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A Mechanically Reconfigurable Chipless RFID Tag for Internet of Things (IoT) Applications

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Abstract

The growing demand for versatile and cost-effective systems for Internet of Things (IoT) applications has paved the way for reconfigurable systems where a single structure can be reconfigured to respond as per the requirements. In the present work, a mechanically reconfigurable chipless RFID tag is presented. The proposed backscatter based RFID tag is built on FR4 substrate with dielectric constant (ε_r) 4.4 and loss tangent ($\tan\delta$) 0.02. The substrate consists of four cavities that can be left empty or filled with some material leading to 16 different combinations. Each combination gives a unique RCS signature that can, in turn, be used for safe and reliable data encoding. One of the biggest limitations of RFID tags is that they are expensive when compared to the traditional barcodes. However, the proposed, being reconfigurable, is easy to fabricate and can be manufactured in bulk, thereby, reducing the overall cost of production. It is also reported that the proposed mechanically frequency reconfigurable RFID tag can give out a large number of (theoretically infinite) RCS signatures if the cavities are filled with materials other than that of the substrate material, thereby, further increasing the diversity of the prototype.

1 Introduction

The phrase Internet of Things (IoT) was first used by Kevin Ashton in 1999 as a concept to enable the computers to collect the data from the physical world with minimum human intervention and using sensors [1]. Since then IoT has managed to gain immense attention from the scientific community, in fact, today it is seen as the backbone of Industrial Revolution 4.0 [2]. IoT refers to the scenario wherein every single object holds some information that is collected and stored by certain identifiers like sensors, uniform resource locators (URLs), barcodes etc. [3]. The data from the identifiers is then communicated to the internet for further processing.

Radiofrequency Identification (RFID) is probably the most promising technological solution for IoT identifiers [4]-[6]. RFID systems are capable to encode the data and communicate it to a receiver which is placed within their radio vicinity. This method of operation is very similar to barcodes, however, RFIDs do not require the receiver to be within its line of sight. RFID systems are used in a variety of applications like object tracking, access control, security systems [7] etc.

Typically, RFID systems consist of a tag or transponder, an interrogator or reader and a host or controller. The tag, typically, refers to an antenna with a semiconductor chip and at times a power source/battery. The reader is an antenna system backed by transceiver module followed by a control unit. The controller is usually a PC, a cell phone or any electronic workstation where the database and the middleware software could be processed. The tag and the reader establish the exchange of information whenever the tag comes within the range of the reader [8]. The presence of the chip on the tag often leads to an increase in the cost of the overall RFID system, therefore, researchers are now focusing on chipless RFID technology [9]. Many chipless RFID tags employ the concept of surface-acoustic-waves (SAW). Such tags consists of an array of acoustic reflectors with an interdigital transducer (IDT) on one of the ends connected to the antenna [10]. However, these types of tags are cost prohibitive and difficult to fabricate when compared with the modern versions of chipless RFID tags. Generally, modern chipless RFID tags make use of multiple resonators where each resonator acts as an individual bit [11]. The presence or absence or a variation in the size of each resonator leads to unique tag responses that could be encoded as per the requirement [12, 13]. Recently, reconfigurable RFID systems have gained some attention from the scientific community. For instance, in [14] a solid state based metal-insulator-metal (MIM) switch is used to alter the resonant frequency of a hairpin resonator. The RCS of the entire system, thus, differs when the state of the switch is changed. Another example of reconfigurable chipless RFID is presented in [15] where a single transmission line is surrounded by eight passive capacitors. Each of the capacitor can be connected or disconnected with the transmission line leading to different tag responses. Reconfiguration paves the path for bulk manufacturing, thereby, reducing the cost of production per unit tag. Also, reconfigurable chipless tags can be re-encoded as per the requirement.

In this paper, a backscatter based mechanically reconfigurable chipless RFID tag is presented. the proposed tag can be reconfigured in four different ways to produce distinct RCS signatures. The rest of the paper is organized as fol-

lows. Section 2 describes the design of the prototype and the underlying theory. In Section 3, the response of the proposed reconfigurable RFID tag is presented followed by the conclusion in Section 4.

2 Theory and Design

Radar Cross Section (RCS) of an object is a measure of its detectability by a radar system. It is defined as [17]:

$$RCS = 4\pi R^2 \left| \frac{E_{scattered}}{E_{incident}} \right| \tag{1}$$

where R is the distance between the radar receiver and the object. $E_{scattered}$ is the electric field scattered by the object and $E_{incident}$ is the incident electric field. If the outer surface of the object is metallic in nature, then, RCS computation becomes fairly straightforward using (1) and by applying techniques like physical optics (PO), geometrical theory of diffraction (GTD), uniform theory of diffraction (UTD) etc. [20]. However, if the object is made up of dielectric material then the determination of RCS becomes significantly complex as the incident radiation enters into the object and traverses a rather complicated path. For example, Nguyen and Shirai reported in [18] that the RCS of a dielectric cuboid with dimensions $u \times v \times w$ can be computed using the following equations:

$$RCS = |\sigma_c|^2 \tag{2}$$

where σ_c represents a complex scattering quantity and is given by:

$$\sigma_c = -\frac{ikuv}{\sqrt{\pi}} \Gamma_{mrc} e^{-ikw} \tag{3}$$

where Γ_{mrc} denotes multiple reflection coefficient from the dielectric cuboid and is expressed as:

$$\Gamma_{mrc} = \Gamma_{src} \frac{1 - e^{2ikw\sqrt{\varepsilon_g}}}{1 - \Gamma_{src}^2 e^{2ikw\sqrt{\varepsilon_g}}} \tag{4}$$

ε_g represents the dielectric constant of the cuboid and Γ_{src} is the surface reflection coefficient and is calculated as:

$$\Gamma_{src} = \frac{1 - \sqrt{\varepsilon_g}}{1 + \sqrt{\varepsilon_g}} \tag{5}$$

From (2), (3), (4) and (5) it is clear that in case of a non-metallic body, the dielectric properties have a major effect on its RCS. It is in this concept that the theoretical foundation of the proposed chipless RFID tag lies.

The proposed tag was primarily developed as a mechanically frequency reconfigurable antenna, as reported in [19]. However, with rigorous analyss it was found that the geometry can be slightly modified to create a highly diverse reconfigurable chipless RFID tag. The geometry of the proposed tag is shown in Figure 1. The prototype consists of a rectangular metallic patch placed on top of a metal backed FR4 substrate with dielectric constant (ε_r) 4.4 and loss tangent ($\tan\delta$) 0.02 with dimensions

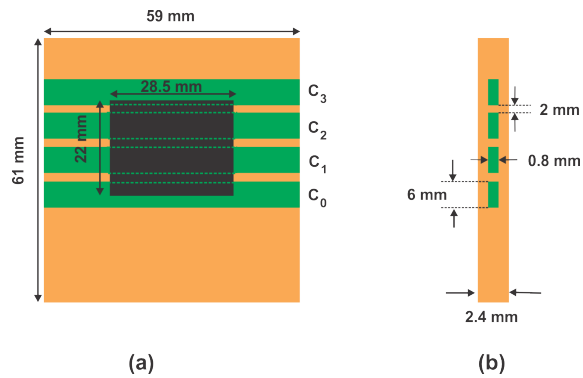

Figure 1. Geometry of the proposed mechanically reconfigurable chipless RFID tag.

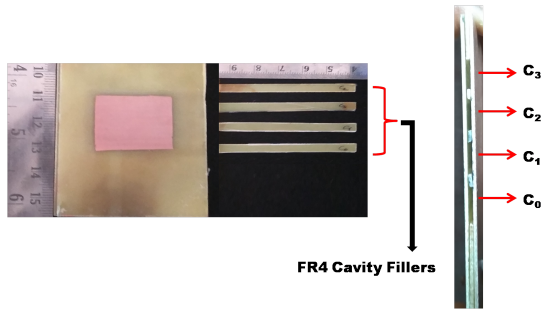

Figure 2. Fabricated mechanically reconfigurable chipless RFID tag.

61mm×59mm×2.4mm. The substrate contains four end-to-end cavities as shown in Figure 1. The dimensions of each cavity are 6mm×59mm×0.8mm. At this point, one can recall that most of the modern chipless RFID tags, as mentioned in [11], contain multiple resonators that act as bits. The presence or absence of each resonator or bit is, generally, symbolized by characters '1' or '0'. For example, if a chipless RFID tag contains three bits then it can be used for a total of 2^3 or 8 different combinations of 0s and 1s, where each combination would yield a unique frequency characteristic or a unique radar cross-section (RCS). In the present case, the four cavities carved out of the substrate of the mechanically reconfigurable chipless RFID tag act as four bits. Therefore, a total of 2^4 or 16 different combinations could be assessed using this design. Cavities filled with air are denoted by '0' while the ones filled with any material other than air are denoted by '1'. Each combination of 0s and 1s alters the overall dielectric constant of the substrate. This, in turn, yields to a unique RCS signature, thereby, establishing the chipless RFID tag like characteristic of the proposed system. Here, in order to prove the concept, the cavities in the prototype are filled with FR4 and the fillers of the cavities are altered by hand. In Figure 1, cavity C_0 represents the lowest significant bit (LSB) while cavity C_3 represents the most significant bit (MSB). The fabricated prototype is shown in Figure 2.

Table 1. Comparison of some known reconfigurable RFID tags with the proposed prototype

Reference	Mechanism of reconfiguration	Reconfigurable property	Number of reconfigured cases
[14]	Electronic (Solid state switching)	|RCS| *vs*. Freq.	2
[15]	Inkjet printing	Capacitance *vs*. Frequency	2-3
[16]	Inkjet printing	|RCS| *vs*. Freq.	4
This work	**Mechanical (Removable dielectric strips)**	**|RCS| *vs*. Freq.**	**16**

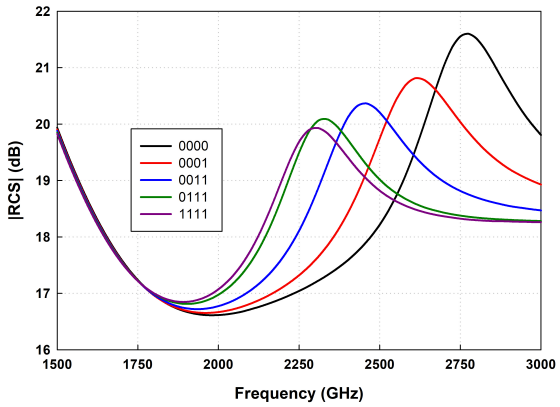

Figure 3. |RCS| of the proposed mechanically reconfigurable chipless RFID tag for five of all 16 combinations.

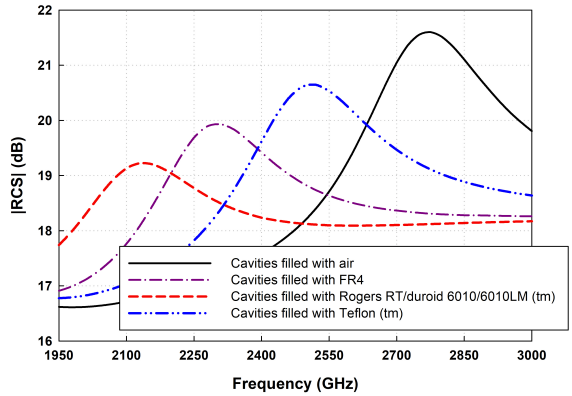

Figure 4. |RCS| of the mechanically reconfigurable chipless RFID tag for the cases when the cavities are filled with Rogers RT/duroid 6010/6010LM (tm), FR4, Teflon and air.

3 Results and Discussions

The RCS of the proposed mechanically reconfigurable chipless RFID for combinations 0000, 0001, 0011, 0111 and 1111 is shown in Figure 3. It is clear that the peak in the |RCS| plot shifts for different combinations. For 0000 case or the case where all the cavities are filled with air, the overall effective dielectric constant of the substrate decreases as the dielectric constant of air is less than that of FR4. In this case, the peak is observed at 2770 MHz. For 1111 case where all the cavities are filled with FR4, the peak is observed at 2370 MHz. The peaks for all the other cases lie in between this frequency range of 400 MHz. The data can be encoded exclusively for a particular case and can easily be re-encoded for upon mechanical reconfiguration. The RCS of the tag is high enough to be detected in a real world environment and does not require highly sophisticated receivers for data reading.

A special case has been studied for parametric analysis, where the cavities were filled with Rogers RT/duroid 6010/6010LM (tm) ($\varepsilon_a = 10.2$ and $\tan\delta = 0.0023$) with dielectric constant greater than that of the substrate material and Teflon (tm) ($\varepsilon_b = 2.1$ and $\tan\delta = 0.001$) with dielectric constant less than that of the substrate material. The observed results are shown in Figure 4. It is observed that the peak is observed at the lowest frequency of 2130 MHz for the case when the cavities are filled with higher dielectric constant material while the peak is observed for the highest frequency of 2770 MHz is observed for the case when the cavities are filled with a lower dielectric constant material. In theory, the cavities can be filled with any material. This fact opens the door for endless number of RCS signatures for different materials and combinations. Hence, the diversity of the proposed prototype increases manifolds.

Research on reconfigurable chipless RFID tags is still evolving and holds a lot of potential. Table 1. compares the performance and diversity of the proposed reconfigurable tag with some of its counterparts. In [14], reconfiguration between 2 states is rather quick and easy due to the presence of the switch. In [15] and [16], reconfiguration between 2 to 4 states is achieved with the help of inkjet printing. The proposed prototype can be easily reconfigured into 16 states.

4 Conclusion

A novel mechanically reconfigurable chipless RFID tag is presented in this paper. The proposed tag can be reconfigured in 16 different combinations to provide unique RCS signature. The prototype is easy to fabricate. One of the main limitations of RFID when compared with tradition barcodes is that the cost of production of a RFID tag is much higher. Reconfigurable RFID tags like the proposed one can be used to solve this problem while being easily manufactured in bulk and reducing the overall cost of production. The proposed mechanically reconfigurable chipless RFID tag can be used in IoT devices like smart locks, sensors, systems where mechanical movement is prominent

etc. Also, from the results it is seen that the RCS measurement of the prototype does not require a high-end sophisticated receiver to detect the response of the tag, therefore, the external circuitry, too, is economical. The freedom of filling the cavities by any material with any dielectric constant just adds to the diversity of the proposed prototype. Unlike its electrical counterparts, the prototype can give, theoretically, infinite number of RCS signatures.

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