750 MHZ ZERO-POWER MEMS-BASED WAKE-UP RECEIVER WITH -60 DBM SENSITIVITY

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ABSTRACT

In this work, we present the first fully-passive RF wake-up receiver (WUR). The WUR relies on a solid-state envelope detector (*ED*) and a MEMS-based cantilever switch (*RS)* acting as a resonant comparator vibrating at 75.3 kHz. The device exhibits a quality factor (*Q)* of 4700 when operating in its linear regime (*i.e.* far from pull-in voltage). The demonstrated WUR enables the achievement of high sensitivity (P_{min}=-60 dBm) while not consuming any stand-by power. For this reason, the presented WUR opens up exciting scenarios in the development of next-generation smart wireless sensors nodes operating within the *Internet-Of-Things* (IoT).

INTRODUCTION

The recent development of the internet of things (*IoT*) has led to an urgent need for low-power wireless sensing nodes (WSNs) communicating within complex miniaturized networks. WSNs are formed by a group of sensors whose captured information is only transmitted when requested by other interrogating nodes. Depending on their operational state (*on* or *idle*), WSNs may drain different amounts of energy from their batteries. In particular, for most practical cases, the battery life of WSNs is significantly reduced by the amount of power they dissipate when operating in their idle state (P_{idle}). For this reason, WSNs relying on RF wake-up receivers (WURs) have been recently proposed to minimize P_{idle}. Such radios use the received RF-power to control both the state of WSNs and the amount of energy released by their batteries. The performance of WURs can be characterized in terms of two key parameters: the stand-by power (P_{sb}) and the sensitivity (P_{min}). P_{sb} is defined as the power consumed when not driven by any input RF-signal. In contrast, P_{min} is defined as the minimum input RF-power (P_{in}) required to trigger them.

In this work, we report on the first fully-passive WUR demonstrated to date (Fig. 1). This relies on a solid-state envelope detector (*ED*) and a MEMS-based resonant cantilever switch [3-4] (*RS*) to achieve high sensitivity (P_{min}=-60 dBm), zero stand-by power (P_{sb} = 0) with low system complexity. The theory, fabrication and the experimental performance of WUR will be reported.

THEORY AND OPERATION

The schematic representation of the WUR demonstrated in this work is shown in Fig. 1. The *ED* includes a diode (D1), an inductor (L1=82 nH) and two capacitors (C1=10 pF and C2=100 nF). L1 is used to resonate the static capacitance of the diode (C_s~0.1 pF) at the desired operational frequency (750 MHz). In contrast, C1 and C2 are used to limit the power released at undesired frequency components and prevent power leakage into the diode. As evident, this signal is generated through an ON/OFF amplitude modulation applied to a RF Continuous-Wave (CW) signal. The modulation is characterized by an optimal duty-cycle value which allows to maximize the mechanical force (F_m) acting on the *RS*. $v_{gs}(t)$ is applied between the gate and source contacts of the RS. This is attained after combining the envelope signal achieved from $v_{in}(t)$ through the ED ($v_{dem}(t)$) with a DC-voltage (V_{gg}) applied between the same RS-terminals through a large biasing resistor (1 MΩ). The large resistor is needed to apply V_{gg} without generating power leakage from the output of the ED into the input of the adopted DC-supply. The use of V_{gg} allows to increase both F_m and its sensitivity with respect to $v_{in}(t)$. It is also important to point out that the use of V_{gg} and V_{dd} also determines a reduction of both the actuation and contact gaps of the RS, thus further lowering P_{min}. The flow of current from V_{dd} determines the activation of the WUR and, consequently, allows to trigger future WSNs relying on their use to minimize P_{idle}.

The built WUR is driven by an amplitude modulated RF-signature ($v_{in}(t)$ (Fig. 2-a)) characterized by a carrier frequency of 750 MHz and a modulation frequency, f_m, matching f_{res}. In particular, when $v_{in}(t)$ drives the *ED*, it is first demodulated ($v_{dem}(t)$) and then applied, together with V_{gg}, between the gate and source of the *RS* (see $v_{gs}(t)$ in Fig. 2-b). Consequently, F_m is generated inducing a resonant displacement of the *RS* that is amplified by its high quality factor. The magnitude of F_m is proportional to the magnitude of $v_{gs}(t)$. So, when the received RF-power exceeds a certain threshold (P_{min} =-60 dBm), the drain and source of the RS come in contact (Fig. 1-c), enabling the flow of current ($I_{ds}(t)$) from a DC-voltage supply (V_{dd}) and, consequently, the activation of the WUR.

It is important to emphasize that, differently from any WUR architecture relying on voltage rectifiers to operate, the presented system has a sensitivity that is only limited by the white-noise of the employed *ED*. This special feature is enabled by the use of the MEMS-component as a high-frequency resonant comparator. In fact, thanks to this system characteristic, the WUR demonstrated in this work can operate with modulation-frequencies that are larger than the corner-frequency relative to the *1/f* flicker noise affecting the operation of the *ED*. So, the noise power affecting the *SNR*, between the gate and source contacts of the RS, is only determined by the white-noise, at the *ED* output (point B in Figure 1), integrated in the narrow frequency band (<20 Hz) of the RS. This explains why the presented architecture has potential to achieve sensitivity as low as -90 dBm through a more optimized and controlled RS-design and fabrication.

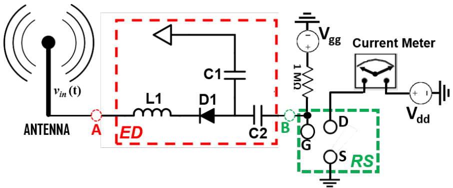

Figure 1: Schematic representation of the WUR demonstrated in this work.

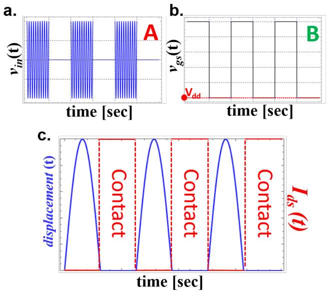

Figure 2: a-b) Representation of the time mode-shapes relative to

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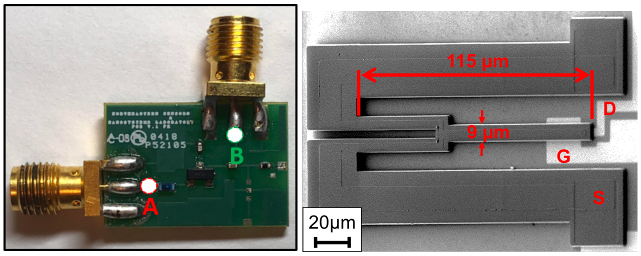
the signals at the input (A) and output (B) terminals of the WUR (in A in Fig. 1)); c) time mode-shape of the displacement and current waveforms, upon contact, relative to the fabricated RS.

FABRICATION AND EXPERIMENTAL RESULTS

The RF WUR is realized by a commercial solid-state envelope detector (AVAGO-HSMS2852) (Fig. 3-a) built on a printed circuit board (*PCB*) and an in-house fabricated MEMS-based resonant cantilever switch (*RS,* Fig. 3-b).



a) b)

Figure 3: a) Top-view of the PCB of the ED; b) Scanning Electron Microscopy (SEM) picture of the RS in this work.

The device relies on a 600 nm actuation gap (between gate and source) and on a 300 nm contact gap (between drain and source). The gate and source area results into a rest capacitance (C_{act}) that is ~30 fF. The position of the three *RS*-terminals is highlighted. It is also important to point out that the *RS*-design relies on an etched slot to attain second-order stress-gradient compensation. The fabricated *RS* was connected to the *ED* through probing and loaded in a vacuum probe station (5×10^{-5} Pa) for testing. A Polytec vibrometer was used to measure the out-of-plane velocity relative to the tip of the beam and, consequently, its displacement. Both the resonance frequency (f_{res}~75.3 kHz) and the quality factor (Q=4700) of the built *RS* were extracted through the direct vibrometer measurements after biasing the *RS* with the same DC voltages applied in the WUR (*i.e.* V_{gg}=15.8 V and V_{dd}=6 V), as shown in Fig. 4. The performance of the built WUR was extracted after driving it through a commercial RF-arbitrary waveform generator, which allowed for a more reliable characterization of its performance. We report, in Fig 5, the measured DC-component of $I_{ds}(t)$ for two received P_{in}-values around the measured P_{min}-value (-60 dBm).

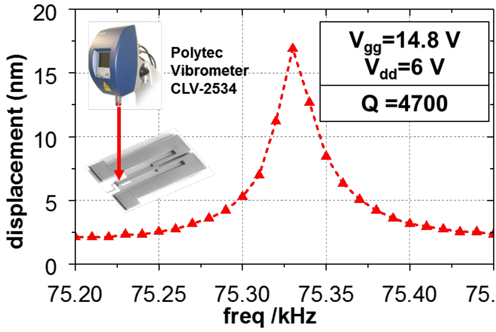


Figure 4: Measured magnitude of the AC-displacement component relative to the tip of the built RS and extracted after applying slightly lower DC-biases than used in the built WUR (Fig. 1) for P_{in}=-55 dBm.

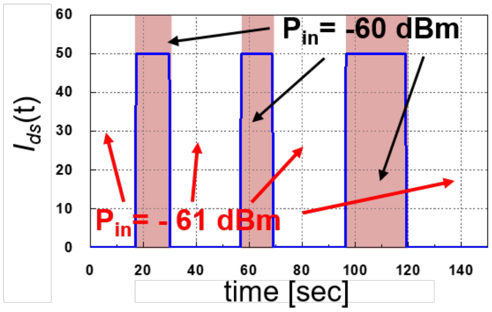


Figure 5: Measured DC-component of $I_{ds}(t)$ and relative to two P_{in}-values randomly swept over few testing cycles. The current value was mostly limited by the high input impedance (>1 MΩ) of the adopted current meter.

The described WUR were also analyzed through a novel *ad-hoc* circuit simulation platform capturing both the electrical behavior of the *ED* and the electromechanical nonlinear behavior of the built *RS*. We report in Fig. 6 the simulated trend of the displacement magnitude relative to the *RS*-tip vs. P_{in}. As evident, the simulated and measured P_{min}-values match closely, further demonstrating the effectiveness of our simulation approach in predicting the complex nonlinear electromechanical behavior of the built WUR.

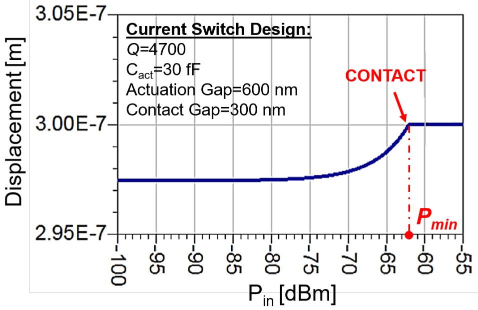


Figure 6: Simulated displacement relative to the tip of the built RS for P_{in}-values ranging from -100 dBm to -55 dBm.

CONCLUSIONS

In this paper, the first fully-passive RF wake-up receiver with zero standby power, high sensitivity and low system complexity was demonstrated. The reported results show its potential as the enabling technology for "Asleep-yet-Aware" ultra-low-power RF systems.

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