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Homogenous Optic-Null Medium Performs as Optical Surface Transformation

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Abstract—An optical surface transformation (OST) method is proposed briefly in this short paper. Compared with Transformation Optics (TO), we do not need to consider what kinds of coordinate transformation should be used when designing a novel device, but only need to choose the shapes of two end surfaces (namely, the input and output surfaces of the device), which are linked by an optic-null medium (ONM) that is a highly anisotropic homogeneous medium. All devices designed by OST can be realized by some ONM. The design process of an optical device with some pre-designed function can be converted to the simple choice of the shape and size of the optical surfaces with the OST, which will become a simple and yet innovative way to design electromagnetic/optical devices.

1. INTRODUCTION

Designing optical devices by a coordinate transformation has become a very hot topic in recent years owing to the theory of transformation optics (TO) and its late development [see, e.g., [1–4] and references cited therein]. Many scattering-related problems can be tackled with the help of TO, e.g., cancelling the scattering pattern of an arbitrarily shaped object [1, 5–7], steering the radiation angle [8, 9], creating the scattering illusions [10–13]. Due to the development of metamaterials (i.e., a kind of artificial materials composed of some subwavelength structures) [14], many devices designed by TO have been fabricated and experimentally demonstrated.

Although TO gives a new approach to the design of novel optical devices, there are some limitations on this theory: Firstly, we have to find a proper coordinate transformation or a well-designed reference space according to the specific device that we want to realize with a pre-designed function. The coordinate transformation can be designed analytically (or numerically), which is not convenient to some engineers who are not good at mathematical derivation. Secondly, the medium designed by TO (i.e., the transformation medium) is often very complicated (e.g., often inhomogeneous anisotropic impedance-matched media), which means that we have to simplify/approximate the ideal media before the experimental realization and scarify some performances of the device.

In this short paper we propose a simple idea for the design of optical devices, namely, the so-called optical surface transformation (OST). Based on the special properties of the optic-null medium (ONM), we find that the design process can be very simple: all we need to do is to design the shapes of the input and output surfaces of the device and use a properly shaped ONM that links these two surfaces.

2. METHOD AND AN EXAMPLE

ONM has been used for different optical/electromagnetic devices, e.g., an optical hyper-lens [15], magnetic hoses [16], field concentrators [17], radome for a phased array antenna [8], etc.. Actually the

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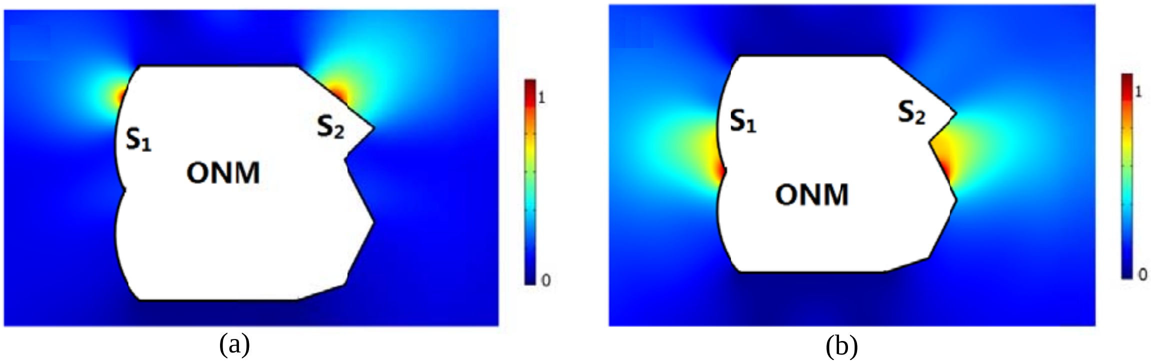


(a) (b)

Figure 1. 2D FEM (finite element method) simulation results: we plot the normalized absolute value of electric field's z component for TE wave case. The white region is filled with the ONM whose main axis is along x direction. The shapes of the input and output surfaces are chosen at random. If we put a line current of unit amplitude 1 A at the input surface S_1 of the device, we will obtain its image point at the output surface S_2 of the device.

role of the ONM is just like a surface projecting medium, which can make a projection transformation from one surface (e.g., the input surface of the device) to the other surface (e.g., the output surface of the device). As shown in Figure 1, two arbitrarily shaped surfaces (having the same projected cross section along the x direction) connected by the ONM with main axis in x direction, will perform equivalently and can be treated as the equivalent optical surfaces (i.e., each point on surface S_1 will be projected to its corresponding point on surface S_2). This means that the ONM with the main axis in the x direction will perform like a projection transformation along the x direction on its two end surfaces. The relative permittivity and permeability tensors of an ONM whose main axis is along the x direction can be described as:

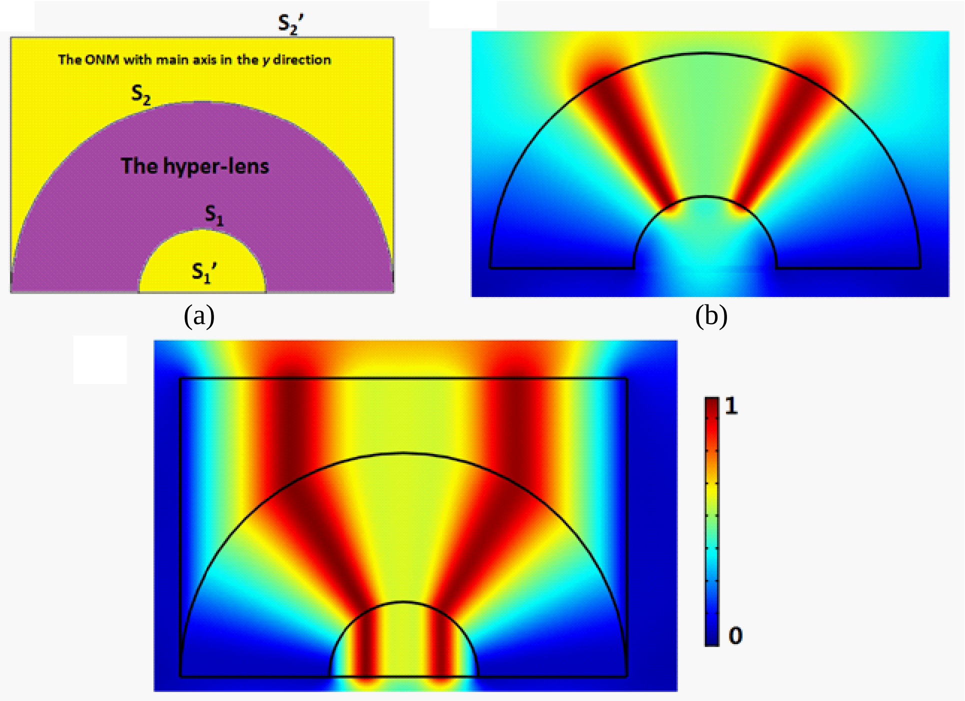
$$\varepsilon'_X = \mu'_X = \operatorname{diag}\left(\frac{1}{\Delta}, \Delta, \Delta\right), \quad \Delta \to 0 \tag{1}$$

Note that label 'X' means the main axis of this ONM is along x direction. Similarly, the main axis of the ONM can be in any other direction, e.g., in the radial direction (in this case the permittivity and permeability of the ONM are extremely large along the radial direction and nearly zero along other orthogonal directions, and its function is to project surfaces along the radial direction). Two arbitrarily shaped surfaces can always be linked by the ONM (or a combination of many ONMs with different main axes), which means that we can always make two arbitrarily shaped surfaces sharing the same projected cross section by projecting many times along different directions. The ONM can be used to perform an OST to its two end surfaces.

We should note that the ONM has been designed for many specific applications [15–17], and has been experimentally realized at a microwave frequency [18, 19]. In this short paper, we propose the idea of using the OST function of the ONM to design optical devices without any mathematical formula. Next we will give an example to show that a device design that has been achieved through TO can be obtained in a much simpler way with the present idea of OST.

A hyper-lens is a super-resolution imaging device that converts the evanescent wave to the propagation wave in the far field region [15, 20, 21]. Actually the hyper-lens can be treated as a special kind of the ONM whose main axis is along the radial direction. The object and image surfaces of a hyper-lens are both cylindrical surfaces, which are not convenient for practical applications. Although TO has been utilized to reshape the object or image surface of a hyper-lens (see, e.g., [22, 23]), these methods require complicated mathematical calculations/derivations/formulas (and new calculations should be made if the size of the hyper-lens changes).

We can simply convert the image and object surfaces of a hyper-lens to flat planes with the help of the present OST. As shown in Figure 2(a), the original hyper-lens (the half-circular ring region of purple color) has a cylindrical object plane S_1 and a cylindrical image plane S_2. We can simple add two ONMs both having main axes along the y direction (the yellow regions) to project the original object and image surfaces (i.e., S_1 and S_2) to the new object and image planes (i.e., S'_1 and S'_2), respectively. The



(a) (b)

(c)

Figure 2. (a) Our idea of using the OST to convert the curved object and image surfaces of a hyper-lens to flat planes. The purple region is the original hyper-lens whose relative permittivity and permeability are extremely large along the radial direction and nearly zero in other orthogonal directions. The yellow regions are the ONM with main axis along the y direction. The original object and image surfaces (S_1 and S_2) are converted to flat planes (S_1' and S_2'). (b) and (c) are FEM simulation results for the normalized absolute value of the electric field's z component for the TE case. As the objects the two incoherent line currents with unit amplitude 1 A are separated by a distance $\lambda_0/3$. (b) The original hyper-lens: the objects are set on the cylindrical object surface of the lens. (c) The transformed hyper-lens: the objects are set on the flat object surface of the lens.

new object and image planes are both flat planes. The imaging ability of the original hyper-lens and the transformed hyper-lens are given in Figures 2(b) and 2(c), respectively. We should note that the object and image planes can also be converted to any other shapes (not limited to flat planes). Compared with the previous TO methods converting the object or image surface of a hyper-lens [22, 23], our OST method is much simpler (no mathematical calculation is needed during the whole design process). When the size of the hyper-lens changes, we can still use the same idea to convert its image or object surface to a flat plane. Furthermore, only one homogeneous anisotropic medium (ONM) with main axis in the y direction is needed to realize the whole device.

3. SUMMARY AND DISCUSSION

Our idea of designing an optical device by an OST is very simple: First we choose two surfaces of arbitrary shape as the input and output surfaces of the device (also as the two end surfaces of the ONM) according to the specific application. Then we find a commonly projected cross section of these two surfaces by projecting these surfaces along different directions, which also determine the direction of ONM's the main axis in each part of the device. There is no mathematical effort (e.g., a coordinate transformation) during the whole design process. All devices designed by the OST can be realized with only one homogeneous anisotropic medium (i.e., the ONM). The ONM may have different main axes in different parts of the designed device, i.e., the optic-null media are the same homogeneous anisotropic material positioned with its main axis along different projecting directions in different parts. The ONM has been experimentally demonstrated at a microwave frequency through metamaterials [18, 19]. An OST can greatly simplify the design process. We will give a detailed description with more examples and applications of the OST in a future full-length paper.

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