Novel compact zero-power wireless sensors based on the harmonic radar principle, featuring low environmental impact and high integrability, for the next generation IoT applications

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***Abstract*—The main objective of the present research is to develop a new class of zero-power wireless sensors based on the harmonic radar concept, which are intended to produce a low environmental impact, being fabricated by using recyclable or organic substrates. Manifold aspects of the new proposed transponders have been investigated: manufacturing technology, harmonic generation, antenna and sensor design. Some new and interesting architectures have been identified and some preliminary results are here shown. All the reported circuits are designed to operate in the low-GHz range, but can be easily tuned to reach higher or lower operating frequencies.**

***Index Terms*—Circuits on paper, crack sensor, flexible electronics, frequency doubler, harmonic radar, slot antenna.**

I. Introduction

According to the vision driven by the emerging Internet of Things (IoT) paradigm, in a very near future almost all everyday objects will be equipped with electronics, so that they could provide useful services and information, make autonomous decisions and assist people during their habitual actions. Short-range wireless sensors are currently finding application in several fields ranging from the monitoring of biological parameters in medicine, to the measurements of mechanical quantities in industrial applications, robot guidance and quality control in supply chain. Consequently, such an approach, involving the use of billions of hardly traceable sensors distributed in the environment, is imposing a deep re-thinking of the next generation electronic apparatuses.

This research is dedicated to the development of a particular class of zero-power wireless sensors, which relies on the harmonic radar principle. The potential of the proposed approach is explored by means of a theoretical analysis and optimization of the single building blocks of the tag, i.e., the harmonic generation, the antenna system and the highly innovative sensors. Thanks to the adoption of highly-scalable, simple and robust architectures, the proposed solutions are intended to be suitable for large-scale mass production. All the proposed sensor tags are designed to be fabricated on unconventional flexible materials by using innovative technologies, in order to reduce their environmental impact and ease their integration with the hosting objects.

This report summarizes the outcomes of the research activity that has been accomplished with the partial help of the IEEE Microwave Theory and Techniques Society (MTT-S) Fellowship 2017 awarded to the author during IMS 2017 Student's Luncheon in Honolulu, Hawaii, USA.

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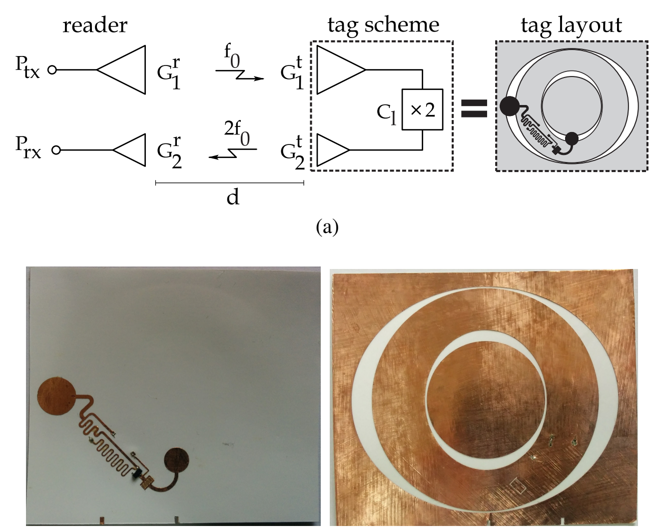
II. Project Outcome

The first step of the proposed research regarded the performance analysis and optimization of a one-bit harmonic transponder manufactured on paper by using the copper adhesive tape technology [1] (parameters of the equivalent composite substrate, including both paper and the glue layers interposed between each copper layer and paper: $\epsilon_r = 2.55$, tan$\delta = 0.05$, $h = 0.37$ mm, trace conductivity: $\sigma_{cu} = 5.8 \times 10^7$ S/m). The architecture of the utilized harmonic system is



(a)

(b) circuitry side (c) antenna side

Fig. 1. Harmonic radar based system: (a) block diagram (after [2]) and (b)-(c) prototype of the harmonic tag on paper. Overall tag area: $7.5 \times 6.5\,\mathrm{cm}^2$ [3].

illustrated in Fig. 1(a). The reader transmits a sinusoidal signal with a frequency f_0 and has its receiver tuned to $2f_0$ to gather the second harmonic power generated by the transponder. The double-layer transponder, shown in Fig. 1(b)-(c), consists of an input antenna at f_0, a frequency doubler and an output antenna at $2f_0$. All these three elements are designed to be matched to an impedance of $50\,\Omega$, so as to ease the eventual introduction of additional circuits and sensing blocks. The transponder is targeted for $f_0 = 1.2\,\mathrm{GHz}$ and $2f_0 = 2.4\,\mathrm{GHz}$.

The harmonic antenna system, consisting of two nested proximity-fed orthogonally placed tapered annular slots has been experimentally tested [3]. The two antennas feature a $-10\,\mathrm{dB}$ fractional bandwidth of $22\,\%$ and $12\,\%$, respectively, and a mutual coupling below $-25\,\mathrm{dB}$ at both frequencies of interest. Moreover, they are linearly polarized and show a maximum gain at their broadside direction of about $3\,\mathrm{dBi}$.

The developed frequency doubler relies on a single lumped component (the low-barrier HSMS-2850 Schottky diode from Avago Technologies), whereas all the other circuit components are implemented as distributed elements on paper. An interdigital capacitor with a floating ground plane (number of digits = 5, digit length $= 0.8\,\mathrm{mm}$, digit width $= 0.2\,\mathrm{mm}$, digit gap $= 0.15\,\mathrm{mm}$) is implemented in the output network. The latter structure was also useful to test the pitch and consistency of the adopted technology. The doubler is optimized for power levels in the order of $-13\,\mathrm{dBm}$, where it achieves a conversion loss of $15.7\,\mathrm{dB}$.

The complete prototype was tested in a wireless indoor experiment, demonstrating a coverage of at least 4 meters, insensitive to tag-to-reader rotations (transmitter EIRP $16\,\mathrm{dBm}$).

Then, the proposed optimized architecture was used to implement a zero-power wireless crack sensor [4],[5]. Fig. 2(a) illustrates the block diagram of the presented transponder. The reader interrogates the tag by sending a sinusoidal signal with a frequency f_0. When the tag is intact ("intact status"), the signal gathered by its input antenna is short-circuited by the stub at the input of the doubler (which is a quarter-wave open-circuited stub). As a consequence, the signal is prevented from entering the doubler and ideally no second harmonic is generated. On the other hand, if a crack occurs ("cracked status") the stub is torn off. In this case the signal can reach the doubler which converts it to $2f_0$. The second harmonic is thus transmitted back to the reader and it is detected by the receiver, which generates an alarm.

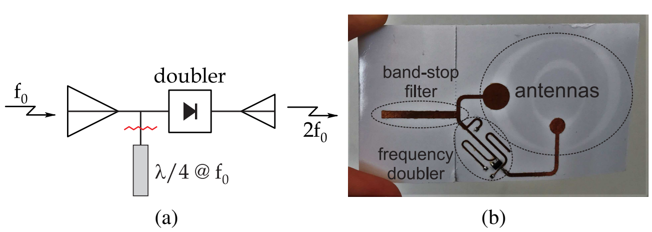


Fig. 2. Crack sensor: (a) schematic and (b) prototype on paper [5].

The complete prototype shown in Fig. 2(b) is target for $f_0 = 2.45\,\mathrm{GHz}$ and weights only 3 grams. A wireless experiment [4] demonstrates an operating range of the sensor from 1 to 5 m for a transmitted power EIRP of $25\,\mathrm{dBm}$. Since the system is based on an alarm logic (i.e., the second harmonic is generated only in presence of a "crack" event), it can deal with the presence of multiple nodes, without requiring any modification at the reader side [5], thus configuring a simple yet versatile system for crack sensing.

The project is still ongoing. I did a five-month internship at the Georgia Institute of Technology, Atlanta, USA, where I studied emerging manufacturing technologies, such as ink-jet and 3D printing, that I tested on the first ink-jet printed flexible millimeter-wave rectenna [6] and an ultra-wideband antenna [7]. Such technologies are currently being applied to the harmonic tags to improve their performance and broaden their field of application.

III. Professional Career Plan

In the immediate future, I am woking to complete my research on harmonic tags and, more generally, on autonomous wireless transponders based on exotic materials and manufacturing processes for the IoT.

After my Ph.D. graduation, I would like to find an academic position and remain in the microwave community. I love working as a researcher and the IEEE MTT-S Fellowship motivated me to actively take part in the MTT-S community and gave me the confidence to interact with the other more experienced scientists from all over the world.

IV. IMS Impression

IMS2017 in Hawaii was my third IMS. I feel such a conference is an amazing opportunity to set up collaborations and make a confrontation with the other scientists in the field. Every year, I had the opportunity to increase my network, learn news and research trends from both academia and industry, and receive feedback on my own results. What's more, I was able to transform the enthusiasm generated by such a big event to renovated energy for my experimental activity.

Acknowledgment

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