

Prototyping Dual-band Artificial Magnetic Conductors With Laser Micromachining

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Abstract:

In this paper we describe a laser micromachining process for prototyping dual-band artificial magnetic conductors (AMCs) with narrow slots in the order of 2mil ($\sim 50\mu\text{m}$) or even narrower. Because these narrow slots cannot be correctly fabricated using standard milling machine, we explore laser micromachining. Although these AMCs can be made inexpensively using mass production processes, prototyping them is difficult. Considering that the period of the dual-band AMC surface is much smaller than the wavelength, we explored the use of a waveguide to measure the reflection coefficient of fabricated prototypes.

Introduction

In recent years, there has been a growing interest in investigating compact electromagnetic bandgap (EBG) structures to address the needs of various communication devices that are gradually being miniaturized. In one branch of EBG research, Artificial Magnetic Conductors (AMC) [1]-[8] play an important role to reduce the sizes of microwave devices, such as low profile antennas, quasi-TEM waveguides, etc. An AMC surface should reflect incident plane waves just like a perfect electric conductor (PEC) but without altering the phase of the wave. Hence it should have an electric-field reflection coefficient of +1 whereas the electric-field reflection coefficient of PEC is -1.

The feature sizes of our compact artificial microstructures are on a scale much less than the wavelength of radiation. Even at microwave frequencies, their lattice constants are only several millimetres. During our recent research on compact dual-band AMC surfaces [8], we demonstrated that, to achieve very compact unit cell size in the periodic structure, the pattern needs slots in the order of $50\mu\text{m}$. Such narrow slots cannot be fabricated using the conventional low cost prototyping methods such as milling machines. Hence we explored alternative prototyping techniques, including laser micromachining. This paper outlines our designs [8], describes the prototype fabrication and testing, and presents theoretical and measurement results.

Design of the dual-band planar compact AMC

We have designed planar surfaces that behave as artificial magnetic conductors over two microwave frequency bands [8]. Such a surface consists of a periodic metal pattern on one surface of a dielectric substrate and a ground plane on the other surface. We found that, to achieve striking performance, the periodic metal pattern need to have slots in the order of 2mil ($\sim 50\mu\text{m}$) width.

Figure 1(b) shows the metal patch in the unit cell of one dual-band AMC surface we investigated. This dual-band AMC design has been achieved by introducing two additional orthogonal gaps to AMC unit cell of [3] shown in Figure 1(a). With this modification, we achieved a lower AMC band at about one third of the original AMC frequency in [3] as well as a higher AMC band which is close to the original AMC band in [3]. This dual-band AMC surface achieved a much lower AMC frequency with a narrow bandwidth and a high AMC frequency with a wide bandwidth at the same time. The unit cell in Figure 1(b) is repeated in two dimensions on a microwave substrate to form the AMC surface. The inductive metal regions and capacitive gaps (L_b , L_{p1} and C_s) in the pattern are also indicated in the same figure. The low-band AMC resonance current mainly passes through L_b ; the high-band AMC resonance current mainly passes through L_{p1} and C_s .

During the design process we found that, in order to make an AMC surface with a lattice constant of about 3.048mm to operate at frequencies below 6GHz, the gap width (shown as “a” in Figure 1) has to be as small as 0.051mm (2mil). The dimensions of a dual-band surface designed to operate around 6GHz and 15GHz are given in Table 1.

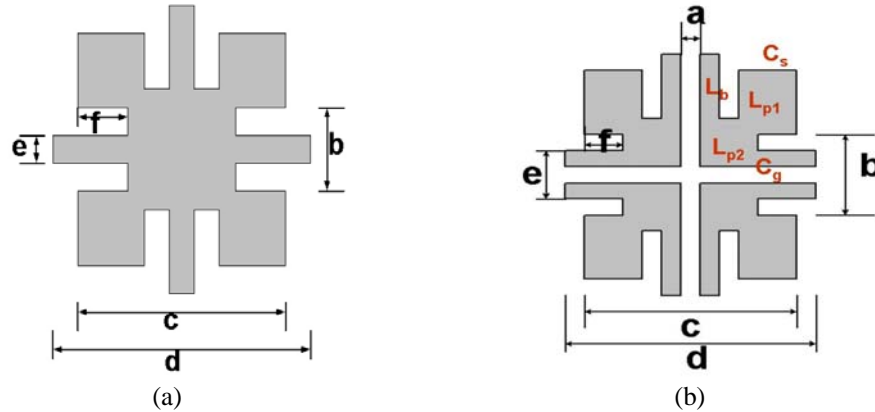


Figure 1: (a) Unit cell of AMC surface in [3]. (b) Unit cell of a dual-band planar compact AMC.

Table 1. Parameters of dual-band planar compact AMC

parameter	a	b	c	d	e	f	h	ϵ_r
Value	0.051mm	1.016mm	2.997mm	3.048mm	0.508mm	0.699mm	0.635mm	10.2

Note: h is height of substrate as shown in Figure 3(c). ϵ_r is relative permittivity of substrate.

Prototyping the dual-band compact AMC surface

Two prototypes of the dual-band AMC design given in Table 1 have been fabricated using laser micromachining process developed by Macquarie University. For both prototypes, we used Rogers RT6010 microwave laminates, which are made out of a ceramic-PTFE composite suitable for microwave and millimetre-wave applications. The thickness of the substrate is 25 mil (0.635mm) and the thickness of the copper layer is $17\mu m$. One surface is 9×20 unit cells and the second one is 36×36 unit cells on $5in \times 5in$ substrate.

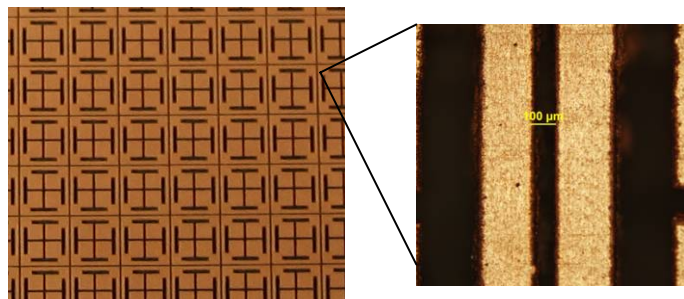


Figure 2. Left: a section of the prototype array based on the unit cell in figure 1. Right: close view of a laser machined feature in the array with $100\mu m$ width and good edge quality.

The laser micromachining was performed using a Copper Vapour Laser operating at 511 nm and 578 nm and 6 kHz pulse rate. The beam was delivered onto the AMC substrate using a 5x objective lens and translation of the substrate was performed by computer controlled stages from Aerotech. A typical spot size of $25\mu m$ (1mil) is achieved with this system making fabrication of the required $50\mu m$ feature sizes quite straight forward. Appropriate powers and translation feed-rates were established to selectively remove the metal layer and not cut excessively into the ceramic layer or indeed through the entire substrate. The required design is programmed directly into the translation stages, or can be taken from a dxf file from a CAD program, allowing for flexibility of design. A spot overlap of 50% was used to ensure full removal of the copper layer and achieve good edge quality (Figure 2.) This meant that when the laser was removing metal, it also removed a part of the dielectric under the metal. We estimated that this substrate cut depth is 200-400 μm depending on the power and feed-rate used. This effect was then included in the theoretical model and the theoretical reflection coefficient was recalculated using HFSS. In this analysis we noticed that the operating

frequencies of the AMC surface are sensitive to the cut depth into the substrate. A cut in this substrate can increase the first operating (AMC) frequency from 6 GHz to 7.7 GHz, as shown in the theoretical curves in Figure 4.

Testing the dual-band compact AMC surface

Generally AMC surfaces are tested in chambers using transmitting and receiving antennas. Considering that the period of the dual-band AMC surface is much smaller than the wavelength, we explored the use of a waveguide to measure the reflection coefficient.

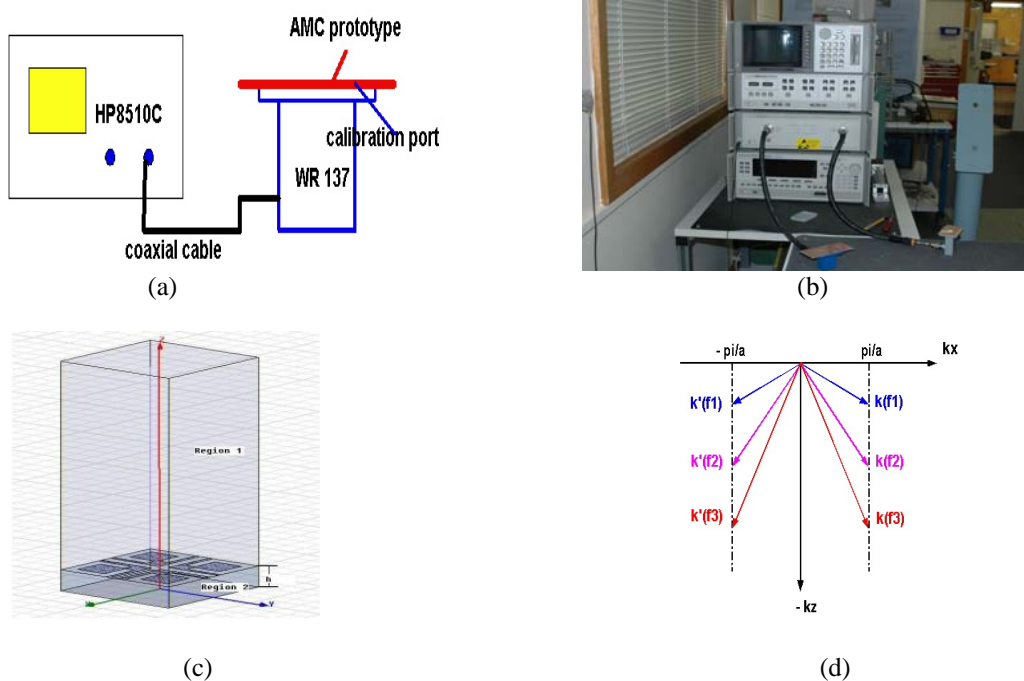


Figure 3. (a) Measurement setup for testing the dual-band compact AMC surface. AMC prototype is put on the exact position of calibration port. (b) Measurement setup in CSIRO. Both port 1 and port 2 are independently calibrated for measuring of 20x9 and 30x15 prototypes respectively. (c) HFSS Simulation model of unit cell with periodic boundary conditions on the four side walls. (d)

The incident TEM plane waves used for HFSS simulation model. Their wave vectors satisfy $k_x = \frac{\pi}{a}$, $k_y = 0$ and $k = 2\pi f / c_0$

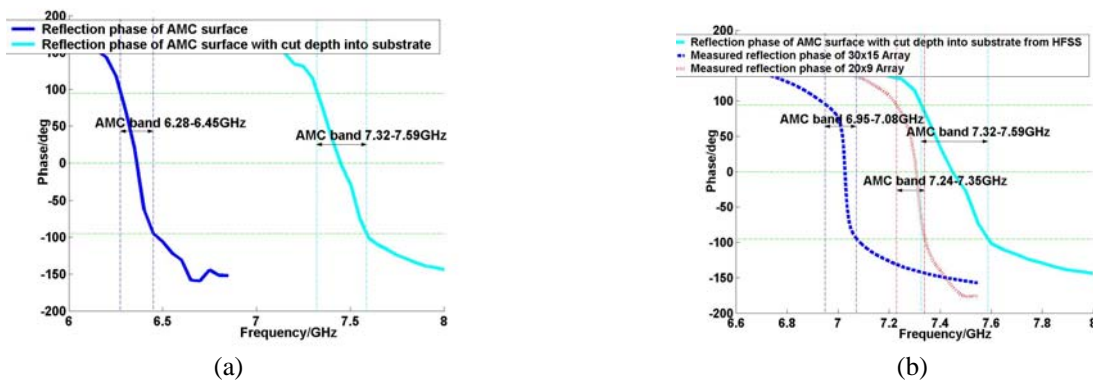


Figure 4. (a) HFSS simulation results with and without cut depth into substrate. (b) Comparison of HFSS simulation result with cut depth into substrate and measured results for 30x15 array and 20x9 array.

Take WR-137 for example, its length along x is 35mm and its width along y is 15.8mm, which means 11 x 5 unit cells can be included into its cross section. Based on transmission line theory, a waveguide terminated by an AMC surface will have electric-field reflection coefficient is equal to 1. The propagating TE_{10} mode in the rectangular waveguide is considered as a superposition of TEM plane waves as shown in Figure 3(d). At each frequency, the angle of incident

plane wave has been calculated and the reflection phase has been calculated for this angle of incidence using Ansoft HFSS commercial software package as shown in Figure 3(c), considering RT6010 substrate in Region 2 and air in Region 1. The simulation results are shown in Figure 4(a) and (b) as compared to measurement results.

The phase of the wave reflection coefficient was measured in CSIRO to test the compact surface. The measurement setup is shown in Figures 3(a) and (b). At first the measured port was calibrated by WR137 waveguide calibration kit from Continental Microwave & Tool Co. Inc. Then the measured port was terminated by the prototype as shown in Figure 3(a). The other end of the waveguide was connected to a HP 8510C vector network analyser through a waveguide-to-coaxial transition, and the phase of the scattering coefficient S_{11} was measured over a range of frequencies around the lower AMC band.

The measured reflection phase is compared with the simulation results in Figures 4(a) and (b). Figure 4(a) compares the HFSS simulation results with and without cut depth into substrate using the simulation model shown in Figure 3(c). The simulation results are sensitive to the cut depth into substrate by laser. Figure 4(b) compares the measured and simulated reflection phases. The measured result for 20x9 array agrees well with the simulation result when the cut depth is taken into account. The 30x15 prototype has reduced cut depth into the substrate and its measured result shows a 0.3GHz shift from the simulation result. Both measured AMC bandwidths (i.e. frequency range within which the reflection phase is between +90 and -90 degrees) are about 0.15GHz less than what is predicted 0.27GHz bandwidth. Due to overmoding of the waveguide, we were unable to measure the performance around the higher AMC band with this measurement set up.

Conclusions

Laser micromachining has been found to be a promising and effective technique to prototype compact dual-band AMC surfaces, which require much narrower slots in a metal pattern printed on a substrate.

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