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Inverse design based metamaterial concentrator and its applications and realization

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ABSTRACT

Unlike the previous design method in which one must know the transformation function beforehand, an inverse design method is proposed to build a metamaterial concentrator in this paper. The required material parameters are independently obtained and expressed as functions of the introduced generator. Scattering magnifying ability of the concentrator and two applications for antenna miniaturization and military camouflage are also investigated. Moreover, to remove the anisotropic parameters and simplify the practical realization of the concentrator, a fan-shaped layered concentrator composed of only alternating isotropic materials is presented based on the effective medium theory. Full-wave simulation results are provided for verification. This work paves a new way for designing metamaterial devices without the need to know the underlying transformation function, and has great guiding significance for the fabrication and application of the concentrator.

1. Introduction

In the past few years, transformation optics has shaped up a revolutionary electromagnetic design paradigm, enabling the researchers to create astonishing metamaterial devices that seemed impossible a decade ago, such as invisibility cloak, perfect lens and illusion device [1–15]. Among various novel devices, metamaterial concentrator as an important wave-manipulation device has recently received considerable attention. Since the cylindrical concentrator was first proposed by Rahm et al. [16], many further investigations on the concentrator have been conducted, including non-rotationally invariant concentrator [17], cone-shaped concentrator [18], arbitrary shaped concentrators [19], homogeneous-materials-constructed concentrator [20,21], concentrator with only axial parameter spatially variant [22], and concentrator with minimized scattering [23]. Moreover, the scope of the research has been gradually extended from optics to acoustics [24], plasmonics [25], elastodynamics [26] and even thermodynamics [27]. The foregoing investigations are really attractive, but it should be pointed out that the design method for all the aforementioned concentrators share a common feature that in order to derive the material parameters of the device, the transformation function between the original space and the transformed space must be known in advance. Furthermore, in the earlier studies, all theoretical analyses and numerical simulations are mainly devoted to the focusing property of the concentrator and its potential application in solar cells or similar devices in which high field intensities are needed. To the best of our knowledge, there is very little research on the other features of the concentrator and its corresponding application.

In this paper, an inverse design method for determining the material parameters of metamaterial concentrator is presented, in which one doesn't need to know the transformation function beforehand. The boundary conditions together with introduced generator replace the corresponding transformation function, and not until all material parameters are determined does the implicit transformation function be uniquely revealed. The effectiveness of such a method and the performance of designed concentrator are validated by full-wave simulation. Potential applications of the concentrator for the antenna miniaturization and military camouflage based on the scattering magnifying ability are also analyzed. In addition, to enhance the realizability of metamaterial concentrator, we also discuss a layered version of the concentrator where fan-shaped alternating isotropic materials are used.

2. Simulation model and method

For the sake of simplicity, we restrict ourselves here to a two-dimensional (2D) case. Fig. 1 shows the schematic diagram of the coordinate transformation for the design of a 2D metamaterial

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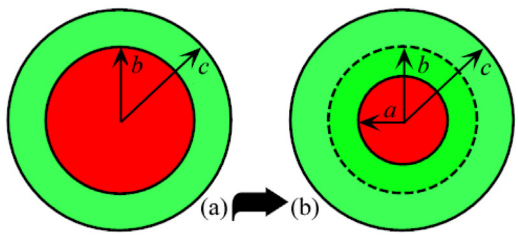

Fig. 1. Schematic diagram of the coordinate transformation for the design of a 2D metamaterial concentrator: (a) the original space, (b) the transformed space.

concentrator. To design such a device, the coordinate transformation is carried out along the radial direction, while keeping the azimuthal and axial directions unchanged. The regions $r' \in [0, b]$ and $r' \in [b, c]$ in the original space (Fig. 1(a)) are transformed into the regions $r \in [0, a]$ and $r \in [a, c]$ in the transformed space (Fig. 1(b)), respectively. After the transformation, two concentric circles with radii of a and c divide the whole transformed space into two cylindrical regions, namely, the core region $r \in [0, a]$ and the annular region $r \in [a, c]$. Next, we focus on how to derive the material parameters of the metamaterial concentrator based on our inverse design method.

As is well known, transformation optics makes use of the form invariance of Maxwell's equations under a spatial coordinate transformation to establish the equivalence between the metric transformation and the change of material parameters. According to this theory, when the original space is assumed to be free space, the material parameters for the transformed space in the cylindrical coordinates are summarized as [6]

$$\mu_r(r) = \varepsilon_r(r) = \frac{r'\mathrm{d}r}{r\mathrm{d}r'}, \quad \mu_\varphi(r) = \varepsilon_\varphi(r) = \frac{r\mathrm{d}r'}{r'\mathrm{d}r},$$
$$\mu_z(r) = \varepsilon_z(r) = \frac{r'\mathrm{d}r'}{r\mathrm{d}r}. \tag{1}$$

where $r' = r'(r)$ represents the transformation function between the original space and the transformed space, and $\mathrm{d}r'/\mathrm{d}r$ denotes the derivative of $r'(r)$ with the respect to radius r of the transformed space. Eq. (1) provides the general expressions of the material parameters for both transverse electric (TE) and transverse magnetic (TM) modes. Here, however, we will limit our analysis to the case of TE-polarized waves, in which electric fields are polarized along the z-axis, and only the $\mu_r(r)$, $\mu_\varphi(r)$ and $\varepsilon_z(r)$ parameters are relevant. The analysis for the case of TM polarization would be similar, and it is not included for brevity. By manipulating Eq. (1), a new set of equations can be derived as follows:

$$\mu_r(r)\mu_\varphi(r) = 1, \quad \mu_r(r)\varepsilon_z(r) = \frac{r'^2}{r^2}, \quad \sqrt{\mu_\varphi(r)\varepsilon_z(r)} = \frac{\mathrm{d}r'}{\mathrm{d}r}. \tag{2}$$

By eliminating the azimuthal parameter $\mu_\varphi(r)$ in Eq. (2), a differential equation only related to the radial and axial parameters (i.e., $\mu_r(r)$ and $\varepsilon_z(r)$) is given as

$$r\sqrt{\mu_r(r)\varepsilon_z(r)}\frac{d\left[r\sqrt{\mu_r(r)\varepsilon_z(r)}\right]}{\mathrm{d}r} = r\varepsilon_z(r) \tag{3}$$

For the annular region of the metamaterial concentrator, the following equation can be obtained by numerically integrating Eq. (3),

$$r^2\mu_r(r)\varepsilon_z(r) = 2\int_a^r r_1\varepsilon_z(r_1)\,\mathrm{d}r_1 + C_0 \tag{4}$$

where C_0 is an unknown integration constant. Combining the boundary condition of $r'(a) = b$ with Eqs. (2) and (4), the unknown constant is found to be $C_0 = b^2$. And then by using another boundary condition of $r'(c) = c$, Eq. (4) is simplified to

$$c^2 - b^2 = 2\int_a^c r_1\varepsilon_z(r_1)\,\mathrm{d}r_1 \tag{5}$$

which is a normalized condition closely associated with the axial parameter of the annular region. Besides, it also plays key roles in determining the other two parameters and finding the implicit transformation function for the annular region. Here, a concentrating generator $g(r)$ proportional to $\varepsilon_z(r)$ is defined, that is $g(r) = C_1\varepsilon_z(r)$, where C_1 is an arbitrary constant. It follows through Eq. (5) that C_1 is automatically canceled and the axial parameter of the annular region is represented in the form of introduced generator

$$\varepsilon_z(r) = \frac{\left(c^2 - b^2\right)g(r)}{2\int_a^c r_1 g(r_1)\,\mathrm{d}r_1} \tag{6}$$

Similarly, the radial and azimuthal parameters can be expressed as functions of $g(r)$ through Eqs. (2), (4) and (6)

$$\mu_r(r) = \frac{2b^2\int_a^c r_1 g(r_1)\,\mathrm{d}r_1 + 2\left(c^2 - b^2\right)\int_a^r r_1 g(r_1)\,\mathrm{d}r_1}{\left(c^2 - b^2\right)g(r)r^2} \tag{7}$$

$$\mu_\varphi(r) = \frac{\left(c^2 - b^2\right)g(r)r^2}{2b^2\int_a^c r_1 g(r_1)\,\mathrm{d}r_1 + 2\left(c^2 - b^2\right)\int_a^r r_1 g(r_1)\,dr} \tag{8}$$

Finally, submitting Eqs. (6) and (7) into Eq. (2), the implicit transformation function for the annular region is determined to be

$$r'(r) = \sqrt{b^2 + \frac{\left(c^2 - b^2\right)\int_a^r r_1 g(r_1)\,\mathrm{d}r_1}{\int_a^c r_1 g(r_1)\,\mathrm{d}r_1}} \tag{9}$$

It is clear from the above derivation process that only after all material parameters are obtained can the implicit transformation function between the original and transformed spaces be found. In other words, the transformation function in the proposed method appears as an option and it is not even necessary to know it. This characteristic is quite different from that of the earlier-reported method where one starts from the specified transformation function and then the required parameters are calculated by constructing the explicit transformation matrix. Therefore, the method presented here can be viewed as an inverse design method. The material parameters for the core region of the concentrator is directly set as $\mu_r(r) = \mu_\varphi(r) = 1$ and $\varepsilon_z(r) = (b/a)^2$. This implies that the incident electromagnetic wave will be concentrated into the core region when passing through the concentrator, and the intensity of power flow there will be increased by a factor of $(b/a)^2$. In the next section, we will make full-wave simulation using commercial software COMSOL Multiphysics to demonstrate the effectiveness of the proposed method and prove the performance of the designed metamaterial concentrator.

3. Numerical simulations and discussion

In the simulation, three different concentrating generators for the annular region are taken into account. The corresponding material parameters and transformation function for each case can be easily calculated through Eqs. (6)–(9), as illustrated in Table 1. Certainly, other choices of generators (e.g., exponential, sinusoidal and even hyperbolic sine functions) are feasible, and it should be stressed that the performance of metamaterial concentrator for all cases is equally perfect in theory. However, these considerations go beyond the scope of this work, and they are not addressed here.