Permittivity sensor using chipless time-coded UWB RFID

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Abstract

This paper presents a permittivity sensor based on chipless time-coded UWB RFID tags. These tags consist of a UWB antenna connected to a microstrip delay line. The principle of operation is based on the change in the delay between structural and antenna modes in the time response of the tags, as a function of the material where they are attached. A linear behavior is observed between delay and permittivity, with up to 350 ps delay increase for a permittivity variation between 2.2 and 5.7.

1. Introduction

Ultra-Wideband (UWB) is a technology that can be used for Radio Frequency IDentification (RFID) applications. Specifically, chipless UWB RFID is a promising low-cost alternative for item tagging [1-2]. A lot of research has been done to add sensing capabilities to RFID tags. These tags not only respond with their ID, but also with parameters of their environment, becoming RFID sensors. In [3-6] several chipless RFID sensors have been presented to detect parameters such as temperature, gas concentration or humidity. In this context, a permittivity sensor using chipless frequency-coded UWB RFID is presented in [7], detecting dielectric permittivities between 1 and 4.3 at 70 cm of distance.

This work proposes a permittivity sensor using chipless time-coded UWB RFID tags. Time-coded UWB RFID tags have proven to be detectable at several meters of distance and robust to the materials they are attached to on their back face [2]. In this work, however, the material is intentionally attached on top of the delay line which is connected at the end of a UWB monopole antenna, instead of on the ground plane. Depending on the permittivity of the material, the propagation velocity of the delay line is modified, and hence the tag response.

This paper is organized as follows. Section 2 presents the theory of operation of the permittivity sensor. Section 3 presents the tag design, measurement setup and characteristics of the materials to be characterized. Section 4 explains the results obtained, and finally Section 5 shows the conclusions.

2. Theory

Fig. 1 shows a scheme of the system. The reader sends through its transmitting (Tx) antenna a pulse $p(t)$ which hits the tag. A portion of the pulse is backscattered towards the reader, and another portion propagates inside the tag. The reader receives two scattering modes at its receiving (Rx) antenna: the structural mode (early reflection) and the tag or antenna mode (late reflection). The structural mode is due to the tag shape, material and size. The tag mode depends on the circuit connected to the tag antenna, in this case, an open-ended transmission line. The tag can be modeled as an equivalent two-port network (antenna) loaded with the open-ended transmission line of length L and characteristic impedance Z_c, as shown in Fig. 1. The signal received at the reader $s_r(t)$ in time domain can be approximated as:

$$s_r(t) \approx s_{Str.}(t) + s_{Tag}(t) + s_c(t) + s_m(t) \tag{2}$$

where $s_c(t)$ is the contribution due to cross-coupling between antennas, $s_m(t)$ is the contribution due to clutter and multipath reflections, and $s_{Str.}(t)$ and $s_{Tag}(t)$ are the responses associated to the structural and tag modes, respectively. They can be approximated as (3):

$$s_{Str.}(t) \approx \alpha S_{11}(t) * p(t) * \delta(t-\tau_p), \qquad s_{Tag}(t) \approx \alpha g(t) * p(t) * \delta(t-\tau_p-\tau_L) \tag{3}$$

where α is the round-trip attenuation factor due to the propagation in free space, τ_p is the round-trip time delay between the tag and reader, $\delta(t)$ is the Dirac delta function, * denotes the convolution operator, $g(t)$ is the Inverse Fourier Transform of $S_{12}S_{21}$ and $\tau_L=2L/v$ is the round trip propagation delay along the transmission line.

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The term $v = c/\sqrt{\varepsilon_{r,eff}}$ is the propagation speed of the transmission line, where c is the speed of light in vaccuum ($3 \cdot 10^8$ m/s) and $\varepsilon_{r,eff}$ is the effective dielectric permittivity of the medium. The structural mode delay or amplitude do not depend on the circuit connected to the tag antenna. On the contrary, the tag mode delay depends on the transmission line length L and on the propagation speed v. If L is kept invariant, but the permittivity of the medium $\varepsilon_{r,eff}$ is changed, the delay of the tag mode will change. The aim of this work is to detect the permittivity of the material $\varepsilon_{r,m}$ attached to the tag from the delay between the structural and the tag modes. The permittivity of the medium $\varepsilon_{r,eff}$ will be modified by the permittivity of the material $\varepsilon_{r,m}$. The structural-tag mode delay is completely independent from the distance/angle between the reader and the sensor. The delay without any material or air ($\varepsilon_{r,m}$ = 1) is previously known and stored as reference.

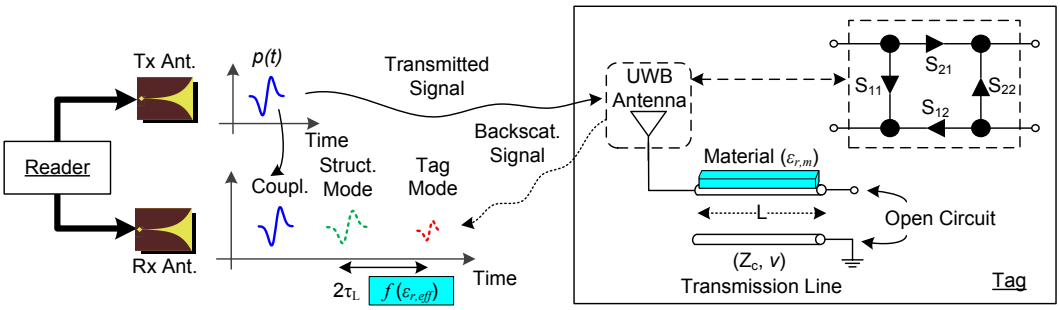

Fig. 1. Scheme of the tag-reader system and signals.

3. Tag design, measurement setup and simulations

A time-coded chipless UWB RFID tag is designed on Rogers 4003C substrate, and simulated using CST Microwave Studio. It is based on the design from [2], but the delay line length L has been increased to increase time resolution. By increasing L there will be a greater change in $\Delta\tau_L$ due to the attached. The proposed reader consists on a commercial low-cost UWB radar from Novelda (NVA6100), which sends a gaussian pulse at the 3.1–5.6 GHz band (with center frequency of 4.3 GHz), complying with the FCC regulation. The reflected pulse at the Rx port is sampled with 512 points and 30 ps between each point (meaning a 15.36 ns window). A period integration of 100 is used to improve the signal-to-noise ratio (SNR). Five thick slabs of materials are considered, with a thickness of 1 cm. As demonstrated in [7], the thickness of the material attached to the tag does not produce any change in the effective dielectric permittivity of the medium when is thicker than 5 mm. The materials characterized in this work and their respective permittivities are: PTFE (2.2) PC (3.2), PET (3.6), PUR (4) and CARP (5.7). Fig. 2a shows the layout of the designed tag. The tag size is 34.5 mm x 69 mm. Fig 2b shows the simulated $|S_{11}|$ parameter. Fig. 2c shows the simulated gain at 4.3 GHz, achieving a maximum gain of 3.41 dBi, and Fig. 2d shows a cut of the simulated gain for the Azimuth (θ) angle. It can be observed that the simulated radiation pattern is very similar to the measured pattern of a similar tag in [2]. Finally, Fig. 2e shows the designed tag with one material attached on top of the transmission line in the simulation environment.

4. Results

The response of the tag when on contact with the materials is simulated using CST Microwave Studio, with a plane wave orientated towards the tag back face (180º in Fig. 2d), and a E-field (farfield) probe at 40 cm. The time-domain solver is used with an accuracy of -30 dB. The plane wave is oriented at the back face for simplicity. Otherwise, the contribution of the material would appear before the contribution of the structural mode of the tag.

Fig. 3 shows the time-domain response of the tag before (left) and after (right) applying the Continuous Wavelet Transform (CWT). The CWT has proven to be very useful to reduce noise in this application [8]. As it can be observed, the structural mode remains invariant for all the measurements, while the tag mode delay increases when the permittivity of the material increases.

Fig. 4 (left) shows the structural to tag mode delay as a function of the permittivity of the material attached to the transmission line. A linear behaviour can be clearly observed. Fig. 4 (right) shows the delay increase with respect to air ($\varepsilon_{r,m}$ = 1) case. Again, a linear behaviour is observed, as in [7], with a delay increase from 100 ps to 350 ps.

Finally, Fig. 5 shows the structural to tag mode ratio as a function of the permittivity of the material.

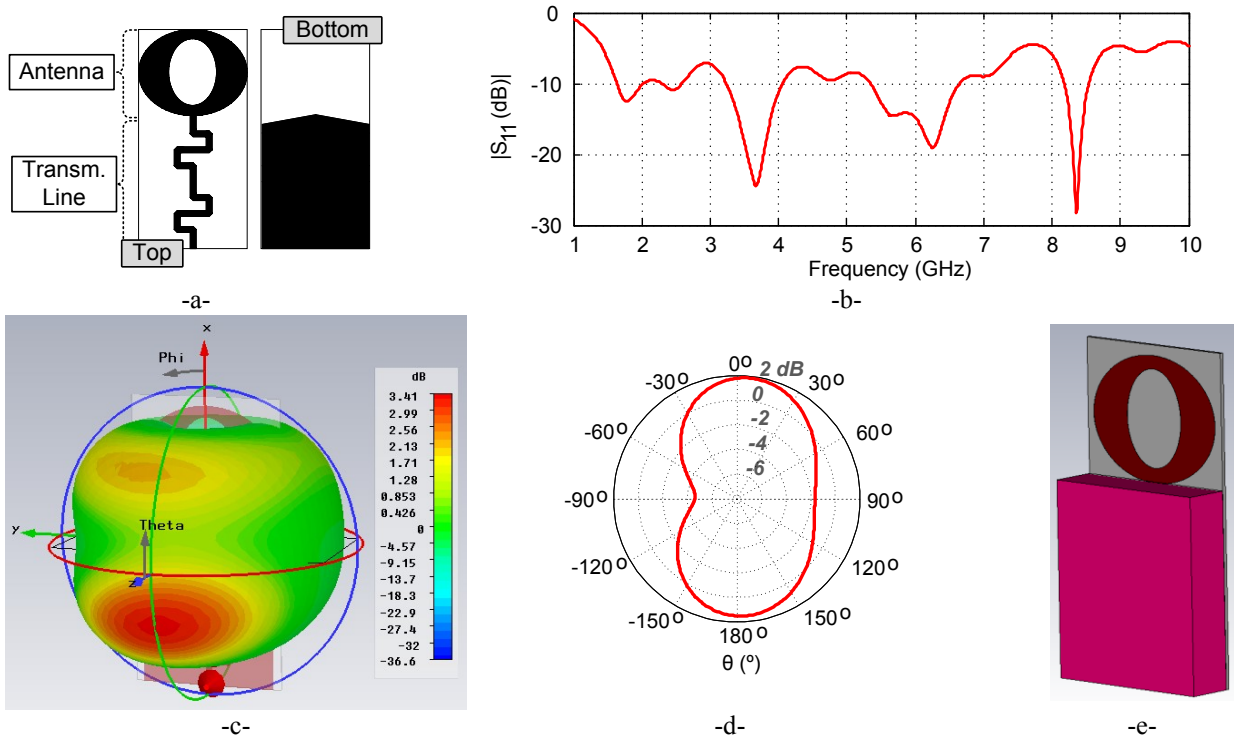

Fig. 2. (a) Layout of the tag. (b) Simulated $|S_{11}|$. (c) Simulated gain in 3D. (d) Cut of the Azimuth plane of the simulated gain. (e) Simulated tag with attached material.

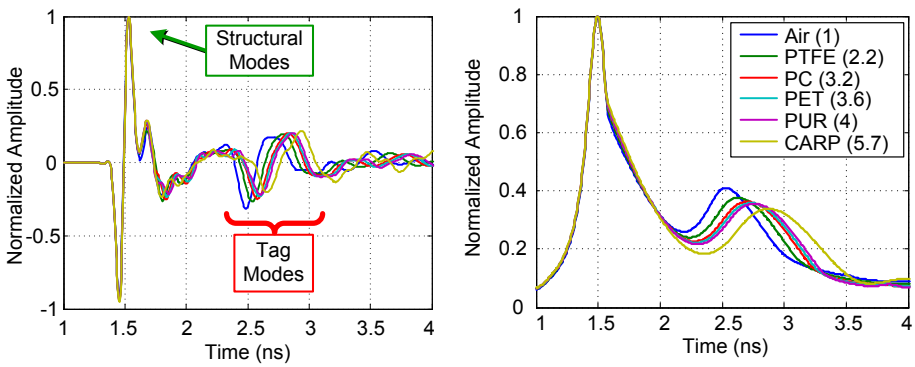

Fig. 3. Simulated time-domain response of the tag with several materials attached on top of the transmission line. (Left) RAW signal. (Right) Continuous Wavelet Transform has been applied to the RAW signal.

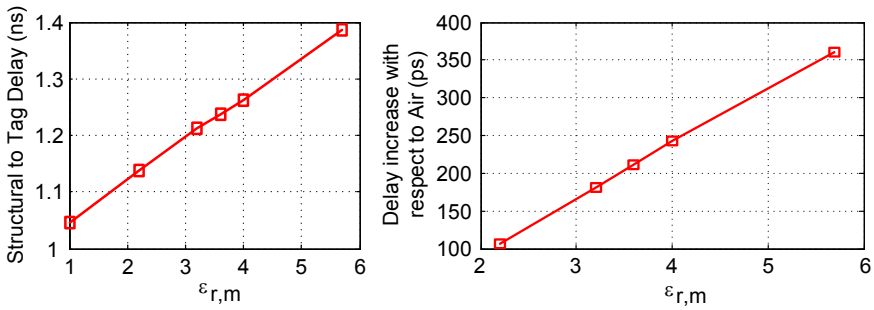

Fig. 4. (Left) Structural-to-Tag mode delay as a function of the permittivity of the material attached to the tag transmission line. (Right) Increase in delay with respect to the air ($\varepsilon_{r,m} = 1$) case.

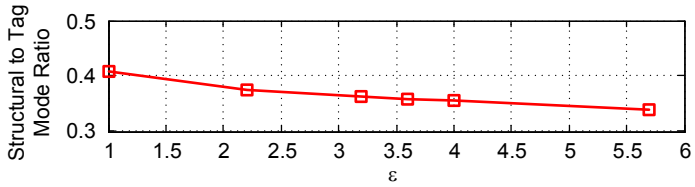

Fig. 5. (Left) Structural-to-Tag mode delay as a function of the permittivity of the material attached to the tag transmission line. (Right) Increase in delay with respect to the air ($\varepsilon_{r,m} = 1$) case.

5. Conclusion

This work has presented the design of a permittivity sensor based on chipless time-coded UWB RFID. The principle of operation is based on the change in the delay between modes in the time response of the tags as a function of the material where they are attached. A linear behavior has been demonstrated, with delay increases from 100 ps to 350 ps for materials with permittivities from 2.2 to 5.7, over a 1.05 ns base delay with air (permittivity of 1).

6. Acknowledgments

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