Performance Evaluation of Greinacher Voltage Multiplier for RF Energy Harvesting at 2.4 GHz

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Abstract: Modern urban environments are saturated with radio frequency (RF) signals transmitted by various wireless communication systems. In addition to their primary communication function, these RF signals can serve as a potential source of renewable energy through ambient RF energy harvesting. Such systems are increasingly being explored for powering low-power electronic devices, including battery chargers, wireless sensor nodes, and portable electronic equipment. A 2.4 GHz frequency band RF energy harvester is proposed in this article. The circuit employs a Greinacher Voltage Multiplier with a low forward voltage drop Schottky diode HSMS2862_20000301 is utilized for circuit implementation. L-C impedance matching is used to enhance the Radio Frequency Energy Harvesting (RF-EH) circuit performance in terms of conversion efficiency and output voltage. The Greinacher Voltage Multiplier is simulated with the Advanced Design System (ADS). The proposed voltage multiplier circuits exhibit the performs optimally at load impedance of 50 kΩ. After simulation, results reveal the return loss is -11.456 dB and 2.375V of dc output voltage with 10 dB RF input power at 2.4 GHz frequency band.

Keywords: **Greinacher voltage multiplier, Radio Frequency energy harvester (RF-EH), wireless sensor nodes, Matching Network, Schottky diode, Conversion efficiency**

1. Introduction

Radio Frequency (RF) energy harvesting has emerged as an attractive technology for powering low-power electronic devices such as wireless sensor nodes, wearable electronics, biomedical implants, and Internet of Things (IoT) devices. The technology captures electromagnetic energy from ambient RF sources and converts it into usable DC power through a rectifying circuit known as a rectifier. Since the available ambient RF power is generally very low (typically between −20 dBm and 10 dBm), the design of a highly efficient rectifier is one of the most critical aspects of an RF energy harvesting system [1,2].

Wireless sensor nodes are compact, low-power electronic devices designed to sense, process, and wirelessly transmit environmental or physical information to a central gateway or base station. These nodes typically integrate sensing elements, a microcontroller, a wireless communication module, and a power source within a small form factor. Due to their compact size and low energy consumption, wireless sensor nodes are extensively deployed in Internet of Things (IoT) applications such as smart agriculture, environmental monitoring, healthcare, industrial automation, smart cities, and structural health monitoring. So most suitable applications as the energy harvesting techniques, particularly radio frequency (RF) energy harvesting, have gained significant attention as sustainable alternatives for powering wireless sensor nodes without frequent battery replacement [24-26].

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 [7-11].

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 the Greinacher voltage doubler are often selected for their ability to rectify and amplify the voltage simultaneously [10-11].

Finally, a 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 [3-4].

Basic Architecture of Greinacher Voltage Multiplier:

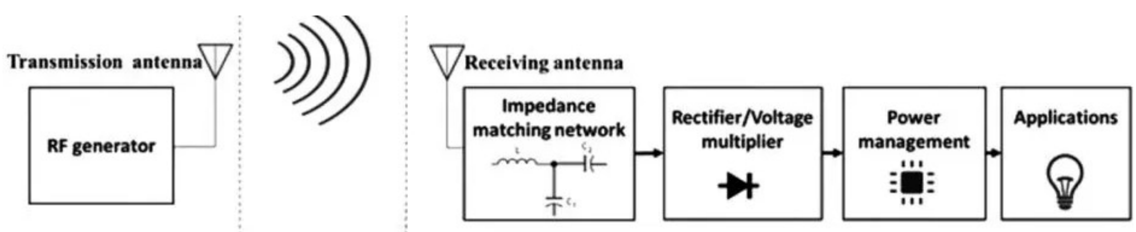

Fig. 1 Block Diagram of RF-EH

Among the various rectifier topologies, the Greinacher voltage multiplier has gained significant attention due to its simple circuit configuration, low component count, and ability to generate a higher DC output voltage from weak RF signals. The topology is widely employed in rectenna systems operating at the 2.4 GHz Industrial, Scientific and Medical (ISM) band, which includes Wi-Fi, Bluetooth, ZigBee, and numerous IoT communication standards [1,3]. The Greinacher voltage multiplier, also known as the Greinacher voltage doubler, is a diode-capacitor circuit that converts an alternating RF signal into a higher DC voltage. It consists of two Schottky diodes and two capacitors arranged so that charge accumulated during alternate half-cycles is transferred to the output capacitor, thereby increasing the output voltage. Operationally, during the positive half-cycle of the RF signal, the first Schottky diode becomes forward biased and charges the first capacitor approximately to the peak input voltage. During the negative half-cycle, the stored charge is transferred through the second diode to the output capacitor. Consequently, the output voltage approaches nearly twice the peak input voltage under ideal operating conditions. However, practical output voltage is reduced because of the forward voltage drop of the Schottky diodes and parasitic losses [2]. The Greinacher multiplier is preferred over conventional half-wave rectifiers because it simultaneously rectifies and boosts the output voltage while maintaining a relatively simple circuit architecture. The Greinacher voltage multiplier offers several advantages for RF energy harvesting applications as simple circuit configuration, low component count, higher output voltage than a single-diode rectifier, low conduction losses, Eeasy integration with microstrip antennas, compact implementation at microwave frequencies, high RF-to-DC conversion efficiency, suitability for low-power IoT devices [1,2].

Despite its advantages, the Greinacher voltage multiplier exhibits several limitations as reduced conversion efficiency at extremely low RF input powers, impedance matching becomes difficult because the rectifier input impedance changes with input power, increasing the number of multiplier stages introduces additional parasitic capacitance and conduction losses, output voltage decreases when supplying heavy loads, component tolerances and substrate losses affect overall performance at microwave frequencies [2,4].

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. It is an Unmatched RF Energy Harvester Circuit. In a traditional rectenna, the IMN is highly tailored for a specific frequency and a specific input power level [20-22].

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 [21-22].

The various voltage rectifier and multipliers like Greinacher, Dickson and Villard were These are discussed in the circuits of RF energy harvesters [23]. 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 (V_P**).**

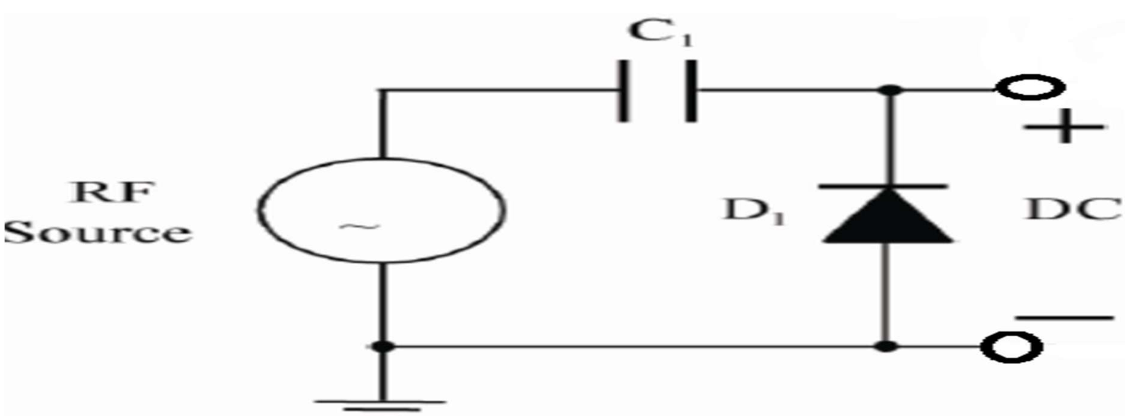

Fig.2. Schematic of Villard Voltage Rectifier

The Greinacher voltage multiplier 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 [1-4].

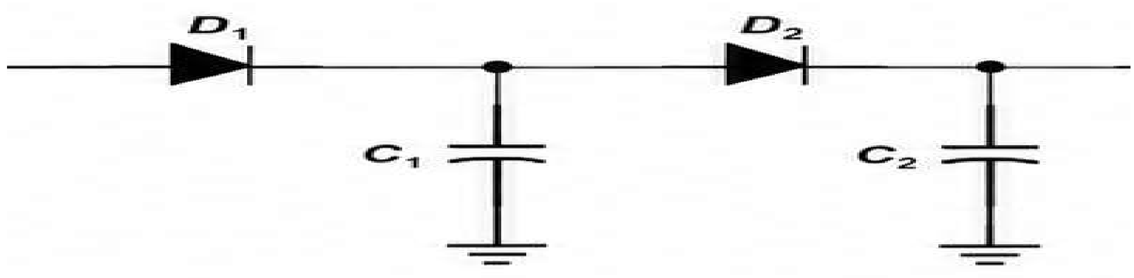

Fig. 3. Schematic of Greinacher Voltage Multiplier

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_HSMS2862_20000301) are employed in the circuit to create a Greinacher voltage rectifier [3-4]. The Greinacher voltage multiplier circuit has a capacitor Cb1 (30 nF) and Cb2 (1 nF). At an output load impedance of 1 kΩ, the circuit is tuned for maximum efficiency.

Table -1 Comparison of the state of the work.

Reference/Year	**Major Contribution**	**Research Gap / Problem**	**Proposed Solution / Future Scope**
[12]/2026	Compared half-wave, full-wave, Dickson, Villard and Graetz rectifiers using ADS at 2.4 GHz.	Efficiency decreases significantly at low input power (<0 dBm).	Optimize Schottky diode selection and multi-stage impedance matching for ultra-low-power operation.
[13]/2023	Proposed a differential rectifier with dual microstrip patch antennas eliminating the power splitter and voltage combiner. Achieved 69.3% PCE and 5.1 mW output at 2.4 GHz.	Operates only at a single ISM band and requires relatively high received RF power.	Develop multi-band differential rectennas with adaptive impedance matching for low-power ambient RF harvesting.
[14]/2025	Investigated multilayer graphene conductors to improve conductivity and conversion efficiency while reducing conductor loss.	Fabrication complexity and higher material cost limit practical deployment.	Develop low-cost graphene hybrid structures or flexible printed conductive materials.
[15]/2024	Reviews antenna enhancement techniques including slots, fractals, arrays and parasitic elements to improve gain and bandwidth.	Most reviewed systems remain narrowband with limited ambient energy capture.	Design compact broadband and multiband rectennas supporting Wi-Fi, GSM, LTE and 5G simultaneously.

[16]/2024	Proposed superdirective antenna architecture with direct antenna-rectifier matching achieving improved efficiency at −20 dBm input power.	Increased design complexity and narrow operating bandwidth.	Investigate simplified superdirective arrays with wider bandwidth and easier fabrication.
[17]/2023	Comprehensive survey of 35 rectenna designs covering antennas, rectifiers, impedance matching and hybrid harvesting techniques.	Lack of standardized efficiency comparison under identical operating conditions.	Establish common testing standards for RF-to-DC conversion efficiency and sensitivity.
[18]/2023	Reviewed integrated rectenna ICs for implantable medical devices operating at ISM bands.	Miniaturization reduces antenna gain and harvested power.	Develop high-gain compact antennas using metamaterials or dielectric resonators.
[19]/2022	Summarized wearable rectennas, flexible substrates and miniaturized harvesting systems.	Human-body loading degrades antenna efficiency and impedance matching.	Employ textile antennas, AMC surfaces and adaptive matching networks for wearable applications.

2. Design of Unmatched Greinacher Voltage Multiplier based Harvester Circuit

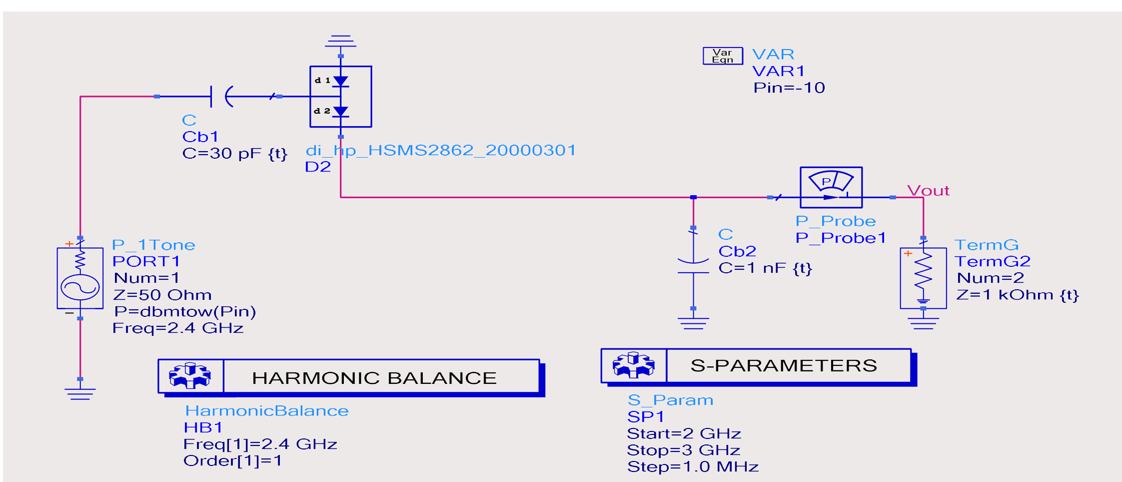

Fig. 4. Schematic of Unmatched Harvester Circuit at 2.4 GHz

The unmatched rectifier circuit's input impedance (Zin) at 2.4 GHz is displayed in Fig. 5. The imaginary part (by Blue line) is −114.791Ω and the real part (by Red line) is 1.289Ω at 2.4 GHz. 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.

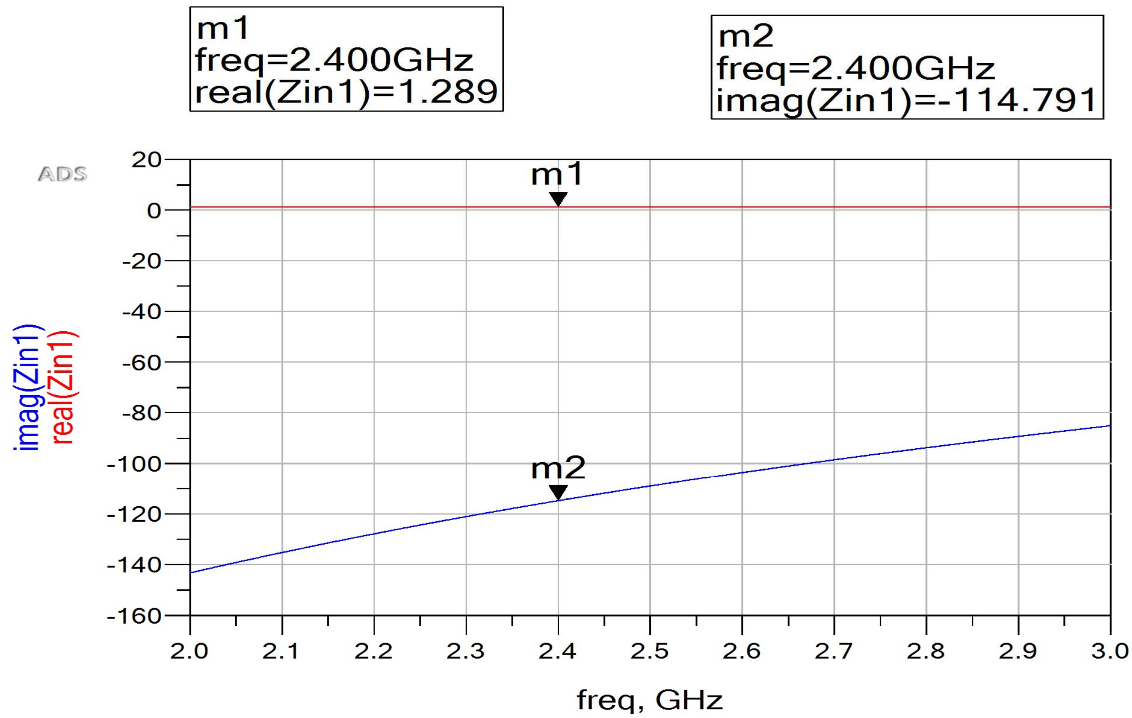

Fig. 5. Input Impedance of Unmatched Harvester Circuit

Figure 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 50.28 % is observed at 10 dBm of Power. Expression for calculation of efficiency rectifier is given equation (1)

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

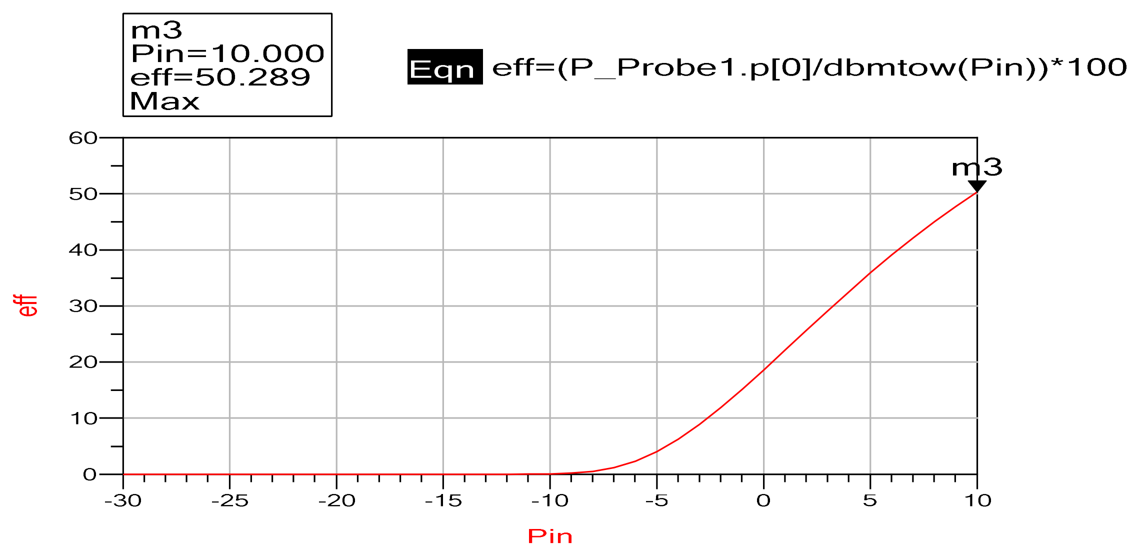

Fig. 6. Conversion Efficiency versus RF power of Unmatched Harvester Circuit

Figure 7 shows the simulation result of return loss versus frequency of the unmatched harvester circuit at 2.4 GHz. In this circuit we observed the value of return loss is -0.071 dB at 2.4 GHz.

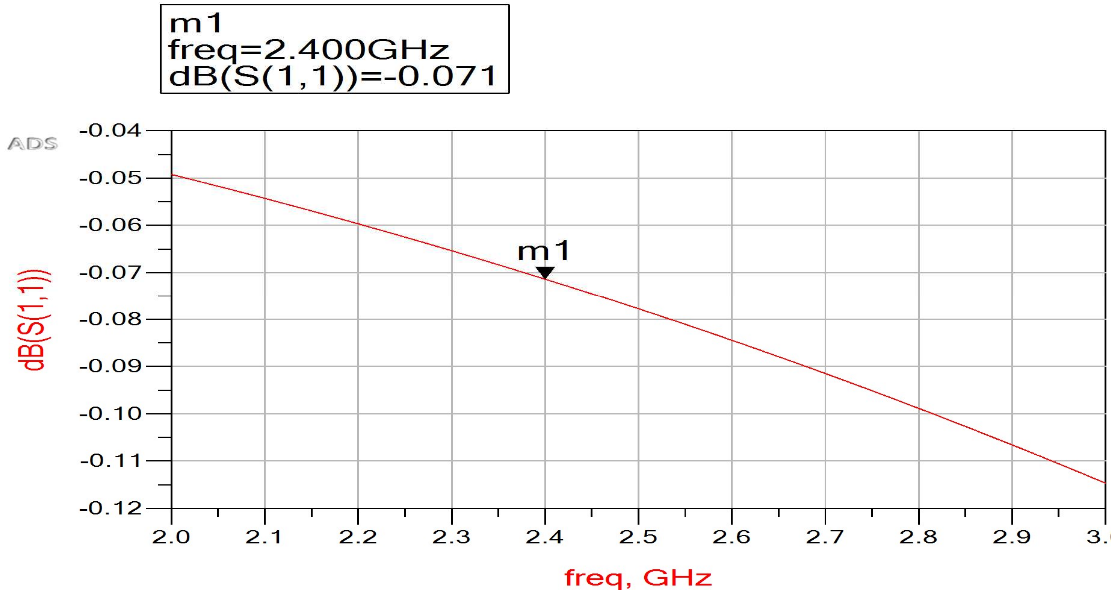

Fig. 7. Return Loss versus Frequency of Unmatched Harvester Circuit

Figure 8 shows the simulation result of dc output voltage versus RF power of the unmatched rectifier circuit at the same frequency, with dc output voltage of 2.243V at 10 dBm.

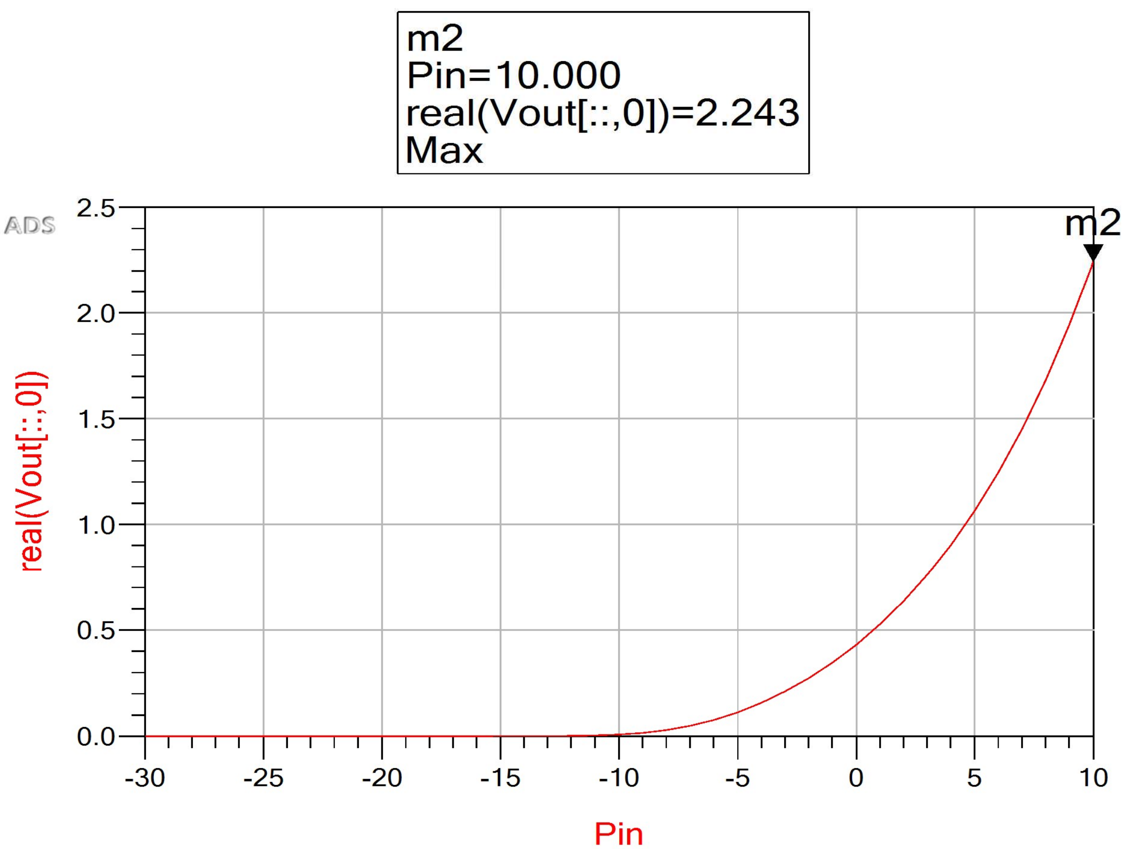

Fig. 8. DC Output Voltage versus RF power of Unmatched Harvester Circuit

3. Design of Matched Greinacher Voltage Multiplier based Harvester Circuit

Figure 9 shows an LC matching circuit applied to the harvester circuit's input side to match the impedance of the source (Zs = 50 Ω) and load (ZL = 50 kΩ). After computation, the values of matching circuits are obtained as C = 0.10208 pF and L = 6.564 nH.

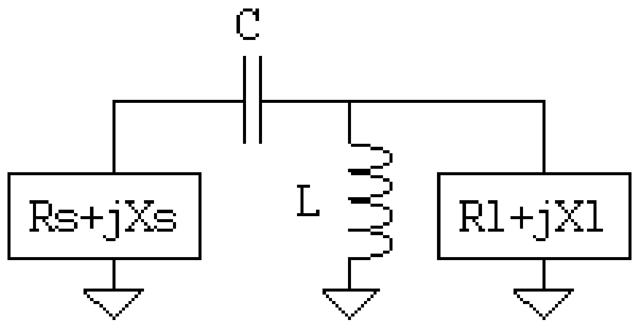

Fig. 9. Schematic of LC-Matching Network

Figure 10 depicts a series-to-shunt conversion for developing a matching circuit. Zs is 50 Ω, ZL is 50 kΩ, and the frequency is 2.45 GHz.

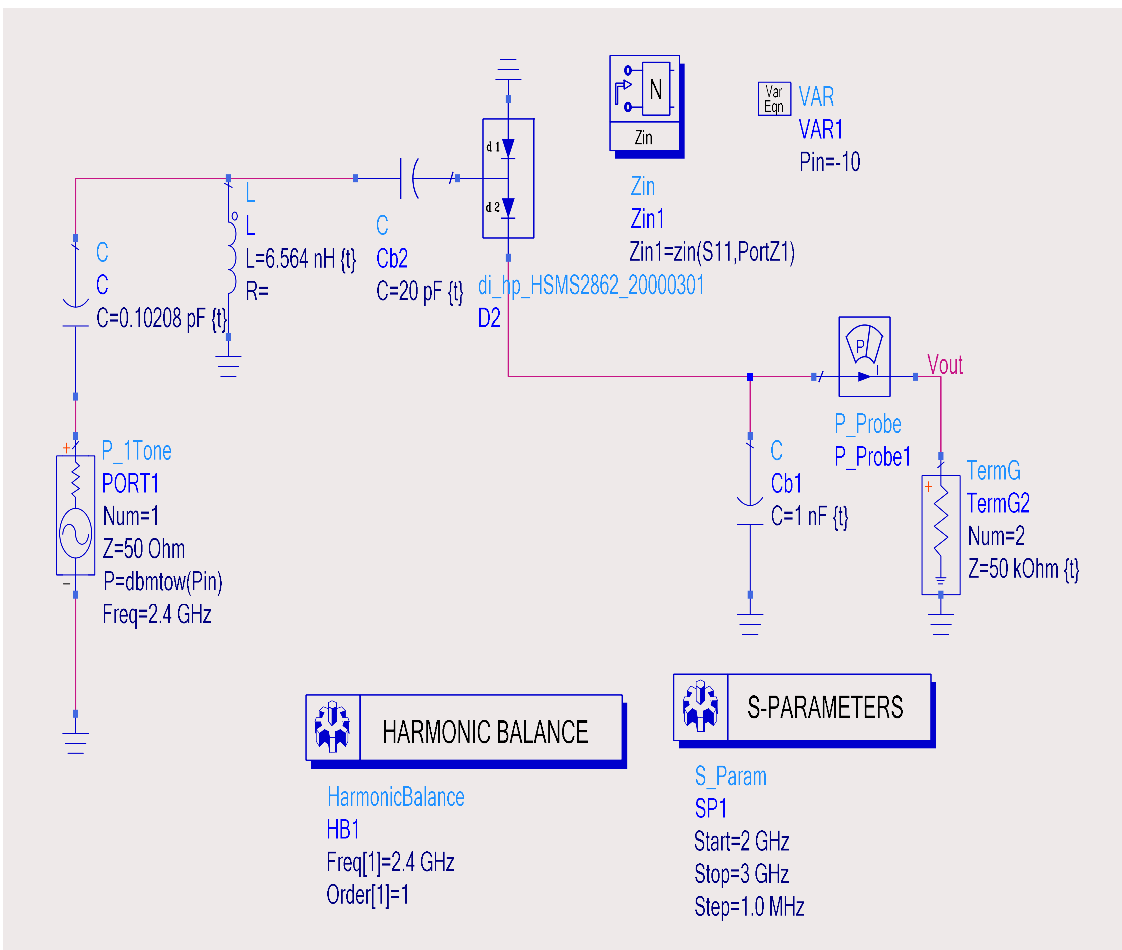

Fig. 10. Schematic of LC matched Harvester Circuit

Figure 11 shows the plot of conversion efficiency (eff) versus input power level (Pin), which shows the conversion efficiency of 7.45% at input RF power level of −23 dBm.

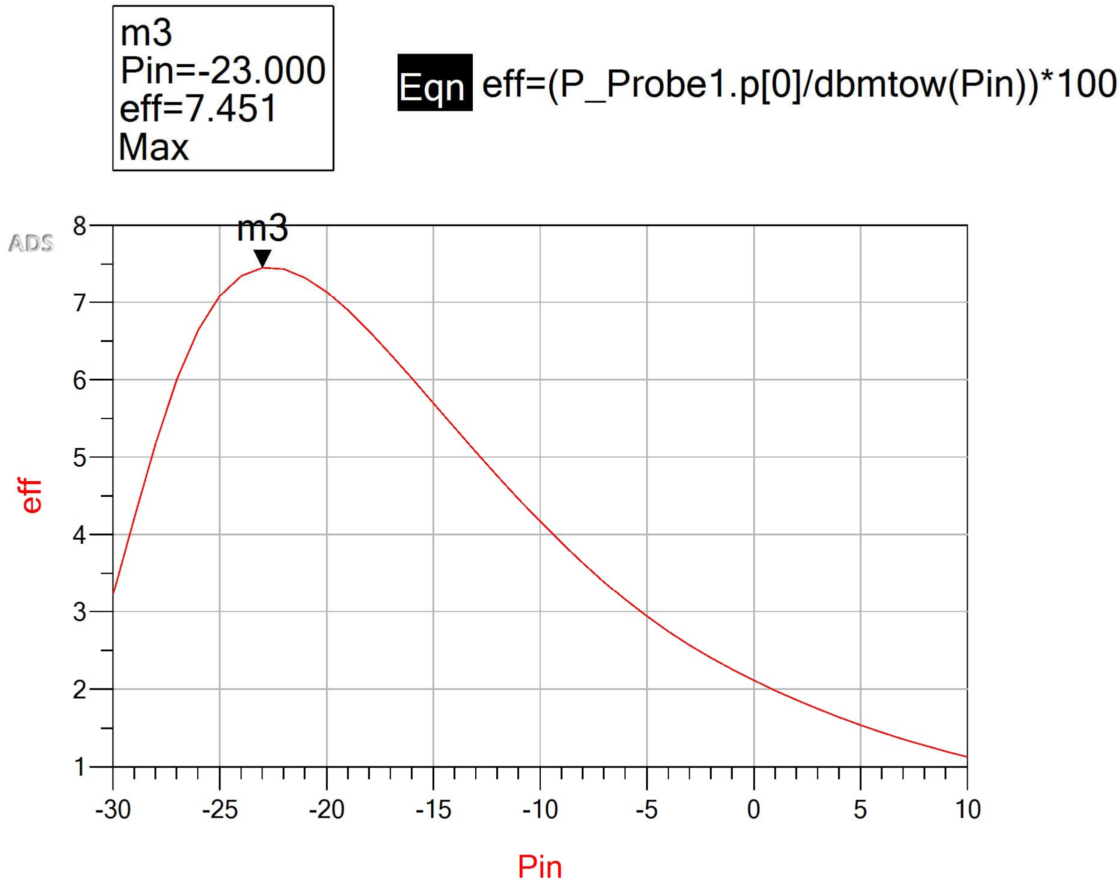

Fig. 11. Conversion Efficiency versus RF power of Matched Harvester circuit

Figure 12 shows the plot for dc output voltage versus RF input power of the matched rectifier circuit in which output voltage of 2.375V is observed at −10dBm power level.

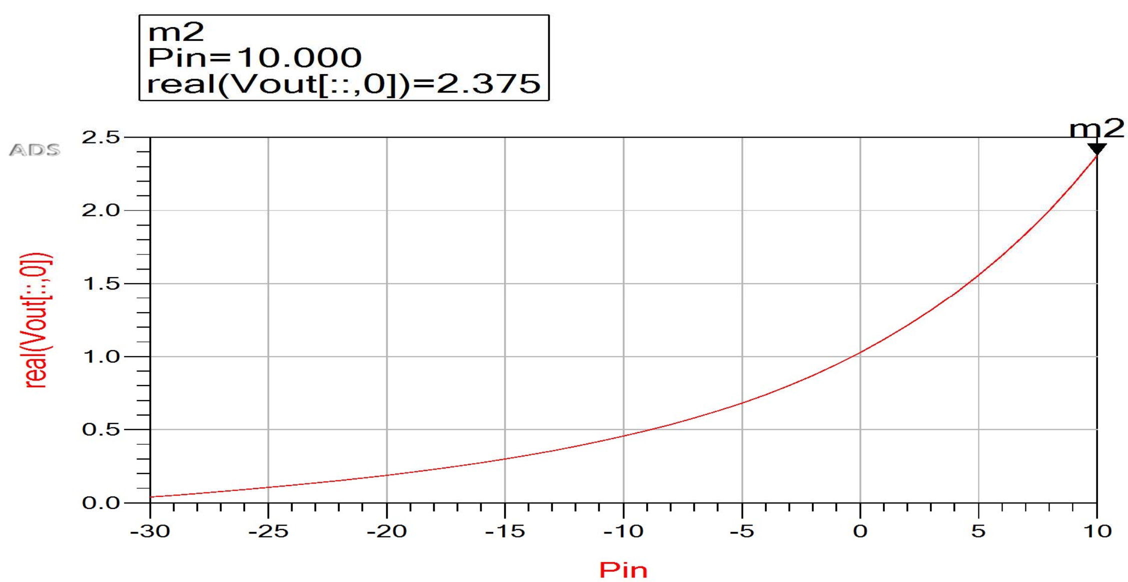

Fig. 12. DC Output Voltage versus RF power of Matched Harvester Circuit

Figure 13 shows the simulation result of return loss versus frequency of a matched harvester circuit at 2.4 GHz. In this circuit we observed the value of return loss is – 11.456 dB at 2.4 GHz.

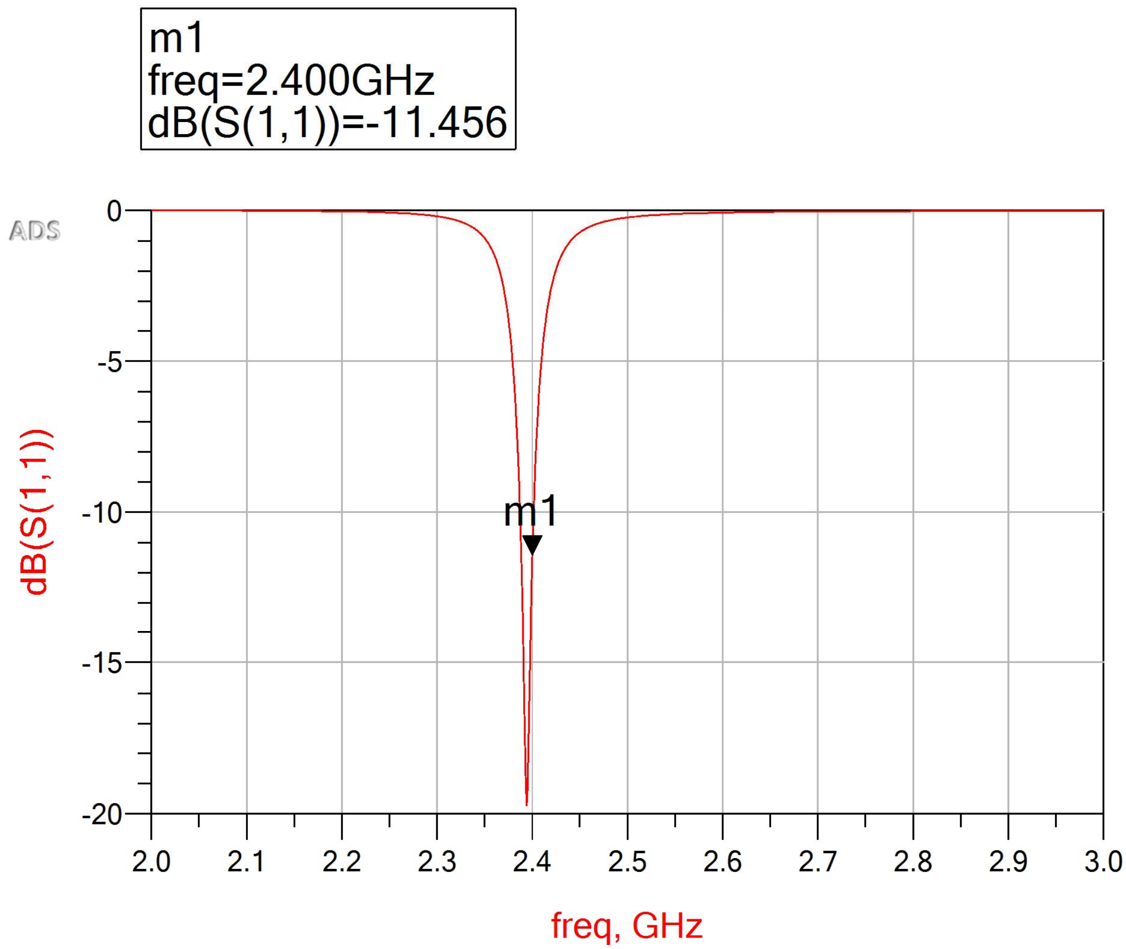

Fig. 13 Return Loss versus Frequency of Matched Harvester Circuit

Table 2 shows the comparison of circuit and performance parameters of an unmatched & matched harvester circuit. In which, it is observed that the dc output voltage is 2.375 V in matched condition whereas 2.243 V in an unmatched condition. The conversion efficiency is 7.45% in matched condition whereas 50.28% in an unmatched condition. In matched condition conversion efficiency is reduced at the expense of increased dc output voltage. So, there is a trade-off between conversion efficiency and dc output voltage due to higher value of load resistance. But the return loss significantly enhanced from -0071 dB in unmatched harvester to -11.456 dB in matched harvester circuit at 2.4 GHz

Table 2 Comparison of Unmatched and Matched Network

Comparison Parameters	Unmatched Harvester Circuit	Matched Harvester Circuit
Source Impedance (Zs)	50 Ω	50 Ω
Load Impedance (ZL)	1 kΩ	50 kΩ
Output Voltage(Volt)	2.243	2.375
Efficiency(%)	50.28	7.45
Return Loss(S11) in dB	-0.071	-11.456

4. Results & Conclusion(s)

The Greinacher Voltage Multiplier based RF energy harvester circuit for the 2.4GHz frequency band is presented in this atricle. This band is extensively utilized for 5G coverage worldwide and Low Power

IoT devices. When combined with input matching, the Greinacher Voltage Multiplier offers substantial benefits in terms of increased conversion efficiency in the 2.4GHz range and at a 50 kΩ load. Prior to matching, a 2.4GHz frequency yields an output voltage of 2.243V and a conversion efficiency of 50.28%. After the insertion of LC type matching network, an output voltage of 2.375V and a conversion efficiency of 7.45% are noted at a frequency of 2.4GHz but the return loss is significantly enhanced from -0071 dB in unmatched harvester to -11.456 dB in matched harvester circuit which implies that more output power is available at the rectifier output in matched condition in comparison to the unmatched condition. Conclusively, there is a trade-off between dc output voltage and conversion efficiency. The circuit is optimized with reference to dc output voltage. As a future scope circuit performance can be optimized with reference to the conversion efficiency. Also in the future, various matching networks, such as T and π matching networks and different multiplier circuits can be used to further explore the future scope.

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