Evaluation of a Low-Cost Inkjet Printed Slot Antenna for Energy Harvesting Applications

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Abstract— **This paper deals with the functionality of an inkjet printed slot antenna for radio frequency (RF) energy harvesting application. The antenna is printed on a paper substrate using an off the shelf inkjet printer with cartridges containing nanoparticle silver ink. The RF performance of the printed antenna is assessed, and compared with another antenna fabricated using conventional etching methods. The reflection coefficient characteristics of the two antennas are very similar. A PowerCast radio frequency (RF) power transfer and energy harvesting system is employed for the final evaluation of the antennas. The inkjet printed antenna is able to harvest a good amount of RF power, though less than the equivalent copper etched antenna on Mylar substrate. The antennas operate at the 915MHz UHF ISM band. Finite-difference-time-domain simulations compare well with test results.**

Keywords— Inkjet printing; RF energy harvesting; slot antenna; internet of things.

I. Introduction

Radio frequency (RF) energy harvesting and self-powered sensors have been attracting significant research interest in the last decade [1]-[3]. This activity is driven by the growing need of going wireless for the internet of things (IoT), and the latest advances in low-powered devices. The fact that most commercial wireless sensors use low power makes them a good target for devices to be powered by energy harvesting methods.

Inkjet printing of electronic circuits is a thriving technology [4]-[12]. In this technology, the printing of the metallic patterns is carried out mostly using nanoparticle silver inks. It is a relatively low cost fabrication technique that can be scalable through a roll-to-roll process. Inkjet printing has been proposed for the fabrication of development of RFID Tags [4]-[5], Sensors [6], RF energy harvesting technology [7], frequency selective surfaces [8], electromagnetic band gap structures [9] and antennas [10]-[12]. Most of the reported work has employed printers that are relatively expensive for home use. Only very recently, inks have been developed for use with low cost printers, and electronic devices have been proposed using this technique [13].

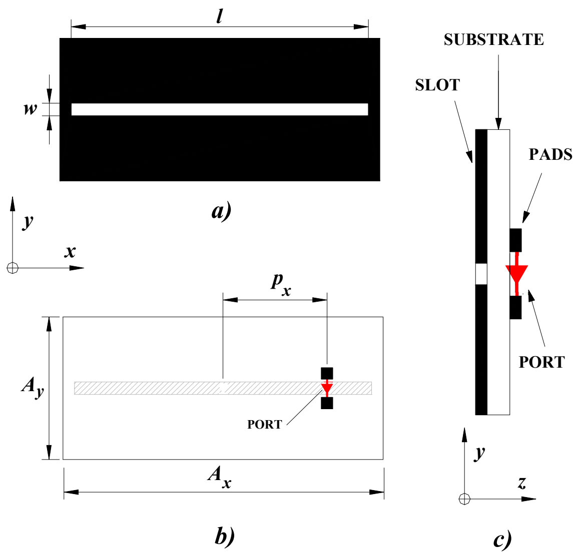


Fig. 1 Slot antenna dimensions: (a) front view, (b) back view, (c) side view

TABLE I Antenna dimensions

	l	w	A_x	Ay	P_x
Dimensions (mm)	158	1	188	96	1.3

This paper presents a study of the effectiveness of fabricating slot antennas using low-cost inkjet printing techniques for use in energy harvesting applications. A slot antenna has been fabricated using commercially available nanoparticle silver ink and an inkjet printer suitable for home or office use. A second identically antenna has been fabricated using standard etching methods on a double sided copper Mylar substrate. The reflection coefficient characteristics of both antennas have been measured and compared. The antennas were then tested in an indoor environment using PowerCast radio frequency (RF) power transfer and energy harvesting system [14]. The performance of the antennas in the energy harvesting configuration are evaluated and discussed.

II. Slot Antenna For RF Energy Harvesting

A. Antenna Design

A slot antenna is a well-known resonator with many useful properties. Its complementary form is a wire or strip and the impedance and data pattern of this form can be used to predict the behaviour of the slot antenna [15]. The large amount of metal used in the slot antenna makes it an attractive solution for inkjet printing technology. This is particularly true if the conductivity of the deposited metallic layers is not very high compared with other fabrication methods. A half wavelength slot antenna was designed to operate at the 915MHz ISM band. The dimensions of the antennas are shown in Fig.1 and table I. As described in [15], the feeding of the slot have to be placed in one side in order to achieve 50Ω input patch. The substrate used was a polyethylene terephthalate (PET) film of thickness 135µm, permittivity, ε_r, of 3 and loss tangent of about 0.02. In order to be able to connect the inkjet printed antenna without damaging the printed tracks, capacitive coupling pads were placed at the back of the antenna (Fig.1b). The dimensions of the metallic pads was 5mm x 5mm. This pads can also work as decoupling capacitors for the RF energy harvesting circuit, though this was not the primary use in the design.

Fig.2 presents the simulated reflection coefficient (S_{11}) of the antenna when the port was connected directly to the slot, and also when the port was connected to the capacitive coupling pads. As can be seen from the figure, the pads have a very minor effect in the S_{11} of the antenna. The resonant frequency decreased by less than 1%. In both cases, the antenna resonated at about 915 MHz with -10dB bandwidth of about 9%.

B. Fabrication and Measurements

The antenna design was exported to a .gbr file and then converted to a .pdf file for printing. A Brother MFC-J5910DW inkjet printer was employed together with the AgIC-CP01A4 paper and AgIC-AN01 Silver Nano Ink [16]. Fig. 3 shows the fabricated antenna on the paper substrate. The substrate had a thickness of 135µm. The sheet resistance of the printed metallic layers is about 0.2Ω/sq [16]. The resistance between any two ends of the antenna was found to be less than 1Ω. The two capacitive coupling pads were fabricated using adhesive copper tape and were attached to the back of the PET film in the location described in Fig.1 b. The pads were connected to a semi rigid coaxial cable which had a 50 Ω SMA connector in the other end. A piece of Polyurethane was used as support for the antenna and connector. In order to assess the performance of the inkjet printed antenna, the same model was fabricated by etching the patterns on the metallic layers of a double-sided copper clad Mylar substrate (Fig.4).

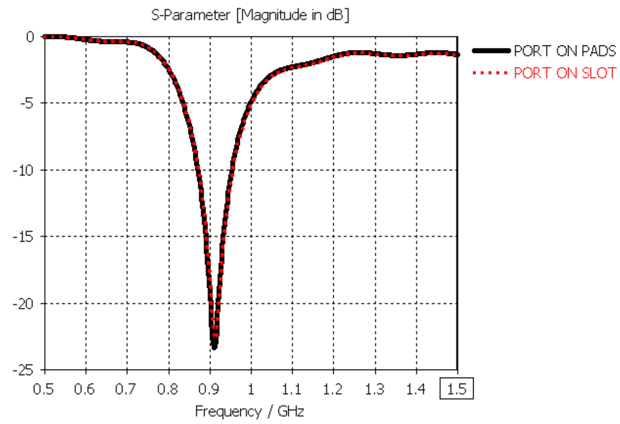


Fig. 2 Simulated reflection coefficient (S_{11})

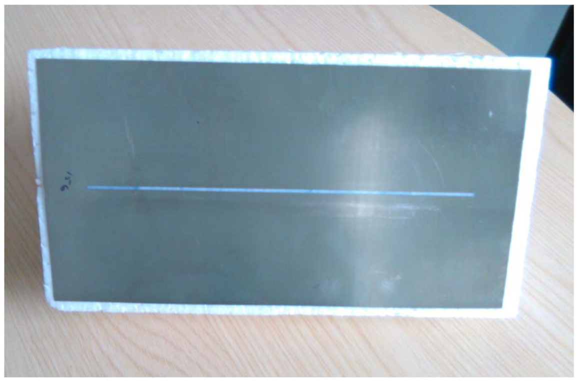


Fig. 3 Inkjet printed slot antenna

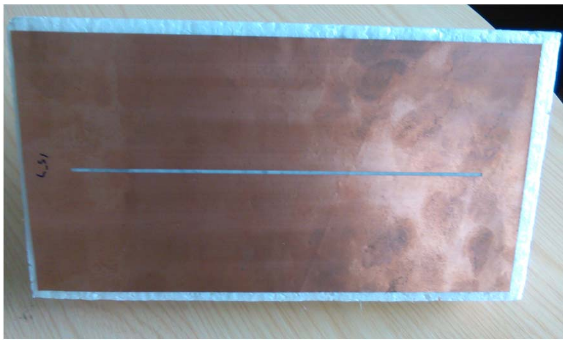


Fig.4 Copper etched slot antenna

The measured reflection coefficients (S_{11}) of the inkjet printed and copper etched antennas are shown in Fig.5. The simulated reflection coefficient is included for comparison. The copper etched antenna resonated at about 900MHz, while the inkjet printed antenna at slightly lower frequency. The two antennas covered the 902-928Mz required for the PowerCast power transfer and energy harvesting system.

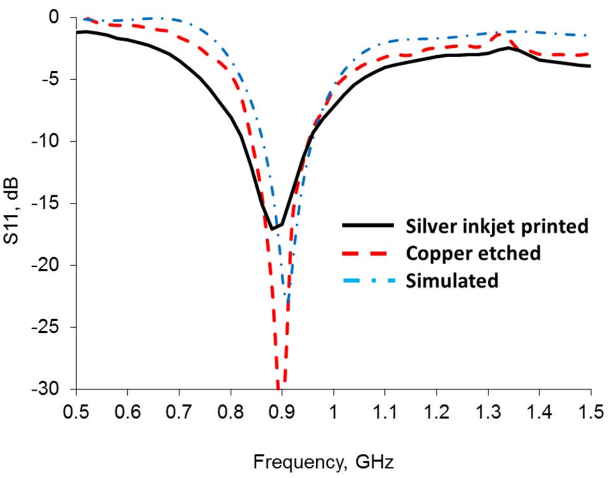
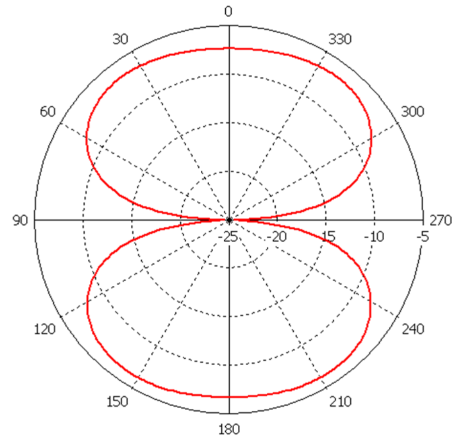


Fig.5. Reflection coefficients (S_{11})

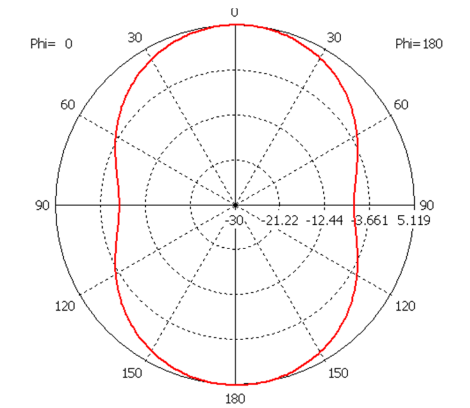
The computed radiation patterns of the antenna at 915MHz are shown in Fig. 6. As expected, patterns were those a slot antenna, and were not affected by the inclusion of the capacitive coupling pads. The gain of the antenna was 4.9dB.

C. *Evaluation of the Antennas using PowerCast Energy Harvesting System*

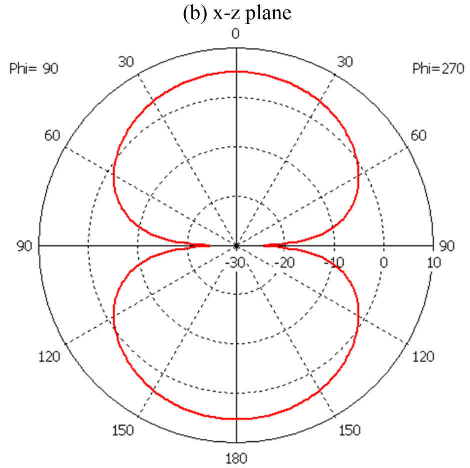
The Lifetime Power® Energy Harvesting Development Kit [14] was used for the assessment of the slot antenna in an energy harvesting system. In this development kit, the source of RF energy was the TX91501 transmitter (Fig.7 (a)) which sends radio waves at 915 MHz. The power output of the TX91501 is a factory fixed (not user adjustable) and equals to a maximum of 3 watts. Besides this frequency, other RF energy sources that operate within a range of 850-950 MHz can also be used to harvest energy from. The harvesting module with the wireless sensor board and an antenna supplied by the manufacturer is shown in Fig.7 (b). The board is equipped with an SMA connector which is used connect the antenna under test. The module uses the the Powercast P2110 power harvester receiver, which has all the RF circuitry necessary to convert ambient RF signals to DC. It also has capacitors as storage devices to power the wireless sensor board without using batteries. The P2110 converts RF energy into DC power and it charges the capacitor until a threshold is reached. When the capacitor is charged, regulated output of Power harvester Receiver is used to power the wireless sensor board until the low-voltage threshold on the capacitor is reached or until the operation is completed by the wireless sensor board.



(a) x-y plane

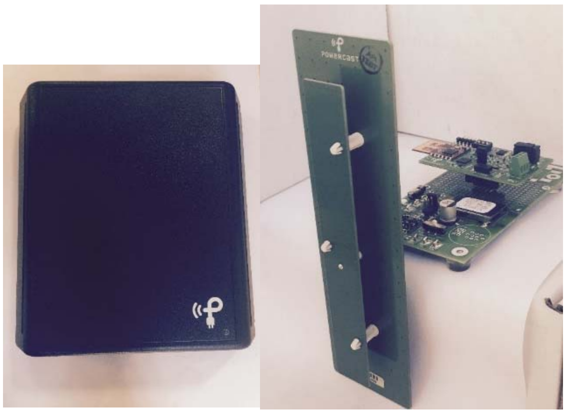


(b) x-z plane



(c) y-z plane

Fig. 6 Computed radiation patterns



(a) (b)

Fig. 7 Main units of the Lifetime Power® Energy Harvesting Development Kit: (a) TX91501 transmitter (b) receiving energy harvesting and wireless sensor module

The TX91501 transmitter is designed to transmit power and data to target devices equipped with the PowerCast power harvester receivers (P2110 or P1110). This is done by transmitting radio frequency power in the form of Direct Sequence Spread Spectrum (DSSS) at a centre frequency of 915MHz. The beam of the radiation pattern is 60 degrees wide, 60 degrees high and vertically polarizes to enhance transmission.

The main operation of the system is as follows. When one of the test antennas is connected to the board, it feeds the power harvester receiver. The power harvester receiver converts the RF energy into DC power which is used to charge a super capacitor on the main board. The super capacitor accumulates energy until a threshold of 1.2 V is reached, it then discharges its energy to a voltage booster. Then, the voltage booster increases voltage level from 1.2 V to 3.3 V which is enough to power a wireless sensor node.

The wireless sensor board is equipped with 2.4 GHz IEEE std. 802.15.4 RF transceiver, 12-pin module and a general purpose 16-bit flash microcontroller. It contains three different sensors mounted on its circuit, one for humidity, another one for light intensity and a third one for temperature. When the wireless sensor board receives power from the super capacitor, it wakes up its microcontroller to perform measurements using the mentioned sensors, then sends gathered data to the sink node in a form of data packet. The wireless sensor board also transmit data related to the RF power received, and DC power converted.

The configuration for the measurements of the power transfer and energy harvesting system is shown in Fig.8. Measurements were carried out in an indoor environment with a fixed transmitter and a movable harvesting receiver.

Fig.8. Power transfer and energy harvesting set up

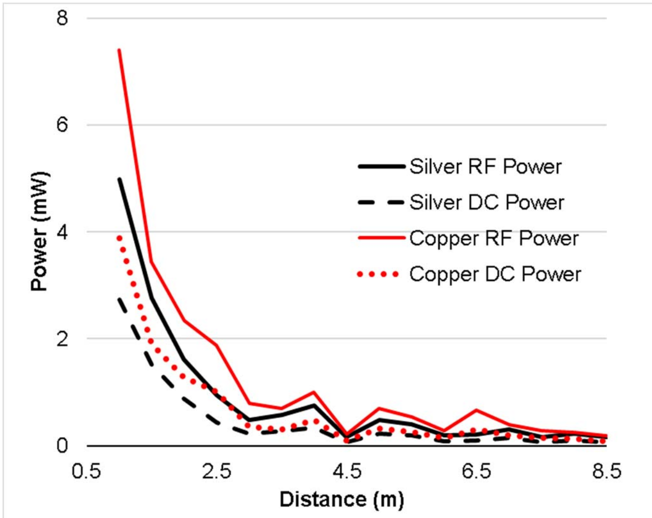


Fig. 9 Harvested RF and converted DC power for the Inkjet printed, and copper antennas

Fig.9 shows the RF power harvested and DC power converted by the module from 1 to 8.5m. In general, the graph of power versus distance follow an exponential decay, with some fluctuations due to the nature of the indoor environment. The average RF power received and DC power converted by the silver ink antenna was about 25% lower than the copper antenna. The maximum distance of operation was about the same for both antennas (8.5m). The available RF power at the receiver antenna was 0.15mW for silver ink and 0.19 mW for copper antenna at maximum operational range. The harvested DC power at the maximum range of operation was 0.07 mW for the silver and 0.09 mW for the copper antenna. The wireless sensing board was still able to activate the sensors and send the corresponding data at 8.5m.

III. Conclusion

Inkjet printing using inexpensive printers with silver nanoparticle ink cartridges can be employed to fabricate planar slot antennas. The characteristics of these antennas allow for resistance values on the surface of the metallic layers to be relatively low. Capacitive coupling pads permit the feeding of the antenna without damaging the printed metallic layers. These types of antennas are able to operate in an indoor power transfer and energy harvesting environment. The maximum distance achieved for this application is about the same than it is for a copper antenna fabricated using standard etching methods. However, the RF power harvested and DC power converted is about 25% lower than for the copper antenna. The main advantage of the silver ink printed slot antennas is that they can be fabricated easily, and are still able to operate reasonably in an energy harvesting environment.

IV. Acknowledgements

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