Novel High Efficiency RF-DC CMOS Rectifier for RF Energy Harvesting

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Abstract — The increasing demand for autonomous and low-power electronic devices has spurred interest in energy harvesting technologies, particularly radio frequency (RF) energy harvesting. RF-DC rectifiers play a critical role in converting RF signals into usable direct current (DC) power for such applications. This paper presents a novel high-efficiency RF-DC CMOS rectifier design tailored for RF energy harvesting applications. Through comprehensive analysis and simulation, we demonstrate the superior performance of the proposed rectifier in terms of efficiency and power conversion the proposed design holds significant promise for enabling self-powered and energy-efficient wireless sensor networks and Internet of Things (IoT) devices.

Keywords: RF DC CMOS Rectifier, Energy Harvesting, 65 nm Technology

I. INTRODUCTION

With the proliferation of wireless communication systems and the Internet of Things (IoT), there is an ever-increasing demand for self-powered and energy-efficient electronic devices. Traditional battery-based power sources are often impractical or unsustainable for certain applications due to limited lifetime, environmental concerns, and maintenance issues. Energy harvesting technologies offer a promising alternative by scavenging ambient energy from the surrounding environment and converting it into electrical power[1]. Block diagram of RF energy harvesting system shown in Fig. 1.

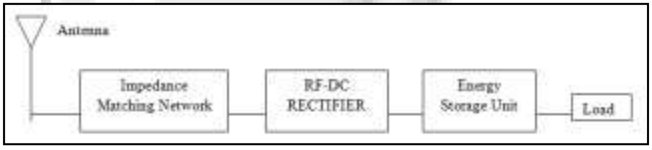

Fig. 1: Block diagram of RF energy harvesting system

Among various energy sources, radio frequency (RF) energy is particularly attractive for harvesting due to its omnipresence in urban environments, courtesy of wireless communication systems, Wi-Fi networks, and other RF-enabled devices. RF energy harvesting enables the development of self-sustaining wireless sensor networks, IoT devices and wearable electronics, thereby eliminating the need for battery replacement or recharging[2].

Central to the RF energy harvesting process is the RF-DC rectifier, which converts the alternating current (AC) RF signal into a direct current (DC) signal suitable for powering electronic circuits. Traditional diode-based rectifiers suffer from high voltage drops and poor efficiency, especially at low input power levels. CMOS-based rectifiers offer a more efficient and scalable solution but often face challenges related to performance, area, and process variability [3].

In this paper, we present a novel high-efficiency RF-DC CMOS rectifier design tailored for RF energy harvesting applications. Through comprehensive analysis and simulation, we demonstrate the superior performance of the proposed rectifier in terms of efficiency, power conversion, and scalability. The proposed design holds significant promise for enabling self-powered and energy-efficient wireless sensor networks and IoT devices [4].

II. BACKGROUND AND MOTIVATION

The quest for sustainable and autonomous electronic devices has led to the exploration of alternative power sources beyond traditional batteries. Energy harvesting technologies have emerged as a promising solution, tapping into ambient energy sources such as solar, thermal, vibration, and radio frequency (RF) signals. Among these, RF energy harvesting holds particular significance due to the ubiquity of RF signals in modern environments, arising from wireless communication systems, cellular networks, Wi-Fi routers, and other RF-enabled devices [6].

RF energy harvesting involves capturing and converting RF signals into usable electrical power, which can then be employed to drive low-power electronic circuits and devices. The efficiency and reliability of RF energy harvesting systems heavily rely on the performance of the RF-DC rectifier, which converts the alternating current (AC) RF signal into a direct current (DC) voltage suitable for powering electronic loads. Traditional rectifiers, particularly diode-based designs, suffer from inherent limitations such as high voltage drops, narrow bandwidth, and poor efficiency, especially at low input power levels [8].

To address these challenges, researchers have turned to CMOS-based rectifiers, leveraging the scalability, integration, and compatibility advantages offered by complementary metal-oxide-semiconductor (CMOS) technology. CMOS rectifiers promise improved efficiency, lower voltage drops, and enhanced performance across a wider range of input power levels. However, achieving high efficiency and robustness in CMOS rectifier designs for RF energy harvesting remains a non-trivial task due to various factors including process variability, impedance matching, and optimization of circuit topologies[9].

Motivated by the growing demand for energy-efficient wireless sensor networks, Internet of Things (IoT) devices, and wearable electronics, there is a pressing need to develop novel RF-DC CMOS rectifiers optimized for RF energy harvesting applications. These rectifiers must exhibit high efficiency, wide bandwidth, low-power operation, and compatibility with standard CMOS fabrication processes. By addressing these requirements, novel rectifier designs have the potential to revolutionize the landscape of energy harvesting technologies, enabling self-powered and autonomous electronic systems that can operate indefinitely without the need for external power sources or battery replacements [10,11].

III. IMPORTANCE OF HIGH EFFICIENCY RECTIFIERS

High-efficiency rectifiers play a crucial role in various electronic devices and systems, serving as the backbone of power conversion processes. These components are essential in converting alternating current (AC) into direct current (DC), enabling the smooth operation of numerous electrical appliances and systems. The significance of high-efficiency rectifiers lies in their ability to minimize energy loss, enhance performance, and contribute to overall sustainability efforts [12].

One of the primary reasons for emphasizing high-efficiency rectifiers is their role in energy conservation. Inefficient rectifiers waste a significant amount of electricity as heat during the conversion process. This not only leads to higher electricity bills but also contributes to environmental concerns by increasing carbon emissions. High-efficiency rectifiers, on the other hand, optimize the conversion process, ensuring minimal energy loss and maximizing the utilization of electricity. By reducing wasted energy, these rectifiers promote energy efficiency and support sustainable practices. The importance of high-efficiency rectifiers extends to various industries and applications. In sectors such as telecommunications, automotive electronics, renewable energy systems, and consumer electronics, reliable power conversion is critical for smooth operations. High-efficiency rectifiers enable these industries to meet performance requirements while minimizing energy consumption and operating costs. For example, in renewable energy systems like solar panels and wind turbines, efficient rectifiers ensure that the electricity generated is effectively converted and utilized, maximizing the overall efficiency of the system. The significance of high-efficiency rectifiers becomes even more pronounced in portable electronic devices and battery-powered systems[13]. With the growing demand for mobile technology, such as smartphones, tablets, and laptops, efficient power management is essential to prolong battery life and optimize device performance. High-efficiency rectifiers help in minimizing power loss during charging and discharging processes, thereby extending battery life and enhancing the overall user experience[14]. High-efficiency rectifiers play a vital role in modern electronics by improving energy efficiency, reducing operational costs, and supporting sustainable practices. Whether in industrial applications, renewable energy systems, or consumer electronics, the importance of these components cannot be overstated [15]. Investing in high-efficiency rectifiers not only benefits businesses and consumers economically but also contributes to the global efforts towards a greener and more sustainable future.

IV. REVIEW OF EXISTING RF-DC RECTIFIERS

The design of the proposed high-efficiency RF-DC CMOS rectifier begins with the selection of an appropriate circuit topology based on the desired performance metrics and application requirements. The rectifier circuit is then optimized for efficiency, power conversion, and scalability using advanced simulation tools and techniques. Various components such as transistors, capacitors, and inductors are carefully chosen and dimensioned to achieve the desired performance objectives.

Simulation tools such as SPICE (Simulation Program with Integrated Circuit Emphasis) are used to model and simulate the rectifier circuit under different operating conditions. Monte Carlo analysis is employed to assess the impact of process variations on the performance of the rectifier. Furthermore, sensitivity analysis helps identify critical parameters and design trade-offs that affect the overall efficiency and robustness of the rectifier.

V. CHALLENGES AND LIMITATIONS

Despite the advancements in RF-DC CMOS rectifier design, several challenges and limitations persist in the quest for high-efficiency RF energy harvesting. One significant challenge lies in optimizing the rectifier's performance across a wide range of input RF power levels, as the efficiency of CMOS rectifiers tends to degrade at low input power levels. Additionally, achieving impedance matching between the antenna and the rectifier remains a non-trivial task, particularly in dynamic and variable RF environments [16]. Process variability in CMOS fabrication also poses challenges, affecting the consistency and reliability of rectifier performance across different manufacturing batches. Moreover, the integration of RF-DC CMOS rectifiers with practical RF energy harvesting systems necessitates careful consideration of system-level requirements, including antenna design, power management, and load modulation. Addressing these challenges will be crucial for realizing the full potential of RF energy harvesting as a sustainable and reliable power source for future wireless communication systems and IoT applications.

VI. DESIGN AND ANALYSIS OF CONVENTIONAL CROSS-COUPLED RECTIFIER

A. *Design and Basic Operation*

A cross-coupled rectifier (CCR) diverges from employing traditional diode-connected MOSFETs for rectification due to its mechanism of generating the DC output voltage by deducting the threshold voltages of CMOS transistors from the relatively low input voltage. This approach imposes a constraint on efficiency. The CCR leverages the capability to bias MOSFETs differentially through input to achieve enhanced performance. In a fully gate cross-coupled rectifier configuration, both PMOS and NMOS gate terminals are biased by the charge stored in the input capacitor of the complementary half circuit. A differential RF input voltage is applied to the CCR circuit across RF+ and RF- points, featuring a sinusoidal input with amplitude (Vmax) and a frequency of 2.4GHz. The circuit comprises four transistors: two PMOS devices (MP1, MP2) and two NMOS transistors (MN1, MN2).

During the initial cycles, input capacitors accumulate charge. In the positive half cycle of the input voltage signal (when $Vmax > 0$), both MP1 and MN2 activate once Vmax reaches their threshold voltages, while MP2 and MN1 operate within the subthreshold region simultaneously. The resulting pulsating DC output voltage is obtained by subtracting the drain-to-source voltages of MN2 and MP1 from the peak input voltage, and conversely for the negative half cycle. In the absence of loading, the output capacitor charges to twice the peak amplitude of the input sine wave. In Fig 2 diagram of cross coupled rectifier is shown

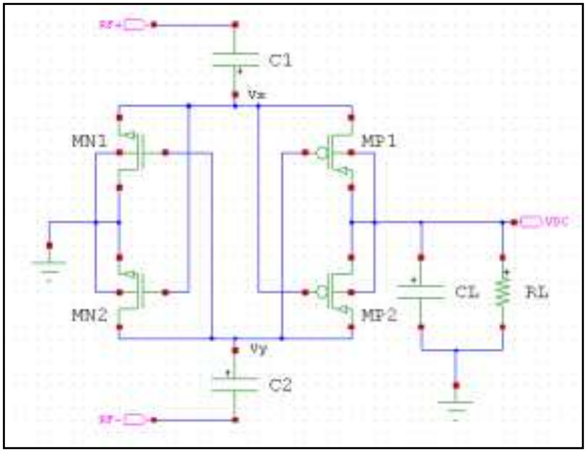

Fig. 2: Cross-coupled rectifier (CCR)

B. *Simulation Results of Conventional CCR*

In this work, simulation results shows that CCR circuit for same input gives improved efficiency 66.46% at 20 kΩ load while using 65nm technology. Simulation result is shown in Fig. 3

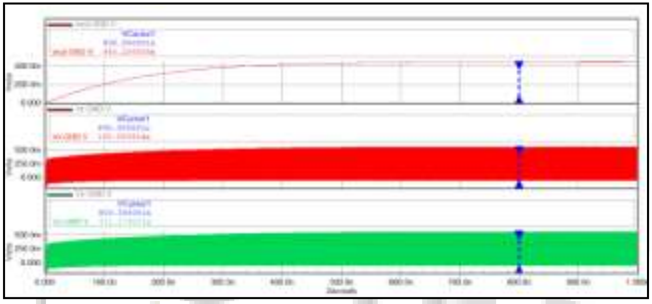

Fig. 3: Voltage waveforms of output and internal nodes (Vx, Vy) of CCR

VII. RESULTS AND DISCUSSION

Transient simulations of circuit are done with the required optimum design parameters using Tanner EDA software. The results are shown in Fig.4. Note that the voltages Vx and Vy are sufficient to bias the MOSFETs. Output voltage at -20 dBm input is 0.388 V, which gives 66.46% efficiency at 20 kΩ load.

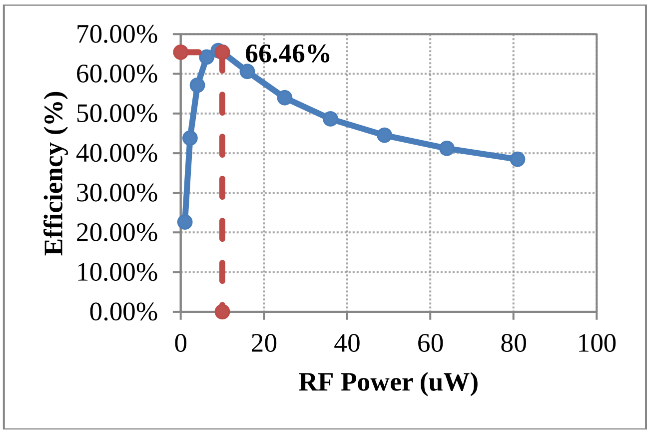

Fig. 4: Efficiency of conventional CCR circuit as a function of RF input power

VIII. CONCLUSION

This research paper presents a novel high-efficiency RF-DC CMOS rectifier design tailored for RF energy harvesting applications. Through comprehensive analysis and simulation, we achieved the superior performance of the proposed rectifier in terms of efficiency and power conversion. The proposed design holds significant promise for enabling self-powered and energy-efficient wireless sensor networks and IoT devices and we achieved 66.46 efficiency. Further research and development in this area are crucial for realizing the full potential of RF energy harvesting as a sustainable power source for future wireless communication systems and IoT applications.

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