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Compact Slot-Based Chipless RFID Tag

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***Abstract*—We present a fully printable, planar, orientation independent, single layer, chipless RFID tag. The tag consists of a circular patch with multiple discretized circular slot resonators nested in it. This design reduces the total size of the tag since the discrete circular slot resonators resonate at a lower frequency than perfect circular resonators for the same diameter. Reader's complexity is reduced as the tag is polarization independent, improving the tags readability from different angles with respect to the reader antenna. Its single layer characteristics make this tag a potential candidate for conductive ink printing. The frequency band is within 6 to 14 GHz.**

I. INTRODUCTION

Radio frequency identification (RFID) technology has been an active research topic over the last years, extending its use into many different applications ranging from warehouse logistics [1] to livestock management [2]. This has been possible due to the flexibility of the technology that gets adapted to different requirements including active and passive tags, near/far field communications or the use of different frequency bands. In essence, all these tags rely on a silicon chip connected to an antenna. The tags store an identification code that can be retrieved wirelessly by an RFID reader. This setup, though flexible and powerful, has some disadvantages. Among these disadvantages is the cost. In certain applications, RFID needs to offer a cost that can compete with other identification technologies like optical barcodes. For these applications a new technology known as chipless RFID has been introduced [3]. This technology offers a huge cost reduction by eliminating the chip from the tags that now consist of a metal structure. In order to encode any data on these metal structures, we make use of their Electromagnetic Signature (EMS). This EMS defines the unique behavior that a given object has in the presence of an electromagnetic wave, or most formally, the variation with time or frequency of the reflection coefficient of an object. Based on this principle, chipless RFID tags can be engineered to provide a unique electromagnetic signature that is used to encode data.

In order to encode any data on these tags, two approaches can be used. The first one is based on the time domain characteristics of the EMS. A short pulse is sent to the tag and the time variation of the reflected signal is used to encode data [4].

The second approach uses the frequency domain characteristics of the EMS to encode data. By using this approach, the encoding can be done based on the presence or absence of a frequency resonance, as in [5], or in the relative position of a resonance with respect to its initial value; a technique called frequency shift encoding [6]. In the present work, we will use the first approach.

Some of the main issues to consider while designing a chipless RFID tag are the size, coding capacity of a given design, the capability of being printed economically (using conductive ink printing on a cheap substrate as paper or cardboard), the frequency band to be used and its regulations, the effects of the host substrate on the EMS of the tag and the polarization and angle of incidence effects.

In our case, the frequency band used will be 6-14 GHz. This band has already been used in other chipless RFID designs as it offers a wide bandwidth that, for frequency encoded tags, results in higher coding capacities. An important limitation while using this portion of the spectrum is the maximum transmit power allowed.

For the tag design, we will focus on a single layer, circular slot resonator, similar to the one introduced in [7]. We have modified this design in order to reduce its size for the same EMS. This type of resonator has some characteristics that help to overcome some of the issues presented before. First, it is a single layer structure that can be printed on any substrate. Second, it is polarization independent, avoiding any misalignment problems and reducing the readers complexity. Finally, multiple resonators can be nested, increasing the coding capacity per square centimeter of the tag. Regarding the size, the objective is to reduce the area needed to print the tag, making it possible to use it on small items. Also the reduction in size is an important factor to increase the coding capacity of the tag.

As mentioned before, to encode data we will use the frequency encoding technique used in [5]. This coding technique will allow us to get a coding density of 3.8 bits/cm^2. Two other designs for polarization independent chipless RFID tags have been reported in the research literature. In [7] a coding capacity of 3.3 bits/cm^2 is achieved, using 8 slot ring resonators in a single layer tag. In [6] a coding capacity of 2.1 bits/cm^2 is achieved, using a two layer ring resonator based tag. These coding capacities are compared in TABLE I.

TABLE I. CODING DENSITIES OF DIFFERENT POLARIZATION INDEPENDENT CHIPLESS RFID TAG DESIGNS

	Coding density (bits/cm^2)
Ref. [7]	3.3
Ref. [6]	2.1
Our design	3.8

II. CIRCULAR SLOT BEHAVIOR

Our objective is to design a chipless RFID tag that can support a high bit coding capacity per square centimeter while maintaining a good readability with variations of the polarization. To meet these requirements we will use a modified version of the slot ring resonator proposed in [5].

A. *Slot Ring Resonator*

In the present work, we present a chipless RFID design based on the circular slot ring resonator introduced in [5], but modified to reduce the total tags dimensions. To achieve this, the circular shape of the resonator is approximated by a discrete shape formed of rectangles with dimensions w x w/2 mm (where w is the width of the circular resonator). These rectangles are located in a grid with a step size of w/2 mm. The circular slot resonator presented in [5] and our new resonator are depicted in Fig. 1. As can be seen in Fig. 2, for a given resonator radius (R) our proposed design resonates at a lower frequency than the perfectly circular resonator. Therefore, to achieve the same resonant frequency, the new design's size can be reduced, increasing the encoding density of the tag.

The resonant frequency of a perfect circular slot resonator is defined by:

$$f = \frac{c}{2 \cdot \pi \cdot R_i} \sqrt{\frac{2}{\varepsilon_r + 1}} \qquad (1)$$

where c is the speed of light in free space, R_i the slot radius, and ε_r the effective permittivity of the substrate.

In the proposed design, the path around the slot for the induced currents is increased, reducing the resonant frequency of the structure. The new resonant frequency is roughly 10% lower than that of the ideal circular slot resonator.

When an incident plane wave impinges on the proposed structure, the backscattered signal will present a null near the slot's resonant frequency. Since this resonant frequency depends on the slot radius, we can tune the structure's electromagnetic signature by varying it.

One important feature of this type of resonant structure is that the 2^{nd} and 3^{rd} harmonics of the resonant frequencies are not present. This is due to the structure of the circular slot resonator, which does not allow currents for the even and odd harmonics. Also, due to its symmetric structure, the backscatter response of the structure is invariant to the polarization of the incident plane wave.

B. *Nested Circular Slots*

Another advantage of the slot ring resonator is that it allows nesting multiple resonators in one structure. Therefore, we can engineer a tag whose electromagnetic signature includes multiple nulls, increasing its coding capacity. The limiting factor to nest multiple slots in the same tag is the coupling between them. This effect becomes stronger when two slots are very close to each other, and hence a minimum distance between slots has to be kept. This will reduce the total number of resonators that can be nested for a given tag, reducing the encoding capacity. Furthermore, provided that a minimum distance is maintained, coupling between slots is still present, which shifts the resonant frequencies of each slot. This effect has to be compensated in the design process ensuring that the resonances occur at the desired frequencies.

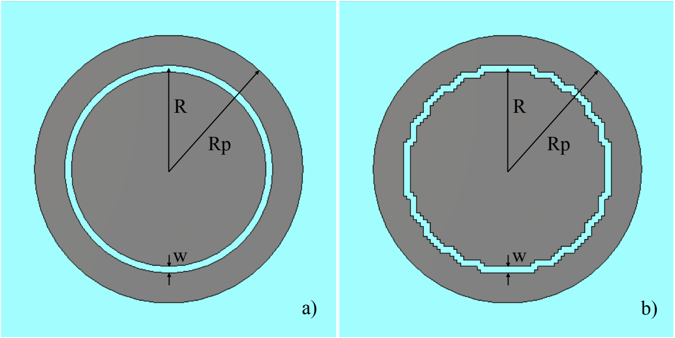

Fig. 1. a) Circular resonator presented in [5]. b) Proposed resonator.

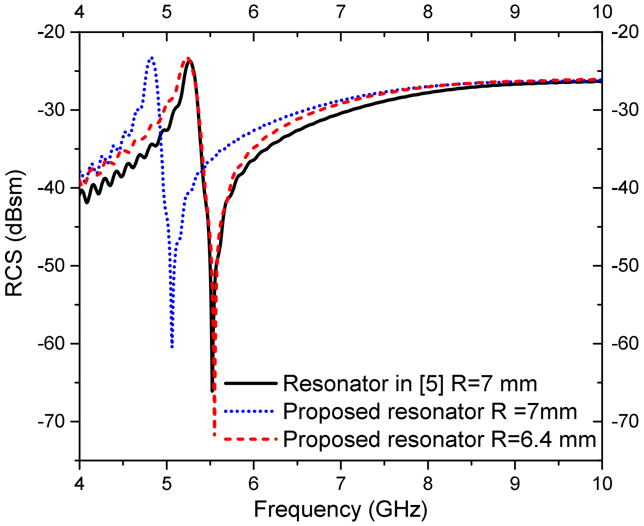

Fig. 2. RCS comparisson of an ideal circular resonator and the proposed resonator.

C. *Tag Design*

As the tag presented in [7] our tag design consists of a circular patch with eight discrete circular slot resonators nested inside. The design is presented in Fig. 3. The patch has a radius of Rp = 7.8 mm, and the substrate is Taconic TLX-9 with a thickness of 0.5mm, electrical permittivity $\in_r$ = 2.5 and a tangent loss tanδ = 0.0019. The width of all the resonators is w = 0.2 mm, the maximum radius Rmax = 5.8 mm and the spacing between resonators Sp = 0.4 mm.

III. VALIDATION

In order to validate our design, different tags have been simulated using the electromagnetic simulation tool CST Microwave Studio. In each case we have characterized the RCS of the tag using a plane wave excitation that propagates in the normal direction of the tag and a radar cross section probe located at 300 mm from the tag.

First, the new design was simulated and compared to the design presented in [7]. In Fig. 4 the RCS of both tags are

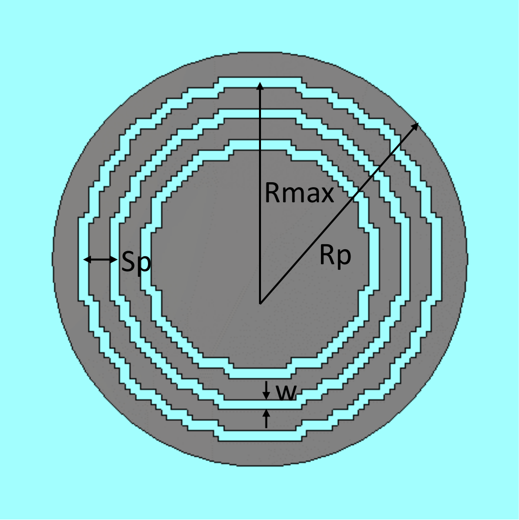

Fig. 3. Structure of proposed tag.

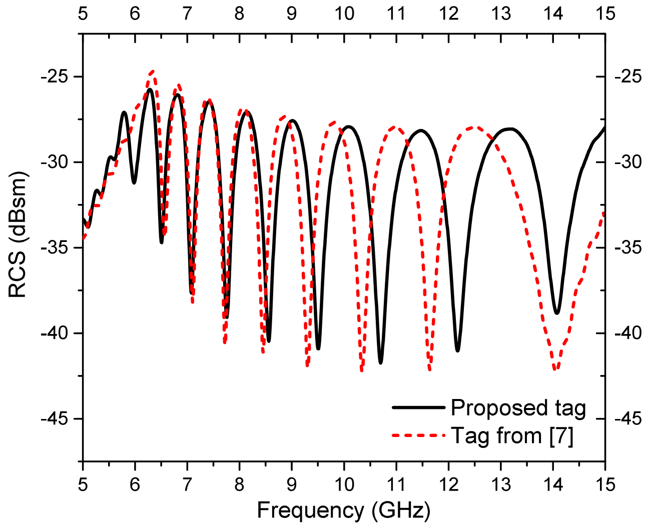

Fig. 4. RCS comparisson of the proposed tag vs. tag from [7]. Notice the extra resonance added in the proposed tag.

shown. Since the new resonators in the proposed tag resonate at lower frequencies than the ideal circular resonators, an extra resonator can be added without increasing the tag's size or the total frequency bandwidth used. Furthermore, the resonance of the smallest resonator is shifted up due to the effects of the inner metal disk. This shift can be avoided by adding an extra resonator, keeping the total bandwidth more compact. This resonator has a radius of 2.1 mm and is kept fixed, as can be seen in Fig. 5 b). The resonance of this resonator falls outside of the tag's assigned bandwidth, as can be seen in the response of this tag's design in Fig. 6 a), and therefore does not impact the tag's readability.

Next, four tags with different bit combinations were designed. The IDs of these tags are provided in Table II. The first bit of the ID is assigned to the lowest frequency resonance and each subsequent bit to the next higher resonance. In each case, a bit set to 1 means that the resonance associated to it is present, while a 0 means the absence of such resonance. The layouts of the four tag designs are shown in Fig. 5.

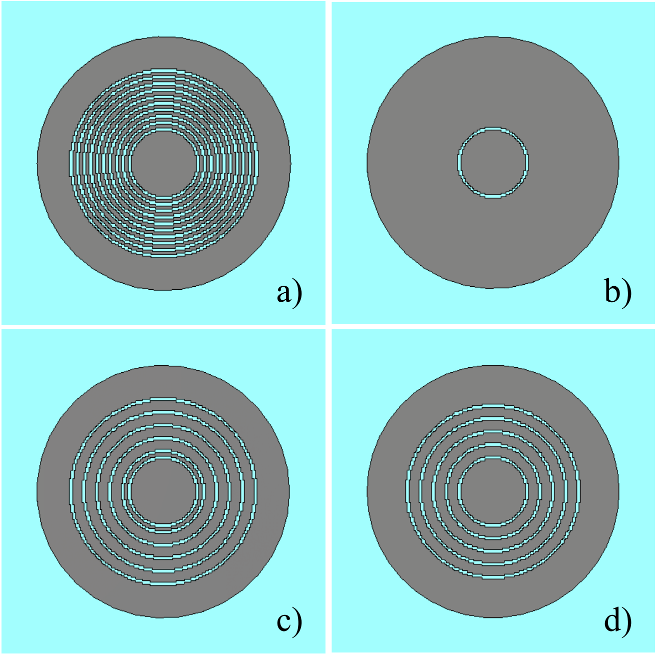

Fig. 5. Layout of the 4 simulated tags with IDs: a) '111111111', b) '000000000', c) '101010101' and d) '010101010'.

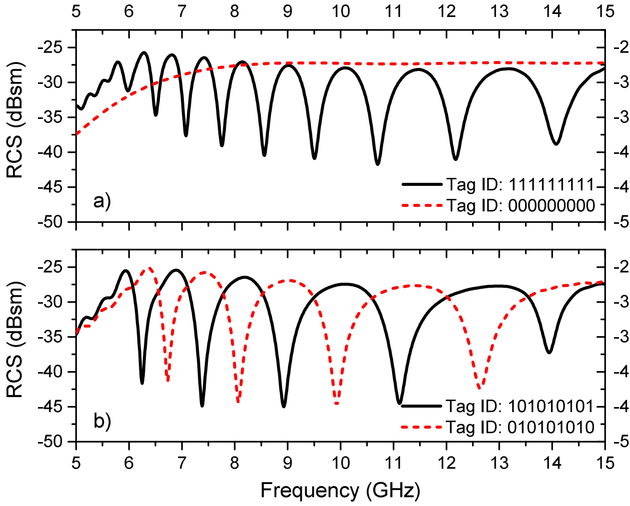

Fig. 6. a) Simulated RCS of tags '111111111' and '000000000'. b) Simulated RCS of tags '101010101' and '010101010'.

Finally, the four different tag designs are simulated in CST.

TABLE II. TAG DESIGNATORS AND IDS

Tag Designator	**Tag ID**	**Tag reference in Fig. 5**
1	'111111111'	a)
2	'000000000'	b)
3	'101010101'	c)
4	'010101010'	d)

Figure 6 a) shows the simulated RCS of tags 1 and 2, while Fig. 6 b) shows the simulated RCS of tags 3 and 4.

IV. CONCLUSION

In this paper a printable chipless RFID tag based on a discrete slot ring resonator has been introduced. It has been shown that this new resonator allows the size reduction of the tag for the same frequency response, thus increasing the coding capacity of the tag. A coding capacity of 3.8 bits/cm^2 has been achieved, which represents the highest coding density for a polarization independent chipless RFID tag to date. This improvement, together with the advantages of being both single layer and polarization independent, makes this design a strong candidate for item tagging applications where the tag can be directly printed on the objects using conductive ink printing technology.

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