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# Design and Manufacture of Resonant Chipless Tags in Millimeter-Wave Band

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**Abstract**—This paper introduces the first chipless tag in the mmWave band based on resonating elements. One goal is to introduce a millimeter-wave communication system based on chipless tags without a ground plane based on traditional low-cost printing methods. For this purpose, millimeter-wave chipless resonant tags have been designed considering the trade-offs such as RCS signal level, losses, and design constraints. The proposed design is based on single-layer printing, where each resonating element is replicated to satisfy constraints related to the chipless reading process at these frequencies. As a result, a reading range up to 20 cm has been noticed in an office environment.

**Index Terms**—Flexible manufacturing system, Millimeter wave circuit, Chipless RFID tag.

## I. INTRODUCTION

The chipless RFID technology is an intermediate technology between the optical and the UHF RFID [1]. A comparison between these three technologies is illustrated in Fig. 1. Chipless tags combine some features, such as a lower cost and some UHF RFID. As barcodes, chipless tags are characterized by a low cost since the tag does not use any chip. Instead, the identifier is directly linked to the geometry of the printed elements. As UHF tags, chipless tags can be read independently of the line of sight configuration due to RF propagation. In this sense, the chipless tags can be seen as a radar target designed to scatter a specific electromagnetic signature. The tag structure is composed basically of metallic ink printed on a substrate. Then no additional circuit components are needed. Passive chipless RFID structures fundamentally rely on their RCS, frequency, or phase changes to encode the information or some combination of these parameters [2]–[5].

Previous millimeter-wave chipless tags were introduced for chipless RFID applications. Most of these applications are related to the Synthetic Aperture Radar techniques (SAR) [6]–[9], where the dimension of the encoding particle is significantly higher than the wavelength. However, these tags do not behave as resonant scatterers. Therefore, the classical information storage based on peak/dip recognition on the spectrum of the backscattered signal cannot be applied to these designs.

In [10], a printed Van-Atta reflectarray structure is analyzed. It is employed for localization purposes and presents a long detection range (2.5 m). However, it is impossible to encode sufficient bits when compared to frequency-based tags within a credit card-sized area, for example, which can be considered

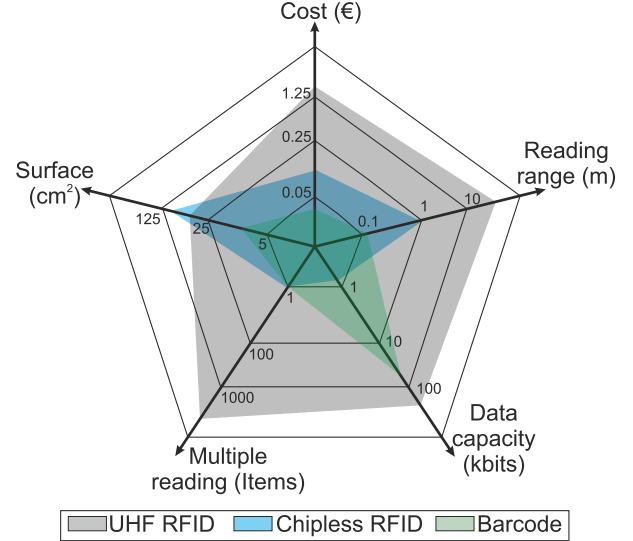


Fig. 1: Chipless RFID positioning in relation to other identification technologies.

a rule of thumb for chipless tags design. Besides, this kind of tag is incompatible with high encoding data capacity. Therefore, in this article, we propose for the first time a chipless tag operating in the mmWave bandwidth based on resonant scatterers.

Compared to UWB chipless tags, the mmWave chipless tags can achieve a better coding capacity. Furthermore, these tags are less impacted by coupling since resonant elements may be spaced further apart relative to the wavelength compared to classical designs.

The main goal is to present resonant mmWave chipless tags compatible with the mono-layer printing process. Furthermore, a tag based on a low-cost PET substrate is evaluated, which adds complexity to the system due to the high substrate losses at these frequencies. Nevertheless, this approach paves the way to identify tags printed on documents (tags printed directly on bio-sourced material) or even on specific manufactured products.

The next sections of this paper are described as follows. Section II details the principle of chipless RFID design for mmWave tags. Section III is dedicated to chipless tag design manufacturing. Finally, in Section IV, the measurement setup

and the results are discussed.

## II. DESIGN OF RESONANT CHIPLESS TAGS IN MILLIMETER WAVES

For frequency-based mmWave chipless tags, the most significant parameters are the RCS level and the  $Q$ -factor of the scatterer. A high backscattered RCS allows the tag to be differentiated from the clutter contributions on which the tag is embedded. The tag  $Q$ -factor permits isolation by temporal windowing and thus improve the detection of the tag in a real environment related to the frequency band associated with each resonator, which directly determines the number of resonators that belongs to the tag. Then, the tag resonators' design must optimize the RCS and  $Q$ -factor.

The main drawback in mmWave chipless tag design relates to losses of low-cost material fabricating the tag. For cost reasons, the manufacturing of tags must also rely on low-cost printing processes (flexography, screen printing, inkjet) and commercial inks or additives of dielectric/conductive pigments.

### A. Design constraints

An essential factor that thoroughly limits the RCS level and quality factor is the manufacturing process limitations, *i.e.*, minimum design conditions that must be respected for the fabrication of the structures. It is noteworthy that a structure without a ground plane requires only one conductive layer, which makes it compatible with direct printing processes on the product. Photolithography and inkjet have similar design constraints; the minimum dimension in the gap and trace width are limited to  $100\ \mu\text{m}$ . For chipless RFID tags, another fundamental characteristic of their design is the presence or absence of a ground plane at the tag structure. Resonators with a ground plane are like resonant cavities, which gives them a high  $Q$ -factor. The presence of the ground plane also allows good insulation with the object on which they are applied. However, adapting these tags using a printing process on low-cost materials is difficult because of the two metal layers' design. Moreover, the RCS is highly impacted due to the quasi-optical reflection originated by the ground plane.

The non-existence of a ground plane generally exposes less marked resonances, which implies in low  $Q$ -factor. However,

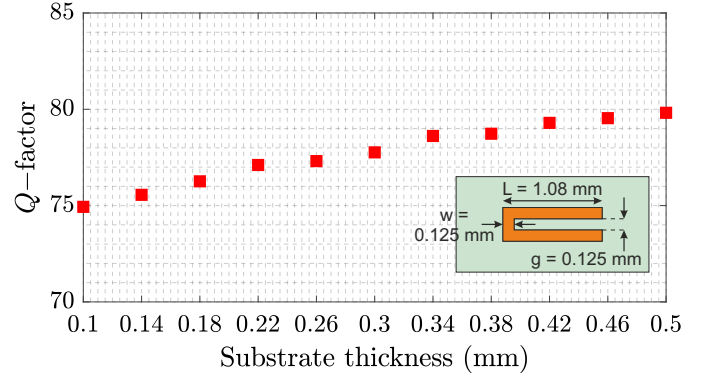


Fig. 4: Variation of the quality factor according to the substrate thickness. All the losses are included with  $\epsilon_r = 2.33$ ,  $\tan \delta = 0.009$ , copper cladding  $t = 50\ \mu\text{m}$  with conductivity ( $\sigma = 5.96 \times 10^7\ \text{S/m}$ ).

it is easier to adapt those tags to a chain process due to its mono-layer characteristic, which relies on cost reduction.

### B. Losses

In general, the losses undergone in microwave circuits built on a substrate are divided into conduction, dielectric, surface, and radiation losses. For mmWave chipless tag, radiation losses become a dominant factor that directly impacts the RCS level [11]. Then, the significant reduction of transmitted and backscattered power limits the reader range in chipless mmWave systems to a few centimeters (20 cm in an office environment). Since the resonator geometry is optimized, the dielectric loss, substrate thickness, and copper cladding thickness are considered for quality factor assessment. The total quality factor is calculated from the measured resonant frequency ( $f_0$ ) and the  $-3\ \text{dB}$  bandwidth ( $\Delta f$ ) around the resonance frequency. Then, the quality factor is defined as ( $Q = f_0/\Delta f$ ). Considering the copper cladding thickness ( $t = 50\ \mu\text{m}$ ), the RCS level and quality factor are driven by the substrate thickness  $h$ . A co-planar quarter-wavelength resonator is evaluated without a ground plane shown in the insets of Fig. 4. Thus, as depicted in Fig. 4, all the losses are embedded in the model. The total  $Q$ -factor is directly proportional to the substrate thickness. That behavior is contrary when microstrip resonators are considered [12].

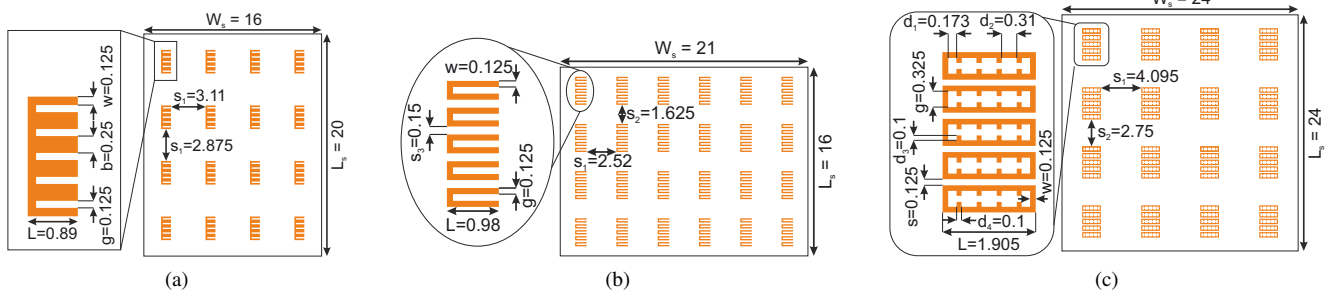


Fig. 2: Design dimensions for the tags without a ground plane. (a) E-shape, (b) C-shape and (c) L-shape. All dimensions are in millimeters.

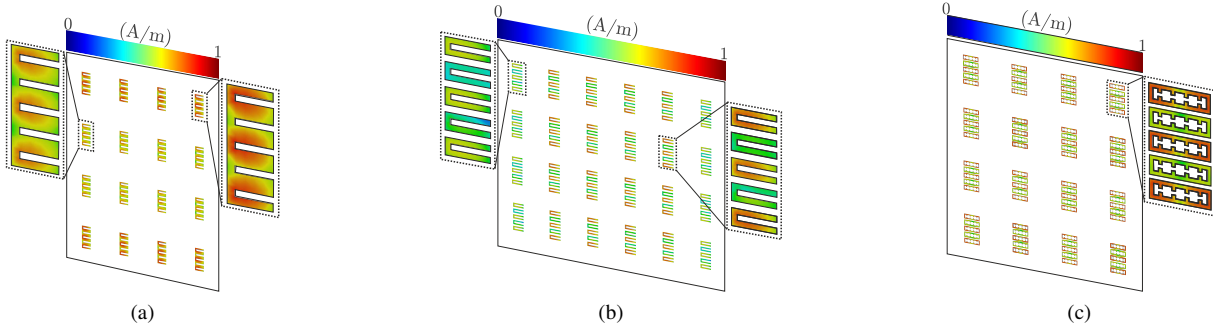


Fig. 3: Simulated current distributions for the proposed chipless mmWave tags at the resonance frequency, (a) E-shape, (b) C-shape and (c) Loop-shape.

### C. Proof of concept mmWave chipless tags

The RF Encoding Particle (REP) design approach [1] is adopted, and one elementary particle is chosen for encoding information. The first step of that approach is to establish a relation between the geometrical parameters of the isolated scatterer and its electromagnetic signature. Well-known tags have been evaluated for resonant mmWave purposes: C-section [4], Loop-shape [13], and E-shape [14]. The tags' geometrical designs, taking account of the constraints, are shown in Fig. 2. Afterward, to overcome the issue related to the tag RCS low backscattered level, each scatterer has been identically replicated to increase the backscattered electric field. The element multiplication does not involve a proportional augmentation to the RCS level. Hence an optimization has been performed. Finally, the result can be extended to the other structures. The electromagnetic responses of whole structures have been evaluated using CST Microwave Studio. The simulated structure is based on a substrate Rogers RT5880 with  $\tan \delta = 0.005$ , permittivity  $\epsilon_r = 2.33$ , and thickness of  $h = 0.127$  mm. The curves shown in Fig. 5 correspond to the RCS of the structures and their respective surface current at the resonance frequency (see Fig. 3). The backscattered signal is received in co-polarization within the far-field radiation zone. The RCS level for all analyzed structures is higher to  $-40$  dBsm, which allows the tag reading (office environment).

As depicted in Fig. 5, the structures are highly selective and present an RCS that allows the reading even in an office environment. Therefore, the tag based on E-shape structures has the best trade-off regarding size and selectivity. Henceforth, the E-shape structure will be used for applications in low-cost PET substrates.

### III. TAGS FABRICATION

Photolithography realization technology is chosen to realize the tags on low-loss flexible substrates. This process has similar design limitations to print-based systems. A one-bit frequency information tag from different shapes has been fabricated to assess the effectiveness of the proposed tags. It is noteworthy that the proposed solution can be easily modified to design tags with different operating frequencies.

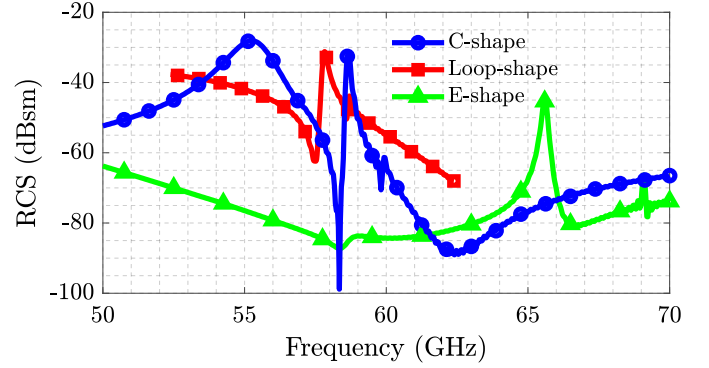


Fig. 5: Simulated RCS as a function of frequency for each proposed tag.

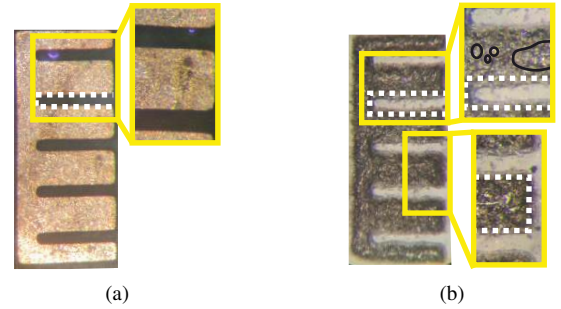


Fig. 6: E-shape tag without ground plane, (a) low loss material (photolithography) and (b) PET (inkjet). The dotted lines indicate the originally designed tag. The black lines show some imperfections in metallic ink transfer.

Two substrates have been investigated; the first one is low losses RT5880 (see Fig. 6(a)). The second one is a low cost PET (see Fig. 6(b)), which has a permittivity ( $\epsilon_r = 3.5$ ) and dielectric loss ( $\tan \delta = 0.03$ ) [15]. The PET material offers good printing, but some inconsistencies in the transfer are noticed, as shown in Fig. 6(b) (black lines), it introduces some discontinuities in the design, which can shift the expected frequency and reduced the RCS level.



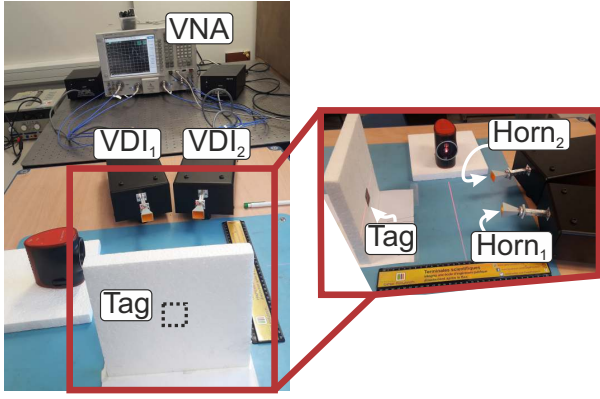


Fig. 7: Setup for millimeter-wave measurements in the office environment. Bistatic configuration is used, and both antennas have a co-polarization orientation.

TABLE I: Performance comparison between the chipless tags without a ground plane.

	C-shape	L-shape	E-shape	E-shape (PET)
$Q$ -factor	73.02	61.92	-80.02	30.72
Resonance peak lv. (dB)	-35.53	-31.48	-31.82	-46.08

#### IV. EXPERIMENTAL SETUP AND MEASUREMENTS

The V-band measurements were performed with an Agilent N5222A (10 MHz–26.5 GHz) PNA with Virginia Extensions (VDI modules) to operate from 65 GHz to 72 GHz. The VDI module is a frequency multiplier combined with a mixer with a WR<sub>15</sub> waveguide output connected to horn antennas on co-polarization configuration. The measurement setup is seen in Fig 7. The tag is positioned on a support made of foam. The tags were placed at a distance of 20 cm from the antennas, and the bistatic configuration, as seen in the insets of Fig. 7, is used.

The magnitude of  $|S_{21}|$  is shown in Fig. 8 for the tags on RT5880 material and E-shape PET-based substrate. The tag is removed from the foam for each measurement and placed in the same position. The resonance can be observed (peak apex) in all cases, which denotes that the backscattered fundamental mode is present in all the responses due to the resonant structure. The EM responses for low-loss tags present a higher RCS when compared to the PET-based tag. Indeed, the losses in PET substrate and metal losses are higher than in the RT5880. A significant frequency shift is seen in E-shape PET due to the permittivity and the imperfections generated in the manufacturing process. The RCS and  $Q$ -factors are resumed in Table I, as seen in the simulation part, the E-shape presents a higher  $S_{21}$  level and  $Q$ -factor.

#### V. CONCLUSIONS

The operating principle of resonant tags for millimeter wave application was evaluated by comparing different designs and substrate realizations. A prospective study of structures already developed in the UWB band and taken to the millimeter waves band shows that the resonant mmWave tags could be

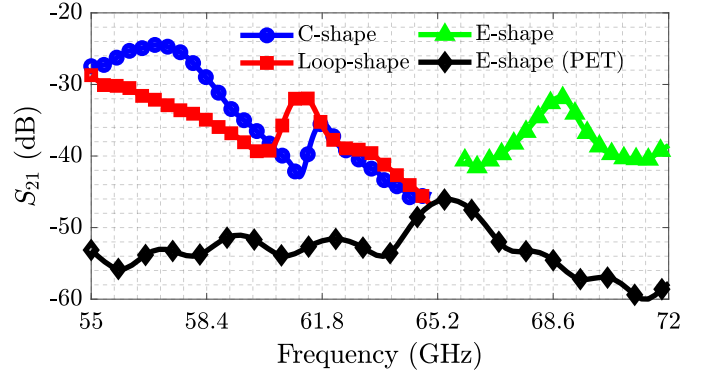


Fig. 8: Frequency domain response measurements in bistatic configuration.

compatible with millimeter-wave applications. However, the constraints on the fabrication process highlight the limitations of the proposed method since a low-cost printing method may be applied. Moreover, these tags have been evaluated without a ground plane, which agrees with low-cost fabrication procedures. Finally, the use of the REP approach was analyzed, and the number of resonators increased. The future work intends to implement a low-cost solution from the paper industry using bio-based and recyclable techniques.

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