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CHIPLESS RFID

Demonstration of a chipless harmonic tag working as crack sensor for electronic sealing applications

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This work proposes a chipless radio frequency identification approach based on the working principle of the harmonic radar. A frequency multiplication stage is performed by a non-linearity (i.e. a Shottky diode) on the tag in order for the tag answer to be insulated from the interrogation signal, thus avoiding the need for clutter cancellation techniques. Firstly, the performance of a simple one-bit harmonic tag relying on a low-power frequency doubler is analyzed and then a novel crack sensor, implemented by adding a disposable band-stop filter, is presented. Both solutions demonstrate tag-to-reader operational distances beyond 1 m. The characterizing blocks (namely the frequency doubler and the filter) are fabricated on cellulose substrates (i.e. regular photographic paper), thus being conformal to their implementation for applications in the new paradigm of Internet of Things.

Keywords: RFID, Circuits on paper, Crack sensor, Harmonic radar

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I. INTRODUCTION

In the last years, the chipless technology has been experiencing an increasing interest as enabling technology for the Internet of Things (IoT) paradigm. The breaking through concept at the base of the chipless radio frequency identification (RFID) approach is that in order to realize extremely low-cost, highly ecofriendly, additive manufacturing compatible, and flexible tags for the widest “object” compatibility, wireless transmission of information, and sensing capabilities should be pursued by getting rid of the inherent limitations of using integrated monolithic circuits for memory storage or signal processing [1, 2].

On the one hand, the challenge of chiplessly encoding and transmitting information has led to the development of several tag designs, which can be classified into three main categories depending on the adopted coding strategies: the most traditional time-domain reflectometry (TDR) [3, 4], where the tag receives a pulse-signal and transmits back a train of pulses delayed by a predefined time, the spectral signature-based technique [5, 6], where the tag encodes the data into the spectrum by means of resonant structures, and the harmonic radar-based technique [7–9], where the tag receives a signal at a fundamental frequency and re-transmits it back at the second harmonic by means of non-linear components. In fact, the chipless tag category also includes tags with discrete components in package [10, 11].

On the other hand, the chip removal has enabled and fostered the diffusion of new concepts and circuit fabrication techniques, such as printing electronics [12], ink-jet printing, aerosol-jet printing [13], roll-to-roll, glued electronics [14], which have paved the way to circuit fabrication on unconventional substrates, like polyethylene terephthalate, textiles, cellulose, cork, and plenty of materials never adopted for electronics before.

In this scenario, the potential of the cellulose as a paradigmatic substrate for electronics is becoming even more evident [15]. In fact paper, being extremely lightweight, flexible, biodegradable, and intrinsically inexpensive, allows RFID fields of application to be broadened by developing low-cost and versatile tag solutions, while reducing the waste volume related to the widespread diffusion of electronic apparatuses into the environment. Although paper features some drawbacks, such as high dielectric losses, surface roughness, lack of ruggedness, and an unstable relative permittivity mainly with respect to humidity variations, there are some applications where it is a natural fit, such as, for instance, microfluidics [16], where its porosity can play a key role.

The aim of the present work is to exploit what is broadly considered to be one of the main drawbacks of the paper substrate, namely its fragility, as a useful characteristic: a wireless crack sensor for sealing purposes has been designed and a proof of concept has been carried out. The paper is organized as follows: in the two next sections a brief description of the

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adopted copper (Cu) laminate technology (Section II) and an analysis of the harmonic radar-based approach (Section III) are given; then in Section IV, the performance of a harmonic one-bit tag are reported and finally the design and prototyping of the crack sensor is described (Section V).

II. TECHNOLOGY AND MATERIALS

The circuits proposed in this work have been fabricated by means of the Cu laminate technique, which has already stated and demonstrated in several RF and microwave circuits [14–17]. This method consists of the shaping of an adhesive Cu tape by standard photolithography and the application of the Cu pattern on the paper substrate by means of a sacrificial layer. The photographic paper used for the circuit fabrication is a 230-μm thick sheet from Mitsubishi™, having a dielectric constant (ε_r) of about 3 below 10 GHz and a loss tangent (tanδ) of 0.08, while the adhesive Cu tape is from 3M™.

Figure 1 illustrates all the steps of this technique. Since a thin glue layer is interposed between each metal and the paper substrate as well as among paper substrates often required to keep control of the whole composite dielectric thickness, a multilayer structure is thus obtained. In [17], an equivalent uniform substrate is defined and its parameters are reported.

This technique, relying on a chemical procedure (which can be avoided by directly shaping the circuit layout with a laser-cutter machine) and a subtractive approach, can be considered more traditional than the other techniques conceived to fabricate circuits on paper, but it shows some interesting advantages, such as higher conductivity ($\sigma_{cu} = 5.8 \times 10^7$ S/m), the possibility to solder surface mount components by means of conventional eutectic alloy, compatibility with printed circuit board (PCB) fabrication equipment, which make it a valuable complementary approach with respect to printing electronics.

III. HARMONIC TAG

As already stated, a harmonic tag is based on the harmonic radar principle, according to which the tag converts the incoming signal at fundamental frequency to the second harmonic in order to efficiently separate the uplink at f_o from the downlink ($2f_o$) and provide full insensitivity to the environmental backscattering. A basic scheme is reported in Fig. 2. In order to perform the frequency conversion stage, at least a non-linear component on board is required. It means that at the moment a harmonic tag cannot be made completely printable or recyclable and this has a residual impact on the tag cost.

However, unlike the other chipless categories, this approach is naturally immune to clutter returns and man-made noise, since the harmonic radar receiver is tuned to the second harmonic of the transmitter. Consequently, the design of one-bit tag is straightforward (see Section IV) and such a system can be employed in several applications within the IoT paradigm: logistics, packaging, safety, electronic article surveillance [18]. On the other hand, this approach becomes more troublesome when multibit data have to be managed and the research in this field is far from the results obtained with the spectral signature-based approach (in [19] a coding capacity of 49 bit has been reached). An important issue to be considered is the operational bandwidth of the non-linearity employed for the frequency doubling, since it could represent a bottleneck for the coding capacity in the frequency domain. Nevertheless, a promising approach which is worth being mentioned is presented in [20], where in a harmonic tag the information is encoded as the phase-difference between two signals transmitted in orthogonal polarization.

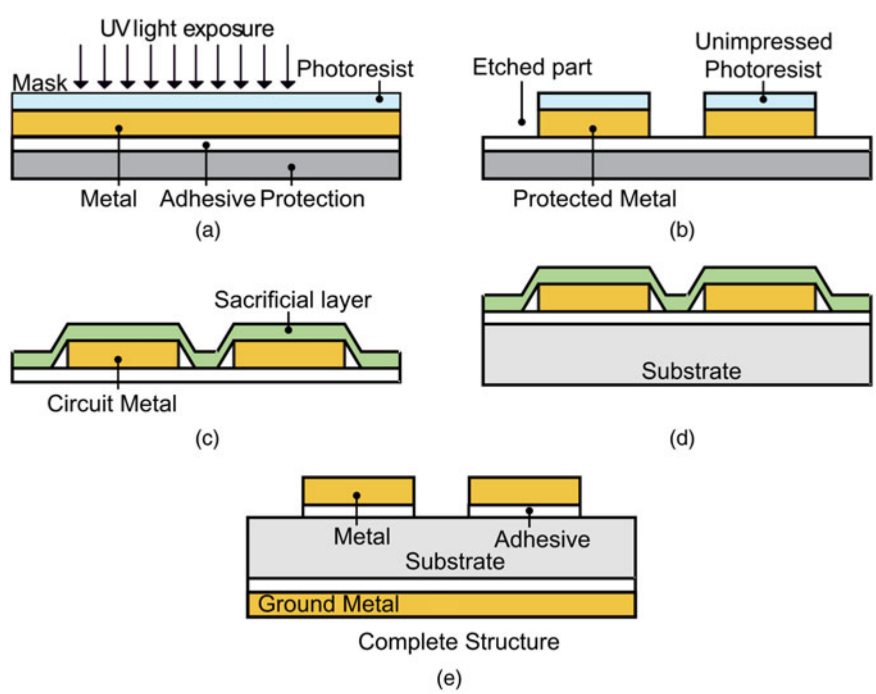

Fig. 1. Cu laminate technology: photoresist deposition and UV light exposure (a); wet etching (b); transferring of the Cu pattern on the paper substrate by a sacrificial layer (c, d); and fabrication of the ground plain with a slab of Cu tape (e).

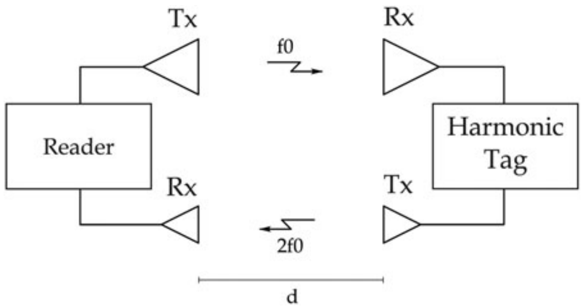

Fig. 2. Harmonic tag working principle: the signal transmitted by the reader at f_o is doubled by the tag, which returns back an answer signal at $2f_o$ [21].

IV. ONE-BIT TAG

In passive harmonic tags, the non-linearity plays a key role, since it determines the efficiency with which the tag is capable of converting the fundamental tone into the harmonics and has an impact on the cost of the tag, which, when adopting a chipless technology, mainly depends on the number of commercial components employed. Therefore, in order to maximize the reading range of the system while keeping the cost very low, the frequency multiplication function has been performed by a passive frequency doubler, based on a single low barrier Schottky diode and designed to feature a low conversion loss at low-input power with a minimum component count.

This design has already been described in [21]. The schematic and the fabricated prototype are reported in Figs 3(a) and 3(b), respectively. The doubler is targeted for $f_o = 1.04$ GHz. Such a frequency has been chosen to prove the system operation in the low GHz range. It has been experimentally demonstrated that the doubler shows a minimum conversion loss of 13.4 dB for an input power of -10 dBm, where the conversion loss is defined as the ratio of the available source power (P_{avs}) at f_o to the output harmonic power at $2f_o$ delivered to the load:

$$C_l = \frac{P_{avs}^{f_o}}{P_{load}^{2f_o}}. \quad (1)$$

A harmonic one-bit tag has been assembled connecting the doubler to suitable antennas. The experimental setup is reported in Fig. 4. In the tag, a helix antenna (gain 4.9 dBi) is used at the fundamental frequency, while a patch antenna (gain 4.3 dBi) is adopted for the second harmonic. The reader antennas are equal to the tag ones. Note that these values of antenna gain are typical for many RFID systems. The reader transmitter has been implemented with a HP8657A source and the receiver was an Agilent N9320B spectrum analyzer. The transmitted power has been set to 10 dBm, whereas the tag-to-reader distance has been varied in a range between 10 and 100 cm. Figure 5 shows the measured power as a function of distance and compares the experimental results obtained in a laboratory room with no special anechoic provisions to a calculated curve based on a link budget analysis. In particular, the received power has been theoretically estimated according to the following formula:

$$P_{RX} = \frac{1}{4} P_{TX} 2G_1 2G_2 C_g G_c \left(\frac{\lambda_o}{4\pi d}\right)^4. \quad (2)$$

The meaning and the value associated to each symbol are reported in Table 1. This equation takes into account that f_o and $2f_o$ antennas are identical for the reader and for the tag. Note that the 1/4 coefficient is due to the fact that the tag-to-reader communication happens at $2f_o$ (i.e. twice the fundamental frequency f_o used for the reader-to-tag link) and the calculation is made on the assumption of a constant conversion loss of 13.4 dB, which corresponds to the actual value only for a distance of approximately 65 cm. As can be seen from the graph, it has been experimentally demonstrated that the tag-to-reader range extends beyond a distance of 1 m, since the received signal is well above the noise floor of typical receivers.

By equating (2) with the radar equation, the harmonic radar cross-section (HRCS) can be extracted. This parameter plays the same role as the conventional RCS for the other chipless RFID systems and as a consequence it represents a useful figure of merit. Thus, from:

$$P_{RX} = \frac{1}{4} \frac{P_{TX}\, G_1\, G_2\, \sigma_h\, \lambda_o^2}{R^4 (4\pi)^3}, \quad (3)$$

where the 1/4 coefficient accounts for the receiver which is tuned to $2f_o$, the HRCS is given by:

$$\sigma_h = G_1\, G_2\, C_g(P_{avs})\, \frac{\lambda_o^2}{4\pi}. \quad (4)$$

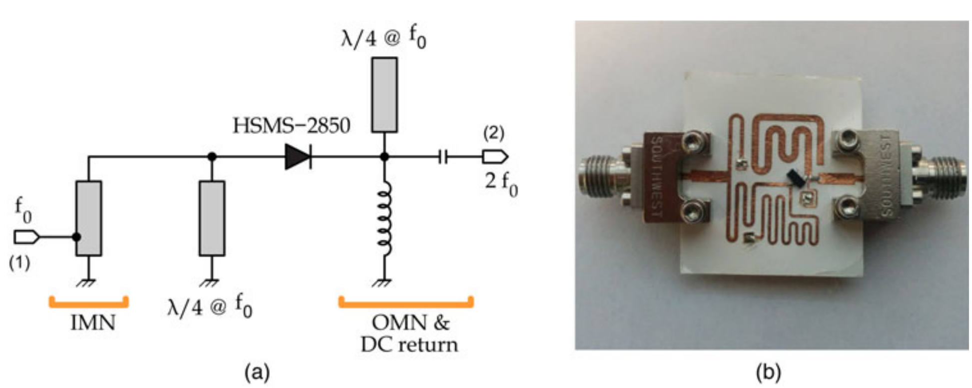

Fig. 3. Frequency doubler: schematic (a) and prototype manufactured in paper substrate (b). All the components, except for the diode and the capacitor in the output-matching network, are implemented as distributed elements in microstrip technology, which have been folded in order to reduce the area occupation. The Schottky diode is soldered on the Cu laminate as in standard PCBs. Active area: 18 mm in length and 19 mm in width [21].

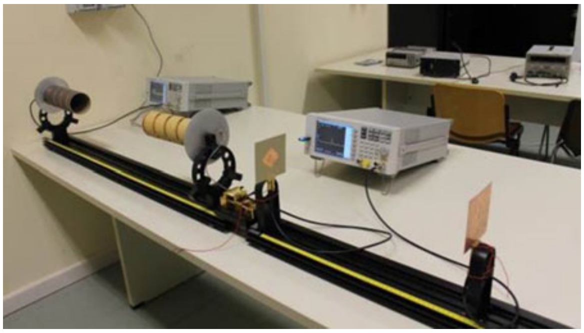

Fig. 4. One-bit harmonic RFID system: experimental setup. The wireless up-link at f_0 has been implemented with helix antennas, whereas the down-link at $2f_0$ has been implemented with patch antennas.

A similar approach is described in [22]. Using the values reported in Table 1, an estimate of the HRCS of the proposed tag can be found:

$$\sigma_h = -26\,\text{dBsm}. \quad (5)$$

It is worth noticing that, unless conventional RCS, the HRCS is distance-dependent, since it depends upon the conversion loss, which in turn varies according to the available power at the input of the doubler.

V. CRACK SENSOR

The proposed tag is intended for those scenarios where an even huge population of tagged objects is present and the aim is to automatically reveal if one of them has been tampered. This can be helpful to speed up goods monitoring in supply chains and as security system in retail. To this end, the tag is based on a disposable band-stop filter and operates according to an invert-logic (Fig. 6).

In fact, in quiescent condition, the tag does not re-radiate a signal when interrogated (referred to as "intact condition" in the following), since the second harmonic generated by the frequency doubler is short-circuited by the band-stop filter at the output side. But when the filter is torn off (referred to as "cracked condition" in the following), the output signal can reach the transmitting antenna, thus causing an alarm.

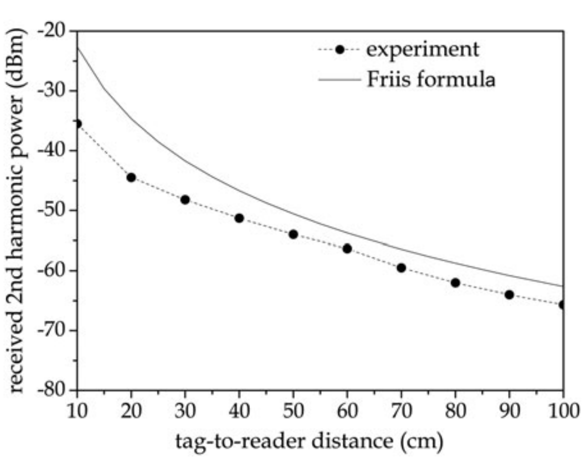

Fig. 5. Harmonic RFID experiment: received signal power versus tag-to-reader distance *d*. The experiment is in good agreement with the link-budget analysis based on the Friis' formula. Similarly to radar, the received power decays as $1/d^4$.

Table 1. Legend of the link-budget formula.

Symbol	Parameter	Value
P_{RX}	Received power	Output of the formula
P_{TX}	Transmitted power	10 dBm
G_1	f_0 antenna gain	4.9 dBi
G_2	$2f_0$ antenna gain	4.3 dBi
C_g	Conversion gain of the frequency multiplier ($= 1/C_l$)	−13.4 dB
G_c	Cable gain (four cables)	−6 dB
λ_0	Fundamental wavelength	28.8 cm
d	Reader-to-tag distance	10–100 cm

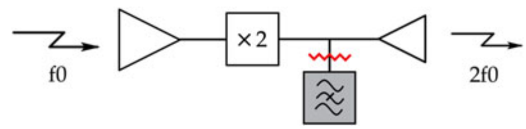

Fig. 6. Schematic representation of the developed disposable crack sensor.

Such a sensor can also be employed to reveal the increase of a crack in a material as well as the tampering of envelops or boxes of interest: for instance official letters for public contests or packages containing precious items. The reader could be a portable instrument, used before the start of a public exam or before the shipping of a box as a security control.

Considering that a quarter-wave open-circuited stub behaves as a series resonant circuit, the band-stop filter can be implemented by inserting such stubs in shunt along a transmission line, provided that the stubs are separated by quarter-wave sections of line, which act as admittance inverters, capable of converting alternate shunt resonators to series resonators.

For the presented application the filter has to be designed with the aim of maximizing its attenuation at the second harmonic ($2f_0$), without affecting the fundamental frequency (f_0). Thanks to these loose requirements (its fractional bandwidth can approach to 2), a simple second-order Butterworth filter has been employed. The characteristic impedances of the stubs are given by Pozar [23]:

$$Z_{on} = \frac{4Z_0}{\pi g_n \Delta}, \quad n = 1, 2, \quad (6)$$

where g_n are the impedance-scaled prototype elements and Δ is the fractional bandwidth. By choosing $\Delta = 2$, the characteristic impedance for both stubs is equal to 22.5 Ω, which corresponds to a line width of about 2.5 mm.

To validate the proposed circuit, the layout of the filter has been fabricated using the previously mentioned technique based on the Cu adhesive laminate and the paper substrate. The circuit design has been carried out by exploiting the electromagnetic solver CST Studio Suite™. The material parameters are quoted in [17], whereas the circuit parameters are reported in the caption of Fig. 7.

If the stubs in shunt are removed (Fig. 8) the circuit becomes a simple 50 Ω line, thus losing its filtering function. In order to ease the stub removal and to guarantee that, in case of tampering, the stubs would be completely removed, a series

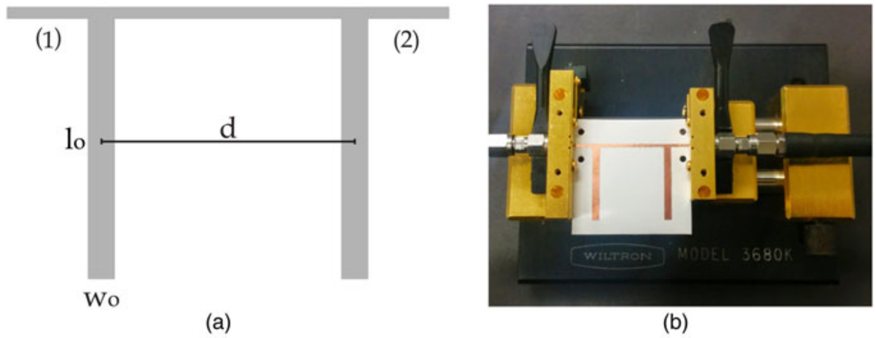

Fig. 7. Layout of the filter (a) and prototype manufactured in paper substrate (b). The band-stop filter is composed of two open-circuit stubs, a quarter wave long at $2f_0$, spaced by a quarter wave. The main circuit parameters are: $lo = 24.9$ mm, $wo = 2.5$ mm, and $d = 22.3$ mm.

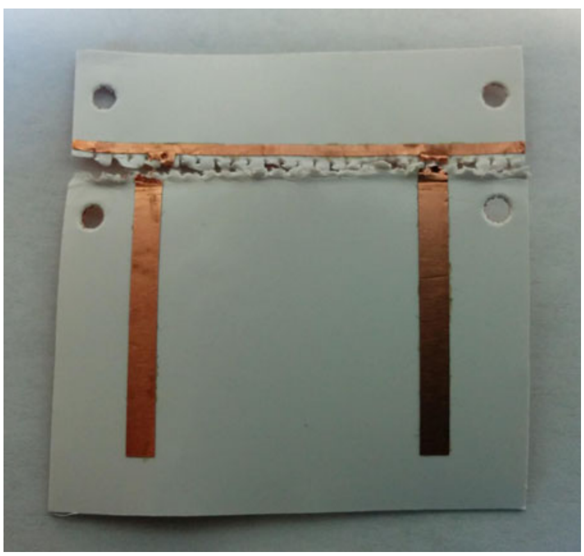

Fig. 8. Band-stop filter prototype after the stub removal.

of equi-spaced holes has been fabricated (Fig. 9(a) shows the filter with holes; whereas (b) represents an example of a possible application).

The transmission coefficient of the disposable band-stop filter is reported in Fig. 10, where a comparison between simulation and measurement is made. The circuit testing has been conducted by means of the vector network analyzer PNA N52230A from Agilent. At the input frequency (2.08 GHz) a variation of more than 60 dB in the transmitted power has been experimentally demonstrated. It is worth noticing that after the stub removal a good matching between the input and the output ports of the circuit under test is experienced ($|S_{21}| = -0.5$ dB) and the signal is allowed to pass toward the output antenna. In Fig. 10, the transmission coefficient of the filter with holes is also reported and it is demonstrated that holes do not significantly affect the filter performance.

In order to assess the performance of the whole tag in an actual environment with respect to its distance from the reader, a suitable experiment has been set up. In Fig. 11, the block diagram of the adopted test bench is reported: a generator, implemented with a HP8657A source and set to 1.04 GHz, is connected to the transmitting antenna at f_0; the wireless signal is received by the receiving antenna of the tag, followed by the frequency doubler described in Section IV. The latter is connected to the proposed disposable filter, which is in turn connected to the tag transmitting antenna at $2f_0$. Finally, the receiving antenna of the reader is connected to an Agilent N9320B spectrum analyzer. All the connections have been made by means of standard cables.

Figure 12 reports the power measured by the spectrum analyzer versus the tag-to-reader distance for an available

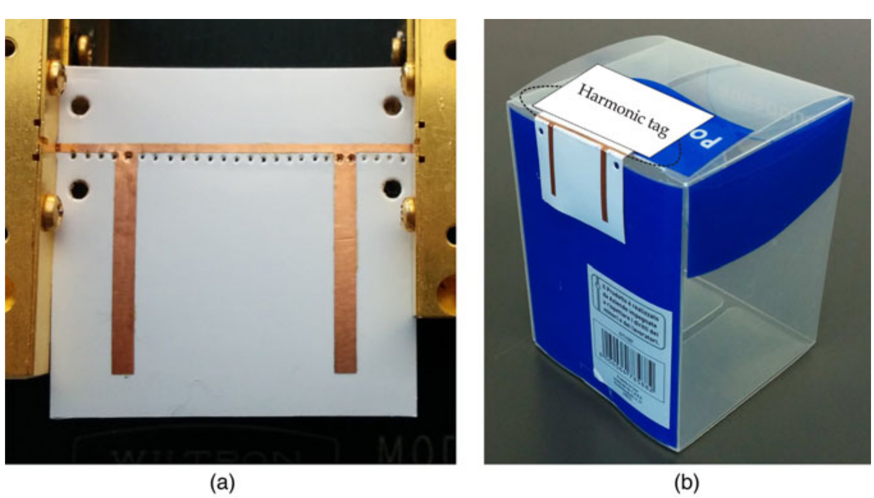

Fig. 9. Band-stop filter prototype with holes (a) and example of a possible application (b).

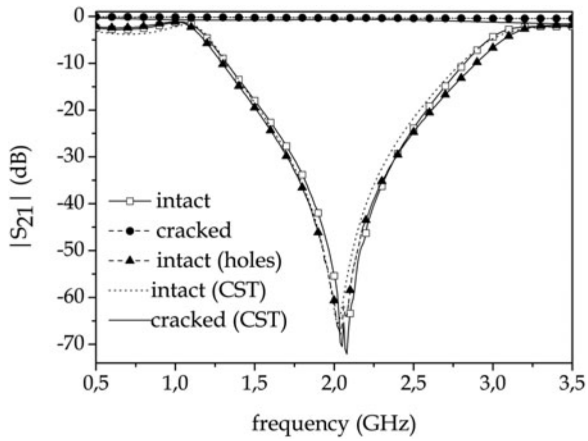

Fig. 10. Comparison between simulation (a) and measurement (b) in terms of transmission coefficients. When the filter is intact, it causes an attenuation of 65 dB on the incoming signal at 2.08 GHz, whereas when the filter is cracked the attenuation introduced is of about 1 dB.

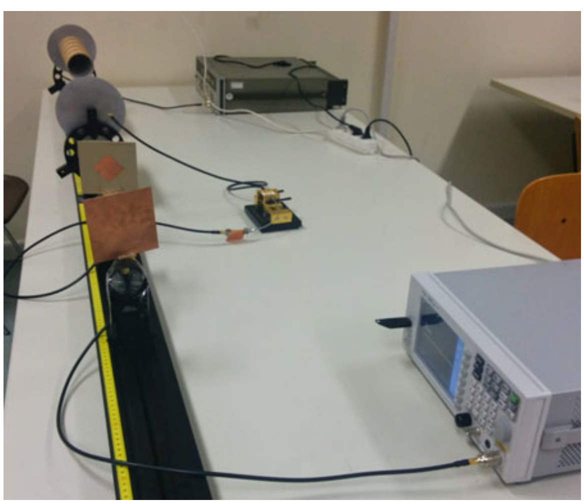

Fig. 11. Measurement chain, in order from the background: a HP8657A generator, a wireless link at f_0, a frequency doubler, the crack sensor, a wireless link at $2f_0$, and a N9320B spectrum analyzer from Agilent.

input power of 10 dBm supplied by the generator at the input frequency 1.04 GHz. The noise floor of the receiver is of about −100 dBm. For a minimum distance of 10 cm the variation in the received power when the filter is intact or cracked is of about 60 dB, thus proving the high dynamic rage of the sensor. Since the received power for the cracked condition decreases with the distance, the intact-to-cracked range decreases as well. Nevertheless, at 1 m the difference in the received power is about 30 dB, thus demonstrating that the two conditions are still well noticeable.

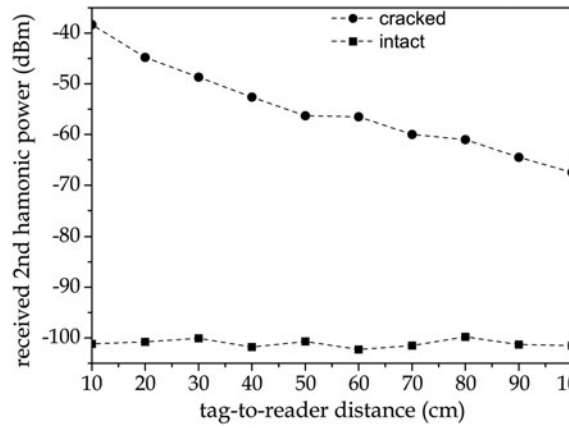

Fig. 12. Harmonic RFID experiment: received signal power versus tag-to-reader distance *d* when the filter is intact and when cracked.

The measurements presented in this paper have been conducted by guaranteeing the alignment between the tag and the reader antennas. Nevertheless, by choosing circular polarized antennas for the reader and linear polarized antennas for the tag, the tag-to-reader orientation issue can be relaxed, at the expense of 6 dB of losses (3 dB for the uplink and 3 dB for the downlink).

Moreover, in order to separate the tag responses and automatically identify the tampered item, spatial separation with the help of a narrow beam reader antenna is a suitable solution. If a semi-automatic approach is still acceptable, then the crack sensor can be used to reveal when tampering happens, while the item identification can be done by visual inspection.

Finally, a comparison with other crack sensors, reported in Table 2, underlines the originality and the robustness of the proposed approach.

VI. CONCLUSIONS

A one-bit harmonic tag working as crack sensor has been presented and the idea has been experimentally demonstrated. A description of the adopted technology has been included together with a report about the harmonic approach. The sensor, based on a disposable band-stop filter, has demonstrated a maximum dynamic range of 60 dB, whereas it is still capable of working for tag-to-reader distances greater than 1 m, where it exhibits a dynamic range of 30 dB.

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Table 2. State-of-the-art.

Reference	RFID type	Encoding strategy	Substrate	Freq.(GHz)	Tag-to-reader distance (cm)	Pavs (dBm)
This work	Chipless	Harmonic-based	Paper	1.04; 2.08	100	10
[24]	Chipless	TDR	Micarta G-10 Glass Epoxy sheet	1–4	15	8
[25]	Chip	Resonance frequency shift	Rogers RT/duroid 5880	0.9–0.92	/	10–22
[26]	Chip	Amplitude modulation	No substrate	0.915	75	36

ADS and CST software licenses respectively. This work was partly supported by the research project "Green Tags and Sensors with Ultrawideband Identification and Localization Capabilities" (MIUR, 2011).

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