Rectenna for Bluetooth Low Energy Applications

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***Abstract*—In this paper, we propose an efficient rectenna design for Bluetooth low energy (BLE) applications targeting the 2.4 GHz ISM band. A miniature meandered planar Inverted-F antenna (MIFA) was designed, simulated, fabricated, and measured, achieving good matching with small profile. In addition, a single-diode rectifier circuit was optimized at -20 dBm input power to convert the radio frequency (RF) energy captured by the antenna into DC power. Simulation results for the rectifier circuit show that it maintains a high RF-to-DC conversion efficiency. Using ideal components, an efficiency of 36% can be achieved at -20 dBm input power. When the non-idealities are considered in the rectifier, an efficiency of 20% at -20 dBm input power can be obtained.**

***Index Terms*—Rectenna, Energy Harvesting, Bluetooth Low Energy (BLE)**

I. Introduction

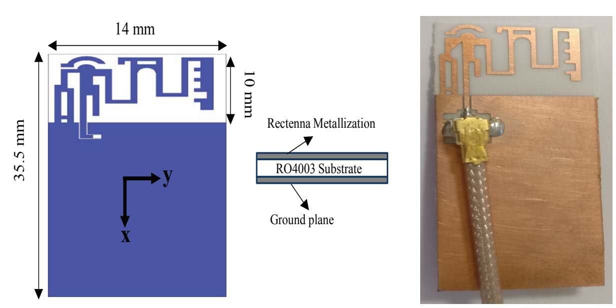
The Internet of Things (IoT), envisioning to connect massive devices, has been gaining momentum [1]. The explosive growth of IoT devices, on the other hand, raises challenges facing the long-term maintenance such as battery replacement. To tackle this issue, some low-power communication protocols like Long Range (LoRa) and Bluetooth Low Energy (BLE) are widely used for IoT networks. In the light of the intermittent nature of most sensor communications, it is even possible to solely rely on the energy harvested from ambient radio frequency (RF) signals for system operation, totally eliminating the requirement of batteries and associated maintenance. Most reported RF energy harvesting systems are focused on two bands, namely, the frequency band around 900 MHz where the commercial UHF RFID systems operates and the Industrial Scientific-Medical (ISM) 2.4 GHz band [2]. For some domestic indoor applications, the ISM 2.4 GHz band is more attractive as billions of devices such as mobile phones and small home appliances are equipped with BLE.

Recently, BLE has been investigated for low-power backscattering communications [3]. However, a battery is still required. Having a miniature efficient BLE rectenna remains a promising area for improvement. In this paper, the efforts of designing an efficient RF energy harvester in BLE applications are made. Reasonable performance, in terms of system profile and energy conversion efficiency, has been obtained by simulation. The designed rectenna, separated into antenna and rectifier circuit, is discussed in Sections II, III, respectively. Section IV discusses the rectifier layout and Section V concludes the paper.

II. Antenna

We choose meandered planar Inverted-F antenna (MIFA) in our design due to its small size, low profile, easy fabrication and integration on PCB boards. This makes it a good candidate for BLE antenna applications. This type of antenna is miniaturized by introducing meander lines, slots, and slits in order to increase the effective electric length of the current path, and thus, miniaturize the antenna as in [4]. Fig. 1a presents the front-view and the cross section of the designed MIFA whose dimensions are 14 mm $\times$ 35.5 mm $\times$ 0.203 mm. It consists of a ground plane, a radiating planar meander-type IFA antenna, a 50 Ω coplanar waveguide (CPWG) transmission line to connect the feed arm of the MIFA to the matching network of the subsequent rectifier section. The antenna was fabricated as shown in Fig. 1b on the dielectric substrate RO4003C of ϵ_r = 3.38 and $\tan\delta$ = 0.0027.

The antenna was designed and simulated using Ansoft HFSS V. 14 software. The optimal parameters were obtained using Genetic Algorithm (GA) optimization method. The reflection coefficient of the fabricated antenna was measured between 2.0 GHz and 3.0 GHz using an Agilent vector network analyzer (VNA). The simulated (dashed curve) and measured (solid curve) reflection coefficient S_{11} of the proposed rectangular MIFA is depicted in Fig. 2. It shows a good agreement between the measured reflection coefficient and simulated reflection coefficient. A 164 MHz (2.371-2.535 GHz) bandwidth is achieved, covering the entire 2.4 GHz ISM band. The simulated radiation pattern of the proposed antenna is illustrated in the inset of Fig. 2. Though the gap between the meandered line and the ground is small, it characterizes omnidirectional pattern in the y-z plane with good gain of 2.14 dBi and high radiation efficiency of 96.8%.



(a) The designed MIFA. (b) The fabricated MIFA.

Fig. 1: Configuration of the proposed MIFA.

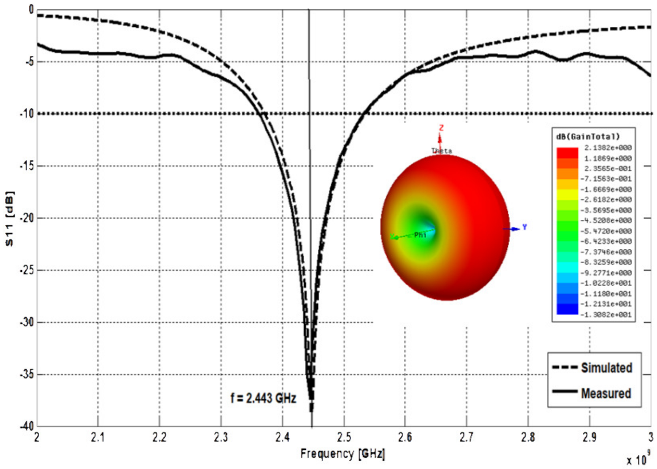


Fig. 2: Measured and simulated reflection coefficients versus frequency for the designed MIFA. Inset: plot of the 3D antenna radiation pattern

III. Rectifier Design

A single-diode rectifier was designed and simulated to achieve a high RF-to-DC conversion efficiency in the BLE operation band (2.4-2.48 GHz). This frequency band features other ambient RF sources such as Wi-Fi signals that can also be harvested. Since we consider harvesting energy from these ambient signals, the rectifier circuit should be optimized for maximum efficiency at very low input power levels. For this reason, we selected a single-diode configuration and optimized our energy harvester to achieve the maximum possible efficiency at -20 dBm input power. Designing an efficient rectifier at such a low input power is a major challenge due to the losses and the highly non-linear behavior of the diode element [2]. The rectifier circuit as shown in Fig. 3 consists of three main blocks; a matching network, a diode followed by a low-pass filter. Diode selection is critical, which has great impact on rectifier efficiency. SMS7630-079 Schottky diode was selected for the design due to its low turn-on voltage and low junction capacitance.

Following the design approach described in [5], GA is applied to optimize the rectifier microstrip dimensions and the values of the lumped elements. The optimization goals were set to achieve high RF-to-DC conversion efficiency and low reflection coefficient simultaneously. The same RO4003C substrate was used for the rectifier design. The optimized microstrip dimensions are labelled in Fig. 3. The optimized values for L_1, C_1, C_2 and R_L are 10 nH, 3 pF, 100 pF and 9 kΩ, respectively. Harmonic Balance (HB) and Large Signal S-parameters (LSSP) tools in Keysight ADS were used for simulating the rectifier. The simulated RF-to-DC conversion efficiency $\left(\frac{P_{DC}}{P_{RF}} \times 100\%\right)$ and the input reflection coefficient S_{11} for the designed rectifier circuit are plotted in Fig. 4. It can be observed that the rectifier circuit can achieve relatively high efficiency $> 31\%$ from 2.4 GHz to 2.46 GHz with a maximum efficiency of 36.4% at 2.43 GHz. The rectifier is well matched for the whole band. To this end, the inductors and the capacitors are assumed to be ideal. In the next section, we will discuss the rectifier layout and also include the non-idealities in the design.

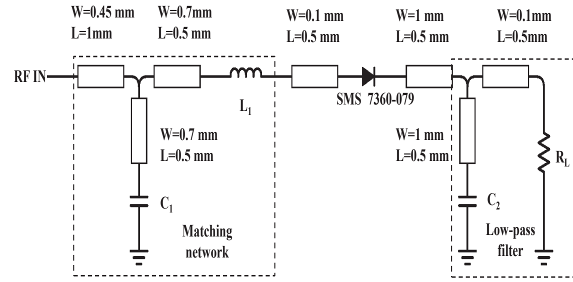


Fig. 3: Schematic of the designed rectifier circuit.

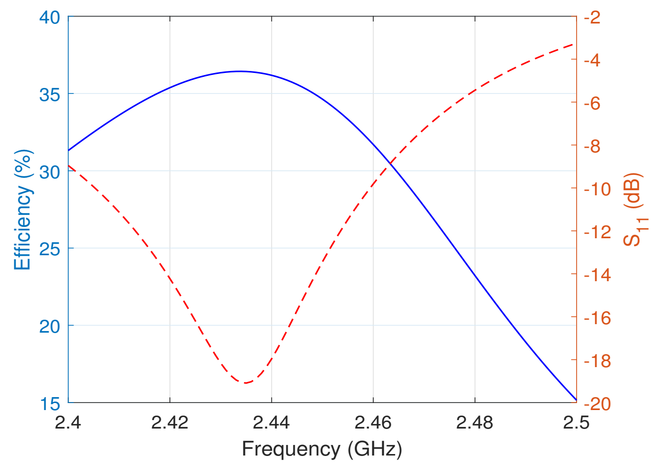


Fig. 4: Simulated rectifier efficiency and reflection coefficient vs. frequency.

IV. Optimization of the Rectifier Layout

In order to generate the rectifier layout, the footprints of all components, as well as the via holes, should be included in the design. To obtain a performance as close as possible to the manufactured prototype, the non-idealities in the circuit components (e.g., capacitors and inductors) should also be considered. Due to the sensitivity of the rectifier to non-idealties, especially at very low input power levels, a re-optimization of the rectifier circuit is necessary. Moreover, the dimensions of the antenna limits the overall size of the rectifier layout. As the ground plane of the MIFA is on the top layer, the rectifier is manufactured on the bottom layer. The position of the vias connected to the feeding line of the antenna in addition to the vias at the ground of each component should be taken into consideration.

Following the above discussion, the rectifier layout is shown in Fig. 5. The degrees of freedom for the GA optimization are: L_1, C_1, R_L, in addition to the transmission lines widths and lengths. We fixed C_2 to 100 pF as before. Again, the goal of the GA is set to simultaneously achieve good matching and

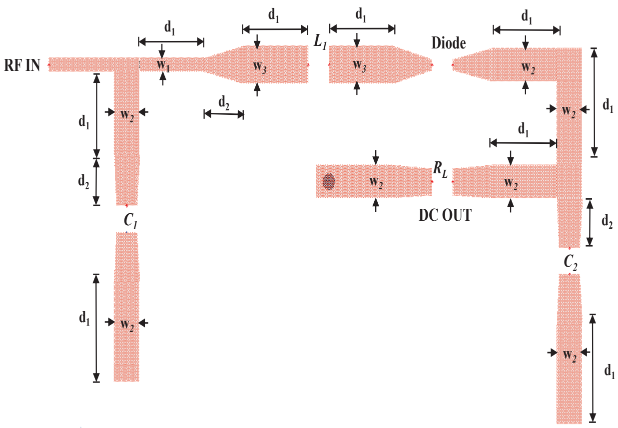


Fig. 5: The rectifier layout.

high RF-to-DC conversion efficiency. The optimized values are summarized in Table. I.

TABLE I: Optimized dimensions and components.

$w_1 = 0.425$ mm
$w_2 = 1$ mm
$w_3 = 1.12$ mm
$d_1 = 2.5$ mm
$d_2 = 1.5$ mm
$L_1 = 1.6$ nH
$C_1 = 1.5$ pF
$R_L = 4\,\mathrm{k\Omega}$

A study of the RF-to-DC conversion efficiency vs. R_L is shown in Fig. 6 at -20 dBm input power. It can be observed that after including the rectifier non-idealities, the efficiency is maximized when $R_L = 4\,\mathrm{k\Omega}$. The obtained efficiency is around 20% which is lower than the case of ideal circuit components discussed in the previous section. Although the efficiency decreases when the layout is generated, it is still high at $P_{in} = -20\,\mathrm{dBm}$ compared to other rectifiers existing in the literature [2, Table. 2]. In Fig. 7, the input power to the rectifier is varied and the efficiency is observed for different frequencies. One can notice that as the input power to the rectifier increases, the efficiency increases. A study of the reflection coefficient vs. frequency for the layout is shown in Fig. 8. It can be noticed the rectifier maintains a good matching level over the whole band.

V. Conclusions and Future Work

In this paper, a rectenna, featuring small footprint MIFA and high efficiency single-diode rectifier circuit, was designed. The simulation results showed good performance for the BLE 2.4 GHz operation. The authors are continuing optimizing rectifier circuits. The entire design, with the MIFA and the rectifier circuit integrated, is currently under fabrication, and the measured results will be compared with other reported designs during the conference. The designed rectenna will ultimately achieve power autonomy for many BLE sensors, especially the BLE backscattering nodes.

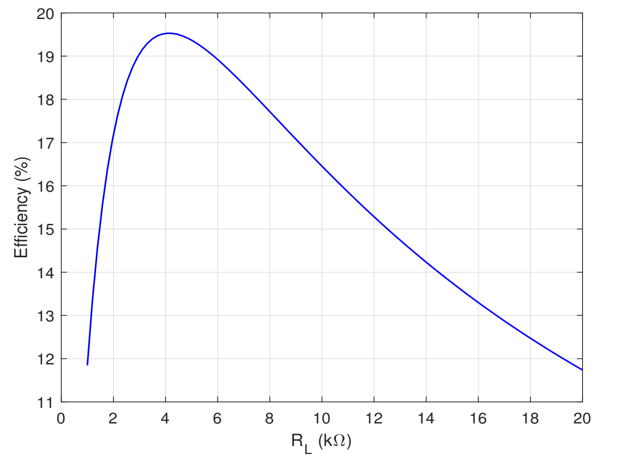


Fig. 6: Simulated rectifier efficiency vs. the output resistance (R_L) at $P_{in} = -20\,\mathrm{dBm}$.

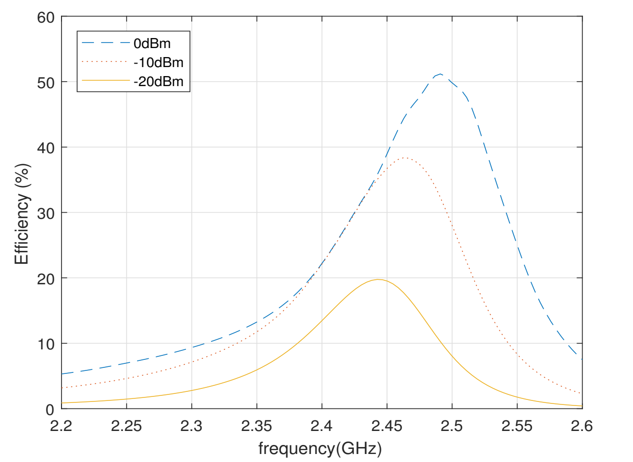


Fig. 7: Simulated rectifier efficiency vs. frequency at different power levels.

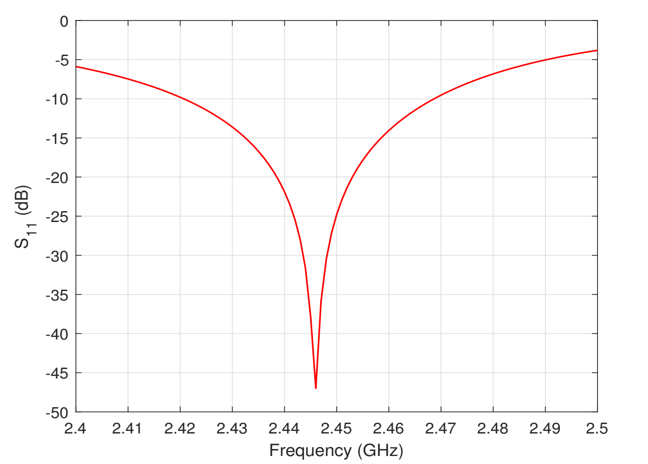


Fig. 8: Simulated reflection coefficient for the optimized layout vs. frequency at $P_{in} = -20\,\mathrm{dBm}$.

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