New trends in antenna design: transformation optics approach

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Abstract. Transformation optics is an emerging field offering a powerful and unprecedented ability to manipulate and control electromagnetic waves. Using this tool, we demonstrate the design of novel antenna concepts by tailoring their radiation properties. The wave manipulation is enabled through the use of engineered dispersive composite metamaterials that realize a space coordinate transformation. Numerical simulations together with experimental measurements are performed in order to validate the coordinate transformation concept. Near-field cartography and far-field pattern measurements performed on fabricated prototypes agree qualitatively with Finite Element Method (FEM) simulations. It is shown that a particular radiation pattern can be tailored at ease into a desired one by modifying the electromagnetic properties of the space around the radiating element. This idea opens the way to novel antenna design techniques for various application domains such as aeronautical and transport fields.

1. Introduction
Transformation optics or transformation electromagnetics (also called coordinate transformation) is a powerful mathematical tool that is used to generate a new transformed space from an initial one where solutions of Maxwell’s equations are known by manipulating electromagnetic waves. As a first step, it consists in imagining a virtual space with desired topological properties, which will contain the underlying physics. This approach has been revived when J. B. Pendry et al. [1] have proposed an interpretation where permeability and permittivity tensors components can be viewed as a material in the original space. It is as if the new material mimicks the defined topological space. Since this pioneering work of J. B. Pendry and that of U. Leonhardt et al. [2], transformation optics is an emerging field where Maxwell’s equations are form invariant under a coordinate transformation. It offers an unconventional strategy to the design of novel class metamaterial devices. The most striking application conceived so far via coordinate transformation concept is the invisibility cloak [3]. Concerning antenna applications, focusing lens antennas [4-6] and the engineering of radiation patterns [7] have been proposed. The performances of an omnidirectional retroreflector [8] and Luneberg lenses [9] have also been experimentally demonstrated. An octave-bandwidth horn antenna has been experimentally validated for satellite communications [10]. Recently, techniques of source transformation [11-13] have offered new opportunities for the design of active devices with source distribution included in the transformed space.

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Using this last approach, we review the design of three antennas where the radiation pattern is tailored specifically in each case. The first one concerns an ultra-directive antenna obtained by stretching a source into an extended coherent radiator [14-16], which is implemented through the use of judiciously engineered metamaterials and the device is shown experimentally to produce an ultra-directive emission. The idea has been extended to a second device, a wave bending one [17], so as to achieve a steered beam antenna via a rotational coordinate transformation. Experimental measurements have shown a beam steering as much as 66°. Finally, we present the numerical design of a quasi-isotropic antenna achieved by expanding the space around a directive source [18].

2. Ultra-directive antenna

The ultra-directive antenna is based on the transformation of a cylindrical space into a rectangular one. The schematic principle of the transformation is presented in figure 1(a). The theoretical underlying physics of the transformation involved here has been detailed recently in [14]. 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 \( \{ r, \theta \} \) into a flat space in squeezed Cartesian coordinates. \( x', y' \) and \( z' \) are the coordinates in the virtual transformed rectangular space and \( x, y, z \) are those in the initial real cylindrical space. We assume free space in the cylinder, with isotropic permeability and permittivity tensors \( \varepsilon_0 \) and \( \mu_0 \). In [15], we have shown that the coordinate transformation can be implemented by a material described with \( \varepsilon = 0.15 \text{ m} \) and \( L = 0.05 \text{ m} \) by \( \mu_{xx} = 1, \mu_{yy} = \frac{1}{(\varepsilon_{zz})^2}, \) and \( \varepsilon_{zz} = 4(\varepsilon_{xx})^2 \).

![Figure 1](image)

**Figure 1.** (a) Transformation of a cylindrical space into a rectangular one. (b) Photography of the antenna. The inserts show the permittivity (left) and the permeability (right) layers of the material. (c) Measured E-plane radiation patterns of the source (red) and metamaterial antenna (blue).

Discrete values are then created for the desired variation of \( \mu_{yy} \) and \( \varepsilon_{zz} \) to secure a practical realization producing experimental performances close to theory. Figure 1(b) shows the photography of the fabricated prototype. A microstrip square patch antenna is used as radiating source. A surrounding material made of alternating electric metamaterial and magnetic metamaterial layers is used to capture the emanating omnidirectional radiation from the patch source and transform it into a directive one. The metamaterial is a discrete structure composed of five different regions where permittivity and permeability vary according to the above equation.

The axial permittivity \( \varepsilon_{zz} \) and permeability \( \mu_{yy} \) 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 and 28 others contain ELCs [15]. Each layer is made of 5 regions of metamaterials corresponding to the discretized values. Far-field patterns measurements are performed in an anechoic chamber, where the metamaterial-based antenna is used as emitter and a wideband [2 GHz – 18 GHz] is used as receiver. The E-plane
radiation pattern is measured at 10.6 GHz. Figure 1(c) presents the comparison between simulations and experiments for the patch source alone and the metamaterial antenna. The transformation of the patch’s omnidirectional radiation into a directive is clearly established. A narrow half-power beamwidth of 13° is observed for the measured antenna.

3. Steered beam antenna

We consider a source radiating in a rectangular space. Theoretically this radiation emitted from the latter source can be transformed into an azimuthal one using transformation optics. The transformation procedure is noted \( F(x',y') \) and consists in bending the emission. Figure 2(a) shows the operating principle of this rotational coordinate transformation. The coordinate transformation is implemented by a material defined by

\[
\varepsilon_{rr} = \left( \frac{1}{br} \right)^2, \quad \varepsilon_{\theta\theta} = 2.8 \quad \text{and} \quad \mu_{zz} = 1.7.
\]

![Figure 2](image.png)

**Figure 2.** (a) Schematic principle of the 2D rotational coordinate transformation. The emission in a rectangular space is transformed into an azimuthal one. (b) Photography of the antenna. (c) Simulated and measured E-plane radiation patterns of the source (red) and metamaterial antenna (blue).

To validate experimentally the azimuthal directive emission, the device shown in figure 2(b) is fabricated. A microstrip square patch antenna is used as radiating source. The metamaterial is a discrete structure composed of 10 different regions where permittivity and permeability vary. The bulk metamaterial is assembled using 30 layers of dielectric boards on which subwavelength resonant structures are printed. The layers are mounted 1 by 1 in a molded matrix with a constant angle of 3° between each. A commercially available liquid resin is used as host and is closely linked to \( \varepsilon_{\theta\theta} \). Its measured permittivity is close to 2.8. From the radiation patterns in figure 2(c), we can clearly observe the transformation of the omni-directional far-field radiation of the patch antenna into a directive one which is further bent at an angle of 66°.

4. Isotropic antenna

In this section, coordinate transformation is applied to transform directive emissions into isotropic ones. An intuitive schematic principle to illustrate the proposed method is presented in figure 3(a). Let us consider a source radiating in a circular space and a circular region bounded by the blue circle around this source limits the radiation zone. The “space stretching” coordinate transformation consists in stretching exponentially the central zone of this delimited circular region represented by the red circle. The material parameters required for this transformation are: \( \mu_{rr} = 1 \), \( \mu_{\theta\theta} = \left( \frac{r'}{qr(r' - \alpha)} \right)^2 \) and

\[
\varepsilon_{zz} = \left( \frac{r}{r'} \right)^2.
\]
Figure 3. (a) Schematic principle of the space stretching coordinate transformation. (b) Simulated E-plane radiation patterns of the source (blue) and metamaterial antenna (red).

Numerical simulations show that a quasi-perfect isotropic emission can be effectively achieved when a high value is used for the expansion factor $q$.

5. Conclusion
To summarize, we have shown how coordinate transformation can be applied to manipulate and control electromagnetic waves at will in order to tailor desired radiation patterns in the antenna fields. Experimental measurements performed on the directive and beam steerable antennas have shown concluding results, making these devices compatible for aeronautical and transport domains.

References
[1] Pendry J B, Schurig D and Smith D R 2006 Science 312 1780
[2] Leonhardt U 2006 Science 312 1777
[3] Schurig D, Mock J J, Justice B J, Cummer S A, Pendry J B, Starr A F and Smith D R 2006 Science 314 977
[4] Jiang W X, Cui T J, Ma H F, Yang X M and Cheng Q 2008 Appl. Phys. Lett. 93 221906
[5] Mei Z L, Bai J, Niu T M and Cui T J 2010 PIER M 13 261
[6] Jiang Z H, Gregory M D and Werner D H 2011 Phys. Rev. B 84 165111
[7] Garcia-meca C, Martinez A and Leonhardt U 2011 Opt. Express 19 23743
[8] Ma Y G, Ong C K, Tyc T and Leonhardt U 2009 Nat. Mater. 8 639
[9] Kundtz N and Smith D R 2010 Nat. Mater. 9 129
[10] Lier E, Werner D H, Scarborough C P, Wu Q and Bossard J A 2011 Nat. Mater. 10 216
[11] Luo Y, Zhang J, Ran L, Chen H and Kong J A 2008 PIERs Online 4 795
[12] Allen J, Kundtz N, Roberts D A, Cummer S A and Smith D R 2009 Appl. Phys. Lett. 94 194101
[13] Popa B I, Allen J and Cummer S A 2009 Appl. Phys. Lett. 94 244102
[14] Tichit P H, Burokur S N and de Lustrac A 2009 J. Appl. Phys. 105 104912
[15] Tichit P H, Burokur S N, Germain D and de Lustrac A 2011 Phys. Rev. B 83 155108
[16] Tichit P H, Burokur S N, Germain D and de Lustrac A 2011 Elec. Lett. 47 580
[17] Wu X, Tichit P H, Burokur S N, Kirouane S, Sellier A and de Lustrac A 2012 Microwave Opt. Technol. Lett. 54 2536
[18] Tichit P H, Burokur S N and de Lustrac A 2011 Opt. Express 19 20551