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The effect of coordinate transformation function on scattering characteristics of cylindrical cloaks with a quantity of discrete layers

Xiaoxia Zhou [a], Ying Chen [a,b,*], Yuan Zhou [a], Zhaoming Luo [b]

[a] Department of Electronic Information and Electrical Engineering, Changsha University, Changsha 410000, China
[b] Key Laboratory for Micro-/Nano-Optoelectronic Devices of Ministry of Education, College of Physics and Microelectronic Science, Hunan University, Changsha 410082, China

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ABSTRACT

We studied the electromagnetic scattering from cylindrical cloaks with a quantity of discrete homogeneous layers. The scattering cross sections (SCS) of electromagnetic cloaks designed by different coordinate transformation function are discussed by using a polynomial transform function. The results show that besides the inner boundary, the interfaces between the adjacent discrete anisotropic layers inside the cloak also affect its performance. Through the proper design of the coordinate transformation order, the electromagnetic field distribution insides the cloak can be optimized and the invisible performance of the cloak could be improved with minimization of SCS. These results provide a better way of designing the cloak to achieve low scattering with only a few layers of anisotropic metamaterials.

1. Introduction

In recent years increasing attention has been focused on the electromagnetic (EM) cloak based on coordinate transformation theory [1–3], which can render arbitrarily sized and shaped objects electromagnetically invisible. Efforts were carried out on the design and theoretical characterization of invisibility cloaks, such as rounded cylinders [2,4], elliptical cylinders [5,6], eccentric elliptical cylinders [7], and even arbitrary shapes [8–10]. However, although the idea has been confirmed by several recent contributions experimentally [2], the realization of an invisibility electromagnetic cloak is still quite challenging, for continuous inhomogeneity and high anisotropy metamaterials with extreme values in the parameters need to be used in construction of a perfect invisibility cloak. Simplified parameters based on the coordinate transformation [11,12], as well as some forms of discretization and truncations [13–15] were utilized to facilitate the physical realization, both in the expense of inherent electromagnetic scatterings. It is necessary to investigate a better way to design a practical cloak with good performance.

According to coordinate transformation theory, coordinate transformation compresses space from the virtual space into transformed space (physical space) to obtain a cloak. There are an infinite number of transformations that can perform the compression, which provides an important design freedom for cloak designing. So far linear, quadratic and a class of high-order coordinate transformation functions have been adopted for designing cylindrical cloaks [16,17]. It is of great interest to study the effect of transformation functions on the cloak's invisibility performances. And for the realization of a cloak, the ideal continuous parameters obtained from the transformation method need to be discretized. Discretization makes the cloak imperfect and lead to intrinsic electromagnetic scatterings. It is important to study the performance of a multilayered cloak composed of discontinuous layers of homogeneous anisotropic dielectric materials. Although cloak shells with a lot of layers can be used to simulate near perfect effects, it increases the construction complexity. On the other hand, reduction in the number of layers causes the performance degradation of the invisibility cloak. Thus, it is desirable to optimize a cloak using a minimum number of dielectric layers. By using genetic algorithms or particle swarm optimization (PSO) technique, low scattering can be achieved with only a few layers without following the transformation method [18,19], but the performance will change quickly when the frequency changes.

In this paper, we focus on the effect of coordinate transformation function on the cloaking performance of cloaks with a quantity of discrete layers of homogeneous anisotropic dielectric materials. By using the polynomial coordinate transformations with a free transformation order number, it has been found that a proper strategy for the choice of transformation function can help to optimize the field distribution inside the cloak and yield better cloaking performance. Rigorous Scattering characteristics analyses

* Corresponding author at: Department of Electronic information and Electrical engineering, Changsha University, Changsha 410000, China.
E-mail addresses: zhouxiaoxia999@sohu.com.cn (X. Zhou), yingchen@hotmail.fr (Y. Chen), zhouyuan304@163.com (Y. Zhou), zhaomingluo@hnu.edu.cn (Z. Luo).

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are presented to give a physical insight of it. These results provide a better way of designing a multilayered cloak with fewer layers.

2. Principle description

For cylindrical cloak, so far linear, quadratic and a class of high-order coordinate transformation functions have been discussed for designing cloaks. Without losing the generality, one polynomial coordinate transform function from virtual electromagnetic space (r', θ', z') to physical space(r, θ, z) is used, which takes the form of [20]

$$r = \frac{(b-a)}{b^{\delta}} r'^{\delta} + a, \quad \theta = \theta', \quad z = z' \tag{1}$$

The transformation order δ can be a rational number other than an integer, which facilitate to choice different coordinate transformation that compresses the cylindrical region $0 < r' < b$ into the annular region $a < r < b$.

The corresponding anisotropic permittivity and permeability tensor components can be determined as

$$\varepsilon_r = \mu_r = \delta \frac{r-a}{r}$$
$$\varepsilon_\theta = \mu_\theta = \frac{1}{\varepsilon_r}$$
$$\varepsilon_z = \mu_z = \frac{b^2}{(b-a)^{2/\delta}} \frac{(r-a)^{(2/\delta-1)}}{r\delta} \tag{2}$$

By a two-step procedure, the above continuous radius-dependent, anisotropic shell can be approximated through layered homogeneous isotropic materials [21]. Firstly, the continuous anisotropic medium could be represented approximately by N discrete layers of homogeneous anisotropic medium. Then each anisotropic layer is simulated by $2 \times M$ alternating layers of isotropic materials A and B with different dielectric coefficients. Here the case of TM wave illumination is considered and only μ_z, ε_θ and ε_r must satisfy the requirement of Eq. (2). Based on the long wave approximation, the alternating layered structures design the effective anisotropic permittivity tensor as

$$\varepsilon_\theta = \frac{\varepsilon_A + \eta \varepsilon_B}{1+\eta}$$
$$\frac{1}{\varepsilon_r} = \frac{1}{1+\eta}\left(\frac{1}{\varepsilon_A} + \frac{\eta}{\varepsilon_B}\right) \tag{3}$$

where ε_A, ε_B are the permittivities of layer A and layer B respectively, and η is the thicknesses ratio of the two layers. Thus the cloak can be simulated by a discrete $2 \times M \times N$-layer structure (Fig. 1).

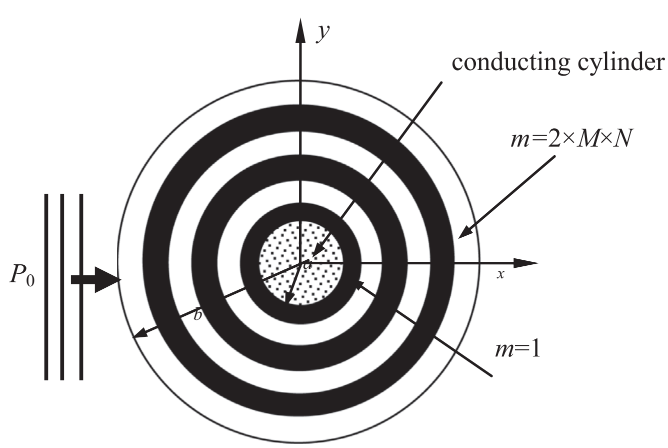

Fig. 1. Illustration of a multilayered cylindrical cloak.

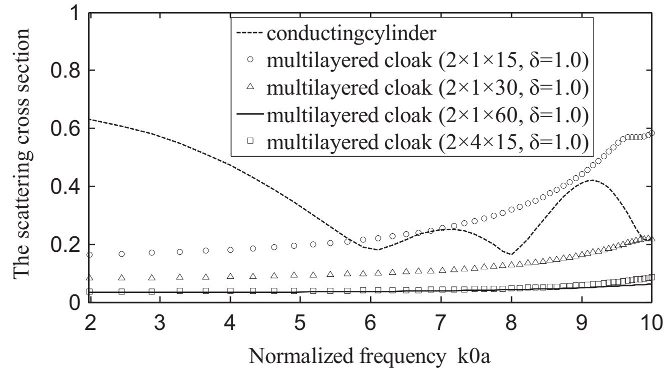

Fig. 2. The scattering cross section of the cloaks with different discretizations as a function of frequency.

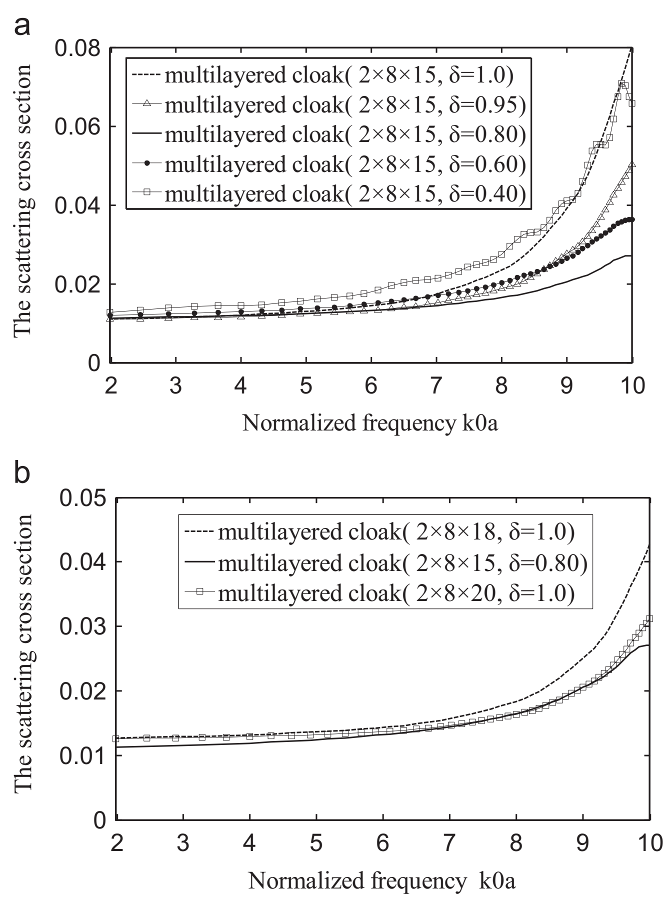

Fig. 3. (a) The scattering cross section for different transformation order n with the same discretizations, (b) The scattering cross section for different transformation order n with different discretizations.

Consider the electromagnetic wave scattering for an infinite conducting cylinder shelled with a concentric layered structure, as shown in Fig. 1. A plane wave with TM polarization is assumed to impinge along the x direction upon the shelled cylinder. The TE case can be analyzed similarly. The axial components of the magnetic field vector H in each region can be expanded in cylindrical coordinates as: