Manipulating light by rotating optical axes

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Abstract

We investigate how light is manipulated using a single type of anisotropic metamaterial. We construct a 2D transformation medium utilizing effective media of layers of varying optical axes, associating to an area-conserving map. For out-of-plane wave propagation, an optical axis profile using the same metamaterial structure can engineer the wavefront.

Recent demonstrations of transformation optics near or at visible frequencies are going in the direction of using simple dielectric media to relieve the loss and the bandwidth issues [1-7]. Among the many implementations of transformation optical devices, there are special examples, e.g. on carpet cloaks and field rotators, that can employ only a single type of anisotropic dielectric medium but with the orientations of the optical axis pointing in different directions at different locations [4-5,8]. In contrary to the general philiosophy of transformation optics in taking advantage of the extreme flexibility in choosing refractive indices in different directions, it emphasizes on using the least degree of freedom to get maximal functionality. This kind of transformation media can be most generally visualized with an array of arrows with each arrow representing the direction of the optical axis at a particular position. Here, we will explore how light can be manipulated by simply rotating and mixing these arrows in the subwavelength scale freely.

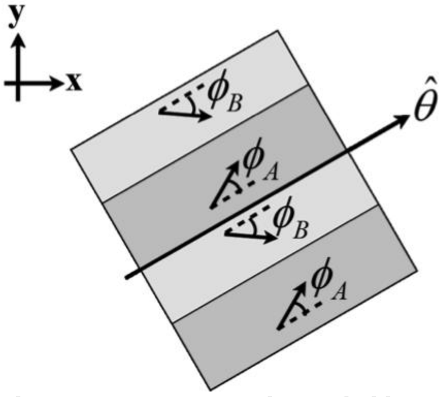

Fig. 1 Effective medium in mixing principal axes (bold arrows) of AB layers

For simplicity, we discuss transformation optics in two dimensions with H-polarization. In our approach, we are confined in constructing the transformation medium by assembling small pieces of the same kind of anisotropic medium with fixed refractive indices (n_α and n_β along the two principal axes) while the optical axes of these different pieces can be chosen freely. An effective medium can be constructed by stacking alternatively two layers of different optical axes periodically. In Fig. 1, the θ-axis denotes the direction tangential to the layers while the two bold arrows represent the two principal axes making angles ϕ_A and ϕ_B to the θ-axis. Under such a scheme, the effective medium in mixing different optical axes give us refractive indices that can vary continuously between the two bounds n_α and n_β along a new set of orthogonal principal axes while the product of the two principal indices will stay at the same constant product $n_\alpha \times n_\beta$. Within the framework of transformation optics, such a class of effective media gives us the flexibility to construct trnasformation optical devices associated with area-conserving mappings. Figure 2(a) shows a wave expander which is constructed from these alternating AB layers. Each layer has slowly varying principal axes with fixed ratio n_α / n_β=2.4. The black lines outline the alternating layers (Fig. 1). A Gaussian beam is incident from the left and leaves the device with a magnified beam width. On another case, a virtual shifter [9] can be constructed with these AB layers to shift the white scatterer back to the center, as shown in Figure 2(b) and (c).

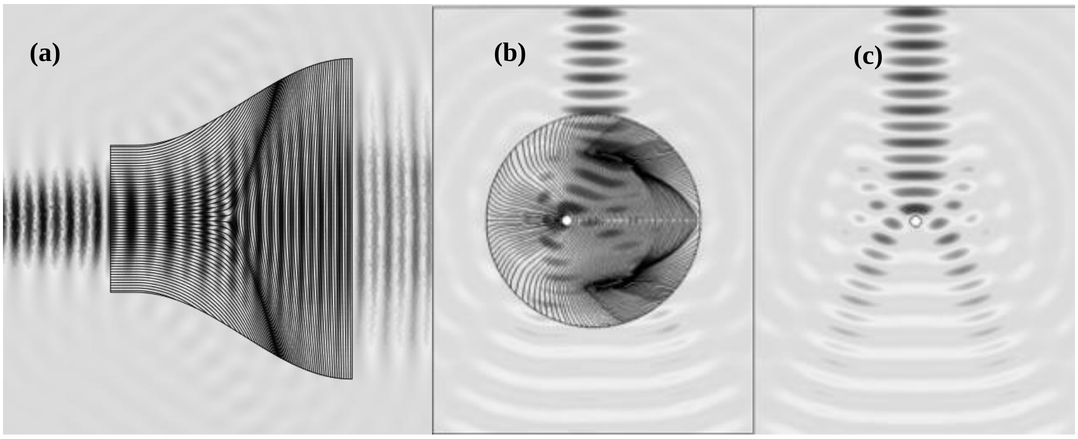

Fig. 2 (a) A wave expander and (b) a virtual shifter constructed from AB layers with fixed anisotropy n_α / n_β=2.4 and continuous varying directions of principal axes within each layer. The virtual shifter shifts the white scattering object back to the center, as if the simulation shown in (c) without the shifter.

We have demonstrated the manipulation of in-plane wave propagation by using an optical axes profile. In fact, an optical axes profile can also be very effective in manipulating out-of-plane wave propagation to create a phase discontinuity across a metamaterial plate [10,11]. Instead of using metamaterial structures of double-resonance, an array of optical axes with profile can be used for manipulating the wavefront. The metamaterial plate (top panel of Fig. 3) consists of a one-dimensional array of the same type of split-ring aperture antennas with variable rotation angle of the optical axes. When a left-handed circularly polarized plane wave impinges on the plate, the phase discontinuity introduced by the plate has a simple linear relationship to the geometric rotation angle of each antenna, as in a conventional Q-plate. The usage of metamaterials allows us to generate an optical axes profile which can vary in subwavelength scale to create a sharper control of wavefront while the phase discontinuity can be introduced with a metamaterial plate much thinner than a wavelength. Fig. 3(a) shows the simulation when a plane wave of left-handed circular polarization impinges on an optical axis of quadratic angle profile. By carefully choosing the working wavelength, 2.2 times of the repeating distance in the array in this case, the transmitted light is completely converted to the right-handed circular polarization while a tight focus (with a width ~ 0.77λ) is formed. While a converging wavefront is formed for the left-handed circular polarization, the same structure creates the opposite phase discontinuity, i.e. a diverging wavefront, for the right-handed circular polarization (as shown in Fig. 3(b)).

In conclusion, we have demonstrated how a profile of optical axes varying in a subwavelength scale can be used as a transformation medium for in-plane wave propagation in realizing any area-conserving maps and can be used as a metamaterial plate to control the wavefront for out-of-plane wave propagation in getting a tight focus.

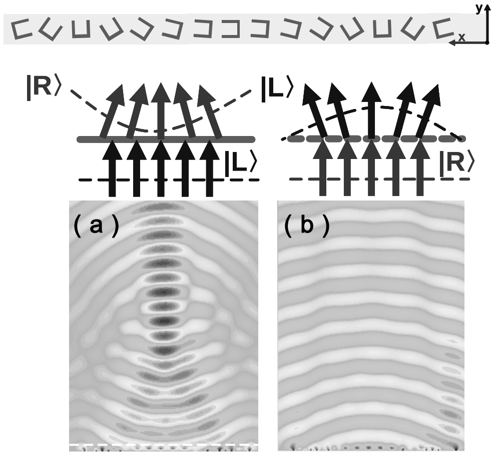

Fig. 3 An array of aperature antennas with variable optical axes (on the x-y plane) for focusing/defocusing (in the z-direction) when a plane wave (of left-handed/right-handed ciruclar polarization) impinges normally to the array. The transmitted light is completly converted to the crossed polarization.

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