A Direct-Write Printed Antenna on Paper-Based Organic Substrate for Flexible Displays and WLAN Applications

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(Invited Paper)

***Abstract*—This paper presents the design, fabrication and measurements of a direct-write printed low-cost and flexible inverted-F antenna on an ultra-low-cost paper-based organic substrate for wireless local area network (WLAN) and flexible display applications. Innovations include the study and utilization of paper as a high-frequency substrate for the first time in the gigahertz (GHz) range, the fabrication technology for the direct-write printing of the antenna as a flexible RF electronic device, and the investigation of antenna flexibility in conjunction with flexible displays. Although paper substrates exhibit relatively high dielectric losses ($\tan\delta \sim 0.065$ at 2.45 GHz), the maximum realized gain of the fabricated antenna is measured to be $+1.2$ dBi giving a total efficiency $\sim$82%. Simulated results of the antenna's return loss and radiation patterns agree well with the measurements, and can lead to a whole new class of flexible low-cost electronic devices of the future.**

***Index Terms*—Antenna, direct-write, flexible display, inverted-F-antenna (IFA), paper, WLAN.**

I. Introduction

RECENT developments in flexible display technology have generated strong research efforts on compatible technologies for flexible electronics, components and materials. Paper is an environmentally friendly (*aka* 'green' material that is organic, flexible and low-cost, yet it is under-utilized for modern electronics. Paper as a substrate is compatible with additive direct-write, inkjet, and copper lamination technologies [1], [2]. It is also suitable for wearable devices and sensors due to its low profile (small thickness and light weight) that makes it an attractive substrate for modern RF applications including mass-produced RFID tags, antennas, microwave filters and modules [3], [4].

Fig. 1. Typical placement and embedding of the flexible antenna onto a flexible and potentially rollable display screen of a commercially available laptop. The antenna locations are shown with dashed and dotted lines. The original screen capture is from [6].

Losses in printed RF electronics are associated with two main factors: a) conductive nanoparticle ink loss, and b) dielectric loss, which for paper can be inherently high. In [5], the average dissipation factor of paper substrate was found to be $\tan\delta_{\rm paper} = 0.072$ from 0.5 to 2.5 GHz. Consequently, and due to this relatively high value (which is more than 10× larger than of commercially available high frequency substrates), the majority of paper research has been limited to applications for frequencies lower than 1 GHz [2]–[5].

Here, paper is evaluated as the core integration substrate for a direct-write printed and flexible RF electronic device (a printed antenna) for flexible displays (such as OLEDs) at the 2.45-GHz WLAN frequency band. Displays are integral parts of today's electronic devices, and most electronic devices are desired to communicate wirelessly with others. The antenna presented here can be used to enable WLAN interconnectivity of practically any device carrying a flexible (or non-flexible) display, whether it is a flexible screen of a mobile phone, a flexible electronic paper, or a flexible laptop screen, because

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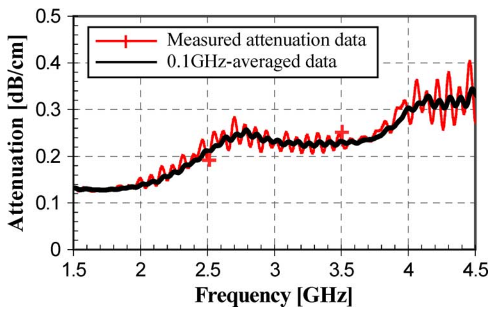

Fig. 2. Measured dielectric attenuation using a 50-Ω microstrip line.

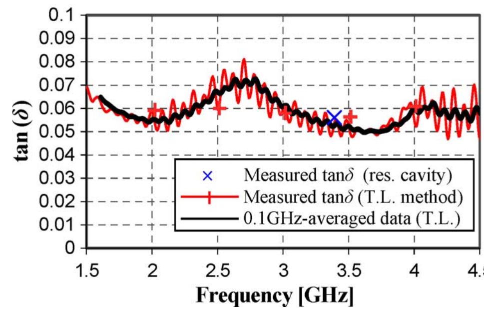

Fig. 3. Extracted dissipation factor of paper versus frequency.

the antenna itself is also flexible. The evaluation is made through an inverted-F-antenna (IFA) that is designed on a paper substrate, direct-write printed and measured. The IFA design is chosen due its many advantages that make it a ubiquitous class of antennas in handset and WLAN applications. IFAs are often embedded on the backside of laptop screens and mobile phones: 1) to be concealed for aesthetic purposes and 2) to radiate to some extent more towards the free-space, and less in the direction of the user's body (i.e. head, torso and hands when typing), which generally acts as an obstacle to the radiated and received waves. Flexible screens require also flexible RF electronics and antennas for appropriate foldability and successful connectivity. IFAs are simple to fabricate, can be easily fed and matched to an input port, and have a nearly omnidirectional radiation pattern, which is ideal for receiver use. The IFA presented is also bendable. An illustration of the placement or embedding of the thin, lightweight, low-cost IFA antenna presented here, into a flexible display in a MIMO configuration for both polarizations is shown in Fig. 1. The flexible antenna is placed at two different locations (shown with dashed and dotted lines) between the flexible display's protective cover and its electronics. With the radiating element placed toward the edges, efficient radiation is achieved. Both the display and the developed antenna can flex more than in the illustration of Fig. 1. Simulated and measured results are presented and are in good agreement, providing a major step toward the adoption of paper technology for use in flexible RF electronics for flexible display, flex-screens and flex-cellular phone applications.

II. RF Characteristics of Paper

To ensure a successful design, paper as a dielectric substrate was first evaluated using the microstrip line method. From a good estimate of paper's relative dielectric permittivity $(\varepsilon_{\mathrm{r}})$ value [3], an approximately 50-Ω microstrip line with $L = 69.5$ mm length and $w = 3.7$ mm width was printed to validate this permittivity and estimate the loss tangent $(\tan\delta)$. Signal attenuation versus frequency was measured and is plotted in Fig. 2. Attenuation increases with frequency as expected, and helps determine the loss tangent using its estimation formula from [7]

$$\tan\delta = \frac{\alpha_{\mathrm{d}}\lambda_0(\varepsilon_{\mathrm{r}}-1)\sqrt{\varepsilon_{\mathrm{r,eff}}}}{8.686\pi\varepsilon_{\mathrm{r}}(\varepsilon_{\mathrm{r,eff}}-1)} \tag{1}$$

where λ_0 is the free-space wavelength, a_{d} is the dielectric attenuation constant and $\varepsilon_{\mathrm{r,eff}}$ is paper's effective permittivity given here by an empirical formula [8]

$$\varepsilon_{\mathrm{r,eff}} = \frac{\varepsilon_{\mathrm{r}}+1}{2} + \frac{\varepsilon_{\mathrm{r}}-1}{2}\left(1+12\left(\frac{t}{w}\right)\right)^{-1/2} \tag{2}$$

where t is the substrate's thickness (approximately 250 μm) and w the line's width. Assuming non-magnetic material, $\varepsilon_{\mathrm{r\_paper}} \approx 3.4$ at 2.45 GHz. Also, from the dissipation factor (Fig. 3), $\tan\delta_{\mathrm{paper}} \approx 0.065$ at the same frequency, and that was similar to the value obtained from the single-frequency resonant cavity method at 3.4 GHz (0.0546).

In addition to the substrate losses, another important factor that should be taken into account is the conductivity of the nanoparticle ink used for the direct-write printing of the device. Conductivity typically increases with the curing temperature and varies with curing time. Here, an ink with 60% bulk silver conductivity was used, which is the value that was measured after one hour of curing at 150 °C. This curing temperature is below the deformation or melting point of most flexible and rigid substrates, including but not limited to: paper (180 °C–233 °C), Teflon (200 °C–327 °C), RT/Duroid (260°C), Liquid Crystal Polymer (280 °C–315 °C), Silicon and ceramics ($>$ 1000°C). This low curing temperature allows practically any solid material to be used as a substrate for the direct-write printing of electronic devices, without alterations in the material's physical or electromagnetic properties. The ink was composed of silver nanoparticles functionalized with polyvinylpyrrolidone. To form the ink, 30% by weight of functionalized silver nanoparticles was added to a solution of 90% by volume distilled water and 10% by volume diethylene glycol. The solvents were chosen to modify both the viscosity and surface tension of the resulting dispersion to meet the requirements of the $\mathrm{M^3D}$ printing process. An analytical description of its nanoparticle manufacturing process can be found in [9]. As an example of the effect of curing temperature, Fig. 4 shows the measured resistance of printed conducting lines on paper versus the curing temperature for 1-hour exposure. The measurements were carried out using a 4-point probe. The printed lines have the same dimensions $(25 \times 0.5\ \mathrm{mm}^2)$ and were printed under the same conditions. As the curing temperature increases, the lines' resistance decreases. This can be explained because when the curing temperature is low, there are large spaces between the nanoparticles of the ink

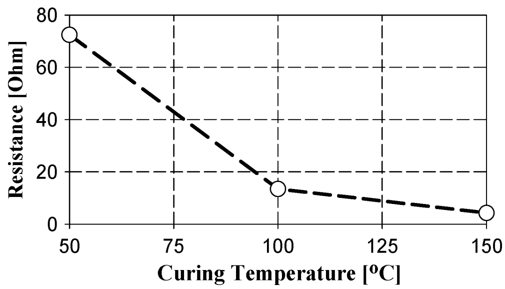

Fig. 4. Resistance of lines fabricated on a paper substrate as a function of the curing temperature.

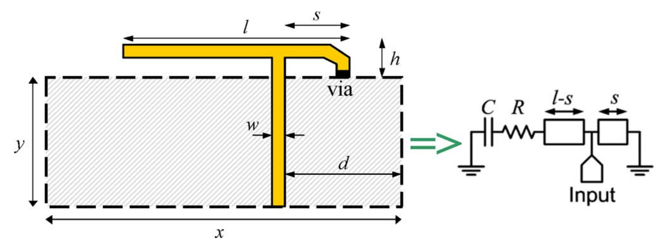

Fig. 5. Design schematic (not to scale) of the inverted-F antenna. The dashed line encloses the ground plane on the backside of the substrate. A drilled via connects one of the antenna's ends to the ground.

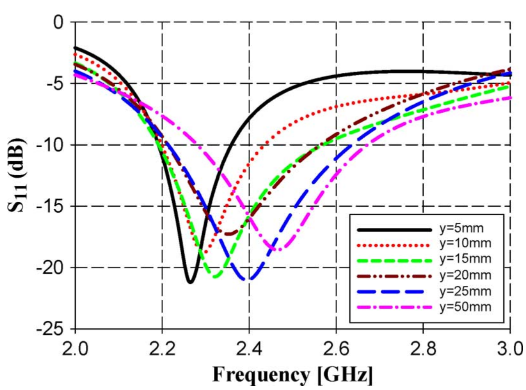

Fig. 6. The effect of the length of the ground plane (y) on the bandwidth and resonant frequency. For this IFA antenna, a length of approximately $y \approx \lambda_g/4$ gives good bandwidth and matching.

resulting in a high resistive path for the RF current. In contrast, high curing temperatures reduce these gaps providing a high conductive path for the current.

III. Inverted-F Antenna (IFA) Design

Using the extracted material parameters, an IFA was designed. The antenna schematic along with its equivalent circuit that can be used for optimization are shown in Fig. 5. The dashed line circumscribes the backside ground plane, while the solid color is the topside metallic layer consisting of the microstrip feed line and the radiating element (antenna). The ground size is 46×25 mm making this structure compatible with small foldable displays and PCMCIA interfaces. Small y-dimension can lead to a hard-to-match antenna with degraded performance [10]. Keeping y close to or less than $\lambda_g/4$ helps maintain a low side lobe level [11]–[13]. As shown in Fig. 6, good bandwidth can be obtained for the y-dimension being approximately $\lambda_g/4$. The feeding line's width w is 0.57 mm,

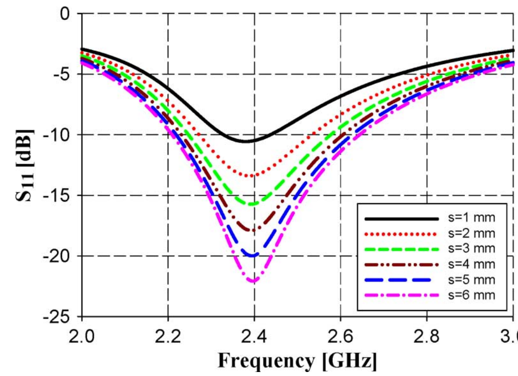

Fig. 7. Effect of the length of the compensating inductive stub s on the return loss of the antenna. An s value of 6 mm tunes out completely the antenna's capacitance, giving purely real input impedance and thus a good 50 Ω match.

TABLE I
Final Dimensions of the Paper-Based IFA Antenna

Dimension	x	y	w	d	h	l	s
Size (mm)	46	25	0.57	10	5	26.15	6

producing the necessary 50-Ω microstrip line. A result of the folded monopole's characteristics is the length $l \approx \lambda_g/4$ as well. One antenna's end (dimension s) is grounded through a via to compensate for the capacitance produced between the folded dipole and the ground plane. The value of that capacitance is affected by the distance h. The design was simulated with finite dielectric (paper) and ground layers using IE3D, a full wave computational electromagnetic software that implements the method of moments[1] and which is suitable (amongst others) for planar, IFA-like structures. Also, the conductivity σ of the silver based nano-ink was taken into account for further accuracy. In Fig. 7, for example, the effect of the length s of the compensating stub on the input impedance is shown. As s increases, the inductance increases tuning out the antenna's capacitance and thus making the input impedance purely real. The dimensions h, d and s were then varied to minimize return loss at 2.45 GHz. In this way, the final dimensions were extracted and are shown in Table I.

The antenna prototype was direct-write printed using the Maskless Mesoscale Material Deposition ($\mathrm{M^3D}$) system[2] . In this system, the conductive ink is first ultrasonically atomized and then printed on a pre-heated at 40 °C platen where the paper substrate is placed. The substrate is heated before printing so that the ink can bond onto it, preventing the ink from spreading out. The pressure and atomizing rates depend on the conductive ink's properties. Here, the flow rates of the atomized ink and the fabrication's speed were adjusted using the $\mathrm{M^3D}$ manufacturer's software both speed and high accuracy at the 2.45-GHz design frequency. This fabrication process can be repeated as many times as required, to achieve a thick conducting layer and to reduce the skin depth effect. Ten passes, each one depositing ink layers approximately 0.3μm thick were used. Fig. 8 shows the antenna during the $\mathrm{M^3D}$ printing procedure. The deposition

[1]IE3D is a Trademark of Zeland Software Inc.

[2]Maskless Mesoscale Material Deposition ($\mathrm{M^3D}$) system is a trademark of Optomec Incorporated.

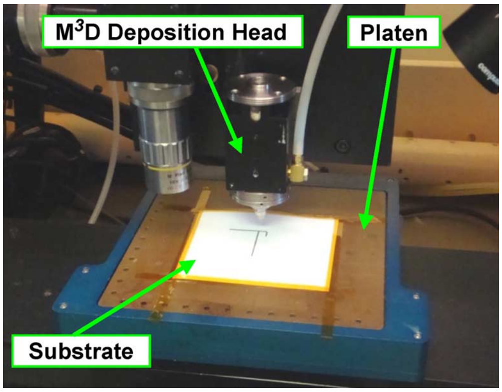

Fig. 8. Direct-write printing of the antenna on paper using the $\mathrm{M^3D}$ machine. The $\mathrm{M^3D}$ fixed head and movable platen can be seen.

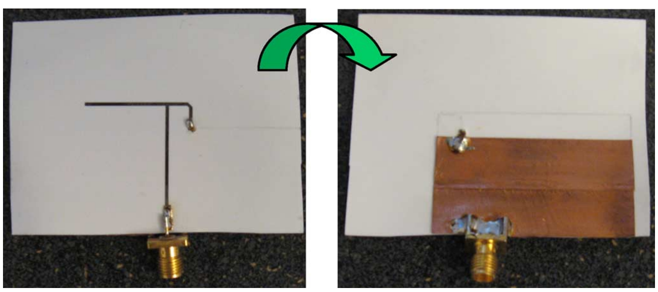

Fig. 9. Photo of a fabricated antenna prototype on organic paper-based substrate: Front side (left) and back side (right). The SMA connector is seen for scaling purposes.

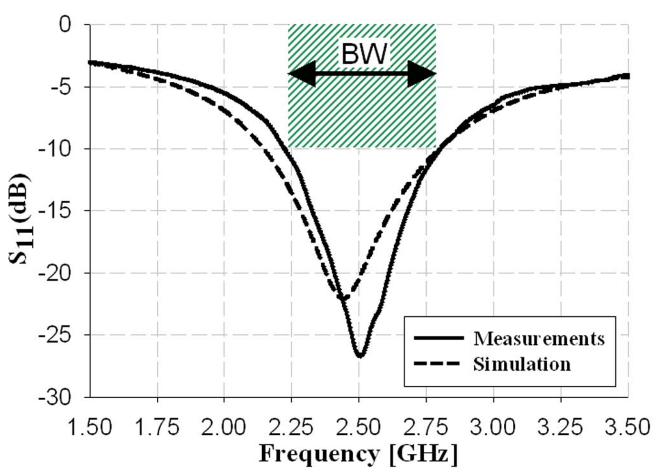

Fig. 10. Measured and simulated return loss of the IFA antenna on paper.

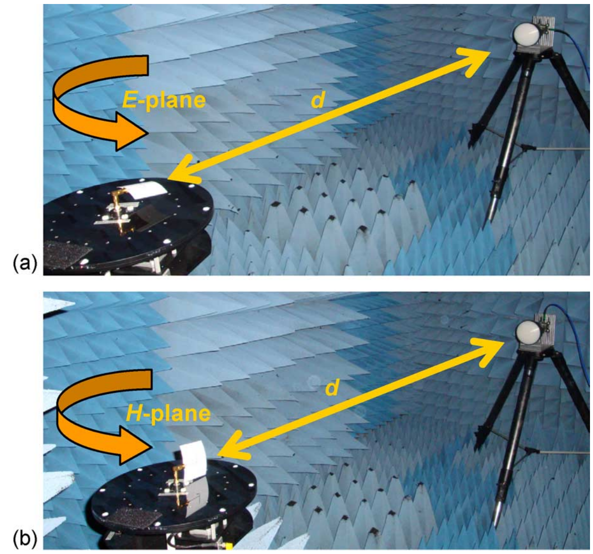

Fig. 11. Photo of the IFA antenna on paper during radiation pattern measurements: a) E-Plane and b) H-Plane.

head can be noticed over the antenna. Fig. 9 shows the fabricated prototype and the connected 3.5 mm SMA is shown for size comparison.

The total fabrication and curing time was approximately 3 hours. For prototyping, the direct-write printing process is much faster than photolithography as it does not involve masks. It is an additive process and thus environmentally-friendly as it does not produce metallic or chemical (photoresist) waste like milling and chemical etching techniques do. Small-scale ink-jet printers are often used for educational and R&D prototyping purposes. However for mass-production applications, fabrication time can be significantly reduced by using commercial inkjet printers with multiple heads [14]. Roll-to-roll [15] and screen-printing [16] techniques can also be used. Fabrication speed may be further reduced using commercial equipment that sinters large areas of ink within a few seconds exposing it to ultraviolet (UV) light or sequences of laser pulses at room temperature[3], [4][17].

IV. Results

The paper antenna was simulated and measured with respect to its return loss and radiation patterns. The return loss was obtained using an Agilent 8753SE Vector Network Analyzer (VNA) and is shown in Fig. 10. A very good agreement can be observed between measured and simulated results. The measured resonant frequency is 2.5 GHz with only a 2% shift from the expected. With its -10 dB bandwidth of $\Delta f_{\mathrm{BW}} = 24\%$, this antenna covers sufficiently the entire WLAN frequency range.

The radiation patterns of the antenna at the two principal planes (E- and H-) were measured in the custom-built anechoic chamber of the South Dakota School of Mines and Technology. The antenna-under-test (AUT) was placed on a Diamond Engineering DAMS 7000 positioner and was aligned to a dual-fed, dual-polarized 2–18-GHz wideband horn antenna with known reference gain (G_{ref}). The antennas were connected to the VNA and separated appropriately to achieve the required far field distance. After a full 2-port calibration, the transmission coefficient (S_{21}) was measured at 2.45 GHz for different angles with a step angle of 2.5° to obtain the antenna's radiation pattern. The S_{21} results were then used to calculate the antenna's gain using:

$$S_{21}^2 = \frac{P_{\mathrm{r}}}{P_{\mathrm{t}}} = G_{\mathrm{AUT}} G_{\mathrm{ref}} \left(\frac{\lambda_0}{4\pi d}\right)^2 \tag{3}$$

where P_{r} is the received power by the AUT in watts, P_{t} is the transmitted power by the reference antenna in watts, G_{AUT} and

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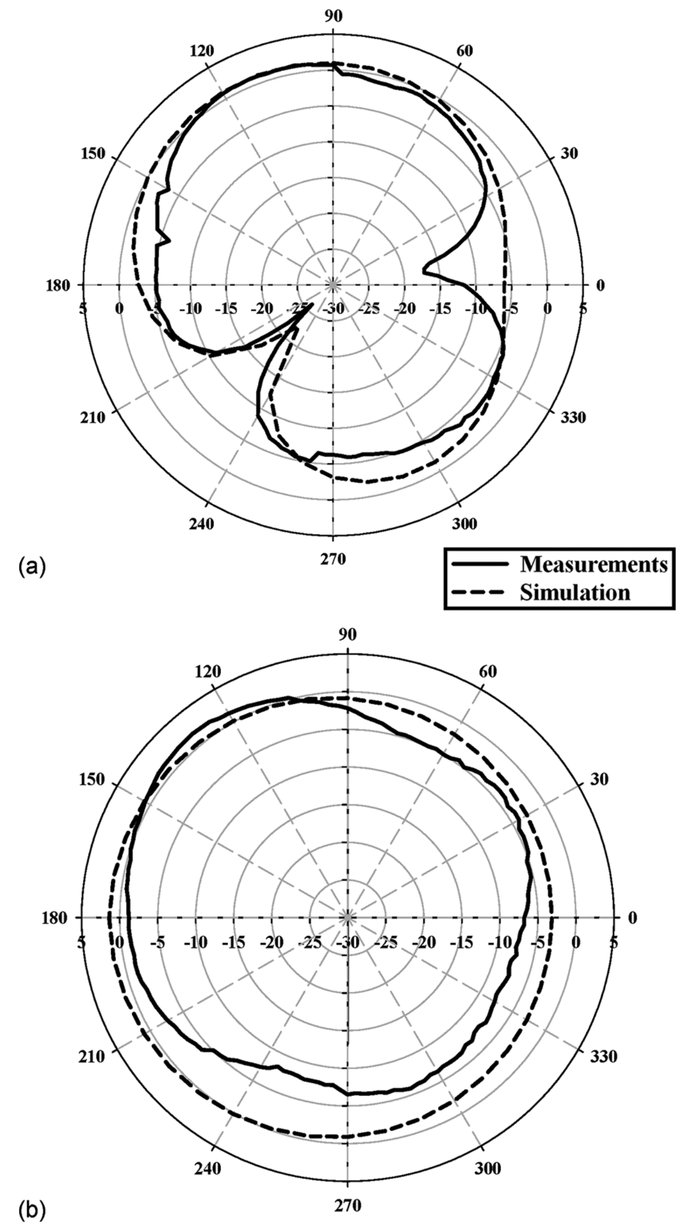

Fig. 12. Measured and simulated radiation patterns of the IFA antenna on paper at 2.45 GHz: a) E-plane and b) H-plane. The results are as expected for an inverted-F type of antenna.

G_{ref} are the AUT and reference antenna gains respectively, and d is the antenna separation distance in meters. Fig. 11 shows the measurement setup used to take the antenna's radiation pattern at both principal planes. The measured results are shown in Fig. 12, superimposed with the simulated ones. The antenna's pattern is similar to the simulated—i.e., almost toroidal, with a close to omnidirectional H-plane cut (since the radiating element is not symmetric, its pattern cannot be perfectly omnidirectional) and a dipole-like '∞'-shape in the E-plane. A good indication of the antenna's efficiency (and thus of the suitability of paper as a high-frequency antenna substrate, and of the conductivity of the nanoparticle ink) can be obtained from the maximum gain of the antenna. The maximum gain was measured to be $+1.2$ dBi at 2.45 GHz with a front to back ratio of approximately -6 dB in both the planes. It is important to note that the maximum simulated directivity and gain of the IFA on paper were 2.3 and 1.43 dBi respectively at 2.45 GHz. Hence, the total efficiency (e_0) is -0.87 dB, which includes the mismatch loss, and the conduction and dielectric efficiencies. This result translates into a total efficiency for the IFA antenna on paper of approximately 82% at 2.45 GHz. Fig. 13 shows a comparison between the simulated antenna's efficiency using the fabrication material parameters, and a very similar IFA antenna designed on a 32-mil thick high-frequency RO4003C laminate, which has inherently extremely low losses. The IFA on the high-frequency low-loss laminate shows a total efficiency of 95% at 2.45 GHz. The paper antenna's efficiency of 82% closely agrees with the expected results.

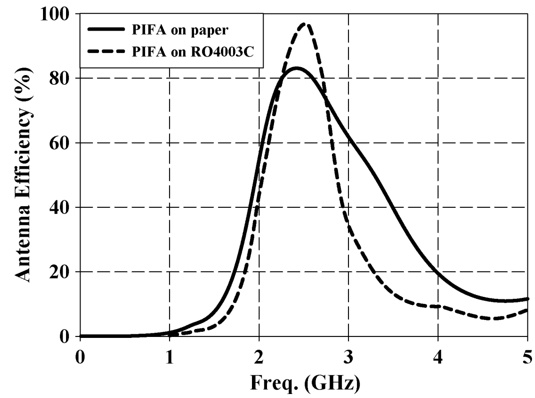

Fig. 13. Simulated total efficiency comparison of the antenna on paper and the antenna on a high-frequency laminate. At the frequency of maximum efficiency, the difference is 13%. The paper antenna efficiency of 82% is similar to that of a good and useful antenna.

V. Flexibility Study

As the antenna is to be integrated into a flexible display, its capability to flex and function properly under bending conditions must be evaluated. Critical parameters are the antenna's RF characteristics (return loss and radiation pattern) as well as the metallic ink's adhesiveness to paper without signs of detachments, cracks or other forms of discontinuities that could result in a faulty operating device. Antenna designs have been studied while being bent [18], [19], and the results indicate a slight increase of the return loss, along with: *a*) a slight decrease of the directivity and a spreading of the radiation pattern in the direction of convex bending, and *b*) a slight increase of the directivity and a narrowing of the radiation pattern in the direction of concave bending. Thus, the main point of interest in this work is the ink's adhesion and conductivity when the substrate is highly bent.

Different radii of curvature were tested (Fig. 14), showing that the antenna can be bent without signs of permanent deformation or performance deterioration. In fact, the sole rigid part of the antenna is its SMA connector, which appears to be the only limiting factor. The antenna flexes easily and repeatedly around test tubes with radius $R_1 = 1.25$ cm and $R_2 = 2.7$ cm both on the front side (as shown in Fig. 14) as well as the reverse side (not shown for conciseness). The antenna was also flexed more than

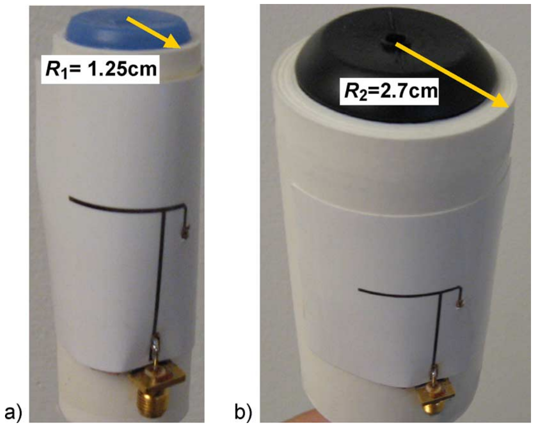

Fig. 14. Photos of the fabricated antenna on paper, bent around cylindrical structures with different radii: (a) $R_1 = 1.25$ cm, (b) $R_2 = 2.7$ cm. The antenna showed no sign of permanent deformation, conductivity deterioration (i.e. cracks) or ink detachment after extensive and repeated bending.

a thousand times in air, for repeatability testing without failure. In addition, in a practical flexible display application, the RF feed is typically integrated with the RF electronics of the device and no bulky SMA connectors are used, thus maximizing device flexibility and minimizing its weight. An illustration of an application of the antenna into a flexible display is shown in Fig. 1.

VI. Conclusion

Paper was used for the first time in a high-frequency WLAN antenna application at 2.45 GHz. The antenna design, fabrication and measurement were described in this work. The fabricated device is a flexible IFA, has dimensions that make it compatible with PCMCIA cards and can be embedded or mounted on flexible displays with excellent results. Using the microstrip line method it was found that the dissipation factor for the utilized paper substrate is $\sim$0.065 at 2.45 GHz. Despite the relatively high dielectric losses, the measured maximum gain is more than 1.2 dBi at 2.45 GHz and the simulated antenna efficiency is 82%, causing the maximum gain value to be 1 dB less than the antenna's maximum directivity. This makes the proposed paper-based IFA an extremely low-cost WLAN receiver, suitable for mass-production applications that are also biodegradable and friendly to the environment. The antenna showed very good return loss and radiation pattern, and can be easily flexed and integrated with a flexible display of a portable computer or even mobile phone.

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