A Low-Loss Rectifier Unit for Inductive-Powering of Biomedical Implants

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Abstract—Biomedical implants have been developed in the recent years with a focus for continuous and real-time monitoring of physiological parameters. Battery-less operation of the implanted unit requires energy harvesting from an inductive link or from the neighboring environment. For efficient conversion of harvested energy to a usable DC level, a rectifier block is employed. However conventional CMOS full bridge rectifier incurs a significant amount of power loss and lowers the overall efficiency of the powering system. In this work a cross-coupled MOSFET based LC oscillator structure has been presented as a modified rectifier circuit. Cross-coupled structure minimizes the loss of the MOS switches and LC tank circuit boosts up the output DC level. The rectifier unit has been designed and simulated using 0.5-µm standard CMOS process. For simulation purposes, different biomedical frequency bands are used to validate the effectiveness of the proposed circuit. Simulation results show that the proposed rectifier circuit can achieve 75% PCE compared to the conventional full bridge CMOS rectifier of only 3% PCE.

I. INTRODUCTION

Implantable medical devices (IMB) are going to be an integral part of future healthcare services providing continuous and real-time in vivo monitoring of different physiological parameters such as neuromuscular stimulators, cochlear implants, or visual prostheses [1,2], monitoring glucose, lactate, pH, CO2, etc [3]. Miniaturized, low-power, light weight and cost-effective are the key features of an implantable unit.

For continuous operation, the implanted units need to be powered up from an external source. Previously tethered cables were chosen for power and data transmission [4]. But this accentuates the potential risks of skin infections and irritation. Implantable battery as the second option might pose potential battery fluid leakage and biohazard. Power transfer using inductive link, as a hot topic in biomedical research area, had been studied by several research groups [5,6].

Inductive power link transmits the power through two loosely coupled resonating coils separated by the human skin. The primary side resides outside of the human body and is driven by Class-E power amplifier (PA). The secondary side is placed just beneath the skin and captures the power in resonant mode. The conventional class-E PA is usually worked as the source to achieve high efficiency. Class-E PA works with zero-voltage switching (ZVS) and offers theoretically 100% drain efficiency (DE). However the drive requirement of the class-E PA incurs extra power loss and provides a lower efficiency defined by power added efficiency (PAE). Previously reported work uses a differential power oscillator to eliminate the loss from the driver circuit and achieves theoretically 98% PAE [7]. The received power signal from the resonance LC tank in the secondary side of the inductive power link passes through the rectifier circuit to convert into DC output. However the power converter efficiency (PCE) of the conventional rectifier circuits is very low especially in the inductive power link system. Chadrakasan et al. reported a bias-flip rectifier with shared inductor to improve the PCE of the rectifier circuit [8]. The rectifier unit is used to efficiently harvest energy from a piezoelectric harvester by periodically not only discharging the internal capacitor but also flipping the bias voltage across the capacitor. For low-voltage low-power applications a subthreshold MOSFET based Class-AB rectifier is reported in [9] with a power consumption of less than 600 nW and 60 dB dynamic range for a supply voltage of 1 V. A CMOS full wave rectifier with built-in backward telemetry has been presented for biomedical applications [10]. The scheme utilizes separate n-wells and an additional pair of transistors to dynamically bias the devices as well as reduce the dropout voltages of the conducting MOSFETs resulting in an improved overall efficiency.
In this work, a new rectifier circuit with cross-coupled MOSFET pair and a resonant LC tank has been presented to improve the overall rectifier efficiency. For comparison purposes a conventional CMOS full wave rectifier has also been presented. All of the structures have been simulated using 0.5-μm standard CMOS process. Three different signal frequencies have been used to validate the performance. Simulation results indicate that the conventional full bridge rectifier has only 3% while the new rectifier circuit shows more than 75% of PCE.

The organization of the paper is as follows. Section II describes about the CMOS rectifier circuits including CMOS full bridge rectifier and the proposed rectifier circuit, section III presents the simulation results and comparative study of the proposed structure with the conventional one and finally section IV draws conclusion.

II. CMOS RECTIFIER CIRCUITS

The main purpose of a rectifier unit is to convert an AC signal to a DC signal. From the early days of microelectronics a simple pn type junction diode is used to convert an alternating signal to a unidirectional signal. Based on the diode circuit configurations, several types of diode rectifiers have been reported. Among all of them, the full bridge diode rectifier is a popular one due to its smaller size, light weight and relatively lower peak-inverse-voltage (PIV). The efficiency of a rectifier unit is defined by,

$$\eta_{RECT} = \frac{P_{DC} \times 100\%}{P_{AC}} = \frac{|V_{out}| \times |I_{out}|}{V_{in} \times I_{in}} \times 100\%$$  \hspace{1cm} (1)

where \(P_{DC}\) and \(P_{AC}\) are the output dc power and the input ac power of the rectifier unit, respectively.

In the following sections a CMOS version of a full bridge rectifier circuit has been presented first and then a modified rectifier circuit has been proposed.

A. CMOS Full Bridge Rectifier

The circuit schematic of a full bridge CMOS rectifier has been shown in Fig. 1. It consists of two PMOS and two NMOS devices. Depending on the polarity of the input AC signal either MP1-MN2 or MP2-MN1 combination works. As a result current signal always flows from the + node to the – node at the output resulting in a unidirectional current flow. However the output voltage is attenuated by \(2V_{ds}\), where \(V_{ds}\) is the drain to source voltage of the MOSFET.

The \(V_{ds}\) voltage drop and power loss in the internal resistance of each conducting MOSFET reduce the output signal as well as the efficiency of the rectifier unit. Fig. 2 presents the transient outputs of a full bridge rectifier compared to the ideal one for an input sinusoidal signal of amplitude 1 V. For the ideal case each MOSFET device works as a zero loss switch and the rectified signal appears as the same strength of the input signal. However practical MOS devices are lossy unless otherwise special techniques are adopted to reduce the loss. As a result the output rectified signal appears as an attenuated version of the input signal. According to eqn (1), for a resistive load of \(R_{L}\), the rectification efficiency of a CMOS full bridge rectifier becomes,

$$\frac{(2V_m - 2V_{ds})^2}{\pi} \times 100\% = 8 \left( \frac{V_m - V_{ds}}{\pi \cdot V_m} \right)^2 \times 100\%$$  \hspace{1cm} (2)

where \(V_m\) and \(V_{ds}\) are the peak values of the input sinusoidal signal and the drain-to-source voltage drop of each conducting MOSFET, respectively. From eqn (2) it is evident that lower the \(V_{ds}\) value higher the rectifier efficiency.

B. Proposed MOS Cross-Coupled Rectifier

The CMOS full bridge rectifier circuit suffers from power loss from the current conducting MOSFETs. To overcome this problem a MOS cross-coupled rectifier with a LC tank has been proposed to not only rectify the AC signal but also to boost the output DC level. Fig. 3 shows the circuit schematic of the proposed rectifier circuit. It consists of a MOS cross-coupled pair and a LC tank. The structure of the rectifier is similar to a PMOS cross-coupled LC oscillator structure. Instead of a DC supply, an alternating signal identical to the oscillating frequency is fed at the source terminal of the MOS cross-coupled pair.
The simplified equivalent circuit model of the proposed rectifier circuit is shown in Fig. 4. It manifests dependent current sources from the MOS cross-coupled pair and an LC tank tuned to half of the input AC signal. In steady state condition, during the positive half cycle of the input signal, current passes to the output while charging the reactive components of the tank circuit. During the negative half cycle, the tank circuit supplies current to the load while circulating current across the tank circuit. This circulating current induces periodic charge buildup across the tank circuit which appears as periodic amplitude changes of the $v_1$ and $v_2$ signals. The periodic amplitude changes of the $v_1$ and $v_2$ signals introduce a level shift at the output current resulting in a DC component at the output.

III. SIMULATION RESULTS

The proposed rectifier circuit has been designed and simulated using 0.5-µm standard CMOS process. For comparison purpose the CMOS full bridge rectifier is also designed and simulated. MOSIS provided 0.5-µm standard CMOS models and ADS simulator are used to simulate the performance of the circuit. Both of the circuits have been designed and simulated for three different frequencies (4MHz, 7MHz and 13.5MHz). In the following the performance of the conventional CMOS full bridge rectifier and the proposed rectifier circuit has been presented.

The CMOS full bridge rectifier consists of two PMOS two NMOS devices. For every cycle of the input signal, two devices work and make unidirectional current flow at the output. However the power loss of the devices lowers the rectification efficiency. On the other hand the proposed rectifier circuit uses cross-coupled structure to reduce the switch loss and LC tank circuit to boost up the output dc level.
A low-loss rectifier circuit has been presented employing MOS cross-coupled structure and LC tank. The structure of the rectifier is similar to a LC oscillator with an oscillation frequency half of the input AC signals. The AC signal is fed at the source terminal of the MOS cross-coupled pair. MOS cross-coupled structure injects current to the LC tank which supplies the current to the output terminal while introducing a DC level shift. Due to the cross-coupled structure the switch loss is reduced and the DC level shift of the output current results in a DC component at the output signal. Simulation results indicate that the PCE of the proposed circuit is 72% higher than the conventional CMOS full bridge rectifier.

Table I shows the performances of the CMOS full bridge rectifier and the proposed rectifier for three different frequencies (4 MHz, 7 MHz and 13.5 MHz) usually used for biomedical applications. For an input signal of 3 V peak the proposed rectifier can generate boosted DC outputs of 4.33 V, 4.35 V and 4.33 V for the frequencies of 4 MHz, 7 MHz and 13.5 MHz, respectively. On the other hand the conventional full bridge rectifier becomes only 3%. In Fig. 7 the input and output powers for the proposed rectifier are 4.05 mW and 3.15 mW, respectively which indicates a PCE of 77.78%.

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Fig. 5 presents the transient outputs of the proposed MOS cross-coupled rectifier. In Fig. 5 the top trace indicates the input signal, middle trace shows the drain terminals output and finally the bottom trace presents the output voltage of the rectifier. Fig. 6 and 7 present the DC output from the full bridge rectifier and the proposed rectifier circuit. For the conventional full bridge rectifier the output and the input DC powers are 554 μW and 17.27 mW respectively. From the simulation results the power converter efficiency (PCE) of the CMOS full bridge rectifier becomes only 3%. In Fig. 7 the input and output powers for the proposed rectifier are 4.05 mW and 3.15 mW, respectively which indicates a PCE of 77.78%.

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![Figure 7. Rectified dc output of the proposed rectifier](image)

**REFERENCES**


**TABLE I. COMPARISON OF THE FULL BRIDGE RECTIFIER AND THE PROPOSED RECTIFIER**

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Input Signal Vp(V)</th>
<th>Output DC (V)</th>
<th>Input Power (mW)</th>
<th>Output Power (mW)</th>
<th>PCE</th>
<th>Output DC(V)</th>
<th>Input Power (mW)</th>
<th>Output Power (mW)</th>
<th>PCE</th>
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<tbody>
<tr>
<td>4</td>
<td>3</td>
<td>4.33</td>
<td>18.32</td>
<td>23.38</td>
<td>78.35%</td>
<td>0.7</td>
<td>0.55</td>
<td>17.8</td>
<td>3%</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>4.35</td>
<td>18.346</td>
<td>24.537</td>
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<td>2.6</td>
<td>6.6</td>
<td>277</td>
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</tr>
<tr>
<td>13.5</td>
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<td>3</td>
<td>7.93</td>
<td>10.198</td>
<td>77.77%</td>
<td>0.25</td>
<td>0.0658</td>
<td>1.74</td>
<td>3.76%</td>
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</table>

**IV. CONCLUSION**

A low-loss rectifier circuit has been presented employing MOS cross-coupled structure and LC tank. The structure of the rectifier is similar to a LC oscillator with an oscillation frequency half of the input AC signals. The AC signal is fed at the source terminal of the MOS cross-coupled pair. MOS cross-coupled structure injects current to the LC tank which supplies the current to the output terminal while introducing a DC level shift. Due to the cross-coupled structure the switch loss is reduced and the DC level shift of the output current results in a DC component at the output signal. Simulation results indicate that the PCE of the proposed circuit is 72% higher than the conventional CMOS full bridge rectifier.