ADVANCED **M**ATERIALS FOR **U**BIQUITOUS **L**EADING-EDGE **E**LECTROMAGNETIC **T**ECHNOLOGIES (AMULET)
WHAT METAMATERIALS CAN DO FOR YOU

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Introduction

Metamaterials have been the subject of much academic research for the last decade. These artificially made materials show properties that are not found (or difficult to find) in natural materials, such as dielectric constants with negative or extremely large values. The use of the special properties of metamaterials is often constrained by narrowband, lossy or unstable behaviour which ultimately is related to electromagnetism fundamental limits.

The work developed under AMULET programme [1] has focussed on using metamaterial concepts applied to practical devices with realistic specifications and performance goals, avoiding the usual metamaterial limitations. A number of prototypes, for a variety of practical applications, have been developed and tested during this programme exploiting the specific properties of different types of metamaterials and artificial dielectrics. The performance of the metamaterial devices has been compared against real specifications and commercial devices to evaluate their true value to improve the current state of the art. This paper gives an overview of the different applications and solutions considered under AMULET.

Biased Ferrite Loaded Metamaterial as antennas for Airborne GPS

Some metamaterial structures, like the Sievenpiper mushroom [2], are able to emulate a perfect magnetic conductor (PMC) over a narrow band. These structures achieve this behaviour by using capacitive elements with a concentrated electric field connected to largely inductive ones where there is only magnetic field. Loading the inductive/magnetic part of these structures with biased ferrites creates a new material with new non-reciprocal properties. One of the most interesting features of the structure is that the metamaterial resonance splits into two modes, one for left handed circularly polarised waves and another one for right handed CP.

Based on this kind of metamaterial structure, we have designed at CTS a small cavity antenna loaded with ferrite, which is mounted on a ground plane. This antenna is fed from a single point, but it radiates CP as a result of the CP ferrite cavity mode. The antenna is non reciprocal and it receives RHCP and transmits LHCP from the same port (or the other way around if the bias DC H field is reversed). In fact, this antenna behaves like a circulator in free space (Figure 1).

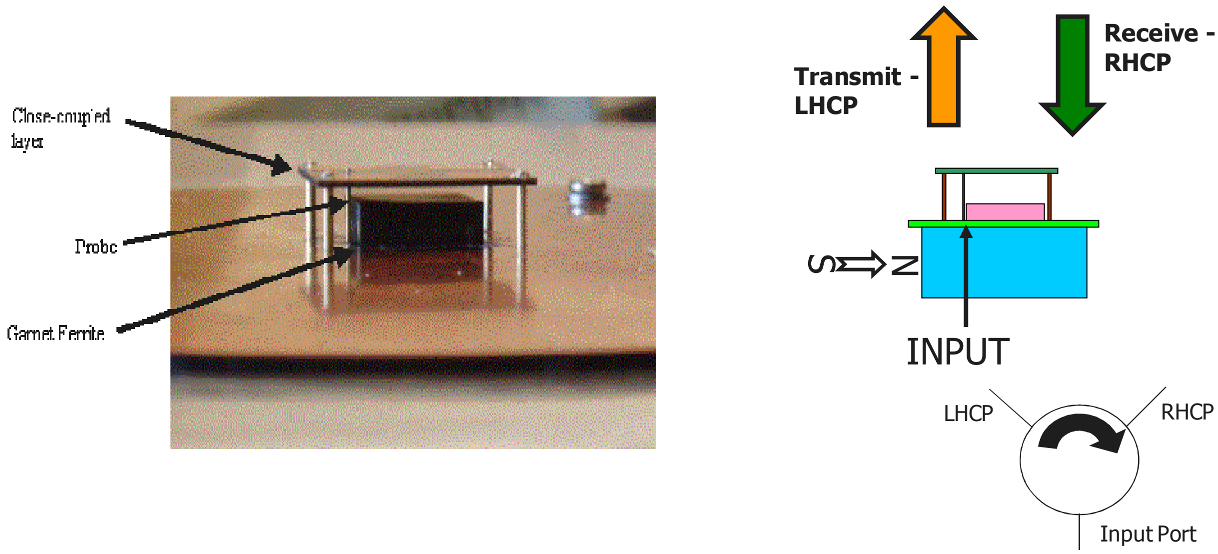


Figure 1: Non reciprocal Ferrite loaded metamaterial antenna concept

GPS antennas for airborne applications have to comply with special requirements in terms of pattern symmetry and axial ratio. This is required to obtain superior accuracy based on using as many visible GPS satellites as possible, including low elevation ones. As a result, airborne GPS antennas require more complicated and lossy feeding networks to ensure the pattern coverage symmetry and good axial ratio at low elevation as specified by RTCA DO-131 rules. In addition, Airborne GPS antennas are required in many cases to have a small footprint, but still cope with extended bandwidths to work with the new GPS codes (i.e. 24MHz for Mcode).

The ferrite metamaterial antenna is able to comply with the RTCA templates (Figure 2) with excellent gain and efficiency (80% measured) without using any feeding network, just the ferrite polarised by a permanent magnet. In addition, the permeability of the biased ferrite is larger than one which allows larger bandwidths beyond the physical limits associated with purely metal and dielectrically loaded antennas on ground planes [3]. The measured bandwidth for a 1” antenna is able to cope with the full 24MHz at L1 (1525MHz).

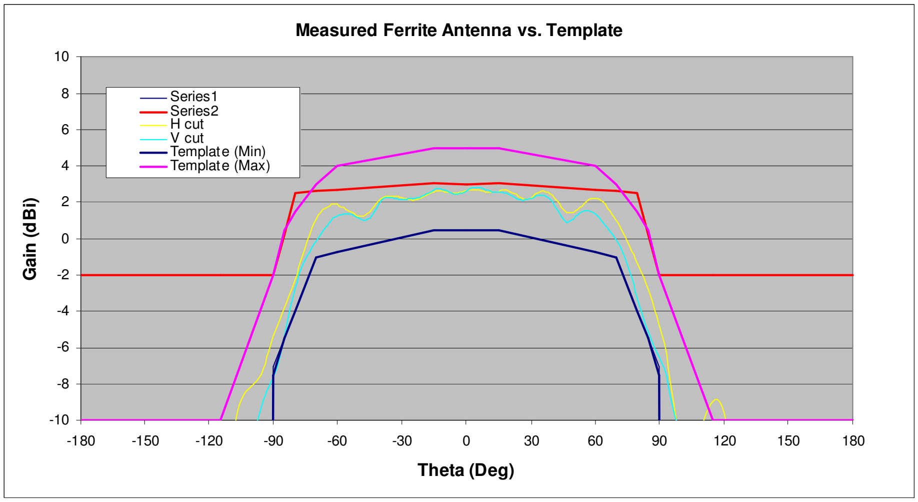
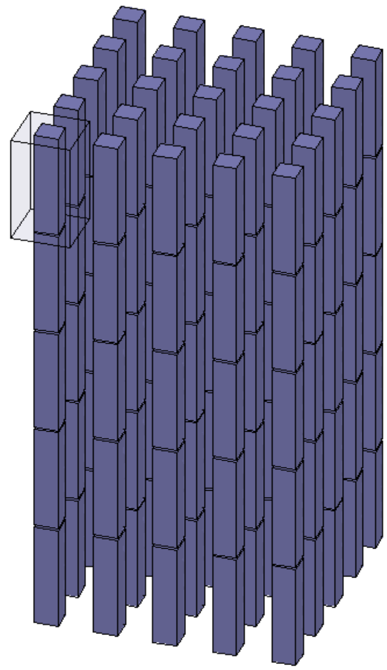


Figure 2: Measured pattern of the Ferrite antenna at L1 GPS frequency compared to RTCA template for airborne GPS

Low loss large DK artificial materials for miniature patch antennas

Many general applications require small radiators, which are typically patch antennas printed on a high DK substrate to reduce its size. These high DK materials are nowadays readily available at low prices. However, these materials are also notorious for relatively high loss and DK variation with temperature, besides high specific gravity.

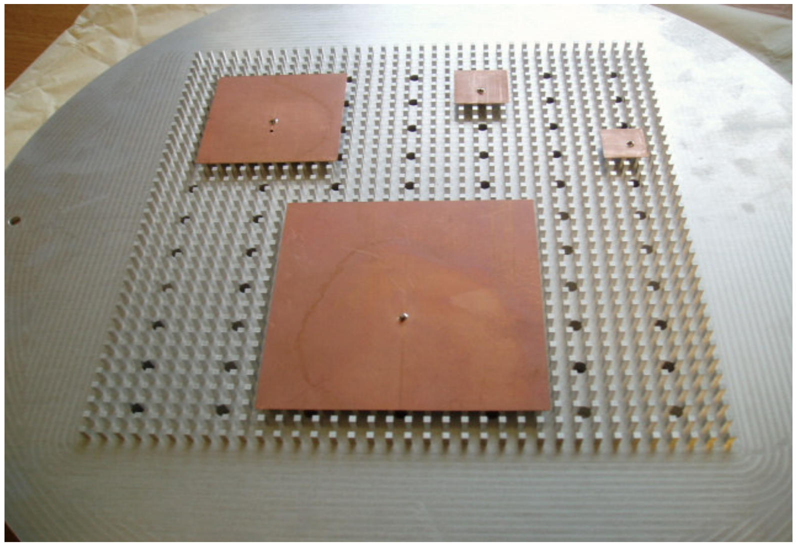
The close coupled dipole artificial material behaves like a dielectric material when the wavelength is much larger than the lattice size of the structure. The effective dielectric constant depends largely on the dielectric material which is placed in between the metal dipoles and the gap between them. If the gap is small enough, it is possible to obtain very large effective DK. However, unlike natural dielectric, the loss tangent of the artificial material remains largely constant and equal to the loss tangent of the dielectric filling the gaps. If the artificial dielectric is realised with a low loss tangent thin substrate (i.e. PTFE based) separating the metal posts, it is possible to achieve large DK keeping the low loss of the thin substrate.



$$\varepsilon_z^{eq} \approx \varepsilon_0\left(1+\varepsilon_r^{gap}\ \frac{L_z}{t_z}\frac{D_x D_y}{L_x L_y}+2\,\frac{D_x+D_y}{\pi L_x L_y}\left(L_z\left(\ln\left(\frac{L_z}{t_z}\right)-1\right)+t_z\right)\right)$$

Figure 3: Close coupled dipole artificial dielectric and effective dielectric constant (zdir) as a function of the geometry

Several patch antennas have been realised using metal posts and thin substrates to demonstrate the feasibility at L and S band. Their return loss, efficiency and patterns have been measured showing similar performance to patch antennas made using high DK substrates but with lower losses corresponding with an effective loss tangent around 0.002. In addition, the specific gravity of the artificial DK substrate is only a fraction of the natural material, making it suitable for applications (UAV) where weight saving is quite important.



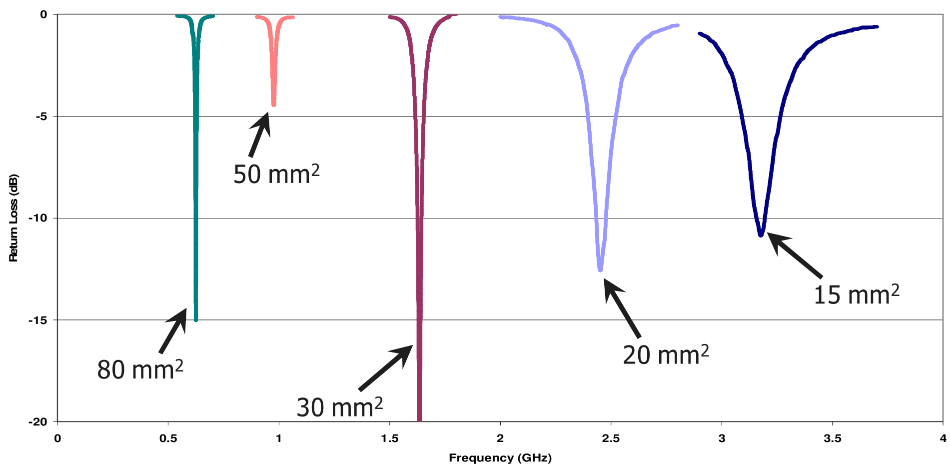


Figure 4: Set of patch antennas on artificial dielectric media (DK≈12) and measured return loss. The measured efficiency was around 80% which corresponded to an effective loss tangent of 0.002.

Metamaterial 20/30GHz Orthogonal CP screen polariser for Ka band Satcom

The design of high gain flat antennas that operate at the satcom Ka band is most challenging due to the large separation of the Rx and Tx band and the implementation of CP in both bands. The antenna design problem can be largely simplified if the antenna only needs to radiate a single LP. Then, using an external screen it is possible to generate CP at both Rx and Tx bands (20GHz and 30GHz).

This screen could not be realized by a conventional polariser (i.e. meander line polariser) because it requires generating opposite polarisation hands (Figure 5) at Rx and Tx (i.e. RHCP at 20GHz and LHCP at 30GHz). Metamaterials concepts provide a solution to this problem as they exhibit a frequency dependent dielectric constant which can be positive (or negative) below a certain resonant frequency and negative (or positive) above this frequency. The Ka band polariser can be implemented as a slab of metamaterial which has the resonant frequency in between the Rx and Tx bands (25GHz), but it has alternate positive and negative dielectric constant for orthogonal LP polarisations.

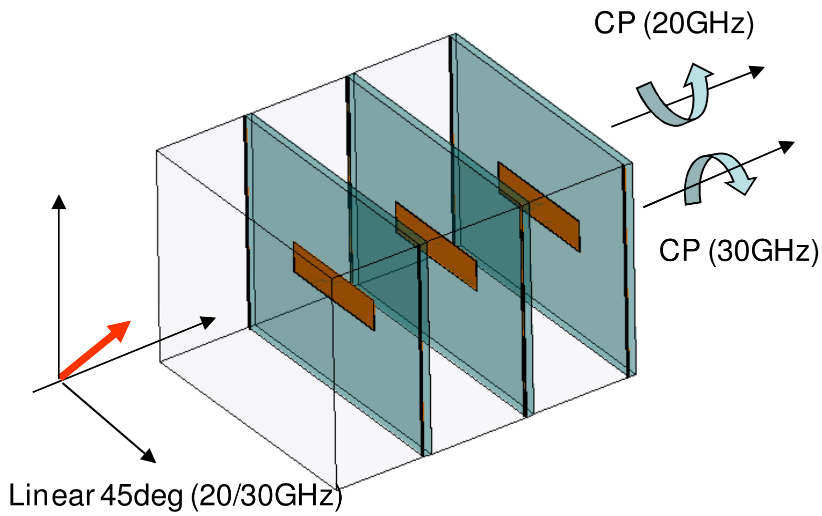


Figure 5: Polariser concept for 20/30GHz Ka band Satcom applications

The polariser has been realised and tested providing excellent performance according to a realistic satcom specification (1dB AR Tx 1.5dB AR Rx) combined with a LP flat plate aperture operating at Ka band, introducing insertion losses around 0.3dB at 30GHz. The polariser concept is currently under patent application status.

Negative Immittance Converter (NIC) for broadband of electrically small VHF Antennas

Active metamaterials have been proposed as broadband implementation of negative dielectric and magnetic constants. These violate Foster's theorem and cannot be implemented in isolation as stable materials as they store 'negative' EM energy. However, these materials can be realised when surrounded by normal materials, so the overall energy stored is positive.

The way that these metamaterials are implemented is based on using active circuit NICs that can emulate negative capacitances and inductances connected to basic elements resulting in overall positive electrical parameters to ensure stability.

This kind of concept can be applied for the broadband matching of electrically small antennas. The negative material can be combined with the normal positive one (i.e. air) to reduce the overall reactive energy in a certain region. An electrically small antenna has a small radiation resistance and a large capacitive reactance, which results in a large Q. The simplest implementation possible is when a NIC emulating a negative capacitance or inductance is connected to an electrically small monopole or loop. In the case of a short monopole, the large capacitance can be cancelled out over a large bandwidth by a negative capacitance.

In practice, there are low frequency applications where an electrically small antenna is used. VHF communications (typ. 20-200MHz) for airborne applications require the antenna to be relatively small for aerodynamic reasons since a resonant monopole at 20MHz will be around 3.75m high. Typically, commercial airborne antennas are blade monopoles around 300mm height with reduced gain (typically -50dBi at 20MHz) due to resistive matching of the input impedance. Using negative capacitors based on NIC circuits, it is possible to reduce the Q of the antenna as a 'material' that absorbs the reactive power.

Negative capacitors operating in the 20-200MHz have been developed and connected to a 225mm blade antenna. The gain has been compared with a commercial airborne 300mm antenna showing typical gain improvements between 5-10dB over the low band (20-80MHz) where the blade is electrically small (Figure 6). This gain improvement is not produced as a result of amplification, but of improvement in the antenna match through a reduced Q.

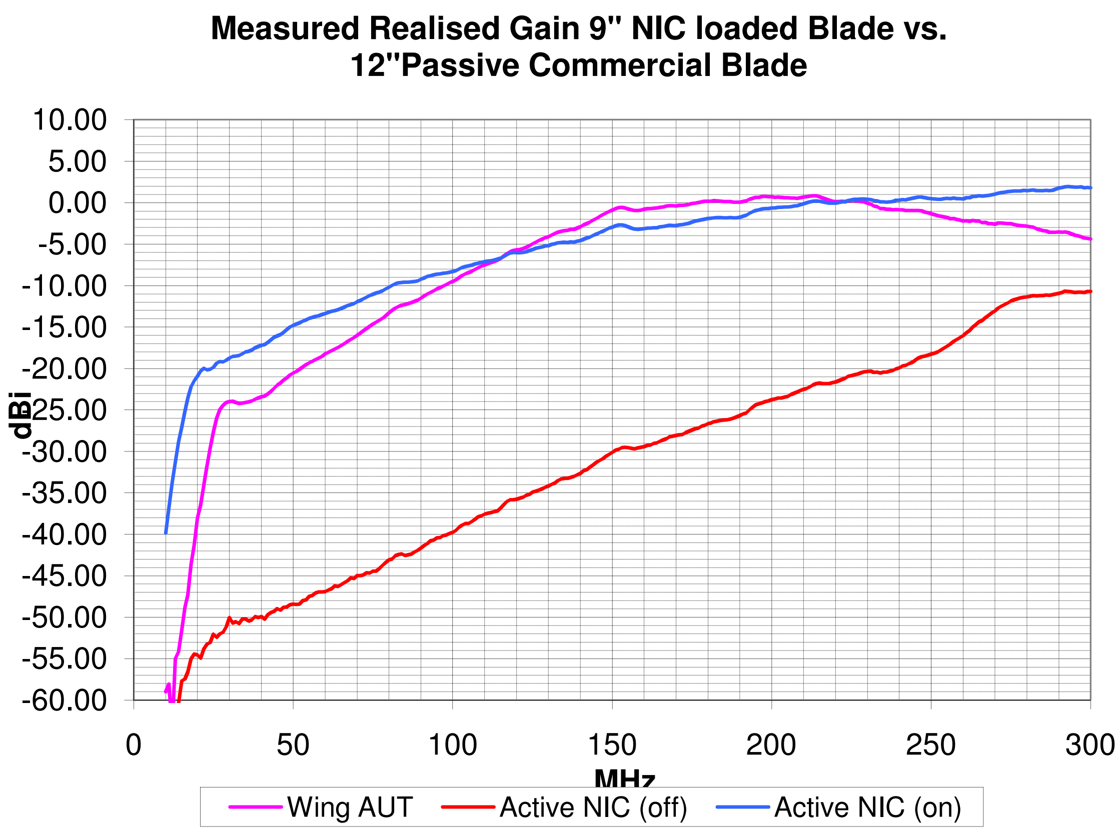


Figure 6: Measured Gain of a 9" Blade antenna loaded with NIC negative capacitor and a commercial 12" blade commercial passive antenna

Radiating Surface Flat Plates for Satcom applications

Flat plate high gain antennas for satcom applications are highly sought after, because of their compactness and good sidelobe control, which is a major requirement to avoid interference with nearby satellites. However, dish antenna solutions are typically preferred, because of losses introduced by beamforming networks (BFN) resulting in poor G/T and the high cost, size and weight of low loss waveguide BFN solutions.

Conventional array solutions, based on printed technology, are able to reduce the cost and weight, but the attenuation of typical microstrip lines makes them impractical for satcom applications in the X, Ku or Ka band. The use of periodic multilayer periodic surfaces is an alternative where low loss printed BFN can be combined with simplified construction for low cost. The periodic surfaces are intended to operate like a FSS (Frequency Selective Surface) with EBG (Electromagnetic Band Gap) properties rather than an array. The whole surface radiates at the same time, not just individual elements, otherwise it will not work since it will excite cavity modes instead of radiating. The layers can be suspended one on top of another, forming open cavities for the full aperture size where cavity modes are not excited. The BFNs (one per polarisation) are based on printed transmission lines on thin substrates (typically 50microns) which are suspended in between the radiating layers using low DK dielectrics. As a result of this construction, the BFN loss is as low as 1.2dB/m at X band and below 1.8dB/m at Ku band.

A number of flat plates have been made at X and Ku band following this technology. As an example, a 430x430mm square antenna at X band shows a G/T of 8dB/K at 7.5GHz (0.8dB NF LNA) and a measured gain of 30.5dBi at 7.9GHz (71% total efficiency) which allows it to compete with the performance of a similar size reflector for real satcom applications, but with a superior sidelobe envelope (Figure 7). These antennas in different sizes are currently commercialised by CTS as standard products.

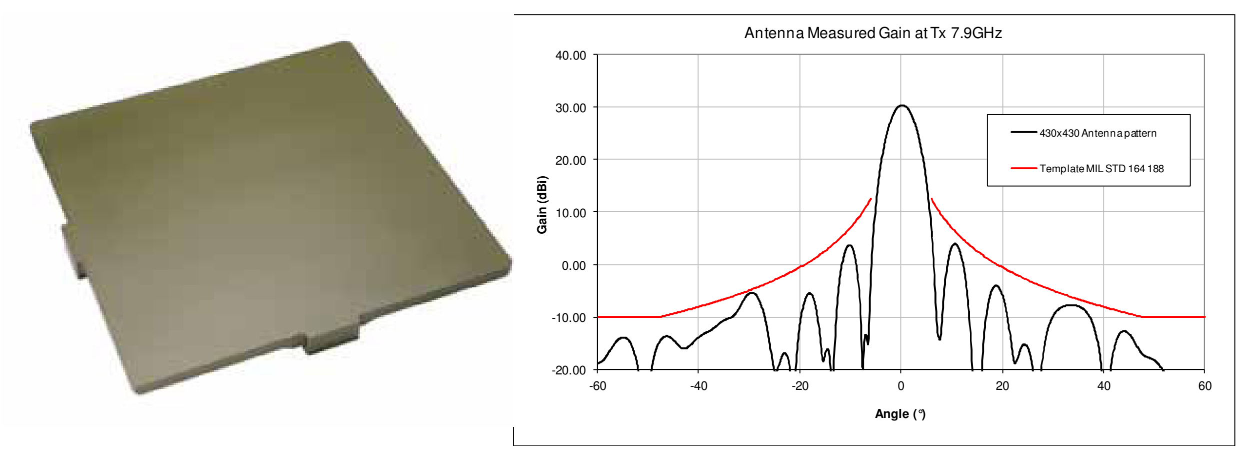


Figure 7: X band Flat plate array using multilayer radiating surfaces (left) and measured pattern against interference standard templates

Acknowledgements

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References

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