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On Chip Modulated Scattering Tag Operating at Millimetric Frequency Band

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ABSTRACT: A miniaturized modulated scattering technique (MST) tag able to operate at millimetric frequency bands is proposed in this work. In particular, the proposed tag operates like an RFID tag, but thanks to the MST technique it does not require a radio frequency front end. The information is carried on by modulating an interrogating electromagnetic wave with a suitable change of load impedance of the tag antenna obtained by means of an electronic switch. With respect to standard RFID tags, characterized by limited operative range, MST tags can theoretically reach any distance up to kilometres. In this work, all the components of the MST tag are directly designed on-chip leading to a very compact design. In particular, the tag has been designed to operate at millimetric frequency bands up to 70 GHz. The preliminary experimental results are quite promising, and they demonstrated the capabilities and potentialities of this technique.

1. INTRODUCTION

In the last decades, modulated scattering technique (MST) tags demonstrated their capabilities and potentialities in different areas of practical engineering applications [1]. In particular, in [2, 3] they have been used in a microwave imaging system, for through-the-wall applications in [4], as long-range radio frequency identification (RFID) tags [5], for the remote inspection of the structural integrity of civil engineering buildings [6], as a sensor for the assessment of air quality [7], and in many IoT systems [8] for sensing applications. Thanks to their compactness, versatility, and capability to operate at microwave frequency bands and high distances, MST tags demonstrated to be a good alternative to RFID and chip-less RFIDs [9–11] tags. Sensors operate thanks to the scattering properties of small antennas [12–14] and without the need for a local oscillator or modulation section, which at high frequency bands are expensive and also difficult to design. Therefore, the absence of any radio frequency front end leads to a strong reduction of the complexity of the tag, and consequently, the required consumption power is also reduced, permitting an extension of the life tag. In particular, with MST the modulation can be introduced in the backscattered wave by changing the scatterer characteristics, such as size, shape, and position of the scatterer (namely the antenna tag), or electronically by using an electronic switch or a device aimed at changing the scatterer properties. As stated above, MST tags transmit information by acting on the scattered electromagnetic wave reflected back to the interrogating structure by properly loading the tag antenna with suitable resistive loads, connected with the antenna tag employing an electronic switch [1]. The changes of antenna impedance produce an amplitude modulation on the backscattered electromagnetic wave, which can be easily demodulated and used to transmit information, with a standard coherent detector. The main drawbacks of MST systems are the low efficiency of the electronic switch, especially at high frequencies, the power consumption and the narrowband behaviour, since they usually make use of PIN diode switches. Recently, different attempts to avoid these limitations have been proposed. In particular, in [15] some guidelines for the maximization of MST systems operative range are proposed, and in [16] a broadband MST tag equipped with a self-complementary antenna is proposed, while in [17] exotic materials such as graphene are proposed to overcome the issues due to the electronic switches which are quite evident, especially when the tags operate at high-frequency bands [18]. Thanks to the recent evolution of radio frequency micro-electromechanical switches (RF-MEMs) technology [19–21], it is now possible to operate at very high frequency with the availability of efficient electronic switches that can be easily integrated into the MST technology as the attempt reported in [23, 24]. Moreover, since RF-MEMs are activated by voltage and not current, they do not raise issues concerning power consumption. In this work, we propose a compact MST tag whose principal components, namely the electronic MEMs switch and the antenna are fabricated and integrated in the silicon substrate in order to obtain a very compact structure. The main innovation introduced in this work is the integration of all the tag parts into a single wafer. Antenna, electronic switches, and all the components have been placed together and realized with a single process. This make possible a strong dimensions reduction, and at the same time it simplifies a large scale fabrication of such kind of sensors. The paper is organized as follows. Section 2 introduces the mathematical

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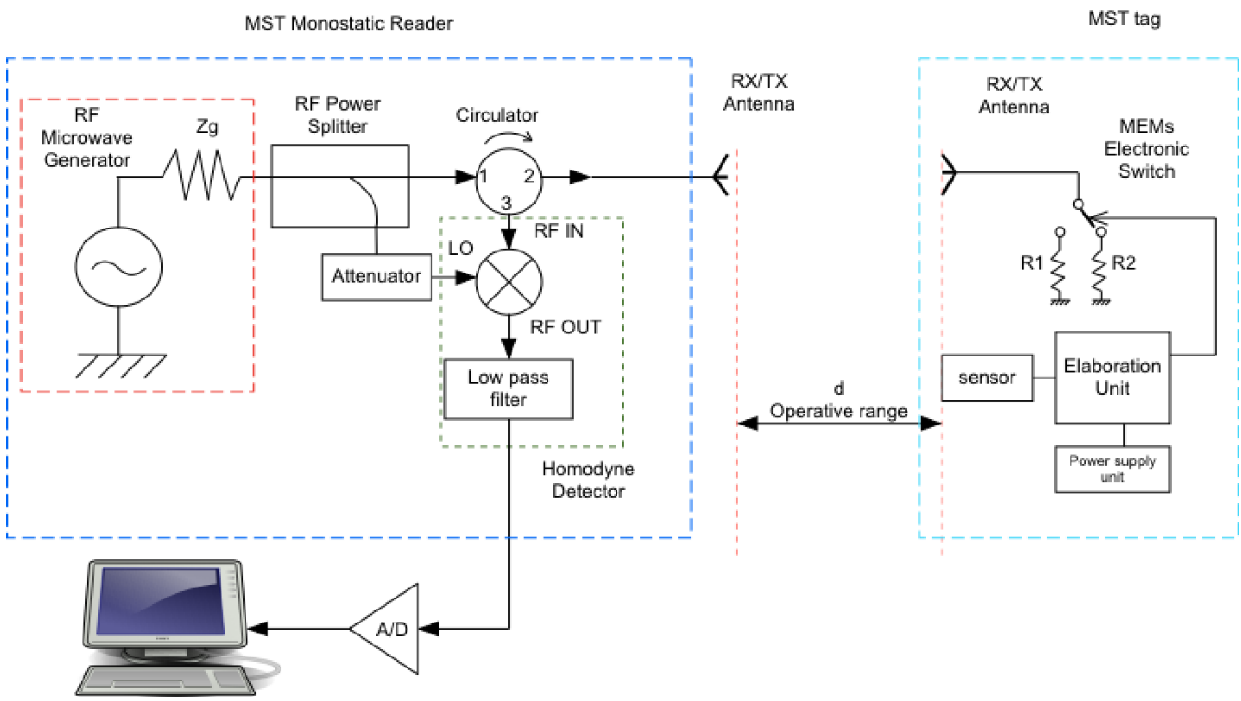

FIGURE 1. Schema of a monostatic MST system.

formulation related to the MST system. Section 3 describes the on-chip MST tag design and fabrication. Section 4 is devoted to the experimental assessment. Finally, Section 5 provides the concluding remarks.

2. MATHEMATICAL FORMULATION

This section aims to describe the MST system shown in Figure 1 and to detail the mathematical formulation which allows the maximization of the operative range of the system itself. The MST system is composed of a reader and a tag, as standard RFID systems. The reader consists of a microwave generator, a homodyne detector, and a circulator. The circulator is mandatory in order to obtain a monostatic version of the system using only one high gain antenna, which can act both as a transmitter and as a receiver.

The signal received by the tag is down converted thanks to a mixer, whose reference signal is provided with a T-junction power splitter and a resistive attenuator. The down converted signal at the mixer output is then filtered utilizing a low pass filter. The mixer, splitter, and filter represent a coherent detector. The output of the coherent detector is then converted by means of an Analog to Digital converter and then post processed with an elaboration unit. The MST tag consists of a transmitting/receiving antenna, a MEMs switch, connected with two resistive loads, a rectifying sub-circuit, and a low frequency square wave generator. The incoming electromagnetic waves are converted into a DC current by means of a rectifying unit. A set of optional sensors could be connected in order to retrieve different environmental parameters. The electromagnetic waves are generated by the reader impinge on the MST tag, and they are reflected back. This backscattered electromagnetic wave contains the information provided by the tag. The MST tag is placed at a distance r from the reader, and this distance is the so-called communication range. The maximum distance at which the reader can retrieve information from the tag depends on the power of the interrogating electromagnetic wave, on the electronic switch efficiency of the electronic switch, and on the value of the two resistive loads values [13–15]. r can be easily estimated considering the following well-known radar equation:

$$r = \frac{1}{2}\left[\frac{\lambda^2 \cdot G_{tx} \cdot P_{tx} \cdot G_{tag} \cdot A_{tag} \cdot ME}{4\pi \cdot P_{rx}}\right]^{\frac{1}{4}} \tag{1}$$

where λ is the wavelength of the interrogating electromagnetic wave, P_{tx} the power of the transmitter, P_{rx} the minimum detectable power at the reader section, and G_{tx} the transmitting antenna gain. G_{tag} and A_{tag} are the antenna tag gain and aperture cross-section, respectively. ME is the so-called modulation efficiency provided by the following relation [25]:

$$ME = \left[\frac{4 \cdot \mathrm{Re}\{Z_{tag}\}^2 \cdot |Z_2 - Z_1|^2}{|Z_{tag} + Z_1|^2 \cdot |Z_{tag} + Z_2|^2}\right] \tag{2}$$

where Z_{tag} is the antenna tag impedance, and Z_1 and Z_2 are the two resistive loads connected by means of the electronic switch as indicated in Figure 1. The modulation efficiency ME can range between 0 and 4, and it only depends on Z_{tag}, Z_1, and Z_2. Normally, Z_1 is set as short and Z_2 as absorbing load, in order to get a perfect match, and they are set respectively equal to 0 and Z^*_{tag}. Considering (1), it is quite evident that the only

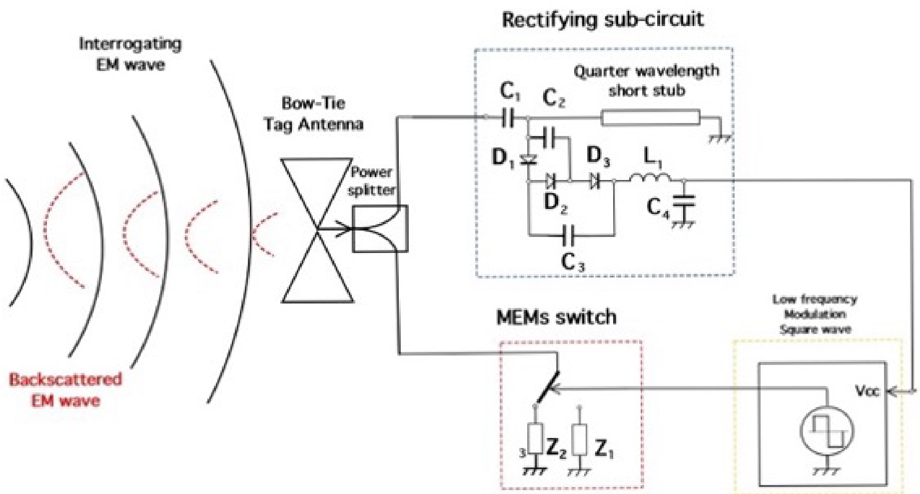

FIGURE 2. Schema of the on-chip MST tag.

way to improve the communication range, given P_{tx}, G_{tx}, and P_{rx}, is to modify the values of the two loads Z_1 and Z_2, or to act on the tag antenna impedance Z_{tag}, with the other parameters of the system fixed.

The loads Z_1 and Z_2 are easy to choose because $Z_1 = 0$ and $Z_2 = \text{Re}\{Z^*_{tag}\}$. In addition, they could be strongly dependent on the considered switching technique. The tag antenna design provides more degrees of freedom to obtain a suitable ME. In particular, the way to maximize the tag performance and to increase the communication range is to maximize the modulation efficiency ME versus Z_{tag}. In particular, the following equations, well described in [26], permit to obtain the real and imaginary values of the antenna impedance that maximize the ME:

$$R_{opt} = \sqrt{R_1 \cdot R_2 \cdot \left(1 + \frac{X_1 + X_2}{R_1 + R_2}\right)^2} \tag{3}$$

$$X_{opt} = -\frac{R_1 \cdot X_2 + R_2 \cdot X_1}{R_1 + R_2} \tag{4}$$

where R_1, R_2, and X_1, X_2, are the real and imaginary parts of the impedance loads Z_1 and Z_2, respectively, and R_{OPT} and X_{OPT} are the optimum values of the real and imaginary parts of the antenna tag impedance that maximize the ME [25].

3. MST SYSTEM DESIGN

In this section, the description of the MST system will be detailed. This section is organized as follows. Section 3.1 describes the reader structure and the considered transmission protocol. Section 3.2 is devoted to the description of the MST tag.

3.1. Description of the Reader and Communication Protocol

The MST reader consists of a microwave generator, a homodyne receiver with a minimum detectable power of -172 dBi, a circulator, and a pyramidal horn antenna with a gain $G_{tx} = 17$ dBi. Thanks to the circulator, the horn antenna acts as both transmitter and receiver. This is a typical monostatic configuration. The output of the circulator is directly connected to the homodyne receiver. The coherent detection is able to efficiently separate the useful signal provided by the MST tag from the background noise and other unwanted signals, by acting on the phase of the backscattered electromagnetic signal [1]. The data provided by the MST tag are modulated using the same protocol as the RFID devices. In detail, the EM4102 protocol and Manchester modulation are used. In the EM4102 protocol, the data are organized as follows: the beginning of the data string is represented by the first nine bits at logical state 1 and serves as a marker sequence. Then, the following bits are organized in 10 groups of four data bits and one even parity bit. At the end in order to close the data stream, four bits of a column parity (even) and a stop bit (zero) are used. The use of EM4102 permits to interface the MST system with all the typical facilities commonly adopted for the RFID system.

3.2. Description of the MST Tag

The schema of the proposed on-chip MST tag is shown in Figure 2.

The incoming electromagnetic power received by the antenna is first split. Half power is provided to a rectifying subcircuit [5] aimed to provide the power supply to the electronic switch and to a low-frequency square wave generator. The other half power is reflected back, and it carries the information thanks to the amplitude modulation introduced by the electronic switch and the two resistive loads. In particular, the square wave generator activates the electronic switch, changing the tag antenna loads every 0.5 ms.

It is composed of a bow-tie antenna, followed by a 3 dB T-junction power splitter. The other tag fundamental section is the antenna. In this design, we used a broadband bow-tie antenna printed on a multi-layer Si-wafer with the first layer of

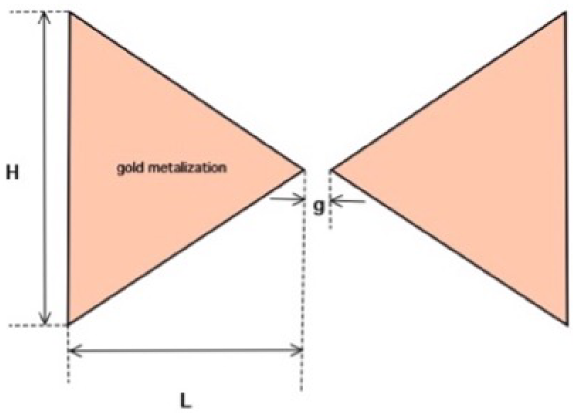

FIGURE 3. Bow-tie antenna geometrical dimensions.

F [GHz]	g [µm]	H [µm]	L [µm]
20.0	300.0	3700.0	5600.0
40.0	200.0	1900.0	2800.0
50.0	100.0	1500.0	2200.0

TABLE 1. Bow-tie antenna geometrical dimensions and related resonance frequencies.

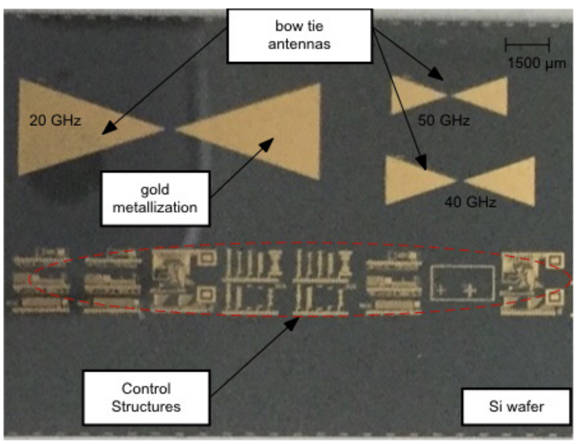

FIGURE 4. Photo of the Si-wafer with the details of the printed bow-tie antenna structures used for the MST tag.

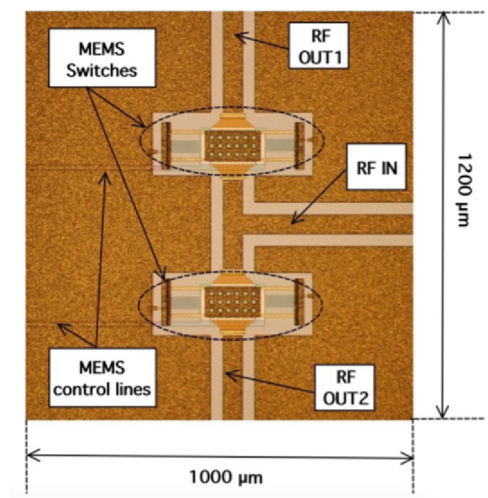

FIGURE 5. Microphotography of the 1S2T MEMs switch.

thickness $650\,\mu\text{m}$ of silicon ($\varepsilon_r = 11.9$) and second layer of silicon dioxide, thickness $1.4\,\mu\text{m}$ ($\varepsilon_r = 3.94$). The antenna structure is fabricated with a layer of gold, thickness $5\,\mu\text{m}$. The antenna impedance has been measured with a vectorial network analyser (namely the Copper Mountain Cobalt C2220 equipped with the calibration kit Copper Mountain S2611). The antenna impedance measurement has been led with suitable probes, and the measured antenna impedance at $f = 20\,\text{GHz}$ is $Z_a = 400 - j60$, as can be noticed with a capacitive reactive component. Thanks to Z_a and relations (3) and (4), it was possible to estimate the values of Z_1 and Z_2, the two impedances at which the antenna tag is loaded thanks to the electronic switch. In particular, Z_1 is made with a resistor $R_1 = 10\,\text{k}\Omega$ and a series capacitor $C_1 = 47\,\text{nF}$ while Z_2 is realized only with a resistor $R_2 = 10\,\Omega$. These values are not the optimal ones that can be reached with relations (3) and (4), but they permit to reach a satisfactory match and ME also considering the limitation due to the fabrication technology. The geometry and related geometrical parameters of the considered bow-tie antenna are reported in Figure 3 and Table 1, respectively. Table 1 also reports the resonance frequency of the considered bow-tie antennas.

The bow-tie antenna, electronic switch, rectifying circuit, and square wave generator are printed on the same Si-wafer in order to obtain a compact design. Figure 4 shows a photo of the obtained Si-wafer with the details of three bow-tie structures, realized with a gold metallization.

Concerning the electronic switch, a 1S2T MEMs switch has been fabricated and directly connected to the antenna structure and to the two resistive loads in order to implement the MST functionalities. A photo of the considered MEMs switch structure is displayed in Figure 5.

The dimensions of the MEMs structure are $1200\,\mu\text{m} \times 1000\,\mu\text{m}$ as indicated in Figure 5. Specifically, Figure 6 provides the scattering parameters of the RF-MEMs switch that has been considered. In particular, Figures 6(a) and (b) show the reflection coefficient $|S_{11}|$ and insertion loss $|S_{21}|$ as a function of the frequency, respectively. It is evident from the data in Figures 6(a) and (b) that the switch's performances are very good, and in particular, the reflection coefficient is below $-25\,\text{dB}$ for

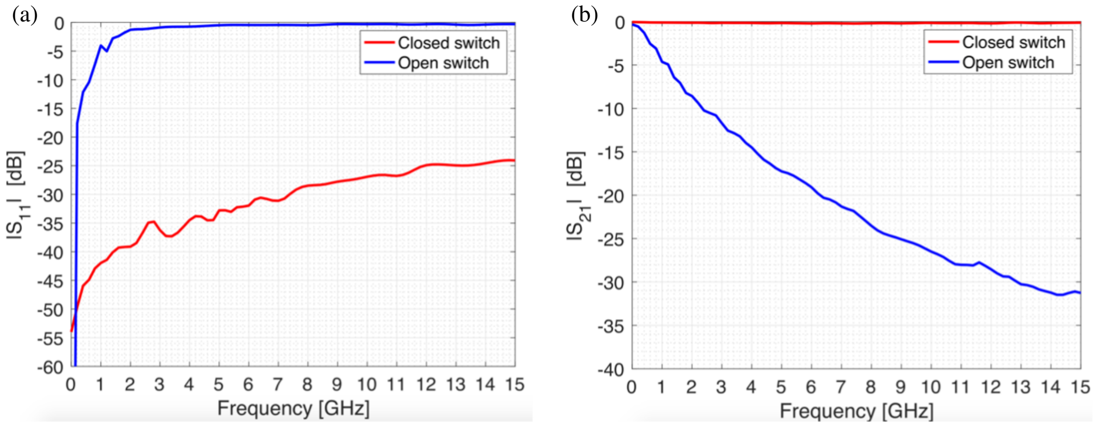

FIGURE 6. RF-MEMs switch. Measurement of the reflection coefficient (a) $|S_{11}|$ and insertion loss (b) $|S_{21}|$ vs frequency.

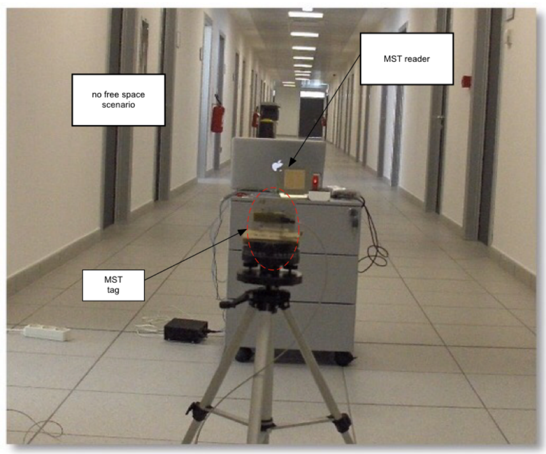

FIGURE 7. Experimental setup.

almost all frequency ranges when the switch is closed, while the insertion loss is less than -0.5 dB.

4. EXPERIMENTAL ASSESSMENT

In order to assess the capabilities of the developed on-chip MST tag, a monostatic MST system has been implemented in a controlled environment. The first tests have been performed in an anechoic chamber. The reader and MST tag have been placed inside the shielded chamber, and the system functionalities have been assessed in a noiseless and free space environments. Then to demonstrate that these system are able to operate also in non free space and noisy scenarios, the system has been placed in a corridor of the university as shown in Figure 7 which shows the experimental setup in noisy and no free space scenario. The MST tag has been placed at a distance $r = 5$ m from the reader, a distance that cannot be reached inside the anechoic chamber due to their limited dimensions.

As can be noticed, the experimental setup has not been implemented inside a shielded room since the MST systems are able to operate in complex, not shielded, and non-free space environments. As stated previously, the data provided by the MST tag are modulated using the same protocol of the RFID devices (in detail the EM4102 protocol and Manchester modulation are used). In this modulation, a low-to-high transition represents a logical 1 state, while a high-to-low transition represents a logical 0 state. The two logic states correspond to the two resistive loads Z_1 and Z_2. The EM4102 protocol permits the integration of various commercial RFID systems, databases, and other RFID assets. The data in the EM4102 RFID protocol are arranged as follows. A marker sequence is used to indicate the beginning of the data string by setting the first nine bits at logical 1. Then, the string is followed by ten groups of four data and one even parity bit. In the end, there are four bits of column parity (even) and a stop bit (0). Figure 8(a) reports an example of the protocol data structure detected at the reader output. In particular, Figures 8(a) and (b) depict respectively the signal received at the reader for an active and inactive MST sensor response, and in fact from Figure 8(b) it is quite evident when the signal is present or not.

Figure 9 reports the signal detected at the reader output and provided by a tag with a bow-tie antenna resonating at 20 GHz. The square wave generator aimed at driving the electronic switch is characterized by a frequency of 2 kHz, and as can be noticed in Figure 9 the signal detected at the reader output is quite stable and clear. The obtained operative range strongly

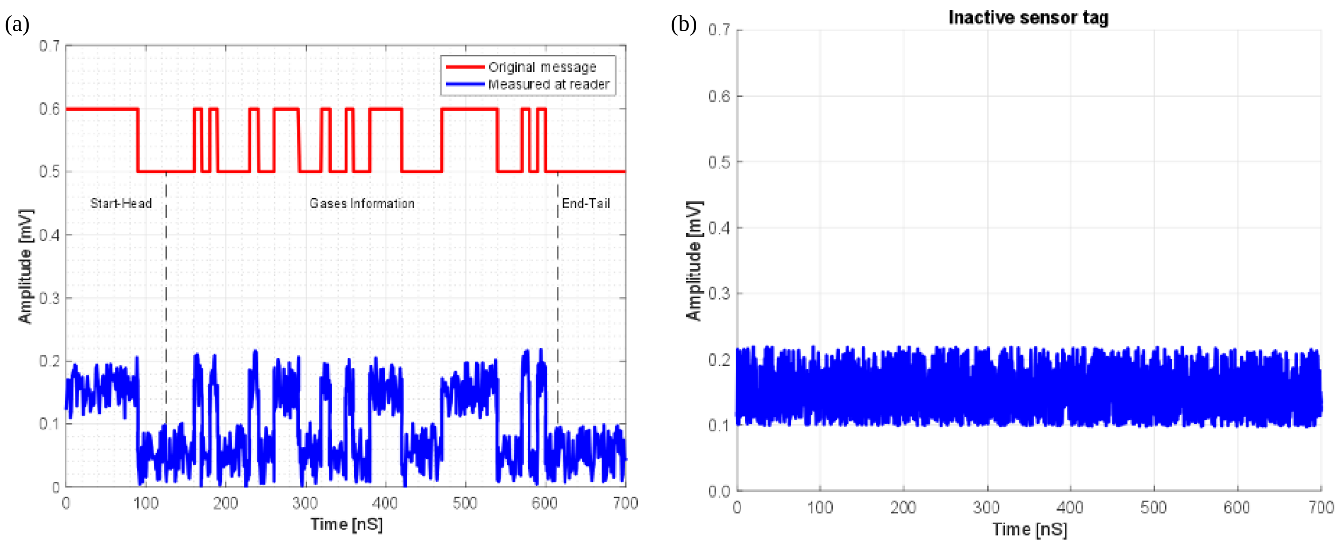

FIGURE 8. Signal detected at the reader output. (a) MST probe transmission protocol, blue line original data, red line signal detected at the reader output. (b) Signal detected at the reader output with an inactive reader.

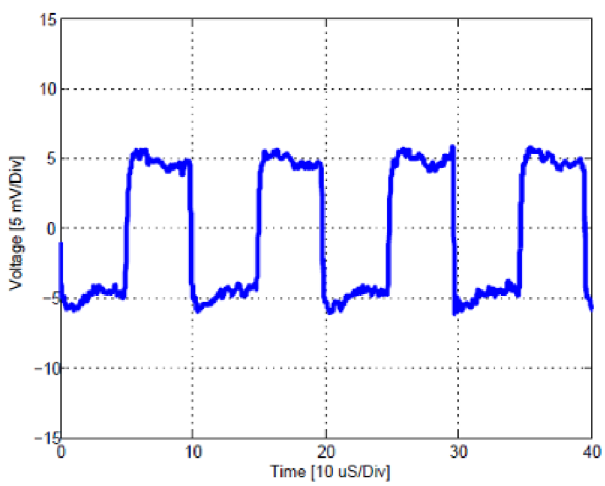

FIGURE 9. Tag signal detected at the reader output. Operative range $r = 5\,\text{m}$. Interrogating EM wave with a working frequency $f = 20\,\text{GHz}$.

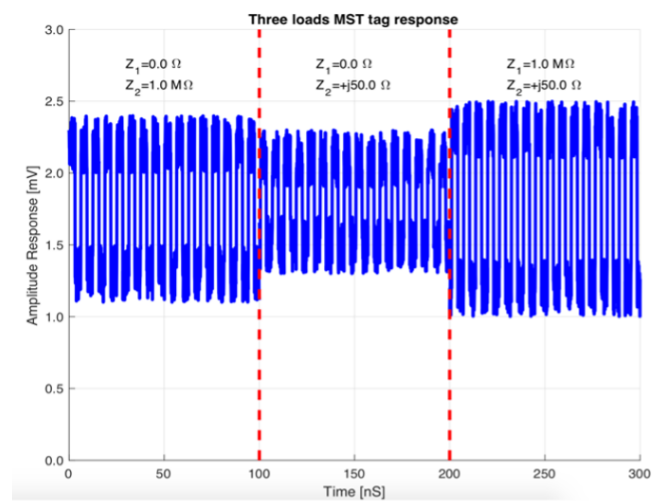

FIGURE 10. Response of the MST MEMs based tag during the impedance changes.

overcomes the range of standard RFID systems with a very low power consumption and requiring a power below 1 mW.

Finally, in Figure 10 an example of the effects of different loads in the backscattered wave is reported. In particular, the signal is collected at the reader output, which is the response of MST MEMs based tag during the impedance changes. Another important improvement introduced by this tag is the strong power consumption reduction. A standard MST tag equipped with an electronic switch based on PIN diode requires a driven current about 10 mA in order to obtain good commutations. The power consumption estimation has been measured considering a square wave activation waveform with a duty cycle of 50%, then we measured the adsorbed current of a tag equipped with a PIN diode and the proposed MEMs tag. The PIN diode and MEMs switches required a current about 7.0 and 1.5 mA. As can be noticed, a current absorption reduction about 78.5% has been obtained. This value is reasonable compared with commercial commercial RF-MEMS switches, such as the model ADGM1003 (Analog Device), a switch characterized with a low voltage driver circuitry (3.3 V) able to operate with currents less than 2 mA.

5. CONCLUSION

A compact modulated scattering technique tag able to operate at high-frequency bands has been designed and experimentally assessed. The tag consists of a bow-tie antenna, an efficient 1S2T RF-MEMs switch, a rectifying circuit, two resistive loads, and a low-frequency square wave generator. The bow-tie antenna and electronic switch are fabricated on the same Si-substrate. The obtained preliminary results are very promising and demonstrate the capabilities of this compact on-chip MST tag as a valid alternative to standard RFID systems.

REFERENCES

[1] Bolomey, J.-C. and F. E. Gardiol, *Engineering Applications of the Modulated Scattering Technique*, Artech House, 2001.

[2] Liang, W., G. Hygate, J. F. Nye, D. G. Gentle, and R. J. Cook, "A probe for making near-field measurements with minimal disturbance: The optically modulated scatterer," *IEEE Transactions on Antennas and Propagation*, Vol. 45, No. 5, 772–780, May 1997.

[3] Caorsi, S., M. Donelli, and M. Pastorino, "A passive antenna system for data acquisition in scattering applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 1, 203–206, 2002.

[4] Donelli, M. and D. Franceschini, "Experiments with a modulated scattering system for through-wall identification," *IEEE Antennas and Wireless Propagation Letters*, Vol. 9, 20–23, 2010.

[5] Donelli, M., "Design of long-range, powerless RFID sensor at 10 GHz," *Electronics Letters*, Vol. 49, No. 20, 1277–1278, Sep. 2013.

[6] Donelli, M. and F. Viani, "Remote inspection of the structural integrity of engineering structures and materials with passive MST probes," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 55, No. 12, 6756–6766, Dec. 2017.

[7] Manekiya, M. and M. Donelli, "An air quality monitoring system with enhanced coverage capabilities by using the modulated scattering technique (MST)," in *2019 PhotonIcs & Electromagnetics Research Symposium - Spring (PIERS-Spring)*, 2235–2240, Rome, Italy, Jun. 2019.

[8] Manekiya, M., M. Donelli, V. Mulloni, and G. Marchi, "Integration of modulated scattering technique (MST) tags with IoT devices," in *Proceedings of the 2022 21st Mediterranean Microwave Symposium (MMS 2022)*, 80–84, Pizzo Calabro, Italy, May 2022.

[9] Manekiya, M., M. Donelli, A. Kumar, and S. K. Menon, "A novel detection technique for a chipless RFID system using quantile regression," *Electronics*, Vol. 7, No. 12, 409, Dec. 2018.

[10] Mulloni, V. and M. Donelli, "Chipless RFID sensors for the internet of things: Challenges and opportunities," *Sensors*, Vol. 20, No. 7, 2135, Apr. 2020.

[11] Aiswarya, S., S. K. Menon, and M. Donelli, "Development of enhanced range, high Q, passive, chipless RFID tags for continuous monitoring and sensing applications," *Electronics*, Vol. 11, No. 1, 127, 2021.

[12] Bracht, R., E. K. Miller, and T. Kuckertz, "An impedance-modulated-reflector system," *IEEE Potentials*, Vol. 18, No. 4, 29–33, Nov. 1999.

[13] Capdevila, S., L. Jofre, J.-C. Bolomey, and J. Romeu, "RFID multiprobe impedance based sensors," *IEEE Transactions on Instrumentation and Measurement*, Vol. 59, No. 12, 3093–3101, Dec. 2010.

[14] Capdevila, S., L. Jofre, J. Romeu, and J.-C. Bolomey, "Passive RFID based sensing," in *2011 IEEE International Conference on RFID-Technologies and Applications*, 507–512, Sep. 2011.

[15] Donelli, M., "Guidelines for the design and optimization of wireless sensors based on the modulated scattering technique," *IEEE Transactions on Instrumentation and Measurement*, Vol. 63, No. 7, 1824–1833, Jul. 2014.

[16] Donelli, M., "A broadband modulated scattering technique (MST) probe based on a self complementary antenna," in *2017 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC)*, 25–28, Verona, Italy, Sep. 2017.

[17] Donelli, M. and F. Viani, "Graphene-based antenna for the design of modulated scattering technique (MST) wireless sensors," *IEEE Antennas and Wireless Propagation Letters*, Vol. 15, 1561–1564, 2016.

[18] Donelli, M., "A 24 GHz environmental sensor based on the modulated scattering technique (MST)," in *2014 IEEE Conference on Antenna Measurements & Applications (CAMA)*, 1–3, Antibes Juan-les-Pins, France, Nov. 2014.

[19] Gentili, F., L. Pelliccia, F. Cacciamani, P. Farinelli, and R. Sorrentino, "RF MEMS bandwidth-reconfigurable hairpin filters," in *2012 Asia Pacific Microwave Conference Proceedings*, 735–737, Kaohsiung, Taiwan, Dec. 2012.

[20] Mansour, R. R., "RF MEMS for space applications," in *2005 International Conference on MEMS, NANO and Smart Systems, Proceedings*, 191–192, Banff, AB, Canada, Jul. 2005.

[21] Iannacci, J., C. Tschoban, J. Reyes, and U. Maass, "RF-MEMS for 5G mobile communications: A basic attenuator module demonstrated up to 50 GHz," in *2016 IEEE Sensors*, 1–3, Orlando, FL, USA, Oct. 2016.

[22] Iannacci, J., "RF-MEMS technology: An enabling solution in the transition from 4G-LTE to 5G mobile applications," in *2017 IEEE Sensors*, 942–944, Glasgow, UK, Oct. 2017.

[23] Donelli, M. and J. Iannacci, "Exploitation of RF-MEMS switches for the design of broadband modulated scattering technique wireless sensors," *IEEE Antennas and Wireless Propagation Letters*, Vol. 18, No. 1, 44–48, Jan. 2019.

[24] Donelli, M., M. Manekiya, and J. Iannacci, "Broadband MST sensor probes based on a SP3T MEMs switch," in *IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, 649–650, Atlanta, GA, USA, Jul. 2019.

[25] Bolomey, J. C., S. Capdevila, L. Jofre, and J. Romeu, "Electromagnetic modeling of RFID-modulated scattering mechanism. Application to tag performance evaluation," *Proceedings of the IEEE*, Vol. 98, No. 9, 1555–1569, Sep. 2010.

[26] Bolomey, J.-C., H. Memarzadeh-Tehran, and J.-J. Laurin, "Optimization of optically and electrically modulated scattering probes for field measurements," *IEEE Transactions on Instrumentation and Measurement*, Vol. 63, No. 1, 154–165, Jan. 2014.