Inverse design-based metamaterial transparent device and its multilayer realization*

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We propose an inverse method to determine the material parameters of a transparent device without any knowledge of the corresponding transformation function. The required parameters are independently obtained and expressed as functions of the introduced generator. Moreover, to remove the inhomogeneity and anisotropy of material parameters, a layered transparent device composed of only homogeneous and isotropic materials is presented based on the effective medium theory. The feasibility of using the layered device in antenna protection is also investigated. Full-wave simulation is carried out for verification. This work paves a new way toward designing metamaterial devices without specifying the underlying coordinate transformation, and has great guiding significance for the practical fabrication of transparent devices.

Keywords: metamaterial, transparent device, inverse design, multilayer realization

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1. Introduction

In recent years, transformation optics (TO) has demonstrated its power in the design of novel functional devices and opened up a whole new avenue for the arbitrary control of electromagnetic waves using metamaterials.[1–6] Following this theory, a large number of intriguing devices, such as the invisibility cloak,[7–14] perfect lens,[15] field concentrator[16] and illusion device[17] have been reported. Furthermore, the application of TO has been gradually extended from optics to acoustics,[18–20] elastodynamics,[21] plasmonics,[22,23] electronics,[24] and even thermodynamics.[25]

Among various devices, metamaterial transparent devices have recently aroused great attention due to their capability of protecting the device inside without affecting their performance—an important property for radome structures. Circular and elliptical transparent devices were firstly proposed by Yu *et al.*[26] Later, the general expressions of material parameters for a transparent device with arbitrarily conformal and non-conformal inner and outer boundaries are developed by Mei *et al.*[27] The foregoing investigations are really attractive and hold great promise for application in antenna protection. However, coordinate transformation for these transparent devices is conducted along the radial direction, resulting in the necessary material parameters being highly anisotropic inhomogeneous. As a result, the practical fabrication of the aforesaid transparent devices is so far unachievable and their applications remain in the realm of theory. To overcome such difficulties, a more feasible strategy is presented by our group for designing diamond-shaped transparent devices with homogeneous parameters based on coordinate transformation along the orthogonal direction.[28] Even though this method eliminates the requirement of material inhomogeneity, the parameter distribution of device in each region is still anisotropic. Moreover, it is noted that the previous two design methods 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.

In this paper, an inverse method for determining the material parameters of a transparent device is proposed, in which one does not need to know the transformation function beforehand. Boundary conditions, in combination with an introduced generator, replace the corresponding transformation function. Not until all material parameters are determined does the implicit transformation function become uniquely revealed, thereby this method reverses the traditional design procedure and can be regarded as a transformation function-independent method. In addition, multilayer realization of a transparent device by alternating homogeneous isotropic materials and its potential application in antenna protection are also discussed. The validity of such a method and the performance of the designed device are confirmed by full-wave simulation. The inverse method enables us to obtain material parameters of the transparent device without knowing the specific transformation function, and the layered design idea will greatly enhance the realizability of the device in practice.

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2. Simulation model and method

Figure 1 shows a schematic diagram of two-dimensional (2D) metamaterial transparent devices, where three concentric circles with radii of a, c, and d divide the transformed space into three cylindrical regions, namely, inner region $r \in [0,a]$, stretching region $r \in [a,c]$, and compressive region $r \in [c,d]$. To design such a device, the regions $r' \in [a,b]$ and $r' \in [b,d]$ in the original space are respectively transformed into the regions $r \in [a,c]$ and $r \in [c,d]$ in the transformed space along the radial direction, while the azimuthal and axial directions remain unchanged. It is stressed that the above-mentioned coordinate transformation can lead to the following boundary conditions: $r'_{\rm str}(a) = a$, $r'_{\rm str}(c) = b$ for the stretching region, and $r'_{\rm com}(c) = b$, $r'_{\rm com}(d) = d$ for the compressive region. Next, we focus on how to derive the material parameters of a transparent device based on an inverse design method.

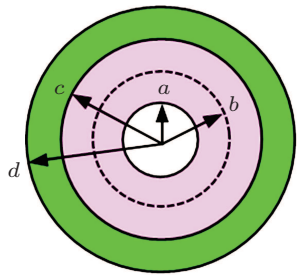


Fig. 1. (color online) Schematic diagram of a 2D metamaterial transparent device.

As is well known, TO employs the form invariance of Maxwell's equations under spatial coordinate transformations to establish the equivalence between metric transformations and changes of material parameters. According to this theory, when the original space is assumed to be free space, the material parameter for the transformed space in the cylindrical coordinates are expressed as[7]

$$\begin{aligned}
\mu_r(r) &= \varepsilon_r(r) = \frac{r'\,\mathrm{d}r}{r\,\mathrm{d}r'},\\
\mu_\phi(r) &= \varepsilon_\phi(r) = \frac{r\,\mathrm{d}r'}{r'\,\mathrm{d}r},\\
\mu_z(r) &= \varepsilon_z(r) = \frac{r'\,\mathrm{d}r'}{r\,\mathrm{d}r},
\end{aligned} \tag{1}$$

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 respect to radius r of the transformed space. Equation (1) provides the general expression of material parameters for both transverse electric (TE) and transverse magnetic (TM) modes. However, here we simply consider the case of TE-polarized waves, in which electric fields are polarized along the z axis, and only $\mu_r(r)$, $\mu_\phi(r)$, and $\varepsilon_z(r)$ parameters are relevant. By manipulating Eq. (1), a new set of equations can be derived as follows:

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

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

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

For the stretching region of a transparent device, the following equation can be further obtained by numerically integrating Eq. (3),

$$r^2\mu_{{\rm str}r}(r)\varepsilon_{{\rm str}z}(r) = 2\int_a^r r_1\varepsilon_{{\rm str}z}(r_1)\,\mathrm{d}r_1 + C_0, \tag{4}$$

where C_0 is an unknown integration constant. On the basis of boundary condition of $r'_{\rm str}(a) = a$, it is easy to find in Eq. (2) that $\mu_{{\rm str}r}(a)\varepsilon_{{\rm str}z}(a) = 1$, and then the unknown constant is solved as $C_0 = a^2$. Additionally, by submitting another boundary condition $r'_{\rm str}(c) = b$ into Eq. (4), we obtain the normalized condition of axial parameter for the stretching region

$$b^2 - a^2 = 2\int_a^c r_1\varepsilon_{{\rm str}z}(r_1)\,\mathrm{d}r_1, \tag{5}$$

which plays an important role in determining the other two parameters and finding the implicit transformation function $r'_{\rm str}(r)$ for the stretching region. Here, a stretching generator $g_{\rm str}(r)$ proportional to $\varepsilon_{{\rm str}z}(r)$ is defined, that is $g_{\rm str}(r) = \delta_{\rm str}\varepsilon_{{\rm str}z}(r)$, where $\delta_{\rm str}$ is an arbitrary constant. Then based on Eq. (5), $\delta_{\rm str}$ is automatically canceled and the axial parameter of the stretching region is represented in the form of the introduced generator

$$\varepsilon_{{\rm str}z}(r) = \frac{(b^2-a^2)g_{\rm str}(r)}{2\int_a^c r_1 g_{\rm str}(r_1)\,\mathrm{d}r_1}. \tag{6}$$

In addition, radial and azimuthal parameters can be easily obtained and written as functions of $g_{\rm str}(r)$ through Eqs. (4) and (6)

$$\begin{aligned}
&\mu_{{\rm str}r}(r)\\
&= \frac{2a^2\int_a^c r_1 g_{\rm str}(r_1)\,\mathrm{d}r_1 + 2(b^2-a^2)\int_a^r r_1 g_{\rm str}(r_1)\,\mathrm{d}r_1}{(b^2-a^2)g_{\rm str}(r)r^2},
\end{aligned} \tag{7}$$

$$\begin{aligned}
&\mu_{{\rm str}\varphi}(r)\\
&= \frac{(b^2-a^2)g_{\rm str}(r)r^2}{2a^2\int_a^c r_1 g_{\rm str}(r_1)\,\mathrm{d}r_1 + 2(b^2-a^2)\int_a^r r_1 g_{\rm str}(r_1)\,\mathrm{d}r}.
\end{aligned} \tag{8}$$

Finally, we substitute Eqs. (6) and (7) into Eq. (2), and the implicit transformation function for the stretching region is determined as

$$r'_{\rm str}(r) = \sqrt{a^2 + \frac{(b^2-a^2)\int_a^r r_1 g_{\rm str}(r_1)\,\mathrm{d}r_1}{\int_a^c r_1 g_{\rm str}(r_1)\,\mathrm{d}r_1}}. \tag{9}$$

The inverse derivation process of material parameters for the compressive region is similar but based on different integral domain and boundary conditions. Integrating Eq. (3), we have

$$r^2\mu_{\mathrm{comr}}(r)\varepsilon_{\mathrm{comz}}(r) = 2\int_c^r r_1\varepsilon_{\mathrm{comz}}(r_1)\,\mathrm{d}r_1 + C_1, \tag{10}$$

where C_1 is an integration constant. Combining the boundary conditions $r'_{\mathrm{com}}(c) = b$ and $r'_{\mathrm{com}}(d) = d$ with Eqs. (2) and (10), C_1 is solved and Eq. (10) is further simplified as

$$d^2 - b^2 = 2\int_c^d r_1\varepsilon_{\mathrm{comz}}(r_1)\,\mathrm{d}r_1. \tag{11}$$

Just like the case of the stretching region, we introduce a compressive generator $g_{\mathrm{com}}(r) = \delta_{\mathrm{com}}\varepsilon_{\mathrm{comz}}(r)$ for the compressive region, in which δ_{com} is an arbitrary constant, and it can be easily eliminated. Then the material parameters and implicit transformation function for the compressive region are summarized as

$$\varepsilon_{\mathrm{comz}}(r) = \frac{(d^2-b^2)g_{\mathrm{com}}(r)}{2\int_c^d r_1 g_{\mathrm{com}}(r_1)\,\mathrm{d}r_1}, \tag{12}$$

$$\mu_{\mathrm{comr}}(r) = \frac{2b^2\int_c^d r_1 g_{\mathrm{com}}(r_1)\,\mathrm{d}r_1 + 2(d^2-b^2)\int_c^r r_1 g_{\mathrm{com}}(r_1)\,\mathrm{d}r_1}{(d^2-b^2)g_{\mathrm{com}}(r)r^2}, \tag{13}$$

$$\mu_{\mathrm{com}\varphi}(r) = \frac{(d^2-b^2)g_{\mathrm{com}}(r)r^2}{2b^2\int_c^d r_1 g_{\mathrm{com}}(r_1)\,\mathrm{d}r_1 + 2(d^2-b^2)\int_c^r r_1 g_{\mathrm{com}}(r_1)\,\mathrm{d}r}, \tag{14}$$

$$r'_{\mathrm{com}}(r) = \sqrt{b^2 + \frac{(d^2-b^2)\int_c^r r_1 g_{\mathrm{com}}(r_1)\,\mathrm{d}r_1}{\int_c^d r_1 g_{\mathrm{com}}(r_1)\,\mathrm{d}r_1}}. \tag{15}$$

It is clear from the above derivation process that only after all material parameters are obtained can the implicit transformation function 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 distinguishable from that of the earlier-reported method where one starts from the specified transformation function and then the required parameters are obtained by constructing the explicit transformation matrix. Therefore, the method presented here reverses the traditional design procedure, and can be viewed as a transformation function-independent method. Although the derived material parameters may be anisotropic and inhomogeneous, it could be realized through a concentric layered structure consisting of alternating layers of two different homogeneous isotropic materials based on effective medium theory, provided that the thickness of each layer is much less than the wavelength.[8] In what follows, in order to facilitate the practical fabrication of transparent device, a layered realization method is introduced.

Taking the stretching region of the device as an example, a schematic diagram of the concentric layered structure for realizing such region is shown in Fig. 2. The whole region is firstly divided into M layers to achieve a stepwise homogeneous layer approximation of the continuous inhomogeneous materials. Then, each homogeneous anisotropic layer is mimicked by the alternating layers (A and B) of isotropic materials with permeabilities and permittivities (μ_i^{A}, $\varepsilon_i^{\mathrm{A}}$ and μ_i^{B}, $\varepsilon_i^{\mathrm{B}}$) which satisfy the following relations:

$$\frac{1}{\mu_{\mathrm{str}r}(r_i)} = \frac{1}{1+\eta}\left(\frac{1}{\mu_i^{\mathrm{A}}} + \frac{\eta}{\mu_i^{\mathrm{B}}}\right),$$
$$\mu_{\mathrm{str}\varphi}(r_i) = \frac{\mu_i^{\mathrm{A}} + \eta\mu_i^{\mathrm{B}}}{1+\eta}, \quad \varepsilon_{\mathrm{str}z}(r_i) = \varepsilon_i^{\mathrm{A}} = \varepsilon_i^{\mathrm{B}}, \tag{16}$$

where $r_i = a + i(c-a)/M$ ($i = 1, 2, 3, \ldots, M$) represents the radius of the i-th layer, $\mu_{\mathrm{str}r}(r_i)$, $\mu_{\mathrm{str}\varphi}(r_i)$, and $\varepsilon_{\mathrm{str}z}(r_i)$ are the discrete material parameters of the i-th layer, and $\eta = d^{\mathrm{A}}/d^{\mathrm{B}}$ is the thickness ratio of layers A and B. Assuming that the value of η is equal to one, and then the effective material parameters of concentric layered structure for the stretching region take the following form:

$$\mu_i^{\mathrm{A}} = \mu_{\mathrm{str}\varphi}(r_i) + \sqrt{\left(\mu_{\mathrm{str}\varphi}(r_i)\right)^2 - \mu_{\mathrm{str}\varphi}(r_i)\mu_{\mathrm{str}r}(r_i)}, \tag{17a}$$

$$\mu_i^{\mathrm{B}} = \mu_{\mathrm{str}\varphi}(r_i) - \sqrt{\left(\mu_{\mathrm{str}\varphi}(r_i)\right)^2 - \mu_{\mathrm{str}\varphi}(r_i)\mu_{\mathrm{str}r}(r_i)}, \tag{17b}$$

$$\varepsilon_i^{\mathrm{A}} = \varepsilon_i^{\mathrm{B}} = \varepsilon_{\mathrm{str}z}(r_i). \tag{17c}$$

Consequently, inhomogeneous anisotropic materials in the stretching region are approximately represented by $2M$ discrete layers of homogeneous isotropic materials. Layered realization of compressive region can be done in the same way, and it is not included herein for brevity. In the next section, we will make a full-wave simulation using commercial software COMSOL Multiphysics to demonstrate the effectiveness of proposed method and show the performance of the designed transparent device.

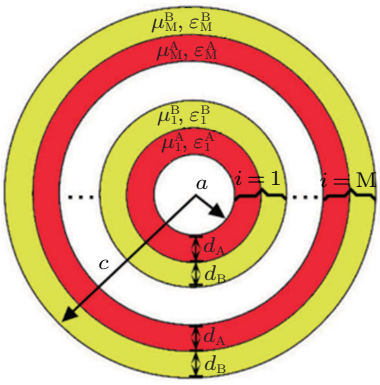


Fig. 2. (color online) Schematic diagram of the concentric layered structure for realizing the stretching region of a metamaterial transparent device.

3. Numerical simulations and discussion

In the simulation, the whole computational domain is surrounded by perfectly matched layers to realize matched absorption without producing reflection. The geometry parameters of the metamaterial transparent device are chosen as $a = 0.5$ m, $b = 0.75$ m, $c = 1$ m, and $d = 2$ m. For simplicity, we suppose that the stretching generator and the compressive generator are identical, and just take into account the three kinds of generators in this paper; that is $g_{\rm str}(r) = g_{\rm com}(r) = r^n$, $g_{\rm str}(r) = g_{\rm com}(r) = (r+\tau)^n$, and $g_{\rm str}(r) = g_{\rm com}(r) = (r+\tau)^n/r$, in which n is an integer greater than or equal to zero and τ is an arbitrary constant. The corresponding material parameters and transformation functions for each case can be easily calculated through Eqs. (6)–(9) and Eqs. (12)–(15), and they are not given here. Certainly, other selections of generator (e.g., exponential, sinusoidal, and even hyperbolic sine functions) are also feasible, and the function expressions of $g_{\rm str}(r)$ and $g_{\rm com}(r)$ can be completely different from each other, but these are out of the scope of the current paper. However, it is worth mentioning that the performance of metamaterial transparent device for all cases is equally perfect in theory.

Figures 3(a)–3(c) correspond to the electric field distribution in the vicinity of transparent device with material parameters derived from the aforementioned three cases. The values of n and τ in the simulation are set as 2 and 3, respectively. Figure 3(a) shows the simulation result when a 0.6-GHz plane wave with unit amplitude is incident from left to right. In Fig. 3(b), a 0.6-GHz Gaussian beam with a beam width of 0.15 m impinges on the transparent device from left to right. Figure 3(c) illustrates the case when a 0.6-GHz line source with a current of 0.003 A/m in z direction is located at the origin. It can be seen from Fig. 3 that although the electromagnetic waves are distorted in the transformation region, they return to the original wave fronts when passing through the device. In other words, the inverse design-based transparent device with material parameters determined from different generators can perform well, and its performance is independent of incident wave-fronts.

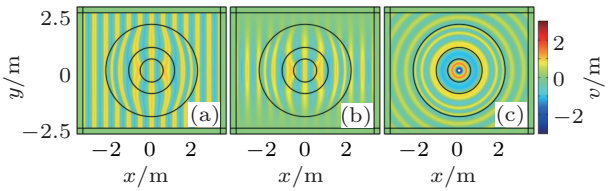


Fig. 3. (color online) Electric field distribution in the vicinity of the metamaterial transparent device with parameters derived from (a) $g_{\rm str}(r) = g_{\rm com}(r) = r^n$, (b) $g_{\rm str}(r) = g_{\rm com}(r) = (r+\tau)^n$, and (c) $g_{\rm str}(r) = g_{\rm com}(r) = (r+\tau)^n/r$. (a) A plane wave is incident from left to right; (b) a Gaussian beam propagates from left to right; (c) a line source is located at the origin.

To accelerate the practical realization of transparent device, the feasibility of a layered device composed of only homogenous and isotropic materials is investigated. It is not difficult to find out that the generators $r^n = (r+\tau)^n = 1$ when n is set to zero. For simplicity, but without loss of generality, we take this particular case as an example and start our discussion. Both stretching and compressive regions are divided into M layers in the simulation, and a 0.6-GHz plane wave propagates along the x axis. Figures 4(b) and 4(c) display the electric field distribution in the vicinity of layered transparent device with $M = 10$ and $M = 20$ layers, respectively. For comparison, the field distribution of an ideal transparent device is also simulated, and the results are shown in Fig. 4(a). It is observed that by increasing the number of layers to smoothen the stepwise approximation, a layered transparent device could achieve reasonable performance, which is even comparable to that of an ideal transparent device.

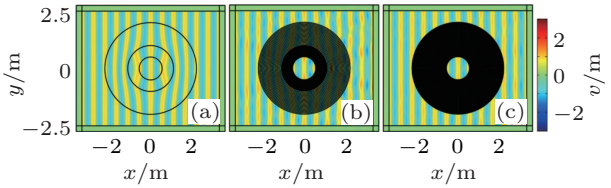


Fig. 4. (color online) Electric field distribution in the vicinity of (a) the ideal device, and layered device with $M = 10$ (b) and $M = 20$ (c) layers.

Moving one step further, we will examine whether or not the proposed layered device can be used for antenna protection in practical applications. Figure 5(a) depicts the electric field distribution in the vicinity of a horn antenna covered by the layered transparent device with $M = 20$ layers, of which a 0.001 A/m line source is located at $(-0.1$ m, 0) to act as an excitation source. The field distribution of a horn antenna exposed to free space is shown in Fig. 5(b). The white flecks in the figure represent overvalued fields. Comparing Fig. 5(a) with Fig. 5(b), it is obvious that the field distribution of the horn antenna with and without the layered device in the region of $r > d$ is almost the same.

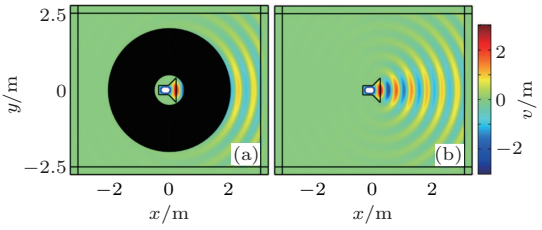


Fig. 5. (color online) Electric field distribution in the vicinity of a horn antenna (a) with and (b) without the layered transparent device.

To quantitatively evaluate the performance of a layered transparent device, the normalized far-field distributions of the horn antenna located inside the layered device and in free space are also plotted, as illustrated in Fig. 6. As can be seen, the far-fields of two cases accord well with each other, and the

layered device has only a negligible effect on the communication quality of the antenna. Thus, it is concluded that a layered device with sufficient layers can be applied as an radome structure, which is able to protect an antenna against adverse weather conditions and guarantee the stability and durability of the antenna during its life-time.

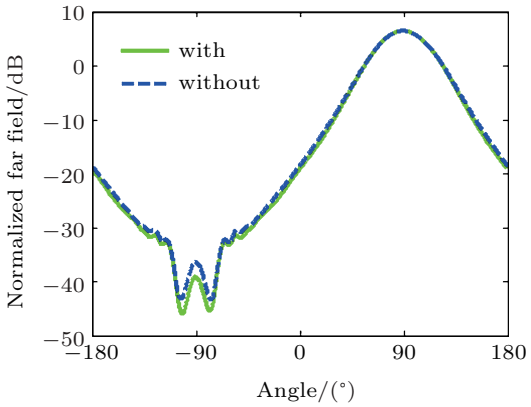


Fig. 6. (color online) Comparison of the normalized far-field distribution of a horn antenna with and without the layered transparent device.

4. Conclusion

In summary, we propose an inverse method to design a metamaterial transparent device, in which the derivation of material parameters is unrelated to the transformation function. The effectiveness of the method and the device performance are validated by full-wave simulation. Results show that the transparent device based on a different generator can work effectively and its performance is independent of incident wave-fronts. Furthermore, to eliminate the inhomogeneous and anisotropic material properties and accelerate the practical realization of a transparent device, a layered device made up of only homogeneous isotropic materials is developed. We found that the layered device with sufficient layers behaves nearly as well as the ideal one, and is able to protect an antenna without sacrificing its performance. It is believed that the method presented here could be extended to a three-dimensional case and also applied to design other metamaterial devices.

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