A High Density 16-bit Polarization-Independent Chipless Passive RFID Tag

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Abstract **─** A compact, polarization-independent, chipless, passive Radio Frequency Identification (RFID) tag with 16 bits binary encoding is presented in this paper. The design is prepared with the placement of 16 Convoluted Square Loops (CSLs), in a nested loop arrangement. The proposed CSL structure is formed by inwards semi-circular bending of each edge of a square geometry. This configuration not only offers high Quality (Q) factor for each resonance but also polarization independence. The design is fabricated on a 1.6 mm thick FR-4 substrate having an area of 20.8 mm × 10.8 mm. The presented design occupies small area with the bit density of 7.12 bits/cm^2 and requires no unit cell repetition for enhancing the Q factor. The tag is tested on the frequency range of 2 to 26 GHz with various E-field polarizations, in order to achieve a polarization independent behavior.

Index Terms **─** Chipless RFID, Convoluted Square Loops (CSL), Internet of Things (IoT), multi-bit, passive tag, polarization independence.

I. INTRODUCTION

RFID tags are finding considerable applications in tracking, sensing, wireless communication and Internet of Thing (IoTs) [1]. RFID tags offer excellent read rate, non-line-of-sight communication and longer reader-to-tag range [2]. RFID tags with integrated chips are expensive for bulk deployment. In order to make RFID tag cost effective, chipless RFID tags are gaining considerable attention [3].

Generally, RFID tags are classified into two categories: time domain based and frequency domain based [2]. Surface Acoustic Wave (SAW) based RFID tags can have a high bit density up to 64 bits but their realization is expensive and challenging. On the other hand, frequency domain based tags can be manufactured economically with standard fornication technologies like Printed Circuit Borad (PCB) [4]. For designing frequency domain based tags, a common practice is to use metallic loops of same shape but different lengths and arrange them concentrically on a substrate. A tag, a reader and a host computer constitute a complete RFID system [4]. RFID encodes data into a unique binary pattern with the help of simple radiators/loops that can be read through the Radar Cross-Section (RCS) response. Electromagnetic waves generated by the tag reader induce simultaneous inductive and capacitive effects on the tag, resulting in the desired resonant behavior. This resonance pattern corresponding to the encoded data is detectable through the RCS response [2]. A number of structures have been proposed in literature such as hexagonal, rectangular or square and E-shaped [2, 5, 6]. The tag proposed in this paper occupies a much smaller area than the tags reported previously [2, 5, 6].

The overall shape of a loop dictates the resonances, Quality Factor (Q) and polarization behavior of the passive RFID tag. Rectangular shape loops produce

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higher Q factor resonance [5]. A symmetric shape makes a tag polarization independent and a non-symmetric geometry limits the tag operation in random orientations [2]. A perfectly symmetric shape such as a circle is best suited for the polarization independence. However, as articulated in [2], a circle does not produce a high Q factor. A trade-off has to be made between the Q factor of resonances and polarization independence. A customized hybrid structure having attributes of both, circle and square has a potential to produce polarization independent response while also exhibiting considerably high Q factor.

The rest of the paper is arranged as follows: Section II describes the design of the proposed loop/resonator. Section III describes the layout of a full tag in consolidated fashion. Results obtained from simulation and testing of the design are discussed in Section IV. Finally, Section V concludes the paper.

II. DESIGN OF A UNIT RESONATOR LOOP

The proposed design of chipless RFID tag is built-up from a single customized resonant loop that is modified from a square shape by bending all edges inwards from the middle in a semi-circular form. The complete geometry of a unit cell is formed by repeating the loops with decreasing size with the same geometric ratio. Two unit cells are placed side-by-side on a single substrate to form the complete tag.

The proposed geometry combines benefits of square loops by offering high Q resonance and the modification on edges allows its frequency independent operation [7]. The high Q resonance is very helpful in encoding large number of data bits within limited bandwidth thus allowing various unique combinations for a single tag. The proposed tag in this work is capable of offering more than 65,000 combinations which is sufficient to cater for medium to large scale tagging requirement. The proposed CSL structure is shown in the Fig. 1 with its surface current density plot at its resonant frequency.

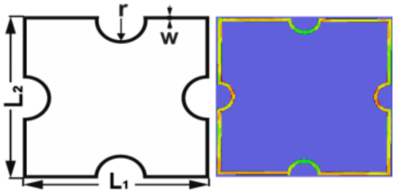

Fig. 1. CSL structure and its surface current density, *dimensions are L1=L2=10.2mm, W=0.2mm, r=0.8mm*.

The area of the CSL is 10.2 mm × 10.2 mm and the edges are bent inside in the form of semi-circle, each with radii of 0.8 mm. When electromagnetic waves illuminate the loop, it responds by resonating at the operating frequency. The presence of resonance at the designated frequency is marked as a bit “1” and the absence of resonance is perceived as a bit “0”. A binary data combination of ‘1101001110011001’ is illustrated in Fig. 2 where the simulated RCS response corresponds to the tag configuration in a particular way.

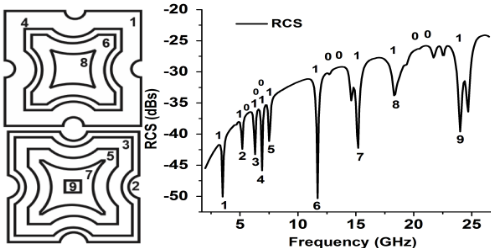

Fig. 2. Simulated RCS results of ‘1101001110011001’ bit combination.

III. OPTIMIZATION OF OVERALL DESIGN

The overall size of CSL is optimized through a full wave electromagnetic simulator HFSS®. The optimized loop is nested 16 times with each loop scaled down in a specific ratio. These CSLs are then arranged in the form of two units of 8 loops each, in a side-by-side configuration. The edge of a loop is scaled down by 1 mm and radius of semi-circle is increased by 0.5 mm in each consecutive inner loop. The outer-most loop of the second unit cell is formed with 9.7 mm edge length and semi-circle of radii 1.05 mm. Inner loops of this unit cell are formed in the same pattern as described for the first unit cell. Separation between loops of both units is kept at 0.3 mm and overall dimensions of the optimized tag are finalized at 20.8 mm × 10.8 mm. All 16 loops are of different electrical lengths thus corresponding to resonant frequencies that represent a 16-bit binary coding scheme.

IV. SIMULATIONS AND MEASUREMENTS

The simulation was setup by placing the RFID tag inside an air box with Perfect Matched Layer (PML) boundary condition on all the edges. In order to compute the RCS of the tag a plane wave excitation was setup which illuminates the tag from the desired direction. A frequency sweep is added to the setup in the bandwidth of interest. The simulation was time consuming since a number of frequency points were included in the sweep. Once the analysis is completed the bi-static RCS was computed in the post processing along the swept frequency. The RFID tag was fabricated through milling on an FR-4 substrate with the thickness of 1.6 mm and copper cladding of 1 oz, as shown in Fig. 3. The measurement setup was established by placing a pair of UWB horn antennas (TDK-HRN-0118) side-by-side and the RFID tag was placed in the front to measure bi-static RCS. Since the tag operates up to 26 GHz, the measurements were taken in parts initially from 1 to 18 GHz and then the wideband double ridge horns were replaced with WR-42 (18 to 26.5 GHz) standard gain horn antennas. The measurements were taken on Agilent N5242A Performance Network Analyzer. Measurement setup is shown in Fig. 4.

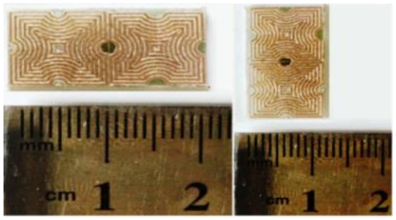

Fig. 3. Fabricated RFID Tag.

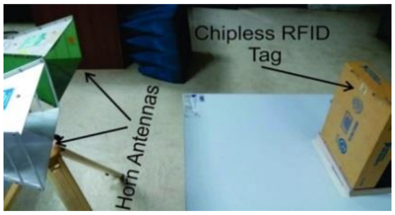

Fig. 4. Measurement setup.

The comparison of the simulated and measured results is presented in Fig. 5. The bits are fairly distinguishable in the measured response. EM analysis of loop resonating at 3.5 GHz is shown in the Fig. 6. Electrical length of this loop is calculated to be 44.4 mm which corresponds to one guided wavelength.

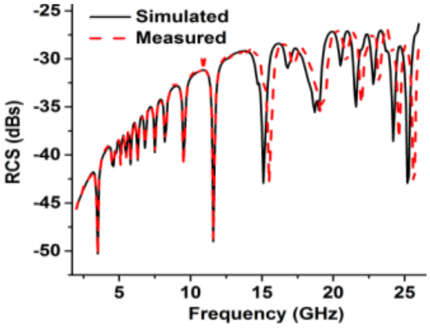

Fig. 5. Measured and simulated RCS plot.

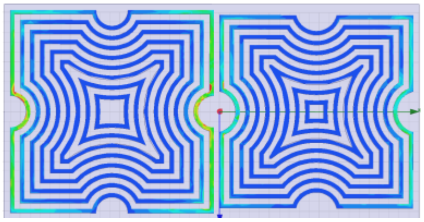

Fig. 6. EM analysis of loop resonating at 3.5GHz.

Contrary to the techniques of replicating unit cells to enhance Q factor, this design does not repeat unit cell. The loop itself offers better Q factor as compared to designs reported in [2, 5, 6]. High Q factor also allows the enhanced interrogation range. However, that is highly dependent on the environmental conditions and the tag background material. In order to verify its polarization independence characteristics, the tag is read at various polarization angles by rotating the RFID tag. The results of 0°, 30°, 45° and 60° polarization angles are presented in Fig. 7 and the encoded pattern is fairly readable.

The tag has a capacity of 16 bits and occupies an area of 2.25 cm^2 which results in the bit density of 7.12 bits/cm^2. The achieved bit density is higher than the designs reported in [2, 5, 6]. A comparison of this RFID tag with recent relative references is presented in Table 1.

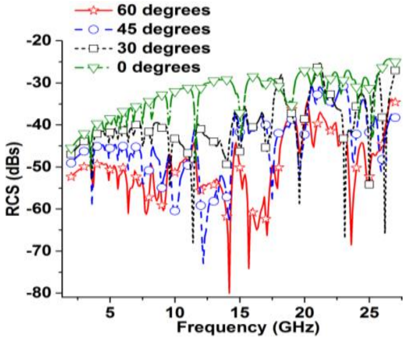

Fig. 7. Measured polarization response.

Table 1: Comparison with other designs

Resonator Shape	No. of Bits	Tag Size (cm^2)	Polarization Independence
CSL (proposed)	16	2.24	Yes
Hexagonal [2]	14	2.30	Yes
Rectangular [5]	03	9.60	Yes
E-shaped [6]	08	17.70	No

V. CONCLUSION

A 16-bit polarization-independent, chipless, passive RFID tag is proposed in this work. CSL structure has been used as a resonating element. The design provides high Q resonance and polarization independence within a compact size of 2.246 cm^2. The tag has high bit-density of 7.12 bits/cm^2 and it offers 16 bits binary encoding option. The tag is fabricated and tested to establish its performance and the results obtained are in agreement with the simulations. The polarization independence has also been tested by rotating the tag at different angles. The large bit capacity of this tag makes it suitable for use in medium to large tagging setup and this proposed tag can offer more than 65,000 unique combinations.

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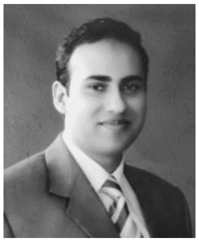

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