Inkjet printed flexible antenna on textile for wearable applications

Yi Li*, Russel Torah, Steve Beeby, John Tudor

School of Electronics and Computer Science
Faculty of Physical and Applied Science
Southampton University
Southampton
UK
SO17 1BJ

yl1g08@ecs.soton.ac.uk*
rnt@ecs.soton.ac.uk
spb@ecs.soton.ac.uk
mjt@ecs.soton.ac.uk

*denotes speaker

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School of Electronics and Computer Science
University of Southampton, England

*Corresponding author, email: yl1g08@ecs.soton.ac.uk

Abstract

We report a direct write inkjet printing technique for fabricating a flexible antenna on textile for use in smart textile applications such as wearable systems (Rienzo et al. 2006). The complete antenna was deposited entirely using inkjet printing. The inkjet printed antenna is based on a half wavelength dipole antenna offering a planar structure and acceptable size. The printable silver nanoparticle-based conductive inkjet ink has a curing temperature of 150 ^{o}C for 10 minutes or 130 ^{o}C for 15 minutes. The theoretical designed peak frequency of the antenna is 2.4 GHz. The entire antenna is directly inkjet printed on three difference substrates; 1) Kapton, 2) polyurethane (PU) coated stretchable textile and 3) pre-treated 65/35 polyester/cotton textile. The difficulty realizing an inkjet printed antenna on the three substrates increases with each substrate since each has increasing surface roughness. All three antennae on the three different substrates show a similar peak operating frequency and impedance output characteristic. The principle of a stretchable antenna is investigated by inkjet printing the conductive silver ink on a pre-stretched textile.

Keywords - Inkjet printing, smart textile, tunable antenna, flexible electriconics.

Introduction

Smart fabrics (E-Textiles) have attracted growing interest in the last ten years, especially for wearable system applications (Rienzo et al. 2006 and Oliver et al. 2006). This paper reports a direct write inkjet printed flexible antenna on textiles for use in such smart textile applications. There is growing interest in flexible antennae on textiles. (Rais et al. 2009). Textile based antennae can be integrated into commercial clothing products. Printing processes simplify the production of a textile antenna. However, the use of direct inkjet printing to fabricate a flexible antenna on a textile has not been previously reported. This approach offers the advantages of rapid prototyping directly to the textile from the desired design's computer image with minimal waste. A stretchable antenna takes this concept further and offers the possibility to tune its operating frequency by stretching the textile.

The first textile based flexible antenna was made in 2007 on 100 % cotton mercerized twill textile by micro-droplet deposition (Patra et al. 2007). The textile used is not a standard textile, since it is mercerized making it relatively easier to print on compared to standard polyester/cotton. The reported process involved depositing two different conductive inks which required subsequent reduction in glucose. In addition, the underlying cotton was not stretchable. Several publications use inkjet printing to fabricate flexible antennae on paper, Kapton (a polyimide) and PET (a thermoplastic polymer) but not textiles. These substrates are also not stretchable (Rida et al. 2009 and Kirsch et al. 2009). The primary challenge in inkjet printing conductive layers on textiles to achieve an antenna is to overcome the surface roughness of the textile which is significantly greater than the thickness of a typical inkjet printed conductive layer at submicron level. This paper will show a set of directly inkjet printed half wavelength dipole antennae on three different substrates; 1) Kapton (polyimide), 2) a polyurethane coated stretchable polyester, cotton and lycra textile used in medical applications and 3) a pre-treated 65/35 polyester/cotton textile.

The method reported here differs from previous work by using inkjet printing as the only patterning tool to print the conductive layer on the flexible textile substrate to achieve a wearable antenna. The inkjet printable conductive ink used is a silver nanoparticle dispersion U5714 from SunChemical Ltd.. The pre-treatment on the 65/35 polyester/cotton was screen printed polyurethane (Fabink-UV-IF1 from Smart Fabric Inks Ltd.). We report experimental results on the inkjet printed antenna giving impedance and operating frequency measurements using a Rohde & Schwarz ZVB4 vector network analyser (VNA).

Stretchable conductive tracks have been made on pre-stretched substrates (elastic rubber) but not by inkjet printing or on a textile substrate (Lacour et al. 2004). A tunable antenna has been made in 2011 based on a horseshoe shaped dipole antenna (Arriola et al. 2011) but it was not inkjet printed on a textile substrate. Other mechanically tunable antennae are more complex and are all based on fluidic metals (So. et al. 2009 and Kubo et al. 2010). However none of them are fabricated by inkjet printing on textile substrates.

Methodology

A. *Inkjet printing technique*

The inkjet printer used in this research work is a Dimatix DMP-2831. This printer uses a disposable piezoelectric head print cartridge with a 10 pL drop volume and a capacity of 1.5 ml. Suitable printable inks have a narrow acceptable range of rheological properties which ensure that the droplets fire continuously in the required landing location. An ideal ink for printing with the DMP 2831 inkjet printer should be a stable suspension with low evaporation, a viscosity of 10 to 12 mPa.s and a surface tension of 0.028 to 0.033 N/m. The printed pattern resolution can be controlled by adjusting the droplet spacing between 5 μm and 254 μm for the DMP-2831. If the droplet spacing is too small the volume of printed ink will be too high per unit area which often results in pattern bleeding. If the droplet spacing is too large then the pattern definition will be poor. In this case, if the droplet spacing is too small there will be no conduction.

The conductive ink was inkjet printed on the substrate with 15 μm droplet spacing at 21 ^{o}C. The nozzle diameter for the DMP-2831 (~20 μm) produces a droplet of 60 μm diameter. For 60 μm droplet diameter, 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. Choosing a 30 μm drop spacing improves the conductivity since the drops overlap but results in strongly castellated edges to the lines. A 15 μm drop spacing provides good conductivity and line edge definition combined with acceptable ink usage.

Surface treatment in inkjet printing is The conductive ink does not require pre-treatment of the polyimide film as the wettability of the conductive silver ink is good. Once the silver conductor is printed, it is cured at 150 ^{o}C for 10 minutes in a laboratory oven. A 150 ^{o}C curing temperature provides a suitable compromise between sufficient conductivity and future compatibility with textiles. A 130 ^{o}C curing temperature for 15 minutes results in the same flexible conductive track.

B. *Stretchable conductive pattern*

Inkjet printing a stretchable conductive pattern is a significant challenge since traditional conductors are not stretchable. Stretchable conductors can be achieved in two conceptually

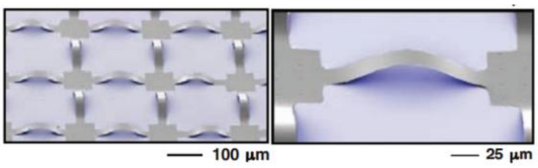


Figure 1. 'Stretchable' silicon membrane bonded to rubber (Rogers et al. 2010).

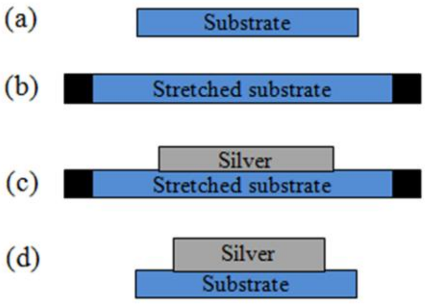


Figure 2. Fabrication of silver layer on a stretchable substrate to achieve stretchable pattern. (a) unstretched, (b) stretched and clamped (c) printing silver (d) removal of clamps.

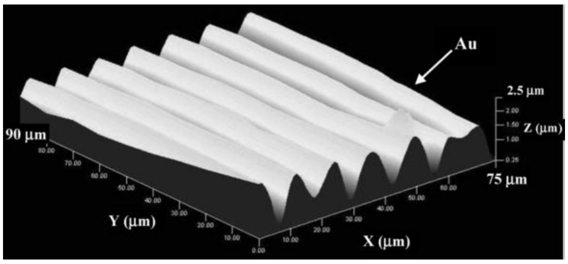


Figure 3. Three dimensional profile of a gold surface wavy film after 15 % pre-stretch (Lacour et al. 2004).

Figure 4. A horseshoe shaped structure layout in L-Edit.

Figure 5. Half wavelength dipole antenna deign in L-Edit.

different, but complementary, ways. One relies on the use of new structural layouts with conventional materials; the other uses new stretchable materials in conventional layouts. In this research, we focus on the structural layout approach to realise stretchable electronics because the few stretchable conductors that exist cannot currently be inkjet printed. Only two solution processed stretchable conductor materials have been realised: 1) stretchable carbon nanotube conductor made of carbon nanotubes mixed with an ionic liquid (Sekitani et al. 2008 and Chun et al. 2010); 2) stretchable metal conductor made by molecular self-assembly process called Electrostatic Self-Assembly (Purohit et al. 2008).

There are three structural layout methods which can use conventional conductive inks to fabricate stretchable conductors. The first method exploits the fact that any material in sufficiently thin form which is flexible does not have to be stretchable, by virtue of bending strains that decrease linearly with the decreasing thickness. A silicon wafer is brittle and rigid, but nano scale ribbons, wires, or membranes of silicon are flexible (Rogers et al. 2010). Then the material's flexibility can be used to achieve a pre-bent structure bonded on a stretchable substrate to realise a 'stretchable' conductor as shown in Fig. 1. In practice the conductor does not actually stretch, but deforms from its bent state, as the whole structure is stretched.

The second method is by pre-stretching the substrate (Fig. 2); by making the thin conductive layer into wavy shapes as shown in Fig. 3 and bonding them into elastomeric substrates yields stretchable systems (Lacour et al. 2004). This effectively pre-stretched printing pattern method combines the wavy structure and the flexible thin film properties to achieve a stretchable and compressible film.

A horseshoe shaped structure (Fig. 4) is the third widely used stretchable structural method which was developed in two projects: SWEET (Vanfleteren et al. 2011) and STELLA (STELLA News, 2010). This method does not take advantage of thin film bending. It achieves stretchability by reducing the strain in the horseshoe shape pattern while being stretched.

C. Substrate selection

Polyimide is the chemical name for the commercial Kapton product which was developed by DuPont. Kapton has very good stability and flexibility over a wide temperature range (normally from -273 ^{o}C to +400 ^{o}C) and resists many chemical solvents. It is also a good electrical insulator. Because of its chemical and physical properties, it is widely used in flexible electronics as a substrate or an insulating layer. Kapton is used as the first substrate in this research because of its flexibility, high temperature resistance and uniformly smooth surface.

Polyurethane coated stretchable textile supplied from Plastibert Ltd. (Polyester, cotton and lycra textile) is commonly used in medical applications. This textile based substrate is chosen as the second substrate because of its stretchability which will lead to an inkjet printed stretchable antenna on textile. However the maximum temperature is 80 ^{o}C continuously. However, a 150 ^{o}C curing temperature for 10 minutes has been tried on the textile, which shows no significant damage or degradation after curing.

65/35 polyester/cotton textile is the most commonly used textile for standard clothing in everyday life. Therefore, this textile is targeted as the final textile substrate for inkjet printing the antenna. However, it has a number of physical properties that make inkjet printing based deposition difficult. The temperature related properties are the challenges since a sufficiently low curing temperature for inks is required; 65/35 polyester/cotton textile has ability to resist temperature 150 ^{o}C for 45 minutes maximum. The maximum working temperature is 180 ^{o}C for 10 minutes. Further its surface roughness is higher than the other two substrates selected: its arithmetic mean deviation of the surface roughness is 143.3 µm. However the textile is pre-treated using a screen printed interface layer before inkjet printing, the surface roughness is reduced significantly down to a few micro meters.

D. Inkjet printed dipole antenna design

Direct inkjet printing is limited to planar electronic device fabrication. Therefore only planar antennae are considered in this paper. There are several potential planar antennae: short dipole antenna, dipole antenna, half wave dipole antenna, small loop antenna, microstrip antenna and inverted-F antenna. In this paper, a half wavelength dipole antenna is chosen for inkjet printing at a target frequency of the 2.4 GHz communication frequency. This is because the designed pattern is relatively small and simple compared to the other possible planar structured antennae. By taking equation (1) with a 2.4 GHz frequency and the light speed constant, at a half wavelength, the quarter dipole wavelength length is 31.25 mm as shown in Fig. 5.

$$\lambda = c/f \qquad (1)$$

where λ is the wavelength in meters; c is the speed of light in meters per second; f is the antenna working frequency in hertz.

E. Antenna fabrication process

The first step is to wipe the substrate surface with standard cleanroom wipes dipped in deionised water. This step removes any contamination on the substrate surface and ensures the surface energy across the whole printing area is uniform. This ensures the contact angles of all printed droplets are the same which results in a sharp patterned layer. The next step is to inkjet print the conductive silver layer of the designed pattern on the substrate. The printing setting is two layers with 15 µm resolution on Plastibert textile and pre-treated polyester/cotton textile, and one layer with 15 µm resolution for Kapton film. The surface energy of Kapton film is lower than the textile coatings. Therefore one more inkjet printed layers are needed for textile substrates than Kapton substrate to ensure sufficient conductivity and good pattern definition. A 15 µm drop spacing provides good conductivity and line edge definition combined with acceptable ink usage. After printing, the conductive pattern is cured for

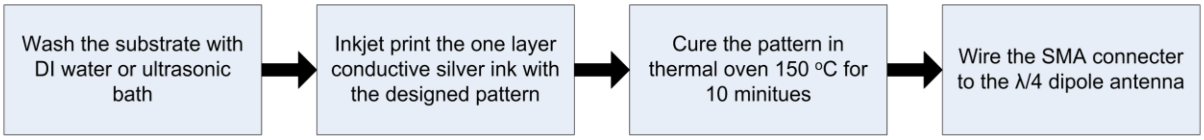


Figure 6. Inkjet printed flexible antenna fabrication flow diagram.

10 minutes at 150 °C to ensure sufficient conductivity of the antennae. Then the last stage is to connect the SMA (SubMiniature version A) connector to the inkjet printed λ/4 dipole antennae with silver epoxy (Circuitworks CW2400). One terminal connects to the inner contact and the other terminal connects to the outer shielding. The SMA is the standard antenna connection in communication measurement. The whole fabrication flow diagram is shown in Fig. 6.

Results and Discussion

A. *Inkjet printed dipole antenna*

The designed 2.4 GHz dipole antennae were inkjet printed on Kapton (Fig. 7), pre-treated 65/35 polyester/cotton textile (Fig. 8) and Plastibert (PU coated stretchable textiles (Fig. 9). All three antennae show similar characteristics in peak working frequency and the impedance measurement. A Rohde & Schwarz ZVB4 vector network analyser is used for the impedance and frequency measurements.

Fig. 10 (a) shows the impedance and the peak operating frequency measurement results for the λ/2 dipole antenna inkjet printed on Kapton. The impedance is 49.0 Ω whereas the ideal impedance is 50 Ω. In addition, the measured peak working frequency is 1.82 GHz (Fig. 10 (a) blue 1). The designed peak working frequency is 2.4 GHz. The peak frequency shift can be explained by the wiring of the antenna to the SMA connector. The wiring part will also count as part of the effective dipole length in the printed antenna. Therefore the total length is increased, by referring to equation (1), the average wiring to the SMA connector from antenna is about 10 mm. Then the theoretical peak working frequency will decrease as the λ/4 dipole length increases up to about 41.25 mm. The new calculated peak frequency should therefore be around 1.818 GHz which is very close to the measured frequency value of 1.82 GHz. The red line in the frequency reflection plot represents the result when the flexible antenna's two dipoles are bent perpendicular to the plane of the antenna. The red line shows a frequency shift up to 2.21 GHz (Fig. 10 (a), red 2). According to the meander dipole antenna theory (Endo et al. 2000), bending deforms the dipole structure resulting in a shorter effective dipole length and a higher peak frequency. The theory can be briefly explained: the antenna length is effectively reduced by bending the linear antenna into a spiral or a meander. However the effective dipole length is determined by a complex calculation dependant on its new dipole shape. Fig. 11 (a) shows the SEM cross sectional image of the printed silver track on Kapton film. It can be seen that the surface of the silver layer is very smooth and uniform. Therefore Kapton is a very reliable flexible substrate for flexible electronic device fabrication.

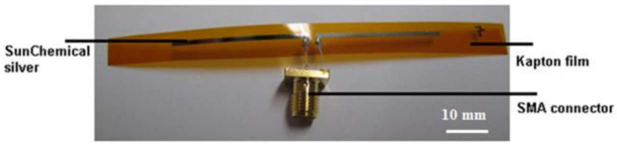


Figure 7. Inkjet printed 2.4 GHz dipole antenna on Kapton.

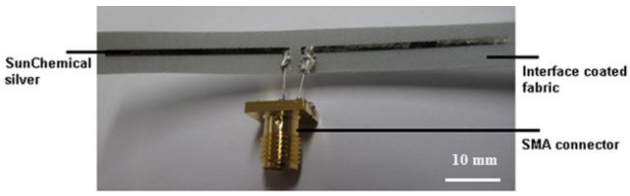


Figure 8. Inkjet printed 2.4 GHz dipole antenna on screen printed interface layer coated textile.

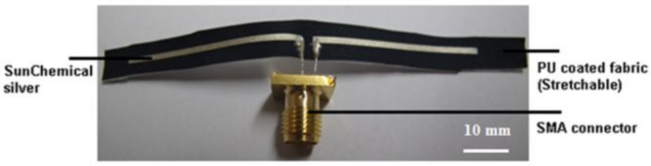
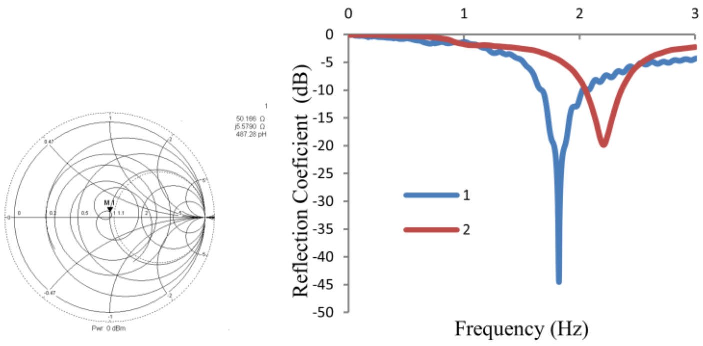
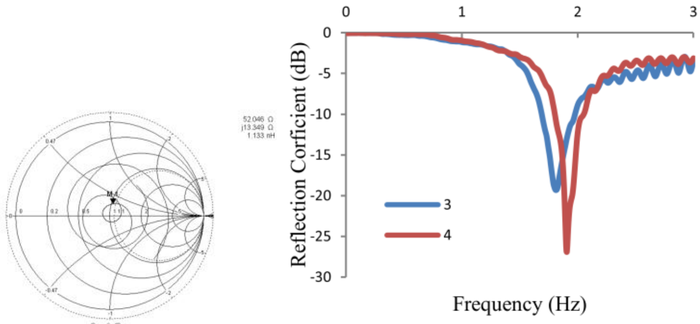


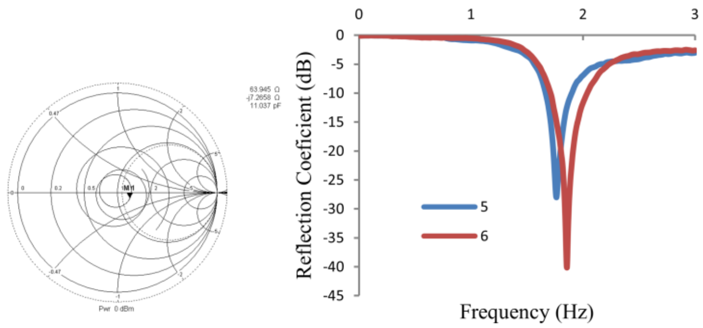
Figure 9. Inkjet printed 2.4 GHz dipole antenna on Plastibert (PU coated stretchable textile).



(a)

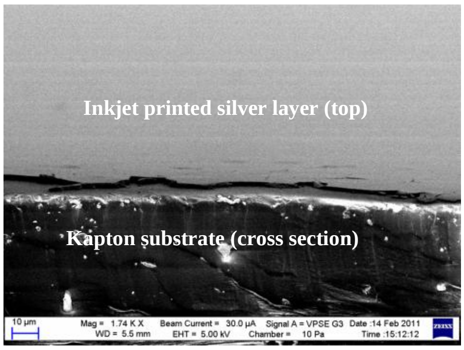


(b)

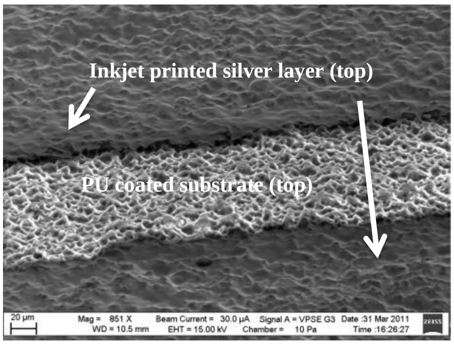


(c)

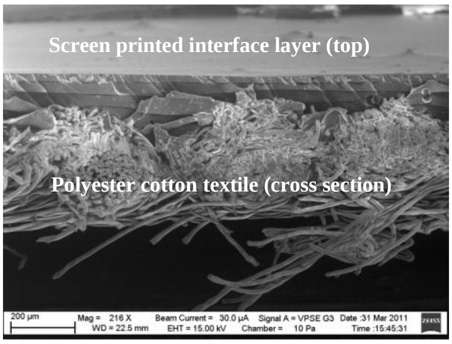
Figure 10. VNA measured results of inkjet printed antenna impedance and frequency reflection coefficient for three flexible substrates; (a) Kapton, (b) pre-treated 65/35 polyester cotton and (c) Plastibert PU coated stretchable textile.



(a)



(b)



(c)

Figure 11. SEM image of three difference flexible substrates; a) Kapton, b) Plastibert PU coated stretchable fabrics and c) interface coated 65/35 polyester/cotton.

Fig. 10 (b) shows the impedance and the peak operating frequency measurement results for the λ/2 dipole antenna inkjet printed on PU coated stretchable textile. The impedance is 52 Ω and the measured peak frequency is 1.82 GHz (Fig. 10 (b), blue 3). There is a peak frequency shift up to 1.91 GHz (Fig. 10 (b), red 4) when bending the antenna similarly to the Kapton based antenna. Fig. 11 (b) shows the SEM top view image of inkjet printed conductive silver ink on PU coated stretchable textile. The light coloured strip in the middle of the image is the uncovered PU coating surface. It can be seen that the surface of the PU layer is non-uniform. The surface roughness is around a few microns across the whole surface. After the silver layer coating, the surface roughness of the silver layer on the textile has significantly improved but still slightly uneven.

Table 1. Resistances measured on the pre-stretched Plastibert textile substrate.

No.	***Pre-stretched (Ω)***	***Released (Ω)***	***10% stretched (Ω)***	***20% stretched (Ω)***
1	26	18	96	141
2	25	19	100	138
3	25	28	87	176
4	23	21	110	160
5	45	26	94	165

Fig. 10 (c) shows the impedance and the peak operating frequency measurement results for the λ/2 dipole antenna inkjet printed on pre-treated 65/35 polyester/cotton textile. The impedance measured is 64 Ω. In addition, the measured peak working frequency is 1.76 GHz (Fig. 10 (c), blue 5). The designed peak working frequency is 2.4 GHz. There is a peak frequency shift up to 1.86 GHz (Fig. 10 (c), red 6) when bending the antenna (Fig. 12) as the same way to the previous two flexible antennae. Fig. 11 (c) shows the SEM image of the screen printed interface layer coated 65/35 polyester/cotton textile. The surface of the screen printed interface layer coating is relatively smooth. It can be used as the substrate for electronic device fabrication without further treatment. The reason to inkjet print electronic devices on 65/35 polyester/cotton textile is because it is the most widely used textile in clothing. The advantage of the interface layer is that it can be screen printed on a specific piece of textile rather than having an entire textile coated as with the commercial PU coated textile.. Ideally, an inkjet printed interface ink would provide the best solution but this is more difficult to achieve and a suitable ink has not yet been identified.

B. *Inkjet printed dipole antenna on stretchable textile*

Six inkjet printed conductive silver tracks were fabricated on pre-stretched PU coated stretchable textile as shown in Fig. 13. There is a printing defect in the fifth track, so it cannot be measured and compared against the others. The defect is caused by the printer nozzle clogging while printing. The five conductive patterns are first measured without releasing the pre-stretching, secondly the resistances was measured after the textile was released. The samples were then

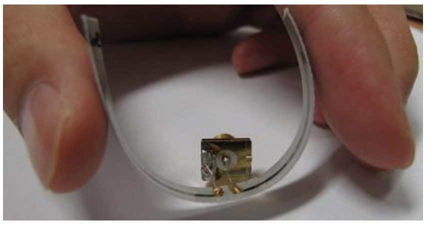


Figure 12. Image of bending inkjet printed antenna.

Figure 13. Inkjet printed conductive silver tracks after curing and release.

measured under 10% and 20% stretching as shown in Table I. It can be seen that the resistance decreases as the pre-stretched substrate is released as the conductive silver particles are squeezed together. Also resistance around or under 200 Ω can provide good signal transceiving strength. This result shows the capability of this technology to realise an inkjet printed mechanical tunable antenna on textiles.

Conclusion

Flexible antennae have been fabricated using inkjet printing on three different substrates; Kapton, Plastibert PU coated stretchable textile and pre-treated 65/35 polyester/cotton. A low temperature process (150 ^{o}C for 10 minutes) has been presented to realise flexible conductive tracks on all three different flexible substrates. The entire inkjet printed antenna is constructed by printing a single conductive silver nanoparticle dispersion ink. Then it is wired by the silver epoxy to SMA connector for VNA measurements of impedance and frequency. The key parameters have been measured and compared between the antennae on the three different flexible substrates. The measured three impedances are relatively close to the ideal communication antenna impedance of 50 Ω. The three measured peak operating frequencies are all below the designed 2.4 GHz frequency. The change in frequency is due to the wiring to the SMA connector which increases the effective dipole length resulting in a lower peak frequency. However by including the wiring length into the effective dipole length, the measured frequencies matched the calculated frequency. These differences could be reduced by compensating for the wiring length by using a shorter dipole length when designing the antenna. In addition, by bending all three different flexible antennae, there is a significant frequency shift up as the effective dipole length decreases according to the meander dipole antenna theory. Inkjet printed stretchable conductive tracks have been made on stretchable textile.

Future work will direct inkjet print a tunable half wavelength antenna on stretchable fabric and measure their frequency shift against percentage of textile substrate stretching.

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