A Novel Inkjet-Printed Wireless Chipless Strain and Crack Sensor on Flexible Laminates

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***Abstract*—We studied a low-cost chipless radio-frequency identification strain sensor tag operating at 2.45 GHz. The sensor is based on a 18.5 x 18.5 mm^2 single split ring resonator which is fully inkjet printed on a flexible substrate. For an applied strain of 20 %, a silver-based ink strip printed on a polyimide substrate showed an irreversible conductivity variation up to 700 %. Correspondingly, when illuminated by an incident plane wave, the printed sensor features an electromagnetic response with a magnitude strongly correlated with the strain applied on it. We recorded up to 15 dB variation in the radar cross section. Both, the simulations and wireless measurements in indoor environment validated the sensor operation.**

I. INTRODUCTION

Wireless sensor technologies have lately attracted a growing interest in the industrial world due their numerous inherent advantages, such as the low deployment cost, the robustness, and the possibility to define a new paradigm for human-machine interface. A massive development of these technologies is expected over the coming years to overcome the major challenges imposed by state-of-the-art applications such as the Internet of Things. The technologies involved in the safety of persons in buildings or on the road are using an increasing number of wireless sensing technologies. Among them, the structural health monitoring of civilian buildings is a hot topic. Besides, passive radio-frequency identification (RFID) [1-2] and chipless tags [3-5] features great advantages in wireless sensing applications because they are relatively low-cost and completely maintenance-free devices (10 $ cents for RFID tag and below 1 $ cents for a chipless tag) and their lack of maintenance. Indeed, they do not require any local battery cell, so no need to change this component after a certain period. Recent work on strain and crack sensors using RFID [1] and chipless technology [5] presents sensors realized with conventional electronics manufacturing techniques. In this work, we propose a fully inkjet-printed chipless sensor tag on a flexible laminate. It requires only one printing stage because the electrical conductivity of the printed pattern is already highly sensitive to the strain.

II. DESIGN AND REALIZATION

To study the impact of strain applied on a printed scatterer to its electromagnetic (EM) response, we decided to use a square shape split ring resonator (SRR) optimized to operate at 2.45GHz. This shape is well-known and exhibits a sharp resonant peak with a compact foot-print. The resonant frequency is correlated with the perimeter of the open loop that is roughly equal to the half of the wavelength. The surface currents' distribution (see Fig. 1 (b)) at 2.4 GHz when the scatterer is subject to an incident plane wave confirms this statement. The tradeoff between miniaturization, sharpness of the resonant peak and magnitude of the radar cross section (RCS) can be tuned with both the side length of the SRR and its gap length. In order to achieve a tradeoff between an RCS value that can be detected easily (above 30 dBsm) and a compact size, we obtained the design shown in Fig. 1 (a). The side length of the SRR is 18.5 mm, and its gap is 6 mm wide. This provides a resonance at 2.4 GHz. The strip width of 2 mm enables high radiation efficiency. The SRR is printed on Kapton polyimide (ε_r = 3.5, tanδ = 0.0027) substrate with the thickness of 50 µm. When subject to a strain, the scatterer will be stretched so that both the frequency and magnitude of the resonant peak are shifted. For the printed scatterer, to detect small strains, it is expected that the variation of the conductivity of the printed pattern affects much more significantly its EM response.

To analyze the change in conductivity as a function of the applied strain, we first printed two layers of Harima NPS-JL

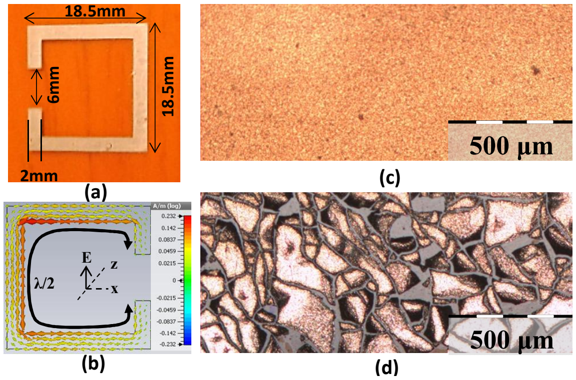

Figure 1. (a) Printed SRR on polyimide substrate (b) Distribution of surface currents on a SRR when excited by a plane wave at 2.4 GHz. (c-d) Microscope view of the printed strip based on silver ink before (c) and after (d) a 12% strain has been applied.

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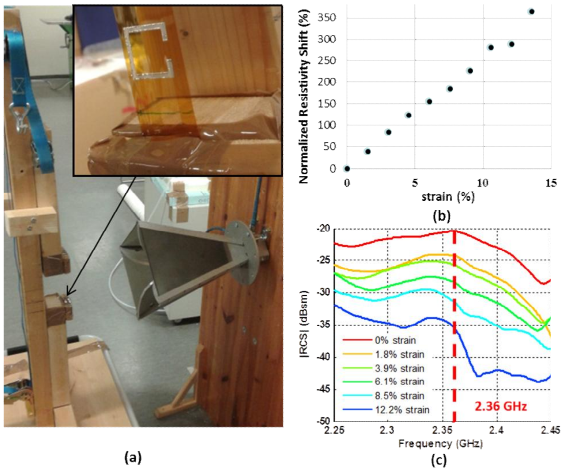

Figure 2. (a) Strain bench and the horn antenna in front of the sensor. (b) Measured normalized DC resistance shift of a printed strip based on silver ink. (c) Measured RCS for various strains applied on the printed SRR.

Silver Nanopaste to make a thin line with a width of 2 mm. We applied up to 15 % strain in the direction along the line. Fig. 1 (c) and (d) show optical microscope images of the printed strip before and after the strain has been applied, respectively. We clearly see the fractures between flakes of joined silver particles in Fig. 1 (d) leading to a notable decrease in conductivity. Fig. 2 (b) shows the normalized variation of the DC resistance of the printed line as a function of the strain. A linear relationship is observed from 0 to 15 % of elongation and a huge resistance shift up to 350 % can be observed. After releasing the strain, the resistance remains constant and cannot reach its initial state anymore. This makes a red / green sensor.

III. VALIDATION

A. *Description of the setup*

To validate the concept of sensing the deformation of structures wirelessly, we implement a frequency stepped continuous wave (FSCW) radar technique with the help of a vector network analyzer (VNA) Agilent PNA E8358A connected to a wide-band horn antenna ETS Lindgren 3164-04 having a gain of 9 dBi around 2.45 GHz. The power delivered by the VNA is 0 dBm. To extract the radar cross section (RCS) of the sensor, we recorded the S11 scattering parameter for a span between 2.3 GHz and 2.5 GHz in different cases [4]. After the measurement of the sensor, the scattering from the background with no sensor was recorded. Further, the response of a reference scatterer was also measured to compensate for the gain non-uniformity over the frequency range. The sensor was attached on a wooden strain bench at 20 cm from the aperture of the antenna as shown in Fig. 2 (a). The upper part of the strain bench is mobile and attached with a cord sling according to a 4:1 pulley configuration to allow for small displacement and an increased pulling force. The length of the scatterer was measured for each strain.

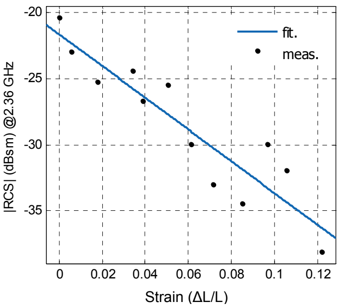

Figure 3. Measured RCS magnitude at 2.36 GHz versus the applied strain.

B. *Measurement results and discussion*

Figure 2 (c) shows the different extracted RCS curves for various strains between 0 and 12%. For 0% of strain, we measure a maximum RCS of -20.46 dBsm at the resonant peak (2.36 GHz), whereas a value close to -33.85 dBsm is recorded for the largest strain. Based on these curves, a relationship between the strain and the RCS of the resonant peak is extracted as shown in Fig. 3. It shows a linear behavior between 0 and 12 % strain with a sensitivity of 1.2 dB per 1 % of strain. The extracted relation presents a RMS error of 1.1% on the strain, and 2.1 dB on the magnitude.

IV. CONCLUSION

The effect of the strain applied on an inkjet-printed SRR has been measured wirelessly using a FSCW radar technique. It reveals that a huge linear variation on its RCS up to 13.4 dB can be measured from 0 to 12 % with a sensitivity of 1.2 dB per 1 % of strain. This large variation is correlated with the irreversible resistivity change of the printed strip based on silver ink nanoparticles. A future work will consist in studying the effect of strain on large areas ("smart skins") covered with SRR printed on various substrates in order to implement to practical applications.

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