МОДИФИКАЦИЯ УСТРОЙСТВА ДВУМЕРНОЙ НЕВИДИМОСТИ ОБТЕКАНИЯ С ИСПОЛЬЗОВАНИЕМ ОДНОРОДНОЙ АНИЗОТРОПНОЙ СРЕДЫ

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Предложена более простая, по сравнению с предложенными ранее, модификация устройства маскировки объектов (двумерной невидимости обтекания), использующая положительную однородную анизотропную среду. Теоретический анализ и численное моделирование показали, что предложенная модификация невидимости обтекания обеспечивает проникновение внешней электромагнитной волны в маскируемую область, не нарушая в то же время маскирующего эффекта для внешних наблюдателей. Обсуждаются особенности конструкции, приведены результаты моделирования.

Ключевые слова: *невидимость обтекания, оптические преобразования, метаматериалы.*

TWO DIMENSIONAL INVISIBILITY ANTI-CLOAK STRUCTURED BY HOMOGENEOUS ANISOTROPIC MEDIUM

© 2016 **Xuan Liu**, graduate student; **Yicheng Wu**, student; **Chengdong He**, student; **Yuzhuo Wang**, student; **Xiaojia Wu**, graduate student; **Jing Zhou***, Doctor of Science

Applied Optics Beijing Area Major Laboratory, Department of Physics, Beijing Normal University, Beijing 100875, P.R. China

E-mail: *jzhou@bnu.edu.cn

A two-dimensional invisibility anti-cloak constructed by positive homogeneous anisotropic medium is proposed, which is easier to implement compared with reported invisibility anti-cloak structures. Theoretical analysis and numerical simulations show that the proposed invisibility anti-cloak can make the external electromagnetic waves penetrate into the cloak region, while the concealing effect of invisibility cloak is not affected for the outside viewers. Design details and full-wave simulation results are provided.

Keywords: *anti-cloak, transformation optics, metamaterial.*

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1. Introduction

Since the first invisibility cloak was designed by the transformation optics [1, 2], the research on cloaking and invisibility has been paid more and more attention [3–7]. And it also has achieved rapid progress due to the development of materials science [8–12]. Since the external electromagnetic waves cannot penetrate into the cloak region, the cloak can be used to hide objects. Then the idea of anti-cloak was firstly proposed in 2008 [13], which could defeat the cloaking effect of the invisibility cloak by adding a complementary medium inside the cloak. With the help of the complementary medium, the external electromagnetic wave could penetrate into the inner part of the invisibility cloak and make the cloaked objects visible for the outside viewer.

Based on this idea, several kinds of invisibility anti-cloak have been reported [14–19], which could make the external electromagnetic waves break into the cloak region while the waveform of the external electromagnetic waves remain unchanged. Thus, the cloaked objects are still invisible for the outside viewer. However, these invisibility anti-cloaks designed by traditional transformation optics usually have spatially dependent parameters or involve extreme values, which are very difficult to implement. In this paper, we use a linear coordinate transformation [20–22] to design a two-dimensional invisibility anti-cloak. Therefore, all the segments of the invisibility anti-cloak have positive homogeneous permittivity and permeability. This will be more convenient for practical application.

2. Design principle

Before showing the design principle of the invisibility anti-cloak, we firstly introduce the electromagnetic invisibility cloak constructed by several homogeneous elements. As shown in Fig. 1a, the invisibility cloak is formed by transforming a small square with the side length of a_0 (referred to as "the square of a_0" below) to the square of a_1, while keeping the edge of the outer square of a_2 unchanged. When a_0 approaches to zero, the cloak region, the pink area between the edges of a_1 and a_2, can act as an invisibility cloak [21]. The central square area of a_1 is the cloaked cavity, which can hide objects and the external electromagnetic wave cannot break in as shown in Fig. 1b. It means that the external electromagnetic waves are undetectable for the viewer inside the cloaked cavity.

In order to make the external electromagnetic wave penetrate into the cloak region and keep the inner object invisible for the outside viewers, we propose to add an anti-cloak structure inside the cloaked cavity as shown in Fig. 2a, which is designed by linear coordinate transformations. The transformation detail is schematically shown in the enlarged figure of the anti-cloak region in Fig. 2b. The small square of a_0, which is same as that used in Fig. 1a, is transformed to the square of a_4, while the edge of the square of a_3 is kept unchanged.

Combining with the transform described in Fig. 1a, we can see that the inner edge of the cloak region (square of a_1) and the outer edge

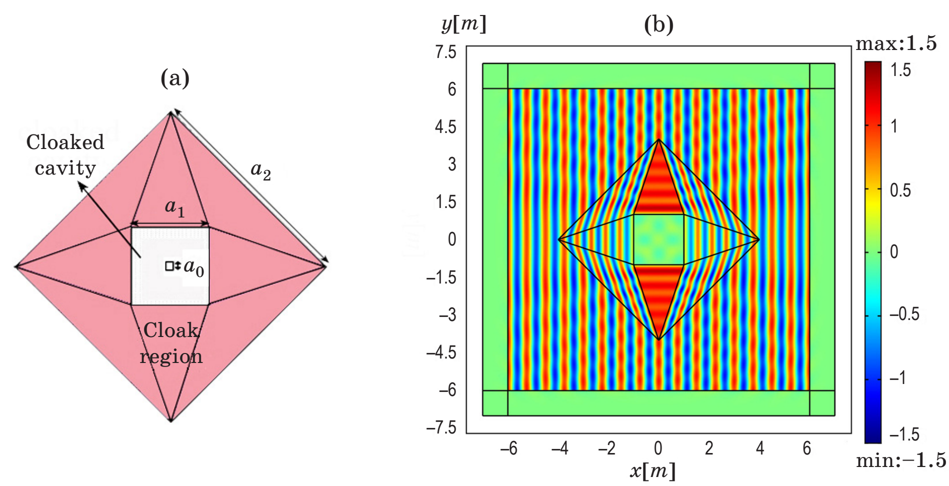

Fig. 1. (a) The structure of the electromagnetic invisibility cloak constructed by several homogeneous elements, (b) the electric field distribution of the invisibility cloak.

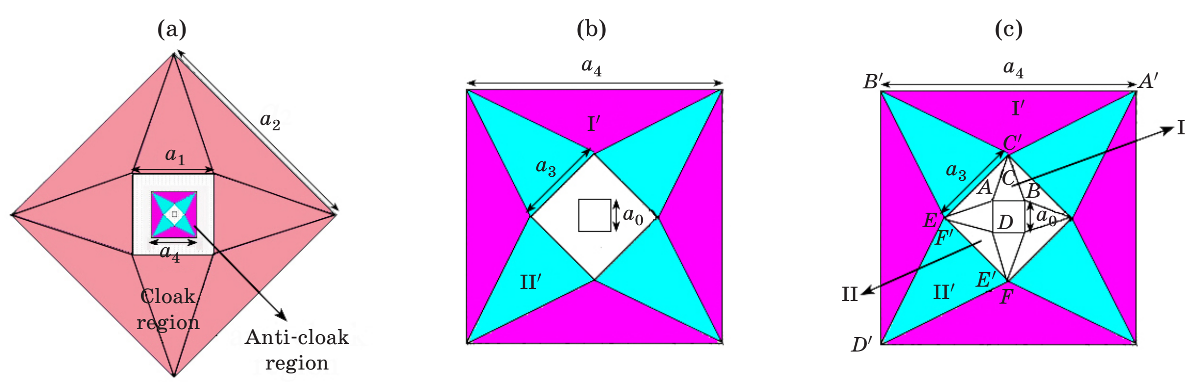

Fig. 2. (a) The electromagnetic invisibility cloak with an anti-cloak region, (b) the enlarged figure of the anti-cloak region in (a), (c) the transformation detail of the anti-cloak.

of the anti-cloak region (square of a_4) are transformed from the same square of a_0. In this case, the external electromagnetic wave will reach these two edges simultaneously, and therefore could penetrate into the cloaked region. Actually, this space transformation includes two kinds of triangular area transformations, which are the transform from the triangular area I to the triangular area I′ and that from II to II′ as noted in Fig. 2c. Since the triangular area transformation can be realized by linear coordinates transformation, the material parameters of the regions I′ and II′ are homogeneous [21, 22]. On the other hand, the folded transformation usually makes the transformed material parameters become negative. In order to get positive material parameters, we exploit twice folded transformation as shown in Fig. 2c. The triangle ABC is transformed to the triangle $A'B'C'$ by folding vertically and horizontally. The triangle DEF is transformed to the triangle $D'E'F'$ by folding twice also. In this case, the material parameters of the regions I′ and II′ in their local coordinates axes (with the x axis parallel to the base of the triangle) are

$$\varepsilon_{I'} = \varepsilon_0 \mathrm{diag}\left(\frac{a_4}{a_0}\frac{\sqrt{2}a_3 - a_0}{a_4 - \sqrt{2}a_3} \quad \frac{a_0}{a_4}\frac{a_4 - \sqrt{2}a_3}{\sqrt{2}a_3 - a_0} \quad \frac{a_0}{a_4}\frac{\sqrt{2}a_3 - a_0}{a_4 - \sqrt{2}a_3} \right), \tag{1}$$

$$\varepsilon_{II'} = \varepsilon_0 \mathrm{diag}\left(\frac{a_3 - \sqrt{2}a_0}{\sqrt{2}a_4 - a_3} \quad \frac{a_3 - \sqrt{2}a_4}{\sqrt{2}a_0 - a_3} \quad \frac{a_3 - \sqrt{2}a_0}{\sqrt{2}a_4 - a_3} \right), \tag{2}$$

where ε_0 is the permittivity of the space before the transformation. It can be seem that all the elements of $\varepsilon_{I'}$ and $\varepsilon_{II'}$ are positive when $(1.414a_0) < a_3 < (a_4/1.414)$, which is easy to be satisfied.

3. Simulation results

To verify the scheme proposed above, we make numerical simulation with Comsol Multiphysics. Fig. 3a and 3b show the simulated electric field distribution of the invisibility cloak without or with the anti-cloak structure respectively. In the simulation, we set $a_0 = 0.04m$, $a_3 = 0.28(\sqrt{2})m$, $a_4 = 0.8(\sqrt{2})m$. Without loss of generality, a TE polarized plane wave is taken as incident wave. The wave frequency is 5×10^8 Hz. Two objects with different material parameters are put in the cloaked cavity, which are marked with Arabic numerals *1* and *2* respectively. The permittivity and permeability of the object *1* are $\varepsilon_1 = 10$, $\mu_1 = 10$ and those of the object *2* are $\varepsilon_2 = 2 - i$, $\mu_2 = 1$. It can be seen that the field distribution outside the cloak region in both Fig. 3a and Fig. 3b are same as incident wave. Nevertheless in Fig. 3b the external electromagnetic wave can get into the cloaked region, the hiddenness role of cloak cannot be affected for the outside viewers.

Figure 4 shows the simulated field distributions of the invisibility cloak without and with the anti-cloak structure when illuminated by a point source located at (–5,5). Comparing Fig. 4b with Fig. 4a, we can find that the external elec-

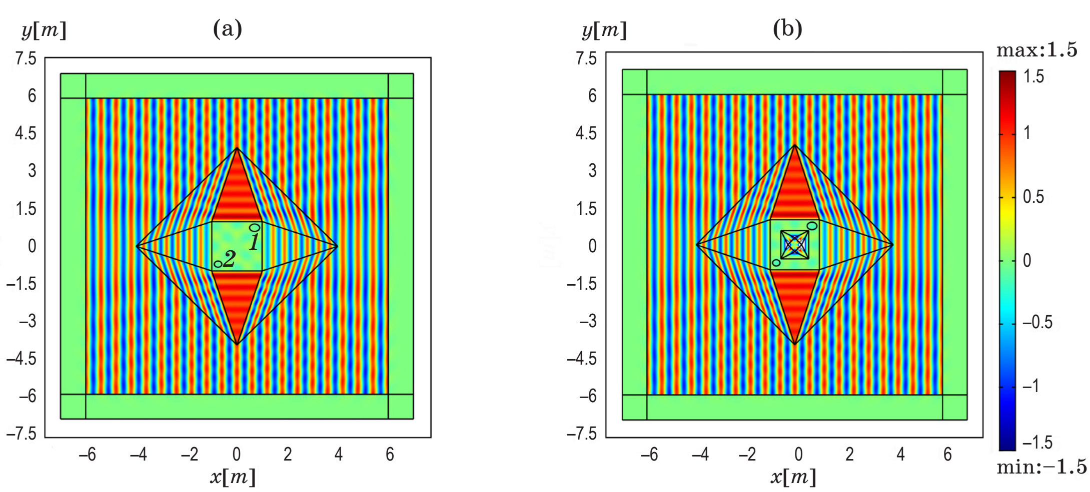

Fig. 3. (a) and (b) are the electric field distributions of the invisibility cloak without and with the anti-cloak respectively. The incident wave frequency is 5×10^8 Hz.

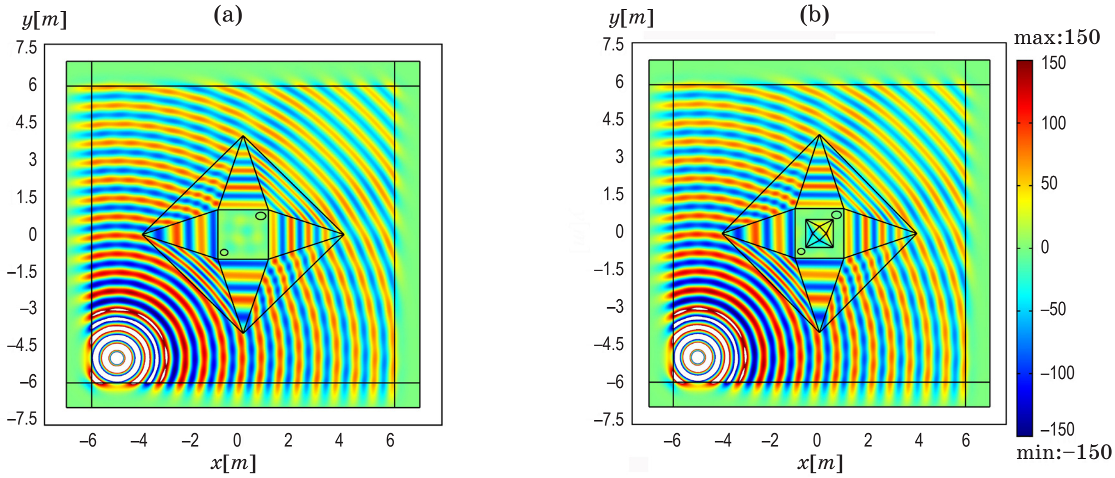

Fig. 4. (a) and (b) are the electric field distributions of the invisibility cloak without and with the anti-cloak when illuminated by a point source located at (−5) respectively.

tromagnetic waves get into the cloaked region, while the waveform of the electromagnetic waves outside the cloak region remain unchanged. This demonstrates that the property of the proposed invisibility anti-cloak scheme is suitable for electromagnetic waves from any direction.

4. Conclusion

In summary, a two-dimensional invisibility anti-cloak structured by several triangular areas with positive homogeneous anisotropic medium is proposed, which is easier to implement than reported invisibility anti-cloak structures. Full-wave numerical calculations demonstrate that the external electromagnetic waves can be detected inside the cloak, while not affecting the hiddenness character of the cloak.

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