Antenna Miniaturization Based on Supperscattering Effect

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Abstract. *Antennas are essential components of all existing radio equipments. The miniaturization of antenna is a key issue of antenna technology. Based on supperscattering effect, we found that when a small horn antenna is located inside of a dielectric core and covered with a complementary layer, its far field radiation pattern will be equivalent to a large horn antenna. The complementary layer with only axial parameters varying with radius is obtained using coordinate transformation theory. Besides, the influence of loss and perturbations of parameters on supperscattering effect is also investigated. Results show that the device is robust against the perturbation in the axial material parameters when the refractive index is kept invariant. Full-wave simulations based on finite element method are performed to validate the design.*

Keywords

Superscattering effect, horn antenna, transformation optics.

1. Introduction

It is well known that the directive coefficient of an antenna is a direct proportion to aperture, but an inverse proportion to the square of wavelength. For a required antenna gain, how to achieve it using a small aperture antenna instead of a large one is a key issue in antenna design.

In the past decade, a fascinating term "metamaterials" [1] has attracted a great deal of attentions since it provides many possibilities to explore unknown physical phenomena and fabricate novel devices such as perfect lens [2], antennas [3-5], and sensors [6], [7]. The idea of transformation optics generalized by Leonhardt and Pendry et al. [8], [9] built up a bridge between the function of metamaterials and material parameter distribution, and provided great convenience to the manipulation of electromagnetic field. Cloak is perhaps the most famous application. Since the first cloak [10] was realized at microwave band based on metamaterial technology, great attentions has been drawn to this area [11-16]. Apart from cloak of invisibility, some other electromagnetic devices [17-24], such as concentrator, transparent structure, field rotator, beam expander and shrinking device can also be realized with this methodology.

Recently, the concept of superscatterer was proposed by Yang et al. [25]. It means that the object looks like a scatterer larger than its geometry size in electromagnetic wave direction. The effect of superscattering plays an important role in electromagnetic camouflage. For example, it is capable of concealing an entrance [26] or building up an invisible tunnel between two waveguide [27]. Based on supperscattering effect, we propose a novel directive antenna with small aperture but the same gain as a large one in this paper. Constitutive material parameters with only axial components varying with radius are derived. Full wave simulation considering the influence of metamaterial loss and material parameter deviation are carried out to validate the performance of the device.

2. Method and Simulation Model

Fig. 1 shows the schematic diagram for the construction of a superscatterer. The core media with a radius a satisfies linear transformation of $f(r'') = cr''/a$, and the material parameters can be easily obtained as $\varepsilon''_r = \mu''_r = 1$, $\varepsilon''_\varphi = \mu''_\varphi = 1$, $\varepsilon''_z = \mu''_z = (c/a)^2$. The complementary media layer colored in black is obtained by folding the air layer bounded between b and c in the virtual space (Ω) into the region bounded between a and b in the physical space (Ω').We suppose the transformation function between the physical space and the virtual space is in the form of $r = f(r')$, where $f(r')$ is a continuous function of r', and it satisfies $f(a) = c$, $f(b) = b$. According to the optical transformation theory and the form invariance of the Maxwell's equations, relative permittivity ε' and permeability μ' of the complementary media can be written as:

$$\varepsilon'_r = \mu'_r = \frac{f(r')}{r' df(r')/dr'}, \tag{1a}$$

$$\varepsilon'_\varphi = \mu'_\varphi = \frac{r' df(r')/dr'}{f(r')}, \tag{1b}$$

$$\varepsilon'_z = \mu' = \frac{f(r') df(r')/dr'}{r'}. \tag{1c}$$

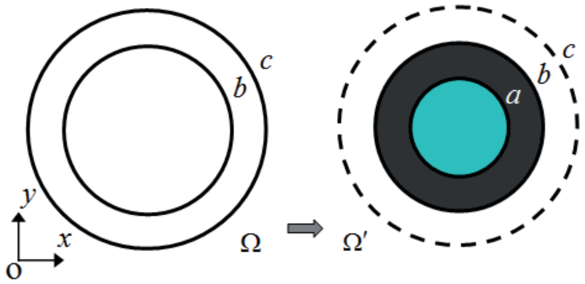

Fig. 1. (Color online) Schematic demonstration for the coordinate transformation of the supperscatterer.

We can notice that numerical values in (1a) and (1b) are reciprocal, that is, if one is set as a constant, the other can be fixed. Suppose that:

$$\varepsilon'_\varphi = \mu'_\varphi = \frac{r'\, df(r')/dr'}{f(r')} = m_0 \cdot \tag{2}$$

Solution of this differential equation is given by

$$r = f(r') = mr^{m_0} \tag{3}$$

where $m_0 = \log_{(a/b)}(c/b), m = b^{(1-m_0)}$. Then material parameters of the complementary media layer with only axial components varying as a function of radius can be obtained as follows.

$$\varepsilon'_r = \mu'_r = 1/m_0\,, \tag{4a}$$

$$\varepsilon'_\varphi = \mu'_\varphi = m_0\,, \tag{4b}$$

$$\varepsilon'_z = \mu'_z = m_0 \left(\frac{r'}{b}\right)^{2(m_0-1)}. \tag{4c}$$

With this coordinate transformation, regions (a,b) and (b,c) are complementary to each other, and the whole physical space is optically equal to a circle of air with radius c, and is thus invisible to any incident wave. If we replace the dielectric core with a perfect electric conductor (PEC), the device with a radius b will have an equivalent scattering cross section to that of a larger PEC with a radius c, and this is the superscattering effect. Now we use this intriguing effect to design a small directive horn antenna with the same functionality as an equivalent large one. Fig. 2(a) shows a large horn antenna made of PEC material is placed in the region of $r < c$ in the original space.

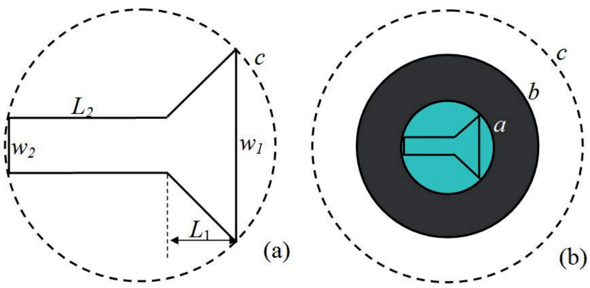

Fig. 2. (Color online) (a) The large horn antenna in the original space. (b) The small horn antenna embedded in the dielectric core of the transformation media.

By compressing the domain ($r < c$) into the domain ($r' < a$), we obtain a small horn antenna embedded in the dielectric core, and coated by the complementary layer, as shown in Fig. 2(b). Geometry size of the small horn antenna is minimized by a factor of c/a with relative to the large one. In the next section, we make full wave simulation to demonstrate superscatterering effect.

3. Results and Discussions

In this section, electromagnetic characteristics of the miniature horn antenna are simulated based on the commercial software COMSOL Multiphysics. We consider the case of transverse-electric (TE) polarization, and only ε_z, μ_r, μ_φ components of the material parameters are required.

Fig. 3(a) shows the electric field distribution in the vicinity of a larger horn antenna, of which the aperture width is $w_1 = 212.1$ mm, the taper length is $L_1 = 76.1$ mm, the length and width of the feeding waveguide is $w_2 = 60$ mm and $L_2 = 177$ mm, respectively. It is excited by a current line source located at the vertex of the taper. The far field intensity is plotted in Fig. 3(c) (the solid line). The half-power beamwidth (HPBW) is about 6.9°. It indicates that this horn antenna possesses a good directional radiation characteristic. Fig. 3(b) displays the electric field distribution in the computational domain of a small horn antenna coated with the transformation media, of which the inner and outer boundaries are $a = 0.05$ m, $b = 0.1$ m, and $c = 0.15$ m. We can clearly observe that outside the region of $r = c$, the functionalities of both the two antennas are almost the same.

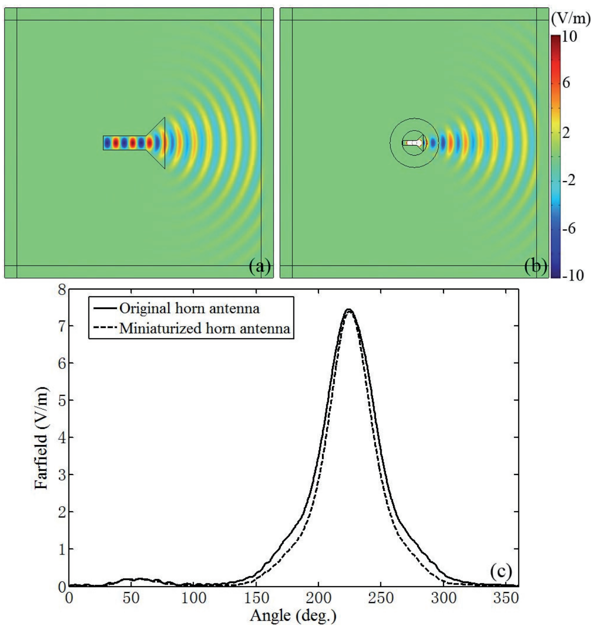

Fig. 3. (Color online) Electric field distribution of a large horn antenna (a) and a small horn antenna coated with the transformation media (b). (c) Far field intensity.

The far field intensity profile is shown in Fig. 3(c) (dashed line). The HPBW is about 7.6 °. As can be seen, the directional property of the small horn antenna coated with the transformation media coincide well with that of the large one. Compared with dielectric lens antenna, of which the directive emission lies on the shape of the lens, the directivity of a horn antenna is mainly determined by the horn aperture size. Besides, since the size of a lens antenna possesses a large electric length, it usually operates at millimeter wave band. The above simulation results indicate that the effective size of a small horn antenna can be amplified based on the superscattering effect, and then the same directivity as a large one can be achieved. That means the effective size of a desired horn antenna can be miniaturized based on the superscattering effect, which is quite important in modern antenna design.

Since metamaterials are always lossy, in what follows, we investigate the influence of loss tangent on the superscattering effect, and material parameter deviation is also considered. Fig. 4(a) shows the scattering pattern of a PEC cylinder with radius of $r = 0.15$ m. The TE plane wave with frequency of 3 GHz and unit amplitude propagates from left to right. Such a large scatterer can be replaced by a smaller supperscatterer, as shown in Fig. 4(b). Geometry size of the superscatterer is two-thirds that of the PEC cylinder.

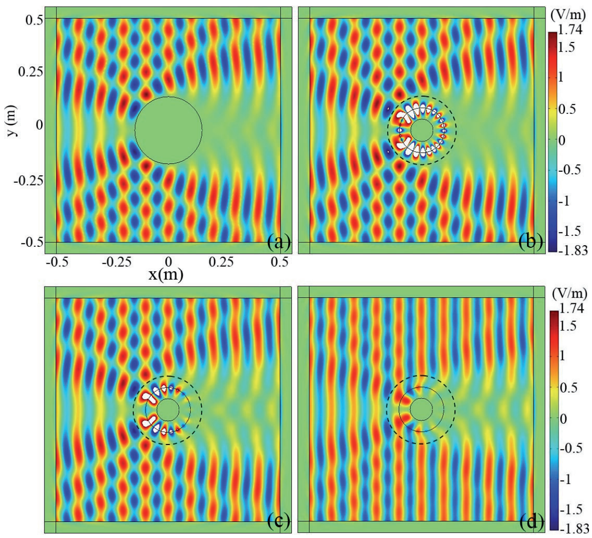

Fig. 4. (Color online) Electric field distribution in the computational domain. (a) PEC cylinder. (b) Ideal superscatterer. (c) $tg\delta = 0.01$. (d) $tg\delta = 0.1$.

Comparing Fig. 4(a) with 4(b), it is clear that field patterns in the region of $r' > 0.1$ m are almost identical. It indicates that the superscatterer effectively acts as a special device with large scattering cross section than its real size. But when loss tangent (tgδ) is introduced into the complementary layer, it will affect the field pattern both in the forward and backward scattering region, as shown in Fig. 4(c) and 4(d). To give a quantitative illustration of the influence of loss on superscattering effect, scattering width defined as $\sigma(\varphi) = 2\pi R |E_{sc}(\varphi, R)/E_{inc}|^2$ is calculated. Here, R is the distance from the object where the far-field scattered field E_{sc} is evaluated, E_{inc} is the incident field, φ is the incident angle. Curves in Fig. 5 show the scattering width of the superscatterer with electric and magnetic loss tangents (tgδ) of 0, 0.001, 0.01, and 0.1, respectively. We can observe that when loss tangent is 0.001, it has little influence on the performance of the superscatterer. Further increase the loss tangent of metamaterials will result in a decrease in scattering width. When loss tangent is equal to 0.01 and 0.1, the deviation of scattering width with respect to the perfect value will be 0.9 dB and 3.5 dB, respectively.

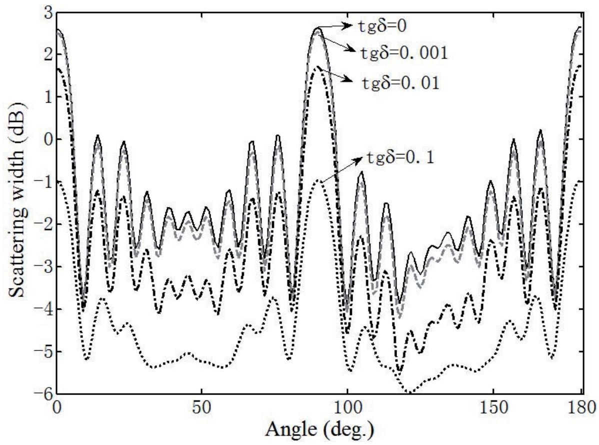

Fig. 5. Scattering width of the superscatterer with loss tangents of 0, 0.001, 0.01 and 0.1 respectively.

To investigate the influence of material parameter deviation on superscattering effect, we simulated the electric field distribution in the computational domain of the superscatterer when the axial component ε_z is multiplied by a coefficient of η. This represents the axial material parameter is slightly deviated from the perfect value. Both the negative ($\eta = 0.9$) and positive ($\eta = 1.1$) deviation is considered. Simulation results are shown in Fig. 6. We can observe that negative deviation in axial parameter has a weak impact on the performance of the superscatterer. But a positive deviation will deteriorate superscattering effect especially in the forward scattering region. When the axial parameter is deviated by a factor of $\eta = 1.1$, the following two cases are considered:

(i) the impedance ($Z = \sqrt{\mu_\varphi / \varepsilon_z}$ and $\sqrt{\mu_r / \varepsilon_z}$) is kept invariant;

(ii) the refractive index ($n = \sqrt{\mu_\varphi \varepsilon_z}$ and $\sqrt{\mu_r \varepsilon_z}$) is kept invariant.

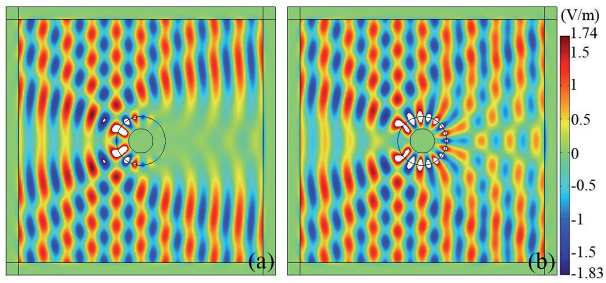

Fig. 6. (Color online) Electric field distributions in the vicinity of the superscatterer when axial parameter ε_z is deviated from perfect value. (a) $\eta = 0.9$. (b) $\eta = 1.1$.

Simulation results of scattering width are plotted in Fig. 7. It is obvious that scattering width of the non-ideal superscatterer agrees well with the perfect one when refractive index is kept invariant. That means keeping the refractive index invariant is the best choice to reduce the influence of material parameter deviation on the performance of the superscatterer.

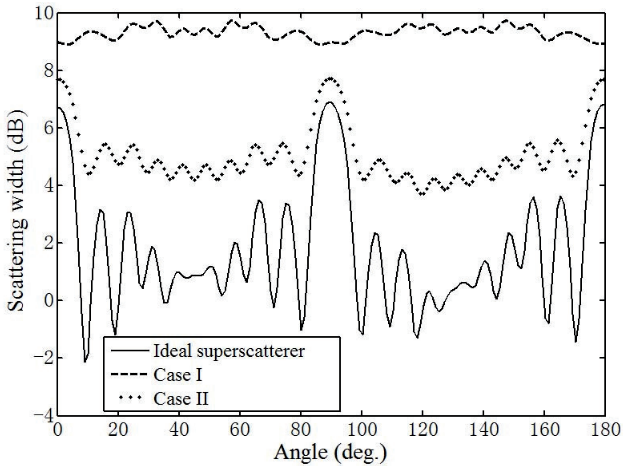

Fig. 7. Scattering width of the superscatterer with positive deviation in axial material parameters. Case I: the impedance is kept invariant; Case II: the refractive index is kept invariant. The solid line denotes the scattering width of the ideal superscatterer.

4. Conclusion

In conclusion, a miniature directive antenna is proposed based on superscattering effect. Using full wave simulation, we demonstrate that when a small horn antenna is located in the a dielectric medium and coated with a complementary layer, its radiation properties will be equivalent to a larger one, which shows some advantages in opening up an avenue for minimizing the size of antennas and may have potential applications in radio engineering.

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