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Article

Design, Simulation, and Performance Evaluation of a 2.4 GHz RF Energy Harvester

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Abstract: A radio frequency energy harvester is a device that can power low-power devices without using typical power sources by converting ambient radio frequency electromagnetic waves into usable electrical energy. A new 2.4 GHz frequency band RF energy harvester is suggested in this article. The circuit employs a voltage multiplier cum rectifier for rectification purposes, and a low forward volatge drop Schottky diode HSMS2860_20000301 is utilized for rectifier implementation. LC impedance matching is used to increase the RFEH circuit performance in terms of conversion efficiency and output voltage. The rectifier is simulated with the Advanced Design System (ADS). The Proposed rectifier circuits exhibits the performs optimally at load impedance of 500Ω. After simulation, results reveal a conversion efficiency of 71.88% and 1.896V of output voltage with 10 dBm RF input power at 2.4 GHz frequency band.

Keywords: Radio Frequency energy harvester (RF-EH), ISM band, Matching Network, Schottky diode, Greinacher voltage multiplier, Conversion efficiency

1. Introduction

The rapid technological expansion in the area of the wireless sensor networks (WSNs), Internet of Things (IoT), and wearable bio-medical electronics has created a huge demand for autonomous, long-term power sources [1,2]. Traditionally, these low-power devices rely on conventional chemical batteries. However, batteries present significant drawbacks, including a finite lifespan, high maintenance costs associated with replacement, and environmental hazards related to disposal [1,2,3].

Radio Frequency Energy Harvesting (RFEH) is a very promising technology developed. Since there is no alternative to this, the limitations are overcome in the following way. Radio Frequency Energy, or Radio Frequency Energy, is the conversion of fields of the surrounding. Converts the electromagnetic waves in the environment to usable DC Voltage. Electronic devices can Not be requiring batteries to be changed by using energy from RF energy in free space. To achieve energy autonomy, energy must be used with minimal effect on the environment [1, 3, 4].

The ambient RF energy covers a wide spectrum, such as wireless cellular bands (GSM, LTE) and digital television (DTV), and one of the most promising areas of interest for energy harvesting is the 2.4 GHz ISM band [1].

The 2.4 GHz frequency is uniquely suited for Radio Frequency Energy Harvesting (RFEH) primarily due to its extreme ubiquity across modern wireless landscapes. As a fundamental band for widely adopted standards such as Wi-Fi (IEEE 802.11b/g/n), Bluetooth, and ZigBee, it permeates both urban and indoor environments. This widespread deployment ensures a relatively continuous and ubiquitous supply of ambient RF energy that can be scavenged effectively to power autonomous systems [7,8].

Furthermore, the 2.4 GHz band offers distinct advantages regarding antenna dimensions. According to fundamental antenna theory, the physical size of an antenna is reciprocal function of operating frequency. At 2.45

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GHz, the free-space wavelength is approximately 12.2 cm. This allows for the development of small, compact, and high-gain microstrip patch antennas that are ideal for the constrained enclosures of smart IoT devices and wearable gadgets, facilitating seamless integration without increasing the device footprint [8-15].

Lastly, the predictability of signal propagation at 2.4 GHz significantly contributes to its viability for energy harvesting. In structural areas with high human density, ambient power levels can be reasonably estimated and modeled, providing a reliable baseline for the design of harvesting circuits. While signal density is high, the consistent presence of these signals in populated areas makes the 2.4 GHz spectrum a prime candidate for sustaining low-power electronic systems through ambient power recovery [13-17].

There are significant engineering challenges in designing an efficient energy harvester operating at 2.4 GHz. The crucial problem is that there is very little power in the ambient RF signals. The power level of the available RF power in other indoor or semi-urban applications is typically in the range of −30dBm to −10dBm (1µW to 100µW). Therefore, typical silicon rectifying diodes can't open up because the arriving voltage changes are far under their threshold voltage. Such a 2.4 GHz harvester should, therefore, be very optimized and make use of low barrier Schottky diodes and a precise matching network to ensure maximum power transmission and power conversion efficiency when operating at very low input power levels [13-19].

2. Basic Architecture of RF Energy Harvesting System

The Components of RF energy harvesting system as shown in Fig.1

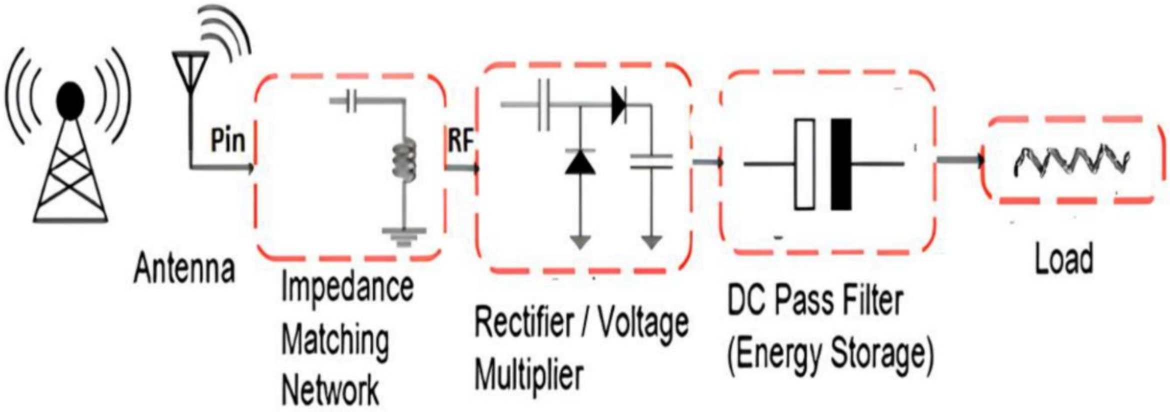

Fig. 1 Block Diagram of RF Energy System

The basic construction of a RFEH device is that of a rectenna (rectifying antenna). It uses a special multi-stage architecture to convert high frequency AC to controlled DC.

The typical architecture of a Radio Frequency Energy Harvesting (RFEH) system begins with the antenna, which is responsible for receiving electromagnetic waves. These antennas are usually designed for circular polarization or omnidirectional reception to account for varying environments and to capture signals from any direction. At the 2.4 GHz frequency, compact microstrip patch or slot antennas are preferred. They are frequently engineered with circular polarization to extract energy efficiently from transmitting Wi-Fi routers or Bluetooth devices, regardless of their physical orientation [1-6].

Following the antenna, the impedance matching network (IMN) serves to cancel out the reflected energy between the antenna and the rectifier circuit. The design of the IMN is considered one of the most mathematically challenging steps in the system development. This complexity is due to the fact that the rectifier's impedance is non-linearly function of the input power and the operating frequency both, requiring precise tuning to ensure maximum power transfer [21-22].

The rectifier acts as the system's heart, transforming the 2.4 GHz Alternating Current (AC) into a Direct Current (DC) signal. To convert microwatts of ambient signals into usable electricity, the system utilizes ultra-low barrier Schottky diodes rather than conventional silicon diodes, as they have a significantly lower turn-on voltage of approximately 0.15V. Circuit topologies such as the Greinacher voltage doubler are often selected for their ability to rectify and amplify the voltage simultaneously [15-17].

Finally, a filter, such as a shunt capacitor or an L-C low-pass filter, serves as a reservoir for the system. This component eliminates the fundamental 2.45 GHz frequency and the higher-order frequency components produced by the non-linear switching characteristics of the diode. The result of this process is a clean, stable DC voltage that can be used to power electronic devices [1-4].

3. Design of Unmatched Harvester Circuit

In energy harvesters, the low power level is boosted by applying voltage multipliers. The received signal was fed into received signal correction circuit to correct the received RF signal to a DC signal [18-19]. This circuit eliminates the traditional Impedance Matching Network (IMN) between the rectifier and the receiving antenna. It is an Unmatched RF Energy Harvester Circuit. In a traditional rectenna, the IMN is highly tailored for a specific frequency (such as 2.45 GHz) and a specific input power level [14–17].

However, because ambient RF energy is constantly changing at many frequencies and power levels, the performance of a fixed matching network can suffer off its design frequency and power. An unmatched design seeks to minimize the requirement to match the frequency, or move it onto the rectifier, or even onto the antenna geometry itself, to achieve highly frequency independent or frequency agnostic harvesting. [1-6].

The various voltage rectifier and multipliers like Greinacher, Dickson and Villard were These are discussed in the circuits of RF energy harvesters [12-13]. The Villard circuit is a simple circuit made up of two components as a capacitor and a diode, as shown in Fig. 2. The Villard circuit is reputed to have poor ripple characteristics, but it does are simple to use. In other words, it's a diode clamping circuit. The Negative high cycles are used to charge the capacitor to the maximum or peak value of the AC voltage (VP) [10].

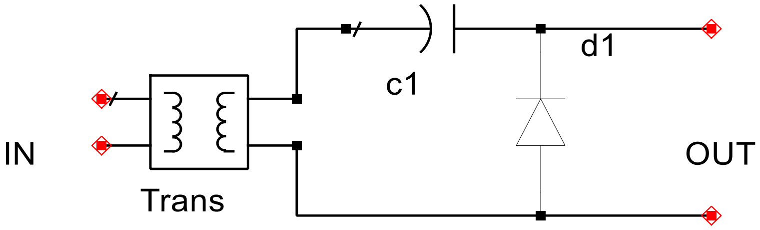

Fig.2. Circuit Diagram of Villard Voltage Rectifier

The Greinacher voltage rectifier circuit diagram is displayed in Fig. 3. At the cost of an extra diode and capacitor, it offers numerous benefits over the Villard circuit. In contrast to the Villard rectifier, this rectifier reduces the sharp variations in the DC output. It offers higher direct current (DC) output voltage at high power and excellent conversion efficiency at low frequency [20].

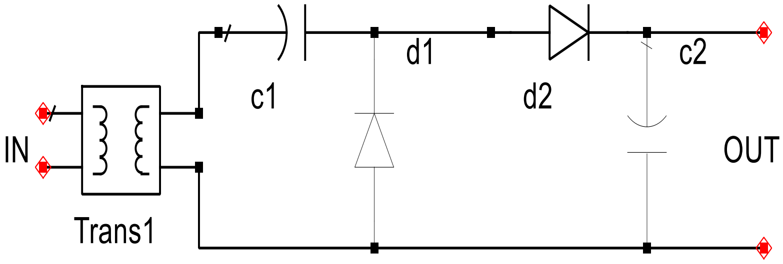

Fig. 3. Schematic of Greinacher Voltage Rectifier

Without input matching, the first RF energy harvesting circuit is developed as seen in Fig. 4. At 2.4 GHz, a source impedance of 50Ω is selected to represent the antenna system. Schottky diodes d1 and d2 (di_hp_HSMS2860_20000301) are employed in the circuit to create a Greinacher voltage rectifier [21]. The Greinacher voltage rectifier circuit has a capacitor Cb1 (0.005nF). At an output load impedance of 100Ω, the circuit is tuned for maximum efficiency.

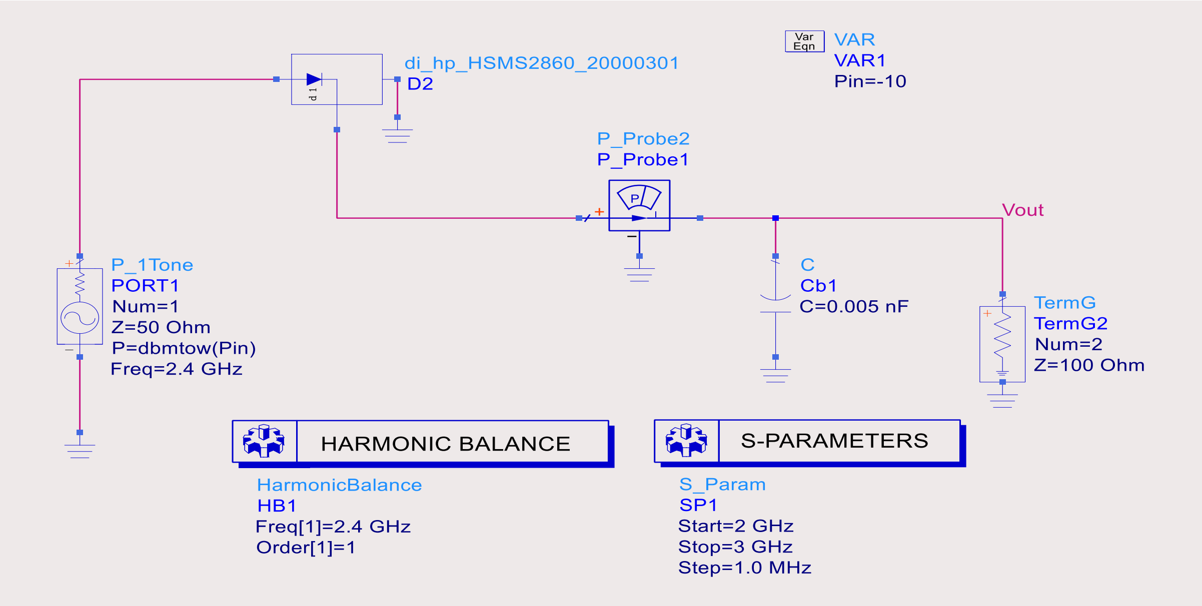

Fig. 4. Unmatched Harvester Circuit at 2.4 GHz

The mismatched rectifier circuit's input impedance (Zin) at 2.4 GHz is displayed in Fig. 5. The imaginary part is −429.69Ω and the real part is 47.86Ω. With a source input impedance of (50+j*0) Ω, this input impedance value indicates that the circuit is closely matched to the real part but large mismatched to the imaginary part.

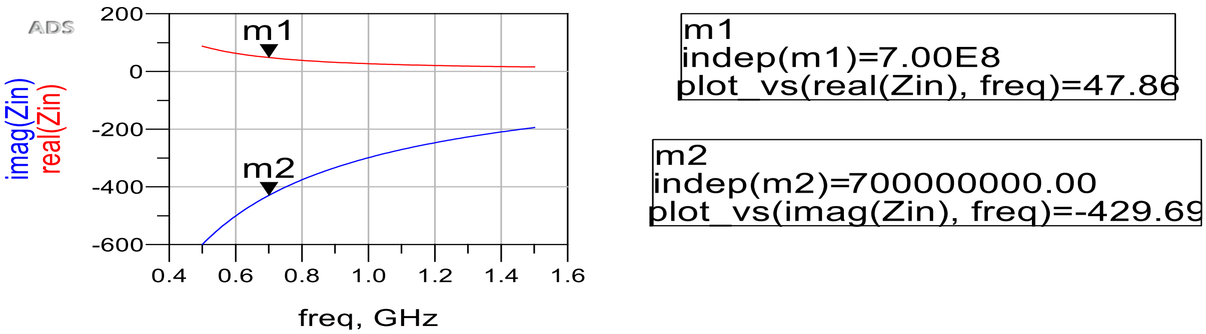

Fig. 5. Input Impedance of Unmatched Harvester Circuit

Fig. 6 represents the curve for conversion efficiency versus RF power. The Equation of conversion efficiency is given in (1), where (P_Probe1.p[0]) is the output DC power dbmtow (Pi). Efficiency of 35.78 % is observed at 10 dBm of Power. Expression for caluation ogf efficiency rectifier is given equation (1)

Eff = (P_Probe1.p[0]/dbmtow(Pin))*100 (1)

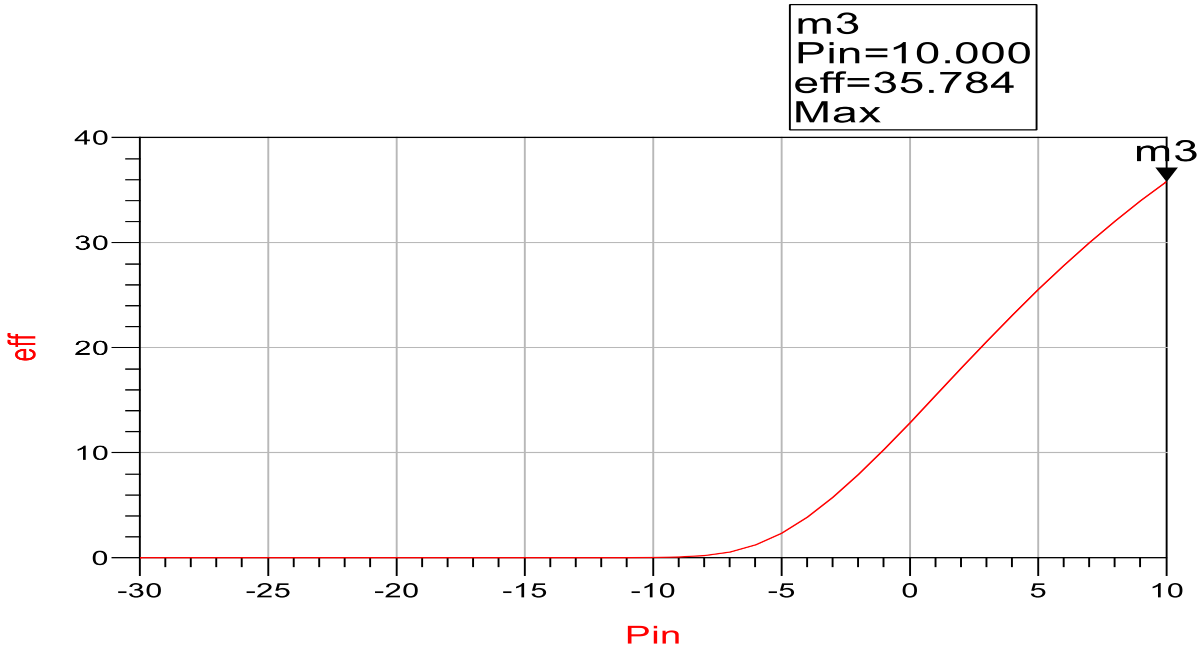

Fig. 6. Conversion Efficiency versus RF power of Unmatched Harvester Circuit

Figure 7 shows the simulation result of output voltage versus RF power of the unmatched rectifier circuit at the same frequency, with an output voltage of 0.182V recorded at 10 dBm.

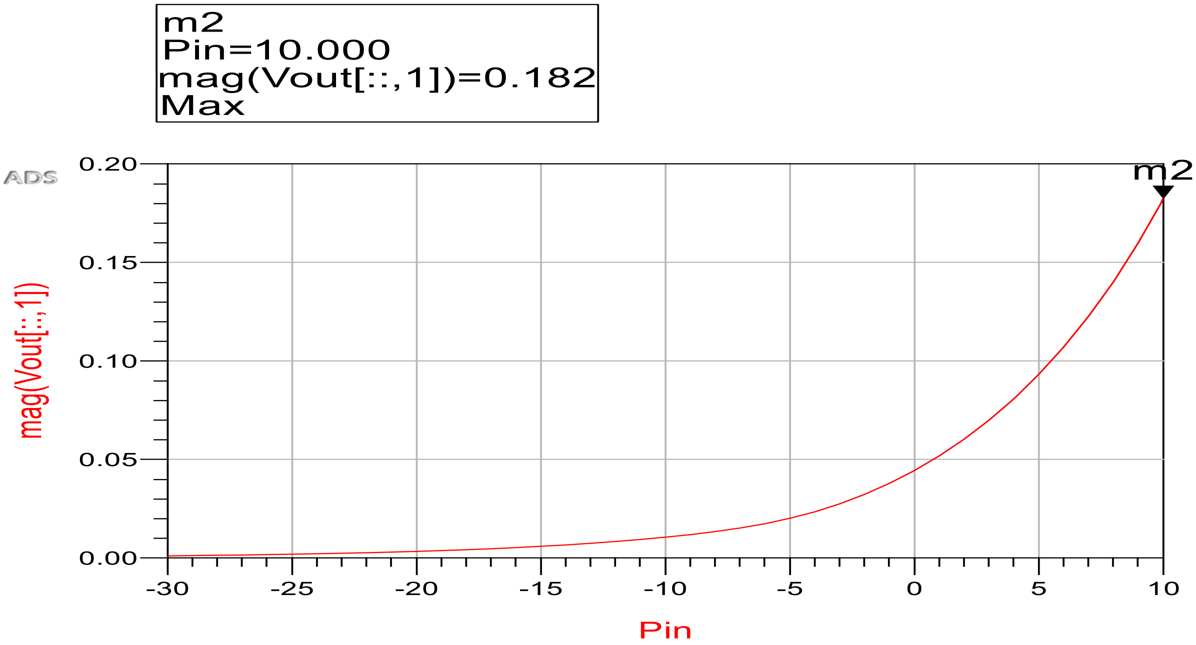

Fig. 7. Output Voltage versus RF power of Unmatched Harvester Circuit

4. Design of Matched Harvester Circuit

Fig. 8 shows an LC matching circuit applied to the harvester circuit's input side to match the impedance of the source (Zs = 50Ω) and load (ZL = 500Ω). After computation, the values of matching circuits are obtained as Cs = 0.5pF, Ls = 6.388646nH, and Cl = 0.420894pF.

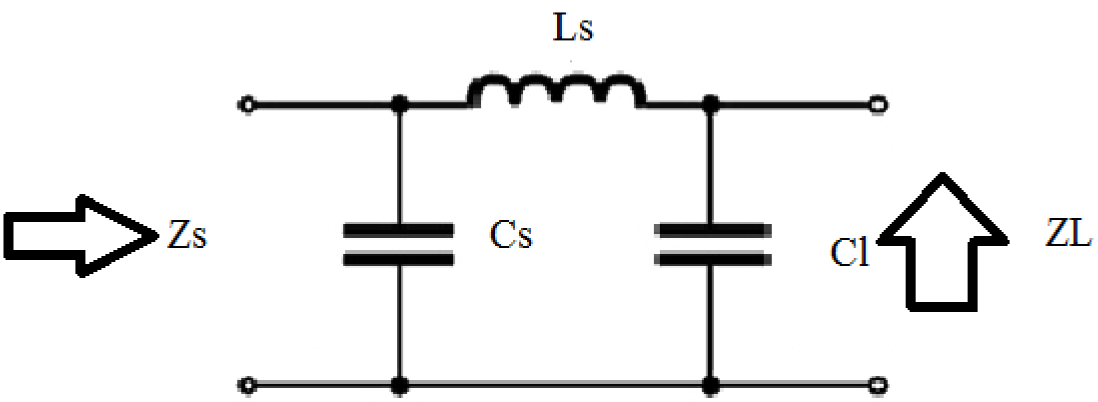

Fig. 8. Circuit Diagram of LC-Matching Network

Fig. 9 depicts a series-to-shunt conversion for developing a matching circuit. Zs is 50Ω, ZL is 500Ω, and the frequency is 2.45GHz..

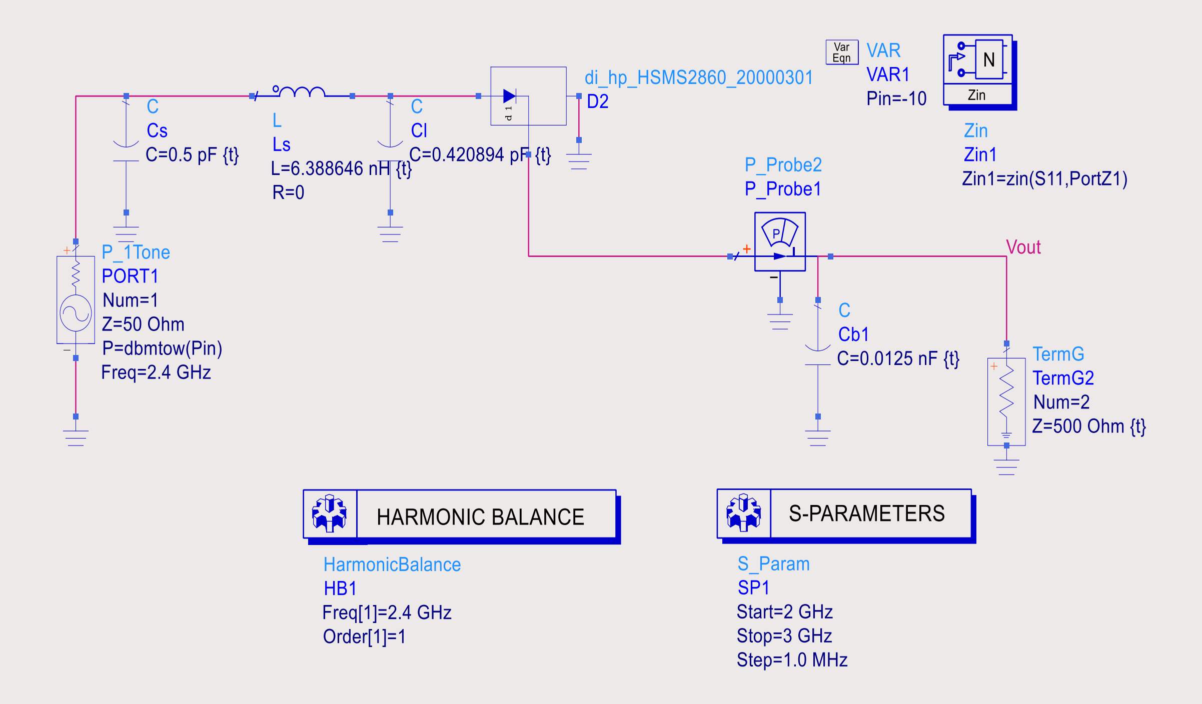

Fig. 9. Matched Harvester Circuit after LC matching

Fig. 10 shows the plot of efficiency (eff) versus input power level (Pin), which shows the conversion efficiency of 71.88% at input RF power level of −10 dBm.

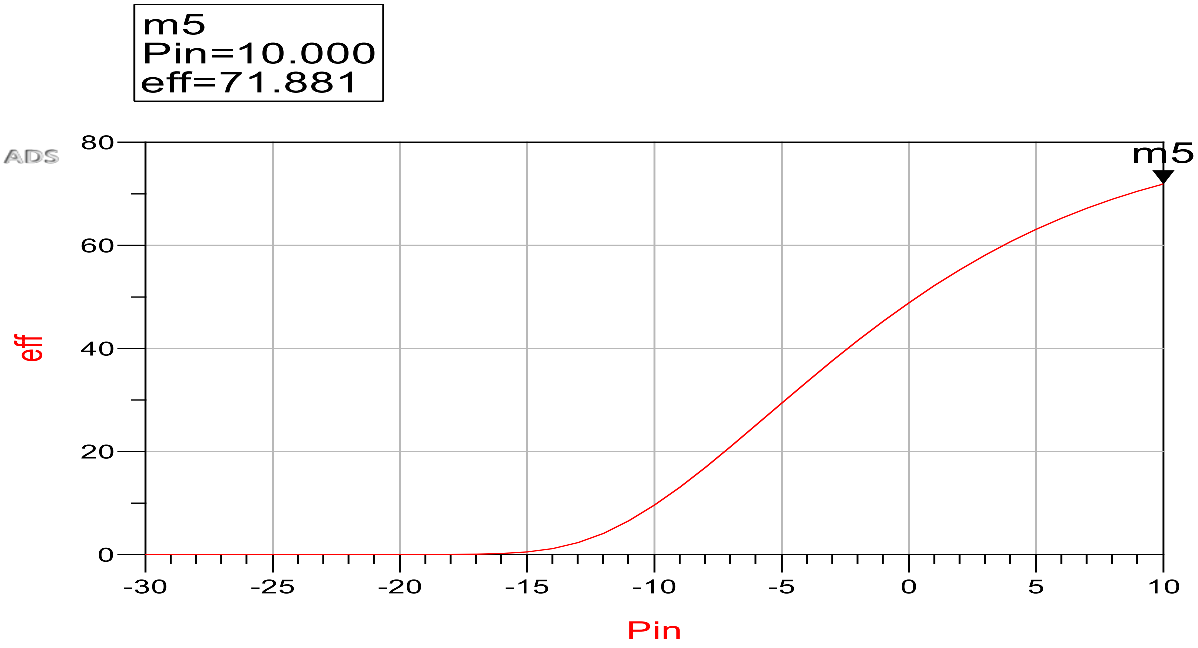

Fig. 10. Conversion Efficiency versus RF power of Matched Harvester circuit

Fig. 11 shows the plot for output voltage versus RF power of the matched rectifier circuit in which output voltage of 1.896V is observed at −10dBm power level.

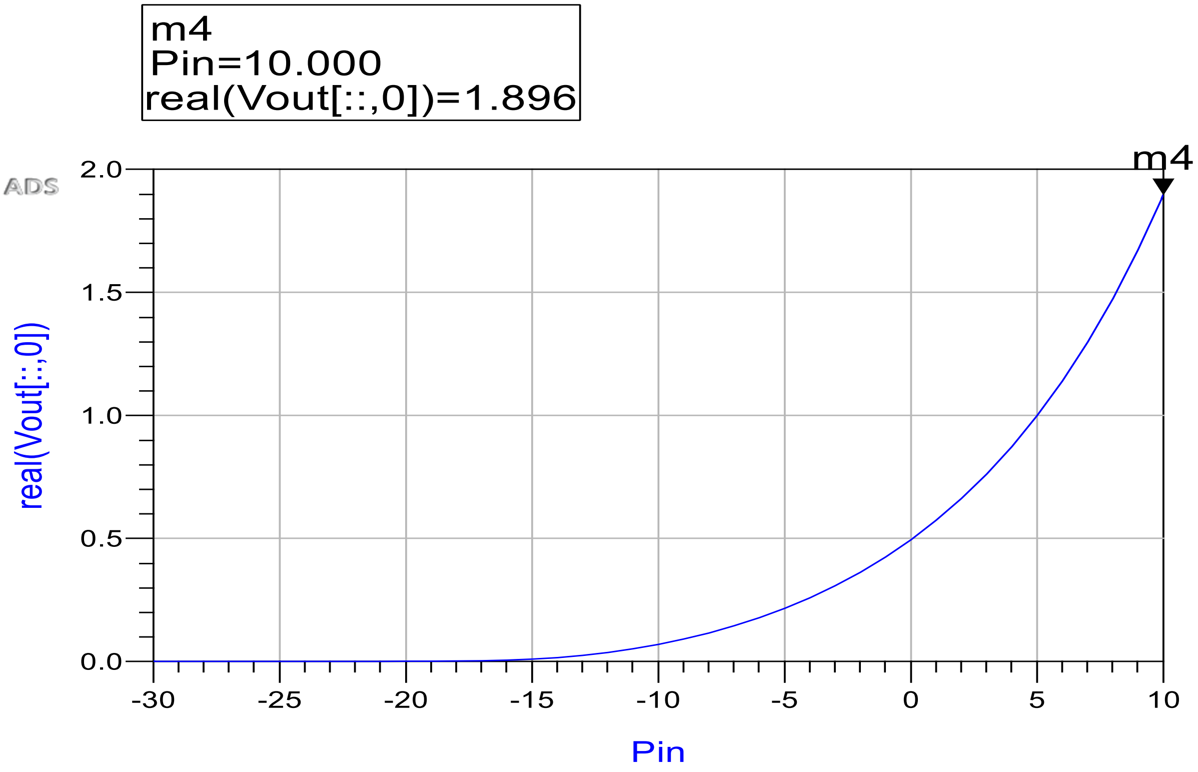

Fig. 11. Output Voltage versus RF power of Unmatched Harvester Circuit

Table 1 shows the comparison of unmatched and matched network in terms of circuit components and performance parameters.

Table 1 Comparison of Unmatched and Matched Network

Comparison Parameters	Unmatched Network	Matched Network
Source Impedance (Zs) in Ω	50	50
Load Impedance (ZL) in Ω	100	500
Output Voltage (Volt)	0.182	1.896
Efficiency (%)	35.78	71.88

Table 2 compares the performance analysis of the proposed circuit to previous similar studies and shows that it acquires a high efficiency of 71.882% at 2.4GHz frequency.

Table 2 Performance Comparison with Previous Work

Ref. Year	Input Power (dBm)	Frequency Band	Rload	Rectifier Topology	Conversion Efficiency (%)
[15] 2023	0 dBm	2.95 GHZ to 4.95 GHz	1 KΩ	HSMS2862 diode & voltage doubler (Rectifier Design-2)	>35%
[18] 2020	−20 dBm	2.45 GHz	4.7 KΩ	Schottky diodes (HSMS2852) & L-network matching	20%
[19] 2018	0 dBm	870 MHz to 2.5 GHz	2 KΩ	voltage doubler with Schottky diode SMS7630-005LF	30%
[20] 2017	10 dBm	250 MHz and 3 GHz	1.3 KΩ	2-diode charge pump inkjet-printed on a flexible substrate	>33%
This Work	-10 dBm	2.4 GHz	500 Ω	Greinacher Voltage Multiplier and Schottky Diode HSMS-2860	71.88%

5. Result & Conclusions

The RF energy harvester for the 2.4GHz frequency band is presented in this research. This band is extensively utilized for 5G coverage worldwide and Low Power IoT devices. When combined with input matching, the Greinacher voltage rectifier offers substantial benefits in terms of high conversion efficiency in the 2.4GHz range and at a 500Ω load. Prior to matching, a 2.4GHz frequency yields an output voltage of 0.182V and a conversion efficiency of 35.78%. Following the use of an LC type matching network, an output voltage of 1.896V and a conversion efficiency of 71.88% are noted at a frequency of 2.4GHz. In conclusion, the output voltage is increased tenfold and the efficiency is doubled. In the future, various matching networks, such as T and π matching networks, and different multiplier circuits can be used to further explore the scope and efficiency. Numerous RF energy harvesting applications can make use of this suggested circuit design.

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