A general transformation designing high gain lens antennas with homogeneous media

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Abstract

By employing finite embedded coordinate transformation method, we propose a general transformation to design a highly directive horn antenna with homogeneous and anisotropic media. Different from the layered lens antenna, our antenna consists of four triangle regions made of homogeneous and anisotropic media, which greatly reduces the difficulty of practical realization. Full wave simulation based on finite element method is performed to validate the performance of the antenna.

I. INTRODUCTION

In the past five years, transformation optics has triggered extensive interests all over the world since it provides unprecedented freedom and flexibility in manipulating the propagation of electromagnetic wave. Its main principle is based on the form invariance of Maxwell equations under coordinate transformation. The most fascinating application of transformation optics is the invisibility cloak [1-5], which is firstly introduced by Pendry and Leonhardt in 2006, respectively [1, 2]. An ideal invisibility cloak can guide electromagnetic wave smoothly flowing around the object inside it. The first free-space cloak with reduced material parameters was experimentally realized with split-ring resonators at microwave frequency by Schurig et al [3]. Besides the invisibility cloak, transformation optics is also used to design the other interesting devices, such as EM field concentrator [6], EM field rotator [7] and illusion optical device [8].

Recently, finite-embedded coordinate transformation method has been proposed to design beam shifter and splitter [9]. Later, it is extended to design the other interesting devices, such as beam compressor and expander [10], waveguide bends [10, 11], cylindrical-to-plane wave converter [12], and highly directive antenna [13]. However, most of devices reported are made of inhomogeneous and anisotropic materials, which greatly increase the difficulty of practical realization as well as limit the operation bandwidth. To remove the obstacles of material inhomogeneity and anisotropy, some novel transformations including quasi-conformal mapping are proposed. In this paper, we proposed a generalized transformation to design a highly directive antenna with homogeneous media. We just need to divide the antenna into four triangle blocks, and each block is made of homogeneous and anisotropic media. The simple material requirement makes the antennas relatively easy be constructed by metamateirals. Full wave simulation based on finite element method is carried out to confirm the performance of the antenna under such a kind of transformation. The simulation results indicate that the radiation directivity of antenna is highly collimated and can be controlled arbitrarily. Thus, such a generalized transformation provides us more freedom and flexibility in designing the antenna with high direction.

II. TRANSFORMATION PRINCIPLE OF ANTENNAS

Fig. 1 shows the geometry structure of antenna. The rectangular area ABC_0D_0 in the virtual space is divided into four triangle areas AO_0B, BO_0C_0, $C_0O_0D_0$, and AO_0D_0, respectively. Simultaneously, the trapezoid area ABCD in the physical space is also divided into four blocks AOB, BOC, COD, and AOD, respectively. Then, the four triangle regions AO_0B, BO_0C_0, $C_0O_0D_0$, and AO_0D_0 in the virtual space (x, y, z) are mapped into the four corresponding areas AOB, BOC, COD, and AOD in the physical space (x′, y′, z′). Here, four blocks AOB, BOC, COD and AOD are denoted by Region I, II, III and IV. The coordinate transformation function of above four mappings can be expressed as

$$(a)\begin{cases}x'=a_{11}x+b_{11}y+c_{11}\\ y'=a_{12}x+b_{12}y+c_{12}\\ z'=z\end{cases}\quad (b)\begin{cases}x'=a_{21}x+b_{21}y+c_{21}\\ y'=a_{22}x+b_{22}y+c_{22}\\ z'=z\end{cases}$$
$$(c)\begin{cases}x'=a_{31}x+b_{31}y+c_{31}\\ y'=a_{32}x+b_{32}y+c_{32}\\ z'=z\end{cases}\quad (d)\begin{cases}x'=a_{41}x+b_{41}y+c_{41}\\ y'=a_{42}x+b_{42}y+c_{42}\\ z'=z\end{cases}\qquad (1)$$

a_{i1},b_{i1},c_{i1},a_{i2},b_{i2},and c_{i2}, can be easily obtained and are found that they are only related to the coordinate value of A, B, C, D, O, C_0, D_0, and O_0, respectively. Here, i=1, 2, 3 and 4 represent Region I, II, III, and IV, respectively.

According to the principle of optical transformation, the material parameters in the four regions can be obtained by

$$\overline{\overline{\varepsilon}}'=\overline{\overline{\mu}}'=\Lambda\bullet\Lambda^T/\det(\Lambda)\qquad(2)$$

in which Λ_i=(a_{i1}, b_{i1}, 0; a_{i2}, b_{i2}, 0; 0, 0, 1), and det(Λ_i)=$a_{i1}b_{i2}$-$a_{i2}b_{i1}$, i=1, 2, 3, 4, which represents Region I, II, III and IV.

III. SIMULATION RESULTS AND DISCUSSIONS

In order to verify the performance of the antennas, full wave simulation based on finite element method is performed. The boundary conditions surrounding computational region are set as perfect matched layer. The outer boundary of the antenna system except right boundary is defined as perfect electric conductor. A line current source with the magnitude of 1A is

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978-1-4673-1604-0/12/$31.00 ©2012 IEEE

located as the point (-0.1, 0.125). The working frequency of antenna is set as 5 GHz. For the sake of convenience and without loss of generality, we focus on the transverse magnetic (TM) incident wave with magnetic field polarizing along z axis. The coordinate values of A, B, C, D, C_0, and D_0, are (0, 0.05), (0, 0), (0.2, -0.125), (0.2, 0.175), (0.2, 0) and (0.2, 0.05).

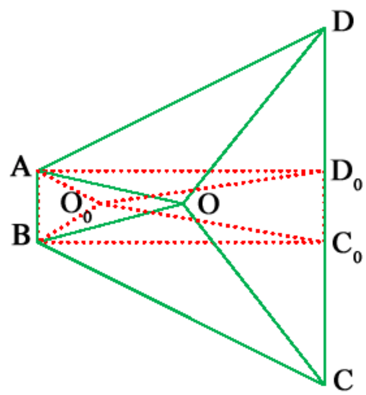

Figure 1(Color online) Schematic structure of high gain lens antenna.

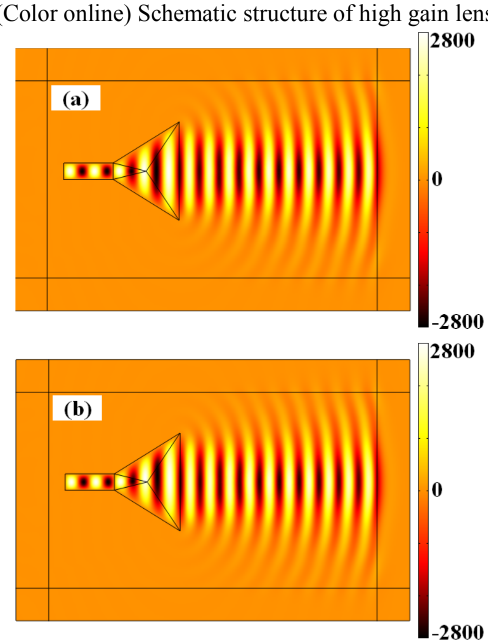

Figure 2 (Color online) Spatial distribution of magnetic field for antennas with different sets of material parameters.

Fig. 2 presents the magnetic field distributions of antennas. When the points O and O_0 are overlapped, and their coordinate values are set as (0.1, 0.025), as shown in Fig. 2(a), the magnetic field inside the antenna are successfully amplified to the whole trapezoid region and its distribution are symmetric. The output wave exiting antenna is highly collimated. Furthermore, since the triangle area ABO is mapped to itself, it is filled with air. Only other three blocks require homogeneous and anisotropic materials. If points O and O_0 do not locate at the same place and the coordinates of O and O_0 are (0.1, 0.025) and (0.1, 0.02), the material parameters of all four blocks are homogeneous and anisotropic. From Fig. 2(b), we find that the antenna stills performs well in radiating highly directive beam and the magnetic field outside the antenna is nearly the same as that of Fig. 2(a) even though the field distributions inside the horn antenna are different. Thus, the general transformation provides us more freedom in designing the high gain lens antennas.

IV. CONCLUSION

In summary, we design a high gain lens antenna by using a general transformation. Such an antenna has one merit that it is made of homogeneous and anisotropic media, and thus is relatively easily constructed with optical metamaterials. Full wave simulation is carried out to confirm the performance of the antenna. According to the simulation results, it is found that the antenna perfectly fulfills the function of radiating EM beam with high directivity. Furthermore, the radiation direction of the antenna can be controlled artificially by varying the geometrical parameters.

ACKNOWLEDGEMENTS

This work was supported in part by the State Key Program for Basic Research of China grants (2011CB922004); the National Natural Science Foundation of China grants (61006090, 10725418, 10874196, 10990104, 11104299 and 60976092); the Fund of Shanghai Science and Technology Foundation grants (09DJ1400203, and 10JC1416100).

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