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Research on monostatic and bistatic RCS of cloaking based on coordinate transformation

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ABSTRACT

Metamaterials with carefully chosen negative permittivity and permeability can guide electromagnetic wave to bypass a target without any scattering theoretically. This paper uses the basic theory of coordinate transformation to generate such permittivity and permeability which can result in such a perfectly cloak effect. The invisibility of the cloak is demonstrated by a cylinder and a sphere wrapped with metamaterial. COMSOL Multiphysics software is utilized to simulate the interaction between incident electromagnetic wave and the cloaks. Monostatic and bistatic radar cross section (RCS) is calculated to show the scattering suppression effect. The results show that metamaterials have an excellent performance in reduction of the scattering. Backscattering RCS can be reduced about 20 dB relative to the non-cloak target.

1. Introduction

In conventional radar stealth technology, the targets deflect most of the incident electromagnetic wave due to the canted shape. Another way is to use (radar absorbing material, RAM) to absorb incident radar wave to reduce the target backscattering. In 2006, Pentry proposed the “cloak of invisibility” theory, which is based on coordinate transformation, give another way to reduce scattering [1]. The cloak of invisibility can make the incoming electromagnetic wave to propagate around the object without any disturbance on the field outside. Thus, the target can get perfect invisible effect in all directions [2].

The implementation of the cloak theory requires that the material to have some anomalous parameters that cannot be seen in natural material. The metamaterial can be designed to have the characteristics to be needed. Unlike conventional materials, metamaterials have a series of anomalous electromagnetic properties. The most important feature is that one can flexibly design the electromagnetic parameters of the metamaterials to control the propagation behavior of electromagnetic waves. These characteristics make the idea of “cloak of invisibility” possible [3].

In this paper, we designed two-dimensional and three-dimensional cloaks to make the targets in the cloaks to be invisible. The inner and outer diameter of the cloaks are 30 mm and 60 mm, respectively. The monostatic and bistatic RCS of the targets wrapped with cloaks are calculated. Considering in application the material has electric or magnetic loss, we calculate the metamaterial with various loss to study the influence of loss to the scattering suppression.

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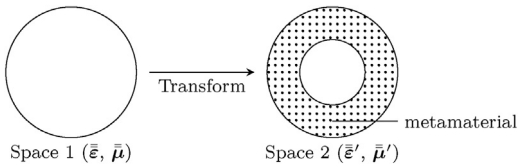

Fig. 1. Schematic representation of cloak of invisibility of design process.

2. The theory and application of coordinate transformation

The design of cloak of invisibility is based on the theory of coordinate transformation. The function of coordinate transformation is to transform a complete space into a space with a shell wrapping around the target [4–6]. Meanwhile, the field outside the target remains the same. Based on the invariance principle of Maxwell's equation, transformation from a flat space x to a twisted space x' is equivalent to the transformation of material parameters in the original flat space. After the transformation, the permittivity tensor $\bar{\bar{\boldsymbol{\varepsilon}}}'$ and permeability tensor $\bar{\bar{\boldsymbol{\mu}}}'$ of the twisted space are transformed from the permittivity tensor $\bar{\bar{\boldsymbol{\varepsilon}}}$ and permeability tensor $\bar{\bar{\boldsymbol{\mu}}}$ of the flat space, which is given

$$\bar{\bar{\boldsymbol{\varepsilon}}}' = \boldsymbol{A}\cdot\bar{\bar{\boldsymbol{\varepsilon}}}\cdot\boldsymbol{A}^{\mathrm{T}}/|\boldsymbol{A}| \tag{1}$$

$$\bar{\bar{\boldsymbol{\mu}}}' = \boldsymbol{A}\cdot\bar{\bar{\boldsymbol{\mu}}}\cdot\boldsymbol{A}^{\mathrm{T}}/|\boldsymbol{A}| \tag{2}$$

where $\boldsymbol{A}$ is the Jacobi matrix. The component of $\boldsymbol{A}$ is $A_{ij} = \partial x_i'/\partial x_j$, where x_j is coordinate in the original system and x_i is coordinate in the twisted system. The Jacobi matrix reflects the geometry change of the original space to the new space. The electromagnetic parameter distribution of the cloak of invisibility can be obtained by mapping the transformation relation to the material parameters of the medium. Fig. 1 shows the design of coordinate transformation for a cloak of invisibility.

2.1. Design and simulation of cylindrical cloak of invisibility

In this section, we design an infinitely long cylindrical cloak of invisibility based on the transformation theory [7–9]. It is assumed that the target for invisibility is a cylinder with a radius R_1 and the cloak of invisibility is located in the annular area $R_1 < r < R_2$. The coordinate transformation formula is:

$$r' = R_1 + r\frac{R_2 - R_1}{R_2} \tag{3a}$$

$$\theta' = \theta \tag{3b}$$

$$z' = z \tag{3c}$$

where r' and r are the radial coordinates of the original and new space, respectively, θ' and θ are the circumferential coordinates of the original and new space, respectively, z' and z are axial coordinates of the original and new space, respectively,

The tensor $\bar{\bar{\boldsymbol{\varepsilon}}}'$ and $\bar{\bar{\boldsymbol{\mu}}}'$ of the cloak of invisibility can be obtained by the coordinate transformation of (3a), (3b) and (3c), the components of which are

$$\varepsilon_{r'} = \mu_{r'} = \frac{r' - R_1}{r'} \tag{4a}$$

$$\varepsilon_{\theta'} = \mu_{\theta'} = \frac{r' - R_1}{r'} \tag{4b}$$

$$\varepsilon_z = \mu_z = \left(\frac{R_2}{R_2 - R_1}\right)^2 \frac{r' - R_1}{r'} \tag{4c}$$

By a coordinate transformation of (4a), (4b) and (4c), the expression of the material parameters of a cloak of invisibility under Cartesian coordinates is obtained, which is

$$\varepsilon_{xx} = \varepsilon_{r'}\cos^2\theta + \varepsilon_{\theta'}\sin^2\theta \tag{5a}$$

$$\varepsilon_{xy} = (\varepsilon_{r'} - \varepsilon_{\theta'})\cos\theta\sin\theta \tag{5b}$$

$$\varepsilon_{yx} = (\varepsilon_{r'} - \varepsilon_{\theta'})\cos\theta\sin\theta \tag{5c}$$

$$\varepsilon_{yy} = \varepsilon_{r'}\sin^2\theta + \varepsilon_{\theta'}\cos^2\theta \tag{5d}$$

Based on the theory above, we made numerical simulation of scattering characteristics of perfectly electric conductive (PEC) cylinder wrapped with cloak of invisibility by plane wave. COMSOL Multiphysics software was utilized. PEC cylinder is wrapped with cloak of invisibility in simulation. The inner diameter of the cloak of invisibility is $R_1 = 30\,mm$, and the outer diameter is $R_2 = 60\,mm$. The incident wave is TE wave with frequency of 10 GHz. The propagation direction is from left to the