Citation for published version

Turki, Badredin and Parker, Edward A. and Wünscher, Sebastian and Schubert, Ulrich and Saunders, Rachel and Sanchez-Romaguera, Veronica and Ziai, Mohamed A. and Yeates, Stephen and Batchelor, John C. (2016) Significant Factors in the Inkjet Manufacture of Frequency Selective Surfaces. IEEE Transactions on Components, Packaging and Manufacturing Technology, 6 (6). pp.

DOI

https://doi.org/10.1109/TCPMT.2016.2561972

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Document Version

Publisher pdf

Significant Factors in the Inkjet Manufacture of Frequency Selective Surfaces

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***Abstract*—Additive fabrication of electromagnetic structures by inkjet printing technology is both cost effective and compatible with a wide range environmentally-friendly substrates, enabling fabrication of frequency selective surface arrays with line dimensions less than 0.1 mm; difficult to achieve with conventional subtractive techniques. Several approaches have been investigated in order to produce low-cost frequency selective panels with acceptable level of isolation, such as savings in ink by depositing it at the edges of dipole elements where the surface current tends to maximize. The FSS transmission characteristics were improved by jetting multiple ink layers on the whole elements and at the edges. The electrical resistance of various arrays have been measured and analysed and has been used to assess the performances of the FSS.**

***Index Terms*—Frequency selective surfaces, inkjet printing, indoor radio propagation, electromagnetic architecture, security.**

I. Introduction

THE wide spread of wireless technologies in recent years, together with the era of Internet of Things particularly in the built environment, has increased concerns for information security, as well as quality of communication arising from adjacent sources of interference, as many of the wireless technology bands have become congested. Various means of improving indoor communication have been considered, such as frequency reuse by reducing the size of the wireless cells. A relatively new approach is to modify the electromagnetic structure of buildings, turning them into smart buildings. Frequency selective panels have been proposed in order to improve the signal - to - interference ratio and also mitigating the issue of user privacy [1]–[3].

Frequency selective surfaces (FSS) have other applications - such as in multiband reflectors in the form of curved or plane secondary mirrors, and as spatial filters used in side lobe suppression and beam forming[4]. Depending on the intended application, a wide variety of designs can be employed ranging from simple dipole elements to highly convoluted structures[5][6].

Submitted on 1/7/2015. This work was supported by the UK EPSRC Grant EP/J000086/1.

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Any frequency selective screen in general contains periodically repeated conducting elements in the form of patches or slots supported by dielectric substrates [7]. Patch versions act as band stop filters, rejecting electromagnetic waves at certain frequency bands, i.e. the transmission/frequency responses (S_{21}) exhibit one or more deep nulls. Classically, FSS for the microwave bands have been fabricated by the conventional copper etching process, which is a subtractive technique where unwanted metal is removed from the substrate.

Inkjet printing of FSS on a range of different substrates such as paper based, textile, glass and polyethylenenapthenate (PEN), with performances similar to the chemically etched equivalents have recently been reported [8]–[11]. Since the technology is an additive mask free printing method, where conducting tracks of metal nanoparticle based inks can be deposited on demand, it is a potentially lower-cost fabrication technique, with potentially lower material wastage, whilst being compatible with a wide range of cheap and environmentally friendly materials including paper, glass and leather[12][13]. Inkjet printing technology has also a potential advantage over chemical etching as it is capable of producing very fine pico-litre and femto-litre sized droplets, enabling the deposition of sub 0.1 mm lines which in turn can reduce the size of electronic circuits.

Minimization of the amount of ink used is desirable in reducing both cost and environmental impact; however there remains a major challenge in overcoming the greater risk of defects in the printed elements which in turn would affect the performance of the FSS. Such defects are typically elements with high electrical resistance, or with total discontinuities in the conducting path; some of those defects are described in [14]. A level of -20dB isolation (null depth) has been chosen as a benchmark; as only 1% or less of the signal passes through the FSS and 99% is reflected back [15]. As reported in [16], an improvement in the carrier-to-interference ratio of 15 dB in wireless communication can lead to a reduction in the outage probability by more than a factor of 20.

The effects of errors in the printing process such as the total absence of elements at random locations, and elements with discontinuities in the conductor, have been reported in [15][17] . It was concluded that randomly localised defects in up to 20% of the elements could be tolerated while still achieving an interference isolation level of 20 dB. However, when the defects were distributed as localised clusters of missing elements at the centre of an FSS panel, only clustering to a maximum of 10% could be tolerated [18].

The principle aim of the study described in this paper was to manufacture frequency selective panels at low-cost, using the minimum amount of deposited ink, consistent with acceptable transmission performance. Trials were made of elements in which conductors were deposited only at the dipole edges (*frame* elements), where the induced surface currents were likely to be maximum, thereby making savings in ink, and yet still achieving the benchmark isolation level of reflection of -20 dB. Furthermore, the deposition of an extra ink layer in form of a frame dipole superimposed upon a solid dipole was also investigated, and compared in terms of ink savings and isolation level with a solid dipole fabricated with the two layers of deposited ink. An element resistance study of all FSS designs is also reported here in order to quantify the relation between the level of isolation and the dc resistance.

II. Solid and Frame dipole FSS

A. Design and Fabrication

Arrays of dipole elements arranged in a skewed lattice, as shown in Fig.1 were used in this study [19]. The dipoles were of length L of 9.4 mm, periodicity P of 10.4 mm, and width $w = 0.4$ mm, with spacing 1 mm in the x-direction (D_x) and 2 mm in the y-direction (D_y). The physical size of the panel was 222 × 194 mm^2, containing 374 dipoles.

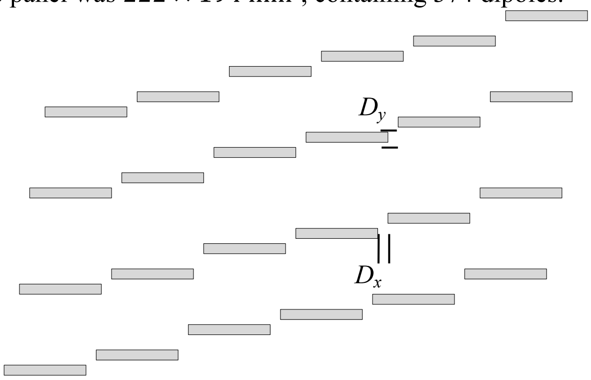


Fig.1 Skewed lattice dipole FSS

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 × 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. For the purpose of this study, the cartridge temperature was varied in order to optimize the jetting conditions. The platen was kept at room temperature.

The printer contained a 10 pl cartridge (DMC-11610) with the cartridge temperature adjusted between 30-45 °C. The silver nanoparticle ink was supplied from Sigma-Aldrich (SunTronic U5603 from Sun Chemicals). It is a 20 wt% dispersion of silver nanoparticles (particle diameter in the range of 50 nm by scanning electron microscope) in an ethanol/ethylene glycol mixture. PEL Nano-P60 paper (PEL paper), representative of the paper class having an inorganic micro-porous receiving layer, was obtained from Printed Electronics Ltd. (Cambridge, UK). In all cases the substrates were purged with a flow of air to remove dust particles prior to use. The FSS were jetted with 1, 2 and 3 layers, with the droplet dot- spacing adjusted to 15μm. Thermal sintering was carried out in a convection oven set at 150 °C for 30 minutes.

The performances of similar FSS manufactured using a conventional copper etch process were used as benchmarks in part of this comparative study. They were etched on a copper clad polyester substrate of thickness 0.045mm and metal thickness of 0.01mm with relative permittivity of $\epsilon_r \cong 3.5$ and loss tangent $\delta = 0.02$.

B. Measurement

Each FSS was placed in an aperture in a large absorbing screen. The physical size of the aperture was 230 × 230 mm^2. Two waveguide horn antennas swept over a frequency range 10-20 GHz were connected to the signal source and the receiver, and placed 1m on either side of the FSS.

The transmission responses of the inkjet printed FSS using 1, 2 and 3 layers of deposited ink are compared with the copper etched counterpart in Fig.2. The three inkjet printed FSS all had reflection resonances at 12.6 GHz with nulls deeper than the required -20 dB level, with depths of -24, -25, and -28 dB respectively.

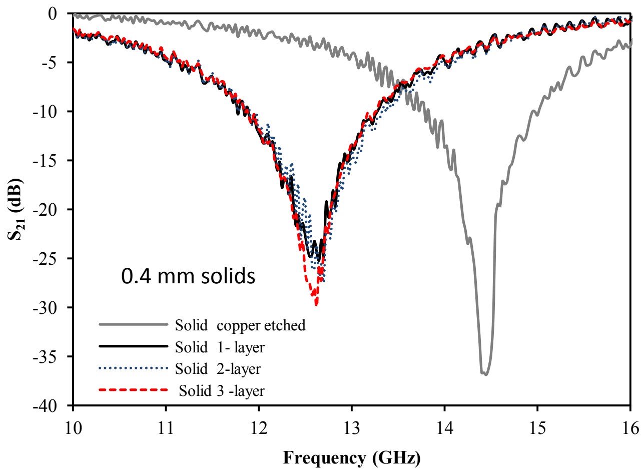
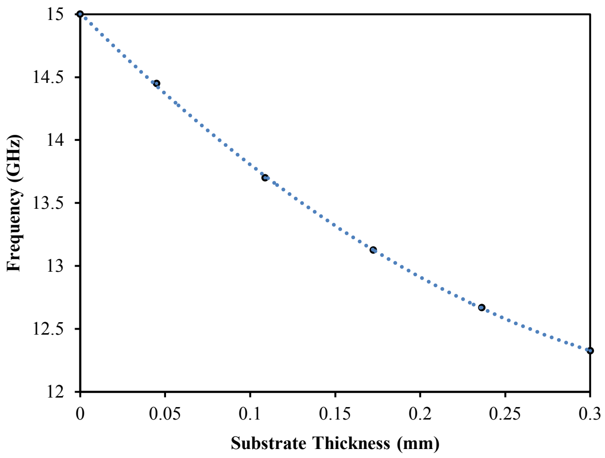


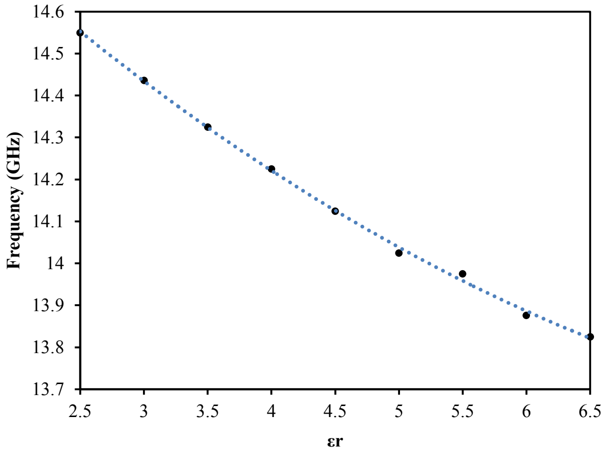
Fig.2 Transmission responses of the copper etched and 1, 2, 3 layer inkjet printed FSS panels.

The displacement in frequency of the transmission nulls between the copper etched and inkjet printed FSS was about 1.9 GHz. The effect of substrate thickness (0.045 → 0.2 mm), permittivity ϵ_r (3.5 → 4), dipole width, conductor thickness and conductor conductivity have been investigated using CST Microwave Studio™ (CST MWS™). As shown in Fig.3 (a) and (b) the substrate thickness was found to dominate the null frequency shift with a displacement corresponding to 88% of the 1.9 GHz change in null frequency, while the permittivity alone gave a 6% change. If the trends in the two diagrams are regarded as linear, the resonant frequency was found to have approximate sensitivities of 9.0 GHz/mm and 0.2 GHz for a change of 1.0 in ϵ_r respectively, for substrate height and permittivity. The other parameters combined caused only a further 6% change in the null frequency.

It is well known that the induced surface currents tend to concentrate toward the edges of strip conductors. Elsewhere it is considerably lower. Consequently, *frame* dipoles are introduced here, where conductor is deposited only at the edges as shown in Fig.4. In [20] the concept of replacing solid dipoles by edge frames was introduced but demonstrated only by chemically etched designs and a single inkjet prototype. Here, a more comprehensive study of frame dimensions and their performance in relation to ink quantity and conductor quality is presented. These elements were considered to be potentially useful in as much as they would reduce the quantity of ink required in manufacture, and hence the total overall cost.

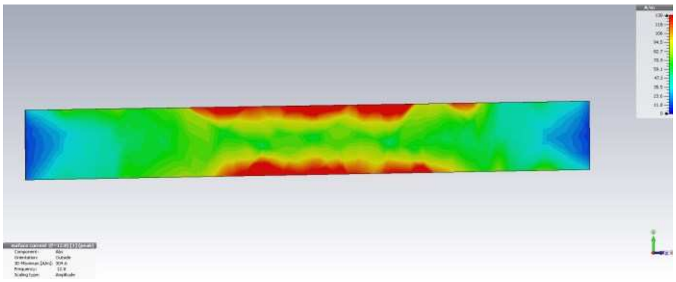


(a) Substrate thickness vs. Resonant frequency

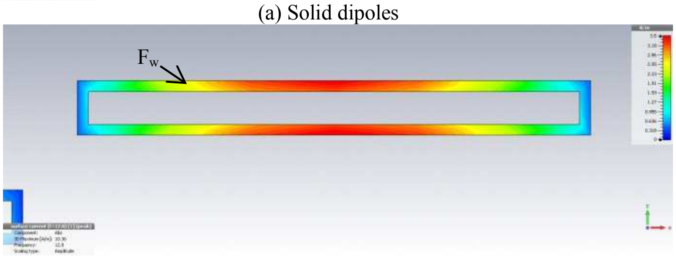


(b) Substrate Permittivity vs. Resonant frequency

Fig.3 Effect of various substrate (a) thickness and (b) permittivity on the array resonant frequency. The broken curves show the best fit trends



(a) Solid dipoles



(b) Frame dipoles

Fig.4 Surface currents induced in (a) solid and (b) frame diople elements at 12.8 GHz

They have the same design parameters (length, periodicity, width, physical size) as the corresponding solid dipoles, but with frame width (F_w) of 0.07 mm as shown in Fig.5.

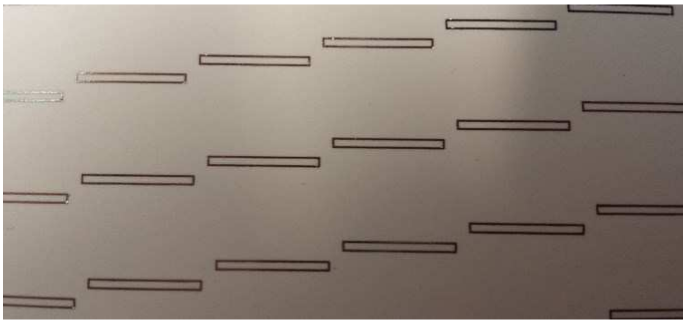


Fig.5 Inkjet printed FSS: frame dipoles

The measured transmission responses were similar to those of their solid counterpart with depth of nulls of -20, -23 and -28 dB for 1, 2 and 3 layers of the deposited ink respectively, where for comparison the equivalent for the 1 layer *solid* dipole was -24 dB, as shown in Fig.6. The depth for the 2-layer frame dipole array was about the same as that for the 1-layer solid, with still a saving in the amount of ink employed.

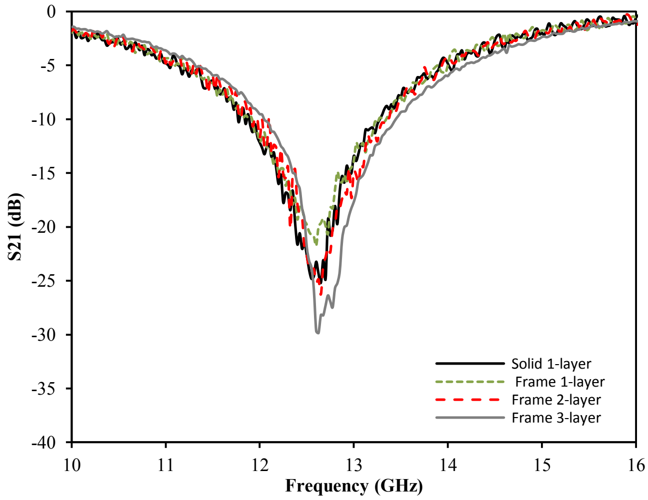


Fig.6 Measured transmission responses: inkjet printed Solid and Frame dipole FSS

In order to evaluate the performance of the frame dipoles by comparing them with their copper etched counterparts, the elements were redesigned, with the solid dipole width w = 1 mm and the frames with widths (F_W) of 0.15 and 0.2 mm. This was to meet the requirements of our copper etching facilities, where the minimum dimensions that could be etched are of about 0.1 mm [20]. Fig.7 shows the measured transmission responses of the inkjet printed FSS.

Although the null depths degraded by about 5dB compared with solid dipoles, the chemically etched frame dipole FSS provided nulls deeper than the -20 dB benchmark [20]. The single-layer *inkjet* printed 0.15mm frame arrays in Fig.7 showed a reduction of about 3 dB in the depth, compared with the 1- layer printed solid dipole FSS, whereas, for the 2- layer frames it increased by about 4dB. This improvement in the response of the FSS was obtained whilst achieving a roughly 50% saving in ink usage when comparing the printed 1-layer frame dipole FSS with the solid dipoles.

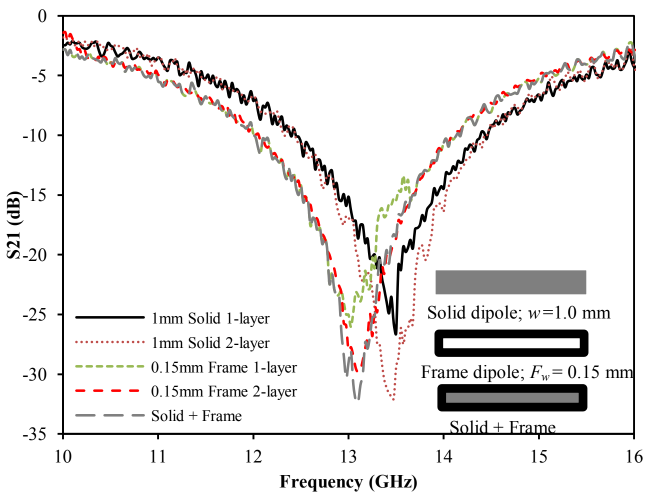


Fig.7 Measured transmission responses of the inkjet printed elements

These results are very encouraging and reflect one of the major advantages of inkjet printing as a fabrication tool. There was also a small reduction in the resonance frequency of about 3.7% in the case of the single layer 0.15 mm frame width compared with the solid dipole. This is linked to the lower quantity of conductor, which led to a slightly higher dipole resistance. An element resistance study of the inkjet printed FSS is discussed in Section IV.

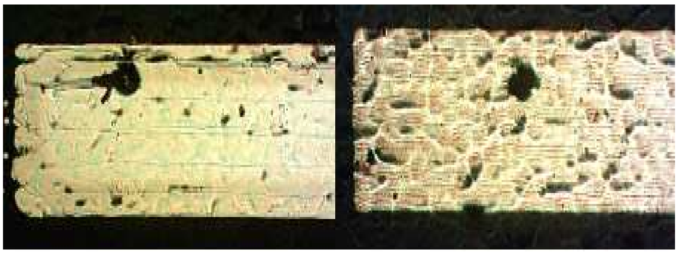
The strategy of depositing ink where the maximum current is likely to flow produces FSS with a response similar to that in the case of printing the whole element. This opens up the possibility whereby a hybrid approach combining features of a solid and frame dipole can achieve further improvements in performance. In Fig.7 transmission responses S_{21} for 1-layer solid dipole, and 1-layer frame dipole arrays are compared with depositing frames on top of pre-deposited dipoles. Adding the frame layer over the solid dipoles improved the isolation by over 5 dB compared with the 1- layer solid dipoles alone. The improvement was 7 dB compared with the 1-layer 0.15mm frame FSS. This was achieved with an approximately 25% concomitant saving in ink over the 2 layer solid dipole.

III. Printing Defects

During the printing process some imperfections in the edge definitions and also defects in the elements were observed as shown in Figs. 9 and 10. The edge of the dipole element in Fig.9 (a) has some discontinuities generated during the deposition of the first layer of the ink. These discontinuities were infilled by the addition of the second layer, resulting in more well-defined edges, as shown in Fig.9 (b).

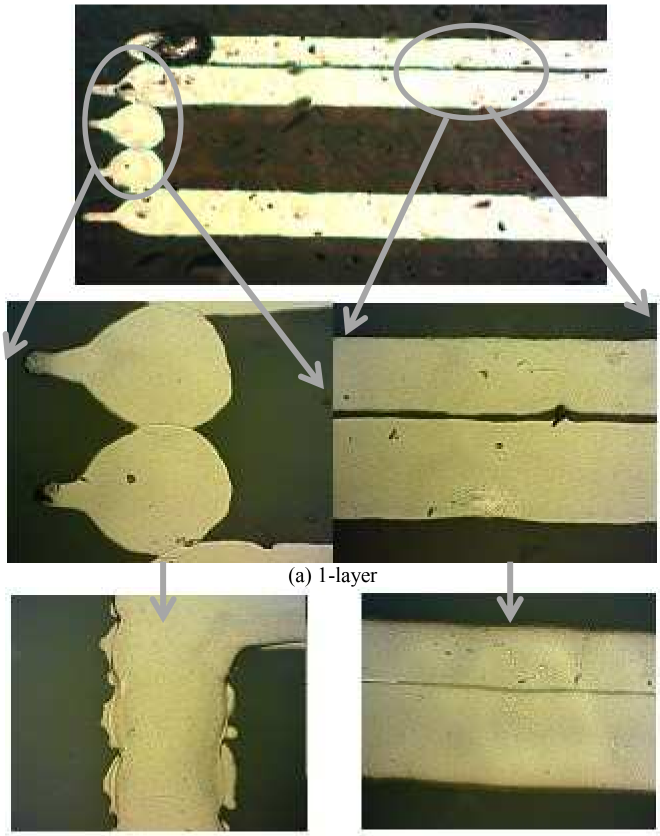
Defects such as horizontal cuts and non-linearity in the vertical edges depicted in Fig.10 (a) were observed in very few of the 0.2 mm frame dipole elements. The vertical cuts are a result of total or partial blockage of the printing nozzles, which results in two separate dipoles, influencing the FSS performance at the frequency of operation, particularly if those defects are more than 20% of the total number of elements, as reported in [15].

The non-linear outlines of the vertical edges are more apparent in the frame dipoles, as they are thinner than the solid dipoles. Such phenomena could increase the element's electrical resistance leading to reduction in the FSS reflectivity, which might lead to a transmission response level (S_{21}) less than the benchmark of -20 dB. However, this issue could also be resolved by the addition of a second ink layer as shown in Fig.9 (b).



(a) 1-layer (b) 2-layer

Fig.9 1mm inkjet printed solid dipole FSS (a) 1-layer of deposited ink (b) 2-layer of deposited ink



(a) 1-layer

(b) 2-layer

Fig.10 0.2 mm inkjet printed frame dipole FSS (a) 1- layer of deposited ink (b) 2-layer of deposited ink

Note that the inkjet printed solid FSS elements were slightly wider than the chemically etched FSS elements owing to drop spreading on the paper substrate, but with little effect on the length as summarized in Table I.

This effect is more noticeable for the frame dipole elements, as they are more sensitive to the droplet spreading effect, as the droplets would spread on both sides of the frame's arms, whereas in case of solid dipole elements it will also be proportionally less significant as they will be overlapping with the adjacent ink droplets. Similarly, additional deposited ink layers also tend to increase the element widths, as more droplets are deposited. The effect of the increase in the width was investigated using CST Microwave Studio™ (CST MWS™) and was found that it only affects the resonance frequency by about 3% (Section II B).

TABLE I
INKJET PRINTED FSS: DIFFERENCE IN WIDTH AND LENGTH COMPARED WITH THE CHEMICALLY ETCHED FSS COUNTERPARTS

Sample Width-mm	Ink Layer	Avg W (mm)	Δw %	Avg L (mm)	ΔL %
0.07 (F)	1	0.118	68.5	9.41	0.1
	2	0.121	72.8	9.43	0.3
	3	0.155	121	9.45	0.5
0.4 (S)	1	0.41	2.5	9.38	-0.2
	2	0.46	15	9.42	0.2
	3	0.53	32	9.44	0.4
1 (S)	1	1.05	5	9.41	0.1
	2	1.188	18.8	9.41	0.1
0.2 (F)	1	0.27	35	9.39	-0.1
	2	0.32	60	9.4	0
0.15 (F)	1	0.21	40	9.41	0.1
	2	0.25	66.6	9.43	0.3
1 (S) +0.15(F)	1+1	1.077	7.7	9.42	0.2

* (S) Solid dipoles, (F) Frame dipoles

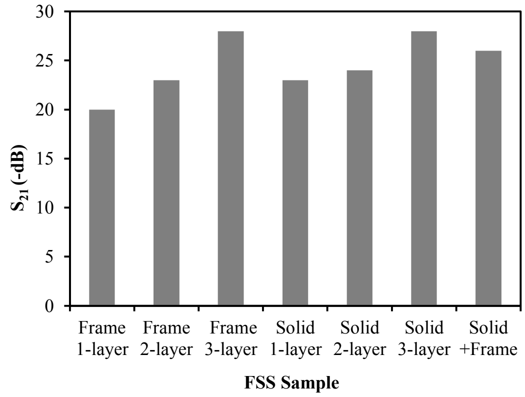
IV. RESISTANCE STUDY

This section investigates the DC point-to-point resistance of the 15 FSS samples studied in this paper. The resistance measurements were carried out using a digital multi-meter measuring every individual element of the 374 elements in each of the FSS arrays. Figs.11 (a) and (b) compare the transmission responses S_{21}, and overall average resistance values in ohms for the 0.4 mm solid and 70 µm frame dipole FSS respectively.

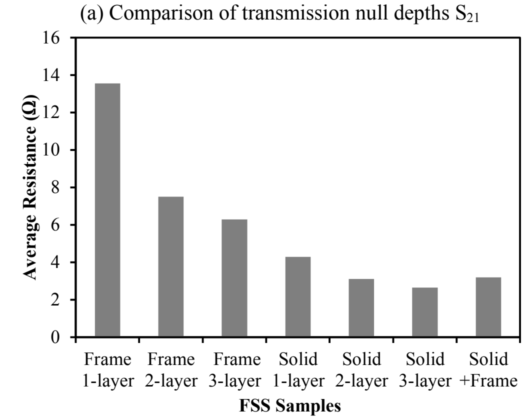
The depth of the transmission null increases as the number of the deposited ink layers increases for the frame and solid dipole FSS, and the resistance values decrease accordingly, as shown in Figs.11 (a) and (b) respectively. The null depth of the 2-layer frame dipole improved from the minimum acceptable level of -20 dB of the 1-layer frame to -23 dB, which is exactly the response of the 1-layer solid dipole while still saving in ink. In addition, the deposition of the 70µm frame on top of the 1 layer solid dipoles has improved the S_{21} response by about 3 dB.

The 2nd deposited layer of ink has reduced the total average resistance of the frame dipole FSS by 6Ω, from 13.5 to 7.5 Ω, and by about 1 Ω in case of the solid dipoles. This reflects the improvement in the null depth as shown in Fig.10 (a). The total average resistance of the solid + frame FSS is also less than the total average resistance of the 1-layer solid dipoles by 1 Ω.

Figs.12 (a) and (b) compare the transmission responses and total average resistances of the FSS with wider elements: the 1 mm solid and 0.15 and 0.2 mm frame dipoles. The impact of depositing more layers has the same positive effect on the depth of nulls and reduces the average total resistance of the arrays, as in the above case of the 0.4 mm solid and 70 µm frame dipole FSS. However, overall average resistances of the 1mm solid, 0.15 and 0.2 mm frames are less than their 0.4 mm solid and 70 µm counterparts. This is a result of the fact that they have more deposited ink; as they are wider.

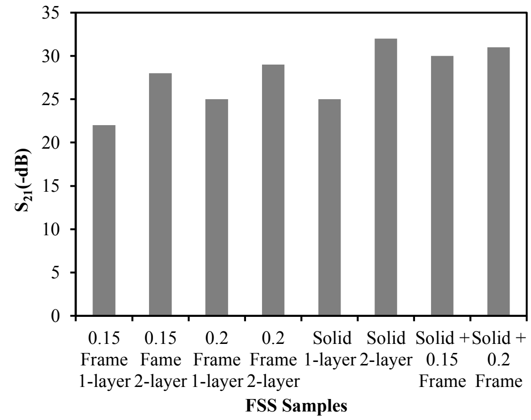


(a) Comparison of transmission null depths S_{21}

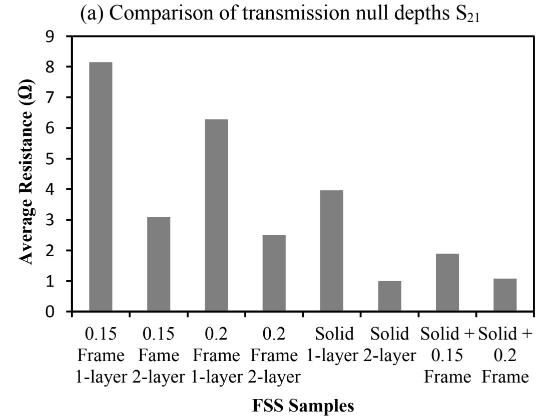


(b) Comparison of resistance values

Fig.11 Transmission responses (a) and resistance values (b) of the 0.4mm solid and 70µm frame dipole FSS



(a) Comparison of transmission null depths S_{21}



(b) Comparison of resistance values

Fig.12 Transmission responses (a) and resistance values (b) of the 1mm solid and 0.15 and 0.2 mm frame dipole FSS

This improvement in the conductivity of the elements also results in deeper nulls in comparison with the 0.4 mm width FSS. The measured resistance values are summarised in Table II.

TABLE II
MEASURED RESISTANCE

Layer 1 Width (mm)		Layer 2 Width-(mm)		R (Ω)	Standard deviation
solid	0.4	-	-	4.3	0.5
solid	0.4	solid	0.4	3.1	0.8
frame	0.070	-	-	13.5	2
frame	0.07	frame	0.07	7.5	1.9
solid	0.4	frame	0.07	3.2	0.5
solid	1	-	-	4	0.6
solid	1	solid	1	0.9	0.13
frame	0.15	-	-	8.2	1.3
frame	0.15	frame	0.15	3.1	0.5
frame	0.2	-	-	6.3	1
frame	0.2	frame	0.2	2.5	0.6
solid	1	frame	0.15	1.9	0.3
solid	1	frame	0.2	1.1	0.3

FSS arrays with higher average resistance than 13.5 Ω did not achieve the required transmission response, as illustrated in Fig.13. It was noticed that those FSS arrays with higher average resistance suffered from severe discontinuities and cracks. Some were completely nonconductive, the result, probably, of errors in the sintering process rather than the deposition sequence, as some of the arrays with very high resistance appeared on visual inspection to be well formed.

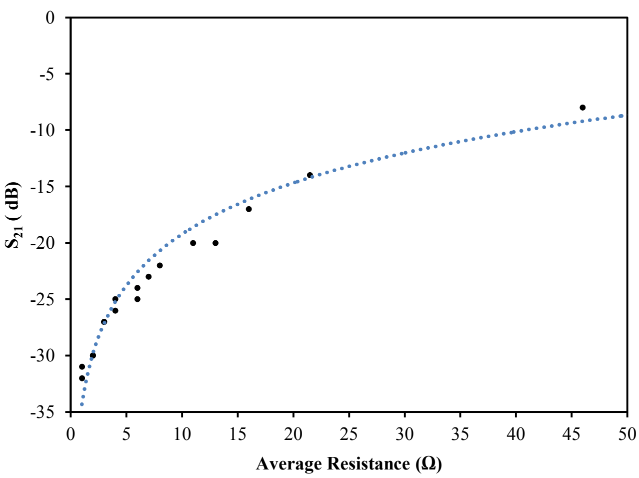


Fig.13 Elements average resistance vs. transmission response

V. CONCLUSION

This paper investigates factors that contribute to the inkjet manufacture of frequency selective surfaces with acceptable levels of performance. Silver nanoparticle inks were deposited on environmentally friendly paper substrates, as might be used in improving the signal -to – interference ratio and user privacy in the built environment. The study focused on dipole element configurations. The principal performance indicator was the depth of the null in the array transmission/frequency response – a measure of the isolation obtainable. Studying the influence of the number of deposited ink layers, together with the ability to deposit droplets on demand allowed modification of the array element design in ways which reduced the amount of deposited conducting material, whilst still achieving the satisfactory benchmark level of isolation of 20 dB. In frame dipoles, the ink is deposited only at the edges, where the surface current maximizes. Such modifications allow savings in ink of about 50% while achieving the required level of isolation of 20 dB in, for example, the case of the single layer frame arrays of just 70 µm frame width. These are difficult to fabricate with conventional subtractive methods. Further modifications to the elements have also been considered, where an extra frame layer was superimposed on a layer of solid dipole elements. This approach, viable only with inkjet printing, improved the isolation level of the FSS by approximately 7 dB relative to that of the 1-layer solid dipole FSS alone. It achieved the same level as that of the corresponding 2-layer solid dipole arrays whilst saving 25% of the ink deposited.

Deposited thin lines are prone to discontinuities, especially in the case of the frame elements used for example in thin paper. The effect of such discontinuities were mitigated by the addition of an extra layer of ink, raising the possibility of repairing defective elements, unlikely with conventional subtractive fabrication techniques.

In addition, the arrays were also assessed in terms of their average D.C element resistance and related to the level of isolation obtained; the highest average resistance to accomplish the benchmark isolation level was 13.5 Ω, that in the case of the 70 µm frames, whereas the lowest resistance observed in this study was 0.9 Ω achieving a level of isolation of 31 dB in the case of the 2-layer, 1 mm wide, solid arrays.

The theme of this study is continuing, with similar investigations applied to complex convoluted element structures [5][6].

REFERENCES

[1] M. Philippakis, C. Martel, D. Kemp, S. Appleton, R. Pearson, and E. A. Parker, "Application of FSS Structures to Selectively Control the Propagation of signals into and out of buildings, Annex 3," *Ofcom ref AY4464*, pp. 1–54, 2004.

[2] P. S. Taylor, A. C. M. Austin, E. A. Parker, M. J. Neve, J. C. Batchelor, J. T.-P. Yiin, M. Leung, G. B. Rowe, A. G. Williamson, and K. W. Sowerby, "Angular independent frequency selective surfaces for interference control in indoor wireless environments," *Electron. Lett.*, vol. 48, no. 2, p. 61, 2012.

[3] G. Sung, K. Sowerby, M. Neve, and A. Williamson, "A Frequency-Selective Wall for Interference Reduction in Wireless Indoor Environments," *IEEE Antennas Propag. Mag.*, vol. 48, no. 5, pp. 29–37, Oct. 2006.

[4] J. A. Arnaud, "Resonant-grid quasioptical diplexer," *Electron. Lett.*, vol. 9, no. 25, p. 589, 1973.

[5] E. A. Parker and A. N. A. El sheikh, "Convoluted array elements and reduced size unit cells for frequency-selective surfaces," *IEE Proc. H Microwaves, Antennas Propag.*, vol. 138, no. 1, p. 19, 1991.

[6] E. A. Parker, J. C. Batchelor, R. Chiang, A. G. Williamson, B. Sanz-Izquierdo, M. J. Neve, and K. W. Sowerby, "Frequency selectively screened office incorporating convoluted FSS window," *Electron. Lett.*, vol. 46, no. 5, p. 317, 2010.

[7] B. A. Munk, *Frequency Selective Surfaces: Theory and Design*. John Wiley & Sons, 2000.

[8] V. Sanchez-Romaguera, S. Wünscher, B. Turki, D. Oyeka, R. Abbel, B. Silvia, T. Daniel J., J. C. Batchelor, E. A. Parker, U. S. Schubert, and S. G. Yeates, "Inkjet printed paper based

Frequency Selective Surfaces and on-skin RFID tags; the interrelation between silver nanoparticle ink, paper substrate and low temperature sintering technique selection," *J. Mater. Chem. C*, 2015.

[9] J. C. Batchelor, E. A. Parker, J. A. Miller, V. Sanchez-Romaguera, and S. G. Yeates, "Inkjet printing of frequency selective surfaces," *Electron. Lett.*, vol. 45, no. 1, p. 7, 2009.

[10] R. D. Seager, J. Bowman, R. Philpott, a. Chauraya, M. Broughton, and N. Nimkulrat, "Fabric based frequency selective surfaces using weaving and screen printing," *Electron. Lett.*, vol. 49, no. 13, pp. 1507–1509, 2013.

[11] E. Arnaud, A. Kanso, T. Monediere, D. Passerieux, M. Thevenot, E. Beaudrouet, C. Dossou-yovo, and R. Noguera, "Inkjet printing of frequency selective surfaces on EBG antenna radome," in *2012 6th European Conference on Antennas and Propagation (EUCAP)*, 2012, pp. 2693–2696.

[12] B. Derby, "Inkjet Printing of Functional and Structural Materials: Fluid Property Requirements, Feature Stability, and Resolution," *Annu. Rev. Mater. Res.*, vol. 40, pp. 395–414, 2010.

[13] B. J. Perelaer, A. W. M. de Laat, C. E. Hendriks, and U. S. Schubert, "Inkjet-printed silver tracks: low temperature curing and thermal stability investigation," *J. Mater. Chem.*, vol. 18, p. 3209, 2008.

[14] J. H. Song and H. M. Nur, "Defects and prevention in ceramic components fabricated by inkjet printing," *J. Mater. Process. Technol.*, vol. 155–156, pp. 1286–1292, Nov. 2004.

[15] B. M. Turki, E. A. Parker, J. C. Batchelor, M. A. Ziai, S. G. Yeates, and V. Sanchez-Romaguera, "Influence of defective elements on performance of frequency selective surfaces," *Electron. Lett.*, vol. 49, no. 17, pp. 1054–1055, Aug. 2013.

[16] A. H. Wong, M. J. Neve, and K. W. Sowerby, "Performance analysis for indoor wireless systems employing directional antennas in the presence of external interference," *2005 IEEE Antennas Propag. Soc. Int. Symp.*, vol. 1A, pp. 799–802, 2005.

[17] B. M. Turki, E. A. Parker, M. A. Ziai, J. C. Batchelor, V. Sanchez-Romaguera, and S. G. Yeates, "Study of printing errors in digitally fabricated FSS," in *2013 Loughborough Antennas & Propagation Conference (LAPC)*, 2013, pp. 429–432.

[18] B. M. Turki, E. A. Parker, M. A. Ziai, J. C. Batchelor, V. Sanchez-Romaguera, and S. G. Yeates, "Study of clusters of defects in low-cost digitally fabricated frequency selective surfaces," in *The 8th European Conference on Antennas and Propagation (EuCAP 2014)*, 2014, pp. 779–801.

[19] S. M. A. Hamdy and E. A. Parker, "Influence of lattice geometry on transmission of electromagnetic waves through arrays of crossed dipoles," *IEE Proc. H Microwaves, Opt. Antennas*, vol. 129, no. 1, p. 7, 1982.

[20] B. M. Turki, E. A. Parker, J. C. Batchelor, M. A. Ziai, S. Wünscher, S. G. Yeates, and U. S. Schubert, "Inkjet Fabrication of Frame Dipole FSS," in *2014 Loughborough Antennas & Propagation Conference (LAPC)*, 2014, pp. 347–349.

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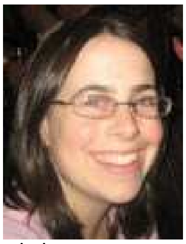

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