Chipless biodegradable tags, theoretical performance estimation

Invited Paper

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***Abstract*— This paper presents a theoretical study of two chipless biodegradable tags which potentially can provide temperature, and humidity estimation, as well as identification. The influence of the substrate material, as well as biodegradable metallized material conductivity, are studied.**

***Keywords* —antennas, electromagnetics, propagation, measurements, RFID, biodegradable.**

I. Introduction

Biodegradable materials are gaining attention, within the scientific community and society, for problems related to food quality, climate change and the generation of electronic waste. Meanwhile, sensors are playing an increasing role in our lives, offering improvements for everyday health and security. Sensors are either cheap and disposable, therefore generating waste, or they contain materials that can be harmful to the environment. Biodegradable sensors offer minimal environmental impact and a degradation behaviour that can be tuned for applications within zero-waste environmental sensing, food quality monitoring or personalized health.

An eco-friendly chipless and transistor-less sensor tag, made from cellulose-based substrate materials and containing no plastics and no other harmful materials, ready for non-hazardous direct biodegradation, disposal or recycling, without any need for return chain logistics or waste separation.

Chipless RFID refers to tags using diverse operation principles but have in common the absence of an IC, combined with the ability to be read remotely using RF waves. The main interest to eliminate IC is the potential reduction in cost and depending on the principle, such tags may also be printed.

Generally, passive wireless sensors are read based on time domain reflectometry (TDR) and frequency modulation (FM) [1 – 8]. Examples of this technique include surface acoustic wave (SAW), delay-line and retransmission-based and RCS back scatterer. One example of an FM-based wireless sensor in the literature is based on coupled LC resonant circuits consisting of a passive LC block, where the inductor (L) or the capacitor (C) represents the sensing element. The quantity to be measured changes the value of the sensitive element (i.e. C or L) and consequently the resonance frequency of the whole circuit. This change in the resonance frequency can then be detected by exploiting suitable electronics connected to the external antenna of the reader.

Another type of passive RF sensor is based on a modulated signal retransmitting or backscattering waves from an external reader (transceiver). In this case, the reader receives and demodulates the signal to retrieve the passive RF-sensor information. Potentially the operational communication range of these RF sensors is much better (2m-10m) than the LC resonant-based solutions. The backscattering can also be seen as a filter for an incident plane wave and multi-resonance or frequency selective surfaces can be effectively used for data bit encoding.

The goal of this paper is a theoretical study of ultra-low-cost simple eco-friendly chipless sensor tags that are read fully automatically without altering existing infrastructure and processes in authentication and logistics, based on our joint expertise in biocompatible and biodegradable materials, sensors, printed electronics and zero power RF systems.

This paper is organized as follows: Section II describes chipless tag operational principles. Section III and Section IV describe the short-range and long-range tag concepts and their theoretical performance accordingly. The realised WG-based phase shifters are discussed in Section IV. The conclusion is provided in Section V.

II. Tag operation principles

Below, we present the most attractive tag concepts based on their operational principles.

The FM passive wireless sensing tag is based on coupled LC resonant circuits consisting of a passive LC block, where its impedance, capacitor or inductor can be modified by the surrounding environment, see Fig. 1.

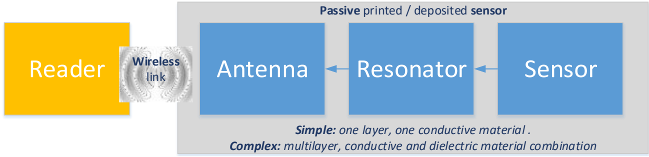


Fig. 1: Conceptual block diagram of the LC-type passive wireless sensor.

Temperature or humidity can change the value of the sensitive element i.e. resistor, capacitor or inductor, and consequently the resonance frequency of the whole circuit, which requires a reader for wireless interrogation. This change in the resonance frequency can be detected by exploiting suitable electronics connected to the external antenna of the reader.

The second approach for the wireless tag is based on the passive backscattering of RF signals, composed of the chipless RF tag and a reader, which is the only active element in the system (Fig. 2). Their operational frequency range will be an ultra-wide frequency band (UWB) (e.g. 3.1-10.6 GHz) that due to wider bands should keep more bits and reach longer reading distance/work in a more difficult environment. The received backscattered signal carries two pieces of information: the data ID (1) and the sensing information (2), with different chipless tags having unique spectral responses.

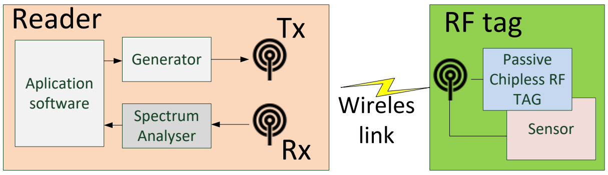


Fig. 2: Backscattered-based temperature sensor: conceptual block diagram.

III. Short-Range Tag Concepts

The chipless tags by operational distance can be divided into short and long ranges as depicted in Fig. 1 and Fig 2 accordingly. The short-range tag (up to 1cm) will use magnetic coupling between the reader antenna and the LC resonant tag and operate at a frequency between 2GHz and 7GHz.

For the detection of a multi-resonances short-range tag, a wideband loop antenna has been designed and optimised. The reader antenna structure is presented in Fig.3. The presented antenna is a single-layer printed antenna on a 0.8mm thick FR4 substrate (ε=4.4, tgδ=0.024).

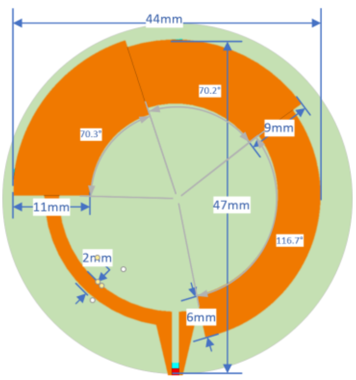


Fig. 3: Theoretical short-range tag resonant frequency performance estimation.

The overall antenna dimension is 44 x 47 x 0.8 mm^3. The antenna S-parameter is presented in Fig.4. As can be seen the antenna is well-matched between the 3.5GHz and 6.5GHz (BW=3GHz), which makes the loop antenna ultrawideband. The antenna bandwidth is achieved by applying a staircase microstrip line design with a well-optimized matching feeding line. If necessary, the proposed antenna topology can be further reduced, which will also degrade the antenna operational bandwidth to 2GHz - 2.5 GHz. Presented in this paper antenna size was chosen to operate with short-range resonance tags, as presented in Fig.5.

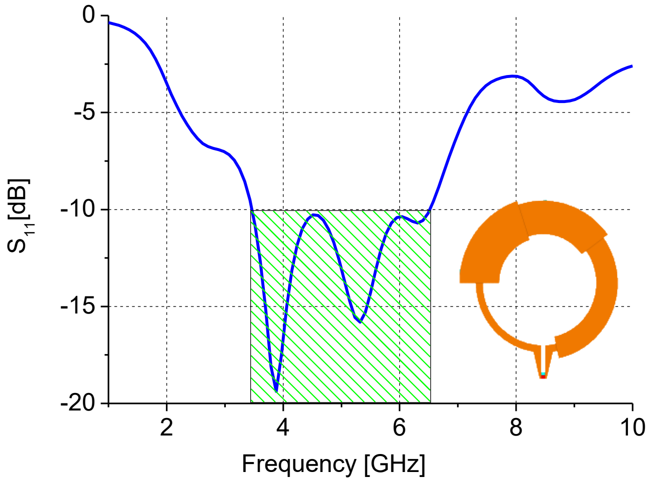


Fig. 4: Short-range tag reader antenna theoretical S-parameter.

The short-range tag is the resonance structure which is composed of a printed microstrip line loop antenna connected to the printed capacitive element (see Fig.5a). This element is in the centre of the tag structure. The tag conductive lines are placed on a biodegradable paper substrate (ε=3.3, tgδ=0.12). The line width of both the loop antenna and the capacitive element is 1mm.

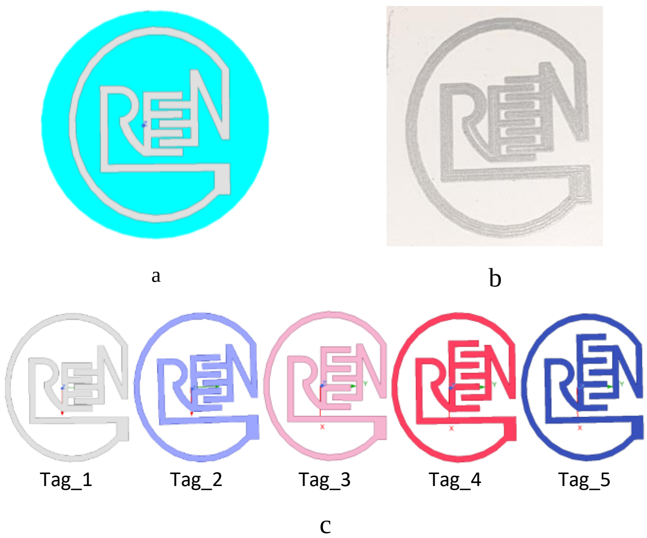


Fig. 5: Short-range « GREEN« tag concept (a), different combinations of the capacitive element (c) and Aerosoljet printed prototype with silver ink. (b).

Our goal is to use eco-friendly material for the chipless sensor tags design. The most difficult is to find a biodegradable conductive material. Zinc is one of the possible solutions. However, all available biodegradable conductive solutions have low electrical conductivity, which directly affects the RF performance of the antenna or an RF passive tag. In Table 1, different material conductivity is presented. The value of silver and zinc inks is averaged.

A commercially available software (Ansys HFSS) is used for the antenna, tag design and theoretical estimation of a different conductive material influence on the chipless RF tag performance.

TABLE I. DIFFERENT MATERIAL CONDUCTIVITY

Material	Conductivity [S/m]
Copper	5.8e07
Silver Ink	1.16e07
Zinc Ink	2.9e06

The theoretical model of the reader antenna and a chipless tag located in front at a distance of 1 mm is shown in Fig.6.

Fig. 6: Short-range tag with the reader antenna model.

The Tag_1 (see Fig.5c) with different conductive materials from Table 1 was placed in front of the reader antenna. The simulated reader S11 parameter shows the Tag with the Zn ink. conductive structure demonstrated slightly less sensitivity in comparison with the silver and copper conductive materials. However, the overall S-parameter curve shape is identical for all cases.

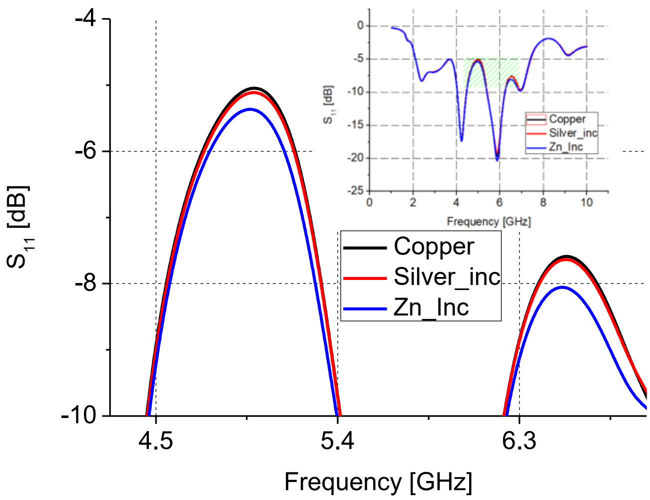


Fig. 7: Tag_1 in front of the reader antenna theoretical S-parameter.

Different short-range tag topologies detectability is presented in Fig.8. In this case, all the presented tags have a Zn conductive ink structure and are placed at an identical distance (1mm) from the reader antenna. The S-parameters are used to compare tags' performance. As we can see the resonance frequencies created by the tags varies from 100MHz to 400MHz. This fact allows us to conclude, that Zn ink can be accepted as conductive material for short-range tags, even if the conductivity is much lower in comparison with silver ink and copper.

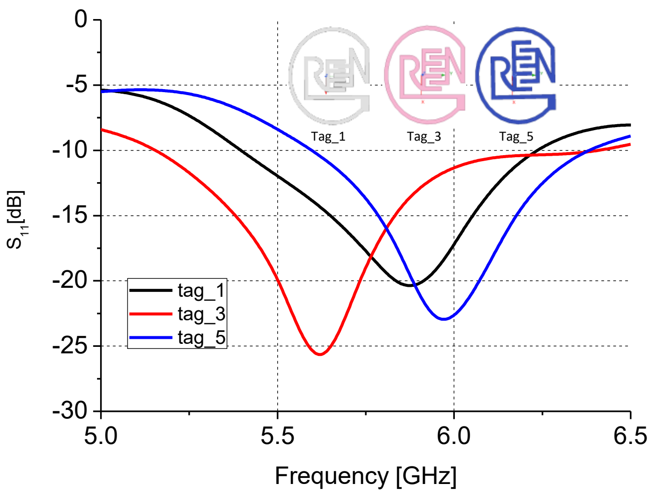


Fig. 8: Short-range tags with Zn ink conductive lines: theoretical results.

Zinc ink's low conductivity can potentially reduce the operational tag range (i.e. the distance between the reader antenna and the tag). The influence of the distance between the reader antenna and the tag is presented in Fig.9. As we can see the tag with Zn ink has a lower coupling with the reader antenna in comparison to the copper where the coupling vs distance is linear.

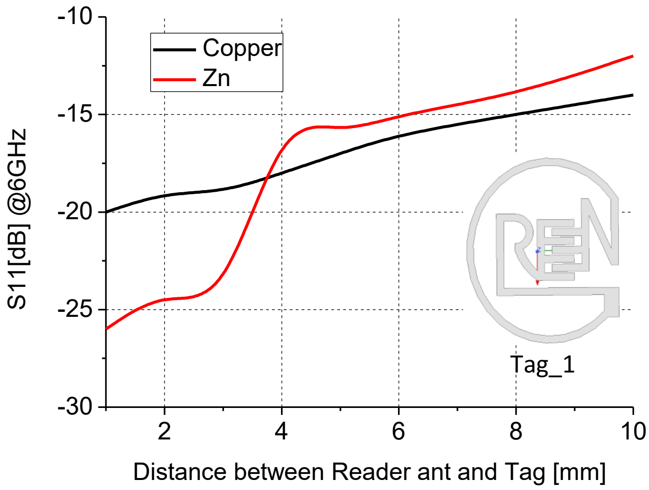
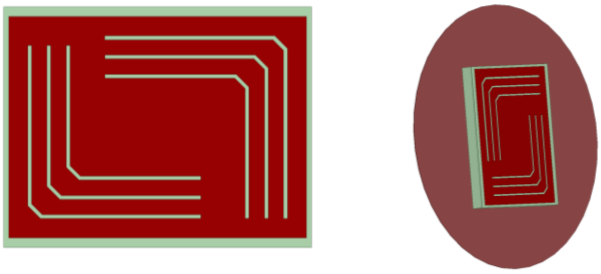


Fig. 9: Short-range tags with Zn ink conductive lines: theoretical results.

IV. LONG-RANGE TAG CONCEPTS

Chipless RFID tags for long-range applications above 0.2m have been investigated intensively within the last decade [10,13] with a strong focus on applicability in real environments [14]. Biodegradable tags require non-toxic metallization, the conductivity of which decreases over time. In this section, the influence of various metallisation on the radar cross-section of a clipless, biodegradable tag is investigated in-silico.

A single-layer, frequency-coded tag structure based on the design from [9] was chosen for the investigation. It features a depolarised resonating slot-line structure for reading in cross-polarisation either with or without a ground plane (Fig.11). The tags with a slot width of 0.4mm consist of 6 resonators of different lengths and are applied to a 0.1mm thick paper with a size of 32 x 25 mm^2. The design is optimised for 6-bit frequency-encoding in the frequency range from 3-5GHz and allows for low-cost, screen-printing fabrication (Figure 10). A thorough analysis of the cross-polarised features of various tag designs is published in [11].



a b

Fig. 10: a) Long-range tag based on a single layer slot line concept printed on a paper substrate based on a design published in [9]; b) Same tag placed 3mm above a ground plane printed on a circular paper with a radius of 30mm. The tag is held by a paper carrier of 1mm thickness creating an air cavity between the tag and the ground plane.

A ground plane printed on paper is additionally placed 3mm behind the tag to minimise the influence of near objects but limit the coded bits to 3 in the same frequency band due to capacitive load. Possibly, the ground plane can be also structured to compensate for the loss while retaining the compact design [12].

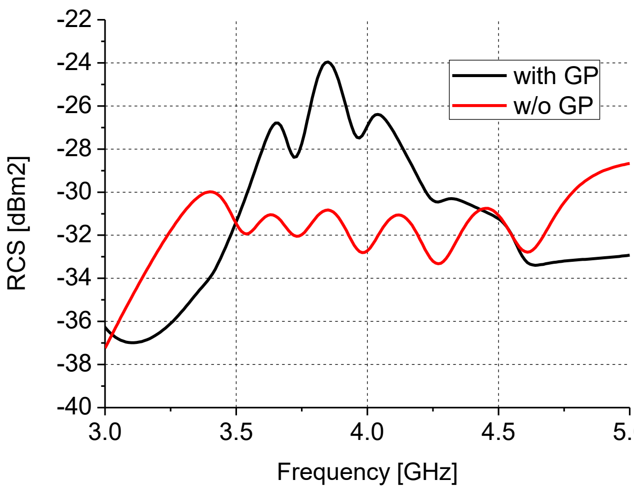


Fig. 11: Cross-polarised radar cross section for a long-range tag with and without a ground plane

A diminishing metallisation conductivity results in a declining quality factor of the resonating slot lines, thus the cross-polarised RCS signal at resonance is reduced and the resonance is slightly shifted towards lower frequencies (Fig. 12). But even at low conductivity metallisation based on Zinc ink, the functionality of the tag is not compromised. In addition, the strong resonance at a high frequency of around 5 GHz might allow for the estimation of the degradation state of the tag.

Similar results, i.e., a loss in the quality factor of the slot line resonators, are observed for an increase in RF losses of the paper substrate due to water intake during the degradation process (Fig. 13). In complex environments, the paper degradation process decreases the readability of the tags in two ways. Hence biodegradable protective coatings, like beeswax, must be applied to prolong the operational readability.

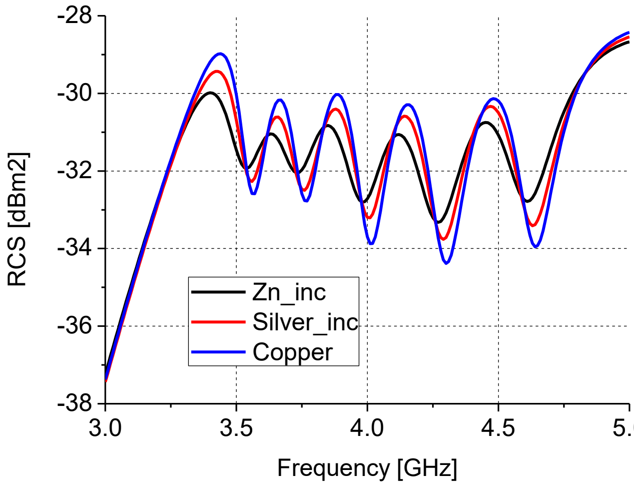


Fig. 12: Cross-polarised radar cross section (RCS) for a single-layer long-range tag with different metallisation: theoretical estimation.

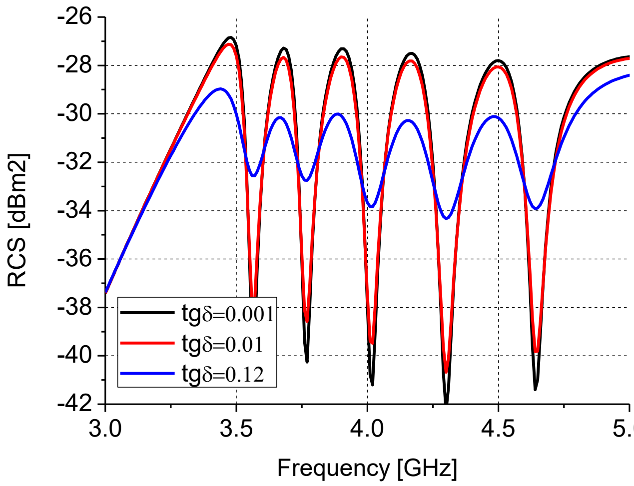


Fig. 13: Paper substrate loss tangent influence: theoretical estimation.

V. Conclusion

This paper presents theoretical study results for two chipless biodegradable RFID tags: short-range and long-range operation. Different conductive materials have been studied, where zinc ink is considered a biodegradable conductive material. Having much less conductivity in comparison with copper or silver, zinc can be considered for chipless bio-tag prototyping. However, its conductivity limits the passive tag’s operational range. Future investigation will focus on the validation of the in-silico observations.

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