An n77 Band Antenna for Energy Harvesting

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2025 National Conference on Communications (NCC) | 979-8-3315-3601-5/25/$31.00 ©2025 IEEE | DOI: 10.1109/NCC63735.2025.10983400

***Abstract*—A wideband microstrip monopole patch antenna is introduced for RF energy harvesting for n77 5G band. The antenna consists of two similar elements with line feed in an array style which is designed on an FR-4 substrate. The operating range of this antenna is from 3.22 to 4.25 GHz with maximum radiation at 3.77 GHz. The gain of antenna is always above 2.7 dBi for entire range with the total efficiency greater than 75%. A single-stage Villard voltage multiplier with inverse hybrid L-type matching has been studied for energy harvesting, which provides a maximum output voltage 3.57 V at 5 dBm input power. The rectifier achieves a maximum efficiency of 44.2% with a 10 kΩ load resistance when operating at 3 dBm input power and 4 GHz frequency. For various frequencies in n77 5G band and variety of input RF power 1 to 4 volts output can be drawn using this arrangement.**

***Index Terms*—microstrip, monopole antenna, line feed, n77 band, wideband, energy harvesting, voltage multiplier.**

I. Introduction

Over the years, the emerging idea of wireless power transmission (WPT) has been investigated with communication technology. To fulfill the purpose, microwave power is collected from the space using an antenna and that is rectified with a diode. A lot of research is accomplished in ISM bands including various antennas viz. rectangular, dipolar, spiral-shaped with different polarization schemes, variety of filters and rectifiers [1].

The devices with low power are generally battery operated. For continuous and efficient working of the system these devices needs to charge in a frequent way due to use of batteries. RF energy harvesting is a non-conventional solution to fulfill this need. The system is composed of a receiving antenna of the microwave frequency whose signal is available in the environment, a converter circuit which convert the received signal in to DC signal and a matching circuit for efficient conversion [2]. The DC output voltage can be used to charge the battery of low power devices or used directly through a regulator. In this way, RF energy harvesting provides a non conventional source to supply constant power and lessen need on conventional batteries.

RF energy harvesting is also a promisable solution to IOT devices as their level of power consumption is heavy as per features and functions and they need frequent charging. Fig. 1 shows the basic block diagram of RF energy harvester. The antenna is the primary reception device of the harvester circuit. The receiving antenna can be designed for the range as per the RF signal spread in the nearby environment. Designers can design their own receiving antenna for harvesting module of a suitable frequency. It goes to a rectifier through the matching circuit which provides the DC output for energy storage as well as for regulated power supplies of low power electronic devices. An Antenna array could be used to receive the power in place of a single antenna to gather sufficient power for the system [3]. Also, the desirable condition for the antenna is to operate at multiple frequencies or in a wide band of frequencies instead of only single short band as there are many communication devices working in different nearby frequencies.

However, due to the complication in feed as well as matching circuits, few previous works have been able to realize a short-band harvesting system. One of the previous research [4] presented a line feed antenna with defected microstrip structure (DMS) optimized for the UMTS 2.1 GHz band. The proposed antenna in this research provided high gain of

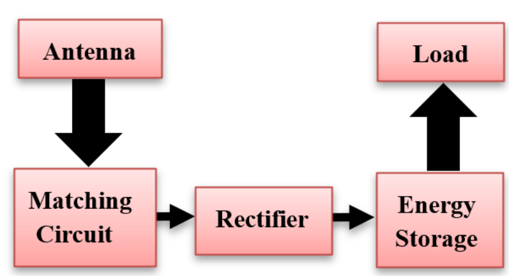

Fig. 1. Block diagram of RF energy harvester.

7.53 dBi with 26.77% compactness. The drawback of this system is its low output of 0.25 V at 10 dBm input power with 49% power conversion efficiency (PEC). Another work [5] presented a coaxial-fed circular microstrip patch antenna optimized for the GSM 1800 band. The proposed antenna in this work has a gain of 5 dBi with power conversion efficiency (PEC) of 29% at -5 dBm input power, with an output voltage of 0.6 V, and a PEC of 28% at 10 dBm input power, achieving an output voltage of 1.67 V. [6] expressed a rectifier circuit for RF to DC conversion at sub-6 GHz 5G bands. It provided maximum power conversion efficiency up to 42.5% for 1.1 kΩ loading and 9 dBm input power. In the above research work antenna design is not discussed. [7] presented a modified printed bow-tie antenna that can be utilized for energy harvesting. This antenna provides a satisfactory peak gain of 3.52 dBi for the frequency range of n78 band (3.3 to 3.8 GHz) which also covers the lower n77 band. In this work, input impedance variation is provided while rectifier response and overall efficiency are not discussed. [8] presented a microstrip hexagonal patch antenna that covers the range of n77 band with a peak gain and radiation efficiency of 3.74 dBi and 86% respectively. This work does not express the input impedance variation, rectifier response, and overall efficiency of the harvesting system. In the above works, some researchers have either designed an antenna or a rectifier circuit for harvesting at 5G new radio (NR) n77 band frequency, which may have a gap. This gap can be filled with antenna design followed by a harvesting circuit to get the results in simulation. Also, at present, the n77 band of frequency is used popularly for 5G communication and many researchers recommended to use the n77 and n-79 band for 5G [9]–[13]. Such designs were not investigated for energy harvesting. For those popular frequencies, a new system can be designed for a wider range of frequencies with improved output voltage and power conversion efficiency.

This research presents a wideband microstrip monopole antenna fed in an array fashion through line feed which works over the entire n77 5G band. This frequency range was chosen as this band of 5G is very much popular to be used in this era and power can be harvested at many places at this frequency range. The RF energy harvesting circuit is designed for the above antenna which provided improved results. Section II of this paper provides the design of antenna while its results are presented in section III. Section IV shows the design of rectifier and matching network with their result, and finally, section V is the conclusion.

II. Proposed n77 Band Antenna

In Fig. 2, the schematic diagram with dimensions of proposed n77 band microstrip monopole antenna is presented. The antenna has two same rectangle elements fed through line feed in an array style. The inner material of elements is removed in a hexagonal shape using parametric analysis to get the desired frequency band. The antenna is designed on a standard FR-4 substrate with a thickness of 1.6 mm due to its

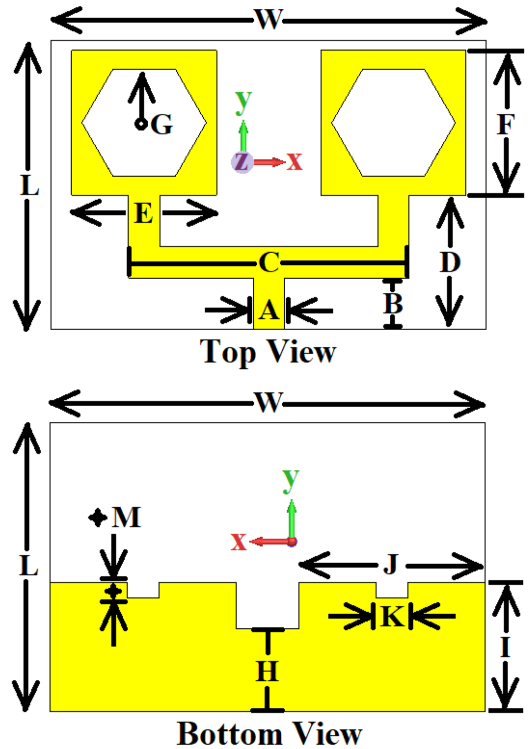

Fig. 2. Design and dimensions of the proposed antenna.

TABLE I
Dimensions of Proposed Antenna

Parameter	Dimensions	Parameter	Dimensions
L	28.00 mm	F	14.00 mm
W	42.00 mm	G	06.00 mm
A	03.00 mm	H	08.00 mm
B	05.00 mm	I	12.50 mm
C	27.00 mm	J	18.00 mm
D	13.00 mm	K	03.10 mm
E	14.00 mm	M	01.50 mm

low cost and ease of availability. The overall structure is of 28×42 mm^2 and a 3 mm broad microstrip feed line is used to fed them with a reference impedance of 50 Ω. The width of feed line is also selected suitably after a parametric study. The dimensions of the proposed antenna represented in Fig. 2 are given in Table I.

A. Design Procedure

The design presented in Fig. 2 is made using 2 elements of engineered squares combined in an array style through a feed line with a dumbbell-shaped defective ground structure on the back side. The square patch is modified by cutting the hexagon of radius 'G' inside the square from the center. At the top middle portion of the ground below each element's feed line, a rectangular cut is made to improve the transition. Both elemental grounds are connected via a wide metallic ground which starts covering the connecting feed line from the top and ends to the bottom zero. Finally, the design is optimized for n77 5G NR sub-6 GHz band using parametric analysis on the dimensions of rectangle i.e. ‘E’ and ‘F’, the radius of hexagon ‘G’ and the width of connecting feed line ‘A’, which is same as width of main line. After completing the analysis in Computer Simulation Technology (CST) software, the values of these parameters were suitably chosen for the band of interest with satisfactory results.

III. Discussion for Results of Antenna

This section presents the simulated results and analysis for reflection coefficient S_{11}, gain, efficiency, and performance of radiation pattern. All the simulated results presented for antenna are produced with CST 2019.

A. Reflection Coefficient

Fig. 3(a) shows the simulated S_{11} of the above antenna. The antenna operates at 4.77 GHz with -10 dB bandwidth from 3.22 GHz to 4.25 GHz. It shows that this covers the entire bandwidth of n77 5G band i.e. 3.3-4.2 GHz.

B. Gain and Efficiency

Fig. 3(b) shows the gain and efficiency in a single plot. The antenna has a satisfactory peak gain of 3.5 dBi in the band of interest while the gain at the center frequency is more than 3.1 dBi which is never less than 2.7 dBi in the entire band of operation. The total efficiency of the antenna is always greater than 75% in the entire band of operation, which approaches to 80% near the center frequency. In this way the antenna has satisfactory performance to use near center frequency for energy harvesting application.

C. Radiation Pattern

Fig. 3(c) illustrate the 2-dimensional radiation pattern for the above antenna. These patterns express the information of radiation in terms of gain. Both H and E plane co and cross pole plots are shown in this figure. The cross pole power is satisfactorily low in the broad side to use this antenna for any application.

IV. Rectifier Design and Matching Network with Their Result

Due to low power transmission and substantial attenuation at the wireless channel, the RF energy harvesting system primarily provides low power density. Consequently, the rectifier’s conversion efficiency is crucial for producing the desired output power from the ambient RF that has been gathered. The efficiency of the circuit is affected by the three separate lossy phases that RF energy goes through throughout the conversion process (Antenna, Matching Network, and Rectifier). Important elements include the impact of reactive, Fresnel, and far-field reception on transmission power as well as line-of-sight communication, which influences the strength of the receiver signal. Furthermore, efficiency is greatly influenced by antenna type and matching networks, rectifier design and voltage multiplier stages affect output and sensitivity, and low-pass filters improve overall performance [11], [12].

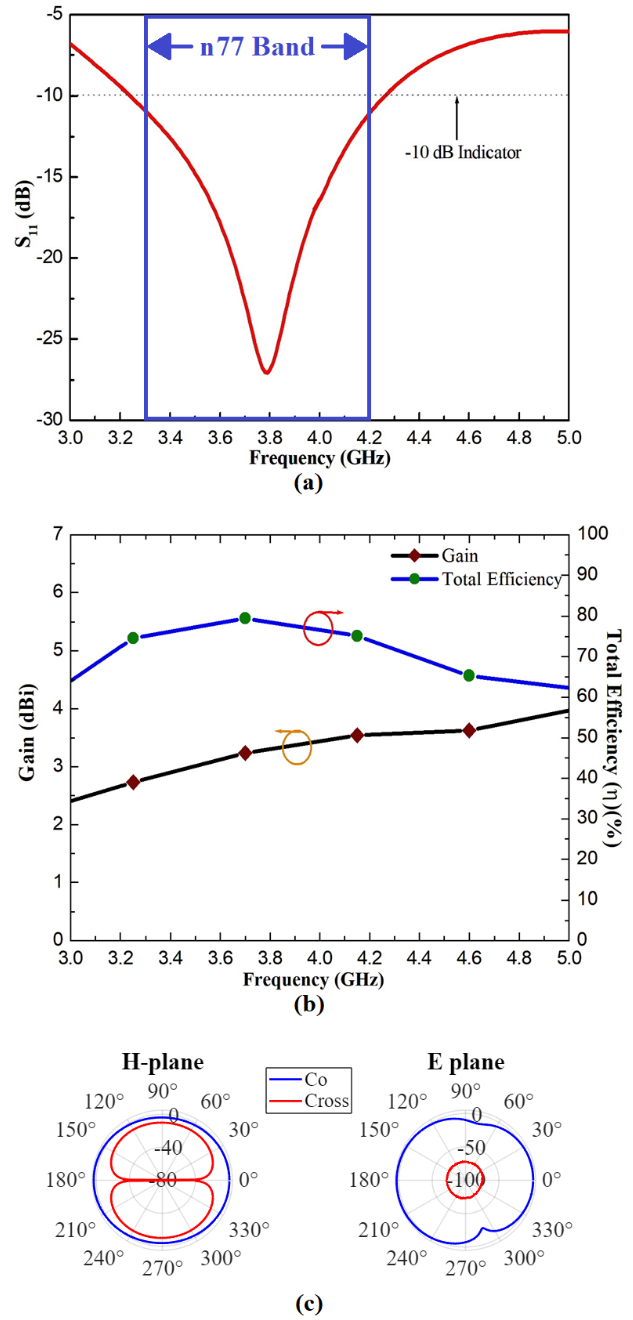

Fig. 3. (a) Simulated S_{11} with frequency, (b) Gain and efficiency plot, and (c) 2-D radiation patterns at 3.77 GHz.

A. Matching Network Design

Due to diode nonlinearity rectifier impedance differs based in input power, frequency and load resistance as depicted in Fig. 4(a) The diode’s nonlinearity causes resonance frequency shifts with input power. Reactance compensation (adjusting inductive and capacitive reactance) can tune the circuit for desired frequencies but limits power transfer and bandwidth. Mismatched impedance reflects power, forming standing waves that reduce output voltage and efficiency, as

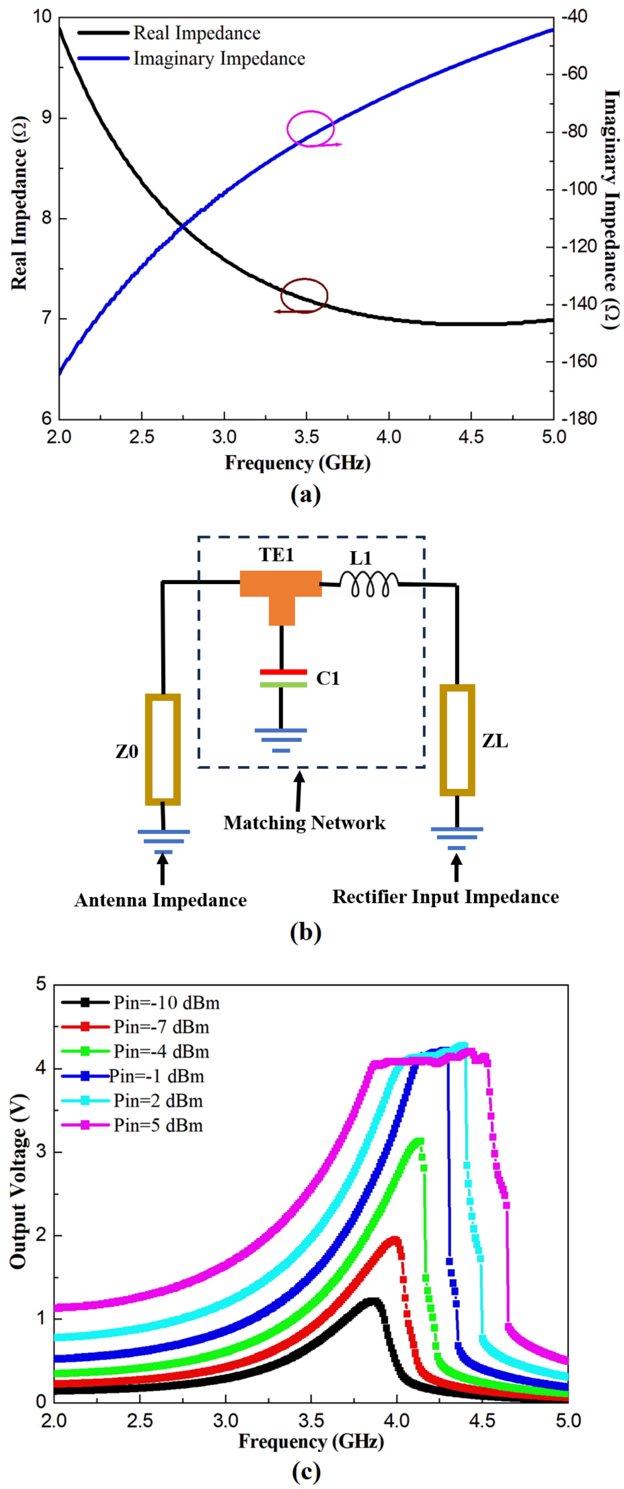

Fig. 4. (a) Input impedance variation of the rectifier with respect to frequency, (b) Matching network circuit, and (c) Rectifier output voltage response over the frequency with matching network.

the diode may not activate with weaker signals. Incorporating a matching network (MN) significantly improves power transfer from source to load. Choosing the right topology and component values in the MN ensures optimal impedance matching.

It has been clear evident Fig. 4(a) that the proposed rectifier input impedance is 7.09-j75.64 ohm at the proposed antenna resonating frequency range 3.2 GHz to 4.2 GHz and source impedance Z_0=50 Ohm. Therefore, an Inverse hybrid (Combination of lumped and distributive element) L-type matching network has been designed to match the source load impedance, which consists of a shunt capacitor (C1 = 3.3 pF), a series inductor (L1 = 4.1 nH) and a distribute T junction (TE1) with width 1.3 mm as displayed in Fig. 4(b).

B. *Design of Rectifier*

Diode choice is crucial for RF energy harvesting efficiency, especially in low power regions [13]. Schottky diodes minimize power loss due to low forward voltage and fast switching. More voltage multiplier stages reduce efficiency at low power ($\leq$ -20 dBm) but boost it at higher power ($\geq$ -20 dBm) [14]. A single-stage Villard voltage multiplier with an inverse hybrid L-type matching network and wide-range antenna addresses low-power demands [15]. The rectifier circuit is implemented using a Schottky diode HSMS-285B (V_{th} = 150 mV) on an FR-4 substrate with a relative permittivity of 4.33 and thickness of 1.6 mm, designed using Advanced Design system-2020 (ADS-2020). The values for the capacitors are C2 = C3 = 3.1 pF.

The unloaded output DC voltage has been studied with different input signal frequencies for different input power ranges from -10 dBm to 5 dBm as depicted in 4(c). The study shows that higher input power enables the rectifier to generate stable DC output across a wider frequency range. Although initially confined to a narrow band, increased input power broadens the effective range for high output voltage, even with narrow-band return loss. This is due to improved load

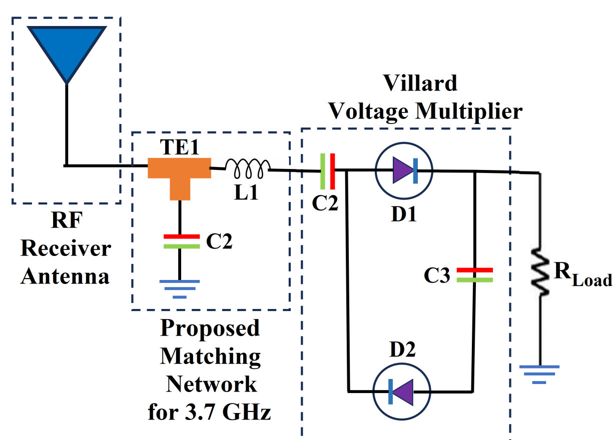

Fig. 5. Overall RF energy harvesting circuit with inverse hybrid L-type matching network.

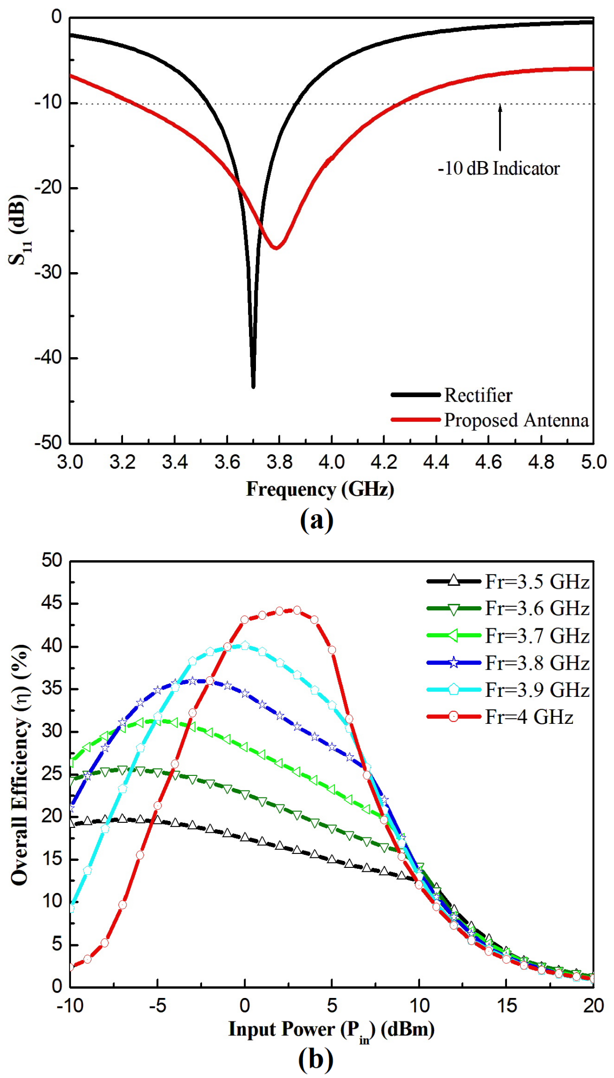

Fig. 6. (a) Simulated S_{11} characteristics of proposed Villard voltage multiplier rectifier and antenna, and (b) Rectifier efficiency variation with input power at different frequencies.

TABLE II
COMPARISON OF PROPOSED ANTENNA TO PREVIOUS LITERATURE

Ref. No.	Subs- -trate (mm)	Dimen- -sions (mm^3)	Freq. range (GHz)	Max. Effic- -iency (%)	Peak Gain (dBi)	Application V_{out}(Volts), P_{in}(dBm), PCE (%)
[4]	FR-4 (1.6)	70×70 ×1.6	1.9-2.2 UMTS 2.1	–	7.53	Energy harvesting 0.25, -10, 49
[5]	FR-4 (1.6)	90×90 ×1.6	1.7-1.9 GSM 1800	–	5.0	Energy harvesting 2.67, 10, 23.8
[6]	5880 RT-D (0.79)	Antenna not designed	3.4-3.6	–	–	Energy harvesting – , 9, 42.5
[7]	FR-4 (1.6)	66.5×32 ×1.6	3.3–3.8	96.00	3.52	Energy harvesting – , – , –
[8]	FR-4 (1.6)	40×48 ×1.6	2.8–4.8	86.00	3.74	Energy harvesting – , – , –
[9]	FR-4 (0.8)	150×75 ×7.8	3.2–6.0	83.00	-	n77/78/79 WLAN 5G – , – , –
[10]	FR-4 (1.6)	36×36 ×1.6	3.9–6.8	77.27	2.53	n77/78/79 Sub-6 5G – , – , –
[11]	FR-4 (1.6)	80×40 ×4.0	3.3–3.8	-	4.53	5G dongle device – , – , –
[12]	FR-4 (0.8)	158×73 ×7.8	3.3–4.5	70.00	-	5G mobile – , – , –
[13]	FR-4 (1.6)	28×56 ×1.6	3.3–5.0	77.00	3.1	n77/78/79 5G NR – , – , –
Pro.	FR-4 (1.6)	28×42 ×1.6	3.3–5.0	80.00	3.5	Energy harvesting 2.97, 3, 44.2

[a] V_{out} is used for output voltage.
[b] P_{in} is used for input power.
[c] PCE is used for power conversion efficiency.
[d] Pro. is used for proposed design.

regulation at higher power, allowing the capacitor to recharge efficiently and sustain output across a broader spectrum.

Since the diode generates both DC and unwanted higher-order harmonics, Harmonic Balance (HB) simulation and Large Signal S-Parameter (LSSP) simulation have been applied up to the fifth harmonic to account for most harmonic effects produced by the diode's nonlinearity. The overall proposed rectifier with its inverse hybrid L-type matching circuit has been shown in Fig. 5. The circuit is tested in ADS software at the antenna's resonating frequency as results shown in Fig. 6(a). Results clearly show that the matching network provides effective impedance matching within the target frequency, ensuring that the source and load impedance are aligned for maximum power conversion efficiency.

The circuit was tested with input power ranging from -10 dBm to 20 dBm and a load resistance of 10 kΩ, as shown in Fig. 6(b). The output voltage rises exponentially with increased input power and load resistance; however, at higher load resistances, the growth rate of output voltage decreases, resulting in reduced conversion efficiency. The conversion efficiency is inversely proportional to the load resistance with respect to input power. Overall conversion efficiency has been experimentally studied for different frequencies as depicted in Fig. 6(b). The output voltage of 2.97 V and 3.57 V has been attained for input power of 3 dBm and 5 dBm for 10 kΩ at 4 GHz respectively, which confirm the 44.2% and 40% conversion efficiency.

The complete RF energy harvesting (RF-EH) system was analyzed through simulation, revealing that the proposed antenna's high gain throughout the operating range significantly enhances received signal strength compared to conventional antennas during fabrication and measurement. This improvement is expected to increase the system's overall output voltage and conversion efficiency once integrated and fabricated.

V. Conclusion

This study presents a wideband microstrip monopole patch antenna for RF energy harvesting in the n77 5G band. Comprising dual elements in an array configuration on an FR-4 substrate, the antenna operates from 3.22 to 4.25 GHz, with peak radiation at 3.77 GHz, maintaining a gain above 2.7 dBi and over 75% efficiency across the range. A single-stage Villard voltage multiplier with inverse hybrid L-type matching achieves a maximum output of 3.57 V with an efficiency of 40% at 5 dbm while an output voltage of 2.97 V with an efficiency of 44.2% at 3 dBm input with 4 GHz frequency and a 10 kΩ load. This system shows strong potential for 5G RF energy harvesting. Future work can aim to enhance rectifying circuit efficiency, optimize n77 bad frequency antennas for higher gain, and explore flexible substrates for wearable IoT devices for 5G band, as wideband and multi-band designs could broaden wireless and energy-harvesting applications.

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