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Cloaking electromagnetic wave with phase shifter

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ABSTRACT

When electromagnetic wave is normally reflected from semi-infinite denser medium, the phase of reflection wave jumps π, when electromagnetic wave is normally reflected from finite thickness denser (or thinner) medium, the phase of the reflection wave will change. According to the electromagnetic wave theory, we designed phase shifter and derived the reflection coefficient and the phase shift of the reflection wave. By comparing phase, we designed phase compensation cloak. The simulation results show that the phase shifter can cloak electromagnetic wave.

1. Introduction

With the development of metamaterial, various kinds invisibility cloak have been designed and fabricated. Many achievements of invisibility cloak have been motivated thanks to the pioneering theoretical works [1–4]. Inspired by those theoretical works, varieties of electromagnetic wave cloak [5–8], acoustic wave cloak [9–11], mass diffusion cloak [12,13], heat flux cloak [14–18], magnetic cloak [19,20], electric cloak [21,22] and matter wave cloak [23,24] have been theoretically designed and experimentally demonstrated. Recently, Ni et al. experimentally demonstrated an ultrathin skin cloak based on the phase of the reflection field is invariant at the wavelength ~730 nm that overcomes the limitations of a bulky cloak [25], they created a metasurface tightly wrapped over an object to render it free from optical detection, the ultrathin layer of the skin cloak restores the wave front scattered from the object by compensating the phase difference. Soon after, Yang et al. [26] theoretically proposed a single low-profile skin metasurface carpet cloak to hide objects with arbitrary shape and size under three different waves, i.e., electromagnetic wave, acoustic wave and water wave, they controlled the local reflection phase of three waves by a metasurface, the metasurface provides an additional phase to compensate the phase distortion introduced by a bump, and the phase of reflection waves are restored as if the incident waves impinge onto a flat mirror. Faure et al. also did a similar work, they designed an acoustic carpet cloak by using a metasurface made of graded Helmholtz resonators [27]. In this work, we designed phase shifter and phase shift compensation cloak, and simulated phase shift compensation cloak, the simulation results show that the phase shifter can cloak electromagnetic wave.

2. Theoretical model and simulation

Fig. 1a shows two semi-infinite media, ε_1 and ε_2 are permittivity in region I and region II, respectively, μ_1 and μ_2 are permeability in region I and region II, respectively. Taking the transverse electric (TE) wave as an example, when TE wave is normally propagating from region I to region II, the electric fields in two regions are

$$E_{IZ} = A_1 e^{ik_{1x}x+i\omega t} + A_2 e^{-ik_{1x}x+i\omega t} \tag{1}$$

$$E_{IIZ} = B_2 e^{ik_{1x}x+i\omega t} \tag{2}$$

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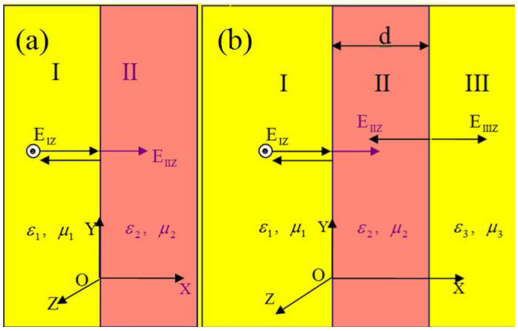

Fig. 1. Electromagnetic wave normal propagation. (a) Two semi-infinite media I and II. (b) Sandwich media I, II and III.

According to Maxwell's equation $\nabla \times \vec{E} = -\mu\partial\vec{H}/\partial t$, we obtain the magnetic fields in two regions

$$H_{IZ} = -\frac{k_{1x}}{\mu_1\omega}(A_1 e^{ik_{1x}x+i\omega t} - A_2 e^{-ik_{1x}x+i\omega t}) \tag{3}$$

$$H_{IIZ} = -\frac{k_{2x}}{\mu_2\omega}B_2 e^{ik_{2x}x+i\omega t} \tag{4}$$

where E_{IZ} and E_{IIZ} are electric field in region I and region II, respectively, H_{IZ} and H_{IIZ} are magnetic field in region I and region II, respectively, ω is the angle frequency, k_1 and k_2 are the wave number in region I and region II, respectively, A_1, A_2 and B_1 are unknown coefficient. According to the boundary conditions, the tangential electric field and magnetic field are continuous on the boundary of x= 0, we obtain the reflection coefficient of TE wave

$$r_{TE} = \frac{\mu_2 k_{1x} - \mu_1 k_{2x}}{\mu_2 k_{1x} + \mu_1 k_{2x}} = |r|\ e^{i\varphi_{TE}} \tag{5}$$

For normal propagation, and we take $\mu_1 = \mu_2 = 1$, $k_{1x} = k_0\sqrt{\varepsilon_1}$, $k_{2x} = k_0\sqrt{\varepsilon_2}$, $k_0 = \omega/c$, we obtain $r_{TE} = (\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2})/(\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}) = |r|\ e^{i\varphi_{TE}}$, φ_{TE} is the phase shift of TE reflection wave. When $\sqrt{\varepsilon_1} < \sqrt{\varepsilon_2}$, $r_{TE} < 0$, i.e., electromagnetic wave is normally propagating from thinner medium to denser medium, the reflection coefficient $r_{TE} < 0$ leads to $e^{i\varphi_{TE}} = -1$, so the phase shift of TE wave $\varphi_{TE} = \pi$, or half wave loss, namely, electromagnetic wave is normally reflected from wave denser medium, the phase of reflected wave jumps π.

Fig. 1b shows sandwich media, ε_1, ε_2 and ε_3 are permittivity in three regions, correspondingly, μ_1, μ_2 and μ_3 are permeability in three regions, correspondingly. When TE wave is normally propagating from region I to region III, the electric fields in three regions are

$$E_{IZ} = A_1 e^{ik_{1x}x+i\omega t} + A_2 e^{-ik_{1x}x+i\omega t} \tag{6}$$

$$E_{IIZ} = B_1 e^{ik_{2x}x+i\omega t} + B_2 e^{-ik_{2x}x+i\omega t} \tag{7}$$

$$E_{IIIZ} = C_1 e^{ik_{3x}x+i\omega t} \tag{8}$$

According to Maxwell's equation, we obtain the magnetic fields in three regions

$$H_{1y} = -\frac{k_{1x}}{\mu_1\omega}(A_1 e^{ik_{1x}x+i\omega t} - A_2 e^{-ik_{1x}x+i\omega t}) \tag{9}$$

$$H_{2y} = -\frac{k_{2x}}{\mu_2\omega}(B_1 e^{ik_{2x}x+i\omega t} - B_2 e^{-ik_{2x}x+i\omega t}) \tag{10}$$

$$H_{3y} = -\frac{k_{3x}}{\mu_3\omega}C_1 e^{ik_{2x}x+i\omega t} \tag{11}$$

According to the boundary conditions, we obtain reflection coefficient of TE wave.

$$r_{TE} = \frac{r_1 + r_2 e^{i2k_{2x}d}}{1 + r_1 r_2 e^{i2k_{2x}d}} = |r|\ e^{i\varphi_{TE}} \tag{12}$$

where $r_1 = (\mu_2 k_{1x} - \mu_1 k_{2x})/(\mu_2 k_{1x} + \mu_1 k_{2x})$, $r_2 = (\mu_3 k_{2x} - \mu_2 k_{3x})/(\mu_3 k_{2x} + \mu_2 k_{3x})$, for normal propagation, and we take $\mu_1 = \mu_2 = \mu_3 = 1$, $k_{1x} = k_0\sqrt{\varepsilon_1}$, $k_{2x} = k_0\sqrt{\varepsilon_2}$, $k_{3x} = k_0\sqrt{\varepsilon_3}$, $\varepsilon_3 \to \infty$, we obtain

$$\tan\varphi_{TE} = \frac{\sqrt{\varepsilon_2}\sin(2k_0\sqrt{\varepsilon_2}d)}{\varepsilon_2\cos^2(k_0\sqrt{\varepsilon_2}d) - \sin^2(k_0\sqrt{\varepsilon_2}d)} \tag{13}$$

In this work, we choose copper slab as region III, the permittivity of copper $\varepsilon_3 \to \infty$. Due to the skin effect, the larger the frequency