Flexible Rectennas for Wireless Power Transfer to Wearable Sensors at 24 GHz

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***Abstract*—This paper presents the design and implementation of efficient & compact flexible rectennas (antenna + rectifier) for wireless power transfer to wearable IoT sensor nodes at 24 GHz. Two different rectifier configurations i.e. shunt and voltage doubler have been analyzed for performance comparison. Experimental results of complete rectenna have also been demonstrated for conformal surfaces. The proposed flexible rectifiers is fabricated through conventional PCB manufacturing method. Measured RF-DC conversion efficiency of 31% and DC voltage of up to 2.4 V is achieved for 20 dBm input power across an optimal load resistance of 300Ω at 24 GHz.**

Keywords—Antenna Arrays, Millimeter-waves, Rectifiers, Rectennas, Wireless Power Transfer.

I. INTRODUCTION

Wireless power transmission (WPT) technology have been studied and implemented for decades. Many studies have been reported on near field and low frequency WPT. Due to emerging trends of millimter wave (mmW) communications and rapid development of Internet-of-Things devices and sensor nodes, the WPT has grabbed attention in wireless power charging and battery-free solutions in these emerging applications [1, 2]. An efficient wireless power transfer system mainly depends on the efficient rectenna (antenna + rectifier) design and specifically a rectifier circuit with high RF-DC conversion efficiency [2]. Therefore most of the research efforts focued on the enhancement of RF-DC conversion efficiency of rectifier circuit specifically for thin and flexible substrate materials [3].

General block diagram of a rectenna is shown in Fig. 1. It consists of a high gain antenna to capture the RF signal, an impdance matching network to match the input impedance of antenna with the impedance of rectifier diode, an output DC pass filter and a higher order harmonics rejection filter to improve the system performance and finally a DC resistive load [4].

There are very few reports available in published literature on flexible rectennas, i.e. a combination of an antenna and a rectifier. Jo Bito et al. [5] presented a flexible, inkjet-printed mmW rectenna with maximum output voltage of 2.5 V with 18 dBm of input power at 24 GHz for wearable IoT applications. Daskalakis et al. [6] developed a 24 GHz rectenna on paper substrate with RF-DC conversion efficiency of 32.5% at 15 dBm input power for RFID applications. Zhening Yang et al. [7] designed and fabricated a crossed dipoles array antenna at Ku band and K band for energy harvesting. The proposed antenna design has a maximum gain of 4 dBi at 22 GHz and a fractional bandwidth of 17% from 21.7 to 25.7 GHz for the K band. Kim et al. [8] presented the design and implementation of a flexible RF energy harvester using hybrid printed technology at UHF RFID band (868 MHz - 915 MHz) for far-field RF energy harvesting applications. The designed energy harvester generates a voltage above 2.9 V with an efficiency of 20 % at -7 dBm of input power. In [9], a textile antenna for wearable energy harvesting at 26 and 28 GHz bands was presented. It exhibits a peak on-body gain of 7 dBi with an omnidirectional radiation pattern and radiation efficiency of 40%. In [10], a millimeter-wave flexible antenna using inkjet printing was proposed for energy harvesting applications at Ka band. It shows a peak gain of 7 dBi from 27 GHz to 31 GHz.

In this research article, we present the design, simulation and implementation of flexible antenna array and two different types of rectifiers depending on their configuration (shunt and voltage doubler) for wireless power transfer applications to wearable IoT devices. Initially the MPA array and the rectifier circuits are individually designed, optimized, fabricated and measured, and then the rectifiers are integrated directly with a conformal antenna array to form a complete rectenna. The whole rectenna was fabricated on a Rogers 3003 substrate with thickness = 0.13 mm, $\varepsilon_r = 3$ and $tan\delta = 0.001$.

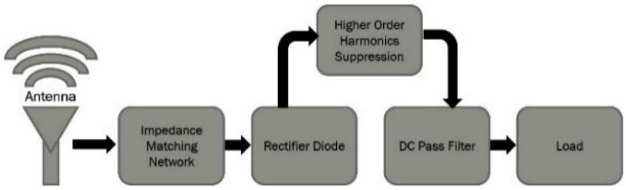


Fig 1. Block Diagram of Wireless Power Transfer System

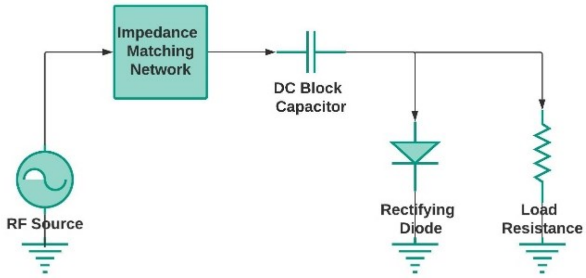


Fig 2. Rectifier circuit in Shunt configuration.

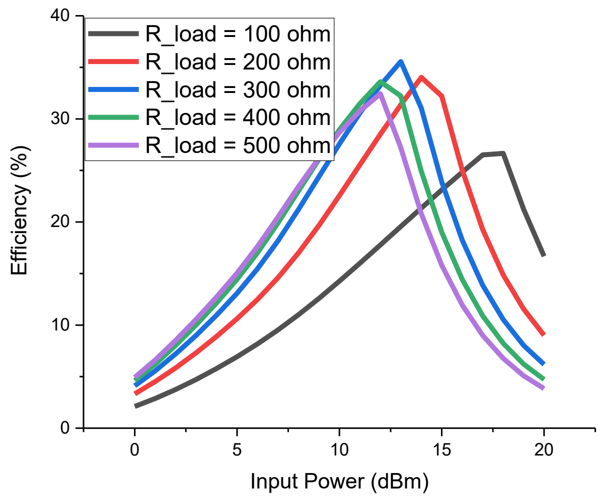


Fig 3. Simulated RF-DC conversion Efficiency as a function of input power across different DC load resistance.

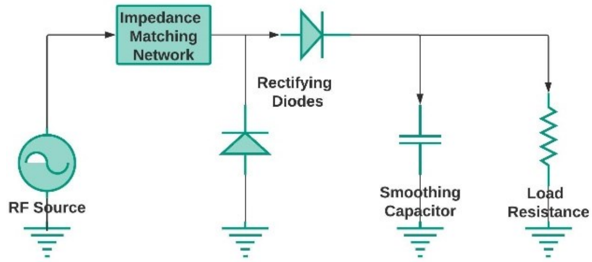


Fig 4. Rectifier circuit in Voltage Doubler configuration.

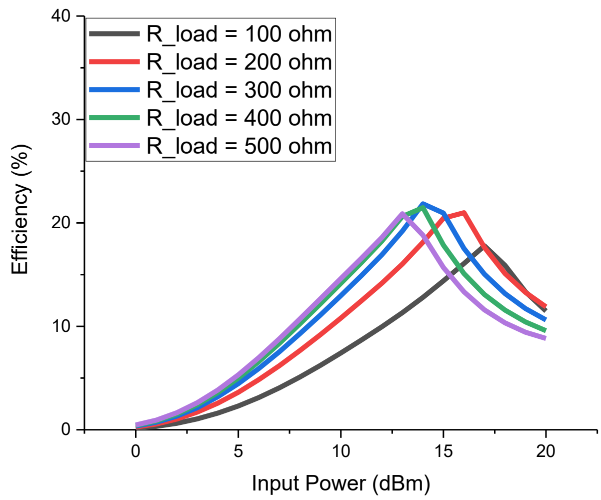


Fig 5. Simulated RF-DC conversion Efficiency as a function of input power

II. Rectifier Designs and Simulation Results

In this research work two different rectifier topologies (shunt and voltage doubler) have been designed and analysed for performance comparison in terms of RF-DC conversion efficiency. RF-DC conversion efficiency is the most critical parameter to evaluate the performance of rectifiers given as:

$$\boldsymbol{\eta} = \frac{\boldsymbol{P_{out}}}{\boldsymbol{P_{in}}}$$

Where $\boldsymbol{P_{out}}$ the output power in DC is, $\boldsymbol{P_{in}}$ is the input RF power. Advance Design System (ADS) version 2015.01 was used to design, simulation and optimization of proposed rectifiers. All rectifier designs parameters like load resistance, smoothing capacitors, the input impedance matching network and the harmonic suppression stubs were optimized to get the maximum RF-DC conversion efficiency. MACOM MA4E2054A schottky diode in SOD-323 package was used in simulation as well as fabrication of rectifiers. A very thin substrate material 0.13 mm was used for the design and fabrication of proposed rectennas to get flexibility.

A. Shunt Configuration

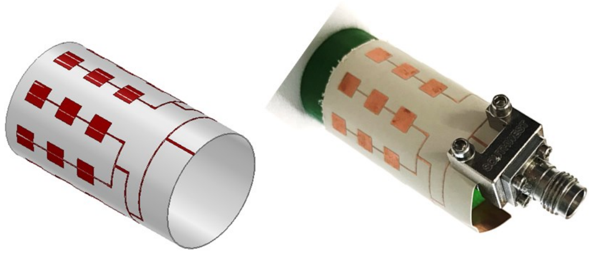
The circuit schematic of flexible rectifier in shunt configuration is shown in Fig 2. The simulated RF to DC conversion efficiency of rectifiers in shunt configuration across different DC load resistance as a function of input power is shown in Fig 3. It can be seen that it gives a maximum RF-DC conversion efficiency of 35% at 300 Ω DC load resistance with an input power of 14 dBm at 24 GHz frequency.

B. Voltage Doubler Configuration

Two diodes and two capacitors were used in this topology to enhance the output voltage as shown in Fig 4. Voltage doubler has a low RF-DC conversion efficiency as compared shunt and series topologies due to more power consumption by the two diodes. It gives a maximum RF-DC conversion efficiency of 20% with 14 dBm input power and 300Ω load resistance as shown in Fig 5.

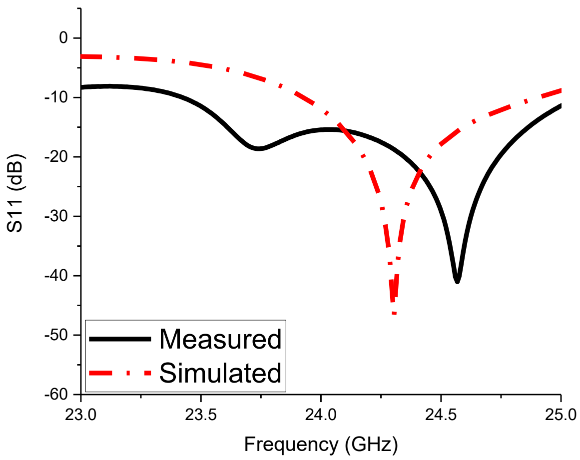
III. Conformal Antenna Array Design

A flexible cylindrical 8x3 MPA array for conformal surfaces and wearable IoT sensor nodes has been designed at 24 GHz. Simulation layout and fabricated prototype are shown in Fig 6(a) and Fig 6(b) respectively. A hybrid feed network was used for the excitation of the patches. After optimizing the simulation results for radiation pattern, the array was fabricated as planar by using very thin substrate material, i.e. Roger 3003 with thickness 0.13mm, and then wrapped array around a 3D printed cylinder of radius *r = 10 mm* to make it conformal and to radiate in all directions. The measured and simulated S-parameters and radiation pattern of conformal MPA array are presented in Fig 7(a) and Fig 7(b) respectively. It has a maximum realized gain of 4.8 dBi at 24 GHz and return loss of less than -40 dB across the 24.125 GHz ISM band. There is some difference in the simulated and measured reflection coefficients i.e. shift in resonant frequency. This shift in the resonant

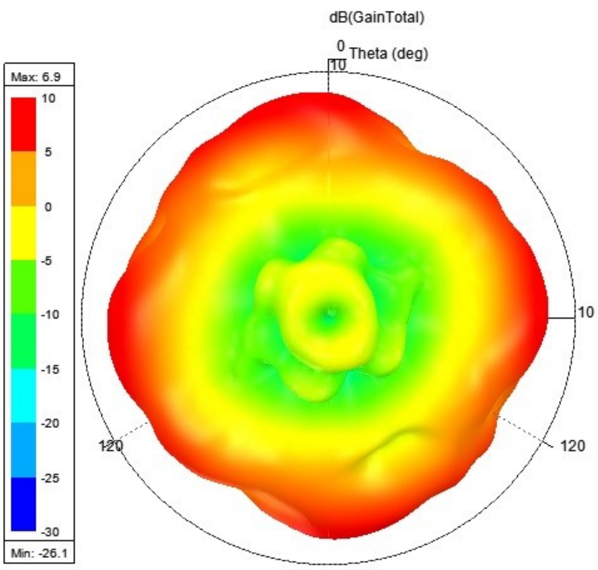


(a) (b)

Fig 6. Conformal MPA array a). Simulation layout b). Fabricated prototype.



(a)



(b)

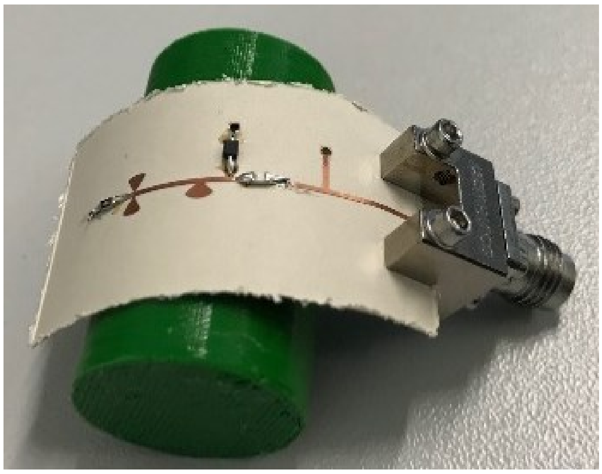
Fig 7. Simulated and measured (a) S-Parameters, (b) 3-D polar plot of conformal MPA array.

frequency could be due to the use of 3D printed dielectric cylinder to wrap the MPA array as shown in Fig 7(a).

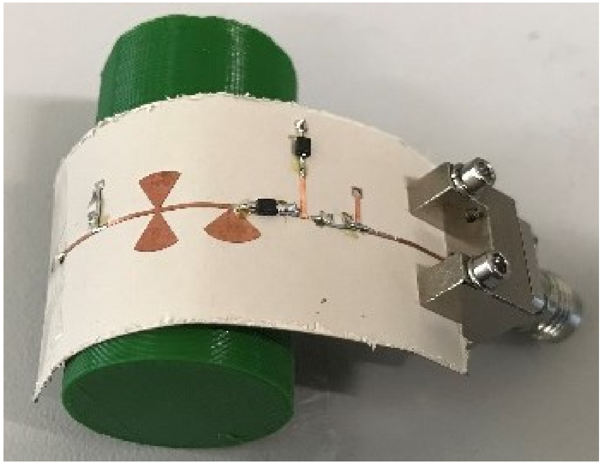
IV. Measured Results and Discussion

A. *Standalone Rectifiers*

An extensive set of simulations as discussed in section II, using Ansys HFSS™ and ADS, were carried out to



(a)



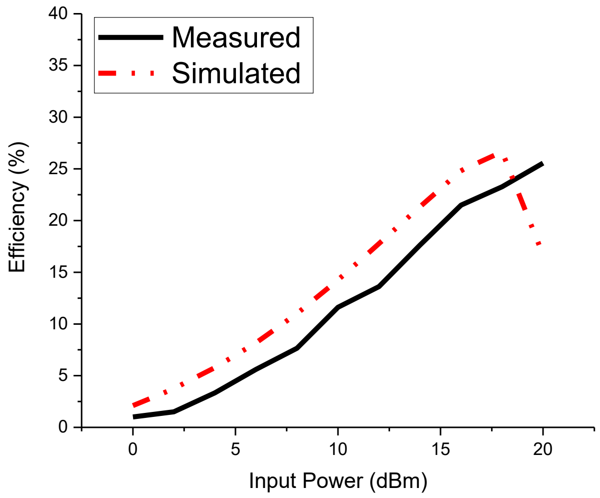
(b)

Fig 8 Fabricated conformal rectifier circuits a). Shunt b). Voltage Doubler.

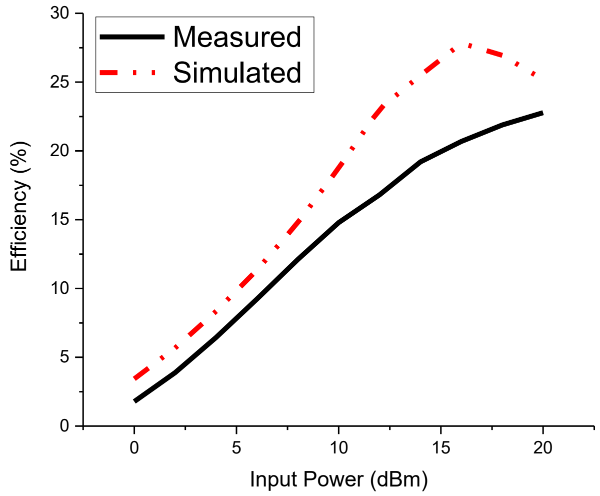
optimize the gain of antenna array and to choose the most optimum rectifier topology among shunt, series and voltage doubler.

To validate the simulated results, the proposed conformal rectifier circuits were fabricated on a 0.13 mm thick Roger 3003 substrate material. Photographs of these fabricated rectifier circuits are shown in Figs. 8. Precision field-replaceable 2.4 mm Southwest Microwave connectors were used to connect the circuits to the coaxial-based measurement equipment. The circuits were measured using a Keysight Signal Generator at 24 GHz. The output voltages of the rectifiers were measured across 300Ω DC load resistance. The comparison of measured and simulated RF-DC conversion efficiency with respect to the RF input power are depicted in Fig 9(a) and Fig 9(b) for shunt and voltage doubler configuration, respectively.

There is some inconsistency between the measured and simulated results due to three basic reasons. First one is the lack of accurate diode model in simulations. Second is the power loss due to mismatch between diode impedance and the input impedance of the rectifier circuit. Third reason could be the imperfections in fabrication and assembly.



(a)



(b)

Fig 9 Measured RF-DC conversion Efficiency of conformal rectifier as a function of input power (a) shunt configuration, (b) voltage doubler configuration.

B. *Combined Rectifier and Antenna (Rectennas)*

In this section the rectifier circuit is combined with the antenna array to form a complete rectenna for WPT to wearable IoT devices at 24 GHz. The fabricated prototype of flexible rectenna on a conformal surface and the measurement setup are shown in Fig 10 and Fig 11 respectively. In this rectenna prototype an 8x3 MPA array connected to 8 individual rectifiers and the voltage across the DC load resistance of each rectifier added up in series by using jumper wires as shown in Fig 10.

As shown the measurement setup in Fig 11. A transmit antenna is connected with a signal generator with a varying transmit power of 0 dBm to 20 dBm at 24 GHz. On the other side the proposed rectenna receives the RF power at a distance of 0.15m and converts it into DC power across the 300Ω load resistance. Fig 12 shows the measured results of output power and RF-DC conversion efficiency of proposed conformal rectenna array. It shows a maximum output DC power of 2.4mW with a transmit RF power of 20 dBm at a distance of d = 0.15m. The RF-DC conversion efficiency

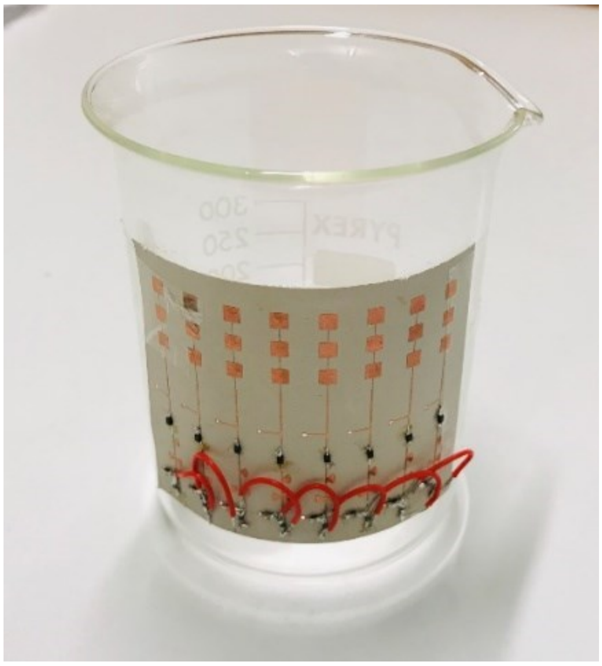


Fig 10 Fabricated conformal rectenna prototypes

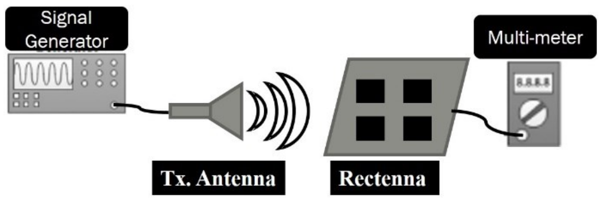


Fig 11 Rectennas measurement setup

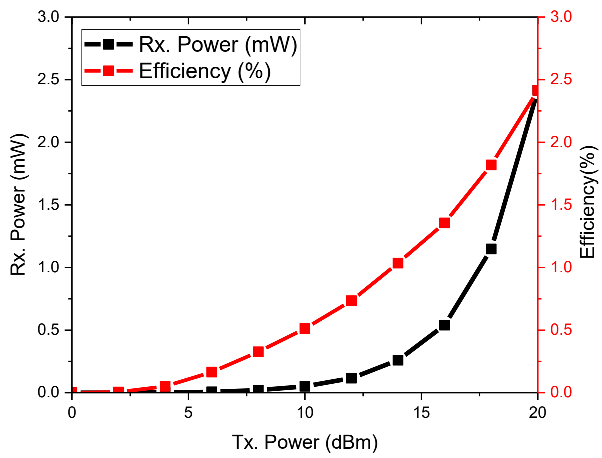


Fig 12 Measured output Power and RF-DC conversion Efficiency of conformal rectenna as a function of input power at d = 0.15mUnits

and measured output power of proposed flexible rectennas will make them a promising candidate for mmW WPT to conformal / wearable IoT devices and on-body medical and health monitoring applications.

V. CONCLUSION

In this research work, design, simulation and experimentation of two types of rectifiers based on different design configurations has been proposed for far field wireless power transfer to wearable IoT sensors. A conformal *8x3* MPA antenna array also presented. The performance of the proposed rectenna has been verified through far-field WPT experiments. It gives an output voltage of more than 2.2 V for input power of 20 dBm at 24 GHz. The proposed mmW flexible rectennas could find numerous applications in the field of wearable IoT devices.

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