Amplifying device created with isotropic dielectric layer*

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Using the concept of optical transformation, we report on an amplifying device, which can make an arbitrary object enlarged. Its potential application to small object identification and detection is foreseeable. The cylindrical anisotropic amplifying shell could be mimicked by radially symmetrical "sectors" alternating in composition between two profiles of isotropic dielectrics; the permittivity and permeability in each "sector" can be properly determined by the effective medium theory. Both the magnetic and nonmagnetic amplifying devices are validated by full-wave finite element simulations. Good amplifying performance is observed.

Keywords: transformation media, amplifier, effective medium

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1. Introduction

The technique of transformation optics[1,2] is a powerful and systematic approach to manipulating electromagnetic waves and producing new functionalities with artificially engineered structures.[3,4] A series of applications has been reported based on this theoretical framework, such as wave concentrator,[5] rotator,[6] beam bend,[7] illusion scatterer,[8] and waveguide connector.[9] Among all these applications, invisible cloaks, including free-space cloaks[10–15] and carpet cloaks,[16–18] have definitely aroused most scientific interest.

Based on the concept of complementary medium, the literature[19] has opened up a new branch for designing illusion devices. The concept of an illusion device is to make an object with a certain shape and material composition appear exactly as an object with other shape and material composition. However, the inclusion of complementary medium in most of the presented illusion devices[19–27] requires constitutive parameters of left-handed material with simultaneously negative permittivity and permeability. Such devices require artificially structured metamaterials to realize the anisotropy and inhomogeneity with negative material parameters. To overcome such difficulties, a shrinking device,[28] which can transform an arbitrary object virtually into a small object with desirable parameters, has been designed and fabricated with artificial metamaterials under an alternative strategy. All constitutive parameters of the shrinking device are positive, therefore they may also lead to a practical realization by normal positive materials, as illustrated in our previous work.[29]

In this paper, considering the inverse problem of the shrinking device, we report on a cylindrical amplifying device, which can make a small object enlarged, and present an approach to practical realization by radially symmetrical layered structures of isotropic materials instead of using the artificial metamaterials with subwavelength structured inclusions. By properly designing the permittivity and permeability in each isotropic dielectric layer, good amplifying performance could be demonstrated.

2. Scheme design

For simplicity, we consider a bi-dimensional case of the amplifying device in a cylindrical coordinate system; in consequence, the shape of the amplifying device is a circular shell with inner and outer radii c and b, as schematically illustrated in Fig. 1(a). Then a small cup surrounding the free space inside the amplifying shell could appear as a large cup of the same shape surrounded by different materials in a circular region with radius a in virtual space, as depicted in Fig. 1(b).

To design such an amplifying device, we carry out the coordinate transformation from virtual space to real space in cylindrical coordinates as follows:

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

in which $k_1 = (b-c)/(b-a)$ is a stretching coefficient for the transformation shell in coordinate transformation. Following the standard procedure of transformation optics, we find that the material of the amplifying device for a transverse magnetic (TM) wave mode should have the following constitutive properties:

$$\varepsilon_r = \frac{r'-c+k_1 a}{r'}, \quad \varepsilon_\theta = \frac{r'}{r'-c+k_1 a},$$

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$$\mu_z = \frac{r' - c + k_1 a}{k_1^2 r'}. \tag{2}$$

In order to remove the magnetic response of the material, which is especially important for making devices at optical frequency, the constitutive parameters of the proposed amplifying device for TM wave illumination can be further simplified into

$$\varepsilon_r = \frac{(r' - c + k_1 a)^2}{r'^2}, \quad \varepsilon_\theta = \frac{1}{k_1^2}, \quad \mu_z = 1. \tag{3}$$

Compared with the parameters of the amplifying device with ideal properties, as depicted in Eq. (2), the reduced parameters in Eq. (3) can provide the same wave trajectory in the amplifying shell. However, it will induce some unfavorable reflections at the outer boundary due to the impedance mismatch ($\eta = \sqrt{\mu_z/\varepsilon_\theta} = k_1$). Similar considerations have been presented for cylindrical cloaks.[30]

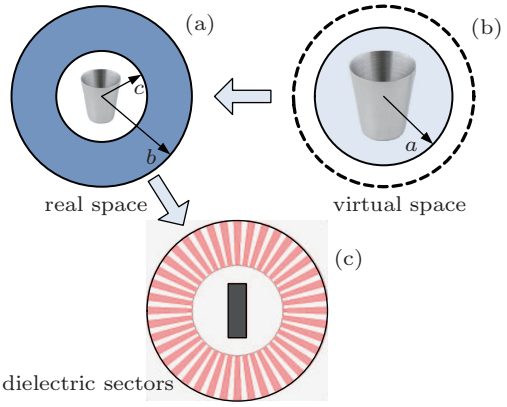


Fig. 1. (color online) Geometries of the cylindrical amplifying device. Panel (a) shows an anisotropic amplifying shell with a small metallic cup enclosed; panel (b) exhibits a virtual large metallic cup inside a circular dielectric; panel (c) displays an equivalent amplifying shell created with radially symmetrical layers of isotropic materials with a small rectangular PEC enclosed.

For saving the object material transformation, we suppose that the small object in real space is made of perfect electric conductor (PEC) material, such as a metallic cup in the core region in Fig. 1(a). The virtual enlarged object is still a metallic cup of the same shape, but the surrounding space should be defined as

$$r = k_2 r', \quad \theta = \theta', \quad z = z', \tag{4}$$

with the parameter $k_2 = a/c$, which could be defined as the amplifying coefficient of the real object. Assuming that the background medium is free space, the properties of the surrounding material of the virtual object are expressed as

$$\varepsilon_r = \varepsilon_\theta = 1.0, \quad \mu_z = 1/k_2. \tag{5}$$

Equation (5) indicates that the surrounding material of the virtual enlarged object could be isotropic dielectric with magnetic response to the TM wave mode. Keeping the refractive index unchanged, the surrounding material depicted in Eq. (5) can also be simplified into

$$\varepsilon_r = \varepsilon_\theta = 1/k_2, \quad \mu_z = 1.0. \tag{6}$$

According to the transformation parameters derived above, we demonstrate the functionality of the amplifying device via finite element simulation. The dimensions of the amplifying shell are given by $b = 0.2$ m, $c = 0.1$ m and $a = 0.15$ m. The excitation source is selected to be a TM plane wave at an operating frequency of 2.0 GHz. Figure 2 shows the desirable properties of the ideal amplifying device. The transverse magnetic field of a small rectangular PEC enclosed inside the amplifying shell is illustrated in Fig. 2(a), where the height and width of the small rectangular PEC are 0.12 m and 0.04 m, respectively. Figure 2(b) illustrates the total transverse magnetic field of a large rectangular PEC (the height and width of the large rectangular PEC are 0.18 m and 0.06 m, respectively) inside a circular dielectric. We find that the small and the large rectangular PECs have the same far-field patterns, indicating that the small rectangular PEC enclosed in the real space shell has been amplified. We also make a comparison of the magnetic field distribution between the nonmagnetic amplifier and the large rectangular PEC in the nonmagnetic surrounding dielectric with parameters shown in Eqs. (3) and (6), respectively. In Figs. 2(c) and 2(d), some differences appear, especially in the forward magnetic field distribution, due to the impedance mismatch.

In the following, we restrict the problem under discussion to the realization of the designed amplifying device. Based on the effective medium theory,[31,32] a series of cylindrical or spherical anisotropic invisible cloaks[13–15] has been mimicked by concentric layered structures consisting of alternating layers of two different homogeneous isotropic dielectric materials on a subwavelengh scale. From the parameters derived in Eqs. (2) and (3), we find that the radial component is always larger than the angular components ($\varepsilon_r > \varepsilon_\theta$), which is different from all the previous cases of invisible cloaks[13–15] and the shrinking device.[29] Such a required cylindrical anisotropy can be mimicked by utilizing radially symmetrical "sectors" alternating in composition between two profiles of isotropic dielectrics, as schematically shown in Fig. 1(c) instead of using the concentric alternating layers. Supposing that the tangential width values of the dielectric profile-A and profile-B are identical, we construct a mapping of parameters between the cylindrical anisotropic shell and isotropic layered shell interlaced profile-A and profile-B as

$$\varepsilon_r = \frac{\varepsilon_A(r') + \varepsilon_B(r')}{2}, \quad \frac{1}{\varepsilon_\theta} = \frac{1}{2\varepsilon_A(r')} + \frac{1}{2\varepsilon_B(r')}, \tag{7}$$

where $\varepsilon_A(r')$ and $\varepsilon_B(r')$ represent permittivity patterns for profile-A and profile-B of the constitutive layers, respectively.

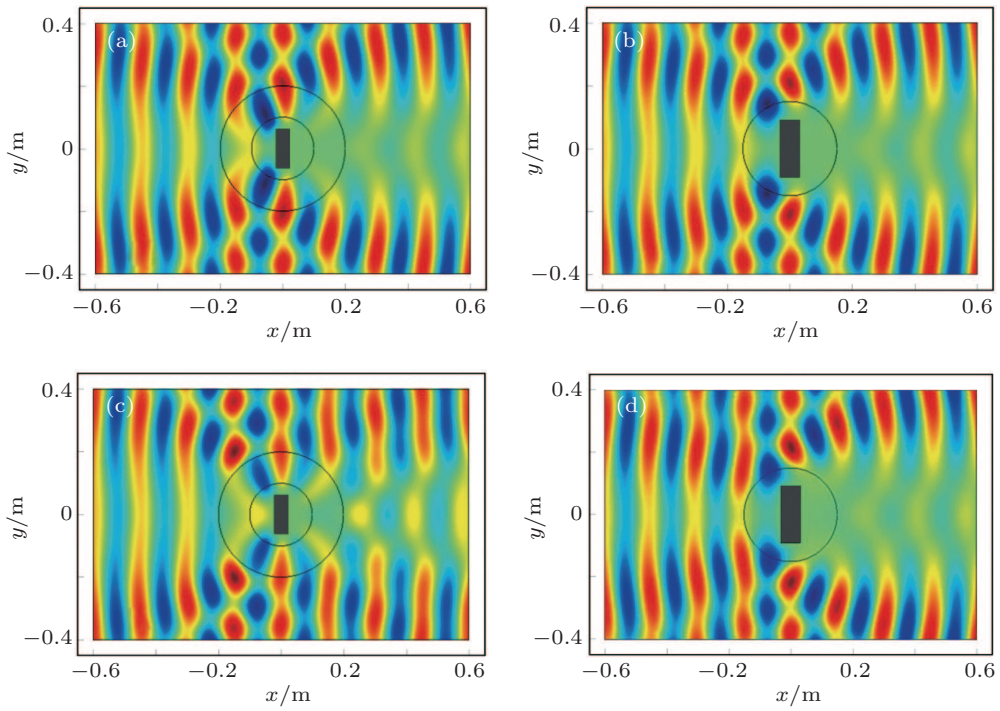


Fig. 2. (color online) Transverse magnetic field distributions of (a) the ideal anisotropic amplifier with a real small rectangular PEC enclosed, (b) the virtual enlarged rectangular PEC inside a circular magnetic dielectric, (c) the nonmagnetic anisotropic amplifier, (d) the virtual enlarged rectangular PEC inside a circular nonmagnetic dielectric.

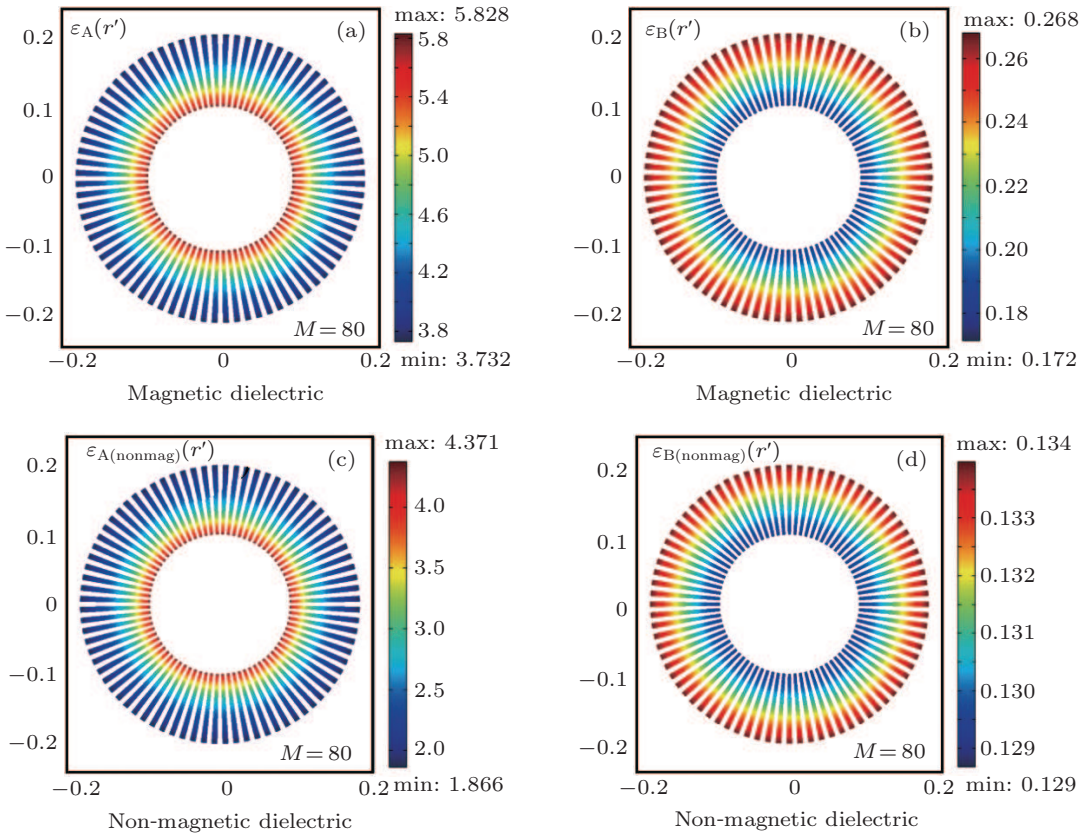


Fig. 3. (color online) Permittivity patterns with magnetic response for profile-A (a) and profile-B (b); permittivity patterns without magnetic response for profile-A (c) and profile-B (d).

Applying Eq. (2) to Eq. (7), the permittivity patterns $\varepsilon_{\mathrm{A}}(r')$ and $\varepsilon_{\mathrm{B}}(r')$ for both profiles with magnetic response can be obtained. Similarly, inserting Eq. (3) into Eq. (7), we can obtain the non-magnetic permittivity patterns $\varepsilon_{\mathrm{A(nonmag)}}(r')$ and $\varepsilon_{\mathrm{B(nonmag)}}(r')$ for the two dielectric profiles. Figure 3 illustrates the permittivity patterns of the two interlaced dielectric profiles obtained by radially discretizing the amplifying shell into $2M = 160$ constituents. It is found that the values of permittivity for both profiles are still positive, indicating that the desirable cylindrical anisotropy can be effectively achieved by magnetic (or nonmagnetic) isotropic right-handed material. For a cylindrical cloaking shell ($\varepsilon_r < \varepsilon_\theta$), a similar configuration as shown in Eq. (7) has been considered.[33] However, one of the permittivity patterns $\varepsilon_{\mathrm{A}}(r')$ and $\varepsilon_{\mathrm{B}}(r')$ should be negative, which is very demanding for the material in practical fabrication.

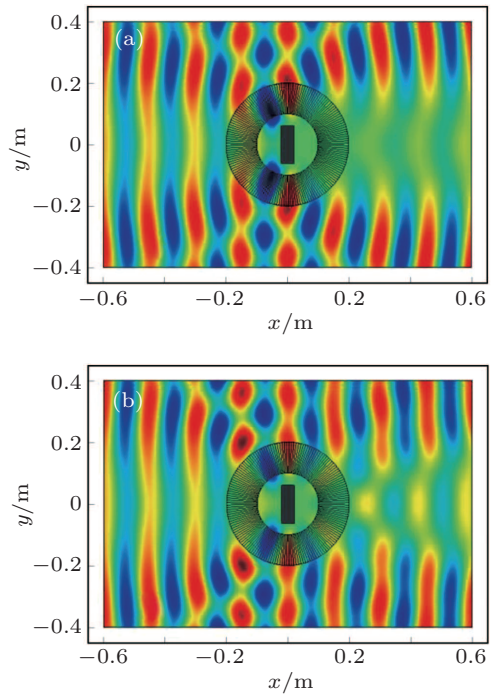


Fig. 4. (color online) Transverse magnetic field distributions of the layered amplifying shell created with (a) magnetic isotropic materials and (b) nonmagnetic isotropic materials.

In order to validate such an isotropic layered amplifying device, the simulation results illuminated with a plane wave are shown in Fig. 4. Following the comparison between Fig. 4(a) and Fig. 2(a), the amplifying performance of the magnetic layered shell is quite pronounced when the discretized number is large enough ($2M = 160$). However, some differences appear in the case of a nonmagnetic layered structure, which is due to the impedance mismatch at the outer boundary, as illustrated in Fig. 4(b). To further validate the capability of the designed isotropic amplifier, in Fig. 5, we simulate scattering cross sections and normalize them for all cases corresponding to plots of Figs. 2(a)–2(d) and Figs. 4(a) and 4(b), in which the performance of the ideal (magnetic) anisotropic shell shows an excellent matching with that of the virtual large object; also, the performance of the magnetic isotropic layered amplifying shell is remarkably close to that in the case of the perfect matching for a sufficient discretization in constitutive layers. In contrast, for the nonmagnetic layered amplifier, the normalized scattering cross section has a significant difference from the reference pattern of the virtual large rectangular PEC in the nonmagnetic surrounding material according to Fig. 2(d), which degrades the amplifying performance. However, the material without magnetic response is more popular in nature especially at optical frequency, thus leading to the easy realization of the optical amplifying device.

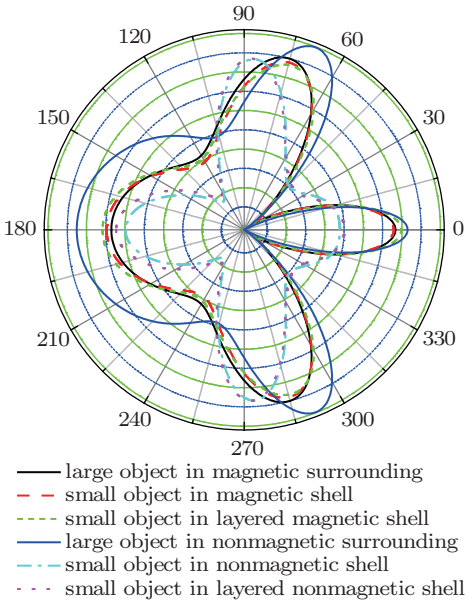


Fig. 5. (color online) Normalized scattering cross sections according to plots in Figs. 2 and 4.

3. Conclusions

In this paper, we proposed an amplifying device, which can make an arbitrary enclosed object enlarged. Based on the effective medium theory, we presented a radially symmetrical layered system in composition of two profiles as an equivalent amplifying device. The constitutive layers could be an isotropic material with or without magnetic response. The finite element method is used to demonstrate the performances of the magnetic and non-magnetic isotropic layered amplifying device; their excellent and good amplifying performances are observed.

References

[1] Pendry J B 2006 *Science* **312** 1780
[2] Leonhardt U 2006 *Science* **312** 1777
[3] Smith D R, Padilla W J, Vier D C, Nemat-Nasser S C and Schultz S 2000 *Phys. Rev. Lett.* **84** 4184
[4] Schurig D, Mock J J, Justice B J, Cummer S A, Pendry J B, Starr A F and Smith D R 2006 *Science* **314** 977

[5] Jiang W X, Cui T J, Cheng Q, Chin J Y, Yang X M, Liu R and Smith D R 2008 *Appl. Phys. Lett.* **92** 264101
[6] Chen H and Chan C T 2007 *Appl. Phys. Lett.* **90** 241105
[7] Yu Z Z, Feng Y J, Wang Z B, Zhao J M and Jian T 2013 *Chin. Phys. B* **22** 034102
[8] Wang Z, Luo X Y, Liu J J and Dong J F 2013 *Acta Phys. Sin.* **62** 024101 (in Chinese)
[9] Zhang K, Wu Q, Meng F Y and Li L W 2010 *Opt. Express* **18** 17273
[10] Schurig D, Pendry J B and Smith D R 2006 *Opt. Express* **14** 9794
[11] Wu Q, Zhang K, Meng F Y and Li L W 2010 *Acta Phys. Sin.* **59** 6071 (in Chinese)
[12] Wu Q, Zhang K, Meng F Y and Li L W 2009 *Acta Phys. Sin.* **58** 1619 (in Chinese)
[13] Farhat M, Guenneau S and Enoch S 2009 *Phys. Rev. Lett.* **103** 024301
[14] Qiu C W, Hu L, Xu X and Feng Y 2009 *Phys. Rev. E* **79** 047602
[15] Qiu C W, Hu L and Zouhdi S 2010 *Opt. Express* **18** 14950
[16] Li J and Pendry J B 2008 *Phys. Rev. Lett.* **101** 203901
[17] Liu R, Ji C, Mock J J, Chin J Y, Cui T J and Smith D R 2009 *Science* **323** 366
[18] Wang S Y and Liu S B 2012 *Chin. Phys. B* **21** 044102
[19] Lai Y, Ng J, Chen H Y, Han D Z, Xiao J J, Zhang Z Q and Chan C T 2009 *Phys. Rev. Lett.* **102** 253902
[20] Lai Y, Chen H Y, Zhang Z Q and Chan C T 2009 *Phys. Rev. Lett.* **102** 093901
[21] Ng J, Chen H and Chan C T 2009 *Opt. Lett.* **34** 644
[22] Zang X and Jiang C 2011 *J. Opt. Soc. Am. B* **28** 1082
[23] Wang Y, Zhang D H, Wang J, Yang X, Li D and Xu Z 2011 *Opt. Lett.* **36** 3855
[24] Yang T, Chen H, Luo X and Ma R 2008 *Opt. Express* **16** 18545
[25] Zang X and Jiang C 2010 *Opt. Express* **18** 6891
[26] Chen Z, Wang L, Wang C and Fang Z 2011 *Chin. Phys. Lett.* **9** 021601
[27] Zang X, Cai B and Zhu Y 2013 *Appl. Opt.* **52** 1832
[28] Jiang W X, Cui T J, Yang X M, Ma H F and Cheng Q 2011 *Appl. Rev. Lett.* **98** 204101
[29] Guo Y N, Liu S B, Zhao X, Wang S Y and Chen C 2012 *Chin. Phys. B* **21** 064101
[30] Cai W, Chettiar U K, Kildishev A V and Shalaev V M 2007 *Nat. Photonics* **1** 224
[31] Wood B, Pendry J B and Tsai D P 2006 *Phys. Rev. B* **74** 115116
[32] Jacob Z, Alekseyev L V and Narimanov E 2006 *Opt. Express* **14** 8247
[33] Cai W, Chettiar U K, Kildishev A V and Shalaev V M 2008 *Opt. Express* **16** 5444