Shrinking device realized by using layered structures of homogeneous isotropic materials*

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We propose the practical realization of a shrinking device by using layered structures of homogeneous isotropic materials. By mimicking the shrinking device with concentric alternating thin layers of isotropic dielectrics, the permittivity and the permeability in each isotropic layer can be properly determined from the effective medium theory in order to achieve the shrinking effect. The device realized by multilayer coating with dielectrics is validated by TE wave simulation, and good shrinking performance is demonstrated with only a few layers of homogeneous isotropic materials.

Keywords: shrinking device, effective medium theory, multilayered structure

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1. Introduction

The exciting issue of transformation-based invisibility cloaking[1−11] has aroused the great interest, ever since Pendry *et al.*[1] proposed the theory of transformation optics (TO). By employing the coordinate transformation approach, various interesting functional EM devices have been investigated, such as free-space invisibility cloaking,[1−8] ground-plane cloaking,[9−11] superscatterer,[12] and reshaping devices.[13] This method provides a clear geometric picture of the designed device, and the permittivity and permeability tensors of the designed functional material can be derived directly from coordinate transformation.

Among the applications of TO, a concept of illusion optics has been proposed: making an object with arbitrary shape and material properties appear exactly like another object of some other shape and material makeup, which is verified by numerical simulations.[14] To realize those devices, complementary media composed of left-handed materials each with simultaneously negative permittivity and permeability are needed.[12−14] However, such media are not easy to realize using present technology.

Recently, in Ref. [15] a shrinking device has been reported, which can convert an arbitrary object virtually into a desired small-size object and was fabricated by resonate split-ring structures in a microwave frequency range. Fabrication by using a split-ring cell structure has a strong requirement for direction and is usually very complex. In order to reduce the complexity, in this paper, we use an alternative method of using a concentric alternating thin layered system to realize the shrinking device. The alternating layered structure is composed of two kinds of normal isotropic dielectrics, thus leading to much easier practical fabrication.

2. Model and method

For simplicity and perspicuity, we consider a two-dimensional (2D) cylindrical case and focus on the transverse-electric (TE) mode, in which the electric field is polarized along the cylindrical axis (the z direction). Figure 1 schematically illustrates a two-dimensional case of the optical shrinking device in a cylindrical coordinate system, which is a circular shell with inner and outer radii a and b, respectively. The

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detailed coordinate transformation from virtual space to real space in cylindrical coordinates to design such a shrinking device is as follows:[15]

$$r = k_1(r' - c) + a, \quad \varphi = \varphi', \quad z = z', \tag{1}$$

in which $k_1 = (b-a)/(b-c)$ is the shrinking coefficient of the device. Based on the transformation optics, the material properties of the shrinking device can be expressed as

$$\begin{aligned} \mu_r &= \frac{r - a + k_1 c}{r}, \\ \mu_\varphi &= \frac{r}{r - a + k_1 c}, \\ \varepsilon_z &= \frac{r - a + k_1 c}{k_1^2 r}. \end{aligned} \tag{2}$$

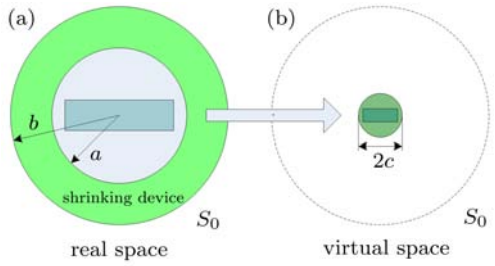


Fig. 1. (colour online) Schematic plots of the shrinking device. (a) A large rectangle in the real space enclosed by a shrinking device. (b) The shrinking device transforms the real object to an illusion object (a smaller rectangle) in the virtual space. The real space and the virtual space share the same boundary S_0.

Based on the effective medium theory (EMT),[16] anisotropic materials with desired permittivity properties can be replaced by a layered structure of thin, alternating dielectric layers (or metal and dielectric layers). The values of permittivity and permeability along the directions parallel and perpendicular to the layer surface are quite different, and can be determined by using the EMT. To simplify the physical implementation, we employ a concentric layered structure to realize the shrinking device mentioned above with radius-dependent, anisotropic relative permittivity and permeability. We first discretize the single shell into M layers of anisotropic medium as a stepwise approximation of the continuously varying anisotropic medium, which is schematically shown in Fig. 2. The radius of each anisotropic medium could be determined as

$$r_p = a + p\frac{b-a}{M}, \quad p = 1, 2, \ldots, M. \tag{3}$$

Then the discrete material parameters for each layer can be obtained by substituting Eq. (3) into Eq. (2) as follows:

$$\begin{aligned} \mu_r^p &= \frac{r_p - a + k_1 c}{r_p}, \\ \mu_\varphi^p &= \frac{r_p}{r_p - a + k_1 c}, \\ \varepsilon_z^p &= \frac{r_p - a + k_1 c}{k_1^2 r_p}. \end{aligned} \tag{4}$$

Afterward, the p-th anisotropic layer could be realized with double-layered isotropic dielectrics with relative permeabilities and permittivities of $\mu_{\rm A}^p$, $\varepsilon_{\rm A}^p$ and $\mu_{\rm B}^p$, $\varepsilon_{\rm B}^p$, respectively. Based on the EMT, in the case where the layer thickness is much less than the work wavelength, such double-layered isotropic dielectrics can mimic an anisotropic layer with[17]

$$\begin{aligned} \mu_\varphi^p &= \frac{\mu_{\rm A}^p + \eta\mu_{\rm B}^p}{1+\eta}, \\ \frac{1}{\mu_r^p} &= \frac{1}{1+\eta}\left(\frac{1}{\mu_{\rm A}^p} + \frac{\eta}{\mu_{\rm B}^p}\right), \\ \varepsilon_z^p &= \varepsilon_{\rm A}^p = \varepsilon_{\rm B}^p, \end{aligned} \tag{5}$$

where $\eta = d_{\rm A}/d_{\rm B}$ is the thickness ratio of the two layers, one can obtain the following equivalent medium parameters for the isotropic layered structure when the thickness of each layer is identical:

$$\begin{aligned} \mu_{\rm A}^p &= \mu_\varphi^p + \sqrt{(\mu_\varphi^p)^2 - \mu_\varphi^p \mu_r^p}, \\ \mu_{\rm B}^p &= \mu_\varphi^p - \sqrt{(\mu_\varphi^p)^2 - \mu_\varphi^p \mu_r^p}, \\ \varepsilon_{\rm A}^p &= \varepsilon_{\rm B}^p = \varepsilon_z^p. \end{aligned} \tag{6}$$

Therefore, a concentric layered shell designed based on Eq. (6) can behave as a shrinking device with the reduced set of medium parameters.

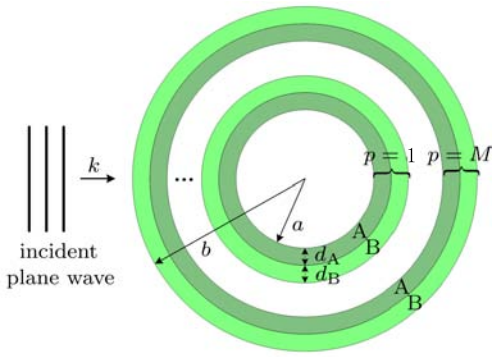


Fig. 2. (colour online) A shrinking device realized by concentric multi-layers and illuminated with a plane wave. The inner and outer radii of the shell are a and b, respectively.

3. Simulation and results

In order to validate the shrinking device as shown in Fig. 2, we make numerical simulations by using the finite-element method. The incident TE plane wave moves from left to right with a frequency of 8 GHz. The material parameters of the ideal shrinking device and the shrinking device with layered structures are described in Eqs. (2) and (6), respectively. The dimensions of the shrinking shell are given as $a = 24$ mm, $b = 48$ mm, and $c = 8$ mm. In this case, we consider an inhomogeneous object with tiny loss inside the shrinking device. In the centre, there is a rectangular dielectric object with $\varepsilon_1 = 3+$ j0.001 and unit permeability, and free space surrounding it. The length and width of the rectangular dielectric object are 30 mm and 12 mm, respectively. Figure 3(a) demonstrates the electric field distributions inside and outside the dielectric object without the shrinking device. Enclosed by the shrinking device, the rectangular dielectric object appears like a virtual object, which is a small dielectric rectangle with a high permittivity of 27 + j0.009 inside a dielectric circle with the permittivity value 9. The electric fields inside and outside the rectangular dielectric object covered by the shrinking device are significantly different from those of the original object as illustrated in Fig. 3(c). We also compute the electric fields of the small virtual object located in free space (see Fig. 3(b)), which are almost the same as those of the big object with the illusion device outside the outer boundary.

Figure 4 demonstrates the above shrinking device realized by using a concentric layered system with homogenous isotropic materials. Figures 4(a)–4(c) illustrates the electric field distributions of multilayered shrinking devices with $M = 8, 12, 20$, respectively. Comparing the devices in Figs. 4(a)–4(c) with the ideal shrinking device illustrated in Fig. 3(c), we can observe that by increasing the number of layers (M) to smooth the stepwise approximation, such a concentric layered system can achieve the performance of the ideal shrinking device as shown in Fig. 3(c).

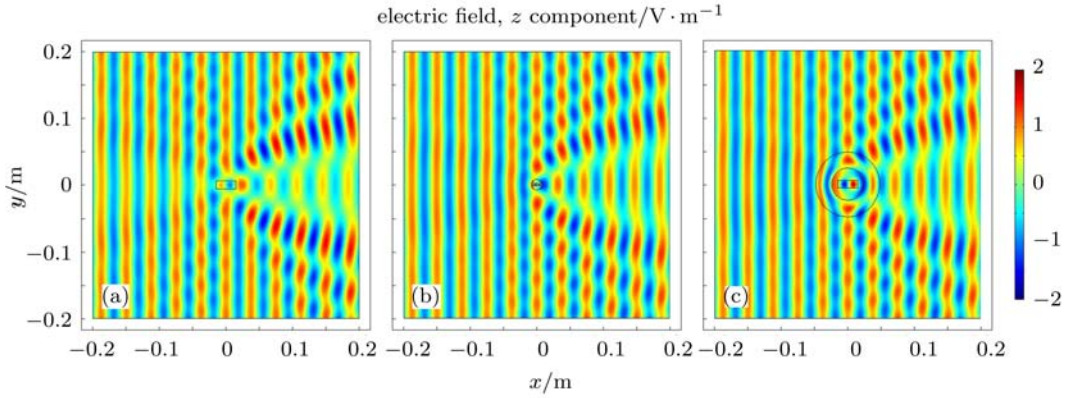


Fig. 3. (colour online) Electric field distribution of (a) a bare dielectric rectangular object with the permittivity value 3 + j0.001 and unit permeability, (b) the virtual object which is a smaller rectangular object inside a dielectric circle, (c) the real object which is a large rectangular object covered by the shrinking device.

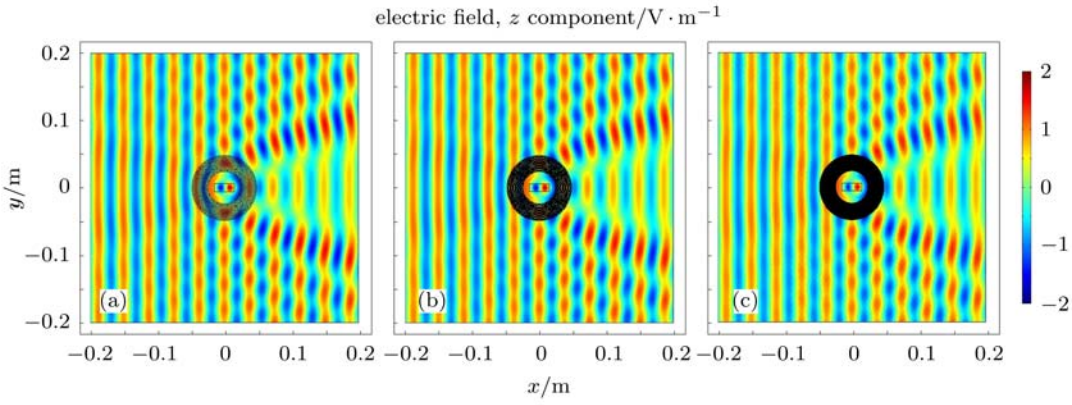


Fig. 4. (colour online) Electric field distributions of a rectangular dielectric object covered by multilayered shrinking devices with $M = 8$ (a), 12 (b), and 20 (c).

To better understand the performance of the multilayered shrinking device, we plot the distribution of the E_z along the line $x = 0.2$, which clearly shows the differences among the ideal shrinking device, multilayered shrinking devices with $M = 8$, 12, 20. As shown in Fig. 5, the E_z distributions of multilayered shrinking devices with $M = 8$, 12, 20 are nearly the same as that of the ideal shrinking device, with the exception of an obvious difference in the y segment of –0.05 to 0.05. We find that by increasing the number of layers (M), the E_z distribution of the multilayered shrinking device is in better agreement with that of the ideal shrinking device.

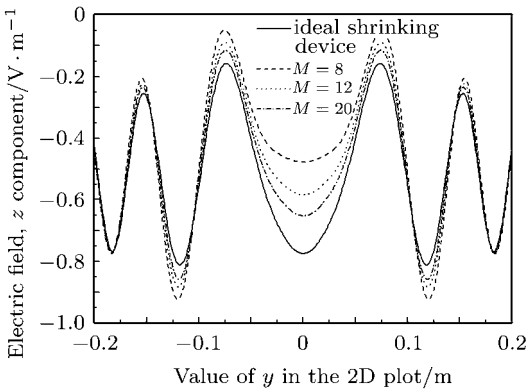


Fig. 5. Electric field distributions of a rectangular dielectric object covered by an ideal shrinking device, multilayered shrinking devices, respectively, with $M = 8$, 12, 20 along the line $x = 0.2$.

4. Conclusions

In this paper, we have proposed an isotropic multilayered structure for use as an equivalent shrinking device. The discretization of a medium value of M in our design reduces many of the strict requirements in realizing a conventional anisotropic shrinking device in which the material needs to be anisotropic and parameters must be radius-dependent. The design of the proposed shrinking device with concentric layered isotropic structures is analysed and verified, and the shrinking effects are well demonstrated.

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