Application of transformation optics concept for the design of an ultra-directive emission

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Abstract

This paper deals with the modelling, practical implementation and characterization of an ultra-directive antenna around 10 GHz. The design of the antenna is based on transformation optics concept by transforming a radiating cylindrical space into a rectangular one. Metamaterials presenting electric and magnetic resonances are used to achieve the transformation. Field intensity mappings and direct far field measurements are performed to experimentally demonstrate the narrow beam profile.

1. Introduction

Metamaterials are intensely used for the design of directive antennas [1-3]. In [1], Enoch *et al.* proposed to use the refractive properties of a low optical index material interface in order to achieve the directive emission. Burokur *et al.* also studied numerically the presence of a Left-Handed Medium (LHM) over a patch antenna where a gain enhancement of about 3dB has been observed [2]. In [3], we have shown the possibility of using a novel composite metamaterial surface as reflector in a Fabry-Perot (FP) cavity system to produce an ultrathin directive antenna. In this present letter, we present the design, implementation and characterization of an ultra-directive antenna at 10 GHz using coordinate transformation concept [4, 5], generally referred to for cloaking application. The latter concept is applied to transform a cylindrical radiation into a directional one. To do so, a bulk metamaterial respecting constitutive electric permittivity and magnetic permeability parameters generated by the transformation is employed. Numerical simulations and experimental measurements are performed to show the performances of the proposed device. Good quantitative and qualitative agreements are found.

2. Design concept

The schematic principle of the transformation is presented in Fig. 1a. The theoretical underlying physics of the transformation involved here has been detailed recently in Ref. [6]. The concept is as follows: the imagined space of our proposed antenna is obtained by transforming a flat isotropic cylindrical half-space with zero Riemann curvature tensor described in polar coordinates {r, θ} into a flat space in squeezed Cartesian coordinates. x', y' and z' are taken to be the coordinates in the virtual transformed rectangular space and x, y, z are those in the initial real cylindrical space. From the theoretical study in [6], we have shown that the coordinate transformation can be implemented by a material obeying the tensors:

$$\theta^{i'j'} = g^{i'j'} \left|\det\left(g^{i'j'}\right)\right|^{-\frac{1}{2}} \theta \qquad (1)$$

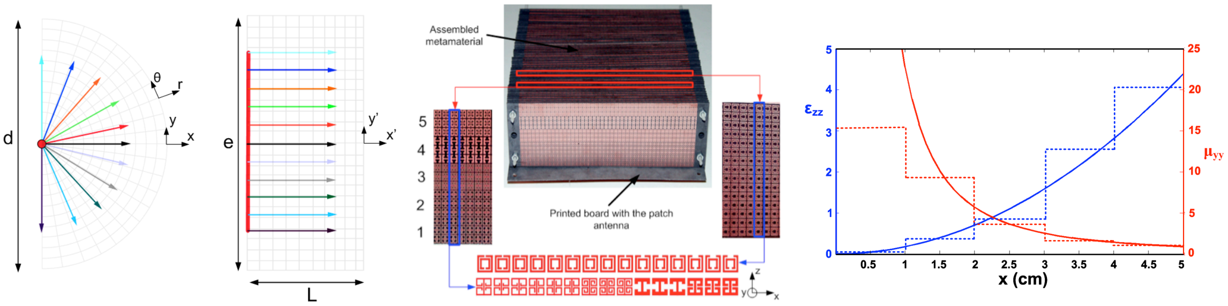
where θ represents the permittivity or permeability tensor and g the metric tensor of our designed space. The material must then be able to produce the following dielectric tensors presenting no non-diagonal components:

$$\varepsilon^{ij} = \mu^{ij} = \begin{pmatrix} \varepsilon_{xx}(x') & 0 & 0 \\ 0 & \dfrac{1}{\varepsilon_{xx}(x')} & 0 \\ 0 & 0 & \alpha\varepsilon_{xx}(x') \end{pmatrix} \qquad (2)$$

where $\varepsilon_{xx}(x') = \frac{\pi x'}{e}$ and $\alpha = \frac{d^2}{4L^2}$, with d representing the diameter of the initial cylindrical space and e and L, respectively the width and length of the rectangular target space. For a practical implementation using metamaterials, the dimensions of the semi-cylindrical space is set so that $\alpha = 4$ in order to obtain achievable values for the electromagnetic parameters. Additional simplification arises from the choice of the polarization of the emitted wave. Here we consider a polarized electromagnetic wave with an electric field pointing in the z-direction, which allows modifying the dispersion equation in order to simplify the electromagnetic parameters without changing Maxwell's equations and propagation in the structure. This leads to a metamaterial which is described by:

$$\mu_{xx} = 1 \qquad \mu_{yy} = \frac{1}{(\varepsilon_{xx})^2} \qquad \varepsilon_{zz} = 4(\varepsilon_{xx})^2 \qquad \text{with } e = 0.15\text{ m} \qquad (3)$$

Discrete values are then created for the desired variation of μ_{yy} and ε_{zz} to secure a practical realization producing experimental performances close to theory.



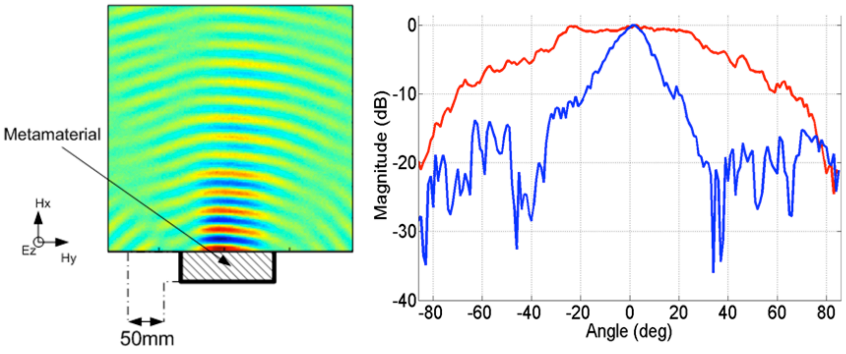
(a) (b) (c)

Fig. 1: (a) Schematic principle of the transformation where the cylindrical space is transformed into a directional rectangular one. (b) Structure of the proposed device. (c) Discrete material parameters used in experiments compared to those given by (3).

3. Simulations and experiments

Fig. 1b shows a photography of the fabricated prototype. A microstrip square patch antenna printed on a 0.787 mm thick low-loss dielectric substrate (Rogers RT/Duroid 5870^{TM} with 17.5 µm copper cladding, $\varepsilon = 2.33$ and $\tan\delta = 0.0012$) is used as radiating source. A surrounding material made of alternating electric metamaterial and magnetic metamaterial layers transforms the isotropic emission of the patch antenna into a directive one. The metamaterial is a discrete structure composed of five different regions where permittivity and permeability vary according to (3) and to the profile of Fig. 1c. The axial permittivity ε_{zz} and permeability μ_{yy} show respectively values ranging from 0.12 to 4.15 and from 1.58 to 15.3. The bulk metamaterial is assembled using 56 layers of dielectric boards on which subwavelength resonant structures are printed. 28 layers contain SRRs [7] and 28 others contain ELCs [8] known to provide respectively a magnetic and an electric response (Fig. 1b). Each layer is made of 5 regions of metamaterials corresponding to the discretized values of Fig. 1c. Because of constraints of the layout, we choose a rectangular unit cell with dimensions 3.333 mm for both resonators. The layout consists of 5 regions, each of which is three unit cells long (10 mm). We are able to obtain the desired ε_{zz} and μ_{yy} by tuning the resonators' geometric parameters. The layers are mounted 2 by 2 with a constant air spacing of 2.2 mm between each. Overall dimensions of our antenna are 15 cm x 15 cm x 5 cm.

To validate the directive emission device performances, two experiment systems are set up to measure the radiated field. The first one consists in scanning the near field microwave radiation by a field-sensing monopole probe connected to a vector network analyser (Agilent 8722 ES). The probe is mounted on two orthogonal linear translation stages (computer-controlled Newport MM4006), so that the probe can be translated with respect to the radiation region of the antenna. The full 2D measured spatial field map of the microwave near field pattern is presented in Fig. 2a. As it can observed the intensity of emitted radiation decreases rapidly since the source transformation operates only in the x-y plane. The other experiment consisted in measuring the far-field radiation patterns of the antenna in a full anechoic chamber. The fabricated prototype is used as emitter and a wideband (2-18 GHz) dual polarized horn antenna is used as the receiver to measure the radiated power level of the emitter. The measured far-field radiation pattern in the E-plane (plane containing E and k vectors) is presented in Fig. 2b for 10.6 GHz. A directive main beam and low parasitic secondary lobes, under -15 dB are observed. The main lobe presents 13 degrees half-power beamwidth in E-plane. This narrow beam width is found to be less than that of a parabolic reflector antenna having similar dimensions (diameter equal to 15 cm), where the half power beam width is around 16 degrees.



(a) (b)

Fig. 2: (a) Measured near-field cartography. (b) Measured far-field radiation pattern in E-plane at 10.6 G Hz for the proposed device compared to that of the microstrip patch radiator alone.

4. Conclusion

We have designed and measured a device able to transform an isotropic radiation into a directive one by using the coordinate transformation concept and metamaterials. Field intensity mappings and direct far field measurements have been performed to experimentally demonstrate the ultra-directive emission, making the proposed device competitive with conventional parabolic reflector ones.

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