Printed 3-D Stacked Chipless RFID Tag with Spectral and Polarization Encoding Capacity

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Abstract: A fully printable 3D stacked chipless RFID tag on a 50-μm thin polyimide film is presented. The tag consists of multi-layer cross-polarized dipole resonators which overlap. The data encoding is performed in the multiresonating circuit which is comprised of multiple stop band resonators. The resonators are printed using screen printing technology using a silver based conductive paste. The chipless RFID tag is designed specifically for security applications which are suitable for mass deployment for low cost items in trillions.

1. Introduction

Research efforts have been put into developing chipless RFID tags with no ASIC in an effort to lower the price of the entire RFID system [1]. In order to minimize cost, tags are made chipless. Chipless RFID tags have been designed and reported by researchers around the world. Encoding data without an IC is overcome with two main chipless tag encoding schemes: time domain reflectometry (TDR) based and spectral signatures. A comprehensive review of chipless tags is presented in [2].

So far, the only commercially available and successful TDR chipless RFID system is surface acoustic wave (SAW) based (developed by RF SAW®) [3]. Although fully operational, SAW tags are not fully printable and planar due to their piezoelectric nature and hence cannot be applied on banknotes, postage stamps or other paper/plastic based items. Printable TDR-based chipless tags have had data capacity and size limitations due to the requirement of long delay lines for data encoding [4].

Printable spectral signature (frequency encoding) tags have been published in significantly higher numbers by researchers due to their compact size, multi-bit capacity and reading range when compared to TDR based tags. The earliest version of a multi-bit 35-bit chipless tag was presented by *Preradovic et al* [5] using a basic presence or absence of resonance for representing logic '0' and logic '1', respectively. A further increase in data capacity was introduced by *Vena et al* which introduced a reduced size and a novel encoding technique based on resonance shifts within a certain frequency band which represent different binary codes [6]. *Islam et al* developed polarization diversity which further increased data encoding by using orthogonal polarizations [7]. Polarization diversity can only apply to applications where the tag's orientation and placement is constant and/or known at all times. If the code is repeated in both polarizations then the tag is orientation insensitive however the data capacity is reduced by half as reported in [8]. Chipless tags insensitive to polarization were presented in [9] which reports on tags using circular polarization scatterers that do not have orientation restrictions.

All of the afore mentioned researched papers present the tags which use copper. The entire purpose of chipless RFID is to reduce the cost of the tag to a fraction of a cent, therefore copper is not acceptable in a final solution. Conductive inks and pastes offer a cheaper and easier way to print tags but at the price of somewhat lower performance due to lower conductivity of silver-based inks/pastes when compared to copper. So far three types of printing techniques have been presented: 1) ink-jet and 2) screen printing and 3) flexography. Work on ink-jet printed chipless tags has been presented by *Vena and Tentzeris et al* with 3 scatterers and a total of 6 bits encoding capacity [10]. Work on screen printed chipless tags with 3 bit data capacity using the presence and absence of resonances was presented by *Nair et al* in [11]. Tags printed using flexography on paper have been reported by *Vena et al* in [12] which reports a tag with 5 resonators for encoding.

This paper presents a novel low cost chipless tag which has overlapping dipole resonators printed in multiple layers and orthogonal polarizations on a low cost substrate. The tag enables the use of 3 dimensional (3D) resonator placement for efficient use of space and enhances the tags application as a security feature. The resonators are printed using screen printing. We investigate the effect of different conductive ink thicknesses on the performance of the tag, tag orientation and the isolation between overlapping orthogonally polarized resonators. This tag is developed for security and anti-counterfeiting applications mainly, where the multilayer aspect of the tag does not automatically identify the true nature of the tag's layout and therefore creates ambiguity for counterfeiters. The chipless RFID tag has been patented.

2. Operating Principle

Fig. 1 shows the photograph of the chipless RFID tag. This tag prototype operates between 1.8 and 3GHz, but can move up in frequency and therefore reducing its dimensions. The tag uses linear polarized shorted dipoles printed in orthogonally polarized orientations on separated by a dielectric layer. In this paper we present the tag in 2 layers but it can easily be done in more, depending on the application. The tag uses dual polarization to either encode more data or enable the tag to be orientation insensitive.

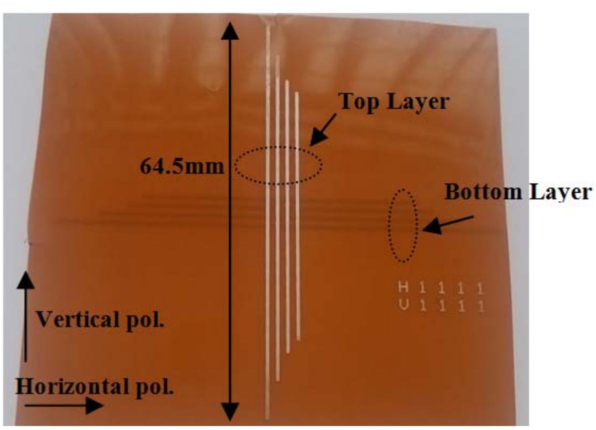

Fig. 1. Photograph of the printed chipless RFID tag.

To enhance the data capacity, each orthogonal polarization is achieved by printing a set of dipoles in vertical polarization and a set of dipoles in the horizontal polarization. In order to interrogated the tag the RFID reader is required to send a signal in both polarizations when polarization diversity is used for encoding or single polarization when it is not. Since isolation between orthogonally polarized signals is very high, both signals with orthogonal polarizations can be transmitted at the same time to reduce reading time. Each shorted dipole has a resonance which acts as a stop-band filter when the tag is set between 2 reader antennas. The number of bits depends on the encoding technique used as presented in Section I. A simple presence or absence of resonance gives a maximum capacity of 8 bits with each resonator encoding 1 bit. However, with encoding technique presented in [6] it can be increased, depending on the reader's frequency resolution and tag resonator separation.

3. Design

3.1. Tag Substrate and Printing

The tag resonators are used to encode data by resonating and different frequencies. Table 1 shows the relationship between the lengths of the resonators used in the tag with their resonant frequency.

TABLE I
CHIPLESS TAG RESONATOR LENGTHS

Dipole resonator Length (mm)	Resonant Frequency (GHz)
64.5	1.85
53	2.21
45	2.51
41	2.8

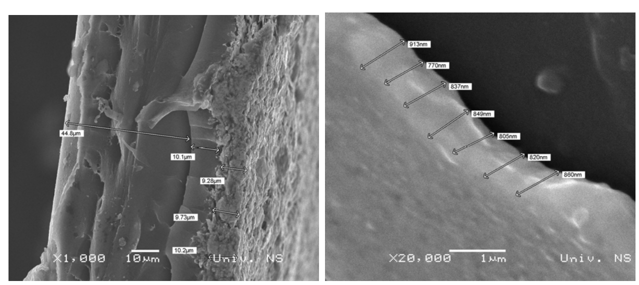

Fig. 2. Photograph of screen printed ink at 0.8 um and 10 um on the 50um polyimide film.

The tag is printed on a low cost Polyimide thin film (εr = 4.8, h = 50 µm, tanδ = 0.04). Using screen printing the conductive paste is deposited in various thicknesses. Fig 2 shows measured thicknesses of 0.8um and 10um using a microscope. From Fig. 2 it is clear that thickness of the ink can vary 15% from the desired thickness so it is important to measure more tags and average the results.

3.2. Tag Resonators

The tag resonators are used to encode data by resonating and different frequencies. Fig. 3 shows the relationship between the length of the resonators used in the tag from Fig. 1 with their resonant frequency. A parametric study of the spiral resonator layout parameters was performed using Ansys HFSS in order to design the optimal resonators based on its attenuation and resonant frequency, and is shown in Fig 3. The resonators are evenly spaced at ~300 MHz.

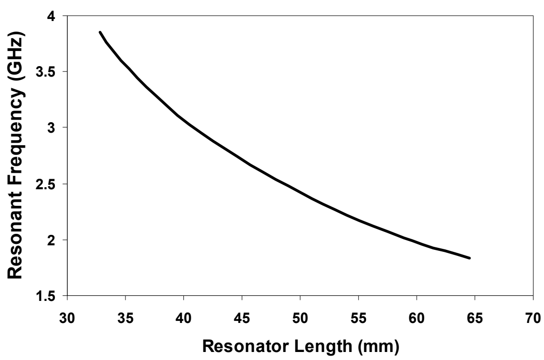

Fig. 3. Simulated variation of the dipole resonant frequency vs dipole length.

The figure of merit for the next parametric study would be the attenuation created by each tag resonator. Better performing resonators were attenuating stronger at their resonant frequency. The tag was placed between 2 reader antennas at a distance of 5 cm from each antenna. The reader antennas were UWB low gain disc monopole antennas. The near far-field region for the monopole antennas is calculated to be at ~2 cm.

After setting the length of the resonators we investigated the effect of the thickness of the printed conductive ink. We calculated that the conductivity of the ink was approximately 3 million S/m. The resonator was set to a length of 64.5 mm resonating at 1.85 GHz. Fig. 4 shows the variation of resonator attenuation with ink thickness. As expected the thicker the deposition of the conductive ink the greater the attenuation. Below 4 um the attenuation of the resonator drops below 10 dB. Below 1.5 um the attenuation starts dropping faster due to the skin effect. The recommended ink thickness should be above 6 um based on results in Fig. 4.

A parametric study of the separation between dipole resonators and width of the dipole resonators are presented in Figs 5 and 6. We set the printed conductive ink thickness as 10 um. Placing dipole resonators next to each other causes them to couple. It is first required to understand the minimum separation between resonators before coupling starts affecting the performance. We observed each of the 4 resonators. From Fig. 5 it is clear that the minimum required separation between resonators is 1000 um.

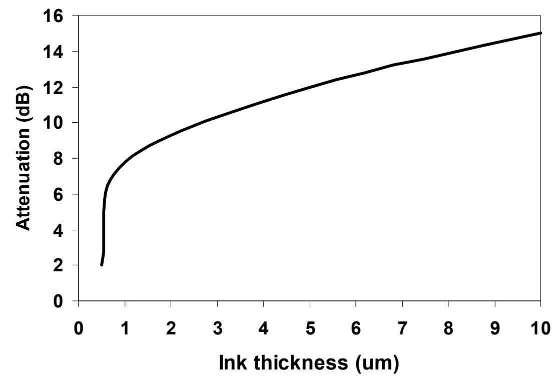

Fig. 4. Measured variation of the resonator's attenuation vs ink thickness.

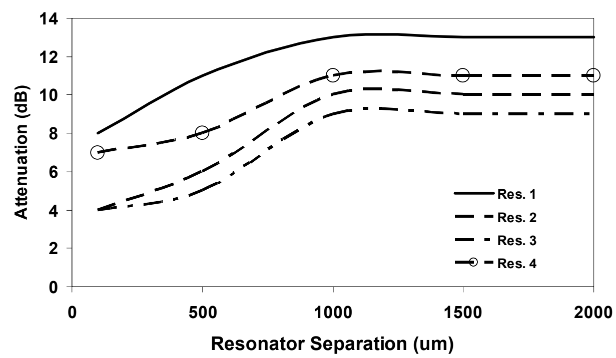

Fig.5. Measured variation of the resonator's attenuation vs separation between resonators.

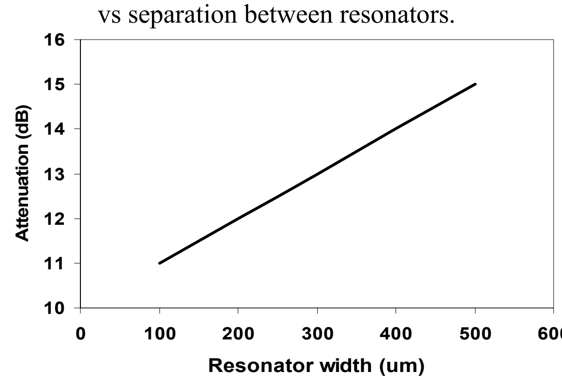

Fig. 6. Measured variation of the resonator's attenuation vs resonator width.

Fig. 6 shows the response of the resonators for different widths. The width of the resonator was varied from 100 um to 500 um. A linear relationship between attenuation (dB) and resonator width (um) was observed. In the following section we will look at tag performance in terms of polarization diversity encoding, orientation sensitivity, reading range and isolation between cross-polarized resonators.

4. Results

4.1. Experimental Setup

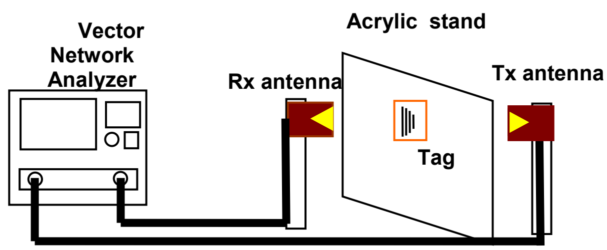

Fig. 7. Block diagram of chipless RFID experimental setup.

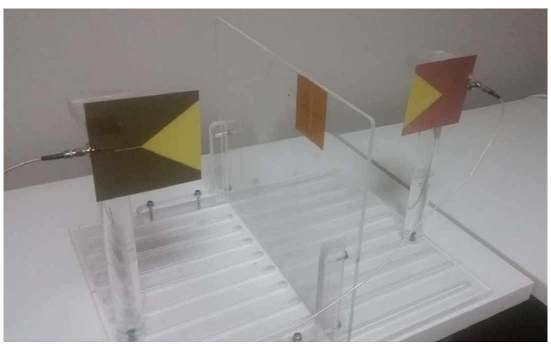

Fig. 8. Photograph of chipless RFID experimental setup.

The experimental setup block diagram and photograph are shown in Figs 7 and 8 respectively. The reader antennas are linearly polarized Vivaldi antennas. Vivaldi antennas exhibit wide bandwidths, directional radiation patterns and high gain. The tag is placed 10 cm away from each Vivaldi antenna. An Anritsu vector network analyzer is used as the reader unit transmitting -10 dBm power. The S21 parameter is measured when the tag is placed between the reader antennas and when it is not present. The s-21 measurement of when the tag is not present is used to calibrate and normalize the received signal from the tag. We will show two modes of tag encoding: cross-polarization encoding and orientation insensitive encoding.

4.2. Cross-Polarization Encoding

In this section the chipless RFID tag is using polarization encoding to enhance the number of resonances used to encode data and therefore enhance its data capacity. The application of the tag in this case is orientation sensitive and must be known to align the reader antennas polarization.

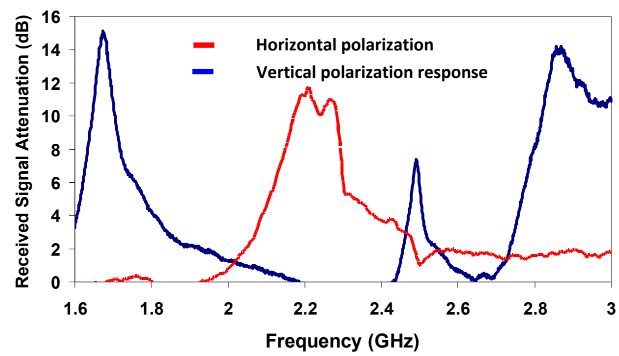

Fig. 9. Measured received signal from the tag 10110100.

Fig. 9 shows the normalized received signal from the tag. The tag encodes the data using 3 resonances in the vertical polarization and 1 resonances in the horizontal. Resonances are removed by not printing the dipole resonator. It is clear from Fig. 9 that the resonators in the orthogonal polarization do not appear in the response. We can conclude that the polarization isolation is very high and that it is possible to have good isolation with the resonators overlapping and separated by a thin 50 um dielectric.

4.3. Orientation Insensitive Encoding

If the application of the tag requires the tag orientation to be unknown or for the tag orientation not to be fixed then the dual polarization capability can be transformed into a polarization insensitive capability by encoding the same code in both polarization planes. Fig. 10 shows the response of the tag when rotated by angles 0, 45 and 90 degrees respectively. In all 3 orientations the tag response remains reasonably constant and uniform therefore enabling orientation and polarization insensitivity.

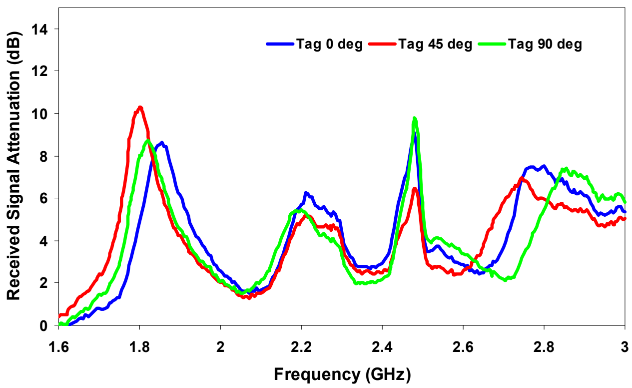

Fig. 10. Measured code of tag 1111 for different rotations.

4.4. Distance

Fig. 11 shows the response of the chipless RFID tag at different distances from the reader antennas. A chipless tag with 4 resonators printed is used in this experiment. A comprehensive study has been reported in [11] on conductive ink printed tags and reading ranges up to 100 cm have been reported. In this paper we experimented up to 20 cm and this is shown in Fig. 11. This reading range should be acceptable for anti-counterfeiting applications such as banknote authentication. From Fig. 11 it is clear that the shifting in resonance frequencies does not occur with the change of distance, the only thing that changes is the amplitude of the attenuation at the resonance frequencies which is expected.

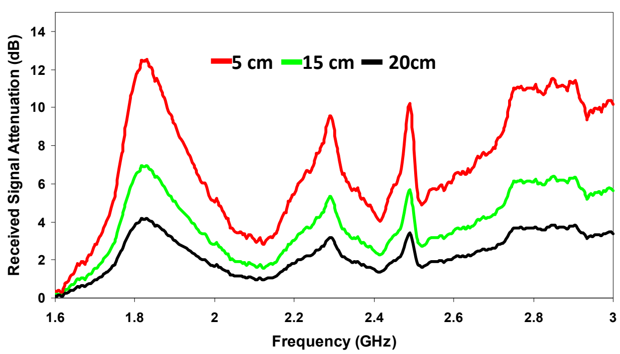

Fig. 11. Measured code of tag 1111 at various distances from reader antennas.

5. Conclusion

A novel chipless RFID tag with 3D stacked dipole resonators printed on a thin 50 um polyimide film is presented. The reported chipless RFID tag is the first tag with overlapping multilayer resonators to be successfully developed and tested. A comprehensive parametric study of the tag's performance with varying resonator length, width, conductive ink thickness, orientation changes, polarization and reading range are presented. The tag operates between 1.8 and 3 GHz and can produce 4 or 8 resonances for data encoding depending on the application requirements. For higher data capacity and orientation sensitivity the tag uses polarization diversity to encode data. For orientation insensitive applications the tag encodes the same data in both orthogonal polarizations therefore being readable in any orientation. The tag is printed using a low cost screen printing technique, on low cost polyimide film and using a lossy conductive ink with a conductivity of 3 million S/m, almost 20 times lower than copper. We have demonstrated that the tag is fully operational and it has the potential to enhance anti-counterfeiting of banknotes and other paper/plastic items.

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