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Inkjet Printing of Frequency Selective Surfaces

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Abstract

As a step towards low cost manufacture of conducting arrays for Frequency Selective Surfaces an inkjet procedure is under development. The plane wave transmission response of a printed array compares well with its conventionally etched counterpart and the predictions of modelling software.

Introduction

Frequency Selective Surface (FSS) technology is well known in microwave and mm-wave aerospace systems but recent applications in UHF mobile bands have given rise to new design and fabrication requirements, including large physical size and low cost manufacture. At such long wavelengths the sizes of even electrically finite arrays can be large [1]. Current mobile and wireless systems are becoming severely capacity limited owing to interference and frequency reuse issues. A possible means to address the problem is to embed potentially large FSS panels within building structures. To be a realistic proposition, these panels must be simple to fabricate and of low cost. Frequency selective surfaces usually take the form of arrays of conductive elements either printed on some form of suitable substrate, or alternatively they are slots of suitable patterns etched into a conductor, usually copper.

In this letter we demonstrate the use of inkjet printing as a facile digital fabrication tool for the low cost manufacture of frequency selective surfaces on low cost flexible substrates. Inkjet is particularly attractive because of its ability to accurately dispense variable volumes of material per drop, 2 - 100pl, with high resolution, +/- 5μm, with feature sizes currently down to 50μm, in the absence of complimentary small feature patterning strategies. A key factor in any such process is the printing of conductive elements having the appropriate conductivity achieved under processing conditions compatible with thermally sensitive substrates.

Experimental Procedure

Materials

A silver nanoparticle conducting ink provided in ethylene glycol/ethanol was used as received (Product No. AG-IJ-G-100-S1, Cabot Corporation, Albuquerque, USA). It was characterized as having 20 wt-% silver, average particle size of 30-50 nm, and dispersion viscosity of 14.4 cPs at 25 ^{o}C and surface tension of 31 mN/m at 25 ^{o}C.

Polyethylenenapthenate (PEN) substrate (QX 65, DuPont Teijin Film) was used as received, having a surface energy of 57.1 mN/m, a contact angle with water of 65 ^{0} and a contact angle with the silver ink of 20 ^{0}.

Instrumentation

A Dimatix DMP-2800 inkjet printer (Fujifilm Dimatix, Inc., Santa Clara, USA) was used in the study using a disposable piezo "ink jet" cartridge. This printer can create and define patterns over an area of about 200 x 300 mm and handle substrates up to 25 mm thick, being adjustable in the Z direction. The nozzle plate consists of a single row of 16 nozzles of 23 μm diameter spaced 254 μm with typical drop size of 10 pL, drop diameter 27 μm. The silver ink jetted reliably and reproducibly as received at 30 ^{o}C, using a 13 V waveform. It was important however to use the primed head within 48 hours if non recoverable nozzle drop out is to be avoided.

The electrical resistance of sintered silver features was measure by the 4-point probe technique. A Jandel multi-position wafer probe system mounted with a cylindrical probe head (solid tungsten carbide needles of 0.40 mm diameter spaced 1.0 mm) was employed. Track width and thickness were determined using a Veeco Dektak 8 Stylus profilometer. Atomic Force Microscopy was used to characterize the surface of printed features using a PSIA XE 100, Parls Systems instrument, in contact mode at 1Hz and a constant contact force of 21.4nN. A soft commercial silicon cantilever was used, with a nominal spring constant of about 0.6 N/m, the back of the cantilever being coated with aluminium to increase signal feedback.

Results and Discussion

Inkjet Printing of FSS

In order to produce individual conductive silver dipoles, the individual droplets have to be printed in such a way that consecutive droplets partially overlap. The degree of overlap is a function of both the substrate and the ink, substrate surface energy, heterogeneity and roughness and the contact angle of the ink on the surface, as well as print strategy [2]. Arrays of individual silver dipoles were single pass printed using the following protocol; length = 9400 μm; width = 450 μm using a 10 μm drop spacing in both the x and y directions (Figure 1a). The width of the lines was slightly wider than expected from the print pattern arising from slight over wetting of the ink on the substrate, leading to dried elements having a uniform width of 522 μm. The lines show a characteristic 'coffee stain' profile as shown in Figures 1b and c, resulting in a line which is 2.5 μm thick at the edges and less than 0.2 μm thick in the middle. The coffee stain profile arises from contact line pining of the rapidly drying ink leading to a net flow of solute to the drying edge [3].

The silver dipoles were sintered in a convection oven at 160^{o}C for 120 minutes. Although it was not possible to measure the conductivity of an individual element without delamination occurring from the substrate, for dipoles on glass in the absence of any coffee stain profile the measured resistivity was 10 μΩ-m, approximately 15% bulk silver.

The Inkjet printed FSS.

Frequency selective surfaces designed to operate in the *microwave* region were fabricated, in order to make sensible performance comparisons with conventional arrays etched onto a copper clad polyimide substrate. The elements were simple linear dipoles approximately 9mm long, arranged on the lattice illustrated in Figure 1a. The electrical behaviour of this kind of surface is well known and has been previously reported [4].

Plots of the measured transmittivity at normal plane wave incidence as functions of frequency for the inkjet printed array, together with computer simulations (broken curve with dots) using software based on a standard Floquet Modal analysis are shown in Figure 2. The agreement between the measurements and simulations for the conventionally etched FSS and also its counterpart produced using inkjet printing is excellent. Both show high reflectivity of the surface at about 14 GHz, indicated by the clear nulls in the transmittivity, and are effectively transparent at 10GHz. The slightly different resonant frequencies for the two surfaces are a consequence of slightly different dipole lengths in the two cases.

Conclusions

As can be seen in Fig.1, there is a noticeable variability in the print quality of the inkjet printed dipole elements. Dipoles prepared by the etching of copper show regular linear edges and a characteristic top hat profile, the conductivity in each being that of bulk copper. However the inkjet printed dipoles show some edge acuity which is not linear, a heavy coffee stain profile and the conductivity is less than 10% of the copper etch control. But the concentration of the conductor towards the outer regions might be an advantage, as the induced currents tend to maximise towards the edges. The line profile does not have a significant effect on the performance of widely spaced lattices such as the one used here, but for more complicated elements where the performance is a function of the effective inductance determined by the conductor width, or capacitance determined by the spacing between conductors, any spreading of the ink would be important and the printing process may well need refinement. This can be achieved in part by reformulating the ink to negate coffee stain drying [5]. These results are particularly encouraging and point the way to a means for rapidly printing FSS on large areas of suitable substrate. In particular work is required to enable very inexpensive paper like porous substrates to be used.

Acknowledgements

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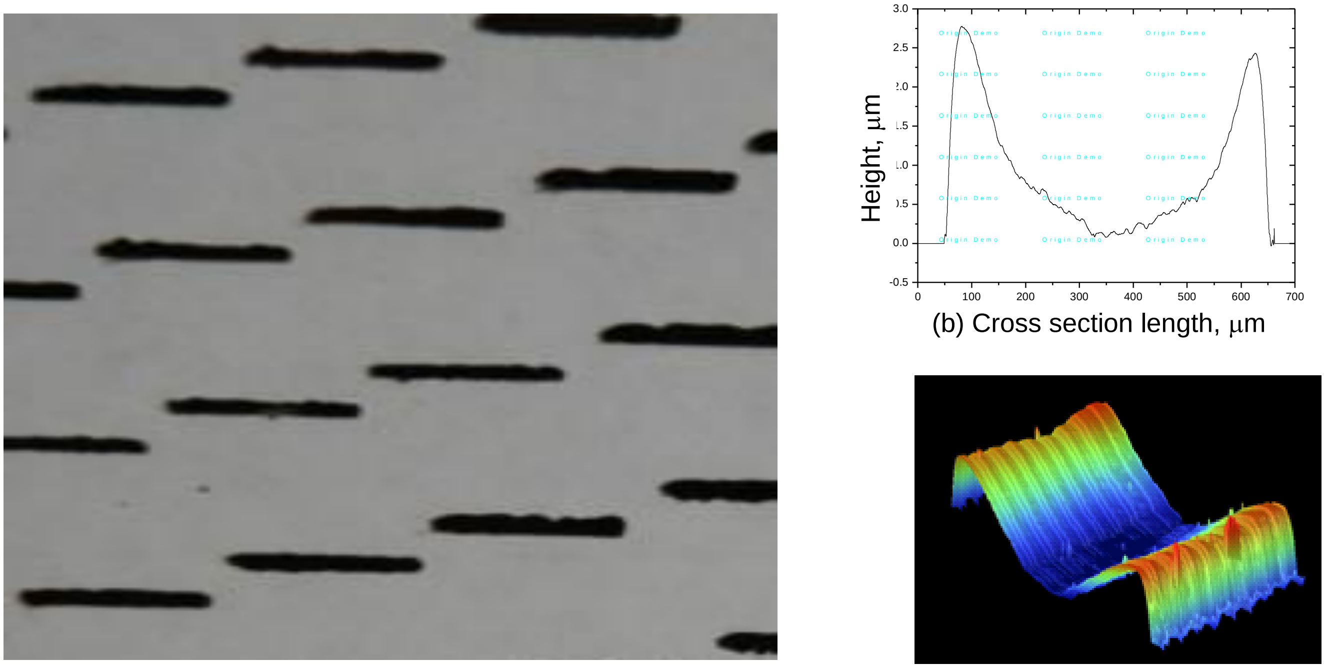
Figure 1. (a) Inkjet printed FSS using an array of simple linear silver dipoles on PEN; (b and c) silver dipole cross-section showing the ‘coffee stain’ profile.

Figure 2. Comparison of measured and simulated transmission curves for inkjet printed and etched frequency selective surfaces.

——— measured
— · · — simulated (inkjet)
– – – – simulated (etched)



(a)

(b) Cross section length, µm

(c) Cross section

Figure 1

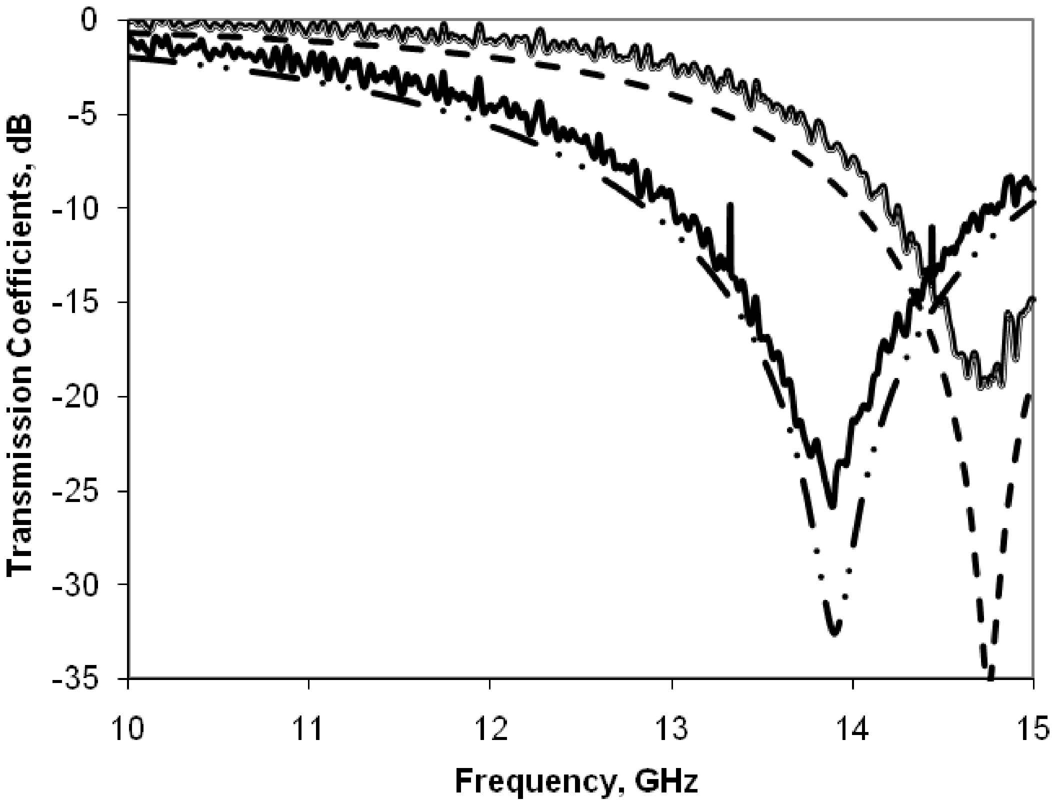

Transmission Coefficients, dB
0
-5
-10
-15
-20
-25
-30
-35
10
11
12
13
14
15
Frequency, GHz

Figure 2