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Resonant Scatterer Quality Factor Increasing based on Sustained Excitation by Multiple Reflections for Wireless Sensor Applications

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Abstract - This paper presents an RF resonator integrated into a guided structure, and remotely interrogated with an antenna presenting a significant increase in the quality factor relative to the resonator alone. The principle consists of self-maintaining the excitation of the resonant loop scatterer used to encode the information by using multiple reflections delayed in time with the guided dielectric. Indeed, a type of Fabry-Pérot structure recovers part of the incident wave to re-excite the resonant loop and thus increases the quality factor of the total structure. This increase is particularly useful for identification or sensor applications, for example in chipless RFID. Increasing the quality factor has some advantages, such as facilitating the temporal separation of the signal coming from the resonators from the quasi-optical reflections of objects in the vicinity of the tag. It also allows more information to be encoded or the resolution of the sensor to be increased by having narrower frequency peaks. Based on this approach, an increase in the quality factor can be as much as 55% in the lossless case, and in measurement with a lossy dielectric, an increase of 23% has been obtained

Keywords- Chipless RFID, coupled resonators, Q factor, sensor.

I. INTRODUCTION

The development of totally passive sensors that can be integrated remotely at low cost and are compatible with harsh environments such as very high temperatures is generating considerable interest [1]. In addition to the sensor function itself, which requires specific work, there is the problem of the lack of power supply and remote interrogation. Chipless RFID provides a technological solution to this problem, addressing each of these issues, in particular the question of sensor identification in addition to the sensor function itself [2, 3]. The idea is based on a radar approach in which, an EM wave is sent in the direction of the sensor tag made up of different resonators. Processing the signal backscattered by the tag will enable information to be recovered, such as the identifier and the value of the physical quantity to be measured [3]. A well-established technique consists of using resonant scatterers at the level of the tag [2, 3]. These scatterers are characterized by a resonance frequency, a quality factor, and a level of electromagnetic field that is backscattered toward the reader. The values of these resonance frequencies are generally used to encode the identifier. Similarly, some of these resonators can be configured as sensors, in which case it is generally the

variation in the resonance frequency that is used to retrieve the relevant information. A significant advantage of this approach is the use of simple resonator shapes (like the rectangular loop), which makes it possible to extract a complete analytical model linking the variation in resonance frequency to the physical quantities to be monitored [4].

However, this approach has several limitations, notably the reading distance of these passive tags and the relatively limited amount of information that can be encoded. Some of these limitations stem from the intrinsic performance of these resonators through their quality factor, which, due to severe dimensional and economic constraints, is usually less than 80 or even 50 in the 3 to 6 GHz band. These values become even lower when the resonator is applied to or in a lossy material. However, the quality factor plays a central role in this technology. For example, the higher the quality factor, the more the band associated with each resonance can be restricted, thereby increasing the amount of information on the tag [2]. Another example is that a high-quality factor allows the oscillation to decrease over a longer period, thus isolating the part of the signal containing the useful information from the contribution of the environment [5]. Finally, the quality factor plays a key role in sensor applications, as the minimum detectable frequency shift is inversely proportional to the quality factor [6, 7]. Increasing the quality factor of scatterer resonators that are compatible with the specific features of chipless RFID remains a promising area of research, particularly when the resonator is to be used in the vicinity of lossy materials.

This paper proposes to integrate a resonant scatterer inside a dielectric waveguide to increase the quality factor of the resulting structure for use in sensor applications. More precisely, the material used for the desired application (for example, a dielectric whose complex permittivity we want to be characterized) will be used advantageously to self-sustain the oscillations of the resonant scatterer loop and thus increase the quality factor. For the proof of concept, a rectangular loop resonator is immersed in a parallelepiped shape dielectric to act as a resonator (similarly to the Fabry-Pérot cavity). The result is a significant increase in the Q factor, even if the dielectric resonators contain losses.

II. SIMULATIONS

The CST time domain solver is chosen to perform the simulations. A plane-wave excitation is used as well as E-Farfield (time and frequency representation) and RCS probes to recover the backscattered field in the opposite direction to the emission. The operation principle of the proposed resonant structure and the role of the dielectric thickness are clarified in the following subsections.

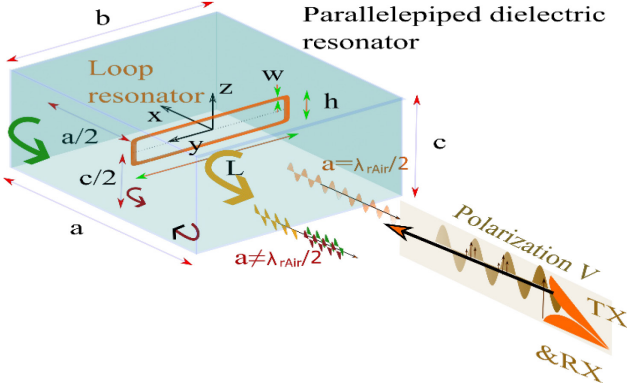


Fig. 1. Description of the structure consisting of two resonators: a rectangular metal loop and a dielectric having a parallelepiped shape.

A. Operating principle

The structure studied is shown in Fig. 1 and consists of two resonant elements: 1. a rectangular wire loop of length L and gap h . 2. a parallelepiped dielectric of permittivity ϵ_r and dimension a, b, c ; a being the length directed in the direction of propagation of the incident wave x . This structure can be seen as an open-circuit dielectric waveguide at both ends. The loop is at the center of the parallelepiped. An antenna linearly polarised along z propagates a wave in the x direction. The wave backscattered by the structure carries useful information, i.e. the frequency f_r and the quality factor Q . The resonance frequency when the loop is in free space will be noted f_{rAir} and f_r (k_r the corresponding propagation constant) when it is immersed in the dielectric ϵ_r . The different geometric parameters are specified in Table I.

Table 1. Characteristic variables in mm of the structure.

a	L	b	h
60	40	75	6.5
c	w	ϵ_r	
50	0.5	2	

The arrows in Fig. 1 show the physical principle behind the increase in the quality factor when the dielectric is present. To the first reflection of the wave on the loop (yellow arrow) is added, with a certain delay related to the length $a/2$, the wave reflected on the end of the dielectric cavity (green arrow) which will re-excite the loop and part of which will arrive in the direction of the reader. Another significant contribution comes from the wave backscattered by the loop which is reflected on the wall facing the reader (red arrow). This wave, which is also delayed, will help to re-excite the loop and here again, part of this signal can be recovered by the reader. For

all of these reflections to add up in phase and therefore maintain the excitation of the loop, the length a must be equal to half the guided wavelength i.e. $a = \lambda_g/2$. In this case, the duration of the oscillation will increase due to these multiple delayed and in-phase excitations, which results in an increase in the quality factor compared with the case without the dielectric. Although there is no completely rigorous closed-form expression for expressing λ_g as a function of the problem data, it is possible to use approximate expressions as in [8] :

$$\lambda_g = 2\pi \cdot \left[k_r^2 \epsilon_r - \left(\frac{\pi}{b} \right)^2 \left(1 + \frac{2A}{\pi b} \right)^{-2} - \left(\frac{\pi}{c} \right)^2 \left(1 + \frac{2A}{\pi c \epsilon_r} \right)^{-2} \right]^{-1/2} \quad (1)$$

where $A = \frac{\pi}{k_r(\epsilon_r - 1)^{1/2}}$. Using the data given in Table 1 for the dielectric guide, the analytical application of (1) allows to calculate λ_g and therefore to deduce the optimal value a : $a \sim 65\text{mm}$ for $f_r = 2.4\text{GHz}$. In same conditions, a fullwave simulation on CST gives a more accurate value with $a \sim 63\text{mm}$. Fig. 2 shows a CST simulation of the E-field backscattered by the scatterer in different configurations to illustrate the effect of the different reflections and their impact on the quality factor. In Fig. 2a, the length of the dielectric has been significantly increased ($a = 3.5\text{m}$) so that the different reflected waves can be separated in time. The wave associated with the first reflection on the resonator is visible, where a damped sine wave can be seen. In this case, the extraction method introduced in [9] makes it possible to extract the complex permittivity of the medium and, considering the portion of the signal represented by the yellow rectangle, we find $\epsilon_r = 2.1$, $\tan\delta = 0.088$, which is close to the expected values ($\epsilon_r = 2$, $\tan\delta = 0.1$).

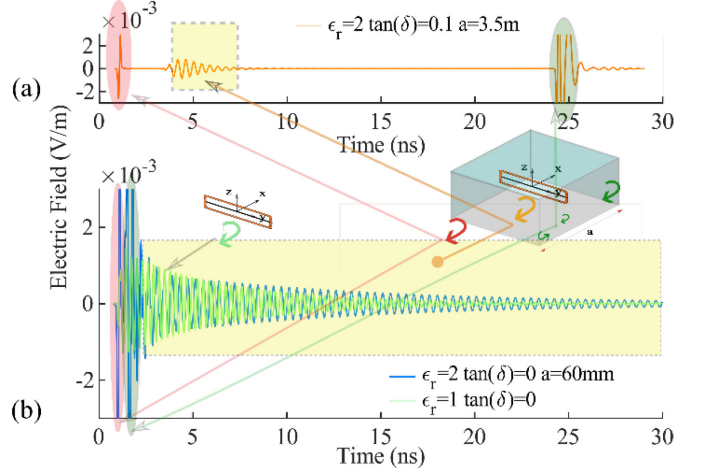


Fig. 2. Simulation of the E-Field backscattered by different scatterers. a) Lossy dielectric of very long length a , b) loop in free space as well as positioned inside a dielectric with optimal length.

Fig. 2b shows a comparison between the case of a loop in free space and one positioned in the dielectric waveguide of permittivity 2 whose length is close to the approximative condition obtained with (1): here $a = 60\text{mm}$ has been considered in the simulation. It is clear in the second case, that

the amplitude and duration of the oscillations is greater, which corresponds to an increase in the Q factor.

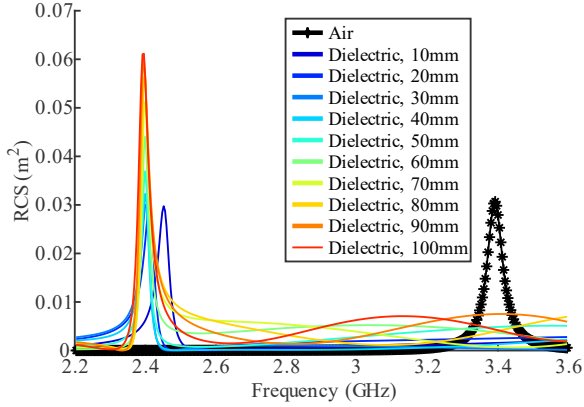


Fig. 3. RCS in frequency of the structure shown in Fig. 1 for different values of a . The loop case in air ($\epsilon_r = 1$) is also shown.

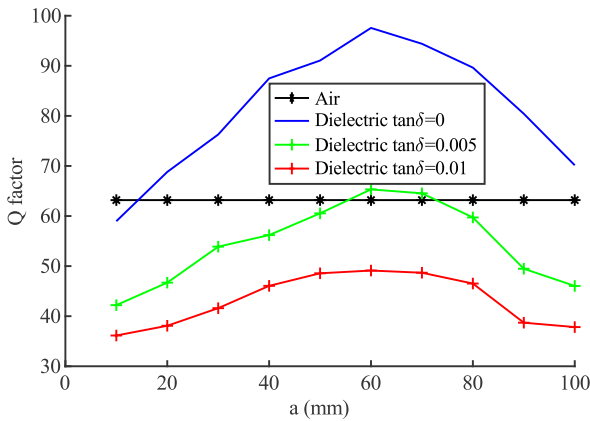


Fig. 4. Quality factor as a function of length a , extracted from the results shown in Fig. 2. Comparison between $\epsilon_r=2$ and without dielectric, and with the presence of losses into the dielectric.

B. Effect of the dielectric thickness

Fig. 3 shows the RCS for different lengths a of the dielectric resonator, as well as with no dielectric ($\epsilon_r=1$), (we have here $f_{rAir} = 3.39\text{GHz}$). We can see that for values of a greater than 20 mm, the resonance frequency f_r becomes constant and equal to $f_{rAir}/\sqrt{\epsilon_r} \sim 2.4\text{GHz}$ where, to a first approximation, for $h \gg L$, $f_{rAir} \approx c/(2L)$ with c the speed of light. For each case, the quality factor is extracted from the temporal representation of the backscattered electric field using a singularity expansion method (SEM) algorithm as in [9]. This approach allows the resonance mode of the structure to be precisely isolated while extracting the resonance frequency and quality factor. Fig. 4 shows the Q factor values obtained. It can be seen that the value of the quality factor is maximum ($Q=97$) for a value of a equal to 60 mm, which is close to the theory, i.e. $a = \lambda_g/2$; and the previously calculated values. With the CST Eigenmode Solver, it is also possible to determine the resonance modes, and by considering the same structure (Table I), we obtain $Q=94.7$ which is close to the value obtained using a time-domain approach.

If we compare this value with that obtained without the dielectric ($Q_{Air} = 63$), a 55% increase in the quality factor is seen. This corresponds to what can be observed in the time signals shown in Fig. 2. The same simulations were performed considering a lossy dielectric $\tan\delta=[0.005, 0.01]$. The extracted quality factors are also shown in Fig. 4. It is interesting to note that even with losses (case $\tan\delta= 0.001$) into the dielectric, the quality factor can be higher than without the dielectric. These results demonstrate the value of the approach where the loop resonator excitation is maintained by different reflections in the dielectric waveguide. The system is then excited for a longer duration.

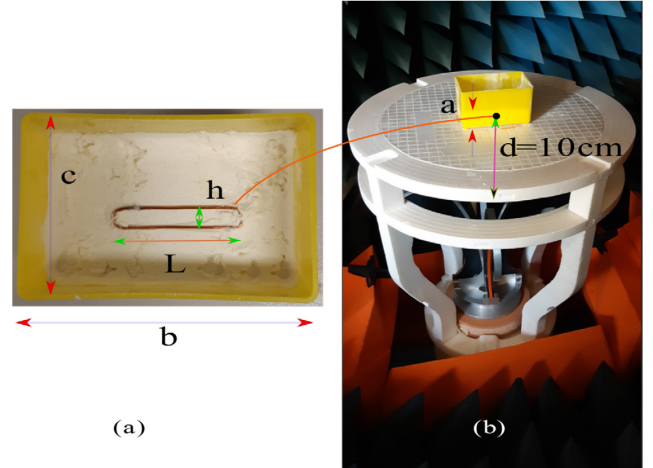


Fig. 5. Measuring bench. a) Rectangular loop with half full sugar level, b) measuring configuration used.

III. MEASUREMENTS

To completely enclose the loop in the dielectric, powdered sugar and a parallelepiped-shaped container are used. The container was half-filled and the metal loop was placed on top of the sugar, as shown in Fig. 5a. An identical volume of sugar was then poured over the loop to produce a structure similar to that shown in Fig. 1. It was thus possible to vary the dimension a of the parallelepiped as in the simulation. The VNA 5222A by Agilent was used. The source power is equal to -5 dBm. The frequency sweep ranging from 2.1 to 2.7GHz with 601 points is considered. As shown in Fig.5b, a monostatic configuration with Satimo (QH800) quad ridged open boundary antennas (0.8-12 GHz) is used and the dielectric resonator is separated by about ten centimeters from the antenna. The dimensions and properties of the materials used are the same as those described in the simulation section and are presented in Table I.

The measurements were carried out in a semi-anechoic environment (MVG StarLab) at a temperature of 17°C and 41% relative humidity. Under these conditions, the permittivity of sugar was extracted following the procedure described in [9], i.e. from two measurements: loop in free space and loop in sugar. Equation (13) from [9] was used to obtain a permittivity value close to 2.

Measurements of the S_{11} parameters around the resonant frequency and for different dielectric widths a (powdered

sugar) are shown in Fig. 6a. The quality factor was extracted as before, and the results are shown in Fig. 6b. The behaviour is similar to that observed in Fig. 4, where the quality factor is maximum for a value of $a=50\text{mm}$. In this case, Q is equal to 73, whereas it is 59 when the rectangular loop is positioned in free space. The measurement was carried out 3 times for $a=50\text{mm}$, and very comparable values for Q were extracted (Fig. 6b), showing good reproducibility in the measurement approach. The difference observed with the simulation ($a=60\text{cm}$) is explained by the presence of a plastic container. Indeed, the boundary conditions are changed on the edges of the dielectric guide: on the sides of the guide as well as on the ends which in the practical case are asymmetrical: the presence of the plastic wall on the antenna side, while no wall is present at the other end (Fig. 5).

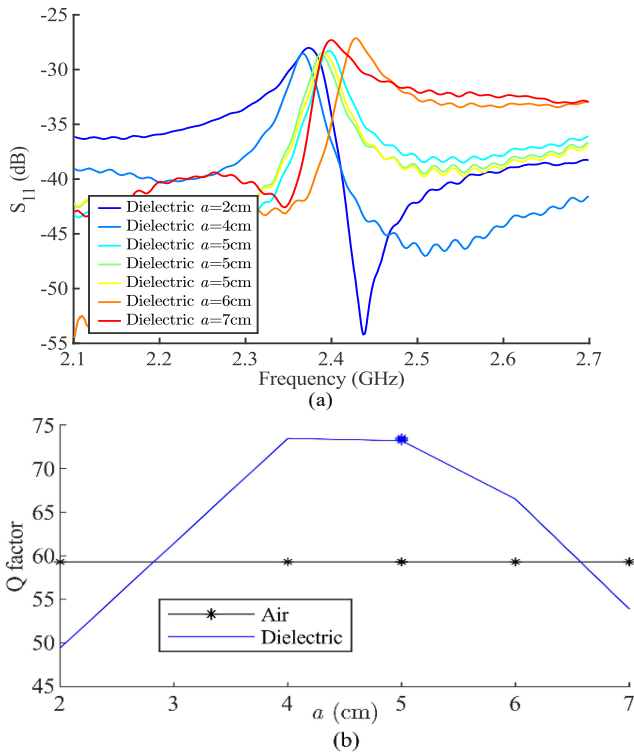


Fig. 6. Measurement results: a) S_{11} Parameter in frequency for different dielectric length values b) Extracted values of the quality factor.

IV. CONCLUSION

The principle of multiple excitations by reflections of a resonant scatterer was used to significantly improve the quality factor of the structure. With different reflections, it is possible to maintain the excitation of the resonator. A 23% increase was measured. This means that the quality factor is higher than without coupling, even if the dielectric material used contains losses (as in the case of the powdered sugar used). This proof of concept could be of particular interest in RFID chipless identification and sensor applications. In some cases, it is particularly interesting to be able to increase the quality factor, especially when the tag is positioned close to everyday objects that most often contain losses, such as paper materials for example. Finally, this approach could also be

used to accurately measure the complex permittivity of powdered materials.

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