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InkJet Printing of Resistively Loaded FSS for Microwave Absorbers

S. N. Zabri, R. Cahill, G. Conway, and A. Schuchinsky

Inkjet printing is proposed as a means to create the resistively loaded elements of a Frequency Selective Surface (FSS) which suppresses radar backscatter when placed above a metal ground plane. Spectral transmission and reflection measurements from 9 to 18 GHz show that the dot density of the printed features and the volume ratio of an aqueous vehicle and nano silver ink mixture can be selected to obtain surface resistances in the range 1.2 - 200 Ω/sq.

Introduction: Thin microwave absorbers composed of metal backed resistively loaded FSS [1]–[3] provide an attractive solution for radar cloaking where the main design drivers are weight and thickness. The equivalent network of the structure consists of a parallel connected FSS sheet impedance, which can be described by an LCR circuit, and the inductance which is presented by the ground plane spaced a distance $< \lambda/4$ apart [1]. At resonance the two reactive components of the complex impedance cancel and the absorber can be impedance matched to free space (377 Ω) by carefully selecting the resistance which is used to represent the FSS loss. Therefore unlike conventional bandstop FSS where it is desirable to employ high conductivity metal to create the resonant elements that form the periodic array [4], [5], absorbers based on this technology require selective patterning of material which exhibits a small surface resistance. For example the authors have recently reported the design of thin FSS based microwave absorbers composed of rectangular [6] and nested hexagonal loop [7] elements with surface resistances in the range 13 -175 Ω/sq. Experimental prototypes of both arrangements were constructed using commercially available graphite and carbon based shielding paint, and the required resistive loading was realised by adjusting the thickness of the ink features [6]. However the minor variations of micron thick paint layers deposited on the stencil printed substrates resulted in measured values that were 20% [6] and 30% [7] higher than the nominal design for optimum computed backscatter response. In this letter we describe an alternative manufacturing strategy which provides a low cost, simple and repeatable means to solve this problem. By employing an ink-jet printer to simultaneously pattern the FSS elements on the substrate and digitally control the dot density of a novel solution composed of an aqueous vehicle and nano silver ink mixture, we show that it is possible to obtain surface resistances that are much closer to the specified values for optimum absorber performance.

Characterisation procedure: Very accurate electrical characterisation of materials at microwave [6] and millimetre wavelengths [8] can be obtained by curve fitting computed transmission coefficients to the experimental spectral response of single and multiple layer FSS. In this study CST Microwave Studio software [9] was employed to obtain the physical dimensions of a periodic array of copper dipoles which was designed to resonate at 15.3 GHz when exposed to TE (vertically) polarised waves at normal incidence. Figure 1 shows the array arrangement and physical dimensions of the dipoles which were printed on a 0.14 mm thick coated PET substrate with permittivity 2.5 (Novele™ [10]). The surface resistance used in the numerical model was adjusted to achieve the best fit with either measured transmission or reflection response plots of inkjet printed FSS with the same dimensions, but constructed with dipoles that were formed by using different volume ratios of a solution composed of Metalon™ JS-B25P [10] nano silver ink and Metalon™ aqueous vehicle. This electrically conductive ink is a water based material with a 25 wt% Ag content that is formulated to give thin film sheet resistances as low as 60 milliohm/sq. To obtain surface resistance values up to a few hundred Ω/sq for single pass traces, 1:5, 1:7 and 1:9 (ink_{mL}: aqueous $vehicle_{mL}$) mixture compositions were prepared and used in an Epson Stylus C88+ inkjet printer which was set to operate with a single ink cartridge and digitally configured for black and white printing and best photo quality resolution. The piezoelectric head delivers ink droplets on request and achieves resolutions of 360 dots per inch in both the vertical and horizontal planes. The 180 nozzles in the monochrome head produce 3 pL ink droplets on the substrate with a maximum thickness of 0.27 mm. The artwork for the periodic arrays was generated with DipTrace software [11] and the RGB colour codes were varied between (0, 0, 0) and (30, 30, 30) to produce a range of 9 different dot densities. In the manufacturing process this setting and the silver ink mixture concentration can be adjusted to obtain precisely the surface resistance value that is required for optimum design of the FSS absorber elements. After inkjet printing, the 15×15 cm^2 dipole arrays were cured at room temperature for 24 hours to ensure complete evaporation of the solution based host material and stabilisation of the connectivity between the silver nano particles. Experimental data was acquired at normal incidence with the FSS placed 47 cm from the apertures of a pair of standard gain horns which cover the frequency range 9 – 18 GHz. For accurate electrical characterisation of materials, numerical data should be fitted to curves that exhibit well defined nulls at resonance [8]. This was achieved by using two different time gated experimental arrangements in an anechoic chamber:

(i) transmission responses of the FSS for surface resistances in the range 1.2 - 20 Ω/sq (an example is shown in Figure 2)
(ii) reflection responses of the FSS placed 4-5 mm above a metal plate were required for surface resistances in the range 20 - 200 Ω/sq

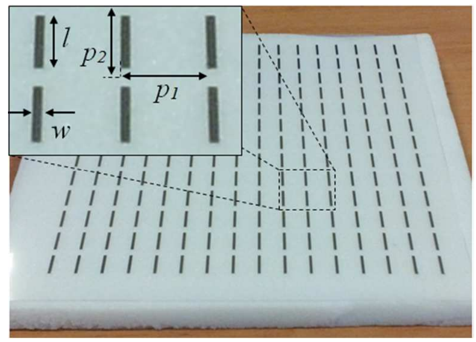

Fig. 1 *Photograph of the* 15×15 cm^2 *inkjet printed resistively loaded FSS and magnified image of six of the 208 unit cells (insert); dimensions* $l = 9$ *mm,* $w = 1.05$ *mm,* $p_1 = 9.45$ *mm and* $p_2 = 12$ *mm*

Results and discussion: Figure 2 shows the measured transmission response of an FSS printed with JS-B25P [10] nanosilver ink and maximum dot density, RGB (0,0,0). The deep null at resonance (15.3 GHz) attests to the high conductivity of the ink and the level is shown to be similar to the simulation results obtained from CST with the dipoles modelled using the bulk conductivity value of copper (5.8×10^7 S/m). Resistively loading the FSS with a conductive ink and aqueous vehicle mixture reduces the current amplitude on the surface of the dipoles and the null depth at resonance is therefore also reduced. The measured transmission coefficients were plotted over the frequency range 9 – 18 GHz for each of the 3 ink mixtures and 9 RGB colour modes that yield a null depth >5 dB at resonance. These were matched with numerical predictions that were obtained by varying the surface resistance of the dipoles in the EM simulator to obtain the best fit. Figure 2 illustrates two examples for the 1:5 (vol) ink mixture where close correlation between the results is obtained with surface resistance values of 1.8 Ω/sq and 43 Ω/sq for RGB printer settings of (13,13,13) and (30,30,30), respectively.

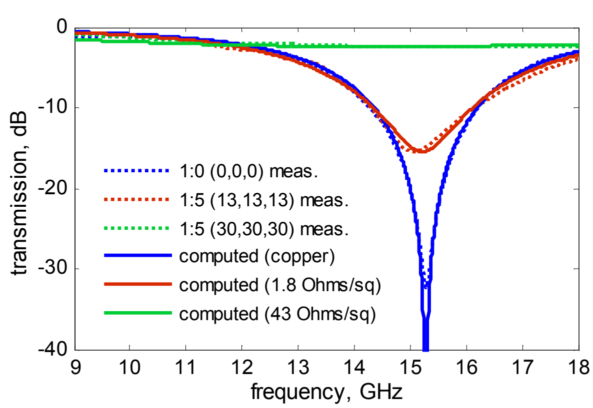

Fig. 2 *Measured spectral transmission plots of inkjet printed FSS at normal incidence and best fit simulated data.*

The null depth is <5 dB for dipoles with a surface resistance ≥ 20 Ω/sq, therefore for these structures it was necessary to perform reflection measurements in order to enhance the FSS resonance, but the same procedure was employed to retrieve the resistance data. Figure 3 shows a summary of the material characterisation results obtained from the 27 inkjet printed FSS samples that were selected for this study. Surface resistances from 1.2 to 200 Ω/sq are plotted as functions of the RGB defined dot densities for each of the 3 ink mixtures. It is observed that the surface resistance can be increased by reducing the dot density and/or the fraction of silver nano particles in the ink composition, and moreover it is possible to engineer the same resistance by choosing different combinations of these two print variables.

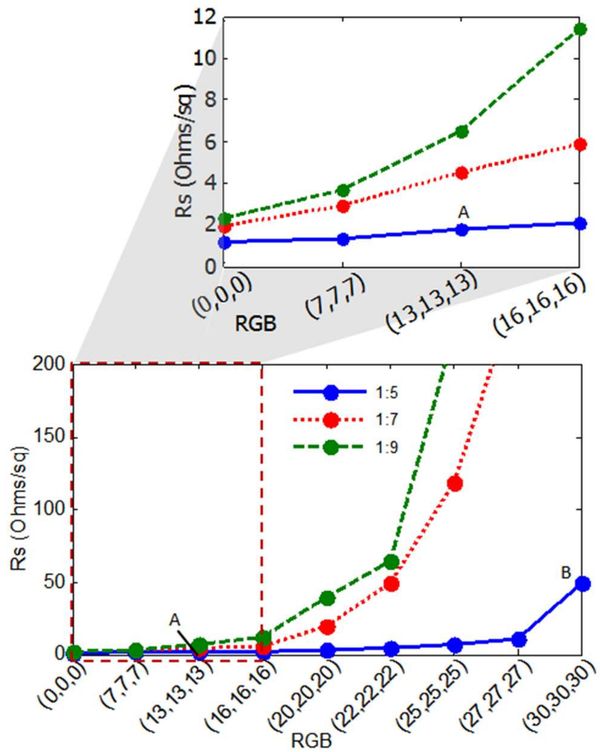

Fig. 3 *Measured relationship between surface resistance and ink mixture compositions for different RGB defined dot densities*

Microscopic images of a dipole printed with a 1:5 (vol) ink mixture and colour modes RGB (13,13,13) and RGB (30,30,30) are depicted in Figure 4. These clearly show the difference in the digitally controlled density of the silver nano inclusions which are ordered along the length of the dipole (and parallel to the incident TE wave) by the motion of the printer head. Moreover the apparent difference in the connectivity rate of the conductive particles shown in the two images is consistent with the difference in the measured surface resistance values of 1.8 Ω/sq and 43 Ω/sq, respectively.

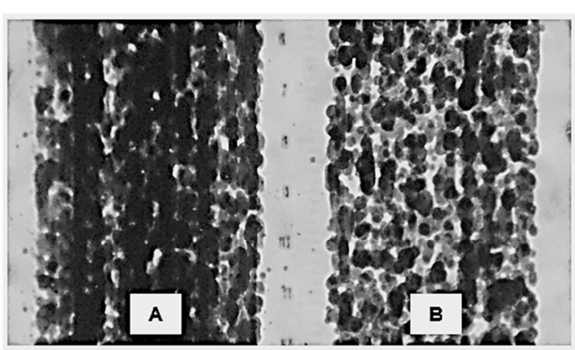

Fig. 4 *Optical microscope image of the FSS dipole surface printed with a 1:5 (vol) ink mixture* (a) *RGB (13,13,13) and (b) RGB (30,30,30)– these corresponds to Point A and Point B respectively in Fig. 3*

Conclusions: An important outcome from this work is the demonstration of a simple, rapid and low cost method for printing FSS elements with material that has a slightly lower conductivity than metals but which is suitable for creating thin microwave absorbers. Good repeatability and a means to obtain surface resistances very close to the desired values are achieved by selecting the composition of the ink mixture and digitally controlling the dot density of the patterned elements. Our results show that this method of constructing resistively loaded FSS for radar absorbers offers a better solution than previously published techniques [6], [7].

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