WPT for medical application with a nonsymmetrical pair of spiral resonator and self-matching rectifier

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Abstract-- This paper presents a WPT nonsymmetrical pair of spiral resonators with a lumped elements on the transmitter side only and a compact receiver designed for biomedical implant applications, with high efficiency the system achieves an efficiency of 68.89% with 16mm Rx and 81% with a symmetric 30mm Rx at operation frequency of 433MHz at a distance of 20mm at air as a medium, the resonator consists of a main inner loop for matching at 50Ω and outer loop with three circular turns to increase coupling, the receiver dimensions are finely tunes to eliminate the need of lamped element at it's side, it also presents a self-matching rectifier… .

Index Terms — wireless power transmission (WPT), resonator, Matching Network, Rectifier.

I. INTRODUCTION

Wireless Power Transfer (WPT) has emerged as an innovative technology that enables the transmission of electrical energy without the need for physical connectors or wires. It has found widespread applications, ranging from powering remote and mobile devices to reducing dependence on traditional wired systems. To transmit energy between two points without a physical link, conventional WPT systems typically employ two coils — one acting as a transmitter (Tx) and the other as a receiver (Rx) — that generate an induced current via magnetic coupling.Among the various WPT techniques, resonant inductive coupling has garnered significant attention due to its ability to achieve high power transfer efficiency (PTE) over moderate distances. This is accomplished by matching the resonant frequencies of the transmitter and receiver coils, thereby maximizing the coupling strength and minimizing energy loss. This study focuses on the design of a WPT system based on resonant inductive coupling, in which energy is transferred through inductive coils tuned to a specific resonant frequency to enhance efficiency. Although this technique offers superior range compared to traditional inductive methods, it also presents key challenges — most notably in optimizing power transfer efficiency (PTE) and extending operational distances while maintaining acceptable performance(d). Several studies were carried out to improve these parameters (PTE and d).

In [1], a dynamic frequency adaptation WPT system was proposed with stacked metamaterials, operating at 50.3 MHz for medical applications. The system achieves a power transfer efficiency (PTE) of 42% at a transfer distance of 18 mm. In [2], two concentric open-loop spiral resonators (OLSRs) are introduced to enhance the magnetic coupling in nonradiative wireless power transfer (WPT) systems. The proposed system operates at 438.5 MHz, achieving a measured power transfer efficiency (PTE) of 70.8% at a transmission distance of 31 mm and a design area of 576 mm². In [3], a wireless power transfer (WPT) system integrating a metasurface for biological applications operates at 430 MHz, with an S21 of -27.9 dB at a transmission distance of 6 cm. The receiver element is implanted 3 mm beneath the skin surface and exhibits a dual-band characteristic, enabling simultaneous power transfer and data telemetry. When integrated with the metasurface, the system achieves a 15.7 dB enhancement in magnetic coupling. In [4], a printed spiral coil integrated with a planar interdigital capacitor is proposed to achieve improved tolerance to angular and lateral misalignment. The WPT system operates at 13.56 MHz, achieving a maximum measured power transfer efficiency (PTE) of 71.84% under perfect alignment at a transfer distance of 25 mm. The study investigates misalignment effects between the transmitter and receiver. In [5], a printed conformal split-ring loop is proposed as a self-resonator that behaves as a series LC circuit at its resonance frequency. A magnetic resonant coupling (MRC) WPT system based on series–series topology is implemented, operating at 433 MHz. At a transfer distance of 22 mm, the system achieves a maximum measured power transfer efficiency (PTE) of 87.9%. [6] presented a design for displacement-tolerant printed spiral resonators with capacitive compensated-plates. The simulations and measurements showed that this design achieves a power transfer efficiency of up to 74.96% at a transfer distance of 15 mm, with good tolerance to both angular and lateral displacements. This system operates at a frequency of 13.56 MHz. In [7], a system for wireless power transfer to implantable medical devices is proposed. The system operates at 403 MHz and consists of two coupled resonators:

- A primary (external) resonator placed 5 mm above the skin.
- A secondary (implanted) resonator located 5 mm beneath the skin, resulting in a total separation of 10 mm. The power transfer efficiency is reported as:
- 5.24% based on experimental data.
- 7.3% based on numerical data."

At the core of efficient Wireless Power Transfer (WPT) systems lies the rectifier — a pivotal component that converts the transmitted high-frequency alternating current (AC) into a usable direct current (DC) output. With the growing demand for wireless charging applications across diverse fields such as consumer electronics, implantable medical devices, and electric vehicles, there is an increasing need for high-performance rectifiers. These rectifiers must not only achieve high power conversion efficiency but also maintain stable operation transmission distances.

Several previous works have explored the performance of RF rectifiers using various Schottky diodes over different frequency ranges. In [8], a rectifier utilizing the HSMS-2850 diode was designed for broadband operation between 1.8–2.5 GHz, achieving a maximum conversion efficiency of 24% at −20 dBm input power, with an S11 of −25 dB, a DC output voltage of 1.8 V, and occupying a large area of 32.43 cm². Similarly, the design in [9], which employed the HSMS-285C diode operating at 2.1 and 2.45 GHz, reached 24% efficiency at 10 dBm, with an S11 of −23 dB and 1.9 V output, within 24.50 cm². In [10], a combination of HSMS-285x and HSMS-286x diodes was used at 2.45 GHz, achieving a notable 51.3% efficiency at −15 dBm, though the S11 parameter was not reported. The output voltage was 0.402 V and the occupied area was 23.68 cm². A more efficient design is presented in [11], where the HSMS-285C diode was used at 1 GHz, achieving 70.5% efficiency at 7 dBm input power, with an S11 of −14 dB and an output voltage of 1.8 V in a compact size of 3.975 cm². The rectifier in [12], based on the HSMS-2850 diode at 900 MHz, reached an efficiency of 50.2% at 2 dBm, with an S11 of −18 dB and an output voltage of 0.75 V, within 3.51 cm². Furthermore, the design in [13], using the HSMS-2860 diode for the frequency range of 2.3–5 GHz, achieved 65.56% efficiency at 18 dBm, with an S11 of −25 dB and a high DC output voltage of 6 V, in a compact 0.756 cm² area.

This paper focuses on the power transfer over air with 20mm to 40mm range, with a compact side and deviation tolerance and also presents an innovative rectifier system coupled with a highly efficient impedance matching network, tailored for wireless power transfer (WPT) applications. The proposed rectifier achieves maximum efficiency 55.2% at the input power 0dB when the frequency 431MHz with size area 0.2925 cm^2, even under load equal 4KΩ.

In this paper, the rectifier circuit was designed and simulated using Advanced Design System 2016 (ADS 2016), whereas both the transmitter and the receiver structures were designed and simulated using Computer Simulation Technology Studio Suite 2023 (CST Studio Suite 2023)

I. Proposed WPT resonator system

The proposed work is made of two parts each with a different substrate material and dimensions, for the transmitter, the substrate is Rogers RO3003 with ε_r of 3 and thickness of 0.76 mm, a diameter Ro of 30mm, track width of 2mm, Rs = 6.1mm, Ri = 2.9mm, Gs = 0.5mm, Gp = 2mm.

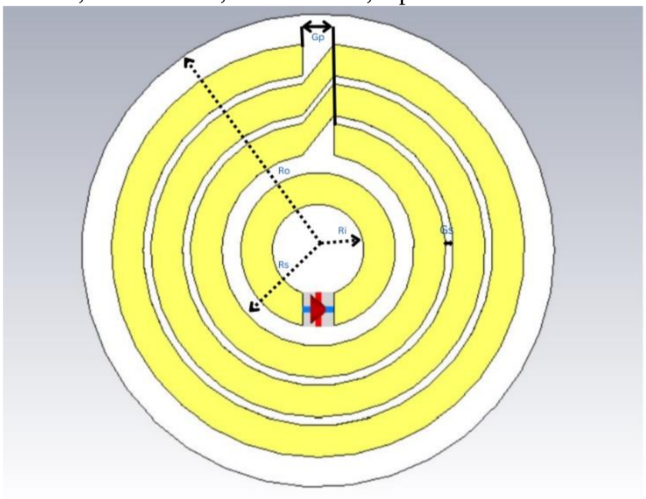


Figure 1 proposed transmitter resonator without the lambed element

The S11 of the proposed transmitter structure is shown in Fig. 1, is as in Fig. 2 with a value of -52dB at 436MHz and an acceptable bandwidth of 6MHz with value under -14dB, this value will be greatly affected with the addiction of the receiver circuit and the resonances frequency will get lower.

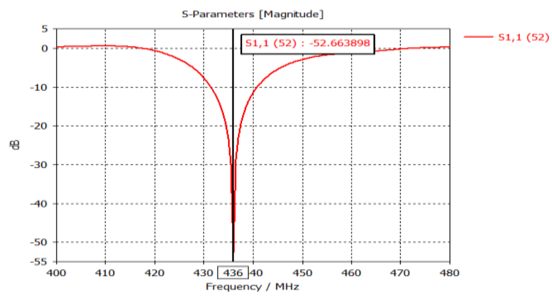


Figure 2 frequency response of the transmitter with the bandwidth shown

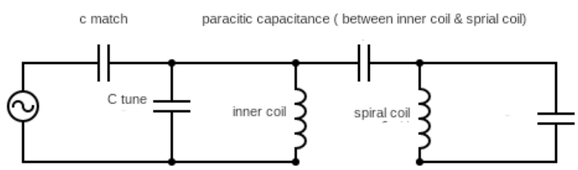


Figure 3 equivalent circuit for the transmitter

Fig. 3 is an approximate equivalent circuit for the transmitter resonator. as for the receiver, it is the same design as the transmitter but with a smaller dimension. The substrate is Rogers RO3006 with ε_r of 6 and thickness of 1.562mm, a diameter Ro of 16.8mm, track width of 1.2mm, Rs = 4.7 mm, Ri = 2mm, Gs = 0.2mm, Gp = 2mm.

III. Performance of the Proposed WPT system

The proposed system has an efficiency of a 42% without the use of the lamped element at the transmitter side at 20mm as shown in Fig. 3

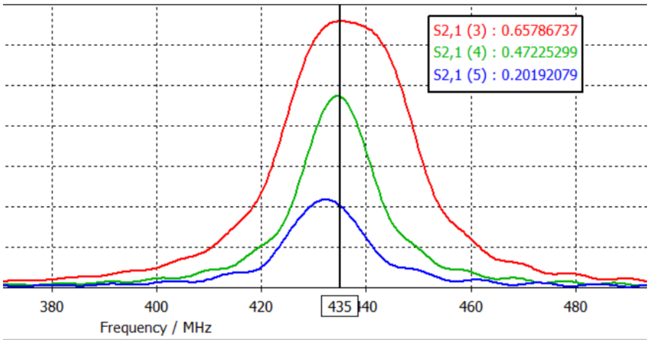


Figure 3 S2,1 as it decreases with distance from 20mm to 40mm.

When the distance goes below 20mm the effect of mutual inductance start to appear as shown in Fig. 4

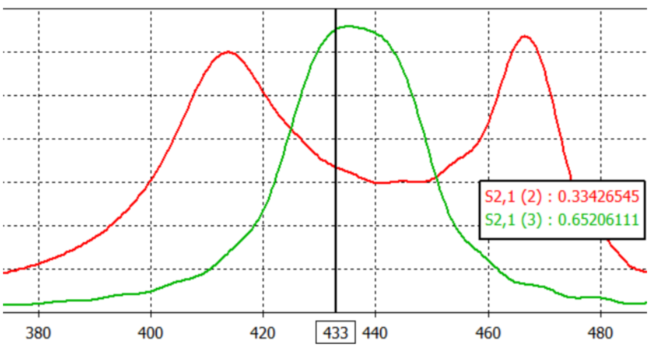
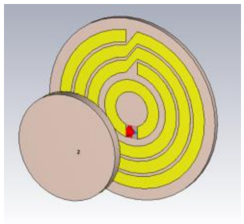


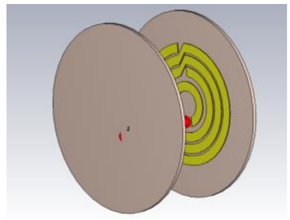
Figure 4 effect of mutual inductance

(for red d=10mm, green d=20)

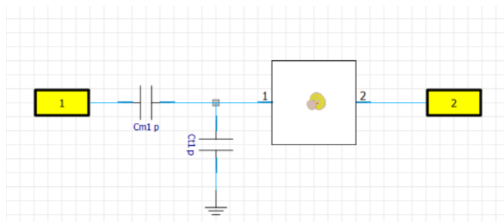
To increase the efficiency a lamped elements Fig. 6 are added for matching (Cm1) and to adjust for frequency a parallel tunning capacitor (Ct1) is introduced, this addition increases the power transfer efficiency to 68.9%, also if the application permits larger size the transmitter resonator can be used at the receiver end with an efficiency of 81%



30mm Tx with the 16mm Rx



two symmetrical 30mm resonator



2Figure 5 Cm1 = 7.4pF, Ct1 =3pF

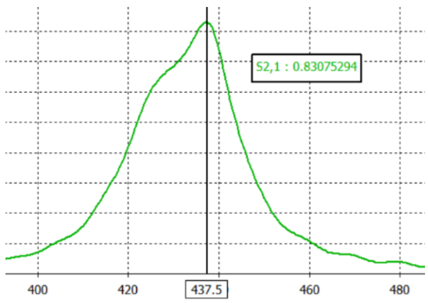


Figure 6 effect of the lamped elements on the efficiency

if the size of the Rx is not a constrain for the medical application two symmetric 30mm resonators can be used to achieve higher efficiency, with a tuning capacitor Ct = 7.2 pF an efficiency of 81% can be obtained, no matching capacitor needed for this configuration.

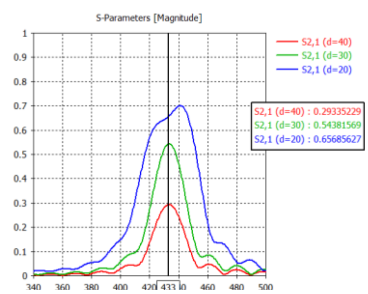


Figure 7 S21 for symmetric 30mm pair as distance changes form 40mm to 20mm. no tuning capacitor

IV. Proposed Self-Matching Rectifier

Recent advances in rectification techniques target self-matching to eliminate the need for a matching circuit or to have a simple matching circuit, so the size of the circuit will be very small compared to the size of using other matching networks. The self-matched structure consists of a diode and a series inductor. In the proposed case, an additional capacitor is proposed in parallel to the diode to offer comprehensive impedance control. This design can achieve a zero-input reactance at an arbitrary frequency of the loading elements . as shown in Figure 7, the input impedance of the proposed design is 50 Ω matching can be achieved by proper design of the series inductor and capacitor, putting in our consideration the internal capacitance and other intrinsic parameters of the used diode at an available input power level and *RL* [15]

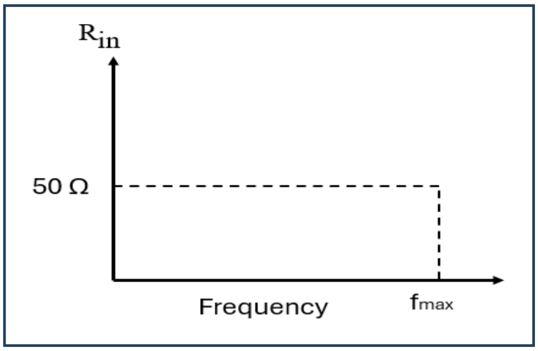


Figure 7 The self-matching design maintains a constant 50 Ω input impedance (Rin) across all operating frequencies

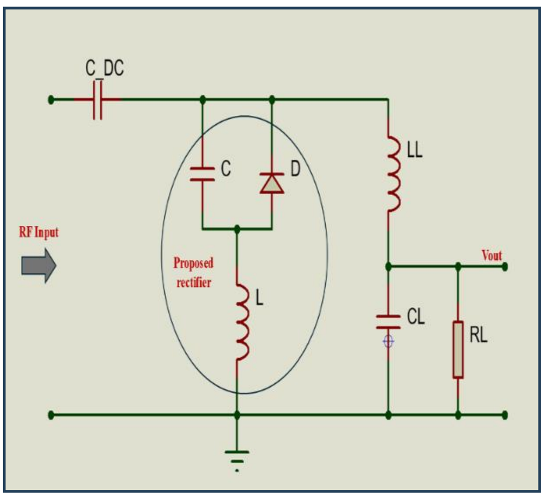


Figure 8 Schematic of the Self-Matched Microwave Rectifier for Low-Power Applications

Figure 8 is the circuit of the proposed self-matched microwave rectifier. In the proposed method, the impedance is pure real [13][14] to know the calculation of Zin.

The Schottky Diode are often favored for operation at low input power constraints due to their lower built-in voltage when compared to other diodes. The diode which used in the design is HSMS2850 which has parameters shown in the table II:-

Table II I parameter of HSMS2850 Schottky Diode

Bv(V)	Vf(V)	Rs(Ω)	Cj(pF)
3.8	0.35	25	0.18

V. Design of proposed rectifier

In this design, it operates at 431MHz with DC output load 4KΩ. the layout of the design as shown in figure 9

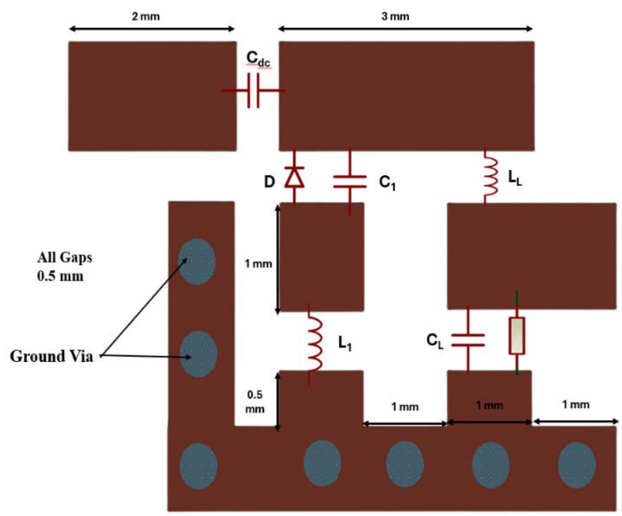


Figure 9 Layout of the Proposed Single-Band Self-Matched Rectifier

The substrate which is used in the design is Rogers RO3003 that has the following parameters:-
Hight = 0.762 mm, metal thickness = 16 µm, Ɛr = 3

The optimized elements of the design that we get its values using ADS is shown in the table III:-

Table III II OPTIMIZED ELEMENTS OF THE DESIGNE

Element	Value	Part Number
D	-	HSMS2850

C_{dc}	0.082 µF	GRM155R71C823KA88
C	0.6 pF	GCQ1555C1HR60WB01
C_L	0.082 µF	GRM155R71C823KA88
L	130 nF	0603DC-R13
L_L	22 nF	0603DC-22N
R_L	4 KΩ	-

VI. Results

The simulation reflection coefficient of the design is shown in Figure 9 at 0 dBm input power, this simulation results confirm that the rectifier is matched at 431 MHz

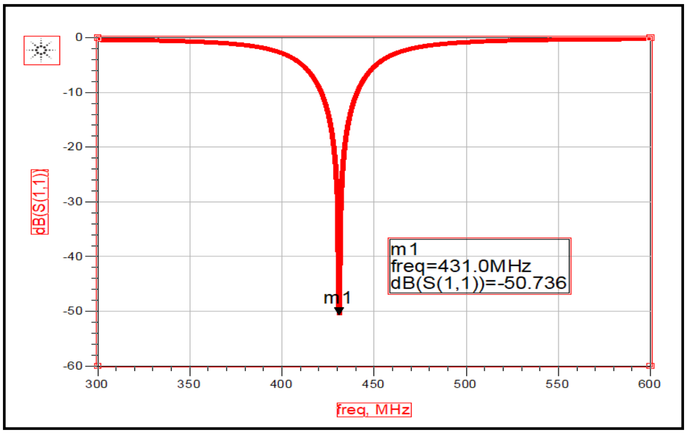


Figure 9 Circuit simulated reflection coefficient (|S_{11}|) using ADS of the proposed Rectifier

Figure. 10 and Figure. 11 shows the RF-DC conversion efficiency ($\eta_{RF\text{-}DC}$) of the design which is calculated as

$$\eta_{Rf-DC} = \frac{V_L^2}{R_L p_{in}}$$

Where P_{in} and V_L are the input RF power, and the output voltage respectively.

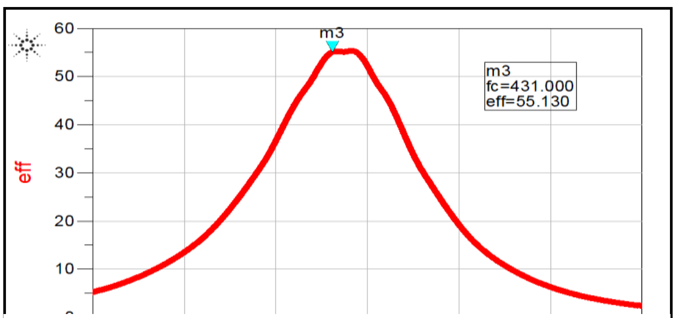


Figure 10 ADS simulated RF-DC conversion efficiency of the proposed Rectifier

In **ADS software**, RF-DC conversion efficiency ($\eta_{RF\text{-}DC}$) of the design which is calculated as

efficiency=100*(mag(vout2[::,0]))*(mag(I_Probe2.i[::,0]))/(db

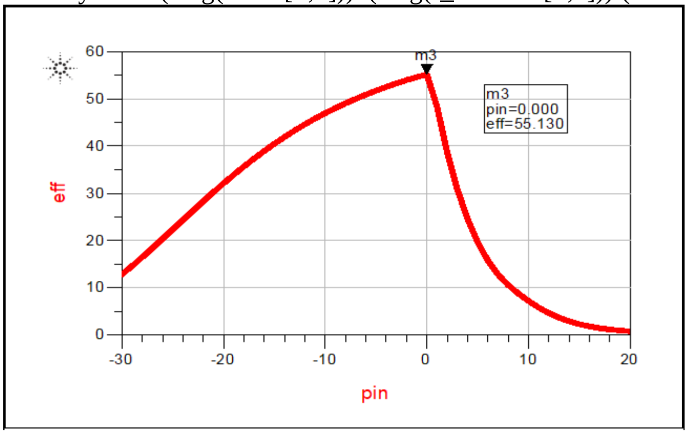
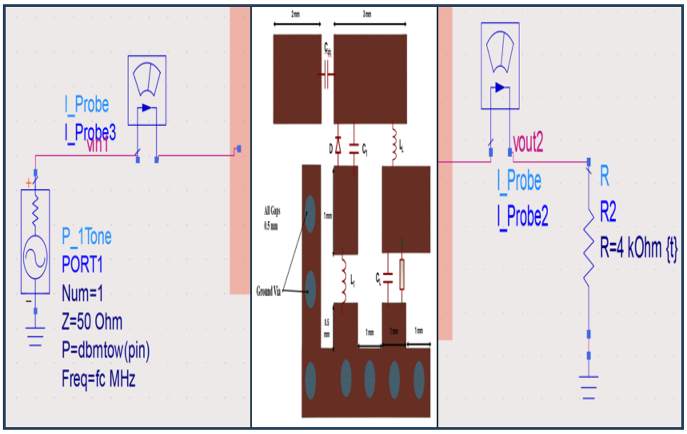


Figure 11 ADS simulated RF-DC conversion efficiency and DC load voltage versus input power

mtow(pin))

where pin is the input power and the connection as shown in Figure 12



this design provide output voltage equal 1.458 V at input power 0dB as shown in Figure 13 at frequency 431MHz

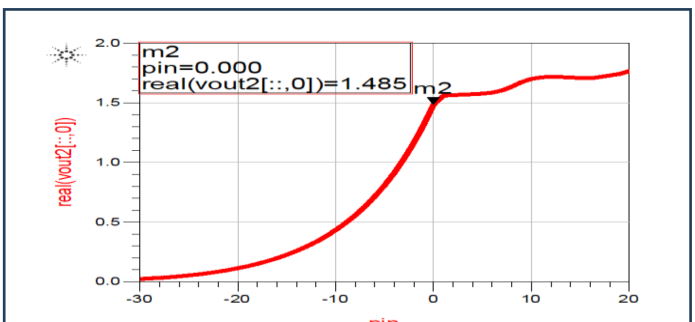


Figure. 13 output voltage vs input power at 0dB

Figure 14 show the input impedance of the proposed rectifier

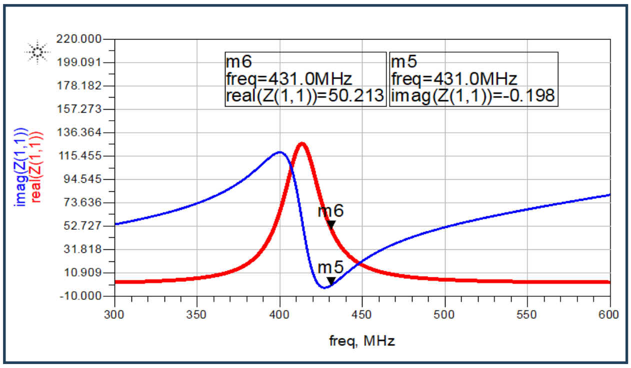


Figure 14. input impedance of the proposed Rectifier

A compact and efficient RF rectifier operating at 431 MHz has been designed and optimized using a novel self-matching technique. This approach significantly simplifies the matching network while ensuring effective impedance control, which enhances the overall performance. The final design achieves an RF-to-DC conversion efficiency of over 55%, with a remarkably small footprint of just 0.2925 cm². Compared to existing designs, this work demonstrates a superior balance between miniaturization and power conversion efficiency, making it highly suitable for modern wireless power transfer applications where space and performance are critical.

Table IV Performance Comparison of the Proposed Rectifier with Recent Works

Reference	Diode type	Frequency (GHz)	Max. conversion efficiency (%) @ input power	S_{11} (dB)	Dc output voltage (V)	Size (cm^2)
[8]	HSMS 2850	Broadband 1.8–2.5	24% @ −20 dBm	-25	1.8	32.43
[9]	HSMS-285C	2.1 and 2.45	24% @ 10 dBm	-23	1.9	24.50
[10]	HSMS-285x and HSMS-286x	2.45	51.3% @ -15 dBm	---	0.402	23.68
[11]	HSMS-285C	1	70.5% @ 7 dBm	-14	1.8	3.975
[12]	HSMS2850	0.900	50.2%@ 2 dBm	-18	0.75	3.51
[13]	HSMS 2860	2.3 – 5	65.56% @ 18dBm	-25	6	0.756
This work	**HSMS2850**	**0.431**	**55.2 @ 0 dB**	**-50.736**	**1.485**	**0.2925**

Table 3 COMPARISON OF THE PROPOSED WPT SYSTEM WITH THOSE PROPOSED IN [1]–[7]

Ref.	Operating frequency (MHz)	Tx size (mm^2)	Rx size (mm^2)	Transfer distance (mm)	PTE (%)	Simulation environment
[1]	50.3	400	100	18	42*	body environment
[2]	438.5	576	576	31	70.8	Free space
[3]	430	900	120	20	2.88*	body environment
[4]	13.56	225	100	25	71.84	Free space
[5]	433	2025	2025	22	87.9	Free space
[6]	13.56	225	100	15	74.96	Free space
[7]	403	90.25	90.25	10	5.24	body environment
This work	433	706	221	20	68.9	Free space

(*) with metamaterial

VI. CONCLUSION

This paper has presented a WPT system with a compact resonator designed with two design options for the purpose of the biomedical implants, and a self-matching rectifier for maximum efficiency the results introduced in the paper are simulated with air, with the intention of further development and testing with the human body as a medium.

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