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PAPER

Design of RF energy harvester for 700 MHz

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Radio frequency energy harvester is the conversion of ambient radio frequency electromagnetic waves into usable electrical energy, powering low-power devices without traditional power sources. In this paper, a novel RF energy harvester is proposed for 700 MHz frequency band. For the purpose of rectification, a Greinacher voltage rectifier cum multiplier is used in the circuit and Schottky Diode HSMS-2852 is used for implementing a rectifier. The LC impedance matching is implemented to improve the circuit performance of the harvester including conversion efficiency and output voltage. Simulation of the rectifier is done using the PathWave Advanced Design System (ADS) software. The rectifier shows the optimized performance at 5 kΩ load impedance. Simulation results show the highest efficiency of 33.1 % and an output voltage of 3.2 V with 8 dBm RF power at 700 MHz input frequency.

Keywords: radio frequency energy harvester (RF-EH), wireless sensor networks, Greinacher voltage multiplier, conversion efficiency, matched rectifier circuit, 5G band

1. Introduction

Wireless Sensor Networks (WSN) are used in numerous applications such as medical, industrial, and security. The battery replacement is not possible for WSN with thousands of embedded nodes, these nodes may be needed energy collected from the environment in a variety of methods such as seismic, thermal, solar, radio frequency (RF), and others. WSNs can be powered via RF energy harvesting (RF-EH) [1]. An RF energy harvesting circuit can provide energy solutions to wireless devices by allowing them to harvest energy from accessible RF signals in the surrounding [2, 3]. RF energy harvesting is used in a variety of applications, including WSN, wearable devices, wireless charging, and Internet of Things (IoT) [3-6]. It is used to harvest energy from the surrounding environment and subsequently used for powering the devices like wireless sensor nodes [1-4].

Rectenna is a high-frequency system comprised of a rectifier and an antenna. The rectenna system is made of the essential components of the RF energy harvester system by which RF energy is received through the antenna and converted into a DC signal using the rectifier [4-8]. Rectifier cum Multiplier is used in the RF-EH circuit to transform the RF-to-DC. Various multipliers like Greinacher, Villard, and Dickson voltage multipliers were used for RF-EH circuits. But Greinacher voltage multipliers are mostly used because they offer large efficiency [4].

One of the most crucial components for combining and converting the incoming RF signal from the environment into DC is the antenna [5, 6, 8]. The radiative efficiency of the antenna and the conversion efficiency of the rectifier are often the determinants of the efficiency or output voltage of the receiver system. The antenna's radiation efficiency indicates how well it can transmit and receive signals [8-9].

The matching circuit ensures that the large power is delivered from the antenna to the rectifier circuit. These characteristics enable efficient and reliable rectification in a wide range of electronic systems. To increase power transfer or reduce reflections from the load, impedance matching is used. For the purpose of rectification, a Greinacher voltage rectifier cum multiplier is used in the proposed RF energy harvester circuit due to its advantages, such as voltage multiplication, simplicity, high voltage efficiency, low cost, and ripple reduction [10-11]. Agilent Technologies 3-terminal Schottky Diode HSMS-2852 is used for implementing a rectifier due to its low forward voltage drop, fast switching speed, high breakdown voltage, small form factor, and three-terminal configuration. Schottky diodes are used in the harvester circuit because due to low voltage drop and a very high speed. Schottky diode hp_HSMS2852_20000301 is used for rectifier implementation [12-15]. A variety of frequency bands, including LTE (Long-Term Evolution) (750–800 MHz), DTV (Digital Television) (550–600 MHz), GSM (Global System for Mobile Communication) band (900–1800 MHz), GPS band (1575 MHz), ISM (Industrial, Scientific, and Medical) (2.1–2.6 GHz), Wi-Fi (Wireless Fidelity) (2.4–2.45 GHz) etc. are widely used for radio frequency energy harvesting [16-17]. 700 MHz band is the most widely used band for 5G applications across the globe.

2. Design of unmatched harvester circuit

In order to convert the received RF signal into a DC signal and to increase the low power level of the received signal, voltage multipliers are utilized in energy harvesting techniques [18-19]. The various voltage multipliers like Villard, Dickson, and Greinacher voltage multipliers were discussed for RF energy harvester circuits [12-13].

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The Villard circuit is made up of two simple components as shown in Fig. 1, which have a diode and a capacitor. The Villard circuit has the advantage of simplicity, but it is also known to produce output with poor ripple characteristics. The Villard circuit is, in simple terms, a diode clamp circuit. Negative high cycles are utilized to charge the capacitor to the AC peak voltage [10].

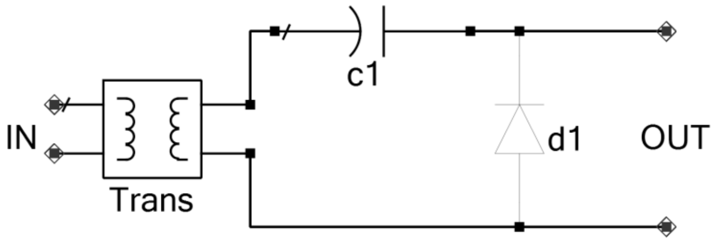

Fig. 1. Circuit diagram of Villard voltage rectifier

Figure 2 shows the circuit diagram of the Greinacher voltage rectifier. It has many advantages to the Villard circuit at the expense of an additional diode and a capacitor.This rectifier smooths the severe fluctuations in the DC output compared to the Villard rectifier. It provides high conversion efficiency at low frequency and increased direct current (DC) output voltage at high power [20].

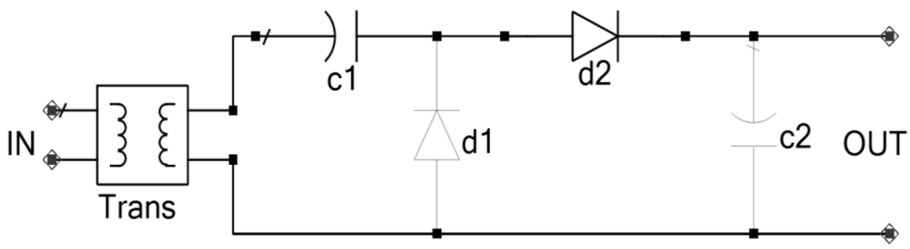

Fig. 2. Circuit diagram of Greinacher voltage rectifier

The first RF energy harvester circuit is designed as shown in Fig.3 without no input matching. The antenna system is represented as a source impedance of 50 Ω at 700 MHz. A Greinacher Voltage rectifier is used in the circuit as implemented by using the Schottky diodes d1 and d2 (di_hp_HSMS2852_20000301) [21]. Two capacitors c1 and c2 (1.0 nF) are part of the Greinacher voltage rectifier circuit. Circuit is optimized for highest efficiency at the output load impedance value of 5 kΩ.

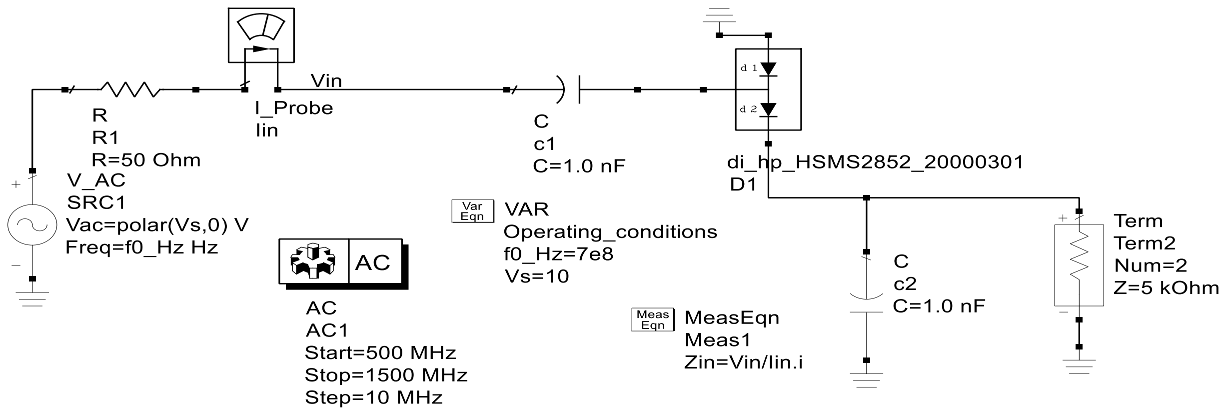

Fig. 3. Unmatched harvester circuit at 700 MHz

The result of input impedance Z_{in} at 700 MHz for the unmatched rectifier circuit as shown in Fig. 4. The real part is 47.9 Ω and the imaginary part is – 429.7 Ω. This value of the input impedance shows the circuit is closely matched to the resistive part but highly mismatched to the reactive part to the source input impedance of $50+j\times 0$ Ω.

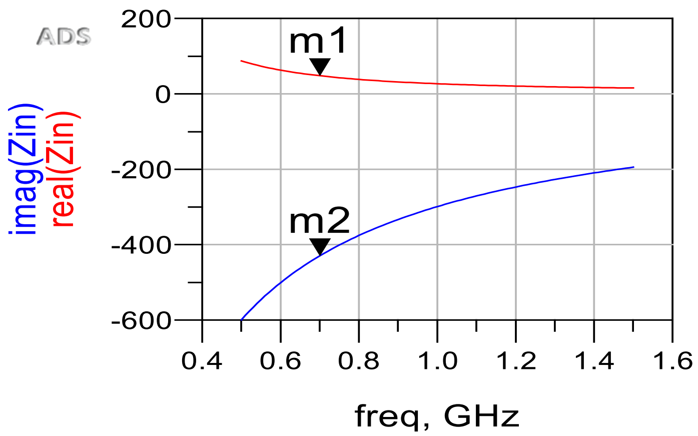

Fig. 4. Input impedance of unmatched harvester circuit: m1 (700 MHz; 47.9 Ω), m2 (700 MHz; − 429.7 Ω)

Figure 5 represents the curve for conversion efficiency versus RF power. Efficiency of 20.5 %, 5.6 % and 0.1 are observed at 8 dBm, – 10 dBm, and – 30 dBm, respectively.

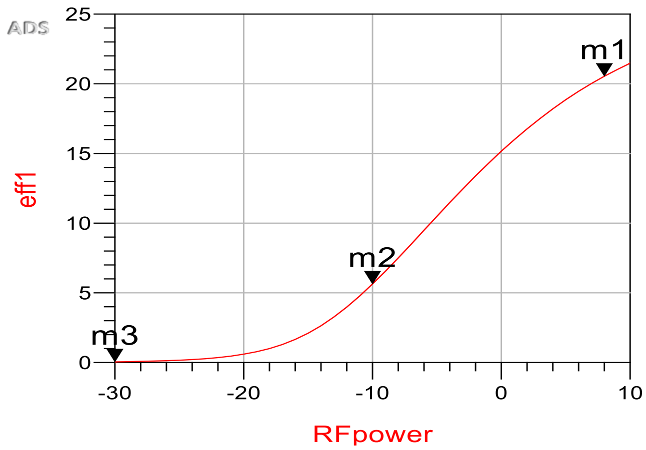

Fig. 5. Conversion efficiency versus RFpower of unmatched harvester circuit: m1 (8 dBm; 20.5 %), m2 (–10 dBm; 5.6 %), m3 (–30 dBm; 0.1)

Figure 6 represents the plot for output voltage versus RFpower of the unmatched rectifier circuit at the same frequency and the output voltage of 2.55 V, 0.17 V and 0 V are observed for 8 dBm, –10 dBm and -–30 dBm input power respectively.

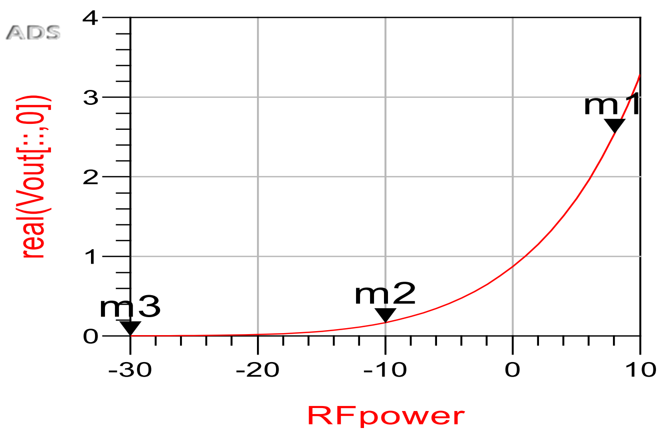

Fig. 6. Output voltage versus RF power of unmatched harvester circuit: m1 (8 dBm; 2.55 V), m2 (–10 dBm; 0.17 V), m3 (–30 dBm; 0 V)

3. Design of matched harvester circuit

LC matching circuit as shown in Fig.7 is applied at the input side of the harvester circuit to match a broad range of impedances. After calculation, the values of matching circuits are found as L=99.87 nH, approximately taken as 100 nH, and C=0.98 pF, approximately taken as 0.5 pF [14-16, 22].

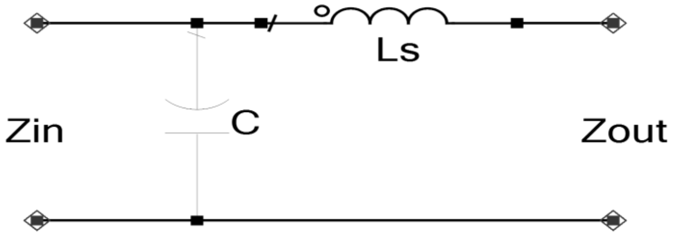

Fig. 7. Circuit diagram of L-match

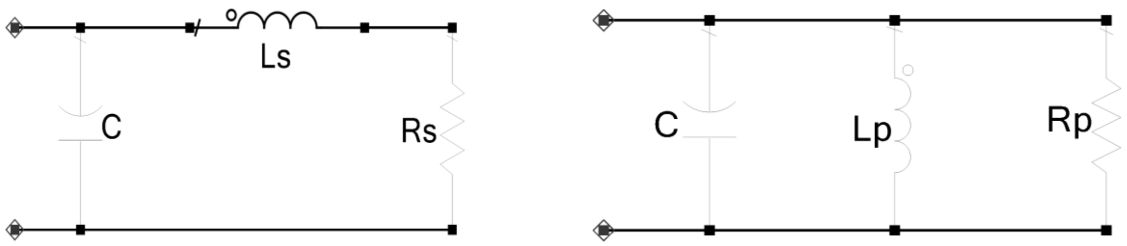

Fig. 8. Circuit diagram of series to parallel conversion

Figure 8 shows the series to parallel conversion for developing matching circuit, where R_S is 50 Ω, R_L is 5 kΩ and the frequency is 700 MHz. The value of quality factor (Q) of 10 is calculated by using (1) and (2). The value of the parallel inductor L_P of 100 nH is calculated by using (3) and (4). The value of series inductor L_S of 99.8 nH is calculated using (5) and (6). Finally, the value of capacitor C of 0.9 pF is calculated using (7) and (8), where $W_0 = 2\pi f_0$ is the desired angular frequency and the value of f_0 for the designed circuit is 700 MHz.

$$R_L = R_S(1+Q^2) \qquad Q = \sqrt{\frac{R_L}{R_S} - 1} \qquad Q = \frac{R_L}{W_0 L_P} \tag{1, 2, 3}$$

$$L_P = \frac{R_L}{W_0 Q} \qquad L_P = \frac{L_S(1+Q^2)}{Q^2} \qquad L_S = \frac{L_P Q^2}{(1+Q^2)} \tag{4, 5, 6}$$

$$W_0^2 = \frac{1}{L_P C} \qquad C = \frac{1}{L_P W_0^2} \tag{7, 8}$$

Matched RF energy harvester circuit is shown in Fig. 9. Input impedance Z_{in} versus inductor L and capacitor C is shown in Fig. 10. Optimized value of the input impedance is achieved at the value of inductor L_S=100 nH and capacitor C=0.5 pF.

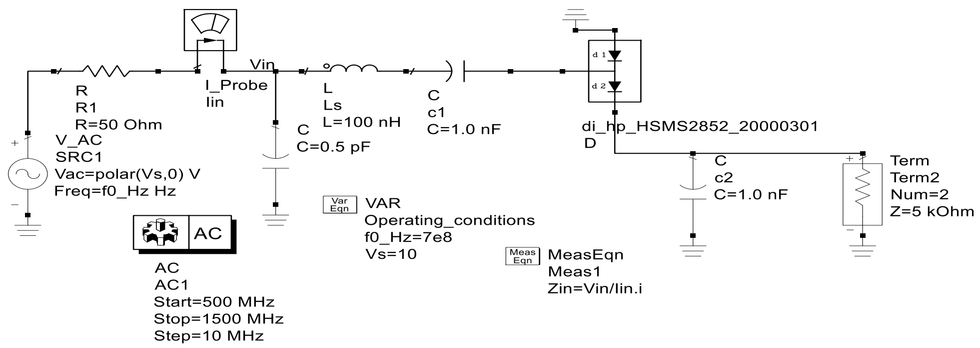

Fig. 9. Matched harvester circuit after LC matching

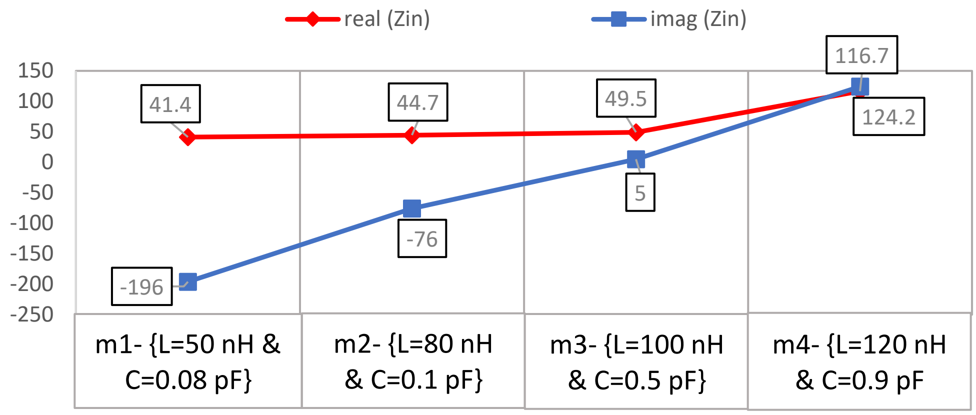

Fig. 10. Input impedance Z_{in} versus inductor L and capacitor C:
m1 (Re{Zin} = 41.4 Ω, Im{Zin} = − 196 Ω), m2 (Re{Zin} = 44.7 Ω, Im{Zin} = − 76 Ω),
m3 (Re{Zin} = 49.5 Ω, Im{Zin} = 5 Ω), m4 (Re{Zin} = 116.7 Ω, Im{Zin} = 124.2 Ω)

The observed result of input impedance Z_{in} for matched rectifier circuit at 700 MHz is shown in Fig.11. The real part is 49.5 Ω, and the imaginary part is 5 Ω, observed for L=100 nH & C=0.5 pF.

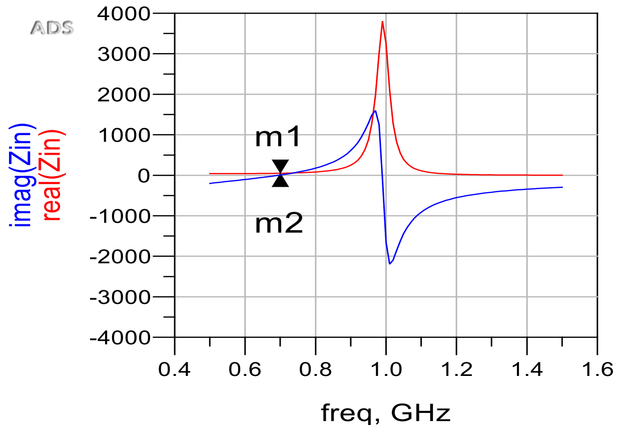

Fig. 11. Input impedance of matched harvester circuit:
m1 (700 MHz; 49.5 Ω), m2 (700 MHz; 5 Ω)

Figure 12 represents the variation of efficiency versus R_{load}. The maximum efficiency is observed as 33.1 % at 5 kΩ.

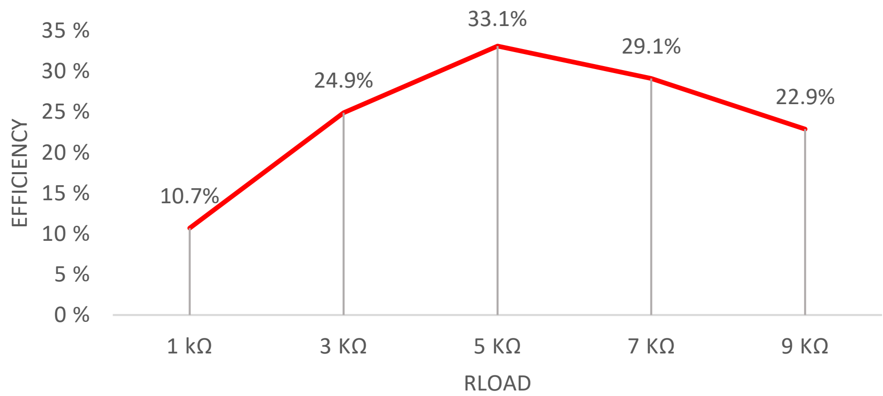

Fig. 12. Efficiency versus R_{load}

Figure 13 shows the variation of conversion efficiency versus RF power for 700 MHz frequency. The conversion efficiency of 33.1 %, 26.7 %, and 8 % are observed at input RF power level of 8 dBm, – 10 dBm and – 30 dBm respectively.

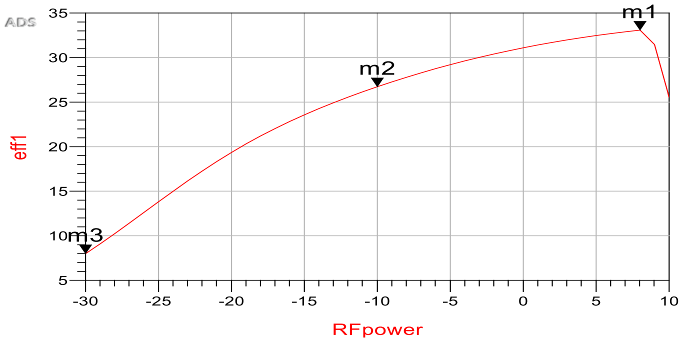

Fig. 13. Conversion efficiency versus RF power of matched harvester circuit:
m1 (8 dBm; 33.1 %), m2 (-10 dBm; 26.7 %), m3 (-30 dBm; 8 %)

To observe the uncertainity, Monte carlo simulation of conversion efficiency versus RF power is performed for the circuit. Figure 14 shows the results of Monte carlo simulation which shows maimum efficiency is 37.95 % and minimum efficiency is 5.12 %.

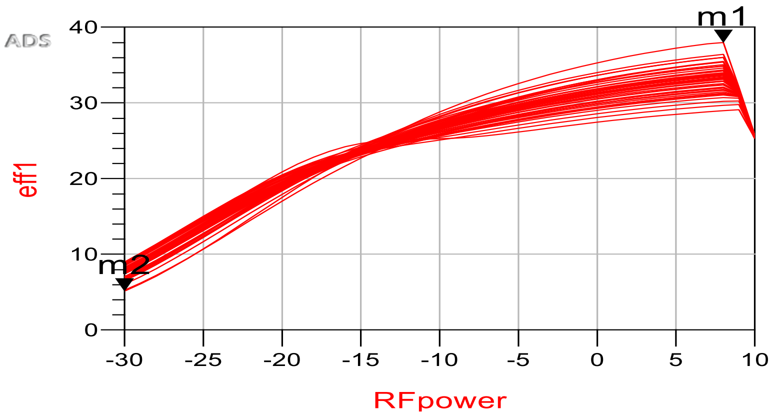

Fig. 14. Monte Carlo simulation of conversion efficiency versus RF power of matched harvester circuit:
m1 (8 dBm; 37.95 %), m2 (–30 dBm; 5.12 %)

Table 1 presents the performance comparison of the proposed circuit with previous similar works, it indicates that proposed circuit achieves large efficiency of 33.1 % at 700 MHz.

Tab. 1. Performance comparison with previous work

Ref. Year	Input power (dBm)	Frequency band	R_{load}	Rectifier element & topology	Conversion efficiency (%)
[15] 2023	0 dBm	2.95 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	Schottky diode SMS7630-005LF & voltage doubler	30%
[20] 2017	10 dBm	250 MHz and 3 GHz	1.3 kΩ	2-diode charge pump and is inkjet-printed on a flexible substrate	>33%
This Work	8 dBm	700 MHz	5 kΩ	Greinacher voltage multiplier and Schottky diode HSMS-2852	33.1 %

Figure 15 represents the plot for output voltage versus RF power of unmatched rectifier circuit. Output voltage values are 3.23 V, 0.37 V and 0.02 V for 8 dBm, – 10 dBm and –30 dBm respectively.

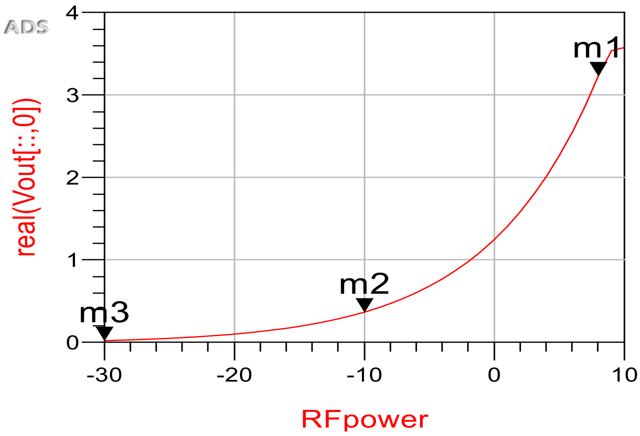

Fig.15. Output voltage versus RF power of matched harvester circuit:
m1 (8 dBm; 3.23 V), m2 (–10 dBm; 0.37 V), m3 (–30 dBm; 0.02 V)

Table 2 presents the variation of efficiency and output voltage of RF energy harvester with the different range of values of Rload, inductor, and capacitor. It is indicated that rectifier shows optimized efficiency and output voltage at Rload of 5 kΩ and L of 100 nH and C of 0.5 pF

Tab. 2. Variation of efficiency and output voltage with passive circuit components

Matching	Frequency	R_{load}	Inductor (L) and& Capacitor (C)	Efficiency (8 dBm RF Power)	V_{out} (8 dBm RF Power)
Unmatched	700 MHz	1 kΩ	–	49.9 %	1.8 V
		3 kΩ	–	29.5 %	2.4 V
		5 kΩ	–	20.5 %	2.5 V
		7 KΩ	–	15.7 %	2.6 V
Matched	700 MHz	1 KΩ	L=50 nH C=0.08 pF	36.5 %	1.5 V
		3 kΩ	L=80 nH C=0.1 pF	38.1 %	2.7 V
		5 kΩ	L=100 nH C=0.5 pF	33.1 %	3.2 V
		7 KΩ	L=120 nH C=0.9 pF	26.1 %	3.4 V

4. Conclusion

This paper presents the RF energy harvester for the 700 MHz frequency band. This band is widely used for 5G coverage across the globe. The Greinacher voltage rectifier along with the input matching provides significant advantages in terms of large conversion efficiency at 700 MHz band and at a load of 5 kΩ. Before matching the conversion efficiency of 20.5 % and the output voltage of 2.5 V is obtained at 700 MHz frequency. After applying LC type matching the conversion efficiency of 33.1 %, and the output voltage of 3.2 V is observed at 700 MHz frequency. As a future scope and efficiency can be further investigated by using other matching like T and Pi matching and other multiplier circuits. This proposed circuit design can be employed in a wide range of RF energy harvesting applications.

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