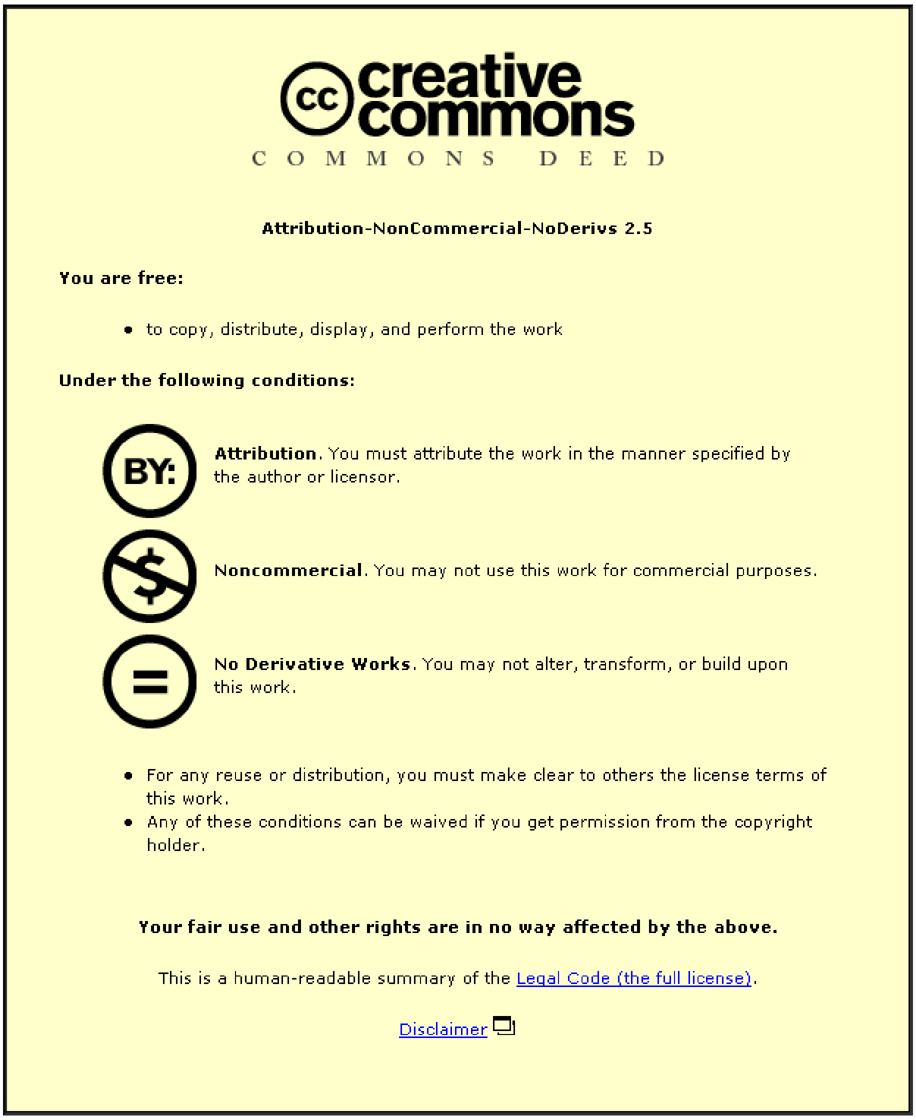

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Inkjet Printed Microstrip Patch Antennas Realised on Textile for Wearable Applications

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***Abstract*—This paper introduces a new technique of inkjet printing antennas on textiles. A screen printed interface layer was used to reduce the surface roughness of the polyester/cotton material which facilitated the printing of a continuous conducting surface. Conducting ink was used to create three inkjet printed microstrip patch antennas. An efficiency of 53% was achieved for a fully flexible antenna with two layers of ink. Measurements of the antennas bent around a polystyrene cylinder indicated that a second layer of ink improved the robustness to bending.**

***Index Terms*—Inkjet printing; textile; wearable electronics; microstrip patch antennas**

I. INTRODUCTION

THE wearable technology market is a growing multi-billion dollar industry that includes consumer electronics, RFID and telemedicine. Wireless connectivity and interaction with our environment will become increasingly important in the coming years. Integrating antennas into clothing can improve the desirability of such systems and novel methods of fabricating conducting structures on textiles will be of benefit to diverse applications.

A review of wearable antennas can be found in [1], [2]. The inherent flexibility of the textiles requires that an additional margin of performance must be included in the design [3]. Integration into clothing means that the washability of the antennas has been considered [4]. The antennas must also function in harsh environments [5]. The effect of bending and crumpling textile antennas on the impedance and radiation patterns has been considered [6], [7].

Various materials and manufacturing processes considered for wearable antennas include conducting paint, conducting metal coated nylon, screen printing, embroidery, weaving and liquid crystal polymers [8]. The technical challenges of embroidering antennas made with conducting threads has been reviewed in [9].

Printing is an alternative method to deposit a conductive layer on substrates. The thickness of the metallisation in terms of skin depths affects the efficiency, however, efficiency values greater than 50% at 2 GHz have been obtained with 50 nm thick gold layers [10]. Screen printing is a feasible printing technique to realize textile antennas as it can easily pattern conductive paste onto fabric to form a flexible strong and suitably thick functional layer [4], [11].

Inkjet printing antennas can be created directly from the final design without the need for a screen and hence allows rapid production for low volumes with the flexibility for bespoke designs. Note, in this work the interface layer is currently screen printed but a standard non-meshed screen could be used for different antenna and circuit geometries. Inkjet printing also facilitates fine resolution and is a widely used technology.

Silver or copper inkjet printed antennas have been reported on paper [12], [13]; PET [14] and Kapton [15]. Due to the finite thickness of the ink layer, it is challenging to inkjet print on rough or porous textiles [16]. Further challenges include the ability of the textile to withstand the ink-curing temperature and maintaining a conductive track while the antenna is bent around cylindrical structures. The majority of papers in the literature do not include efficiency values for inkjet printed antennas as these are typically low. A more comprehensive review of inkjet printing can be found in [17] which demonstrated that two inkjet conducting layers with the interface layer gave superior performance to 5 layers without.

This paper develops a method of inkjet printing antennas onto textiles. Section II outlines the fabrication process with emphasis on the inkjet printing and the method of enabling the electrical connection. Section III includes the measured efficiency and radiation pattern results and the effect of bending the antenna. Finally, conclusions are made in Section IV.

II. FABRICATION OF ANTENNAS

A. *Interface Layer*

The target fabric used in this research work is a standard 65/35 polyester cotton fabric which is a blend of the two most common fabric yarns and which is widely used in everyday clothing. This fabric has a woven structure consisting of interlacing warp and weft yarns. Fig. 1 (a) shows this woven structure and illustrates the impact this has on the surface profile of the material. To create a more uniform surface for subsequent printing processes the fabric is pre-treated with an intermediate screen printed interface layer. This interface material transforms the relatively high surface roughness (>150 µm from SEM) by filling in the weave of the fabric. The interface layer is screen printed directly onto the fabric to facilitate subsequent inkjet printed conductive layers as shown in Fig. 1 (b).

The interface layer used in this work, Fabink UV-IF1, is a polyurethane based screen printable interface paste supplied by Smart Fabric Inks Ltd (www.fabinks.com). This paste is UV curable so does not require a thermal heating process. Note, thermally cured pastes can release potentially harmful volatile organic compounds. The interface layer has a surface free energy of ~39 mN/m (measured using a Kruss DSA30B tensiometer) which enables wetting of the majority of solvent based inkjet printable electronic inks which have a lower surface tension, typically around 30 mN/m. The ink's wettability, representing the interaction between ink and substrate, defines the pattern definition before the curing stage. The interface layer has good thermal resistance and can withstand 150°C for 30 minutes in a conventional thermal oven, without observable degradation, which may be required for subsequently printed inks. In addition, the interface has good chemical resistance properties and shows no obvious damage when exposed to widely used organic solvents such as ethanol, isopropanol and 1-hexanol.

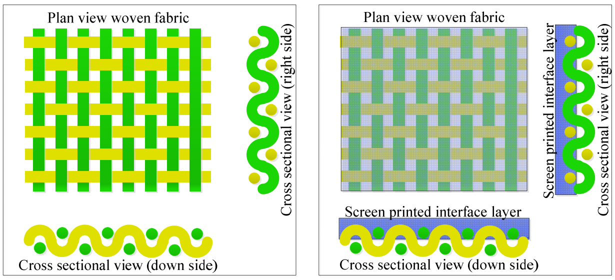

Fig. 1. Plan and cross sectional view of (a) standard woven fabric structure and (b) standard woven fabric structure with screen printed interface layer

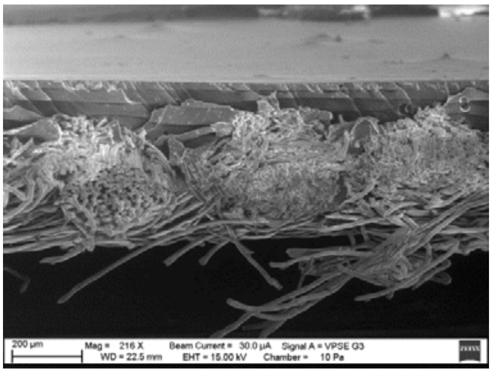

Fig. 2. Cross-sectional isometric view SEM image of standard 65/35 polyester cotton fabric yarn structure with screen printed interface layer on top

The average thickness of the screen printed interface layer is around 100 µm with a surface roughness of 5µm, see Fig. 2. The advantage of using a screen printed interface layer is that it can easily provide sufficient material thickness in a few prints whereas inkjet printing would require 100 or more sequential prints to achieve the same thickness. The screen printed interface layer is only applied in the area required for printing the subsequent inkjet printing area, thus maintaining a greater degree of fabric flexibility and breathability compared to commercial laminated or transfer coated fabrics.

B. *Inkjet Printed Patch Antenna*

Inkjet printing is the most widely used direct write printing technique in the additive manufacturing industry. The inkjet printer used at the University of Southampton for this research work is a Dimatix DMP-2831 inkjet printer. This printer uses a disposable 10 pL piezoelectric print cartridge with an ink capacity of 1.5 ml. Commercially available inkjet printable silver U5714, supplied by SunChemical, was selected for its compatibility with the DMP 2831 printer. After printing, the silver layers were each cured for 10 minutes at 150°C in a box oven. The chosen curing temperature is a compromise between sufficient silver conductivity and degradation of the fabric. The selected curing condition gives good silver conductivity (5.7 Ω/sq at 610 nm thickness) and no observable damage.

When inkjet printing inks with electronic functionality, the resolution is critical to the performance of the printed ink. The average diameter of droplets is around 60 µm. Therefore, the maximum droplet spacing is 60 µm to achieve a conductive line. However, choosing a droplet spacing equal to the drop diameter results in poor conductivity since the drops do not overlap. Previous experiments [17] have shown that 15 µm drop spacing provides the optimum setting for printing the conductive silver pattern. This drop spacing provides good conductivity and line edge definition combined with acceptable ink usage. It was found that printing two silver layers was the optimum with a 15 µm printing resolution. Printing just a single layer of silver on the interface layer tends to result in a few pinholes across the patch (Fig. 3 (a)) while two inkjet printed layers provides a more uniform 3 µm thick layer and has no observable pinholes (Fig. 3 (b)). Printing three silver layers shows no significant improvement in film quality and can lead to cracking after bending.

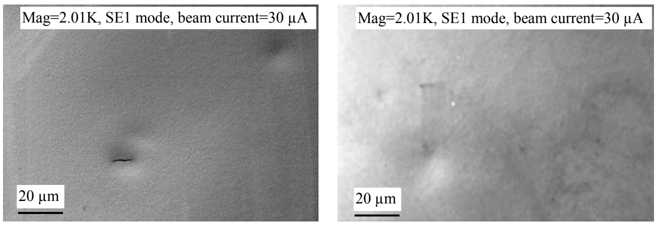

Fig. 3. Plan view SEM images showing the surface of the silver layer for (a) one silver layer on fabric interface, (b) two silver layers on fabric interface

Fig. 4 shows the fabrication steps to achieve the realization of an inkjet printed textile patch antenna. The interface layer deposition is followed by a UV curing stage. Subsequently, the two conductive silver layers are deposited sequentially and then simultaneously thermally cured to create a solid conductive silver layer.

C. *Assembly and connection*

The fully fabric patch antenna was assembled as follows. Two layers of 0.8 mm thick felt were attached to a 90 × 90 mm conducting nylon rip-stop Nora Dell ground plane by using upholstery glue that is activated by ironing. The process in Fig. 4 could be extended by printing a 2nd interface layer and the ground on the back of the fabric. A probe feed was implemented by using an ultra-small flexible co-axial cable of diameter 1.32 mm. The inkjet printed side faced the ground plane and was connected to the probe via highly conductive silver epoxy paint, see Fig. 5. The inkjet printed patch on a polyester cotton substrate was attached to the felt using the same upholstery glue. Note the thin coaxial cable and the glue were chosen for their flexible and compact properties and less lossy alternatives are available.

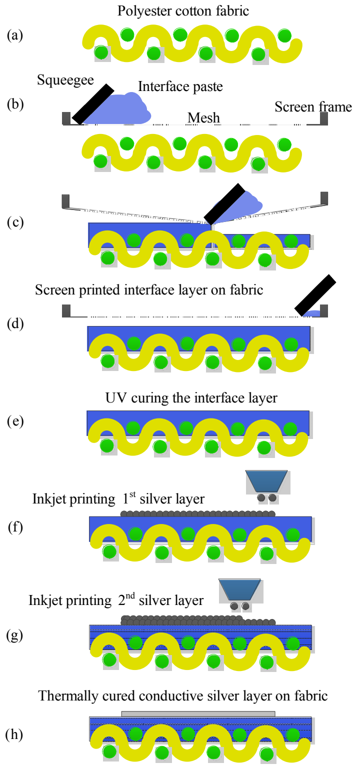

Fig. 4. Flow diagram of the fabrication process: (a) Cross sectional view of standard polyester cotton fabric; (b, c and d) Screen printing stage to deposit the interface layers on top of polyester cotton; (e) UV curing stage to harden the printed interface layer; (f and g) inkjet printing two deposits of the conductive silver; (h) Thermal curing stage to solidify the printed silver layer

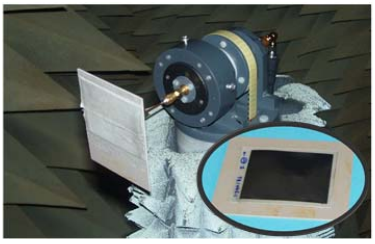

Fig. 5. The inkjet printed patch antenna in the anechoic chamber and inset the patch antenna before the connection was made

III. MEASURED RESULTS

In order to assess the performance of the inkjet printed antennas, three antennas were compared with an etched patch on a low loss substrate. Details of the geometry are given in Table 1. The low loss substrate used was Taconic RF - 45 (ε_r = 4.5, tanδ = 0.0037) with a copper ground plane. To maintain the 2.4GHz resonance frequency, the patch dimensions were increased with the felt substrate (ε_r = 1.229, tanδ =0.001).

A. Efficiency and gain measurements

The theoretical efficiency of the etched patch was calculated to be 85% at 2.372 GHz on FR45 and 97% at 2.6 GHz on felt using Personal Computer Aided Antenna Design (PCAAD) 6.0 software from Antenna Design Associates, Inc. The four antennas were measured in an anechoic chamber at Loughborough University – see Table 1. The measured efficiency of the etched patch antenna was 79%. The efficiency reduced to 57% with the inkjet patch printed glued on the same substrate. A similar efficiency was measured with the felt substrate but this reduced to 37% when only one layer of ink was used. Variations in the felt properties and thickness caused small variations in the frequency between the two fully fabric antennas. The simulated efficiency of the etched patch on felt with a copper patch was 78% using EMPIRE XCcel finite-difference time-domain (FDTD) software. Reducing the simulated conductivity of the ink layer to 1 MS/m approximately replicated the measured efficiencies with both one and two layers of ink.

The results indicate that reasonable efficiency levels were achieved with just one layer of ink and were improved by the addition of a second printed layer.

TABLE I
MEASURED RESULTS OF PATCH ANTENNAS

Substrate height is in mm *BW = bandwidth*	Etched patch on FR45 substrate	Inkjet patch (2 layers of ink) glued on FR45 substrate	Inkjet patch (1 layer of ink) on felt	Inkjet patch (2 layers of ink) on felt with
Patch size (mm)	37.4 × 28.1	37.4 × 28.1	47.7 × 36.9	47.7 × 36.9
Substrate height	1.6	1.6	1.9	1.9
Frequency (GHz)	2.378	2.480	2.405	2.505
S11 (dB)	-13.39	-14.89	-10.05	-9.95
10dB BW (MHz)	22.5	24.5	17.5	N/A
Directivity (dBi)	7.39	7.55	8.38	8.72
Gain (dBi)	6.37	5.09	4.02	5.98
Efficiency (%)	79	57	37	53

B. Radiation patterns

The radiation patterns of the fully fabric antenna with 2 inkjet layers is shown in Fig. 6. The others were similar.

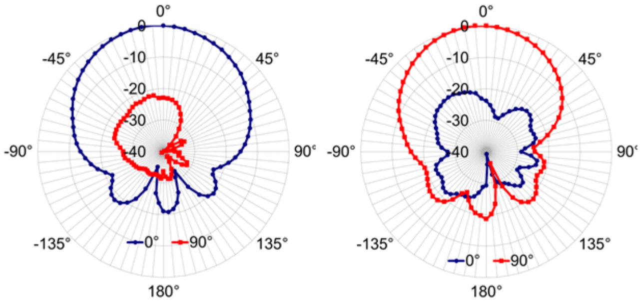

Fig. 6. Measured patterns of patch (2 layers of ink) on polyester cotton and felt at 2.505 GHz: (a) y-z plane (E-Theta Plot) and (b) z-x plane (E-Phi Plot)

C. Measurements on polystyrene cylinder

Inkjet printed antennas are sensitive to bending as the inkjet layer can be damaged by the physical act of compressing and tensioning the conducting surface. The fully fabric antennas were measured on polystyrene cylinders of radius 70 and 125 mm. The patch antennas were bent in two dimensions with respect to the feed. The antennas on the larger cylinder generally maintained their S11 performance compared to the flat antenna. The S11 results for the fabric antenna with one and two layers of ink on the 70 mm radius cylinder are shown in Fig. 7. The S11 results with one inkjet layer show that the connectivity between the conducting ink flakes is adversely affected by bending and the antenna becomes extremely lossy and does not function. However, the conventional resonance at 2.4 GHz resumed when the antenna was unbent even after approximately ten measurements. SEM images indicated that with one layer of ink; micro-cracks are formed which disappear when re-flattened. The 2nd layer of ink increased the robustness due to bending. There was a degree of detuning and the S11 results indicate that bending in the horizontal direction is preferable in this regard.

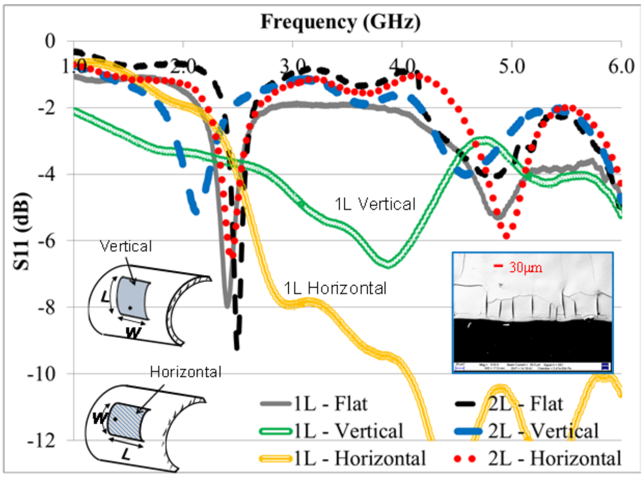

Fig. 7. The measured S11 of the textile inkjet patch on felt with one (solid) or two (dotted/dashed) layer(s) of ink bent around a 70 mm radius cylinder. Inset: SEM image of inkjet printed layer when bent

IV. CONCLUSION

This paper has reported a novel method of fabricating wearable antennas using inkjet printing. The efficiency of the fully fabric patch antennas was improved with the second layer of ink. Simulations and SEM analysis indicate that this second layer of ink had two functions: i) creating a more consistent surface and ii) increasing the thickness in terms of the skin depth of the conducting layer which has an approximate conductivity of 1 MS/m. Therefore, the efficiency is expected to decrease at lower frequencies. The radiation patterns were similar to a regular antenna which indicates that the printing was symmetric. The antenna did not significantly change its performance after bending around a 125 mm radius cylinder which indicated that the inkjet and the interface layers formed a cohesive structure without damaging the conducting surface. However, bending the antenna with only one inkjet layer around a 70 mm cylinder temporarily stopped the antenna functioning. Placement of the antenna to minimise the bending radius relative to the feed is desirable. The printing technique addressed in this paper could be particularly beneficial at higher frequencies where the skin depth is less of an issue and also the high resolution of inkjet printing can be exploited.

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