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A wireless motion sensor operating down to -28dBm energy harvesting

Yero Dia, *Student Member, IEEE*, Helena Ribeiro, *Student Member, IEEE*, Laurent Oyhenart, Elie Zaraket, *Student Member, IEEE*, Ludivine Fadel, Valerie Vigneras, Corinne Dejous, *Member, IEEE*, Nuno Carvalho, *Fellow, IEEE*, and Simon Hemour, *Senior Member, IEEE*

Abstract—ZeroPower devices are the next generation of Internet of Things. Typically tapping from ambient energy, or activated by a remote reader, their first and foremost challenge is the operation distance from the nearest RF source. Unfortunately, these systems can only be activated within a range of a few tens of meters due to their minimum activation power (also named reading sensitivity). This work reduces the harvesting power to a new threshold of -28dBm (1.5 μ W). We demonstrate a wireless motion sensor operating in burst mode with as low as 120 mV of DC voltage and 0.72 μ J of stored energy. This efficient operation is achieved without any DC/DC conversion thanks to a four-stages rectifier biasing a tunnel diode Voltage-controlled oscillator (VCO).

Index Terms—RFID, ZeroPower, ambient power, transponder, tunnel diode, rectifier, energy harvesting, backscattering.

I. INTRODUCTION

The Fourth Industrial Revolution, often called Industry 4.0, describes the present stage of industrialization that merges the physical and digital worlds. It entails a novel approach to manufacturing processes by integrating virtual and real-world elements. This new industry blends digital design and engineering with physical products and systems [1].

Industry 4.0 is based on the Internet of Things (IoT), which has enabled the connection of sensor networks and their market deployment. In 2019, the number of these connected devices was estimated at 34 billion and is projected to reach \$93.86 billion by 2023 [2]. Also, it is widely recognized that radio transmission of those wireless devices in embedded systems is the most energy-consuming part of the energy budget [3]. Although low-power communication protocols exist (such as Bluetooth Low Energy or Zigbee), they are often integrated into transmitters that consume at least twenty milliwatts [4]. Thus, energy efficiency remains a crucial consideration for wireless sensor nodes (WSN) [5], as decreasing the energy used for communication can appreciably enhance the longevity of wireless sensor nodes.

Recent advancements have provided viable solutions to overcome the challenges of energy efficiency in sensor networks, including the development of more compact and

energy-efficient networks. A notable approach involves duty-cycling the radio, wherein the transmitter periodically switches between active and inactive states to lower power usage [6]. However, this method still incurs power consumption during idle periods. A more sophisticated alternative is backscattering communication, which offloads the wireless communication energy cost to the reader device.

Originating in the late 1940s [7], this approach enables a transponder to reflect data when illuminated by a reader signal. Radio Frequency Identification (RFID) technology, which leverages this principle, uses RF wave energy to both transmit data to the tag and power the transmission circuit. Despite its low power consumption (Fig. 1a), RFID needs continuous power supply from a nearby system for operation.

Many attempts have been made to enhance the distance between the RFID tag and the power source, and one popular method is to incorporate a repeater structure between the reader and the tag [8], [9]. However, it should be noted that this approach is not entirely passive due to the energy consumption associated with amplification. Moreover, a potential approach to improve range capabilities is by implementing bistatic systems, which involve physically separating the carrier emitter and the backscatter receiver. This separation enables an extended range, although it necessitates an additional energy source to power the second antenna [10], [11].

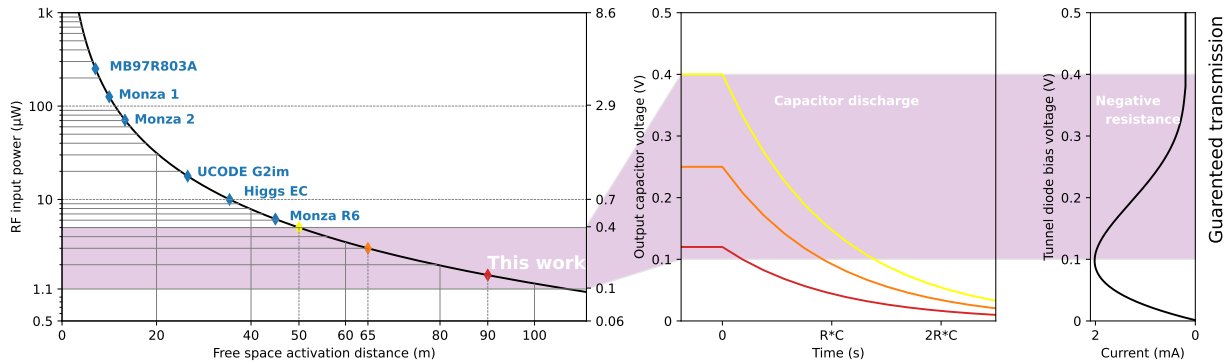
The advent of ambient backscattering introduces the potential to eliminate the dependency of RFID tag being near a power source [12]–[14]. By harnessing energy from ambient RF waves, it becomes feasible to operate over larger areas without direct power sources. Maximizing this technology's efficiency requires integrating an energy-harvesting system with an ultra-low voltage transmitter, potentially utilizing a tunnel diode [15] known for its negative resistance feature (Fig. 1a). In addition, incorporating this component offers a practical resolution for reducing power consumption in wireless transceivers by eliminating the need for power amplifier and RF synthesizing circuitry, which are the primary power-consuming elements in the budget link. The implementation of such a system can greatly contribute to minimizing the losses incurred due to tool disappearance within the industrial environment.

Indeed, in aviation, the pervasive issue of foreign object damage (FOD) has posed a significant risk for an extensive period. This problem has resulted in catastrophic incidents and fatalities, contributing to an exorbitant cost of approximately \$4 billion annually [16]. To address this challenge, we propose

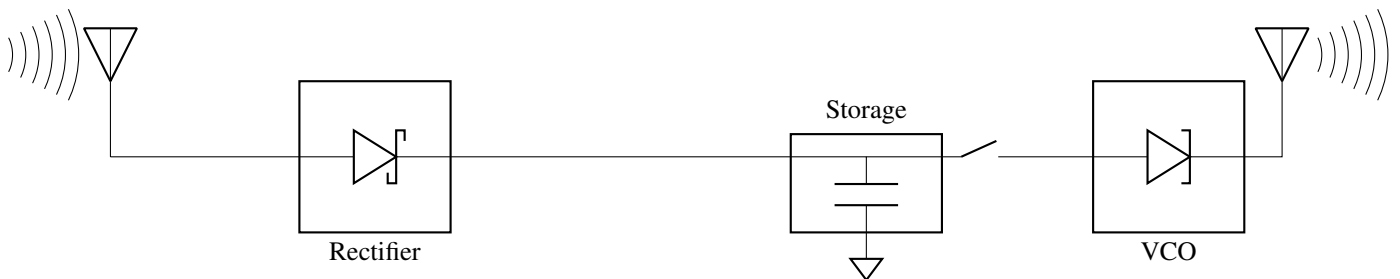
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(a) **(Left graph)** Theoretical free space activation distance of few industrial RFID tags: using their read sensitivity and Friis equation with a 36 dBm EIRP source at 956 MHz with a transmitter antenna gain of 5 dB and a receiver antenna gain of 2 dB. **(Middle graph)** Upon triggering, a capacitance can be discharged into a tunnel diode, yielding Frequency-Modulated Continuous Wave (FMCW) signal. **(Right graph)** I(V) characteristic of the tunnel diode. Purple area correspond to negative differential resistance region, where oscillation condition can be found.



(b) Architecture of the proposed system: a rectifier based on Schottky diode will convert radiofrequency waves from an antenna into DC voltage in a storage capacitor. Then a tunnel diode VCO will lead to emission of radiofrequency waves when oscillation criteria are reached.

Fig. 1: Performance of few industrial RFID tags and architecture of the proposed system.

a battery-less connected tag that can be attached to tools, mobile equipment, or products to facilitate their location upon movement through the use of a motion sensor.

Various approaches have been suggested in the existing literature to tackle the problem of minimal power activation, including the utilization of fully passive components or the enhancement of signal reception by the reader [15], [17]–[19]. Nevertheless, none of the solutions discussed in the literature have ventured into reducing power sensitivity through modifications to the rectifier side of the system that could help to reduce significantly the power of activation.

In our previous study [20], we briefly introduced an ambient backscattering system utilizing a voltage-controlled oscillator with a tunnel diode. In this extended edition of our research, we strive to explore deeper into the energy harvesting system by presenting a comprehensive analysis and an elaborated model of the complete system.

The paper is structured as follows: the initial section will introduce the rectifier used for RF to DC power conversion. The second section will present the voltage-controlled oscillator circuit and the construction of the simulation model. Lastly, we will discuss the constructed test bench and the obtained results.

II. RECTIFIER

Radiofrequency energy harvesting can be utilized to power a system thanks to a rectenna [21]. Thus, through an antenna, the RF waves produced by the surrounding communicating systems are captured and converted through an RF to DC conversion circuit, the rectifier.

In this work, the node will be powered by an external source to highlight the proof of concept.

Rectifier circuits allow for the conversion of an RF signal into a DC signal. However, at the working frequencies (around 900 MHz), these circuits see their input impedance change depending on the input power, frequency, and also the load. Likewise, there are numerous topologies to maximize the output voltage or its efficiency.

This section will present the design choices and characterization of the rectifier used to operate in the GSM band and power the oscillator presented in the following section.

A. Matching network

The input impedance of the rectifier, mostly capacitive has to be matched to the 50 Ω output impedance of the antenna.

Thus, a L-matching circuit is used combining a discrete component followed by a shunt short-circuited distributed

component (stub) as at microwaves frequencies, the parasitic components contained inside lumped elements becomes more and more perceptible [22].

Moreover, a degree of liberty is lost also since those lumped components are available for discrete values. A final advantage of having a mix of discrete and distributed components for impedance match is the ability to tune the circuit after being manufactured.

B. Topology

In literature, various rectifier topologies can be found, however, voltage multipliers are deemed the most preferable option for RF to DC rectification due to their straightforward design and its ability to answer to the target voltage requirement. Mathematically, the output voltage of a voltage doubler is $V_{out} = 2V_{in} - 2V_j$ where V_j corresponds to the junction voltage of the diode used (Fig. 2a).

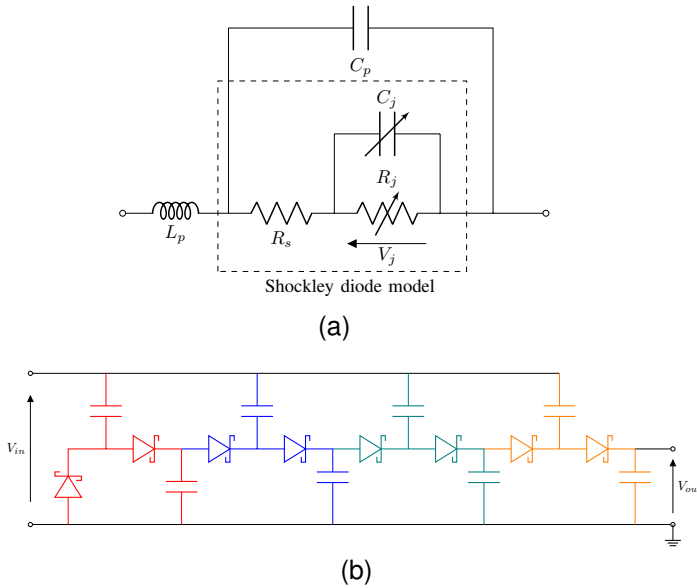


Fig. 2: (a) Shockley model of a packaged Schottky diode and (b) Improved voltage doubler topology for RF rectification: 100 pF capacitors are connected to the input while 100 nF are connected to the ground.

In traditional low frequency (LF) rectifiers, multiple stages of voltage multiplication are often connected in series to boost the output voltage. However, this approach can cause significant power loss in RF rectifiers due to the high frequency signals involved. This is because at RF frequencies, the capacitors used in voltage multiplication stages can act as inductive loads, leading to undesirable reflections and resonances. These effects can result in signal distortion, reduced efficiency, and increased losses in the rectifier. Therefore, alternative approaches are required to address these challenges in RF rectification [23].

Therefore, it is more advisable to utilize an alternative topology wherein the rectifier stages are cascaded in a pseudo series-parallel arrangement. In this configuration, the outputs of the rectifiers are linked in series (daisy-chained), while their inputs remain in parallel with the RF input. By employing this

technique, it is also possible to apply it to the voltage doubler rectifier, resulting in the creation of multiple stages (Fig. 2b).

C. Diode choice

Choosing the appropriate diode is a critical aspect in the design of a rectifier for low power energy harvesting situations. The efficiency of rectification is greatly influenced by this selection process. Schottky diodes are frequently preferred for RF to DC conversion because they possess a low barrier voltage (V_j), which makes them suitable for such applications [24].

The conversion is done through the bias of the capacitance and junction resistance of the Shockley model of the diode. The resistance R_s represents the losses of the diode and C_p and L_p are packaging capacitance and inductance. The lower the impedance of the resistance and junction capacitance, the less they will hinder the conversion. Additionally, when an RF current flows through the junction, the capacitance C_j will draw more current if its impedance is lower than that of the junction resistance, although ideally it should pass through the non-linear junction resistance R_j .

To summarize, the impedance of the junction capacitance (C_j) should be lower than the resistance of the junction (R_j) to draw more RF current. Both C_j and R_s should be chosen as low as possible to minimize their impeding effects and improve the rectifying operation [25].

Parameter	Unit	HSMS-285x	SMS-7630
B_v	V	3.8	2
C_{J0}	pF	0.18	0.14
E_G	eV	0.69	0.69
I_{Bv}	A	3e-4	1e-4
I_S	A	3e-6	5e-6
N		1.06	1.05
R_S	Ω	25	20
$P_B (V_j)$	V	0.35	0.34
$P_T (XTI)$		2	2
M		0.5	0.4

TABLE I: Datasheet of two Schottky diode in radiofrequency energy harvesting.

This study aimed to identify the optimal choice between two diodes, specifically the HSMS-2850 and SMS-7630. The junction potentials of these diodes were measured to be 0.35 V and 0.34 V, while their breakdown voltages were recorded as 3.8 V and 2 V respectively (Table I). Full wave rectifiers were constructed using these diodes in order to rectify at 900 MHz and measure their sensitivity. The results (Fig. 3) clearly indicated that the sensitivity is dependent on the input power, with superior results observed for the HSMS-2850 diode. In other works, the first diode was chosen because it shows the best results for power conversion efficiency at low power [26], [27].

After choosing the diode to be used, it is important to determine the number of stages. It is reminded that the goal is to have a sufficiently high voltage for very low power supplies.

Increasing the number of stages in a circuit beyond four may lead to a decrease in output voltage due to the additional complexity and associated losses incurred during signal propagation. This can result in a decrease in overall circuit

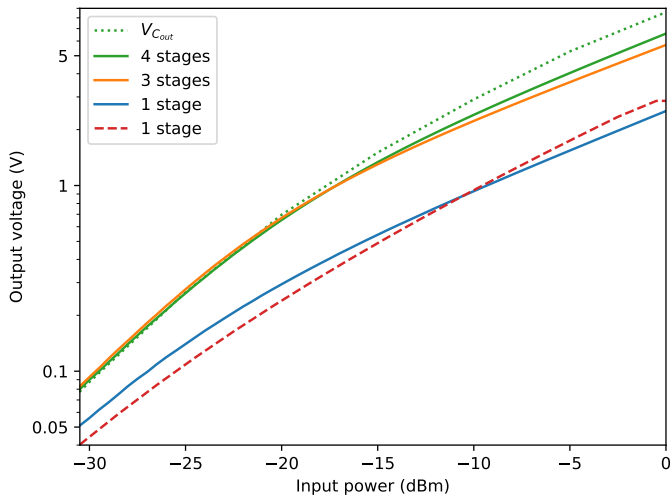


Fig. 3: Output voltage of different stages vs. Input power: *the solid and dotted line curves use the HSMS2850 diode while the dashed curve uses the SMS 7630 diode.*

efficiency and output power [28]. Indeed, as presented in our previous studies, adding a stage thus improves sensitivity to low power levels but reduces efficiency for the same load [29], [30]. However, a similar efficiency is achieved at a higher load since the optimal load corresponds to the sum of all the diode junction resistances at low power levels and decreases as the input power increases. As shown in Fig. 3, the output voltages of a 3-stage and a 4-stage rectifier converge. Also, previous studies have been conducted to select a 4-stage rectifier that allows for obtaining the highest possible voltage for low powers [30], [31]. At -30 dBm, the optimal load found is around 60 k Ω .

D. Characterization

In the case of the low-power RF harvester, the energy is stored in a capacitor or other storage element for later use by the application. This accumulation mode prioritizes power sensitivity over power efficiency during the charging process. During characterization, the rectifier is disconnected from the load, which represents the equivalent impedance of the actual application being powered. This allows for a more precise measurement and analysis of the harvester's performance in this specific mode of operation.

The rectifier is produced using mechanical engraving on a FR-4 printed circuit board, which has a relative permittivity ϵ_r of 4.7 and a loss tangent $\tan(\delta)$ of 0.014. The board has a thickness of 1.6 mm and is coated with 35 μm of copper.

The blue curve in Fig. 4 represents the anticipated DC voltage at the rectifier output for an input power of -28 dBm in the GSM downlink frequency band. This is demonstrated in red in Fig. 4, which also shows the superposition of the return loss at the same power level. It is noticeable that the maximum voltage peak coincides with the frequency at which the return loss is minimum. As a result, the operating frequency of the rectifier will be 949 MHz, which will provide the highest voltage output for low input power. Nevertheless,

measurements of output voltage and reflection coefficient present a close form response with respect to the simulation results with a shift of around 20 MHz mainly due to fabrication issues.

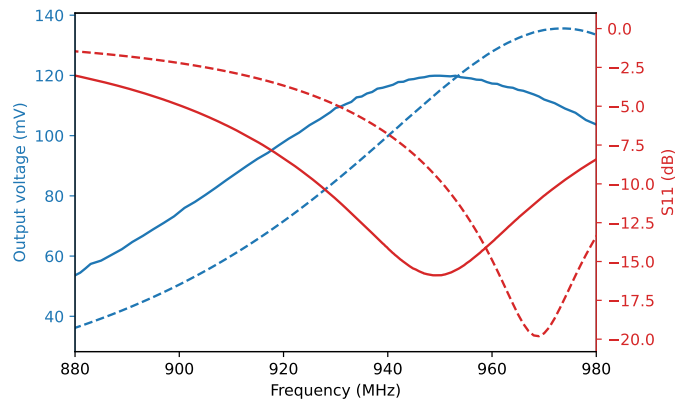


Fig. 4: Rectenna frequency characterization at -28.6dBm: **(blue)** Measured return loss S11 of the 4-stages rectifier. **(red)** Measured output voltage of the 4-stage rectifier at 949 MHz. *Solid lines curves are experimental results while dashed one are simulation results.*

Batteries are utilized for sensors that require a significant amount of power, ranging from milliwatts to several hundred milliwatts. However, one drawback of these devices is that their capacity deteriorates after a few thousand cycles [32].

On the other hand, capacitors possess a capacity that can support numerous charge cycles [33]. Additionally, their low power density enables them to charge at a faster rate compared to batteries.

Consequently, a capacitor can be employed to store and release charges once a certain threshold is reached. To evaluate this, a 100 μF capacitor is added to the output of the rectenna and subjected to characterization. The rectifier is a novel time characterized at 949 MHz, with an input power ranging from -30 dBm to 0 dBm (Fig. 3, green dots).

III. VOLTAGE CONTROLLED OSCILLATOR (VCO)

There are two types of oscillators commonly used: ring type and LC type oscillators. Ring type oscillators utilize CMOS technology and employ NOT gates arranged in a ring configuration. On the other hand, LC type oscillators generate oscillations using parasitic components within the circuits. Previous studies such as [34], [35] have shown the use of ring type oscillators in various applications. However, LC type oscillators offer advantages such as lower fabrication cost and a reduced bias voltage limitation.

While Power Amplifiers (PAs) are widely favored for radiofrequency transmission due to their high efficiency, they do have a significant drawback. The activation requirement for PAs is relatively high, typically greater than 0.4 V [36]–[39]. This is due to the threshold voltage of the transistor, which is limited compared to the low voltage capabilities of tunnel diode oscillators. In an ambient RF energy harvesting scenario [40], the low power levels (as shown in Figure 1a, left) may

result in insufficient voltage conversion to adequately power a power amplifier (PA).

In this project, the focus will be on LC type oscillators using readily available lumped components. This approach aims to lower the fabrication cost and overcome the bias voltage limitation associated with PA. By exploring the potential of LC type oscillators, this research aims to contribute to the improvement of oscillator technologies for various scientific applications.

A. Principle of a VCO

When considering electrical components (Fig. 5), a system will begin oscillating at a frequency f only if there is a negative sum of resistances (R_l and R_{in}) and a zero sum of reactance ($X_{in} = X_L$) due to transient excitation or noise. This occurs when loss is balanced by gain, as stated by the Barkhausen criterion for energy generation [41], [42].

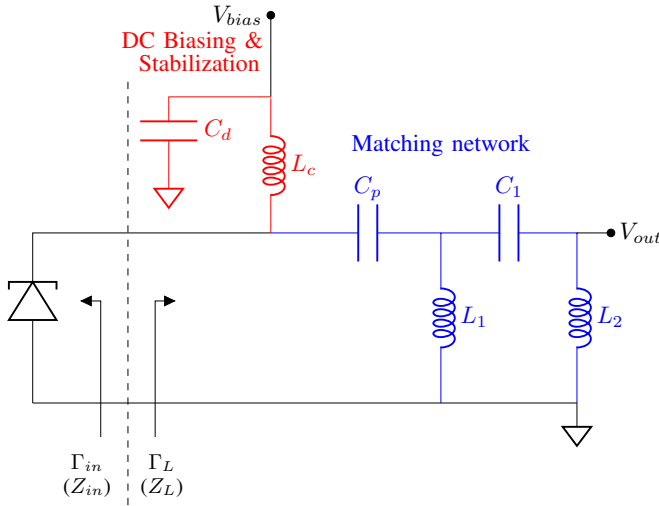


Fig. 5: Schematic of the tunnel diode voltage controlled oscillator.

The operating principle of a Voltage-Controlled Oscillator (VCO) is based on the phenomenon that the frequency output of an oscillator can be controlled by varying an input voltage. When a varying control voltage is applied, it modulates the capacitance or resistance of the voltage-sensitive element, which in turn alters the resonant frequency of the tank circuit. This modification of the resonant frequency directly proportional to the control voltage leads to a variation in the output frequency of the VCO.

B. VCO circuit design

Tunnel diodes present inherent properties for voltage controlled oscillators (VCOs): on the one hand, they exhibit negative differential resistance (which leads to instability potential [42]) when correctly biased, and on the other hand, their junction capacitance and junction resistance vary significantly with the applied voltage, which improves the VCO sensitivity. The oscillation conditions are relatively simple and are fulfilled when the total circuit equivalent resistance becomes zero.

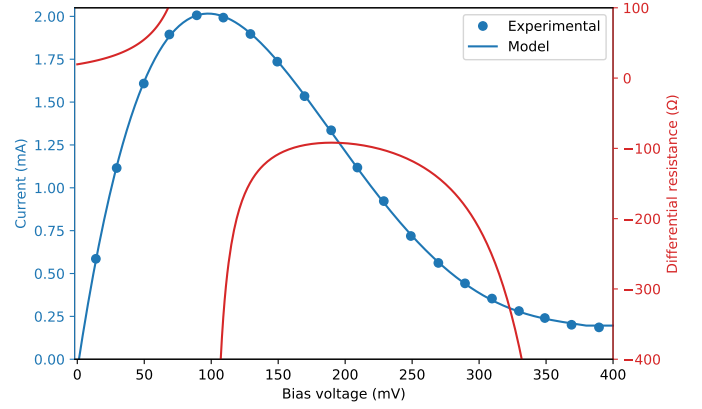


Fig. 6: Measured and modeled tunnel diode's IV characteristic with its negative differential resistance.

Before creating a prototype using a tunnel diode, it is essential to determine the direct current (DC) voltage and current (IV) relationship of the tunnel diode. The N-type gallium-arsenide (Ga-As) tunnel diode, model 3I306E, is selected and its current-voltage (I-V) characteristic is measured. In the voltage range of 120 mV to 450 mV, the current decreases, which corresponds to the region of negative dynamic resistance as depicted in Fig. 6.

C. Simulation framework

The VCO frontend can be seen in Fig. 5 and comprises a tunnel diode, a DC biasing and stabilization network, and a matching network as presented in [20], [43].

To improve the precision of the simulation performance, it is important to extract a model of the tunnel diode. The diode's S-parameters and IV curves were extracted using a PNA-X and a power analyzer to achieve this. The acquired values were subsequently employed to model the charge equation and IV curve accurately through polynomial fitting.

The use of an equation-based model in Advance Design System (ADS) allows for the study of a tunnel diode as a nonlinear component using the symbolically defined device (SDD).

This model can accurately simulate the behavior of the device, both for small signals and large signals, without the need for source code. A 7th order polynomial equation (1), $I(v)$, is specifically utilized to accurately simulate the DC or harmonic balance simulation of a tunnel diode [44]:

$$I(v) = \begin{cases} 10^{-12}(\exp^{\frac{v-0.2}{26 \times 10^{-3}}} - 1) + 1.96e - 4 & \text{if } v > 0.38 \\ A + Bv + Cv^2 + Dv^3 + Ev^4 + Fv^5 + Gv^6 + Hv^7 & \text{else.} \end{cases} \quad (1)$$

The charge curve is needed for the tunnel diode model because it provides information about the behavior of the diode at different levels of applied voltage.

The charge curve shows the relationship between the voltage applied to the diode and the amount of charge stored within it (Equation 2). This relationship is crucial for understanding

how the tunnel diode behaves at different voltages, as it determines the point at which the negative resistance occurs.

$$Q(v) = \begin{cases} 9 \times v - 0.28 \times 10^{-12} & \text{if } v > 0.35 \\ 0 & \text{if } v < 0 \\ v(A + Bv + Cv^2 + Dv^3 + Ev^4 + Fv^5 + Gv^6 + Hv^7) & \text{else.} \end{cases} \quad (2)$$

The various values of the equations for the characteristics $I(v)$ and $Q(v)$ are compiled in Table II.

TABLE II: Parameters of the Polynomial in the $I(v)$ and $Q(v)$ curves.

Parameter	Value for $I(v)$	Value for $Q(v)$
A	-6.31e-5	6.2e-12
B	0.05	3.6e-11
C	-0.41	-6.3e-10
D	1.11	6.55e-9
E	-0.55	-3.93e-8
F	-3.22	1.36e-7
G	7.46	-2.47e-7
H	-5.75	1.84e-7

The parasitic element of this tunnel diode can be simplified as a 2.09 nH inductor with a diode serie resistance of 1.5 Ohm. The SDD block from ADS was used to simulate the behavior of a tunnel diode. The final model of the tunnel diode can be seen in Fig. 7.

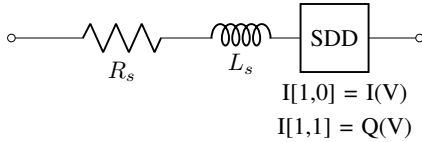


Fig. 7: Tunnel diode model using the Symbolically-Defined Device (SDD) in Keysight ADS. The first equation $I[1,0]$ refers to the current flowing through the port 1 of the device, i.e. $I(t)=I(v(t))$, using the equation 1. The second equation $I[1,1]$ refers to the current flowing through the port 1 of the device with time differentiation in the time domain, i.e. $I(t)=\frac{d}{dt}Q(v(t))$.

A transient simulation of the tunnel diode using the SDD block is able to reproduce the experimental results obtained during the discharging of the output capacitance of the rectifier (Fig. 8, right). The results show two different regimes, appearing with two different slopes. Below 380 mV, the tunnel diode exhibits negative resistance, leading to oscillations, current demand, and voltage drop. It is within this range that the oscillations can be observed, as shown in Fig. 1a. Also, as seen in Fig. 8, left, the wireless sensor needs 20 seconds of harvesting time (under -28dBm exposure) to reach the 720nJ necessary to transmit a burst, while it takes only around 1 second under -22 dBm RF harvesting power.

The oscillation frequency range of the designed circuit is influenced by its DC Biasing and Stabilization network. The oscillation frequency can be actively adjusted by varying the DC bias between 0.15 V and 0.33 V. To achieve the desired oscillation frequency, L_c and C_d have been set to 10 nH and

1 nF, respectively. The matching network consists of two 10 nH inductors and a 4 pF capacitor. In Fig. 6, it is possible to observe that the signal generated by the VCO does really appear on the negative differential resistance part.

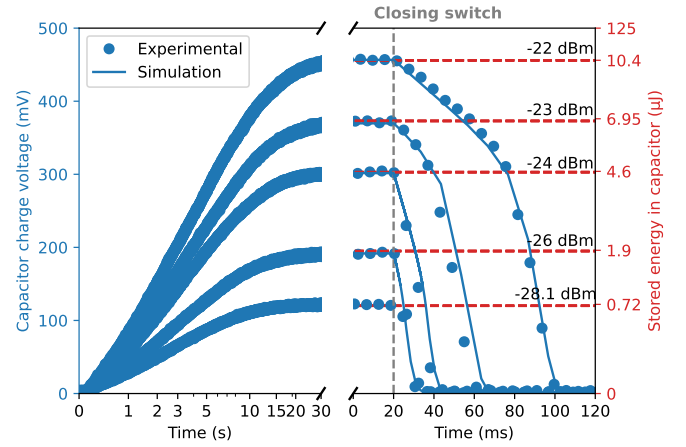


Fig. 8: Experimental discharges of the 100 μ F capacitor into the tunnel diode and its simulation.

IV. MEASUREMENTS AND DISCUSSION

A. Test bench

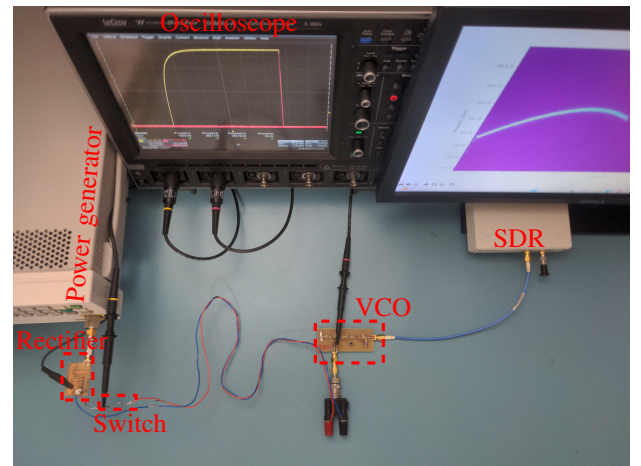


Fig. 9: Experimental bench designed for the measurements: the power generator (Keysight/Agilent N5182A) powers the rectifier presented in section II. A tilt switch will allow the rectifier to bias the tunnel bias VCO presented in section III. Output frequency is measured thanks to a radio receiver (NI USRP 2901) and voltage thanks to an oscilloscope (Lecroy 104MXs-A).

As part of the system validation, the Voltage-Controlled Oscillator (VCO) is powered by the output of a RF-to-DC converter (rectifier) to demonstrate the system concept. In contrast to amplifiers and most 2-ports microwave devices/circuits, oscillators and generators just have one RF (output) port. However, it is interesting to observe the DC biasing (DC link from the rectifier to the oscillator), given in Fig. 8. Also,

in a power transmission application, the rectifier would be connected to an antenna operating in the GSM frequency band. However, the focus is on demonstrating the system concept. To accomplish this, a Keysight/Agilent N5182A power generator is used to power the rectifier.

Similarly, a NI USRP 2901 radio receiver is connected to the output of the VCO to measure the frequency and power of the generated output signal. The measurements will be performed using the open-source software GNU Radio and processed digitally using Python.

To initiate the discharge of the capacitor in the VCO circuit, a tilt switch, which is sensitive to movement is placed between the subsystems. Moving it will cause the switch to close and the oscillation to start.

Finally, a Lecroy 104MXs-A oscilloscope is used to measure the voltage across the capacitor and at the entrance of the VCO circuit. Fig. 9 presents the whole test bench.

B. Characterization

In our experimental setup, the input power to the rectifier is adjusted to replicate the level that can be obtained in an urban environment [40]. We then measure the output voltage of the rectifier and plot the frequency as a function of it (Fig. 10). Our results demonstrate that a minimum input power of around -28 dBm is necessary to generate a high-frequency signal.

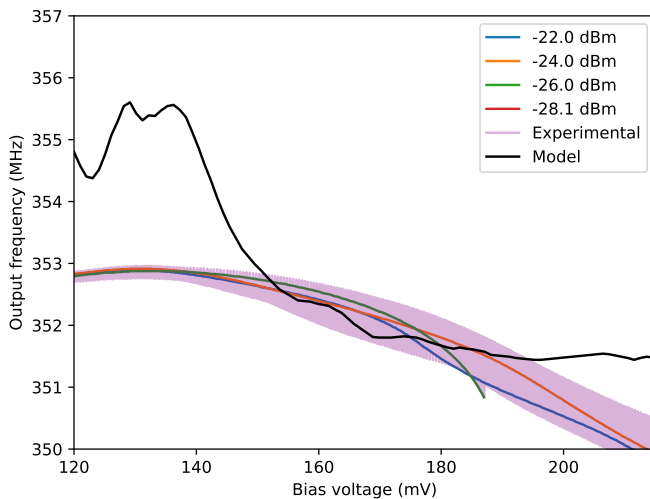


Fig. 10: Output frequency of the generated signal: *solid lines are experimental results and dashed one is simulation. The purple "experimental" zone corresponds to the upper and lower limits of a set of 18 experimentally measured curves, which are not displayed here.*

The oscillation frequency is shown in Fig. 10. As the voltage stored in the capacitor is decreasing over time, the tunnel diode circuit is biased by a swept voltage. Since a variant junction capacitance and negative differential resistance correspond to every bias voltage, the conditions of oscillations and generated frequency varies accordingly. The experimental values are compared to simulation, according to the methodology described in [45]. The simulation modeling involves the derivation of measurement data. This turns into

significant challenges when attempting to accurately model the high resistance corresponding to the Tunnel diode peak's current. We acknowledge increased modeling uncertainties in this region. This is also attributed to the utilization of a 50 Ohm Vector Network Analyzer (VNA) for diode characterization: while a VNA is proficient in accurately measuring impedances of around 50 ohms, it is not ideal for measuring resistances in the magnitude of thousands of ohms.

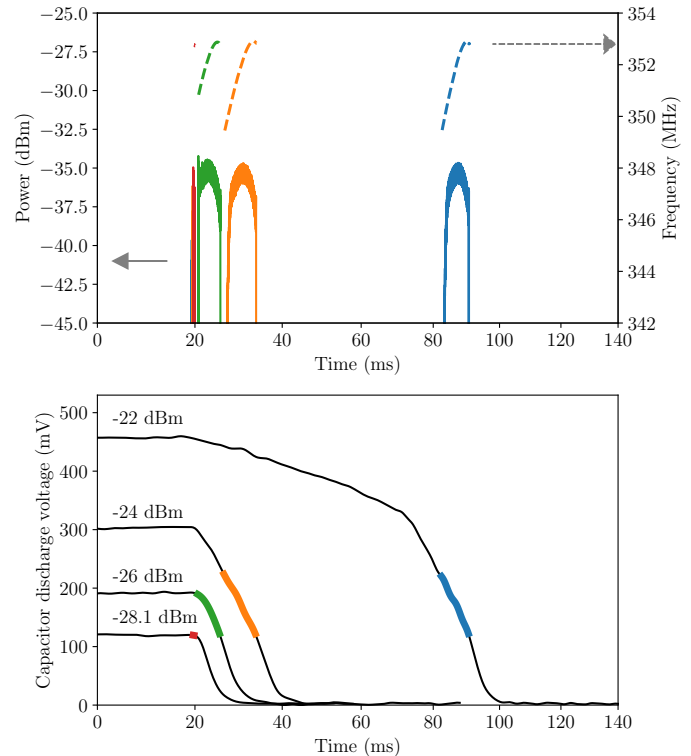


Fig. 11: Transient results of the constructed VCO. *Top: generated chirp by the system and output power of the generated signal. Bottom: Discharging capacitor into the VCO circuit, in solid colored line, the generated oscillation.*

These changes in capacitance and resistance lead to a decrease in the oscillation frequency. An increased junction capacitance causes the overall resonant frequency of the circuit to decrease, as the capacitive reactance becomes larger. This results in a lower frequency of oscillation for a given resonant circuit. Similarly, an increased junction resistance dampens the oscillation, causing the frequency to decrease even further. This phenomenon is known as the "degeneration" of the oscillator, which occurs as a result of the increased junction capacitance and resistance [46].

Finally, after calibrating the USRP, the power of the high-frequency output signal is determined (Fig. 11-top). This measurement demonstrates that the system implemented is resilient to the input power of the system and will be able to generate a sufficiently powerful signal for transmission via a 50 Ω antenna.

Similarly, the oscillation time is approximately 8 milliseconds. However, when the polarization voltage is below 220 milliseconds, the oscillation time reduces further (Fig. 11-top).

TABLE III: Performance comparison

Ref	F_{in}	F_{out}	P_{min}	d_{act}	V_{min}
[15], 2020	900 MHz	5.8 GHz	-5 dBm	6.64 m	88 mV
[17], 2020	865-868 MHz band	4 GHz	-13 dBm	17.37 m	NA
[18], 2019	5.8 GHz	5.8 GHz	-16.7 dBm	3.97 m	80 mV
[19], 2017	5.8 GHz	5.8 GHz	-16.9 dBm	4.06 m	NA
This work	900 MHz band	350 MHz	-28 dBm	90.1 m	120 mV

Table III facilitates the comparison of this work with other research papers showing that the system designed generates the signal with the lowest power at the input of the rectifier circuit. This is due to the fact that all the components are off-the-shelf (COTS) components requiring no external power supply. Also, the theoretical free space activation distance is computed allowing to understand how far the system can be from the source.

The calculation is made using Friis equation with 6 dBm EIRP source at their working input frequency and power activation, with a transmitter antenna gain of 5 dB and a receiver antenna gain of 2 dB.

V. CONCLUSION AND FUTURE WORKS

This work describes the design and measurements of a RFID tag with very low reading sensitivity. This system revolves around a tunnel diode that creates oscillation through its negative resistance, all powered by a rectifier that can utilize ambient energy harvesting. The presented tag operates at power levels on the order of microwatts (-28 dBm) and is capable of outputting an oscillating signal at -35 dBm. Such an application is particularly interesting for low RF power environments such as inside factories and buildings.

The built system can still be improved by adding antennas at the input and output of the assembly. Similarly, by adding a diplexer, the system can become more compact by having a single antenna that allows both energy conversion and signal transmission.

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