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Toward an Energy-Autonomous Wearable System for Human Breath Detection

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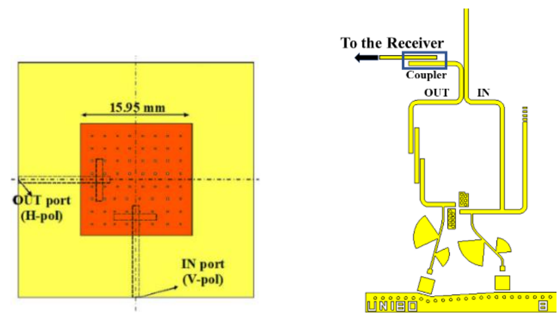
***Abstract*—This work presents a research about a 5.8 GHz system for vital signals monitoring, specifically human breath. The system consists of two main components: a Self-Injection Locked Oscillator (SILO), whose input and output ports are aperture-coupled to a dual-polarized patch antenna, and a passive receiver, coupled to the SILO output port, consisting of the cascade connection of a peak detector and a full-wave RF-to-DC rectifier. The SILO generates the carrier, that is frequency-modulated by chest displacements and backscattered to the SILO itself. The latter is loosely coupled to the passive receiving sub-system. In this way, the SILO output signal is simultaneously demodulated by the detector, and DC-converted to provide energy for the wireless communication of the received vital signals, e.g. by means of an IoT (Internet of Things) low-power node. The system is designed for being fully wearable; it can be mounted inside a plastic case and worn by the user under test at chest-level position. Critical breath rates can be detected and sent to a caregiver, thus enabling monitoring of chronic diseases, such as bradypnea or tachypnea, while performing a normal life.**

Keywords—SILO, eHealth, breath detection, wearable, SWIPT, rectifier.

I. Introduction

Contactless technologies for health monitoring are recently investigated massively for their results and benefits, e.g. for vital signals detection while performing a normal life at home or in clinical environments. Moreover, by means of radar techniques, the detection of sub-centimeter displacements enables heartbeat or breath monitoring by processing the backscattered wave in frequency, phase, and time of arrival, thus allowing to measure motion speed, breath or heart rate [1]. Very interesting solutions have been proposed based on a suitable implementation of the Self-Injection Locking (SIL) radar technique [2]. Wearable short-range sensors have a great interest for various biomedical areas due to their sub-centimeter accuracy, low energy consumption, robustness, and cost; furthermore, thanks to the development of integrated circuits, actual radar systems are characterized by small weight, little dimensions, and high efficiency [3].

This paper expands a previous work about a 5.8 GHz self-injection locked active antenna (Fig. 1 (a)) for breath monitoring [4] to realize a fully wearable, energy autonomous solution.



(a) (b)

Fig. 1. (a) Front and (b) bottom view of the self-injection-locked oscillator, with the quarter-wavelength microstrip coupler to be connected to the sensor receiving part.

In the previous experimental studies, the FM (Frequency-Modulated) reflected signal transmitted by the SILO was received by a UWB (Ultra-Wideband) antenna, placed at one-meter distance from the subject, connected to the spectrum analyzer and was able to transduce the chest movement from oscillation frequency variation with sufficient accuracy. In this work, a wearable and simple solution for the receiving sub-system is proposed, by a quarter-wavelength microstrip coupler (Fig. 1 (b)) coupled with the SILO output path and connected to a passive demodulator/rectifying circuit. In this way the signal processing is carried out in real-time and on board (Fig. 2). The idea is to support the overall energy requirements of the system, as will be described in the following, although the full energy autonomy is not reached yet. In the present system realization, the oscillator biases come from a unique 3.7 V battery and are controlled by a low-power voltage regulator, unlike before when they were connected to a DC generator for feeding the drain and the gate voltages at 3.7 V and 0.6 V, respectively, making available an output power of 13 dBm at 5.8 GHz [5].

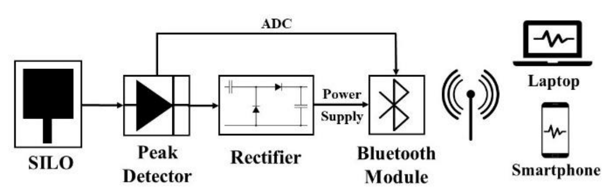


Fig. 2. Block diagram of the entire system for simultaneous energy harvesting and breath detection.

II. SWIPT Circuit for Breath Rate Detection

A. *Design of the Passive Peak Detector*

Once the SILO transmits the RF (Radio Frequency) wave, the reflected one is phase, frequency, and amplitude modulated by the chest movements; thus, the baseband signal can be acquired by frequency or amplitude demodulation techniques.

In [3], a similar system is proposed where the SIL and the frequency demodulation can be realized by means of integration and derivation sub-circuits, respectively. Indeed, the first-order differentiator straightforwardly allows to derive time variations of a biomedical signal; the differentiator output is then connected to an active peak detector and to a baseband amplifier.

Conversely, in this work the demodulation procedure is carried out by adopting a fully passive peak detector of the 5.8 GHz signal modulated by the user's chest displacement, in order to achieve a proper SWIPT (Simultaneous Wireless Information and Power Transfer).

The simple peak detector circuit schematic, including the component values, is reported in Fig. 3: its load is chosen equal to 2.3 kΩ, emulating a Bluetooth chip that will be connected afterwards to send the detected data.

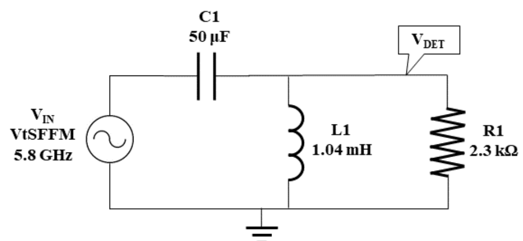


Fig. 3. Circuit schematic of the peak detector to be weakly coupled to the SILO output with the aim of detecting the breath rate of the subject under evaluation.

As shown in Fig. 3, the output SILO signal (represented as input voltage V_{IN} at the receiver circuit) is modelled by a frequency modulated voltage source (VtSFFM), with the carrier frequency of 5.8 GHz, the frequency modulating signal corresponding to the breath rate (i.e., 0.27 Hz for 16 breaths/min), and the modulation index *h* equal to:

$$h = \frac{\Delta f}{f_m} \quad (1)$$

where Δf is the maximum deviation of the instantaneous frequency from the carrier frequency (about 10 MHz in this case) and f_m is the highest frequency component belonging to the modulating signal.

B. *Design of the RF-to-DC Rectifier at 5.8 GHz*

With the aim of further exploiting the RF SILO output power to power supply a Bluetooth radio placed on board of the sensor, a full-wave (or voltage-doubler) rectifying circuit at 5.8 GHz has been designed and placed downstream of the peak detector.

The typical circuit schematic of the full-wave RF-to-DC rectifier [6], including the passive components values, is represented in Fig. 4. The two diodes are the Skyworks SMS7630-079LF; the rectifier load is R_{LOAD}=0.51 kΩ, representing the optimum load for a buck-boost DC/DC converter (i.e., Texas Instruments bq25570), that has been chosen due to its specific behavior for harvesting energy from low-voltage, low-power sources (down to 100 mV and 15 µW).

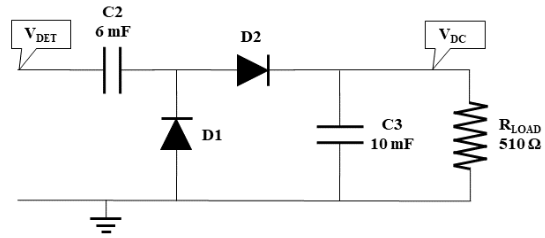


Fig. 4. Layout of the voltage-doubler rectifier at 5.8 GHz.

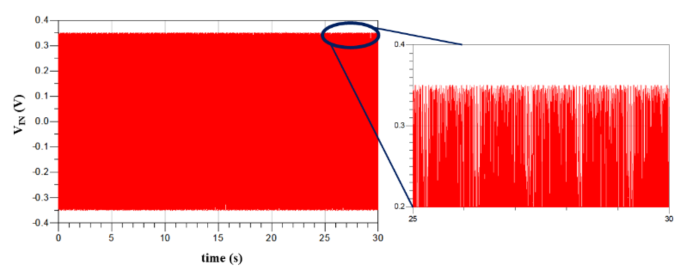
III. Circuit Simulation Results

First, a transient simulation of the system of Fig. 3 is carried out, with an ideal sinusoidal voltage source of amplitude V_{IN}=0.35 V at 5.8 GHz, frequency-modulated by a signal with h=10˙000 and f_m=1 Hz, to emulate realistic tachypnea in adult subjects (typical values: from 30 to 60 breaths/min).

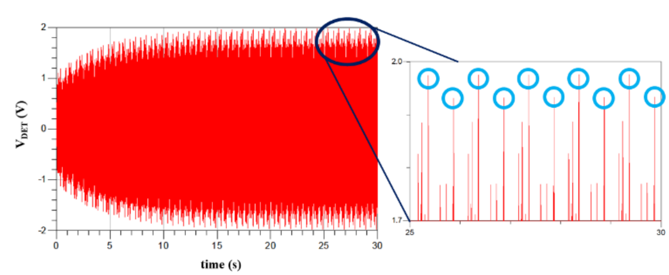
Figs. 5 (a) and 5 (b) show the waveforms of V_{IN} and V_{DET} respectively, for a time duration of 30 seconds. In this case, for every period (1 second) of the modulating signal, it is possible to notice two peaks, one for the inhalation and one for the exhalation, which have been highlighted in Fig. 5 (b) in order to demonstrate that the adopted topology is able to detect the breath rate at 1 Hz.

The same situation occurs for a respiratory rate of 0.5 Hz (30 breaths/min), as it is possible to distinguish from the peaks in the last five seconds of the simulation reported in Fig. 5 (c).

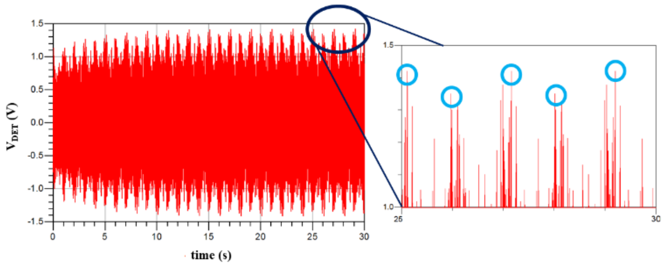
It is worth mentioning that the callouts for the last 5 seconds are shown in order to emphasize peaks that can however be noticed also for the previous 25 seconds of the simulation.



(a)



(b)



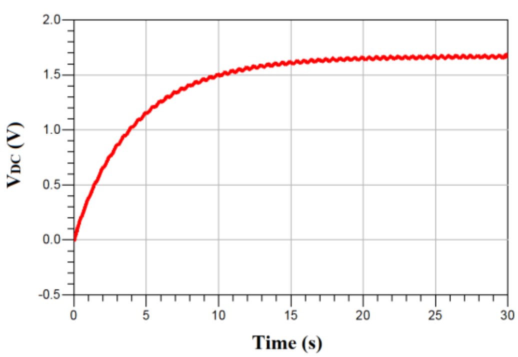
(c)

Fig. 5. Simulated behaviour of (a) V_{IN}, and V_{DET} for a transient simulation of 30 seconds and considering a modulating signal (breath) of (b) 1 Hz and (c) 0.5 Hz. The callouts show the difference between the waveforms of V_{IN} and V_{DET} for detecting the peaks of the modulated signal, corresponding to inhalations and exhalations.

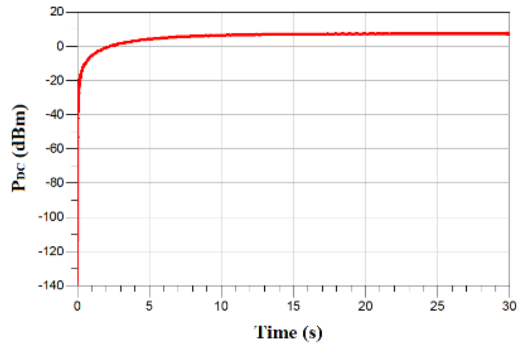
In a second step, in order to predict the energy harvesting capabilities of the proposed system, the peak detector is loaded by the rectifier and the whole system is analyzed in steady-state conditions, by means of the HB (Harmonic Balance) technique with the same sinusoidal excitation spanning the frequency band of interest (from 5.79 to 5.81 GHz), covered by the modulated signal representing the breath rate. No significant performance variations have been observed all over the band. The predicted DC output power is 7.6 dBm, for a RF input power of 10 dBm, resulting in a RF-to-DC efficiency of 57.8%. Similar results have been obtained by the time-domain simulation of the whole circuit, under modulated conditions: in this latter case, the computed DC output power is 7.4 dBm. Conversely, adopting the same circuit for a simulation in the time domain performed with modulating signal at 0.5 Hz, the DC output power drops at 1.4 dBm.

Figs. 6 (a) and 6 (b) show the transient behavior of the system DC output in terms of V_{DC} and P_{DC}, respectively. In particular, considering the breath rate at 1 Hz, a V_{DC} of 1.68 V and a P_{DC} of 5.5 mW are obtained after a transitory time of 15 seconds, perfectly in line with the minimum levels enabling the operation of the modern buck-boost DC/DC converters mentioned in Section 2.

As regards information concerning simulation times, the HB with 4 harmonics took only 5.38 seconds, whereas a transient simulation of 30 seconds (maximum time step: 1 ms) lasts 7 seconds.



(a)



(b)

Fig. 6. Simulated values of (a) V_{DC} and (b) P_{DC} in the time domain for a 30 seconds transient simulation.

IV. Conclusion

In this work, the design of a circuit for simultaneous wireless information and power transfer has been presented. In particular, the effectiveness of a fully passive peak detector consisting of only two passive components (capacitor and inductor), has been demonstrated.

Moreover, part of the signal coming from the SIL oscillator can be pulled from the output port and also harvested in order to guarantee, for example, the feeding of a microcontroller and a Bluetooth module to be integrated in the same board, in order to send the information concerning the breath rate of the subject under test.

Future work previews the practical realization of the prototype and measurement campaigns in order to substantiate these allegations, and the subsequent inclusion of the SWIPT circuit in the same SILO wearable device.

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