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Carpet cloak with photonic crystal shield that permits information exchange

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ABSTRACT

Carpet cloaks designed by optical transformation usually include a perfect shield, which exclude the electromagnetic fields from the under cloaked region. Due to the shield, observers in the cloaked area cannot "see" the outside. In this article, we report a flat carpet cloak that permits information exchange with outer environment by using one- or two-dimensional photonic crystal structures as substitutes for the perfect shield. The lateral shifts at the reflecting surface of the effective shields, which make the carpet cloak detectable, are considered and calculated with a Gaussian beam illumination. In order to counteract the lateral shifts, we redesign the parameters of the cloaking slab based on the coordinate transformation. Good agreements have been obtained between the adjusted carpet and ideal carpet with a perfect shield.

1. Introduction

Transformation optics has rapidly emerged as a new frontier in optics and materials science [1] and lots of novel and interesting optical and microwave devices have been investigated, such as the invisibility cloak in free space [2–9], concentretors [10,11], and waveguide bends [12]. Of special interest is the 'carpet' cloak [13–17], which topologically compresses an object in only one direction into a conducting sheet. When the object is under a curved reflecting surface with the carpet cloak on top of it, the object appears as if it is the original flat reflecting surface, so it is hidden under a 'carpet'. The reflecting surface here means a highly reflective metal surface and it is usually regarded as a perfect conductor. Taking the advantages of nonsingular parameters and weak anisotropy, many carpet cloaks were successfully demonstrated by experiments in microwave range [18–21] and more recently in optical range [22–28].

In fact, both conventional invisibility cloak in free space and the carpet cloak lead in principle to a perfect conducting shield, excluding lightwave from the cloaked region. Due to the shield, observers inside the cloaks cannot see the outside as shown in Fig. 1(a). In order to mitigate this constraint of communication, some new kinds of free-space cloaks have been proposed, such as the open-cloak [29], external cloak [30,31] and the cloak shielded by photonic crystal [32]. The open-cloak has an open window and permits both cloaking and information/matter exchange with outer environment, but its cloaking performance is degraded by the window. The external cloak cancels an object within a certain distance outside by creating an 'antiobject' embedded inside a cloaking shell, but it contains complementary media, which are composed of left-handed materials with simultaneously negative permittivity and permeability. As a result, they are extremely demanding of material parameters. More recently, a cylindrical cloak with photonic crystal (PC) shielding permits inside lightwave signal to transmit to outside, but it involves no performance of signal transmission to inside.

In this paper, we apply photonic crystal structure as an effective shield in the simplest flat carpet cloak design as show in Fig. 1(b) and we report two kinds of carpet cloak, based on one-dimensional photonic crystal layers and two-dimensional photonic crystal with triangle airhole array in dielectric substrate, respectively. Both proposed cloaks successfully function without disturbing the reflecting light path for an invisible frequency lying in band gap of the photonic crystal. For a pass band frequency, the lightwave can bidirectionally transmit to both inside and outside, leading a real communication of the carpet cloak with the outside. However, lateral shift of the reflected lightwave caused by the dielectric PC structures, whose value is often comparable to the height of the hidden object, making the object detectable [33]. In order to counteract the lateral shift, we analytically calculate the values on the surface of 1D and 2D photonic crystal, and then

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redesign the parameters of the cloaking slab keeping its geometrical size unchanged. Simulation results, based on finite element method (FEM), show good agreements between the adjusted cloak and ideal cloak with a perfect shield.

2. Design scheme

2.1. Carpet cloak with one-dimensional photonic crystal layers

Now, let us first consider a conventional carpet, as shown in Fig. 2. Consider a perfect reflecting surface at the origin, where a light ray with incident angle θ is plotted. In the transformation, the virtual space $0<y<k$ is crushed into the physical space $k-d<y<k$. Using the transformation approach [1,15,33], the resulting relative permittivity and permeability of the physical carpet are $\mu=k/d$ and $\varepsilon=diag(k/d, d/k)$ for transverse magnetic (TM) wave. The effect of such a carpet is to have the reflecting surface appear to be at the original plane at $y=0$ while in reality it has been moved to the plane at $y=d$ so that there is room space $0<y<d$ to hide objects. Fig. 2(b) shows a TM Gaussian beam incident at 45° onto the flat carpet, corresponding to the ray tracing diagram in Fig. 2(a).

For simplicity, we first construct a one-dimensional photonic crystal layers as a substitute for the perfect shield in the conventional carpet cloak. Suppose the midgap wavelength of the band gap is λ_c, and the thickness and refractive index of the layered constituents satisfy the equation $n_a d_a = n_b d_b = \lambda_c/4$. A thirteen-layered configuration gives *ababababababa*, where *a* and *b* represent the constituent layers, for forming an effective reflection band gap. The reflection band gap of this multilayer structure is calculated by means of a transfer matrix [34]:

$$M_j = \begin{bmatrix} \cos(k_y^j d_j) & i\frac{1}{q_j}\sin(k_y^j d_j) \\ iq_j \sin(k_y^j d_j) & \cos(k_y^j d_j) \end{bmatrix} \quad (1)$$

where M_j is the transfer matrix of the *j*th layer, $q_j = k_y^j/k$, and the reflection coefficient can be calculated by

$$r(k_x) = \frac{[q_0 X_{22}(k_x) - q_s X_{11}(k_x)] - [q_0 q_s X_{12}(k_x) - X_{21}(k_x)]}{[q_0 X_{22}(k_x) + q_s X_{11}(k_x)] - [q_0 q_s X_{12}(k_x) + X_{21}(k_x)]}$$

where X is the elements of the total transfer matrix $M = M_1 M_2 \cdots M_9$. Fig. 3 gives the reflection spectrum of the thirteen-layered structure with different magnetic polarization incoming wave angles, where we have set the midgap frequency as 3.0 GHz. As illustrated in Fig. 3, the band gap center is 3.0 GHz with a normal incidence and the band gap will move to a higher-frequency region as the incident angle increases and gradually disappears (the TM wave band gap closed).

If we take the center frequency 3 GHz as an invisible frequency, the carpet functions well as it locates in the band gap, while it can transmit through the layers when the incident angle become larger enough as demonstrated in Fig. 4(a) and (b), where the detecting TM Gaussian beam is incident at azimuth angles $\theta = 30.8°$ and 54° (the incident angle upon PC $\theta' = 50°$and 70°), respectively. So this carpet is constrained to a small range of azimuth angle.

However, if we choose another frequency 2.0 GHz in the pass band for communication goal, the beam can easily propagate through the layered structure as depicted in Fig. 4(c), leading the communication between the cloaked region and out environment. To demonstrate the performance of signal transmission, a horn antenna is placed in the hidden region with working frequency of 2.0 GHz. Good performance is obtained as show in Fig. 4(d).

Moreover, it is essential to consider the lateral shift on the equivalent reflecting surface of dielectric multilayered structure, which will lead the carpet cloak be detected. The previous work has proven that there is an obvious lateral shift near the edge of the forbidden band gap of a one-dimensional PC and it can be calculated analytically as $\Delta = -d\Phi/dk_x$ [35], where Φ is the phase of the reflection coefficient $r(k_x)$ in Eq. (2). The lateral shift also can be measured by calculating the distance between the centers of the reflected beams at the up boundary when the carpet cloak is shielded by a perfect reflector and 1D photonic crystal, respectively. Fig. 4(e) gives the comparison of lateral shift between

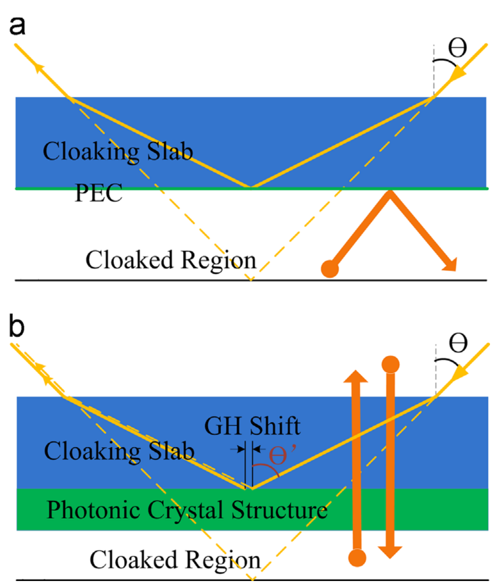

Fig. 1. Flat carpet cloak with (a) a perfect shield, (b) a photonic crystal shield.

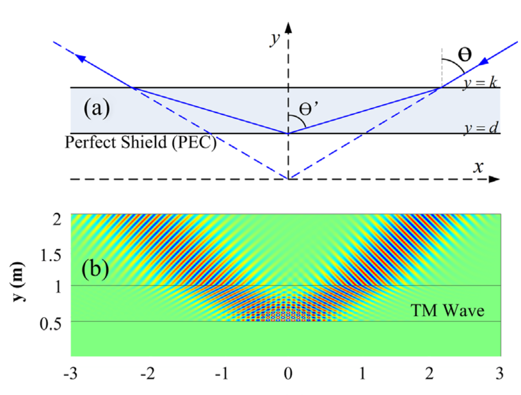

Fig. 2. (a) Ray tracing diagram of the carpet. (b) A TM Gaussian beam impinging onto the carpet with a perfect shield.

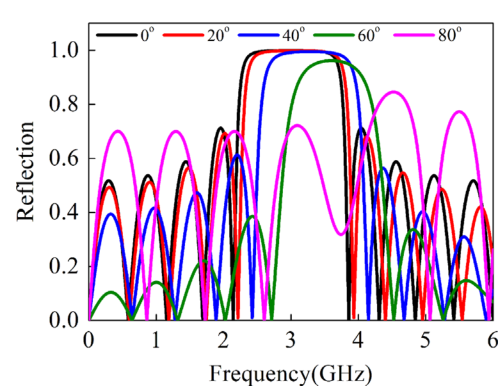

Fig. 3. Reflect spectrum of the 13-layered structure for TM wave with different incident angle θ'.