Rotogravure Printed UHF RFID Antennae Directly on Packaging Materials

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Abstract

In this work, rotogravure printing was employed to print conductive antenna patterns for radio-frequency identification (RFID) tags. A total of eight paper-based packaging substrates and one PET film were printed. A gravure cylinder was engraved at different resolutions, in order to evaluate the effect of engraving parameters on antenna performance and print attributes. Two silver-flake inks, water-based and solvent-based, were printed. The gravure print trials were conducted on a narrow-web flexographic press, modified to achieve transfer of the ink from an engraved image carrier directly onto the substrate, as in traditional rotogravure press set-up. Various test features were included in the printed image, such as RFID antennae designs for antenna performance measurement, and different lines for print quality and resistance measurements.

Multiple measurement methods were used to characterize the properties of printed samples. The resistance of the lines was obtained using low frequency AC measurement equipment. The dimensions (length and width) of the lines were measured using an image analysis system. The resistance and dimension results were combined to calculate sheet resistivity of the lines printed on each substrate. Further tests were performed to measure the radio frequency (RF) performance of the printed antennae.

Solvent-based and water-based ink systems showed differences in terms of pattern printability. From the three tested engraving resolutions, only two were found to be appropriate for obtaining acceptable antenna characteristics for both ink systems. Sheet resistivity and printed antenna performance results showed a dependence on the quality of the printed ink layers. A connection between antenna performance and AC resistance was investigated and a relationship established.

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Introduction

RFID belongs to automatic identification technologies and over the last few years it has been proven and is further expanding its applications. RFID system consists of three main components, i) RFID tag or transponder device, which carries information about the item to be identified, ii) reader that communicates with RFID transponder through radio waves, iii) computer system, which processes transmitted data and converts the analog signal to digital form. RFID tags are categorized according to operational frequency, which will determine their application. Presently, the main obstacle in broader application of this technology is the price of a RFID tag. The main driving force for lowering the cost of RFID tags is to improve the accuracy of product information (location, value, quantity, etc.) in different stages of the supply chain from manufacture, through transportation and distribution to retail stores (Clarke, 2002). An RFID tag consists of two main components, i) coupling element or antenna, through which it receives the signal from reader and then transmits the signal back, and ii) electronic microchip carrying information about the tagged item (Finkenzeller, 2003). It was believed that RFID tags would once replace widely used barcodes. However, the price of RFID tag is yet not sufficiently low for such item level applications.

The first step in lowering the price of RFID tags is to lower the manufacturing cost of antennae by replacing subtractive techniques such as stamping and etching of metal with additive processes, such as printing, that are capable of patterning highly conductive metal inks on labels or directly onto packaging materials. Among printing technologies, screen-printing has been used in the electronics industry for several decades, mainly due to its ability to deposit thick ink film (Gilleo, 1996). Although it is an easy and economical process for smaller quantities and shorter runs, the speed limitations of screen printing drive forward the use of other high-speed printing processes, such as rotogravure and flexography. The availability of reliable conductive inks for printed antennae facilitates the utilization of these processes. In fact, the main RFID label manufacturers in USA and Japan recently started to use gravure printing in manufacture of UHF RFID antennae (Harrop, 2006). Performance of an RFID tag antenna depends on several factors, such as antenna shape, impedance and surrounding environment (Foster, 1999). It has been reported that for some antennae, printed silver ink performs as well as etched copper and that differences in material impedance can be eliminated by optimizing the antenna design (Nikitin, 2005).

Gravure printing is the highest quality printing process used for printing catalogues and magazine, stamps, packaging labels for cigarettes, food and cosmetics, etc. The gravure printing unit consists of i) engraved cylinder rotating in inking pan, ii) doctor blade wiping the ink from non-image areas, iii) impression roller, which brings the substrate into contact with the cylinder and helps transfer the image and iv) a dryer (Gillett, 2003). Robustness of cylinder and improvements in engraving technologies make gravure an excellent candidate for high volume and high resolution printing required in printed RFID.

Conductive inks used for printed antennae are usually silver-flake filled inks, because they form better conductive traces than spherical particles by close packing, without melting the flakes (Pudas, 2005). Even though, the use of silver nanoparticles leads to significantly lower sintering temperature and thus sufficient conductivity (Dearden, 2005), the price of such inks is still high for printed RFID applications. Considering the processes, it would be beneficial to print RFID antenna directly on packaging substrates, and eliminate the need for various converting operations. Paper-based materials are advantageous for their low price; they are made from renewable resources and can be recycled.

This paper focuses on performance of RFID antennae, which were gravure printed onto several different paper-based packaging materials. The effect of engraving resolution, as well as ink and substrate type, is reported.

Experimental

The image design for the rotogravure cylinder was prepared with respect to further examination of print quality attributes, dimensional changes, electrical properties, and radio-frequency (RF) performance of printed antennae. This paper focuses mainly on electrical aspects of printed conductive traces (lines) and antennae.

The cylinder for the print trial was engraved using laser imaging of the mask resist followed by chemical etching (Southern Graphics & Systems, Inc.). This process of gravure cylinder engraving is also known as indirect laser engraving (Kipphan, 2001). After engraving, the cylinder was chromium plated by traditional methods. Three different cell volumes were used on one gravure cylinder. This was achieved by changing the resolution of the cylinder image (200, 300 and 400 lpi). Since only one cylinder was used for all three of the resolution bands, cell depth (20 μm) was constant and only the cell opening changed.

A narrow-web flexographic press XP 5000 (Comco/Mark Andy) was modified to enable the first printing unit to be converted to a gravure-printing unit by mounting the gravure cylinder in place of the anilox roll, removing the plate cylinder and incorporating an impression roller. After such modifications, the press was used to print on paper-based substrates. For the drying of prints, a total of five hot-air driers were used. Three of them were operating at drying temperature of 126.5 °C and two additional units at 29.5 °C.

During the trial a total of eight commercially available packaging substrates were printed. Four different grades of label paper (marked from P_1 to P_4) and two PE (polyethylene) extruded paperboards and one clay-coated paperboard (marked from B_1 to B_3) were used. Also, PET film was printed as a reference substrate. Two commercially available inks (Acheson/Electronic Materials), solvent-based (SB) and water-based (WB) conductive inks were used during the print trial. These inks contain silver flakes, providing electrical conductivity of final printed areas. During the print trial, a sufficient number of printed samples from each substrate-ink combination was collected and afterwards was kept in the laboratory room under the TAPPI standard conditions of 23°C and 50% RH (ASTM D 685).

In order to obtain electrical characteristic (sheet resistivity) of printed features, lines with designed area of 50 squares (50 mm length by 1mm width) were measured for AC impedance and dimensional changes (deviation from designed dimensions). Dimensions of the printed lines (line length and width) were measured by ImageXpert system based on software processing of images taken with a CCD camera. High precision optical measurement provides a full suite of image analysis algorithms to characterize the quality of printed output. (Wolin, 1998).

The ink film thickness of the printed traces was measured using an optical microscope (Nikon, max. magnification 1500X). The samples were embedded in an epoxy resin and then ground and polished, using an automated grinder/polisher (Leco Corporation) to achieve a smooth surface. The cross-section of the ink-substrate interface in the print direction was used to measure the ink film thickness.

An Agilent 4338B Milliohmmeter was used to perform the AC impedance measurements. This instrument performs 4-point probe measurements using a 1 kHz current source reference. Using known current magnitude and phase, the device measures the magnitude and phase of the voltage waveform across the device under test and computes the complex impedance in terms of (Carlson, 2000):

$$Z = R + j \cdot X \tag{1}$$

where *R* is the electrical resistance in Ω,
X is the reactance in Ω, and
j is $\sqrt{-1}$.

The sign of X defines whether the impedance at 1 kHz is inductive (positive) or capacitive (negative) and can be used to estimate the magnitude of the inductance or capacitance.

After resistance characterization of printed features, printed antennae were tested for their RF performance (Agilent Agilent 4396B Network/Spectrum Analyzers). Antenna testing was conducted at multiple levels of radio frequency continuous wave (CW), reflected impedance, and RFID dynamic time waveform capture. The testing provided the insight into the ability and usefulness of various combinations of substrates and inks for printed antennae. The antenna testing set up consists of a fixed reference antenna at a defined distance (3.6 m) to a test antenna placed on a movable pedestal. The tested (printed) antenna was mounted on top of a movable pedestal, which was able to move in X-Y directions (X-rotation 360°, Y-elevation ±45°). The Alien Technology UHF RFID tag “squiggle” (2^{nd} generation) antenna design was used as a pattern for the printed antenna. In order to compare the performance of the gravure printed antennae with commercially available ones, permission to use original copper etched Alien “squiggle” antenna was obtained.

Results and Discussion

Before full examination of printed samples, a control test was carried out to determine whether additional increase in electrical conductivity of the printed features can be achieved by heat treatment. During this test samples were exposed to TAPPI drying temperature 105 °C at increasing time segments. It was found that even after a 17 hour treatment, the improvement in conductivity is significant. Therefore, the testing of antenna performance after the same curing conditions was performed, which showed that final performance of printed antennae did not significantly changed after 20 min. Based on these findings, a postcuring time of 20 minutes at 105°C was used as a post treatment for all samples.

Figure 1 shows the results from AC impedance measurement. For the data collected, an average and standard deviation from at least 5 samples were calculated. Measured reactance part (jX) was insignificant when compared to the resistance part (R) for all measurements, indicating purely resistive character of printed lines and therefore the reactance contributions were neglected from further considerations and are not shown in charts.

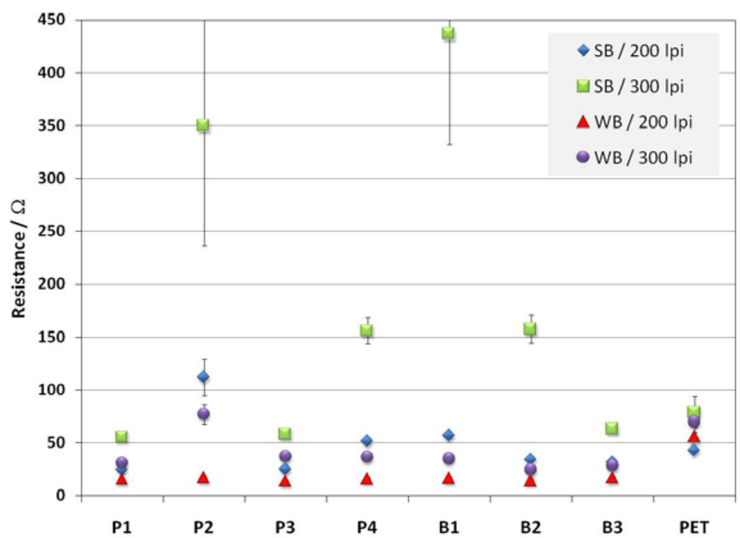

Figure 1 AC Resistance of lines printed with solvent-based and water-based ink at 200 and 300 lpi resolution

Only results for two out of three tested resolutions are presented. Samples printed at the resolution of 400 lpi did not provide satisfactory conductivity (or were not conductive at all) and thus were eliminated from further studies. Such high resolution did not transfer sufficient amount of conductive ink from cylinder to the substrate. Even though the edge definition was good for 400 lpi, the thickness of dried ink film was very low and ink coverage on larger areas was not uniform and complete (Figure 2) resulting in poor electrical performance of printed features. Also, it can be seen (Figure 1) that, for both ink systems, lower resolution is better in terms of resistance value. For the reference substrate PET, the differences in resistance values for the two tested resolutions are minimal.

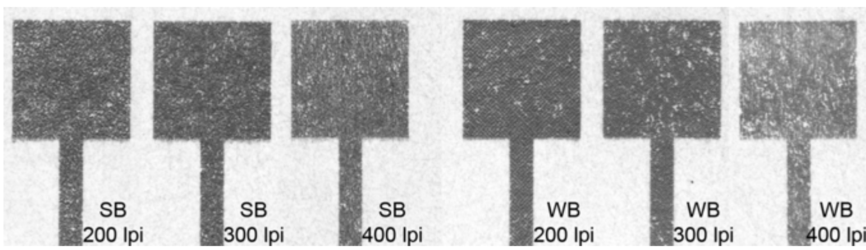

Figure 2 Printed feature (on end line used to conductivity measurement) on substrate P_1 with both inks (SB and WB) for all resolutions (200, 300, 400 lpi) (Magnification 3.5 x)

Figure 3 presents the measured dimensions of lines, which were later used for calculation of sheet resistivity of printed samples. For all samples and inks, the measured line width values are very close to the specified value (dot-dashed line determines nominal value of 1 mm). For a few paper samples, the “gain” in line width is negative. There is no significant difference between samples printed at the 300 lpi and 200 lpi resolution, because all variances are within the standard deviation. The same statement can be made for the comparison between studied inks.

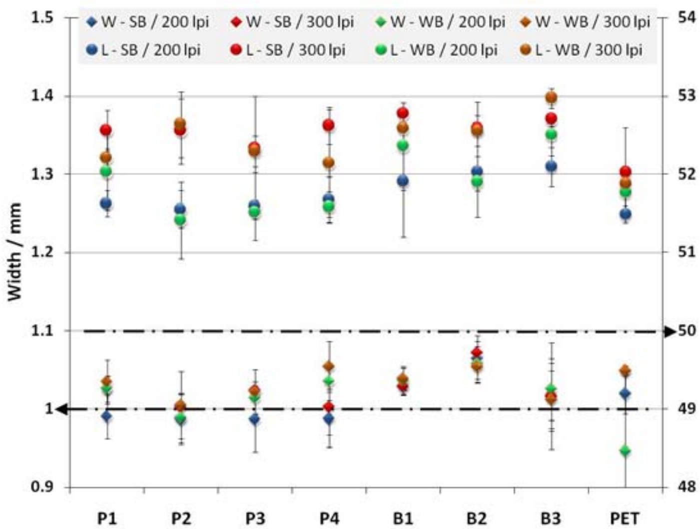

Figure 3 Measured dimension of printed conductive lines and their deviation from designed values (W-width, L-length)

Considering the line length measurement, most of the lines printed at 200 lpi have a lower length gain then those printed at the 300 lpi. But for all samples, the length values exceed the designed value (dot-dashed line determined 50 mm value).

Finally, AC resistance values and dimensions of printed lines were combined in equation 2 to calculate sheet resistivity of printed features (Sze, 1981).

$$R_S = R \cdot \frac{l}{w} \tag{2}$$

where R_S is sheet resistivity in Ω sq^{-1},
R is the AC resistance in Ω,
l is length in mm and w is width in mm.

Results obtained using Equation 2 are summarized in the Figure 4. The best conductivity (the lowest sheet resistivity) was achieved for traces printed with water-based silver ink at 200 lpi resolution. Since dimensional changes of printed features after the printing process were minimal, the trends for sheet resistivity are similar to AC resistance. That means better conductivity for features printed at lower resolution. Also, it can be observed that, for most cases, water-based ink performs better in terms of electrical conductivity then solvent-based ink for both resolutions. Comparison of paper substrates with PET substrate revealed that, for the most of the ink-resolution combinations, paper substrates yield better conducting traces then the PET substrate.

Between paper substrates (label papers and paperboards), there is no clear trend. At 200 lpi features printed with water-based ink on paper substrates are at the same level of resistance. Broader values in the group of paper substrates were observed for solvent-based ink at 300 lpi resolution.

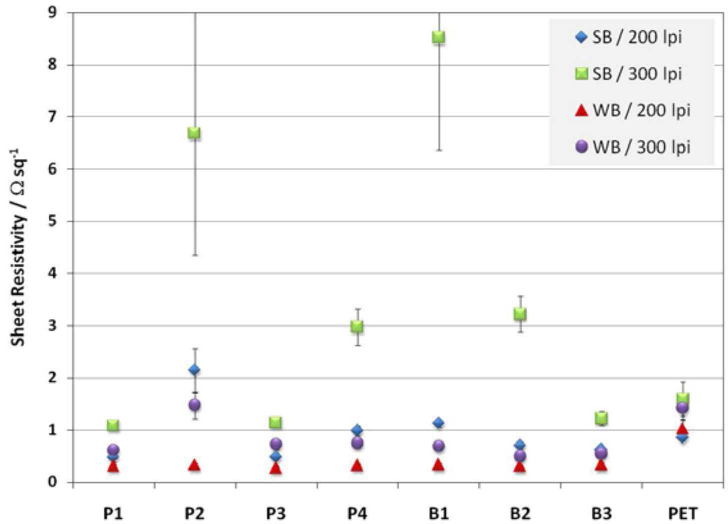

Figure 4 Sheet resistivity of lines printed with solvent-based and water-based ink at resolution 200 and 300 lpi

Next, printed antennae were tested for their performance in RF range from 860 MHz to 960 MHz. Results of the tests are calculated as an average loss magnitude across frequencies ranging from 902 MHz to 928 MHz for -5, 0 and 5 degree elevation and 360° azimuth. Multiple measurements of antenna performance were done to ensure reliable results and an average was calculated for each condition. It was calculated that for evaluating range, a -46.4 dB loss magnitude could be expected. Thus, each antenna with loss magnitude higher than -46.4 dB was considered as acceptable.

Figure 5 shows the results from the antenna performance measurements. The dot-dashed line represents the limit for acceptable performance value (-46.4 dB). To compare experimental results obtained for printed antenna with performance of commercialy available antennae, copper etched antennae on PET substrate were tested. The final result for commercial antennae is marked in Figure 5 with dashed line at -39.5 dB of loss magnitude.

The 90.6 % of printed antennae fall within the area between the acceptable magnitude and magnitude measured for commercial antenna. According to these results it can be stated that almost all printed samples met the requirement for sufficiently performing antenna, however none of them reached the performance of copper etched antenna. The closest level of performance to copper antenna was measured for antennae printed with water-based ink at 200 lpi resolution. On the other hand, antennae printed with solvent-based ink at 300 lpi resolution performed the worst.

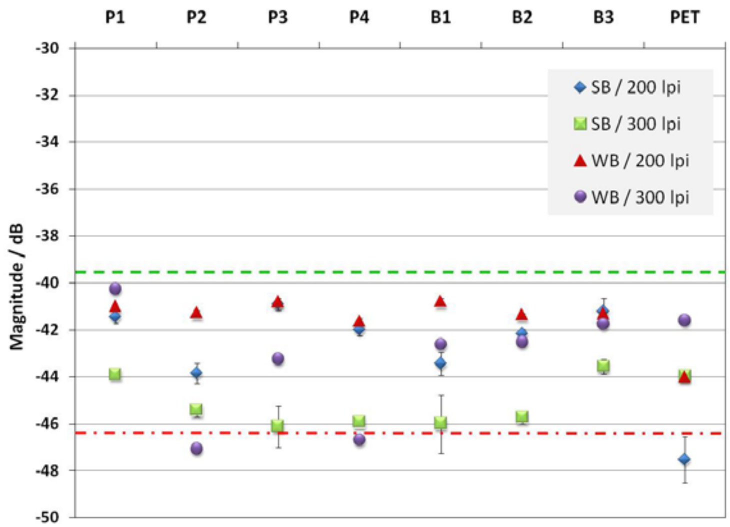

Figure 5 Antenna performance measurement results for antennae printed with solvent-based and water-based ink at 200 and 300 lpi resolution

In general, antenna performance depends on impedance of the material it is made of (Foster, 1999). In this work, it was noticed that lower impedance samples provided better performing antennae, however no strong correlation was found between antenna performance results and sheet resistivity values measured at low frequency (1 kHz). From these results it cannot be established what is the minimal conductivity that is needed to achieve acceptable antenna performance. It seems that the antenna performance is not just a function of conductivity (resistance) but it is a more complex relationship also involving topography and thickness of printed film and other print quality attributes such as edge definition. Substrate properties are also playing an important role in this relationship, since these are influencing all the factors mentioned above.

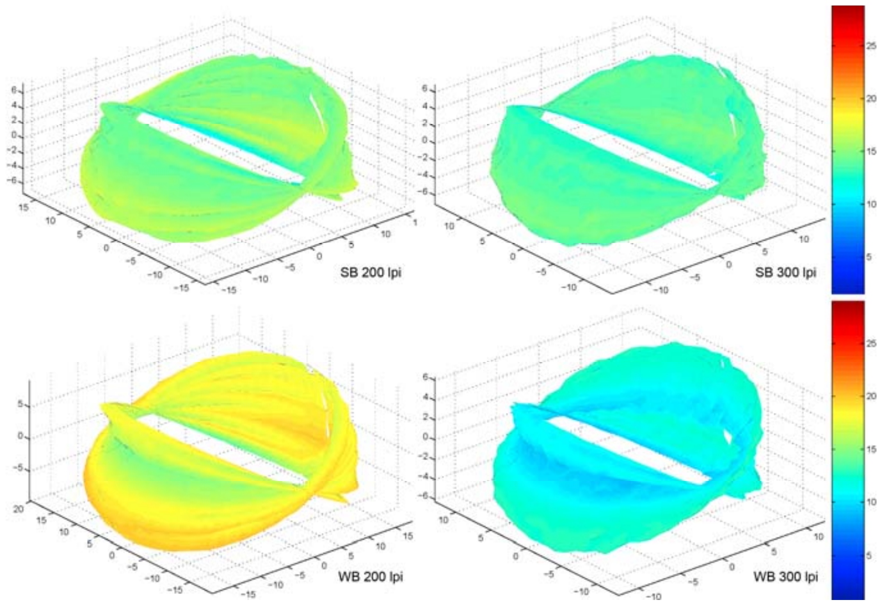

Figure 6 3D plots of performance for printed RFID antennae with solvent/water based inks at resolution 200 and 300 lpi (frequency 916 MHz, elevation ± 5°, azimuth 360°)

Figure 6 shows 3D images of performance for printed antennae on substrate P_2. Such images are used to express how the performance is changing with elevation and azimuth. Areas with the color closest to the red region (top of the scale) have better performance than areas close to the blue region (bottom of the scale). It can be seen that as elevation is changing, performance is changing too. All antennae have certain "weak" regions of performance, which is the nature of a particular antenna design and not an error caused by any used ink system or printing process. Also these 3D presentation of results confirmed that the best performing antenna was printed with water-based ink at the lowest resolution and that considering the ink system, higher resolution is providing lower performing antennae than those printed at low resolution.

As already discussed, none of the printed antenna reached performance of the copper antenna. One of the possible reasons might be the insufficient ink film thickness and/or unevenness of ink thickness. Results from ink film thickness measurement (for 200 lpi resolution) are reported in Figure 7. The significant high standard deviation of the measurements reflects the unevenness of the ink film.

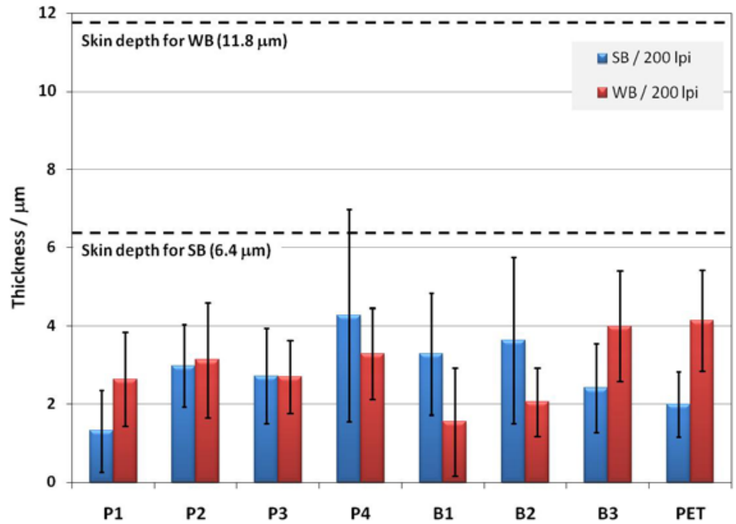

Figure 7 Ink film thickness for traces printed with solvent-based and water-based ink at 200 lpi

For RF performance, it is important to consider skin depth effects, which are dependent on the material impedance and the frequency (Ramo, 1984). Skin depth can be defined as the maximum thickness of a particular material at given frequency that will contribute to reducing the RF impedance. Thus, thicker ink films will reduce RF impedance until the skin depth is reached. Ink film thicknesses greater than the skin depth are not necessary and would be a waste of material. For inks used in this work, skin depth was calculating for frequency 916 MHz and the values are 6.4 μm for solvent-based ink and 11.8 μm for water-based ink (dashed lines in Figure 7).

Conclusions

Two commercially available conductive inks were printed on paper-based packaging substrates and tested in terms of their electrical conductivity of printed traces and radio-frequency performance of printed UHF RFID antenna. It was shown that, with proper printing conditions, it is possible to directly print the working RFID antennae on paper substrate (Figure 8).

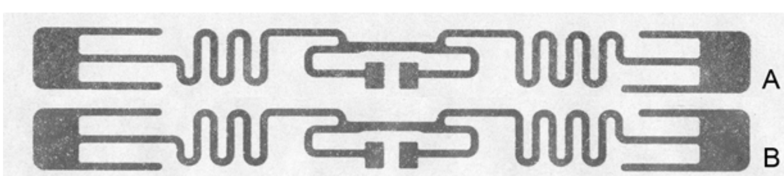

Figure 8 Working printed UHF RFID antennae on paper substrates (A-Solvent-based ink, B-Water-based ink; substrate-P_1)

From the three tested resolutions, only two provided conductive traces and functional antennae. The resolution of 200 lpi provided better conductive traces and performing antennae than 300 lpi, while maintaining good print quality. On the other side, resolution of 400 lpi provided insufficient conductivity of printed traces. For 200 and 300 lpi, most of the printed antennae performed at acceptable level and can be used as alternatives to traditionally produced RFID antennae. However, none of the printed antenna achieved equal performance of copper etched antenna.

For better understanding of relationship between electrical conductivity and antenna performance a deeper study on influence of ink film properties and the base substrate itself would be necessary.

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