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A Novel Wireless Power and Data Transmission AC to DC Converter for an Implantable Device

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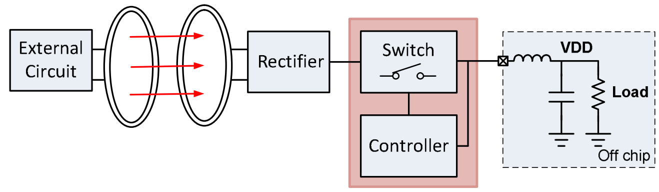
***Abstract*— This article presents a novel AC to DC converter implemented by standard CMOS technology, applied for wireless power transmission. This circuit combines the functions of the rectifier and DC to DC converter, rather than using the rectifier to convert AC to DC and then supplying the required voltage with regulator as in the transitional method. This modification can reduce the power consumption and the area of the circuit. This circuit also transfers the loading condition back to the external circuit by the load shift keying(LSK), determining if the input power is not enough or excessive, which increases the efficiency of the total system. The AC to DC converter is fabricated with the TSMC 90nm CMOS process. The circuit area is 0.071mm^2. The circuit can produce a 1V DC voltage with maximum output current of 10mA from an AC input ranging from 1.5V to 2V, at 1MHz to 10MHz.**

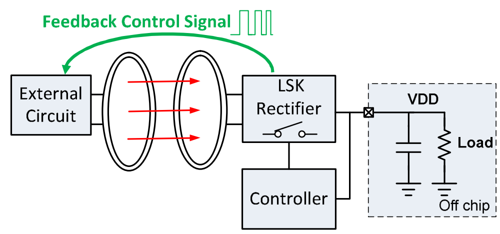
I. Introduction

Power supply is an important issue for the modern implantable device. Implantable devices usually use the battery to supply power. However, the battery should be replaced by surgery when necessary. As a result, recent implantable devices usually are supplied power by wireless power [1], using inductive power transmission to transfer energy through skin. Unfortunately, wireless power transmission cannot supply power stably. It's also affected by the transmission distance easily because the transmission efficiency is lower when the transmission distance is longer. It requires using the power management circuits, such as rectifier and other regulation circuit, which can supply stable voltage source for other implantable circuit.

Fig.1(a) shows the method of the traditional wireless power transmission system. It transfers power from the external circuit by coils and then supplies a stable voltage by the rectifier and the regulator such as DC to DC converter. The rectifier [2], transfers signal back to external device by load shift keying (LSK) [3]. LSK transfers signals by turning on/off the PMOS switches of the rectifier. Turning on/off the PMOS switches causes the rectifier output voltage to rise or drop. As a result, the PMOS switches are similar to the power MOS switch of the DC to DC converter. Therefore, the rectifier can achieve the function of DC to DC converter by controlling the PMOS switches of the rectifier on/off. Fig.1(b) shows the proposed circuit. The power which is transferred from the external circuit is converted to DC voltage by LSK full wave rectifier. The time of charging can also be controlled by using the controller to control the PMOS switches of the LSK rectifier according to different input voltage and output load. Compared with the traditional transmission, the proposed circuit can provide the required voltage without an additional



(a)



(b)

Fig.1 (a) The traditional and (b) the proposed power transmission system.

regulator. As a result, the proposed circuit can reduce not only the circuit area, but also the power consumption.

In the structure of Fig.1(b), when controller outputs the control signal to the LSK rectifier, the input impedance of the rectifier is varied heavily. Consequently, the control signal is sent to the external device by LSK, without an additional transmission circuit and coils. The external circuit can determine if the input power is not enough or excessive by the feedback control signal and then adjust the output power of the external circuit accordingly, making the transmission efficiency higher.

II. Architecture

Fig.2 shows the architecture of the total circuit, which comprises the LSK full wave rectifier and the controller.

1. LSK full wave rectifier

The LSK full wave rectifier is composed of a CMOS rectifier and multiplexers. The CMOS rectifier is composed of the PMOS $M_{P1,2}$ and $M_{N1,2}$. The PMOS $M_{P3\text{-}6}$ are used to keep the PMOS body voltage at the highest voltage between $RF_{+/-}$ and V_{out}, which can avoid leakage and latchup.

The multiplexer structure is shown in Fig.3. The multiplexer contains level shifter, buffer and transmission gates. First, the control signal is boosted to the highest voltage by the level shifter when the output logic is 1 to let the transmission gates work correctly. Finally, the control signal is inputted to the transmission gates through a buffer, and the multiplexer outputs the selected signal.

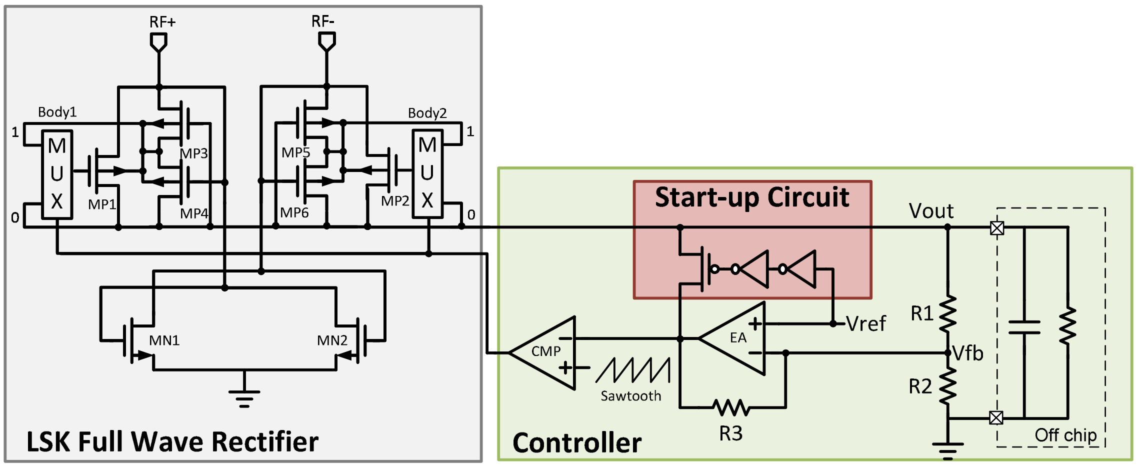


Fig.2 The architecture of the AC to DC converter

The multiplexers control the rectifier as Fig.4. When the input signal to the multiplexers is logic 0, the multiplexers output the V_{out} voltage to the gate of the $M_{P1,2}$, The $M_{P1,2}$ is similar to the diode connected MOS, so the LSK rectifier works as general rectifiers. When the input signal is logic 1, the multiplexers output the highest voltage of the rectifier to the gate of the $M_{P1,2}$. The $M_{P1,2}$ is turned off, and cannot output current to the output load.

Furthermore, by using the multiplexers to switch the PMOS of the rectifier, the $M_{P1,2}$ is similar to switching the switch between input and load of LSK. Turning on/off the switches varies the input impedance of the rectifier heavily, so it can achieve the result of LSK data transmission by the variation of impedance.

2. Controller

A. The Main Structure

The controller in the proposed circuit is similar to the controller of the buck mode PWM DC to DC converter. It generates a PWM signal with different duty determined by different input voltage and output load. The controller controls the PMOS switches of the LSK rectifier by the PWM signal, so it can achieve the goal of regulation.

At first, the operation of the controller utilizes error amplifier to amplify the voltage difference between the feedback voltage V_{fb} and V_{ref} of the voltage reference circuit. The amplified voltage difference is compared with the sawtooth wave by the comparator. Fig.5 shows the sawtooth wave generator. It uses the reference voltage, resistor R_1 and NMOS N_1 to generate a current source. The current source charges the capacitor C_1 by the current mirror and raises the voltage of V_{saw}. When V_{saw} is higher than the high threshold voltage of the Schmitt trigger, the N_2 is turned on. The V_{saw} is then short to ground and the C_1 starts to be discharged. When V_{saw} is lower than the low threshold voltage of the Schmitt trigger, the NMOS N_2 turned off. The C_1 can be charged by the current source once again. The repeated charging and discharging generates the sawtooth wave. The frequency of the sawtooth wave is proportional to $1/R_1C_1$. The output signal of the error amplifier is compared with the sawtooth wave, generating output signal with different duty cycle, such as PWM signal. Consequently, the controller generates the

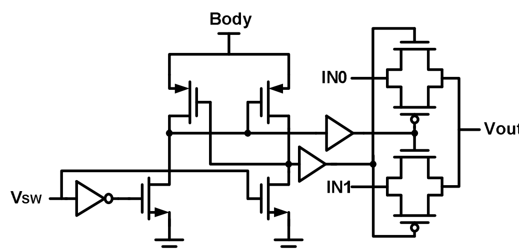


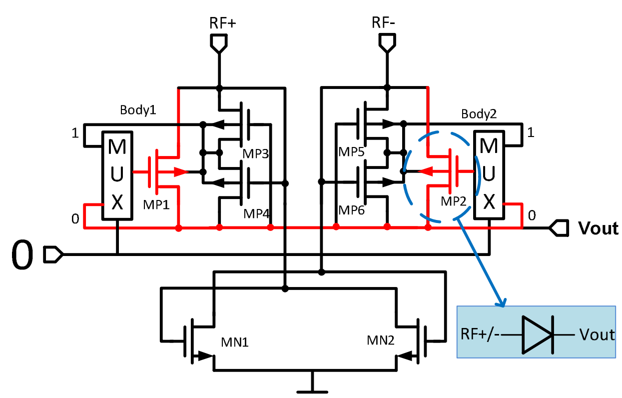
Fig.3 Multiplexer

different duty PWM control signal under the different condition of input voltage and output load.

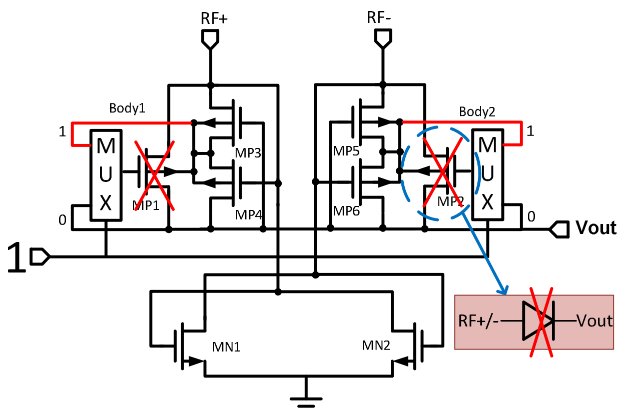
The controller controls the PMOS switches of the rectifier to control the output voltage. The total circuit forms a close loop and achieves the function of regulation.

B. Startup Circuit

Due to the power of the controller is supplied by the output of the rectifier, in the process of raising the output voltage from 0V to the required output voltage, the reference voltage also rises to the required reference voltage. Before rising to the required voltage, the lower reference voltage would let the rectifier output be lock at the error voltage. To avoid the error condition, the startup circuit is utilized in the controller as Fig.2. It's composed of two inverters and a PMOS. At the beginning, the V_{ref} does not high enough to turn on the first inverter, so the first inverter outputs high signal and the second



(a)



(b)

Fig.4 The operation of the PMOS switches

one outputs low signal, turning on the PMOS. The controller provides 0 signal to the multiplexers, so the LSK rectifier is like the general rectifier. The output voltage of the rectifier isn't affected by the reference voltage. When the reference voltage rises to a certain level, the first inverter is turned off so the PMOS is turned off. The startup circuit stops transmitting 0 signal to the multiplexers, and controller is switched to normal operation.

While the controller regulates the output voltage of the LSK rectifier, the multiplexers continue to switch the PMOS switches of the rectifier. It causes the input impedance of the rectifier to be changed continuously. Therefore, the PWM control signal which controls the LSK rectifier is sent to the external device by LSK. The external device can get the power supply condition of the implantable device by the feedback of the PWM control signal. A PWM signal with long duty means the PMOS switches are turned off for a long time. The long duty signal indicates that the input power from the external device is too large. On the contrary, a signal with short duty indicates that the input power is not enough. As a result, the external device can adjust the output power of the external device by the feedback of the PWM signal, making the efficiency of the total circuit higher.

III. Simulation Result

The presented AC to DC converter is designed and fabricated by the TSMC 90nm CMOS process. The input is an AC voltage with amplitude from 1.5V to 2V, and the frequency is from 1MHz to 10MHz. The output load capacitor is 10μF. The circuit provides a 1V DC voltage, with maximum output current of 10mA. Fig.6 shows the layout of the total chip. The circuit area is 0.071mm^2. Fig.7 shows the output generated from the AC input at 1.5V and 2V. The regulator can provide a stable output under different input signal.

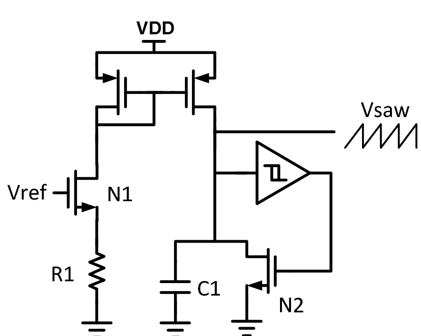


Fig.5 Sawtooth wave generator

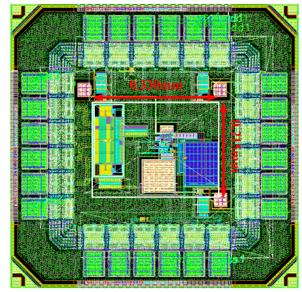
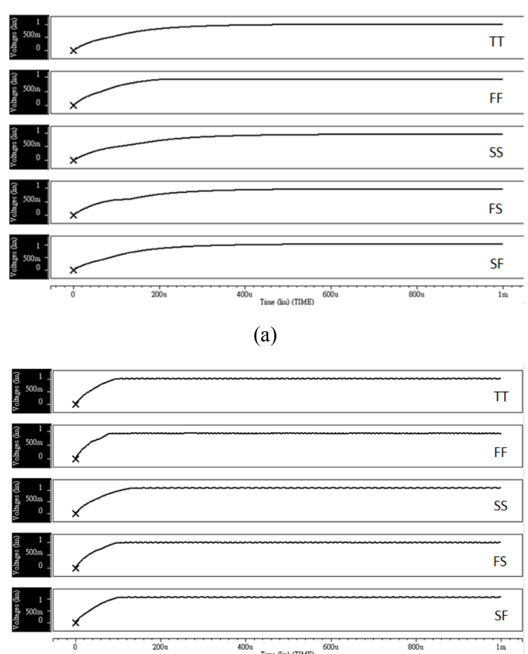


Fig.6 Layout of proposed AC/DC converter

The simulation environment of the load shift keying transmission between the external and implantable device is shown in Fig. 8. R_1 and L_1 are the resistance and inductance of the primary coil. R_2 and L_2 are the resistance and inductance of the secondary coil. K is the couple coefficient between the two coils. The value of these parameters are R_1=1.116 ohm, L_1= 2.46μH, R_2=6.992 ohm, L_2=4.7μH, and K=0.5. The information of coils is shown in Fig. 9 and Table I.

Fig.10 shows the simulation result of the LSK transmission. When the controller controls the switches of the rectifier, the input impedance of the rectifier would be changed. The reflected impedance and the current of the primary coil would also be changed. By the variation of the current of external coil, we can get the feedback signal. From Fig.10, it can be observed that the current of the primary coil is changed according to the control signal. Consequently, the control signal can be transferred from implant device to external device.



(a)

(b)

Fig.7 The output result of proposed AC/DC converter at input AC (a) 1.5V and (b) 2V

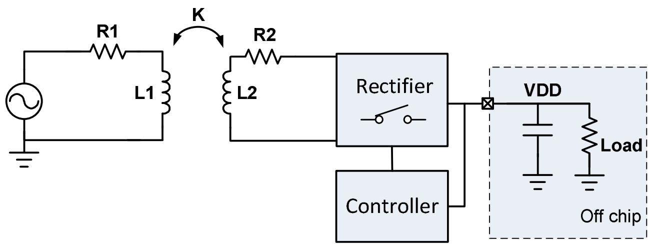


Fig.8 The simulation environment of LSK operating.

TABLE I. Coils Data

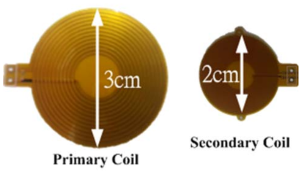


Fig.9 The photo of coils.

Parameter	Primary Coil	Secondary Coil
External Diameter	30mm	20mm
Thickness	0.14mm	0.14mm
Number of Turns	12	18

The post layout simulation result of the proposed AC to DC converter is listed in Table II. Performance comparison between the proposed AC/DC converter and selected recently-published AC/DC converter is shown in Table III. Compared to other circuit, the proposed circuit can not only rectify, but also regulate at the same time requiring no regulator. The PCE of this work is the result with rectification and regulation, and other circuits of Table III. are the result with just rectification.

IV. Conclusion

Combining the functions of the rectifier and DC to DC converter, this paper presents a novel AC to DC converter. The circuit can directly convert the input AC voltage to DC voltage, and get the result of regulation at the same time. Using the power MOS of the rectifier as the switch can eliminate the large switch of the general DC to DC converter, which reduce the circuit area.

The total circuit area is 0.071mm^2. The consumed power of regulation is 160.1µW. This circuit also combines the function of LSK transmission, which feedback the control signal to the external device. The feedback control signal can be used to monitor the output load. The output power of the external device can be adjusted according to the feedback signal which makes the efficiency higher.

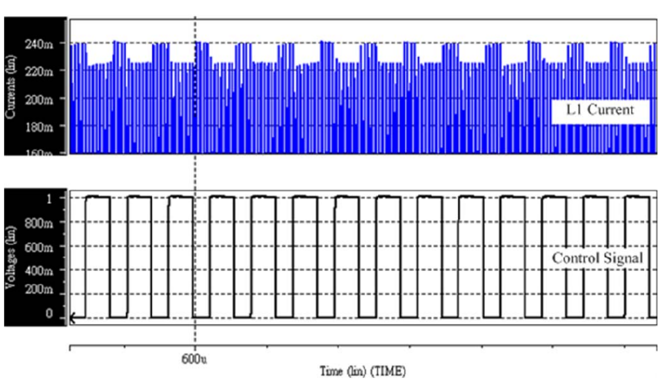


Fig.10 The simulation result of LSK

TABLE II. Simulation Result of AC/DC converter

Parameter	Post Layout Simulation
Power Supply	AC 1.5V~2V
Frequency(MHz)	1~10
Output Voltage(V)	1.02
Max Load Current(mA)	10
Control Circuit Quiescent Current(µA)	157
Regulation Consumption Power(µW)	160.1
Load Regulation(mV/mA)	2.44
Line Regulation(1/10Mhz)*	0.052
Ripple Voltage(mV)	<15
Chip Size(mm^2)	0.071
PCE(%)	63

* Line regulation is the result of the varied input AC voltage results the output voltage variation.

TABLE III. Performance comparison with recent published AC/DC converter

Publication	[4]	[5]	[6]	This Work
Technology	0.18um CMOS	0.18um CMOS	0.5um CMOS	90nm CMOS
$V_{IN,peak}$(V)	0.8	1.25	3.8	1.5
V_{REC}(V)	1.8	0.96	3.12	1
R_L(Kohm)	270	2	0.5	0.1
f_c(MHz)	13.56	10	13.56	1-10
Area(mm^2)	0.83	0.86	0.18	0.071
PCE (%)	59.4	76	80.2	63
Regulation Consumption Power(µW)	N/A	N/A	953.6	160.1

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