From Active Metamaterials to Transformation Electromagnetics: AMULET from the academic's perspective

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Introduction

Metamaterials have captured the imagination of scientists and engineers, as well as the general public, with the promise of the practical realisation of devices that are seemingly out of science fiction. The ability to control the properties of a material by altering its geometrical structure is an old idea, but due to the convergence of a number of factors, this has led to a recent paradigm shift in the approach to the solution of electromagnetic problems, as well as to device design. These approaches have led to realisations of invisibility (1; 2) and illusion cloaks, optical black holes, improved lenses, and a host of other devices (3; 4; 5; 6; 7; 8).

Transformation electromagnetics is a recently developed methodology that allows the construction of a range of electromagnetic structures (1; 2; 9; 10; 11; 12). The basic idea is that a mathematical transformation of space can be represented by a change in the material properties. To create an invisibility cloak for example, the space around an object is transformed into a point, and so it appears infinitesimally small to any incoming electromagnetic waves. The drawback is that the resulting materials may have unnatural or hard to find properties (anisotropic, magnetic, or with $\varepsilon,\mu<1$). As is the case with antennas, fundamental limitations will restrict their properties such that they are narrow-banded and lossy (13; 14). We will demonstrate tools for realising many of these structures using commonly found materials (particularly isotropic dielectrics). We will also discuss our work into the next step in the evolution of metamaterials: active metamaterials (15).

Transformation Electromagnetics

The strengths of transformation electromagnetics as a tool for device design was demonstrated in 2006, specifically with the task of developing an invisibility cloaking scheme (1; 2; 9). The principle drawbacks of these cloaks were that they were composed of a range of spatially dispersive, anisotropic materials, for which extreme properties were necessary ($\varepsilon,\mu<1$). The reason for this is that, in order to maintain the phase profile of the incident wave, a faster-than-light phase propagation velocity is necessary. This means that the material properties must be artificially created using metamaterial techniques (i.e. via geometrical structuring). Furthermore, it has been shown that in order to achieve these material properties, there are fundamental physical limitations which force the materials to be highly dispersive, and therefore narrow-banded and lossy (13).

In order to circumvent this issue, the ground-plane cloak was proposed (10). For this particular scheme, an object is located above a ground plane, and the cloaking structure encapsulates the object. It has been shown that the anisotropy factor in this case is very small, and there are relatively few areas requiring extreme-valued material properties. Therefore, if anisotropy and extreme values were to be ignored, the cloaking performance would still be good. Furthermore, if cloaking is limited to only one polarisation, the cloak would be made entirely of isotropic dielectrics; materials which are found in abundance in the natural world. The resultant cloak is virtually dispersionless, and therefore extremely broadbanded.

At QMUL, the finite-difference time-domain technique has been improved and extended to enable the electromagnetic modelling of anisotropic, dispersive metamaterials (16; 17; 18; 19). The FDTD technique is now capable of modelling invisibility cloaks and other transformation-based media, for which the material properties are spatially dispersive, exhibit extreme values, and are anisotropic (even including off-diagonal components). This has enabled the modelling of a large range of novel devices, ranging from invisibility cloaks (11; 20) to extraordinary transmission devices (5) and flat lenses (6). Of particular interest is the technique detailed by Kallos *et al.* (11) in which the spatial domain is discretised; it was shown that relatively few dielectric blocks could be used to create a quasicloak, in which significantly decreased structural complexity (and therefore fabrication difficulty) is achieved at the expense of a small loss in performance of the cloak.

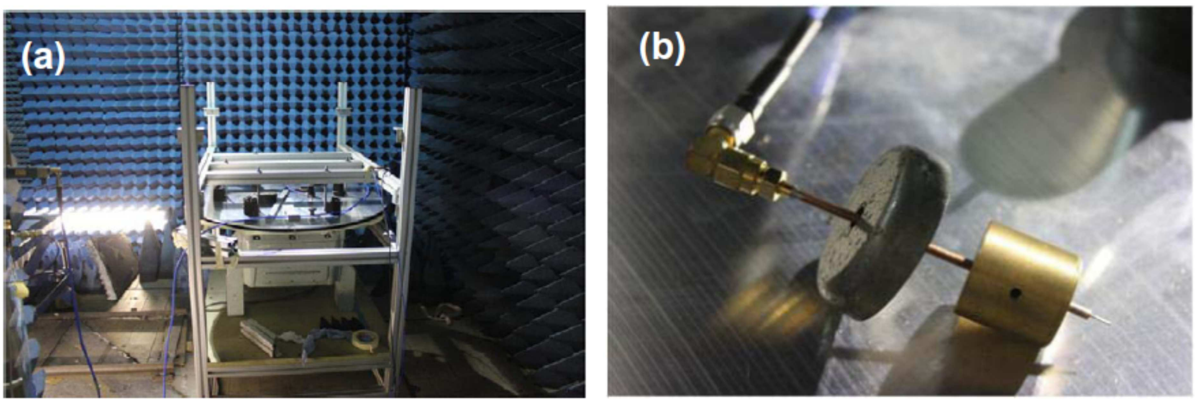

Figure 1 - The cloaking measurement system. (a) Near-field scanning system in anechoic chamber. The incident wave is launched from an X-band horn waveguide. (b) Monopole for probing the electric field.

Structures such as the invisibility cloak have been tested and measured using these techniques (20). The cloaking materials were made of Barium Titanate-loaded Polyurethane foam, which results in a controllable low-κ dielectric material. The material properties were measured at low frequencies (1 MHz) using an Agilent 4294A Impedance Analyser with an Agilent 16453 Parallel-Plate Dielectric Test Fixture. The materials were then characterised at microwave frequencies using an X-band waveguide. On producing the required range of dielectrics, the invisibility cloak was made of blocks of the different dielectrics. These were arranged in a near-field scanning system developed at QMUL (see Figure 1). This allowed measurement of the fields in 2-dimensional space in the vicinity of the cloaking structure. Measurement results showed that the cloaking material significantly reduced the scattering caused by a metallic perturbation, restoring the field profile to that of the incident wave. Furthermore, the cloak was shown to be operational over a large frequency band, covering the entire X-band over which the system was testable.

Active Metamaterials

Eventually, it would be of significant interest to be able to incorporate active elements in metamaterials. It has been shown that causality restricts the bandwidth of passive, extreme-valued metamaterials, making them unacceptably lossy (13). However, the incorporation of active elements into metamaterials can overcome these issues to some extent, at the expense of stability (14). Negative impedance converters (NICs) have been proposed as a method of increasing the bandwidth and adding gain to metamaterials (21; 22).

Transistor-based NICs were proposed in the 1950's by Linville (23), as a method for providing signal boosts in analogue telephony relay stations. They experienced widespread use worldwide, until the advent of digital communications. The NICs work by reversing the sign of the current (voltage) while keeping the voltage (current) the same. They later were used for the broadband matching of electrically small antennas, but have recently been proposed as a method of modulating the properties of metamaterials (21; 22). Performance of NICs has historically been limited to operation at low frequencies, but with improved transistor performance, it is possible to fabricate NICs that are operable at UHF, and even up to GHz frequencies.

A chief drawback of active metamaterials, as mentioned previously, is the possibility of instability. Careful consideration must be taken in the design of the effective medium, otherwise instability will make the device inoperable. In (15) we provided a full analysis of the stability of an active magnetic medium, accounting for all mutual coupling and periodicity effects, in both finite and infinite media. It was shown that, although there are limitations imposed by stability considerations, the bandwidth of an active medium can be significantly improved to far beyond that of a passive counterpart.

In this presentation, we will demonstrate some of the important results in metamaterials research that we have achieved, ranging from transformation electromagnetics to active metamaterials. We will demonstrate both simulation and measurement of electromagnetic invisibility cloaks, as well as the performance of a variety of other transformation electromagnetics structures. Finally, we will cover the state-of-the-art in active metamaterial research, focusing on NIC-loaded media.

Bibliography

1. *Optical conformal mapping.* **Leonhardt, U.** 2006, Science, Vol. 312, pp. 1777-1780.

2. *Controlling electromagnetic fields.* **Pendry, JB, Schurig, D and Smith, DR.** 2006, Science, Vol. 312, pp. 1780-1782.

3. *Cloaking devices, electromagnetic wormholes, and transformation optics.* **Greenleaf, A., et al., et al.** 1, 2009, Siam Review, Vol. 51, pp. 3-33.

4. *Design and experimental realization of a broadband transformation media field rotator at microwave frequencies.* **Chen, H., et al., et al.** 18, 2009, Physical Review Letters, Vol. 102, p. 183903.

5. *Experimental demonstration of broadband transmission through subwavelength aperture.* **Bao, D., et al., et al.** 13, 2010, Applied Physics Letters, Vol. 97, p. 134105.

6. *Discrete coordinate transformation for designing all-dielectric flat antennas.* **Tang, W., et al., et al.** 12, 2010, IEEE Transactions on Antennas and Propagation, Vol. 58, pp. 3795-3804.

7. *Experimental verification of a broadband planar focusing antenna based on transformation optics.* **Mei, Z., Bai, J. and Cui, T.** 2011, New Journal of Physics, Vol. 13, p. 063028.

8. *A spacetime cloak, or a history editor.* **McCall, M. W., et al., et al.** 2, 2011, Journal of Optics, Vol. 13, p. 024003.

9. *Metamaterial electromagnetic cloak at microwave frequencies.* **Schurig, D., et al., et al.** 5801, 2006, Science, Vol. 314, p. 977.

10. *Hiding under the carpet: a new strategy for cloaking.* **Li, J. and Pendry, J. B.** 20, 2008, Physical Review Letters, Vol. 101, p. 203901.

11. *Ground-plane quasicloaking for free space.* **Kallos, E., Argyropoulos, C. and Hao, Y.** 6, 2009, Physical Review A, Vol. 79, p. 63825.

12. *Broadband ground-plane cloak.* **Liu, R., et al., et al.** 5912, 2009, Science, Vol. 323, p. 366.

13. *Criterion for Negative Refraction with Low Optical Losses from a Fundamental Principle of Causality.* **Stockman, M. I.** 177404, 2007, Physical Review Letters, Vol. 98.

14. *Causality and Electromagnetic Properties of Active Media.* **Nistad, B. and Skaar, J.** 036603, 2008, Physical Review E, Vol. 78.

15. *Stability of Active Magnetoinductive Metamaterials.* **Rajab, K. Z., et al., et al.** 054904, 2010, Journal of Applied Physics, Vol. 108.

16. **Hao, Yang and Mittra, Raj.** *FDTD modeling of metamaterials: Theory and applications.* Boston, MA Artech House, 200 .

1 . *Accurate modelling of left-handed metamaterials using a finite-difference time-domain method with spatial averaging at the boundaries.* **Zhao, Y., Belov, P. and Hao, Y.** 200 , ournal of Optics A Pure   Applied Optics, ol. 9, pp. 46 -4 5.

1 . *Full-wave finite-difference time-domain simulation of electromagnetic cloaking structures.* **Zhao, Y., Argyropoulos, C. and Hao, Y.** 9, 200 , Optics Express, ol. 16, pp. 6 1 -6 30.

19. *A radially-dispersive finite-difference time-domain method for the evaluation of electromagnetic cloaks.* **Argyropoulos, C., Zhao, Y. and Hao, Y.** 5, 2009, IEEE Transaction on Antennas and Propagation, ol. 5 .

20. *All-dielectric invisibility cloaks made of BaTiO3-loaded polyurethane foam.* **Bao, D., et al., et al.** 103023, 2011, New ournal of Physics, ol. 13.

21. *Meta-materials with wideband negative permittivity and permeability.* **Tretyakov, S. A.** 3, Nov. 2001, Microwave and Optical Technology Letters, ol. 31, pp. 163-165.

22. *Veselago materials: What is possible and impossible about the dispersion of the constitutive parameters.* **Tretyakov, S. A. and Maslovski, S. I.** 1, February 200 , IEEE Antennas and Propagation Magazine, ol. 49, pp. 3 -43.

23. *Transistor negative-impedance converters.* **Linvill, J. G.** 6, une 1953, Proceedings of the I E, ol. 41, pp. 25- 29.