Creation of Multiple Beams Following a Spiral Path by Transformation Electromagnetics Concept

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Abstract

Transformation optics offers an unconventional approach for the design of novel radiating devices. Here we propose an electromagnetic metamaterial able to split an isotropic radiation into multiple directive beams. By applying transformations that modify distance and angles, we show how the multiple directive beams can be steered at will. We describe transformation of the metric space and the calculation of the material parameters. Full wave simulations are performed to validate the proposed approach. The idea paves the way to interesting applications in various domains in microwave and optical regimes.

1. Introduction

Transformation electromagnetics (or coordinate transformation) concept, an innovative approach to design new class of electromagnetic devices, allow an unprecedented control of light rays. This method was first used by U. Leonhardt [1] and J. B. Pendry [2] to design an electromagnetic invisibility cloak in 2006 [3]. Since then, the invisibility cloak has been a subject of intensive studies and later, other systems resulting from coordinate transformation have emerged. Recently, techniques of source transformation [4-13] have offered new opportunities for the design of active devices with source distribution included in the transformed space. Transformation optics concept has thus been applied to transform the signature of a radiating source [13]. We have shown that a linear space compression followed by a space expansion, makes the radiation pattern of a small aperture antenna appear like that of a large one. By the use of a metamaterial shell, the apparent size of a small source presenting an isotropic radiation was transformed into a larger one with a directive radiation.

In this present paper, we propose to create multiple directive beams from an isotropic radiation by applying a transformation that decomposes the initial space into multiple segmented ones. We demonstrate that adjusting the transformation enables to control the number and the angular direction of the radiated beams. The material parameters generated from the transformation are discussed and the results are validated by numerical simulations.

2. Transformation formulation

We consider a radiating source with an aperture much smaller than the wavelength, therefore isotropic in the xOy plane. To achieve the transformation of this small aperture source into several much larger ones that are steered, we discretize the space around the latter radiating element into a zone which will split the isotropic beam into several steered beams. In this zone defined between circular regions with radius R1 and R2, a transformation of the angular part in function of the radial part which assures perfect impedance matching at some specific locations on the external material boundary is performed (Fig. 1). The angular part transformation can be performed using three different transformations: a positive exponential transformation, a negative exponential transformation, and a linear one. A free parameter q allows adjusting electromagnetic achievable parameters of the metamaterials for realization. To divide the space into different segments and to steer the beam in each segment, we first study a linear transformation that takes the form:

$$\theta' = g(r,\theta) = \frac{\theta}{1+N/2} + \alpha\left(\frac{r-R_1}{R_2-R_1}\right) \tag{1}$$

The other transformation have an exponential form that can be expressed as:

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$$\theta' = g(r,\theta) = \frac{\theta}{1+N/2} + \alpha\left(\frac{e^{q(r-R_1)}-1}{e^{q(R_2-R_1)}-1}\right) \tag{2}$$

The parameter α is an angle which can be viewed as the output angle of the transformed material. It is introduced in the transformation in order to rotate the beam in the material. The transformations used are general and to validate the possibility of theses transformations, we need to consider different cases. The denominator $1+N/2$ of the function θ' has to be an integer meaning that N can only take 0 or positive even values. For example when $N = 0$, there is no multi-beam creation due to non-segmentation of the space.

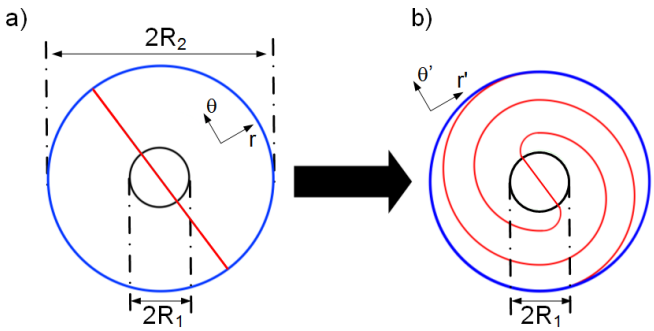

Fig. 1: Representation of the proposed coordinate transformation: (a) initial space and (b) virtual space. The transformed zone allows creating several radiation beams and rotating them in a spiral way as indicated by the transformation of the red line.

3. Numerical validation of the spiral-like multi-beam emission

In order to validate the proposed multiple beam steering concept, we use the commercial software Comsol MULTIPHYSICS to perform numerical simulations of the different transformation cases. All the simulations are run in the microwave domain at 20 GHz in a two-dimensional configuration in a transverse electric mode (TEz) (E parallel to the z-axis). A current source of dimension $d = 4$ mm placed perpendicular to the xy plane is used as a radiating element. Continuity and matched conditions are applied to the boundary of the transformed zone. Fig. 2 shows the variation of the tensor for the exponential transformation case and when N is different from zero, so as to be in a multi-beam configuration. The parameters are $q = -30$, $N = 2$, $\alpha = 300°$.

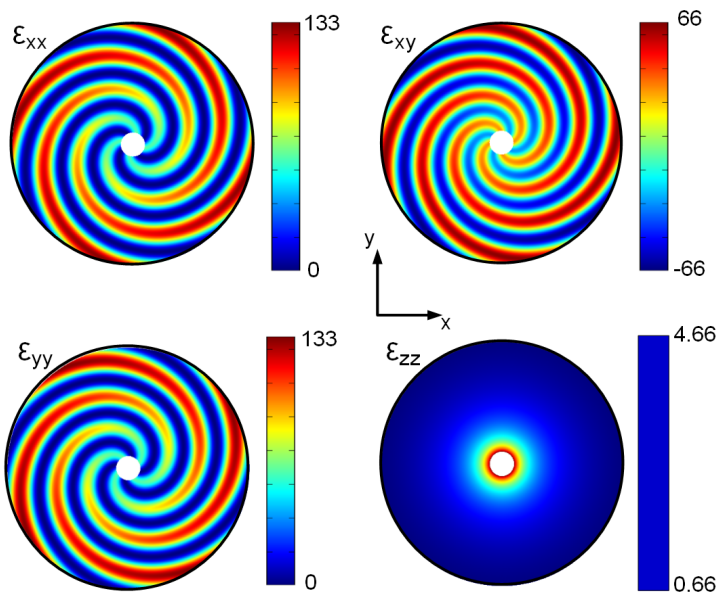

Fig. 2: Variation of the components in Cartesian coordinates of the transformed region. The permittivity and permeability are respectively plotted for the exponential transformation with $q = -30$, $R_1 = 5$ mm, $R_2 = 50$ mm, $N = 2$ and $\alpha = 300°$.

In Fig. 3, the linear transformation of the radial part in region 2 is followed by an exponential one with N different from zero, $q2$ = -30 and α = 300°, corresponding to the material parameters presented in Fig. 2. Figs. 3(a)-(b) show the electric field distribution in the proposed device for N = 2. Two steered beams can be clearly observed.
The cases for N = 4 and N = 6 are respectively shown in Figs. 3 (e)-(f) and Figs. 3(g)-(h) respectively. In each case, the electromagnetic field is rotated in the material as shown in Figs. 3(c)-(d). When α increases, the radiation tends to be more and more tangential to the surface of the material, and the interferences observed in Fig. 3(g) between the emitted beams decrease in Fig. 3(h).

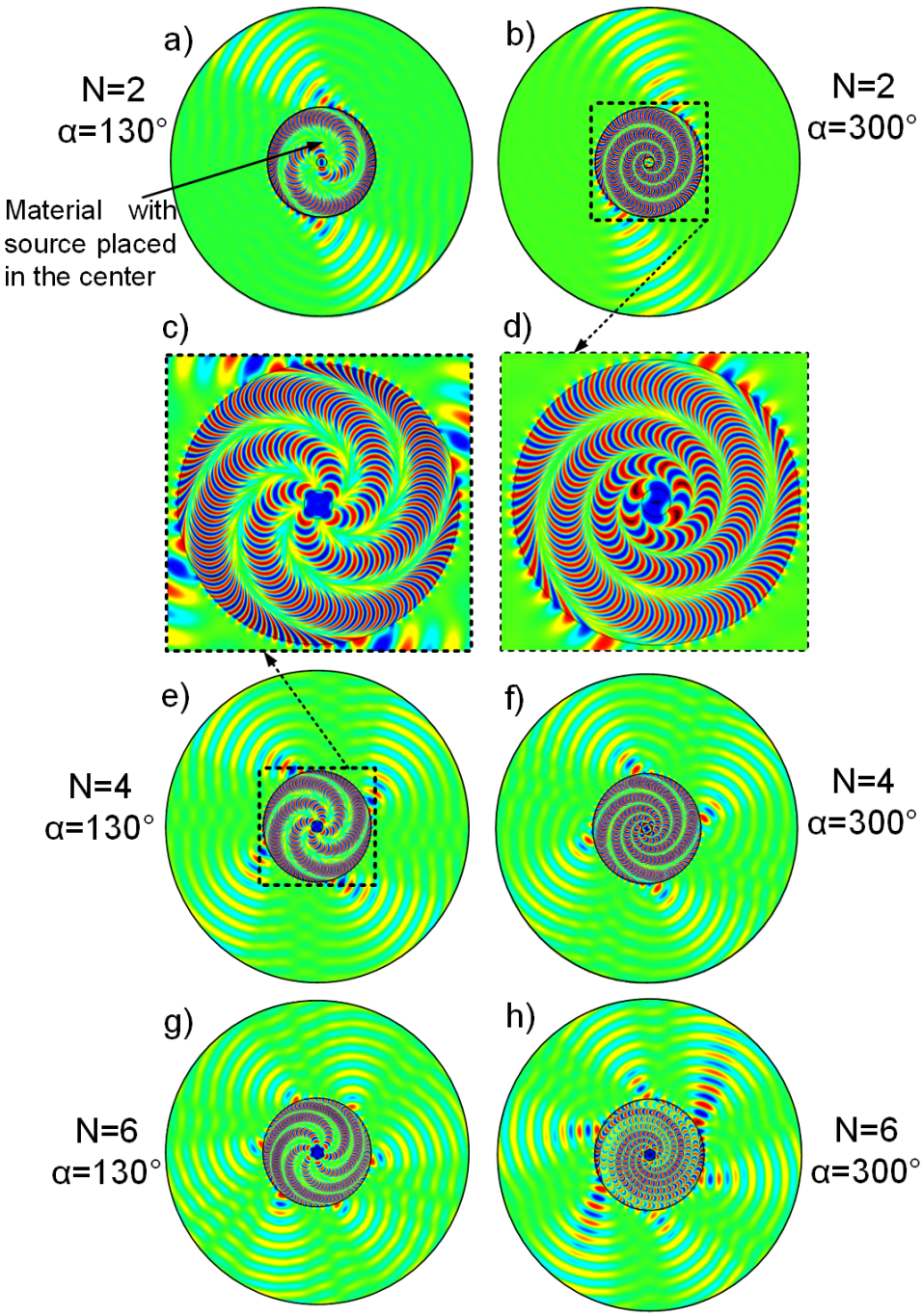

Fig. 3: Electric field (z-component) distribution of a source with dimension d = 4 mm with material defined with α = 130° (a, c, e, g) and 300° (b, d, f, h) at 20 GHz. Multi-beam emission is shown for N = 2 (a, b), N = 4 (e, f), N = 6 (g, h). Electric field distribution for α = 130° and 300°, q_2 = -30: the electromagnetic field is rotated in the material as shown in the zooms presented in parts (c) and (d).

4. Conclusion

This work points out the use of transformation electromagnetics concept to design an artificial shell which allows creating multiple directive beams. The latter concept makes use of a transformation that divides and rotates space. Numerical simulations have confirmed the operating principle of the transformations. The concept has also been applied to create more than two directive steered beams. Space has to be divided into different segments so as to channel directive beams from an isotropic source. For a possible future prototype fabrication, choosing a polarization in a fixed direction of the electromagnetic field will lead after the parameters reduction procedure to two variations of permittivity or permeability in a spiral-like eigen-base, which can be achieved by common metamaterial structures. This study shows the great possibilities that transformation electromagnetics can offer for the design and synthesis of new devices in both microwave and optical wavelength regimes.

5. References

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