A Low-Cost WLAN "Green" PIFA Antenna on Eco-Friendly Paper Substrate

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Abstract

This work shows for the first time the practical application of paper as a substrate in real-life wireless local area network (WLAN) applications. Photographic paper is used here in the design, fabrication and testing of a printed inverted F-antenna (PIFA) operating at 2.45GHz. Although paper substrates exhibit relatively high dielectric losses (tanδ ~ 0.07 at 2.45GHz), the maximum gain achieved by the fabricated antenna is +1.2 dBi and its total simulated efficiency is approximately 82% at resonance. The simulation results of the return loss, as well as the radiation pattern of the antenna agree with the corresponding measured results that are presented in this work.

Introduction

The increased demand for low-cost, flexible, and environmentally friendly (AKA "green") electronics makes paper an excellent candidate substrate solution for mass production applications. Paper has low cost, is organic and is compatible with the direct write ink-jet printing technologies [1, 2]. It has low thickness and weight, and thus it is suitable for wearable devices and sensors [3]. These properties have made paper an attractive substrate for modern RF applications including but not limited to RFID tags, antennas, microwave filters and modules [3, 4]. A characteristic of paper is that it is a relatively high loss substrate, which was also calculated and measured in this research using the microstrip line method to evaluate its applicability at higher frequencies. In a paper-based direct-write printed antenna, losses are associated not only with the substrate's dielectric losses, but also with the conductivity of the used silver-based nanoparticle inks. In [5], the average dissipation factor of paper was found to be tan$\delta = 7.7\times10^{-2}$ from 0.5 to 2.5 GHz. However, all previous research on antennas on paper has been limited to designs at or below 1 GHz [2-5].

PIFA Antenna Design and Direct-Write Fabrication

This work describes the utilization of paper for WLAN antenna applications at 2.45GHz. It is the first time that paper is used on higher than 1GHz applications. Its applicability as an antenna substrate is demonstrated through a printed inverted F-antenna (PIFA), which was designed and direct-write printed on a low-cost photographic paper substrate that has a thin Kaolin coating. The PIFA design is a ubiquitous class of antennas in handset and WLAN devices, which due to its small size and relatively omnidirectional pattern, justifies its selection in this work. Fig. 1 shows the design's schematic and dimensions. The dashed line

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represents the ground plane of the structure, while the solid line represents the microstrip 50Ω feed and the radiating element. The size of the ground is compatible with a PCMCIA interface. The *x*-dimensions is 46mm. The *y*-dimension is 25 mm or approximately $\lambda_g/4$ at the resonant frequency and should not be made smaller for matching [6] and size reduction purposes, as well as to reduce the side lobe effect on the radiation pattern [7]. A result of the folded monopole's characteristics, is the ~ $\lambda_g/4$ length *l*. One PIFA's end is connected through a via to the ground to compensate for the capacitance produced between the folded dipole and the ground. The design was simulated with a finite dielectric (paper) layer using IE3D [8]. The dimensions *h* and *d* were varied to minimize S_{11} at 2.45GHz. Also, the conductivity, σ, of the silver based nano-ink was taken into account for accuracy.

The ink's conductivity increases with curing temperature but can vary with curing time. Here, using an in-house fabricated ink [9], a 60% of bulk silver's conductivity was obtained by curing for one hour at 150°C. This very low curing temperature that does not affect paper's physical condition. The same ink can also be used with other substrates such as LCP and Kapton that withstand higher curing temperatures and thus are expected to lead to more efficient (conductive) designs at the disadvantage of higher cost. Fabrication took place at the Printed Electronics and Research Laboratory (PEARL) of SDSM&T. The antenna is shown during the M^3D printing procedure in Fig. 2, and after fabrication in Fig. 3. The deposition head can be seen over the antenna.

Measurements of the PIFA on Paper Substrate

The final prototype was measured at the custom made anechoic chamber of SDSM&T with an 8753SE VNA. The gain was also measured using a reference wideband horn antenna. Its radiation patterns were obtained with a 2.5° step angle, using the DAMS 7000 antenna positioner. The simulated and measured return loss is shown in Fig. 4. Very good agreement was be observed.

The measured resonance occurs at 2.5 GHz with only a 2% shift from the simulation. The -10 dB bandwidth of 22.5%, while the increased return loss at higher frequencies indicates low resistive losses on the ink. This antenna covers sufficiently the WLAN band.

Pattern measurements (not shown here for brevity), illustrated an almost omni-directional *H*-plane and a dipole-like toroidal *E*-plane. The measured maximum gain is +1.2 dBi at 2.45GHz. The front to back ratio is approximately -6dB in both the planes. From the simulated maximum directivity and gain which are 2.3 and 1.43dBi respectively at 2.45GHz, one can deduct that the total efficiency (e_0) is ~ 82%. This efficiency takes into account the mismatch loss and conduction and dielectric efficiencies. Fig. 5 shows simulations of the efficiency for the designed PIFA on paper with the actual fabrication material parameters, versus a PIFA designed on a low-loss 32-mil RO4003C substrate. The PIFA on RO4003C has a total efficiency of 95% at 2.45 GHz.

Conclusions

Paper was used for the first time in a high-frequency WLAN antenna application at 2.45GHz. The antenna design, fabrication and measurement were described in this work. The fabricated printed inverted F-antenna (PIFA) has dimensions that make it compatible with PCMCIA cards. Using the microstrip line method it was found that the dissipation factor of the paper substrate used is 7.2×10^{-2} at 2.45GHz. Although paper's losses are relatively high, the measured maximum gain was more than 1.2 dBi at 2.45GHz. The antenna's total simulated efficiency is 82%. This causes the maximum gain to be 1dB less than the maximum directivity at the WLAN band. This makes the proposed PIFA on paper antenna an extremely low-cost WLAN receiver, suitable for mass-production applications that are also biodegradable and friendly to the environment.

Acknowledgement

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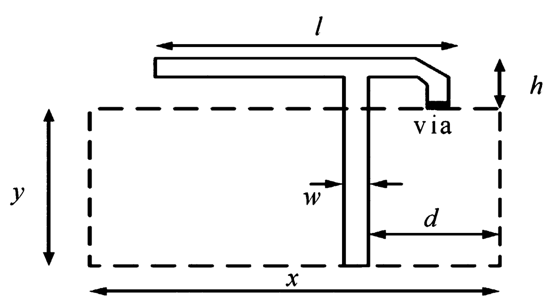
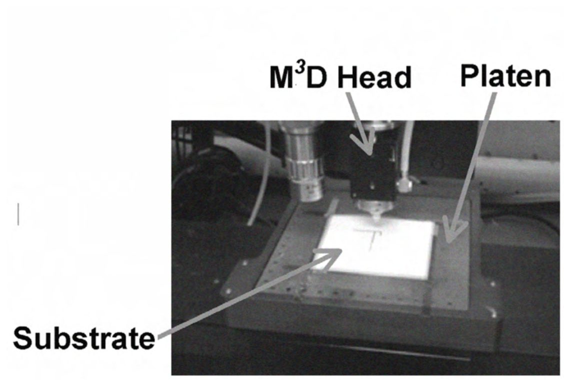


Table I: PIFA dimensions

w	0.57mm	*h*	5 mm
d	10 mm	*l*	26.15 mm

Figure 1. PIFA antenna on paper design schematic.



a)

Figure 2. PIFA antenna during fabrication placed on the M^3D platen. The M^3D still head can be seen.

b)

Figure 3. The fabricated PIFA antenna on photographic paper substrate.

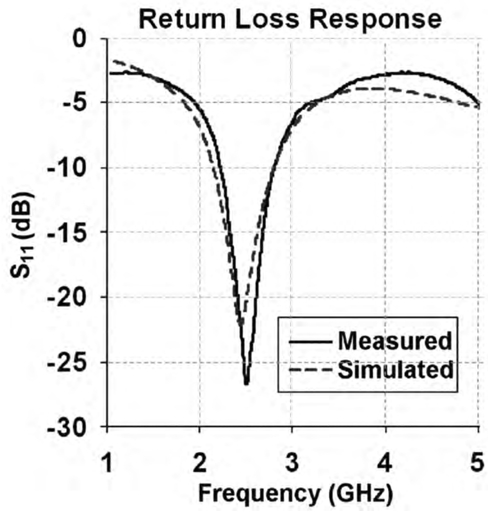


Fig. 4. The simulated and measured return loss response of the PIFA on paper (superimposed).

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[8] IE3D™ is a trademark of Zeland Software Inc.

[9] Low temperature conductive ink, intellectual property of LAEC, South Dakota School Mines & Technology.