One-Directional Perfect Cloak Created With Homogeneous Material

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Abstract—A one-directional invisibility cloak is presented in this letter. Perfect invisibility can be achieved for TM waves along certain directions. The parameters are just homogeneously anisotropic and relatively easy for practical realizations. Nonmagnetic cloak is also studied to further reducing the complexity of the cloak parameters. Thin layered systems with alternating isotropic materials are then designed to model the parameters of such kind of cloaks.

Index Terms—Cloak, coordinate transformation, metamaterial.

I. INTRODUCTION

PRECURSORY efforts [1]–[4] have been made on the invisibility devices, among which, Pendry et al. theoretically proposed full wave perfect invisibility cloaking based on the coordinate transformation method [1]. Later, finite element method based simulations [5], [6] were carried out to verify the behaviors of cylindrical cloaks. And the cylindrical cloak with simplified parameters was then experimentally fabricated and validated [7]. Theoretical methods such as ray tracing [8] and full wave scattering theory [9], [10] have also been utilized to demonstrate the effectiveness of the spherical and cylindrical cloaks. In virtue of the flexibility of the coordinate transformation method [1], arbitrary transformation functions and shapes can be utilized to design invisibility cloaks [11]–[15].

The requirement of continuously inhomogeneous and highly anisotropic material for point and line transformed perfect cloaks [14] is a serious restriction for the practical realizations. Simplified models with less constraints on the parameters were then proposed to reduce the complexity of realizations [5], [7]. However, the inherent scatterings [16] caused by the simplification are unavoidable. Meanwhile, the simplified parameters are still continuously inhomogeneous, thus it is also inconvenient for fabrications. In [17] and [18], the scattering of cylindrical objects is reduced using hard surfaces, however, the objects are still visible.

In this letter, we present a one-directional perfect cloak composed of only homogeneously anisotropic materials. The idea is raised based on the fact that there will be no scattering when TM polarized waves incident onto an infinitesimal PEC surface, with the electric fields perpendicular to the surface. Therefore, by transforming a diamond space containing the infinitesimal PEC surface to the space with a diamond PEC inner boundary (see Fig. 1), the topology [8], [19] of the space stays unchanged and a perfect cloak for TM waves is obtained. The advantage of this kind of cloak is that the parameters are only homogeneously anisotropic, which will facilitate practical realizations. One directional nonmagnetic cloaks are also proposed based on the simplified parameters. Finite element based simulations are carried out, showing the effectiveness of the proposed cloak.

II. TRANSFORMATION SCHEME

Consider the two-dimensional case of a transformation between the original space \((x, y, z)\) and the transformed space \((x', y', z')\) shown by Figs. 1(a) and (b) respectively. The diamond space in the original space demonstrated by the angle \(\alpha\) is compressed into the space \((\alpha - \beta)\). Taking the space in the first quadrant as an example, the transformation equations are

\[
x' = x, \quad y' = \kappa y + \tau (\alpha - x), \quad z' = z,
\]

where \(\kappa = (\tan \alpha - \tan \beta) / \tan \alpha\) and \(\tau = \tan \beta\). Following the procedures in [8], the parameters are then obtained as

\[
\xi = \eta' = \begin{pmatrix}
1 / \kappa & -\tau / \kappa & 0 \\
-\tau / \kappa & \kappa + \tau^2 / \kappa & 0 \\
0 & 0 & 1 / \kappa
\end{pmatrix}.
\]

By combining four pieces of such material together, a diamond hole determined by the angle \(\beta\) is created as shown in Fig. 1(b). In order to keep the topology of the space during the transformation, the boundary of the hole is set to be PEC. Then one
can imagine that, when an $E_y$ polarized wave incident onto the cloak, perfect invisibility can be achieved.

It’s interesting to see that the constitutive parameters shown by (2) are spatially invariant, which can be expressed as diagonal constant tensors in their local principal coordinate system $(u', v', w')$, obtained from the time original coordinate rotated by the angle $\theta$ shown in Fig. 1(b), with

$$\theta = \frac{1}{2} \arctan \frac{2\psi}{k^2 + \tau^2 - 1}. \quad (3)$$

III. FULL PARAMETER CLOAKS

For example, we create a cloak with $a = \lambda$, $\alpha = \pi/3$ and $\beta = \pi/4$, where $\lambda$ is the wavelength of the incident wave. Then the parameters in the first quadrant are $\varepsilon_{uu} = 0.201$, $\varepsilon_v = 4.953$ and $\mu_{vv} = 2.366$ in their local coordinate system, with $\theta = 42.4^\circ$. For a TM plane wave with unit magnitude incident along $+x'$ direction, the magnetic field distribution and the Poynting vectors can then be obtained from the numerical simulation as shown in Fig. 2. We can see that the fields outside the cloak stay unperturbed, that is to say, a perfect cloak can be achieved. Actually, there exists some minor scatterings in the simulation because of the numerical errors, which almost cannot be observed in Fig. 2. When passing through the cloak, the power is compressed and then undergoes negative refractions on the interface at $x' = 0$. On the PEC inner boundary, surface currents are exited to match the boundary condition and no scattering is aroused. And the small perturbations of the material used near $x' = \pm a'$ will have little effect on the performance of the cloak.

As shown by [22]–[24], a thin layered system with homogeneous and isotropic permittivity and permeability parameters can be treated as a single anisotropic medium. Making use of this concept, as shown by Fig. 3, thin layered system is utilized to model our proposed cloak. Here, the thickness of the layers are kept identical. For the above perfect cloak, the permittivity parameters for the two types of materials are $\varepsilon_1 = 0.102$ and $\varepsilon_2 = 9.804$, respectively, where $\varepsilon_1$ can be realized by electric plasmas, and the permeability are $\mu_z = 2.366$ for both of them.

Then the thin layered system is established for the numerical simulations, in which the field distributions can be obtained. Then the far field scattering pattern can be obtained from the near field using the Stratton-Chu formulas [25], as shown by Fig. 4. The solid line shows the normalized far field scattering efficiency of the bare PEC square, which indicates large scattering in the $+x'$ (forward) and $\pm y'$ directions. When the PEC square is coated by a cloak with 18 layers (9 periods) of the proposed structure, the scattering is reduced for almost all the directions as shown by the dotted line. As a result of the homogenization of the layered system, near-zero scattering can be achieved as long as there are enough layers in a single wavelength.

IV. NONMAGNETIC CLOAKS

Since it is much easier to create cloaks with only dielectric materials in practice, a one directional nonmagnetic cloak [12] with the simplified parameters $\varepsilon_{uu} = 0.478$, $\varepsilon_v = 11.7$ and $\mu_{ww} = 1$ is then obtained from the above perfect cloak. The dash dotted line in Fig. 5 shows that a reduction of about 22 dB for the forward and 28 dB for the backward scattering has been achieved by using such a nonmagnetic cloak. This kind of nonmagnetic cloak can also be achieved by the layered system with $\varepsilon_1 = 0.241$ and $\varepsilon_2 = 23.2$ respectively. As the scattering properties shown by the dashed line and dotted line in Fig. 5, a reduction in the scattering can also be observed when the number of layers increases.
polarized waves, where the gray surfaces represents the direction and taking a PEC inner boundaries. Performance for netic cloak with 9 layers (dashed line), with 18 layers (dotted line), and with homogeneously anisotropic parameters (dash dotted).

In conclusion, one directional perfect cloaks composed of homogeneously anisotropic materials are proposed. By transforming an infinitesimal PEC surface to a volume in the transformed space, a cloak is formed with perfect performance for certain polarized waves. Meanwhile, the parameters are quite simple. One directional nonmagnetic cloaks are also proposed. Thin layered systems are then utilized to model such kind of cloaks. Our results show the possibility to realize perfect invisibility in practice.

REFERENCES