# An UHF rectifier with 100% bandwidth based on a ladder LC impedance matching network

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***Abstract*—In this paper an efficient for low power input, low-cost and low-complexity rectifier is designed and simulated including component and layout parasitics. The rectifier consists of a charge pump and a ladder LC matching network. It has also a wideband RF-dc conversion efficiency which remains constant within ±2% from 300 MHz to 900 MHz. The rectifier was based on two commercial off-the-shelf Schottky diodes and low cost paper substrate was used for the layout. Three ladder LC impedance matching were simulated and it was verified that by increasing the number of LC sections to three, it is possible to cover the desired frequency bandwidth.**

## I. Introduction

In the recent years, the number of ambient radio frequency (RF) emitters has increased dramatically. Around us there are many transmitters such as GSM, TV, FM, stations and WiFi routers. In addition to the communication purpose, those ambient signals can be used for power supply small low power devices such as sensors [1]. These devices could collect their energy employing an RF harvesting technique in order to extent their operation, or operate without batteries [2], for example by charging small capacitors. The RF harvesting in farfield is achieved with rectifiers and antennas. Each rectifier consists of a matching network and a charge pump for RF-dc conversion.

Research efforts have been made for the design of multiband rectifiers [3]. Wideband rectifiers operating over an octave bandwidth have been proposed in the recent literature based an non-uniform transmission line [4] and based on synchronous rectifier designs [5]. The passive design of [4] has a more uniform RF-dc conversion efficiency over its operating band for a wider input power range. The disadvantages of a non-uniform transmission line are the potentially large length of the line and the limitation to achieve high characteristic impedance values due to fabrication tolerances. As a result the use of a ladder type LC network to implement an equivalent non-uniform transmission line circuit is explored in this work.

An efficient for low power input low-cost (paper substrate utilization), and low-complexity (double rectification system with two single Schottky diodes) rectifier is presented. The simulated RF-dc conversion efficiency including component and layout parasitics is constant within ±2% from 300 MHz to 900 MHz resulting in a 100% operating bandwidth for an input power of -20 dBm (Fig. 7). For -10 dBm the efficiency is constant within ±4% from 300 MHz to 900 MHz (average efficiency: 21.5%). The operating bandwidth includes UHF TV broadcast signals and UHF ISM band.

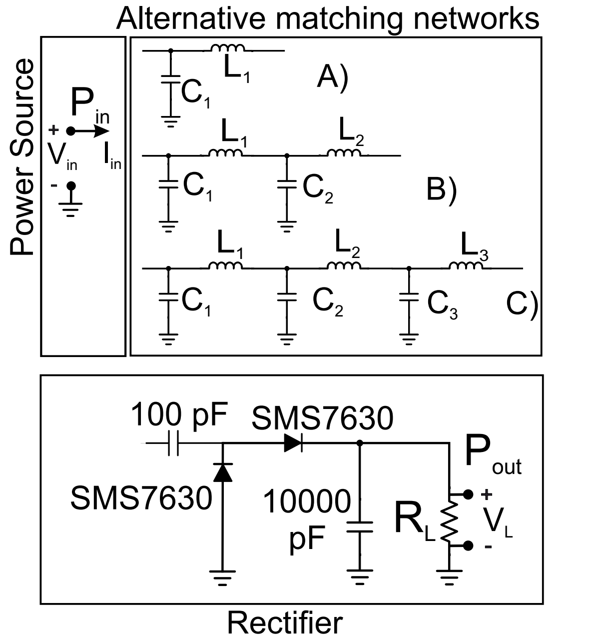


Fig. 1. Circuit diagram of the simulated rectifier design. The system consisted of the power source, the matching network and the double diode rectifier. In this work three different matching networks was simulated.

The work is summarized as follows: in Section II, the analysis of the rectifier and simulation of three matching networks is presented. In Section III, the wideband rectifier is designed and simulated. The work is concluded in Section VI.

## II. Rectifier Analysis

The Bode-Fano criterion provides the theoretical minimum reflection coefficient magnitude which can be achieved by impedance matching a parallel RC circuit such as the one corresponding to the equivalent circuit of a diode rectifier using a lossless matching network over a frequency bandwidth ($B$) [6]:

$$|\Gamma_m| \geq e^{-\frac{1}{2BRC}}. \qquad (1)$$

In this work we assumed a voltage doubler rectifier circuit with two diodes shown in Fig. 1. Harmonic balance was used to compute the equivalent parallel RC circuit of the

TABLE I
OPTIMIZATION COMPONENT VALUES.

| # | A) net | B) net | C) net | C) net OPT |
|---|---|---|---|---|
| $C_1$ (pF) | 0.10 | 0.194 | 0.24 | 0.5 |
| $L_1$ (nH) | 48.07 | 23.4 | 15.03 | 12 |
| $C_2$ (pF) | - | 2.10 | 3.01 | 3.6 |
| $L_2$ (nH) | - | 68.9 | 38.48 | 27 |
| $C_3$ (pF) | - | - | 1.70 | 2.5 |
| $L_3$ (nH) | - | - | 72.40 | 39 |
| $R_{\mathrm{L}}$ (kOhm) | 3.39 | 4 | 4.73 | 4.37 |

rectifier for different input power and load values and the minimum reflection coefficient was computed using 1, in order to estimate the performance of the matching network. For example, for a given input power of -20 dBm and a load resistance of 4.1 kOhm, the minimum reflection coefficient becomes $20\log_{10}(|\Gamma_m|) = -4$ dB.

Rectifier analysis was deployed with study of three different matching networks as depicted in Fig. 1. Each matching network consists of a number of cascaded LC sections. The input RF power is converted to dc power through two low-cost Schottky single diodes SMS7630 as shown in Fig. 1.

Each matching circuit reduces the reflection losses of the incoming wave, while the capacitors before and after the diodes were introduced in order to stabilize the obtained dc voltage. The capacitors were fixed at 100 pF and 10000 pF while the output power supplies a load $R_L$ at the end of following the charge pump.

The rectifier was simulated using the harmonic balance analysis of the circuit simulator Keysight ADS. An optimization process was deployed with one of the goals, the maximization of the RF-dc efficiency:

$$\eta = \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} = \frac{V_{\mathrm{L}}^2/R_L}{P_{\mathrm{in}}}, \tag{2}$$

with $P_{\mathrm{in}}$, $P_{\mathrm{out}}$ the input and output power and $V_{\mathrm{L}}$ the dc voltage across the load $R_L$. The second goal was the minimization of reflection coefficient,

$$\Gamma_{in} = \frac{Z_{in} - 50}{Z_{in} + 50}. \tag{3}$$

The input impedance $Z_{in}$ is defined as:

$$Z_{in} = \frac{V_{in}}{I_{in}}. \tag{4}$$

The optimization parameters were the inductor and capacitor components of matching network $A$, $B$ and $C$ and the load $R_L$. The optimal design component values are presented in Table I for each network separately. The circuits were designed by optimizing the RF-dc efficiency for a fixed input power of $-20$ dBm. The components of matching network depend on the output load ($R_L$) and the $P_{in}$ due to the non-linear nature of diodes. In Fig. 2 the simulated reflection coefficient for three different matching networks is depicted. It is shown that in case of $A$ the rectifier has a narrowband operation

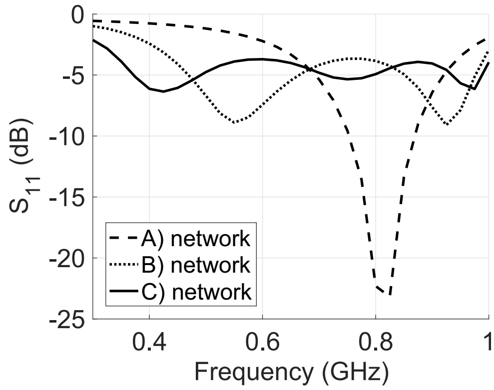


Fig. 2. Reflection coefficient at the input of rectifier for three different matching networks. Power input was fixed at -20 dBm.

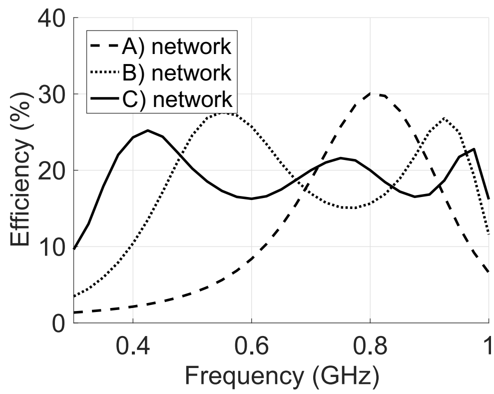


Fig. 3. Rectifier efficiency versus frequency for three different matching networks. Power input was fixed at -20 dBm.

with optimal resonance below 810 MHz. In case of $C$ the operation is wideband with a bandwidth of 600 MHz and the average reflection coefficient value has been decreased. The simulated efficiency versus frequency is depicted in Fig. 3. With the single network $A$, there is a maximum efficiency of 30% at 800 MHz. Using the $B$ and $C$, the efficiency has been decreased in a wider frequency range. The maximum efficiency of network $B$ is 27% and 26.8% for 550 MHz and 925 MHz respectively. Network $C$ achieved a maximum efficiency of 25.2% at 425 MHz. It is observed that there is a trade off between the operation bandwidth and the efficiency of rectifier. Fig. 4 shows the simulated voltage values across the 4.37 kOhm load. The voltage curves follow the efficiency curves for each matching network.

## III. OPTIMAL DESIGN

After the experimentations with matching networks, network $C$ was selected for the wideband rectifier with three inductors and three capacitors. Firstly the layout geometry of the rectifier was designed and is depicted in Fig. 5. The substrate was selected to be photo paper and was modelled with $\epsilon_{\mathrm{r}} = 2.9$, $\tan\delta = 0.045$ and substrate height 210 $\mu$m. The conductor thickness was assumed to be 3 $\mu$m, which is

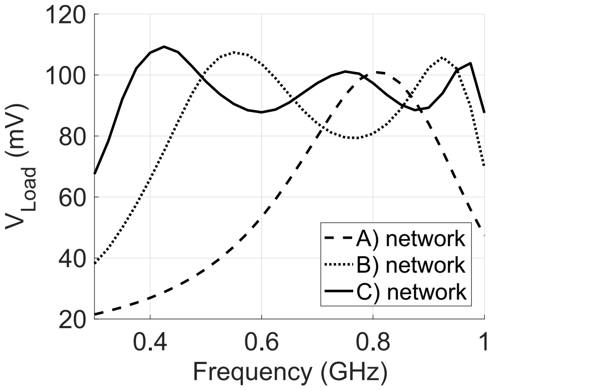


Fig. 4. Rectifier voltage across the load ($V_{load}$) versus frequency for three different matching networks. Power input was fixed at -20 dBm.

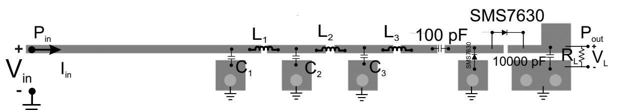


Fig. 5. The double diode rectifier layout design with lamped components.

a typical value that can be implemented with inkjet printing processes [1]. The obtained layout was simulated using the Momentum simulator of Keysight ADS in order to estimate the losses from the paper substrate, the conductor and the electromagnetic coupling between element ports. Next harmonic balance optimization was employed taking into account the non-linear behaviour of the diodes. The optimization is proposed in order to enhance the rectifier efficiency and sensitivity, for low power input. The design was optimized using equations 2 and 3 as simultaneous goals. The degrees of freedom were the matching network components $(C_1, L_1, C_2, L_2, C_3, L_3)$ and the load $(R_L)$ at the output. Following the harmonic balance optimization using the layout parasitics, the $L$ and $C$ components were progressively substituted with fixed real component values and models and the remaining components were re-optimized until all $L$s and $C$s were matched to an existing standard component. The final lumped components are depicted at the fourth column of Table I.

The simulated $\Gamma$ is close to the theoretical $\Gamma_m$ (minimum $\Gamma$) and is depicted in Fig. 6. It should be noted that the theoretical minimum reflection coefficient assumes a lossless matching network. Losses in the implemented network further reduce the obtained reflection coefficient and this should be taken into account when comparing the obtained performance to the theoretical minimum reflection coefficient value. It is shown that the rectifier's reflection coefficient is bellow $-3$ dB for frequency between 300 MHz and 900 MHz for $P_{\text{in}} = -20$ dBm. In Fig. 7 is depicted the efficiency versus frequency. The efficiency varies between 5% and 8.2% for a frequency window of 600 MHz. The efficiency for 400 MHz, 650 MHz, and 900 MHz, is 7.2%, 6% and 7.9% respectively. Fig. 8 shows the voltage across the optimum 4.37 kOhm load. It can be observed that the line of voltage follows the line of

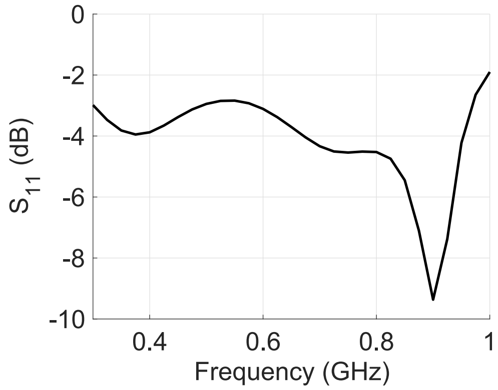


Fig. 6. Reflection coefficient at the input of optimal rectifier. Power input was fixed at -20 dBm and optimal load is 4.37 kOhm.

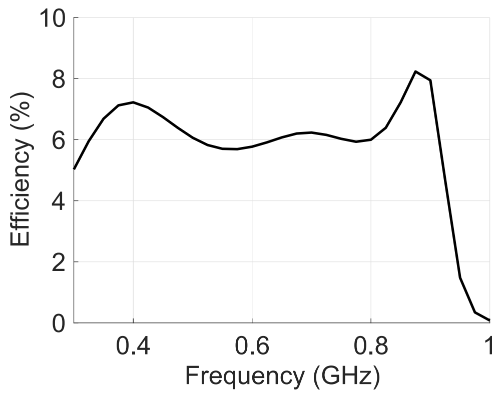


Fig. 7. Optimal rectifier efficiency versus frequency for fixed power input at -20 dBm and optimal load 4.37 kOhm.

efficiency (Fig. 7) in the same bandwidth. The voltage for 400 MHz, 650 MHz, and 900 MHz, is 56 mV, 52 mV and 59 mV respectively.

It is known that the efficiency is a function of frequency, as well as load and power input, due to the diode non-linearity. This non-linear relation is demonstrated below. Fig. 9 depicts the relation between the efficiency and the load for three different frequencies. Is is observed that optimal load (the load that the efficiency is maximized) is close to 4.37 kOhm as expected form the optimization process. For the simulation results of Fig. 9 we have assumed fixed $P_{\text{in}} = -20$ dBm. In Fig. 10 the efficiency versus $P_{\text{in}}$ is shown for 400 MHz, 650 MHz and 900 MHz. It is evident that the maximum efficiency take place for 400 MHz and 900 MHz but the difference with 650 MHz remains small for a wide range of input powers, demonstrating the fact that the rectifier maintains relatively well its frequency response for a wide range of input power levels.

## IV. Conclusion

In this work a wideband rectifier was designed and simulated. Three different matching networks were tested, connected with the a double diode charge pump. A wideband

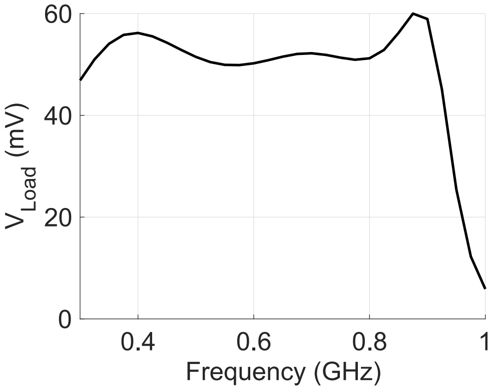


Fig. 8. Optimal rectifier efficiency versus voltage across the load for fixed power input at -20 dBm and optimal load 4.37 kOhm.

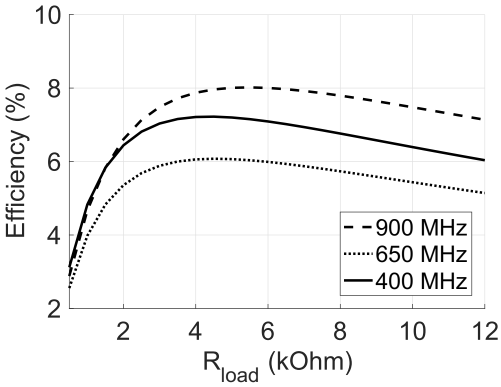


Fig. 9. Optimal rectifier efficiency versus load for three different frequencies. The power input was fixed at -20 dBm.

matching circuit was selected for the final design and the layout was modelled on paper substrate. Future work should be focused on the fabrication and measurements of the final rectifier design.

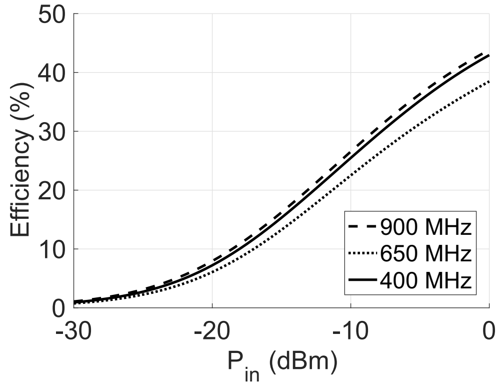


Fig. 10. Optimal rectifier efficiency versus power input for three different frequencies. The load was fixed at 4.37 kOhm.

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