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Flat designs of impedance-matched nonmagnetic phase transformer and wave-shaping polarization splitter via transformation optics

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ABSTRACT

Based on transformation optics, we propose a method to realize an arbitrary wavefront transformation through an impedance-matched nonmagnetic slab. First, we follow the principle of equal optical path length to realize arbitrary phase transformations by a flat configuration, adopt a nonlinear coordinate transformation to ensure impedance match, and preserve the dispersion relation to render the device nonmagnetic. Applying this method, a phase transformer is designed such that both the wave shape and propagation direction can be changed. Second, we choose distinct deflection angles for two orthogonal polarizations and combine the two sets of material parameters into an anisotropic slab, whereby a wavefront-controllable polarization splitter is achieved. The results are further validated by numerical simulations. The method proposed can be used to develop all-dielectric, lossless and broadband devices that can be easily constructed at optical frequencies.

1. Introduction

Within the past few years the new research field of transformation optics (TO) has triggered enormous interest [1,2]. TO provides a general method to manipulate electromagnetic waves at will using metamaterials. Employing this method, a host of striking electromagnetic devices have been demonstrated [3–5], the first of which was the invisibility cloak [6]. Following the cloak was a large body of work devoted to controlling the path of light rays resulting in beam shifters [7], beam bends [8–10], and wave scaling devices [11–15]. By combining two beam shifters for TE and TM waves into one device, a polarization splitter was achieved [16,17]. Meanwhile, researchers applied TO in order to manipulate the phase to create phase transformers [18–21]. On this topic we have proposed a method of phase transformation (PT) between any two wavefronts through a compact slab [22,23]. Applying this method, the device configuration remains flat irrespective of its function.

Despite their success, TO devices are confronted with two problems: scattering and implementation. Undesired scattering results from impedance mismatch at the device interface because: (i) A two-dimensional (2D) transformation is adopted for simplicity in most literature, which inevitably leads to an asymmetric transformation and thus an impedance mismatch [8]. Such a mismatch does not occur to three-dimensional (3D) symmetrical transformations [24]. (ii) The coordinate transformation (CT) chosen is often linear. Such a CT can determine the positions of two boundaries in the virtual and physical spaces. However, it does not have a third parameter to guarantee that the impedance is matched to the surrounding medium. Cai et al. found that such an impedance mismatch can be eliminated by employing a high-order CT [25]. Up to now, such a nonlinear transformation method has been used to control the light paths in symmetrical transformations, including cylindrical cloaking with minimized scattering [26–30] and an Eaton lens without singularities [31–33]. Practical implementation of the devices is difficult because (i) The materials resulting from TO are both electrically and magnetically anisotropic. (ii) The dispersive nature of metamaterials leads to high loss and a narrow frequency range of operation. This has caused

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researchers to simplify material parameters [6] and adopt all-dielectric media alternatively [25,34]. Li and Pendry have proposed the use of quasi-conformal CT to reduce the anisotropy in the invisibility cloak [35]. This method was most recently applied to 3D isotropic transformation media [36].

As far as TO devices controlling phase are concerned, these two problems provide a challenge to achieve PTs in more general cases (e.g., asymmetric PTs) by realizable materials with minimized scattering and compact profiles. In this paper we focus on these issues and propose a method to realize any PT by an impedance-matched nonmagnetic flat medium. We follow the method in Refs. [22,23] but adopt a nonlinear CT to ensure impedance matching, use a quasi-conformal CT to simplify the material parameters [35,37], and keep the dispersion relation unchanged to allow the device to become nonmagnetic [6,25]. Applying this method, a phase transformer is designed such that the wave shape and propagation direction can be changed. Then, we choose distinct deflection angles for TE and TM waves and combine the two sets of material parameters into an anisotropic slab, thereby achieving a polarization splitter. In contrast to previous splitters [16,17], this design allows one to control splitting angles and wave shapes of the two polarizations. The results are further confirmed by numerical simulations.

2. Method of PT by an impedance-matched nonmagnetic slab

In this section we investigate how to accomplish the conversion between any two wavefronts by an impedance-matched nonmagnetic flat medium. This method does not depend on the symmetry of the PT. We follow the principle of equal optical path length [22,38] to attain a flat configuration and adopt a nonlinear CT to ensure the impedance match.

2.1. A general PT method for the conversion between two arbitrary wavefronts

Realization of a flat profile: For simplicity, we consider the 2D wave problem. To change a wavefront, the incident wave surface can be transformed directly to the desired wave shape, i.e. from $B'C'$ to $A'E'$ as shown in Fig. 1(a), which may be named the direct transformation method (DTM) [18,19]. As such, the virtual space $OB'C'D$ is transformed into the physical one $OA'E'D$, resulting in a design with an irregular shape. To obtain a planar device, we have proposed an indirect transformation method (ITM) based on the principle of equal optical path length [22,23]: *the profile of the spatial separation between the original and desired wavefronts is converted to a plane surface*, i.e. from AE to BC, as shown in Fig. 1(b). Here it is the virtual region $OAED$ that is transformed into the flat physical one $OBCD$. The effective optical path lengths involved in ITM and DTM are equal, thereby resulting in the same function.

Let the incident wave front $B'C'$ be denoted as $x' = p_i(y')$ and the outgoing one $E'A'$ as $x' = p_o(y')$. Applying ITM, one can follow the spatial distortion from $OAED$ to $OBCD$, which can be written as

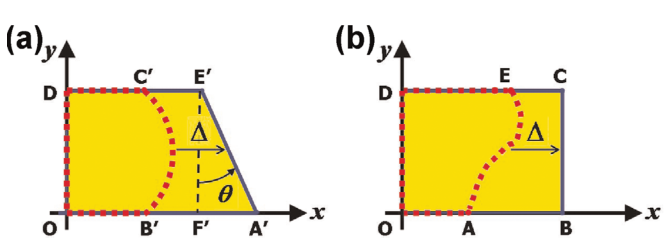

Fig. 1. Schematic diagram of the space transformation to deflect one curved phase front into another by (a) the direct transformation method in the literature and (b) the indirect transformation method in the present work.

a general mapping:

$$x = f(x'), \quad y = y', \quad z = z', \tag{1}$$

plus two boundary conditions:

$$x = 0 \quad \text{for} \quad x' = 0, \tag{2}$$

$$x = b \quad \text{for} \quad x' = \Delta. \tag{3}$$

Here b is the width of the slab and $x' = \Delta$ corresponds to the profile of spatial separation between the two wavefronts AE with

$$\Delta = a + p_i(y') - p_o(y'). \tag{4}$$

Therein a is a flexible constant that affect the material properties but not the function. Note that Δ determines the result of PT, namely the function, while $f(x')$ is the CT fashion adopted that is independent of the function.

There are countless forms of $x = f(x')$ to satisfy the boundary conditions Eqs. (2) and (3). For Eq. (2) the entry boundary of the virtual space is the same as that of the physical space, hence there is no reflection. Eq. (3) indicates that there exists a discontinuity in the CT between the two exit boundaries. This may lead to an impedance mismatch at the exit interface. In order to eliminate undesired scattering and realize the resulting material in a practical way, we need to impose appropriate conditions on the CT.

Minimization of material anisotropy: We follow the quasi-conformal CT technique [35,37] and only consider the CT in the x direction that is set independent of y' (i.e., $\partial x/\partial y' = 0$ and $\partial y/\partial x' = 0$). As a result, the Jacobian matrix is diagonal:

$$J = \mathrm{diag}[\partial f(x')/\partial x', 0, 0]. \tag{5}$$

This will greatly simplify material parameters. According to TO, the permittivity tensor $\boldsymbol{\varepsilon}$ and permeability tensor $\boldsymbol{\mu}$ in the transformed coordinate system are connected with the original $\boldsymbol{\varepsilon}_o$ and $\boldsymbol{\mu}_o$ by the relationships: $\boldsymbol{\varepsilon} = J\boldsymbol{\varepsilon}_o J^T/\det(J)$ and $\boldsymbol{\mu} = J\boldsymbol{\mu}_o J^T/\det(J)$ [6]. Applying these equations to Eq. (1) yields a general result of the relative material parameters:

$$\boldsymbol{\varepsilon}(\boldsymbol{\mu}) = \mathrm{diag}\left[\partial f/\partial x', (\partial f/\partial x')^{-1}, (\partial f/\partial x')^{-1}\right], \tag{6}$$

for the conversion between two arbitrarily curved wavefront. Here the original space is considered to be vacuum. Note that all x' in Eq. (6) should be replaced by $x' = f^{-1}(x)$.

Nonmagnetic implementation: It is well known that the propagation property is completely determined by the dispersion relation of wave in the medium. Therefore, if we adjust the individual values of $\boldsymbol{\varepsilon}(\boldsymbol{\mu})$ while keeping the dispersion relation unchanged, the propagation dynamics will be the same. For a TM wave (the magnetic field along the z direction), we multiply ε_{xx} and ε_{yy} by μ_{zz} in Eq. (6) and obtain the following nonmagnetic parameters:

$$\varepsilon_{xx} = \varepsilon_{zz} = \mu = 1, \quad \varepsilon_{yy} = (\partial f/\partial x')^{-2}. \tag{7}$$

Then there is no magnetic dependence, leading to an all-dielectric PT device.

Impedance matching: We require the impedance at the exit interface to be matched to free space. That is, the x component $Z_x|_{x=b} = \sqrt{\mu_{yy}/\varepsilon_{zz}}|_{x=b} = 1$ which is satisfied automatically and the y component:

$$Z_y|_{x=b} = \sqrt{\mu_{xx}/\varepsilon_{zz}}|_{x=b} = \partial f(x')/\partial x'|_{x=b} = 1. \tag{8}$$

By fulfilling Eq. (8), we can fix the function $f(x')$ together with all the material properties and achieve a phase transformer with minimized scattering.