}_2\sqrt{\varepsilon_2}e^{i\bar{k}_t\bar{r}}$, respectively, where $\bar{k}_i$ ($\bar{k}_t$) is the wave vector of the incident (transmitted) wave, $\hat{o}_1$ and $\hat{o}_2$ are the unit vector in the directions of the optical axes of two media. We can readily find that $|\bar{H}_i| = |\bar{H}_t|$, $\sqrt{\varepsilon_2}|\bar{E}_i| = \sqrt{\varepsilon_1}|\bar{E}_t|$ and $\sqrt{\varepsilon_2}|\bar{S}_i| = \sqrt{\varepsilon_1}|\bar{S}_t|$. These features can be applied to achieve reflectionless diffraction-free bending, splitting, compressing/expanding of TM polarized EM waves.

Fig. 2 shows obtuse-angled (120 degree), right-angled and acute-angled (60 degree) reflectionless diffraction-free EM wave bending cases applying the reflectionless transmission condition. Three TM polarized Gaussian waves (with waist size of 0.2 wavelength) propagate in regions formed by infinitely anisotropic media oriented in different directions. We can find from Fig. 2 (a)(c)(e) that when the finite components of two infinitely anisotropic media are the same and the boundaries between the adjacent two media are along the angle bisector line of the angles formed by the optical axes of two media, the propagation of EM waves are both reflectionless and diffraction-free regardless of the bending angles. Fig. 2 (b)(d)(f) show the magnetic field distribution and the wave vectors. These imply a near free circuit-like manipulations of EM waves.

Besides bending, if we re-design the boundary between two media in a way as shown in Fig. 3, we can readily realize reflectionless diffraction-free splitting of EM waves. As can be seen in Fig. 3(a), when a TM polarized Gaussian beam (with a waist size of 0.2 wavelength) propagates through the boundary of two infinitely anisotropic media (the reflectionless condition is satisfied), the wave is split into two waves right along the central line of the Gaussian beam, and each of the waves maintains half of the Gaussian profile after the splitting. If we put a perfect conducting mask

with two slits (the center to center distance between two slits is $1/10$ wavelength, and the width of two slits is $1/10$ wavelength) in the path of the wave propagation, two subwavelength ray-like waves are generated by the two slits and propagate without interfering with each other. When two ray-like waves go through the re-designed boundary, they are split downward and upward respectively without reflection, then re-directed to propagate in $+\hat{x}$ direction. Note that the waves go through two subwavelength-distanced slits will soon interfere with each other in free space after a very short distance of propagation, making them impossible to distinguish or split. However, in infinitely anisotropic media, the information of two slits can not only be maintained, but also split to a much larger distance so that the waves can still be distinguished even they are coupled to free space.

At last, we discuss EM wave compressing and expanding with infinitely anisotropic media. When we take different values for the finite permittivity components of two infinitely anisotropic media in Eq. (2), we can realize reflectionless diffraction-free compressing and expanding of EM waves. As can be seen from Fig. 4 (a), the permittivity tensors of two media used are $\{\infty, \varepsilon_1\}$ and $\{\varepsilon_2, \infty\}$, respectively, where $\varepsilon_1 = 9\varepsilon_2$. The angles formed by the optical axes (the axes where the finite permittivity components lie in) of two infinitely anisotropic media and boundaries are θ_1 and θ_2 , where $\theta_2 = 3\theta_1 = 71.57^\circ$ ($\theta_1 + \theta_2 = 90^\circ$), satisfying the reflectionless transmission condition. A TM polarized Gaussian beam (with a waist size of 0.2 wavelength) is incident from the left side of the region. When the TM polarized Gaussian beam propagates through the first boundary, it is compressed to $1/3$ of its original width and the wave energy density is tripled. Specifically, the amplitude of the electric field is tripled, while the amplitude of the magnetic field is unchanged, as shown in Fig. 4(b). Fig. 4(c) shows the normalized energy density along the cross lines Line1 and Line2 (white solid lines in Fig. 4(a)). During the whole bending and compressing process, the propagation of the EM wave is free from both diffraction and reflection. We can also make the compressed wave propagate in the same direction of the incident wave. As can be seen

in Fig. 4(d), the permittivity tensors for three media are $\{\infty, \varepsilon_1\}$, $\{\varepsilon_2, \infty\}$ and $\{\infty, \varepsilon_2\}$, where $\varepsilon_1 = \varepsilon_3 = 9\varepsilon_2$. The angles formed by the optical axes of the media and the boundaries are $\theta_2 = 3\theta_1 = 71.57^\circ$ and $\theta_3 = 45^\circ$, satisfying the reflectionless transmission condition at both boundaries. When a TM polarized Gaussian beam propagates through the first boundary, we can see that the wave is firstly compressed to 1/3 of its original width and bent downward after propagating through the first boundary as in Fig. 4(a). Then the beam gets bent back to its original propagating direction after propagating through the second boundary. Fig. 4(e) shows the magnetic field distribution and Fig. 4(f) shows the normalized power density along the cross lines Line3 and Line4 in Fig. 4(d).

If we inverse the whole structure, as shown in Fig. 4(g-i), EM wave can be expanded to triple of its original width and the energy density of the EM wave is diluted to 1/3. By changing the ratio of the finite components oriented angles of infinitely anisotropic media, we can in theory realize arbitrary compressing and expanding of EM waves without reflection or diffraction. Particularly, when $\varepsilon_2 \rightarrow 0$ (means $\varepsilon_1/\varepsilon_2 \rightarrow \infty$), the wave can be compressed to an infinitely small width with infinitely large energy density, which matches the “supercoupling” phenomenon of ENZ media.

In summary, we have discussed the diffraction-free property and the reflectionless transmission in infinitely anisotropic media. Making use of these properties, EM wave bending, splitting, compressing and expanding can be achieved, which are further verified by numerical simulations. This work furthers the study of infinitely anisotropic media and can be useful for manipulation and interconnection of subwavelength photonic information.

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Figure. 1 Comparison between wave propagations in isotropic media and infinitely anisotropic media. (a)(d) Isofrequency contours of isotropic media and infinitely anisotropic media. The thin arrows denote the wave vectors supported and the wide arrows denote the Poynting vectors supported. (b)(e) TM polarized Gaussian beams propagation in an isotropic medium and an infinitely anisotropic medium. The waist size is 0.6 wavelength. (c)(f) Waves scattering when TM polarized Gaussian beams hit a perfect conducting obstacle with a random shape and a size of approximate one wavelength. The waist size is 0.6 wavelength.

Figure. 2 Reflectionless diffraction-free electromagnetic wave bending with infinitely anisotropic media. (a)(c)(e) Power density distribution of TM polarized Gaussian beams bent by 60, 90 and 120 degrees, respectively. The waist size is 0.2 wavelength. The dashed lines denote the boundaries. (b)(d)(f) Magnetic field distribution and wave vectors (black arrows).

Figure. 3 Reflectionless diffraction-free electromagnetic wave splitting with infinitely anisotropic media. (a) Splitting of a TM polarized Gaussian beam. (b) Splitting of waves passing through two subwavelength-distanced slits. The slits have size of 1/10 wavelength and the center-to-center distance between two slits is 1/10 wavelength. The dashed lines denote the boundaries.

Figure. 4 Reflectionless diffraction-free electromagnetic wave compressing and expanding with infinitely anisotropic media. (a)(b) Power density and magnetic field distributions of TM polarized Gaussian beam compressing and bending. (c) Normalized power density along the cross lines Line1 and Line2 (white solid lines) in (a). (d)(e) Power density and magnetic field distributions of TM polarized Gaussian beam compressed in its original direction. (f) Normalized power density along the cross lines Line3 and Line4 (white solid lines) in (d). (g)(h) Power density and magnetic field distributions of TM polarized Gaussian beam expanded in its original direction. (i) Normalized power density along the cross lines Line5 and Line6 (white solid lines) in (g).

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