Novel multifunctional optical device with only axial material parameter spatially variant

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Based on the concept of complementary media and theory of coordinate transformation, a novel kind of optical device, exhibiting the multiple performances of a complementary cloak and a transparent device, is proposed. Only the axial material parameter of the proposed device is spatially variant, and the transverse material parameters are constant. The multiple functions of the proposed device are validated by full wave simulations. In addition, the effects of loss and parameter perturbations on the performances of the device are also investigated. These results can be used in field of antenna protection and other electromagnetic field engineering.

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Pendry *et al.* proposed the coordinate transformation theory to manipulate the spatial electromagnetic fields and designed an ideal cloak to perfectly hide arbitrary object inside in 2006[1]. However, this ideal cloak needed complex medium, such as inhomogeneous, anisotropic, even singular, which is hard to be physically realized. Cummer *et al.* firstly reported full-wave electromagnetic simulations of this cloaking structure in cylindrical version using non-ideal electromagnetic parameters[2]. In the same year, Schurig *et al.* presented the first practical realization of electromagnetic cloak with metamaterials at microwave frequencies[3]. Motivated by the above pioneering work, the design of invisible cloaks with simplified parameters and different shapes has attracted much attention[4−8]. These studies have shown that the electromagnetic field cannot penetrate into the cloak and the object hidden in the cloak cannot communicate with the outside. Different with the above traditional cloak, Chen *et al.* proposed a new kind of invisible cloak according to the concept of complementary medium and theory of coordinate transformations[9]. This complementary cloak allows the inside object to "see" outside but to be invisible from outside. This theory opened up a new branch of metamaterials applied in field of invisible cloaks and illusion device[10,11]. Other novel applications of transformation optics, such as concentrators, supperscatterers and transparent devices, have been proposed recently[12−16]. However, most of previously proposed devices exhibit only a single function, either hiding the object as cloak, or protecting the devices inside without affecting their performance as transparent device.

In this letter, based on the concept of complementary medium and theory of coordinate transformation, a novel kind of multifunctional device served as a complementary cloak and a transparent device is investigated using the finite-element method. The simulation results validate the performances of the proposed device. The practical realization of such kind of device needs metamaterials with negative and positive refractive index. In the past few years, the metamaterial cloak with positive refractive index has been realized, such as based on split ring resonator (SRRs) unit cells[3,17]. With the coming forth of more and more metamaterials structures, the metamaterials with negative refractive index were also proposed[18−20]. Therefore, the proposed device can be realized with metamaterials in future. In order to be closer to practical applications, the effects of loss and parameter perturbations on the performances of the device are also analyzed.

Figure 1 shows the schematic diagram of the device consisting of four regions. Region III ($d< r <a$) is the stretching region, region II ($a<r<b$) is the folding region, outer region I ($b<r<c$) and inner region IV ($r<d$) are free space. Firstly, region II is folded into region I. In order to restore the optical path, region III is stretched to regions I, II, and III. Based on the techniques described in Refs. [1] and [5], the relative permittivity and permeability in the transformed space with the given form of the transformation equation $f(r)$ can be expressed as

$$\varepsilon_\varphi = \mu_\varphi = rf'(r)/f(r), \tag{1}$$

$$\varepsilon_r = \mu_r = f(r)/[rf'(r)], \tag{2}$$

$$\varepsilon_z = \mu_z = f'(r)f(r)/r. \tag{3}$$

Clearly, $\varepsilon_\varphi(\mu_\varphi)$ and $\varepsilon_r(\mu_r)$ in Eqs. (1) and (2) are reciprocals. If one is set as the constant, the other can be fixed. Suppose $\varepsilon_\varphi = \mu_\varphi = m_0$, by solving the above differential Eq. (1), the general solution can be obtained as

$$f(r) = m_1 r^{m_0}, \tag{4}$$

where m_1 and m_0 are the unknown constants. The constants of m_1 and m_0 can be easily obtained as follows:

$$\text{Region II}: m_0 = \log_{b/a}(b/c), m_1 = (1/b)^{m_0-1};$$

$$\text{Region III}: m_0 = \log_{d/a}(d/c), m_1 = (1/d)^{m_0-1}.$$

The material parameters for regions II and III can be easily obtained as

$$\varepsilon_\varphi = \mu_\varphi = m_0, \tag{5}$$

$$\varepsilon_r = \mu_r = 1/m_0, \tag{6}$$

$$\varepsilon_z = \mu_z = m_0 m_1^2 r^{2(m_0-1)}. \tag{7}$$

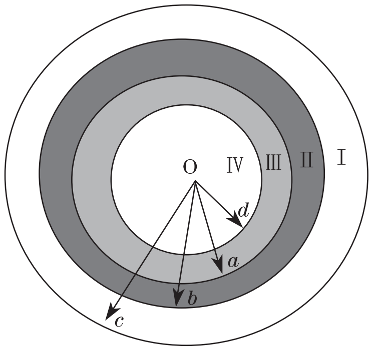

Fig. 1. Schematic diagram of the multifunctional device.

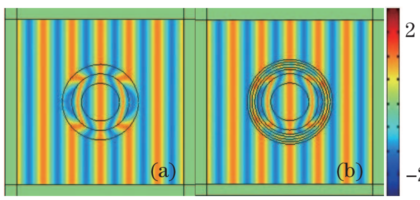

Fig. 2. (a) Electric field distributions in the vicinity of the device; (b) electric field distributions in the vicinity of the device with circular sheet and corresponding anti-object in the regions I and II, respectively.

Because the transformation medium is matched with surrounding medium and inherently reflectless, the waves are perfectly restored inside and outside the device. When the device is used as a complementary cloak, the object needed to be hidden and corresponding "anti-object" can be placed in regions I and II, respectively. When the device is used as a transparent device, the object needed to be protected, such as antenna, can be placed in the inner region IV.

To demonstrate our idea above, the performances of the device are simulated by finite element software COMSOL under transverse electric wave irradiation. In the simulations, the frequency is 0.5 GHz, and the geometry parameters of the device are set as a =0.6 m, b=0.8 m, c =1.0 m, d =0.4 m, respectively. In Fig. 2 (a) the wave is incident from left to right. It is clearly observed that the waves are distorted in the transformation regions (regions II and III), and can recover the original propagation status in outside and inside of device (regions I and IV). Figure 2(b) shows that a circular shell with ε =3 and μ =3 is added in the region I (0.85 m $< r <$ 0.9 m) and the corresponding anti-object is located in the region II (0.687 m$< r <$ 0.74 m). It can be found that the electric fields outside and inside the device are undisturbed and the circular shell is perfectly hidden. These results show that the device exhibits invisible performance of the complementary cloak. Moreover, this device can also be used as a transparent device. We take the horn antenna as example to demonstrate the transparent performance of the proposed device. The electric field distributions of a horn antenna located in free space and in the device are simulated shown in Figs. 3(a) and (b), respectively. It is evident that the field distribution of the horn antenna covered by the device is the same with that in the free space. This demonstrates the transparent performance of the proposed device.

Since artificial metamaterials are always lossy in practical applications, it is necessary to investigate the effect of loss tangent on performances of the device. Figure 4 shows the electric field distributions in the vicinity of the device with different electric and magnetic-loss tangents (tan a = 0, 0.1, 0.01, and 0.001). Comparing Figs. 4 (b) and (c) with (a), we can see that the electric field distributions are almost unaltered when the loss tangent is small. In such case, the effect of loss can be ignored. When the loss tangent is 0.1, the invisibility performance of the device mainly in the forward-scattering region deterorates, but the fields are almost unaltered for the back-scattering region and other regions, as shown in Fig. 4(d). Figure 5 shows the effect of different loss tangents on the far field pattern of the horn antenna covered by the device. Compared with the lossless case, it is obvious that the far field pattern of the antenna is almost unaffected when the loss tangent is

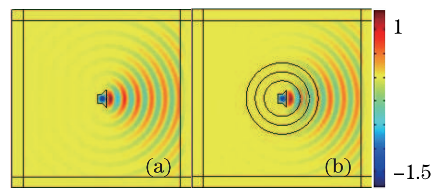

Fig. 3. Electric field distributions of the horn antenna (a) in the free space and (b) covered by the device.

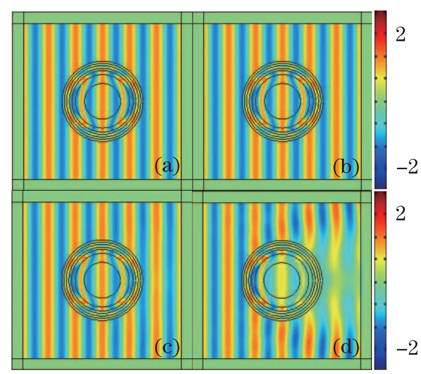

Fig. 4. Electric field distributions in the vicinity of the device with different loss tangents of (a) 0, (b) 0.001, (c) 0.01, and (d) 0.1.

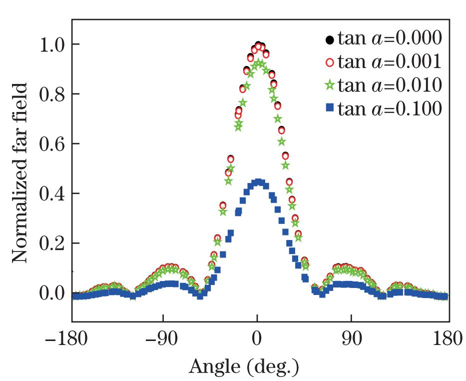

Fig. 5. Far field patterns of horn antenna covered by the device with different loss tangents of 0, 0.001, 0.01, and 0.1.

0.001 or 0.01. However, when the loss tangent is 0.1, the far field patterns of the antenna are seriously affected because of serious energy loss.

Finally, the robustness of the device with non-ideal parameters is investigated. In simulation, different percentages of parameter perturbation are taken into consideration, such as 0.1%, 1% and 5%. The perturbations are negative for the negative parameter and vice versa. Figure 6 shows the effect of perturbation on the invisible performance of the device. It is obvious that the electric field distributions are almost unaltered when the parameter perturbations are 0.1%, and 1%. But when the perturbation is 5%, it deteriorates the invisibility performance of the device mainly in forward scattering region, as shown in Fig. 6(d). Figure 7 shows the effect of different parameter perturbations on the far field patterns of the horn antenna covered by the device. It is evident that the far field patterns of the horn antenna are almost unaltered when the parameter perturbation is 0.1%. When the perturbation is more than 1 %, the far field patterns of the horn antenna change obviously. In such case, the transparent performance of the device is seriously deteriorated.

In conclusion, a multifunctional device with only axial material parameter spatially variant, which can be used as a complementary cloak and a transparent device, is proposed and investigated. The full-wave simulation re-

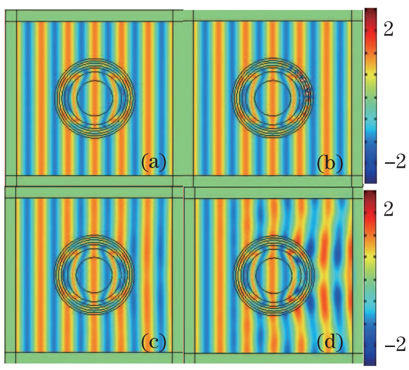

Fig. 6. Electric field distributions in the vicinity of the device with different parameter perturbations of (a) 0%, (b) 0.1%, (c) 1%, and (d) 5%.

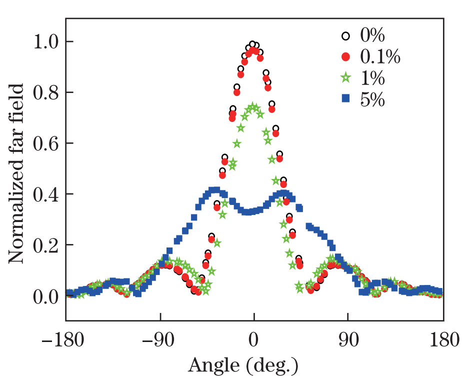

Fig. 7. Far field patterns of horn antenna covered by the device with different parameter perturbations of 0%, 0.1%, 1%, and 5%.

sults verify the effectiveness of the device. Furthermore, the effects of loss tangent and parameter perturbations on the performances of the device are analyzed. The results show that the performances are almost unaltered when the loss tangent is less than 1% and parameter perturbation percentage is less than 0.1%. All the results can be used in field of antenna protection and other electromagnetic field engineering.

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