Design and Analysis of Harmonic Tag with RF Energy Harvesting Circuit

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Abstract—**In this paper, the design and analysis of a harmonic tag with an RF energy harvesting circuit is performed. In the first research stage, a low power passive harmonic tag has been designed at 2.45/4.9 GHz whose main function is to receive the fundamental signal and transmit harmonics. In the second stage, an RF energy harvesting circuit is designed at 2.45 GHz by using voltage doubler RF rectifier. Additionally, a diplexer was inserted between the harmonic tag and the RF energy harvesting circuit to separate the fundamental signal from the second harmonic. Impedance matching is performed between the antennas and the harmonic tag, as well as between the harmonic tag and the RF rectifier, with aim to obtain maximum power transfer. Results accomplished by ADS simulations for different input power levels provide a performance evaluation of the harmonic tag and the RF energy harvesting circuit in terms of RF-DC conversion efficiency, DC power, and second harmonic power. For the observed input power levels (-20 dBm to 10 dBm), the gained RF-DC conversion efficiency varies between 7 % and 17 %, the output DC voltage varies between 0.1 V and 3.6 V, while the second harmonic power goes from -61 dBm to -3 dBm.**

Keywords—**Harmonic tag, Schottky diode, Voltage doubler, RF rectifier, RF energy harvesting.**

I. Introduction

Harmonic tags are wireless devices that exploit nonlinear components to generate and reflect signals at harmonic frequencies of the incident signal. Their ability to operate at harmonic bands enables effective clutter suppression and interference reduction, making them especially useful in environments where conventional backscatter systems encounter difficulties. Harmonic tags have been predominantly utilized for RF-based identification and tracking of animals and insects [1]. In the last decades, these tags also show potential for broader applications, including cardiopulmonary monitoring and motion analysis [2-6].

In recent years, wireless power transfer and electromagnetic energy harvesting have appeared as significant areas of scientific research, due to the increasing demand for sustainable energy solutions in low-power electronic systems. These technologies offer energy supply to devices without the need for wired connections or conventional batteries. One of the most significant applications lies in the biomedical field, where they can be utilized in surgical procedures, body-wear sensors and implantable sensors that operate at low power levels. The key component in the RF energy harvesting circuit is the RF rectifier, which converts received radio frequency (RF) energy into direct current (DC) power [7-11].

The objective of this paper is to design and estimate the performance of the harmonic tag with the RF energy harvesting circuit using the Keysight Advanced Design System (ADS simulator). The tag may be used in the system Doppler radar-harmonic tag for the vital human signs detection, whereas the energy harvester enables DC power for the tag or for some other sensors tracking body parameters. The design method comprises two textile patch flat antennas operating at 2.45 GHz and 4.9 GHz, the harmonic tag consisting of a nonlinear component-Schottky diode which generates harmonic frequencies and operating at 2.45/4.9 GHz, the frequency diplexer, and the RF energy harvesting circuit consisting of the voltage doubler RF rectifier and operating at 2.45 GHz. Also, to ensure maximum power transfer, it was necessary to apply adequate impedance matching between the antennas and the harmonic tag, as well as between the harmonic tag and the RF rectifier. The range of the input power levels (Pin) chosen for the simulations varies from -20 dBm to 10 dBm, but all impedance matching in the harmonic tag and the RF energy harvesting circuit is performed for the 0 dBm input power by using ADS single-stub element and impedance matching tool. Some of the main ADS simulation results point out the generated second harmonic power, RF-to-DC conversion efficiency, and harvested DC power.

II. Harmonic Tag with RF Energy Harvesting Circuit

The antenna operating at 2.45 GHz receives an incident signal from some transmitter such as the Doppler radar [2, 5] and transfers it to the harmonic tag consisting of a nonlinear component, such as a Schottky diode, which generates harmonic frequencies. The fundamental signal (at 2.45 GHz) is directed through the upper branch of the diplexer (Fig. 1) to the RF energy harvesting circuit, while the second harmonic (at 4.9 GHz) is extracted via the second branch of the diplexer and can be transmitted back to the Doppler radar through a secondary antenna operating at 4.9 GHz. The RF energy harvesting circuit includes a RF rectifier that converts the fundamental RF signal into direct current (DC) power. In order to assess topology performance, the power of the second harmonic generated at the tag output is analyzed as well as the harvested DC voltage, power and the RF-DC conversion efficiency at the output of the RF energy harvesting circuit by using the ADS software.

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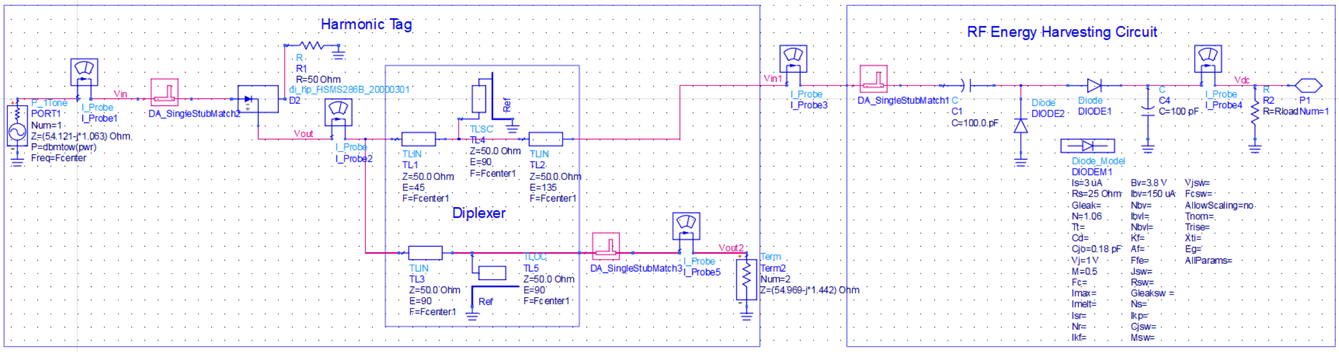


Fig. 1. ADS design schematic of harmonic tag with RF energy harvesting circuit.

A. Harmonic Tag Design

The principal functions of a harmonic tag are: efficient reception of incident radiation at the fundamental frequency, generation of harmonic frequency components from the received fundamental signal, and effective retransmission of the second harmonic back to the reader.

To ensure efficient reception of incident radiation by the harmonic tag, the tag antenna must be impedance-matched to the diode at the fundamental frequency of 2.45 GHz [5]. The main function of the diode is the generation of the harmonic signals, which depends on the selected Schottky diode and its nonlinear characteristics. To enable efficient transmission of the generated harmonic signals, the tag transmitting antenna should also be matched with the diode output at the second harmonic frequency, 4.9 GHz.

The textile flat patch antennas [12, 13], whose parameters were obtained by simulation using an in-house TLM solver [14], were used for the harmonic tag design. The antennas are designed on a substrate with relative permittivity $\varepsilon_r = 2.1$, and substrate thickness, h = 2 mm. For the first antenna, whose resonant frequency is 2.45 GHz, the length of the radiation patch is l = 39.5 mm, while the width of the radiation patch is w = 50 mm. The length of the substrate (L) and the width of the substrate and ground plane (W), are $W = L$ = 100 mm. While for the second antenna with a resonant frequency of 4.9 GHz, l = 19.45375 mm, w = 24.625 mm, $W = L$ = 50 mm. The gain of the tag antennas is 7.849 dBi and 8.36dBi at fundamental and second harmonic frequencies, respectively. The antennas impedances at fundamental and second harmonic frequencies are (54.121-j1.063) Ω and (54.969-j1.442) Ω, respectively.

The S-parameters of the tag antennas were exported and utilized in the ADS simulator by Large-Signal S-Parameter (LSSP) simulation of the antenna–diode configuration, providing the S-parameters of the complete tag.

The Avago's HSMS 286B Schottky diode was selected for the harmonic tag, and LSSP analysis was conducted for 0 dBm input power level of the fundamental signal at 2.45 GHz [5].

To achieve optimal design, impedance matching between the antennas and the diode is required at both the fundamental and harmonic frequencies. The diode input impedance at fundamental frequency is (234.359-j83.720) Ω while its output impedance at the second harmonic is (64.612-j158.832) Ω. Impedance matching was performed with the LC elements and also by using the ideal transmission lines (TL). In this research, we chose the transmission line matching because it gives better results.

Between the harmonic tag and the RF energy harvesting circuit, a frequency diplexer was inserted to separate the fundamental signal and the second harmonic. The ADS design schematic in Fig. 1 combines harmonic tag, diplexer and RF energy harvesting circuit. The input power and the impedance of the tag antenna at 2.45 GHz are given as source parameters. The generated harmonic powers, observed at the output of the tag terminated by the transmitting antenna impedance, are obtained by Harmonic Balance simulation.

B. RF Energy Harvesting Circuit Design

The standard architecture of the RF energy harvesting system includes an antenna, impedance matching circuit, an RF rectifier, and a load [9]. The RF energy is captured by the receiving antenna and directed through an impedance matching network, designed between the antenna and the RF rectifier, which converts the RF signal into a DC output.

In this paper, the RF energy harvesting circuit was designed to operate at 2.45 GHz and include the impedance matching of the RF rectifier with the previously designed harmonic tag. For the impedance matching, LSSP parameter analysis is applied, while for obtaining the RF-DC conversion, DC output power and voltage, Harmonic Balanced analysis is utilized.

The RF energy is received by the antenna operating at 2.45 GHz and sent through an impedance matching network to the harmonic tag, after which the fundamental signal is extracted via upper branch of the diplexer and directed to the RF rectifier through another impedance matching network, as shown in Fig.1. In the RF energy harvesting circuit, a single-stub TL impedance matching network is inserted between the harmonic tag and the RF rectifier. This TL network matches the output impedance of the harmonic tag including the upper branch of the diplexer (215.438-j154.337) Ω to the RF rectifier input impedance (29.864-j194.045) Ω at 2.45GHz.

The input RF signal is converted to DC voltage by the voltage doubler RF rectifier, which consists of two HSMS 285x Schottky diodes and two capacitors [10].

Fig. 2 gives the simulated S_{11} of the designed RF energy harvesting circuit, showing a resonance at 2.45 GHz with a minimum value of approximately -10 dB.

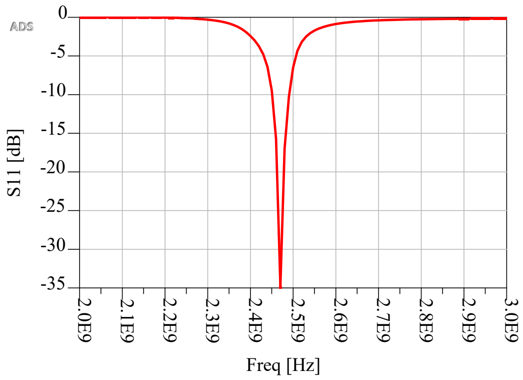
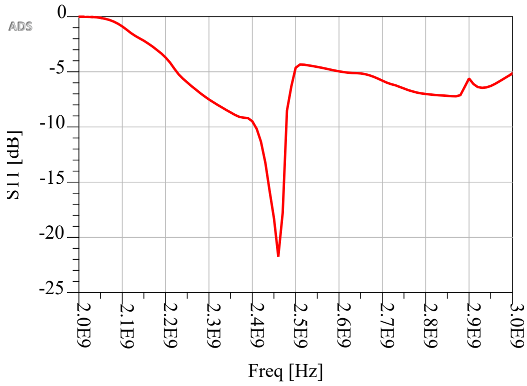


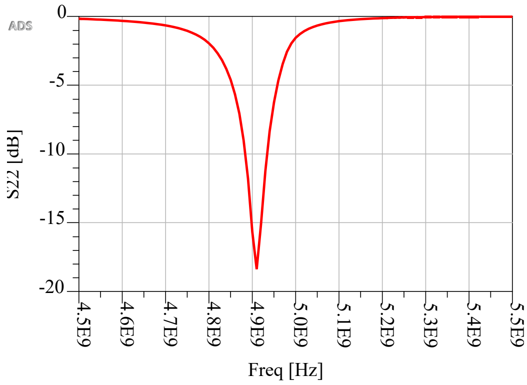
Fig. 2 S_{11} parameter of RF energy harvesting circuit.

III. Results

The designed harmonic tag with the RF energy harvesting circuit was assessed in the ADS simulator for various input power levels (Pin) from -20 dBm to 10 dBm and a load resistance of 10 kΩ.



(a)



(b)

Fig. 3. a) S_{11} and b) S_{22} parameters for harmonic tag with RF energy harvesting circuit.

The S-parameter analysis results are represented in Fig. 3 for 0 dBm Pin. Figure 3a) shows the simulated S_{11} parameter of the overall circuit consisting of the harmonic tag and the RF energy harvesting circuit, showing a resonance at 2.45 GHz with a minimum value of -18 dB, while Fig. 3b) illustrates the simulated S_{22}, showing a resonance at 4.90 GHz with a minimum value of -15 dB.

Figure 4 shows the power of the second harmonic ($Pout_{2h}$) generated at the output of the harmonic tag at the input of the transmitting antenna operating at 4.9 GHz characterized with gain of 8.36 dBi. The second harmonic power goes from -61 dBm to -3 dBm for the observed Pin span, and reaches -15 dBm at 0 dBm Pin.

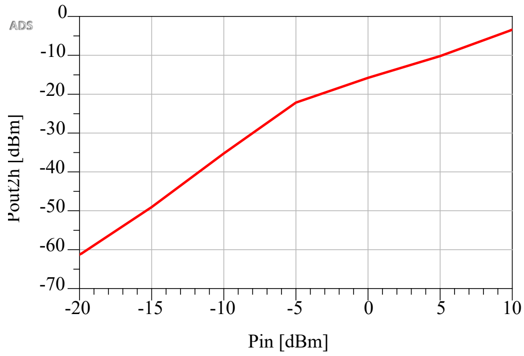


Fig. 4. Second harmonic power.

The input power (PinEH) of the RF energy harvesting circuit is presented in Fig. 5. The PinEH, for the observed input power levels from -20 dBm to 10 dBm, is in the range from -20 dBm to 5.8 dBm, where for Pin of 0 dBm, has a value of -4 dBm.

Figure 6 shows output DC power (Pdc) and output DC voltage (Vdc) of the RF energy harvesting circuit as a function of the input power (Pin), respectively. The Pdc, for the observed input power span, is in the range from -31 dBm to -2 dBm and, and for 0 dBm Pin, the output DC power has a value of -9 dBm. The Vdc varies between 0.1 V and 3.6 V for the observed Pin range, while for 0 dBm Pin, the Vdc is around 1.5 V.

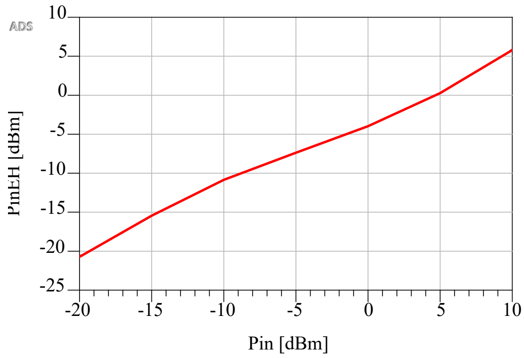


Fig. 5. Input power of RF energy harvesting circuit.

Figure 7 represents the RF-DC conversion efficiency of the RF energy harvesting circuit, EffEH (red curve), and the RF-DC conversion efficiency of the complete circuit-harmonic tag with the RF energy harvesting circuit, Eff (blue curve). Within the observed Pin range, EffEH goes from 9 % and reaches maximum of 32 % at 5 dBm Pin, and after that decrease to 17 % for 10 dBm Pin. The Eff reaches its maximum of 17 % for -10 dBm Pin, drops to 12 % for 0 dBm Pin, and further declines to 7 % for the highest Pin level.