# Zero-Power Wireless Pressure Sensor based on Backscatterer Harmonic Transponder in a WPT context

Raffaele Salvati
*Department of Engineering*
*University of Perugia*
Perugia, ITALY
raffaele.salvati@studenti.unipg.it

Valentina Palazzi
*Department of Engineering*
*University of Perugia*
Perugia, ITALY

Giordano Cicioni
*Department of Engineering*
*University of Perugia*
Perugia, ITALY

Guendalina Simoncini
*Department of Engineering*
*University of Perugia*
Perugia, ITALY

Federico Alimenti
*Department of Engineering*
*University of Perugia*
Perugia, ITALY

Manos M. Tentzeris
*School of Electrical*
*and Computer Engineering*
*Georgia Institute of Technology*
Atlanta, GA, USA

Paolo Mezzanotte
*Department of Engineering*
*University of Perugia*
Perugia, ITALY

Luca Roselli
*Department of Engineering*
*University of Perugia*
Perugia, ITALY

2022 Wireless Power Week (WPW) | 978-1-6654-8445-9/22/$31.00 ©2022 IEEE | DOI: 10.1109/WPW54272.2022.9854038

***Abstract*—The era of Internet-of-Things is leading to the widespread of sensors in medical and consumer applications, where electronics is aiming at being wireless, battery-less, low-cost and wearable. In this context, pressure sensors are of particular interest since they can be used to monitor parameters such as human posture, motion and interaction with the environment. This paper presents a novel zero-power pressure sensor with wireless communication and wireless powering feature, with a flexible sensing element. The key component of the sensor is a Schottky-diode harmonic transponder connected to a piezoresistive transducer. The piezoresistor is placed along the DC path of the rectifier circuit in order to control the rectifying behaviour of the diode and thereby encoding the information about pressure on the backscattered signal. This sensor is a proof of concept of a novel fully-passive and wireless pressure sensor with a flexible sensing element.**

***Index Terms*—frequency doubler, harmonic generation, pressure sensor, wireless power transfer, backscattering, piezoresistor.**

## I. INTRODUCTION

Pressure sensors can find application in many industrial, medical and consumer scenarios. Just to make a few non-exhaustive examples, they can be used to monitor medications [1], fall of a person [2], plantar pressure [3]–[5], and to perform gait analysis [6].

In this context, flexible materials are of particular interest for the realization of flexible and wearable sensors [7], [8], and, more in general, they can easily conform to the object to be measured. Among them, 3M Velostat is a piezoresistive material already used in the scientific literature thanks to its low-cost and ease of processing [9], [10].

A limiting factor in the state-of-the-art pressure sensors is that they are usually wired. On the other hand, wireless platforms are usually based on active circuitry. Piezoresistive pressure sensors generally require an active circuit to measure the resistance variation [11], while both piezoresistive and piezoelectric sensors typically require a physical connection between the transducer and signal acquisition stages like charge amplifiers and analog-to-digital converters [12]. With the emergence of the IoT framework, the design of novel sensors always considers power consumption and wireless communication capabilities, since battery replacement and wires installation are impractical for many relevant applications. Moreover, this kind of frameworks enables the possibility to simultaneously combine WPT and wireless data transmission [13], [14].

We present a novel pressure sensor formed by a piezoresistor inserted in a fully passive wireless harmonic backscatterer which is based on a Schottky diode [15]. This configuration allows for a sensor which still completely passive. In particular, the piezoresistor is used to vary the rectifying behaviour of the diode, and consequently the backscattered signal, as described in section III.

## II. PRESSURE SENSOR

This paper presents a passive wireless pressure sensor made up of the following key building blocks: a piezoresistor (based on Velostat, a pressure-sensitive conductive sheet) and a passive frequency doubler. The block diagram of the system is depicted in Fig. 1. It is conceived to have a simultaneous wireless power transfer (WPT) and data transmission: information which come from the pressure sensor described in this work.

The system of Fig. 1 consists of the backscattering harmonic tag-enabled pressure sensor and a reader. The reader transmits a radiofrequency signal at a frequency $f_0$ towards the tag. The signal received by the tag passes through a diode-based frequency doubler that generates a self-polarizing voltage and

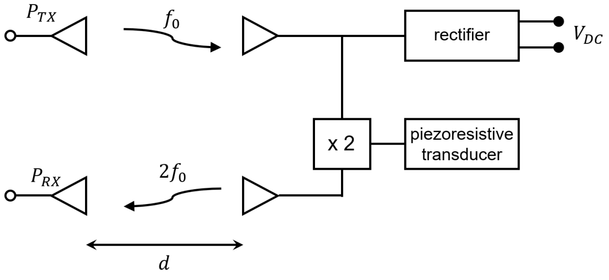


Fig. 1: System block diagram. The reader is a transceiver that interrogates the harmonic tag at frequency $f_0$ and expects to receive back a signal at $2f_0$. The tag is designed to simultaneously produce a DC voltage and a backscattered signal. The transmitted signal is modulated in amplitude according to the transducer resistor value, function of the sensed pressure.

an harmonic signal at frequency $2f_0$, the amplitude of which depends on the resistance value of the piezoresistor.

### A. Piezoresistor

The stackup of the proposed piezo-resistive transducer is shown in Fig. 2. The core element of this device is the Velostat film: a pressure-sensitive conductive sheet. The considered Velostat sheet has a thickness of 0.1 mm and is cut in a 1 cm$^2$ square shape. Two adhesive copper tapes are employed as electrodes to contact the Velostat element. These tapes are glued on Polylactid Acid (PLA) substrates which act as mechanical supports for the copper electrodes place at the top and bottom sides of the device. The two PLA substrates are kept in place using a piece of tape. Two wires are then soldered on the two copper pads to measure the resistance value of the transducer.

When a pressure is applied perpendicularly to the transducer, the two PLA mechanical supports compress the device along its vertical axis, so that a change in the resistance value can be observed. Fig. 3 shows the results of the experimental characterization of the piezoresistor. In the considered pressure range, from 0 to 80 kPa, the resistance varies by more than two order of magnitude, from 8.8 kΩ to about 30 Ω. Considering the same measurements in the form of a conductance, the device features an almost linear response: behaviour which is in accordance with the results obtained in [7].

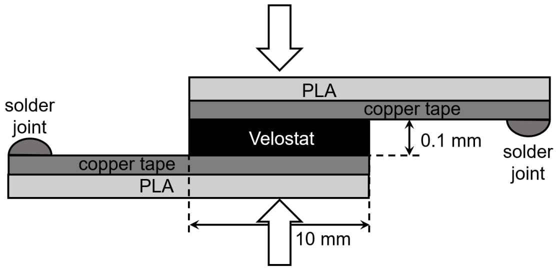


Fig. 2: Piezoresistor stackup. The transducer is made of: PLA substrates for mechanical support, copper tapes which act as electrodes and a Velostat conductive sheet. A change in the resistance value can be detected once a perpendicular pression is applied.

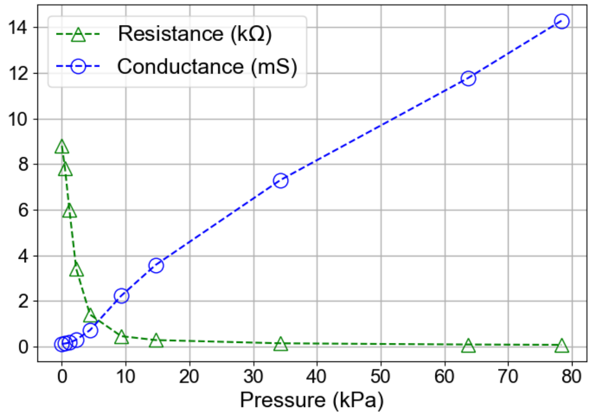


Fig. 3: Resistance and conductance of the transducer as a function of the applied perpendicular pressure. In the conductance form the device shows an almost linear behaviour.

### B. Frequency doubler

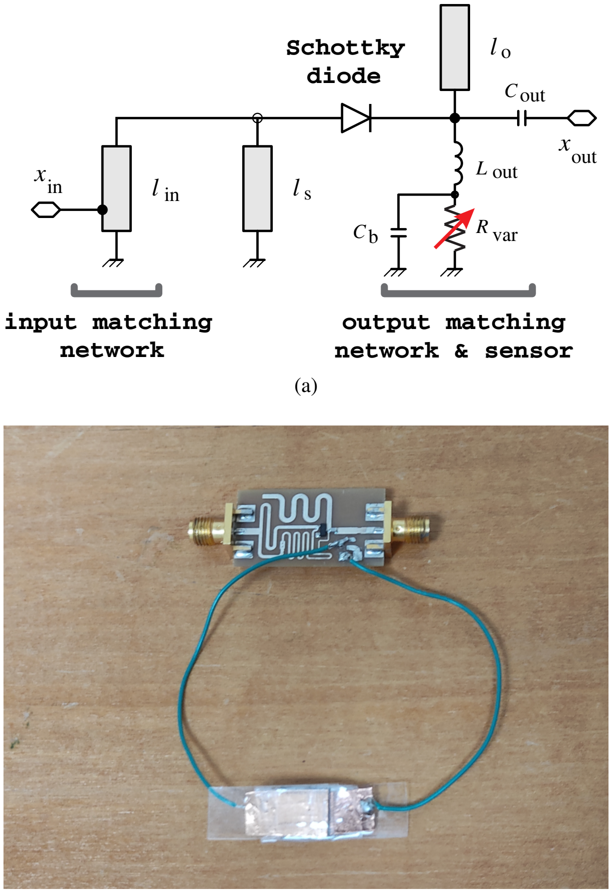
The proposed passive wireless sensor is based on a Schottky-barrier diode frequency doubler whose schematic is shown in Fig. 4(a). The Schottky diode (model HSMS2850) is connected in series, between two parallel stubs working as harmonic filters. Input and output matching networks are used to match the circuit to a source impedance and an output load of 50 Ω. The output matching network, a simple LC network, also provides a path toward ground for the DC signal component self-generated by the diode.

The piezo-resistive transducer, displayed as $R_{var}$ in Fig. 4(a), is connected along the aforementioned DC path. The increase of the transducer resistance produces an increase of the DC voltage drop across its terminals. As a result, the diode is reverse-biased and the conversion loss of the doubler increases. A bypass capacitor $C_b$ is connected in parallel with the piezo-resistor, so that RF signals are not affected by parasitics of both the transducer and the connection wires.

The circuit is designed with the CAD Advanced Design Studio (ADS). The distributed components of the circuit being implemented in microstrip technologies are first electromagnetically simulated with Momentum; the results of these simulations are then interfaced with the circuit model of the lumped components using the ADS Harmonic Balance simulator. As a final design improvement, the lines were folded to reduce the area occupied by the circuit.

## III. RESULTS

Firstly, in order to validate the concept, the sensor was tested in wired mode. A signal generator (model 8664A from HP)



(a)

(b)

Fig. 4: Realized frequency doubler connected to the piezoresistive transducer: (a) schematic and (b) prototype. Main parameters of the doubler: $l_{in} = 43$ mm, $l_s = 50.5$ mm, $l_o = 41$ mm, $L_{out} = 6$ nH, $C_{out} = 1$ pF, and $C_b = 100$ pF.

was connected to the input port of the frequency doubler to provide the $f_0$ signal, and a spectrum analyzer (model N9320B from Agilent) was connected to the output port to measure the output signal at $2f_0$. The input power of the frequency doubler is set to -10 dBm. Avariable pressure from 0 kPa to 80 kPa, monitored with a weight scale, was applied on top of the sensor. A pressure that produces a variation of the piezoresistive transducer resistance. In case of no pressure, the transducer resistance exhibited its maximum value which corresponded to -33 dBm output power of the frequency doubler. Once the pressure was increased, the output power increased as well until it reached its peak at -24 dB for a resistance values lower than 380 Ω (or pressures higher than 15 kPa), reported in Fig. 5 with a black line. The maximum sensitivity of the sensors is experienced in the pressure range from 1 to 10 kPa, where an output power increase of approximately 0.65dB/kPa is observed. A comparison of the experimental measurements with the simulation data is reported in Fig. 5. Some minor discrepancies can be observed, due to inaccuracies in the model of the lumped components

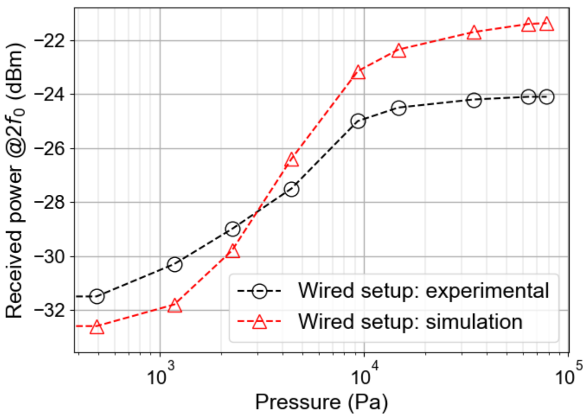


Fig. 5: Received power at $2f_0$ for the wired setup with an input power of -10 dBm in both simulated and experimental scenarios.

of the circuit. The sensor was then integrated into the wireless setup shown in Fig. 6. The frequency doubler was connected to two patch antennas, one working at $f_0 = 1.04$ GHz and the other at $2f_0 = 2.08$ GHz. Two helical antennas were used to interrogate the prototype at $f_0$ and measure the backscattered signal at $2f_0$. The antenna gain is equal to about 5 dBi for the transmitting antenna and about 10 dBi for the receiving antenna, respectively. The transmitting antenna was connected with the HP signal generator, while the receiving antenna to the spectrum analyzer. The two $f_0$ antennas, and similarly the two $2f_0$ antennas, were placed at a distance of 50 cm, with the input power of the $f_0$ transmitter antenna set to +10 dBm. The distance between the antennas of the reader and the transponder is 50 cm, to ensure that the experimental setup is demonstrated in far field conditions. The estimated free space losses at $f_0$ and $2f_0$ are 26.8 dB and 32.8 dB, respectively. This results in an input power at the doubler of about $-10$ dBm. In case of no pressure applied to the sensor, taking into account the conversion gain of the frequency doubler, the estimated power received by the spectrum analyzer at $2f_0$ is nearly -57.6 dBm. The results of the wireless measurement are shown in Fig. 7. As visible from the image, in case of no pression the measured backscattered power at $2f_0$ is -61.5 dBm. Moreover, in a similar way to the wired case, the conversion gain increases as the applied pressure increases, reaching its peak for pressure values higher than 15 kPa and achieving a received power of -50 dBm. Furthermore, a theoretical maximum reading distance of the tag can be estimated considering the free space losses variation. With a lower limit of -100 dBm for detecting a signal using the spectrum analyzer, a maximum reading distance of about 5 m is achieved.

## IV. CONCLUSION

In the present contribution a fully passive wireless pressure sensor is obtained combining a Schottky diode-based frequency doubler with a piezoresistive transducer. The applied

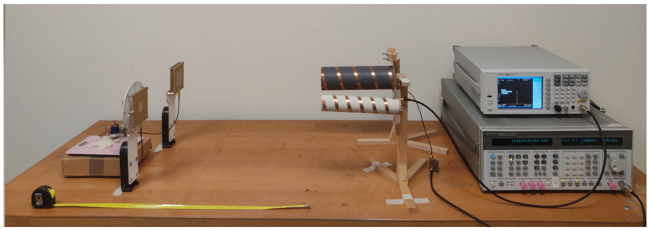


Fig. 6: Experimental setup for the wireless test. On the right side, two helical antennas were used to transmit at $f_0$ and receive at $2f_0$, respectively. In a similar way on the prototype side, two patch antennas were used to receive the $f_0$ signal and transmit the backscattered signal at $2f_0$.

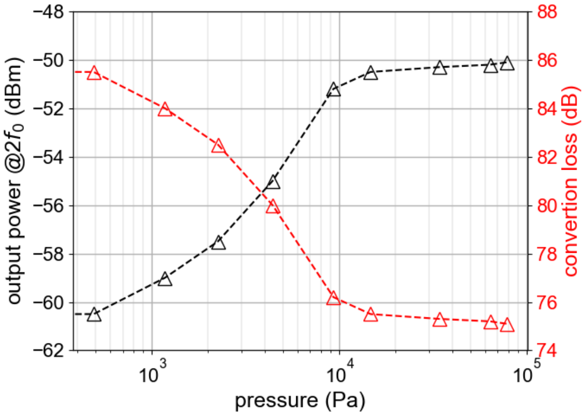


Fig. 7: Received power at $2f_0$ for the wireless setup with an input power of +10 dBm.

pressure changes significantly the resistance of the transducer, which in turn affects the conversion loss of the frequency doubler. The proposed device shows significant sensitivity to pressure, sensing up to 15 kPa and with an excursion of approximately 10 dB of the received signal in both wired and wireless applications. These results encourage further developments of this new class of sensors. They might be fully implemented on alternative substrates enabling the realization of new wearable sensors, that are able to leverage the pressure sensitivity of piezoresistors keeping the overall sensor completely passive and wireless.

## REFERENCES

[1] C. Miozzi, N. D'Uva, F. Camera, S. Nappi, S. Amendola, C. Occhiuzzi, and G. Marrocco, "Zero-power flexible rfid sensor for pressure monitoring of elastic compression bandages," in *2021 IEEE International Conference on Flexible and Printable Sensors and Systems (FLEPS)*, 2021, pp. 1–4.

[2] W. Banno and N. Shinomiya, "Monitoring system for the elderly on staircase using passive rfid sensor tags," in *2019 IEEE 8th Global Conference on Consumer Electronics (GCCE)*, 2019, pp. 816–817.

[3] X. Lin and B.-C. Seet, "Battery-free smart sock for abnormal relative plantar pressure monitoring," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 11, no. 2, pp. 464–473, 2017.

[4] H. A. Ghaida, S. Mottet, and J.-M. Goujon, "Plantar pressure cartography reconstruction from 3 sensors," in *2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 2014, pp. 578–581.

[5] X. Zhao, X. Ma, Y. Shan, and X. Gong, "A wearable foot pressure sensor," in *2021 IEEE International Conference on Artificial Intelligence, Robotics, and Communication (ICAIRC)*, 2021, pp. 8–11.

[6] S. J. M. Bamberg, A. Y. Benbasat, D. M. Scarborough, D. E. Krebs, and J. A. Paradiso, "Gait analysis using a shoe-integrated wireless sensor system," *IEEE Transactions on Information Technology in Biomedicine*, vol. 12, no. 4, pp. 413–423, 2008.

[7] S. Khan, S. Tinku, L. Lorenzelli, and R. S. Dahiya, "Flexible tactile sensors using screen-printed p(vdf-trfe) and mwcnt/pdms composites," *IEEE Sensors Journal*, vol. 15, no. 6, pp. 3146–3155, 2015.

[8] S. Chen, J. Lach, B. Lo, and G.-Z. Yang, "Toward pervasive gait analysis with wearable sensors: A systematic review," *IEEE Journal of Biomedical and Health Informatics*, vol. 20, no. 6, pp. 1521–1537, 2016.

[9] X. Lin and B.-C. Seet, "A linear wide-range textile pressure sensor integrally embedded in regular fabric," *IEEE Sensors Journal*, vol. 15, no. 10, pp. 5384–5385, 2015.

[10] L. Yuan, H. Qu, and J. Li, "Velostat sensor array for object recognition," *IEEE Sensors Journal*, pp. 1–1, 2021.

[11] S. Kumar, P. K. Rathore, and P. Rangababu, "Implementation of operational amplifier for the designing of novel piezoresistive pressure sensor," in *2018 2nd International Conference on Smart Sensors and Application (ICSSA)*, 2018, pp. 126–129.

[12] S. Rajala, R. Mattila, I. Kaartinen, and J. Lekkala, "Designing, manufacturing and testing of a piezoelectric polymer film in-sole sensor for plantar pressure distribution measurements," *IEEE Sensors Journal*, vol. 17, no. 20, pp. 6798–6805, 2017.

[13] K. Nakanishi and M. Sasaki, "Data transmission system using magnetic resonance wireless power transfer," in *2017 IEEE Wireless Power Transfer Conference (WPTC)*, 2017, pp. 1–3.

[14] M. Ishii, K. Nakanishi, and M. Sasaki, "High efficiency frequency shift keying data transmission system using magnetic resonance wireless power transfer," in *2018 IEEE Wireless Power Transfer Conference (WPTC)*, 2018, pp. 1–4.

[15] V. Palazzi, F. Alimenti, P. Mezzanotte, M. Virili, C. Mariotti, G. Orecchini, and L. Roselli, "Low-Power Frequency Doubler in Cellulose-Based Materials for Harmonic RFID Applications," *IEEE Microwave Wireless Compon. Lett.*, vol. 24, no. 12, pp. 896–898, Dec. 2014.