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Development of Power Recovery Circuit for Bio-Implantable Stimulator

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ABSTRACT

This paper presents a modified design of low power recovery circuit in micro-system implanted device to stimulate the human nerve and muscle. The amplitude shift keying ASK was used to modulate data by using operating frequency 6.78MHz ISM industrial scientific medical band to be less invasive to tissue. The proposed system consists of an external part which has ASK modulator and class-E power amplifier with 94.5% efficiency. The internal part has half wave rectifier and voltage regulator to generate very stable 1.8VDC using 0.35um CMOS technology. The Orcad pspice 16.6 and MULTISIM 11 software were used to simulate the design of power recovery and class-E power amplifier respectively. The regulated voltage utilised to power the sub-electronic device implanted inside human body with very stable voltage even change implanted load resistance. The proposed system has 12.5%modulation index and low power consumption.

Keywords: ASK modulator, class-E power amplifier, inductive coupling, rectifiers, LDO low dropout regulator and power recovery

INTRODUCTION

Implantable biomedical systems were introduced to achieve superior data transmission and energy efficiency with minimal power consumption and optimal operating frequency according to the ISM industrial scientific medical band (Mandal & Sarpeshkar, 2008). The implanted micro-system stimulator is classified as bio-implantable device and aimed at stimulating

the nerves and muscles when disorders happen because a neural action is absent or when there is damage in the neural signal conduction pathway. An implanted micro-system made up of two main components whereby an external component is placed outside of the skin while an internal component is located under the skin.

Implant devices that are powered by RF signals through inductive coupling links help to reduce the complexity of the system, ensure the patient is not harmed in any way, avoid repeat surgeries and minimise cost(Asgarian & Sodagar, 2009; Atluri & Ghovanloo, 2007). The bio-implanted devices require very efficient RF to DC rectifier and efficient DC-to-DC converter. These devices provide the essential DC voltage to power the implanted micro-system. However, the most common technology used a signal diodes rectifier or MOSFET transistors in bridge rectifier connection (Rakers, Connell, Collins, & Russell, 2001).

The diodes are not suitable for implementation into the human body due to its size, thermal nose and they have larger threshold voltage compared with MOSFET devices (Jia, Chen, Liu, Zhang, & Wang, 2008). The voltage regulator is used to regulate the input voltage that supplies the implanted remote electronics with stable DC voltage to achieve the desired operating conditions. The linear method can be used to control the output voltage, and the reference voltage is compared with the output voltage and used for controlling the regulator feedback loop (Hoon-Kyeu & Dong-Chul, 2000). In praxis, there are different topologies based in the voltage regulator such as basic series regulator and basic shunt regulator. However, the LDO low dropout voltage regulator based on series structure is efficient and a suitable structure compared with shunt structure in power harvesting application (Heidrich et al., 2010). In this paper, low power recovery system is designed to generate a very stable 1.8VDC. This system is operated on 6.78MHz with modulation index of 12.5% and tested in air medium. The Orcad pspice 16.6 and MULTISIM 11 were used to simulate the design of power recovery and class-E power amplifier respectively.

System Architecture

The wireless power transmission (WPT) in biomedical implanted device is used to stimulate the nerves and muscle. The power recovery system design consists of two parts: the external part which touches the skin from outside and consists of ASK modulator and class-E power amplifier to drive the power and data to transmitter coil. The external part located inside the body consists of a receiver coil to receive data and power, half wave rectifier to convert AC to DC signal and LDO low dropout voltage regulator to generate 1.8VDC for powering the sub-electronic implanted as shown in Figure 1.
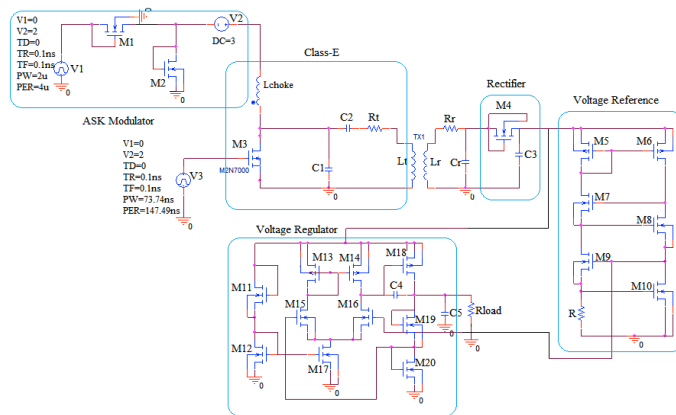
Figure 1. Power recovery system architecture

External unit

The external part consists of ASK modulator, Class-E power amplifier and RLC circuit which act as a transmitter antenna as described in Figure 1. The ASK modulator shown in Figure 2(a) is used to modulate the data and consist of two NMOS (M1&M2) act as resistor for voltage divider and one dc voltage (V2) to adjust the modulation index to be 12.5% by using equation (1).

$$Modulation\ Index = \frac{V_H - V_L}{V_H + V_L} \qquad (1)$$

The ASK modulator offers (3-4) dc voltage, which is enough to power the class-E power amplifier. The second part is the class-E power amplifier as shown in Figure 2(b), which is widely used to drive the RLC transmitter antenna in biomedical application due to simple architecture and the need for only one active device (Kazimierczuk, 1986).
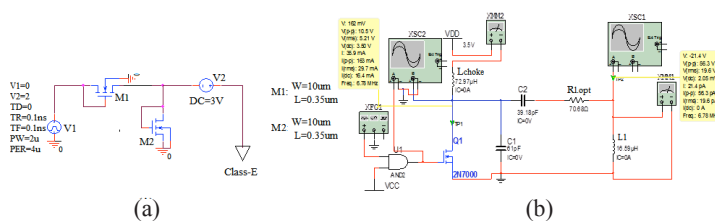

(a)   (b)

Figure 2. (a) The class-E power amplifier structure; (b) The ASK modulator structure

The class-E was powered using a 3.5 DC V to obtain an efficiency of 94.5%, and it can be observed that the model consists of two major blocks- a unit pole MOSFET transistor switch, that is the selected type (3TEN-2N7000) to reduce the transistor's switching losses (Abbas, Hannan, & Salina, 2012), along with the impedance series network which is calculated by using the equations as given in (Abbas et al., 2012; Suetsugu & Kazimierczuk, 2004). The values of class-E component are shown in Table (1).

Table 1
Class-E amplifier values

	Operate freq. F0	Choke inductor Lchoke	Trans. inductor L1	optimum resistance load Rt	Shunt capacitance C1	Series capacitance C2
Value	6.78MHz	72.79uH	16.59uh	70.68	61pf	39.18pf

Inductive coupling link

The inductive coupling link was designed to transfer data and power from the external part to the internal part. Generally, the inductive coupling link contains secondary and primary coils. The primary side has series resonance to provide a low impedance load for driving the transmitter coil, whereas the secondary side is almost invariably parallel, and uses LC circuit for better driving of a nonlinear rectifier load (Saad Mutashar, Mahammad A Hannan, Salina A Samad, & Aini Hussain, 2014). The optimum resistance RL.opt is still large, and it is not suitable to be used for subcutaneous applications which needs very low impedance called parasitic resistance Rt (Noor & Duffy, 2010). Therefore, the values of parasitic resistances depend on geometric of transmitter and receiver coils, which have dimensions d_{out} =44mm, d_{in} =7.92mm and d_{out} =10.5mm, d_{in} =6.61mm respectively (Alghrairi, Sulaiman, Sidek, & Mutashar, 2016).

There are many variable effects on inductive coupling link such as transmitted coil inductance (Lt), receiver coil inductance (Lr), resonance frequency (f_0) and coupling coefficient (K). The coupling coefficient must be 0<K<1 and calculated as per equation (2).

$$K = \frac{M}{\sqrt{L_t \times L_r}}$$
(2)

The values of the inductive coupling link are shown in Table (2).

Table 2
Inductive coupling link values

	Inductance μH	Capacitance PF	Coupling coefficient	Quality factor	Resistance Ω	Efficiency
Transmitter	16.59	39.18	0.105	70.28	10.05	84.76%
Receiver	0.654	827.17	0.105	51.56	0.54	87.77%

Internal unit

The proposed inductive coupling link technique faced weak coupling. Hence, the RF signal received at the embedded coil was seen to be lesser than the RF signal transmitted. Thus, the implantable biomedical devices required a very effective rectifier and a regulator that can provide the necessary DC voltage for powering the device. The first part from the internal power recovery is a rectifier. The rectifier refers to a voltage conversion part that converts the AC to the DC voltage in the implanted devices. It is very challenging to improve the rectifier efficiency, especially in the case of low power. For improving the efficiency of the RF-DC

MOSFET rectifier, the switching loss transistor (channel size) should be taken into account. In this paper, we developed a half wave rectifier by using a low-drop voltage along with the low-leakage CMOS diode with the help of one NMOST and one capacitor. The proposed design is presented in Figure 3(a). The structure is a very simple design comprising a small capacitor and one N-MOSFET. This design increased the gate-source transistor voltage more than the output voltage, which allowed a decrease in the VTH by a similar value as the output DC voltage. The relationship between voltage drops and the transistor channel size can be rearranged to solve for (W/L) from equation (3) (Yi, Ki, & Tsui, 2007).

$$\left(\frac{W_n}{L_n}\right) = \frac{C_{load}}{\tau \, \mu_n \, C_{ox}(V_{DD} - V_{TH,n})} \times \left[\frac{2V_{TH,n}}{V_{DD} - V_{TH,n}} + l_n\left\{\frac{4(V_{DD} - V_{TH,n})}{V_{DD}} - 1\right\}\right] \tag{3}$$

This equation is used to size a CMOS circuit for the rectifier to achieve a desired minimum rising or falling propagation delay and also to manage constraints such as rise time/fall time or rise/fall symmetry assuming that the Cload and other parameters are known.

The second part from internal power recovery is LDO voltage regulator. An efficient voltage regulator in bio- implanted device requires voltage reference to generate a steady regulated voltage. The human body temperature has a limited variation and the implanted device with surrounding tissue has a constant temperature due to blood flow in self-surrounding tissue leading to dispense from using a band gap circuit (Saad Mutashar, M. A. Hannan, S. A. Samad, & A. Hussain, 2014). The multiple independent voltage reference circuit is a good choice in bio-implantable device (Amir M Sodagar & Najafi, 2006; A. M. Sodagar, Wise, & Najafi, 2006). The development on the circuit is produced to provide multiple independent voltage reference. The value of reference voltage (2) is 900mV which is obtained by adjusting the size of the MOSFET M9 and M10 and the value of the resistor R as shown in Figure 3(b).

The LDO voltage regulator usually incorporates an error amplifier with a negative feedback where its stability against various load conditions is of great concern. The proposed LDO voltage regulator which is modified from (Chua-Chin, Ya-Hsin, Chio, & Yu-Tzu, 2004) by replacing the passive element with NMOS transistor as a resistor, leads to decrease in size and to generate 1.8 DC output voltage. An LDO voltage regulator consists of an error amplifier as one-stage high gain differential amplifier (M11 to M17) transistor, pass power transistor PMOS (M18), a resistive voltage divider (M19 to M20) and small feedback capacitor (C4) 3 pf connected between the series-pass transistor gate and the drain to increase and ensure system stability. The goal is to design an LDO limited by the following constraints: The output voltage is to be set at 1.8 V utilising an unregulated supply voltage of 5.7 V. Figure 3(c) presents the proposed regulator's general structure. The pass transistor must have a very large width. This is to enable the transistor to source currents that have large loads with a reasonable gate-source voltage, the length is kept at minimum value towards keeping the threshold voltage low, and instead of using voltage divider resistors, (NMOS) transistors are employed at regulator output. This is to feed a fraction of the output voltage back towards the input; in doing so, the feedback path's power consumption is minimised since very little current passes through it.
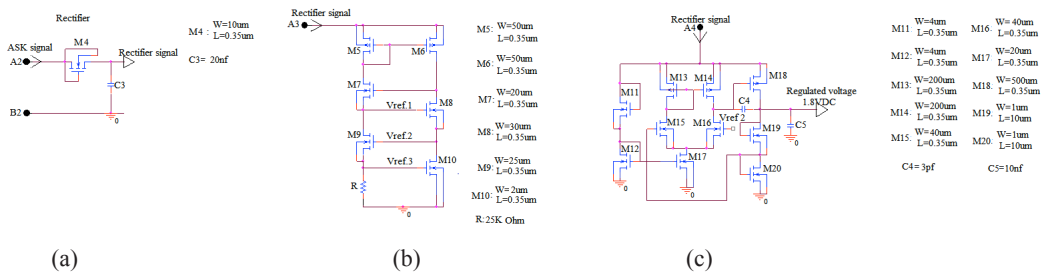
(a)   (b)   (c)

Figure 3. (a) Half wave rectifier for low power recovery; (b) Multiple supply independent voltage reference; (c) The basic LDO structure

RESULTS AND DISCUSSION

It is worth mentioning that there are many limitations in this research such as power consumption, size, feasibility and the design of the embedded biomedical device. The proposed framework includes two sections, the external section and the embedded one, as depicted in Figure 1. The first section, s the external one, comprises ASK modulator and class-E power amplifier to conduct the transmitted coil for transmitting data and power. The embedded section comprises received coil, half wave rectifier, as well as voltage regulator to produce efficient and constant 1.8 DC voltage without ripple for powering other parts of the embedded device. The system utilized a low-frequency 6.78 MHZ ISM band to prevent any harm to the tissue. Also, in order to power the class-E power amplifier, the ASK modulator is utilised to deliver 3 to 4 DC voltage. Moreover, the class-E power amplifier was composed with low power consumption and least amount of switching losses. The operation of class-E switch (M3) is as per the following: the Drain to Source voltage is equal (0) when the switch is in dynamic state (1) and Gate to Source voltage is (1) when the switch in the state (0), and produces a stable sinusoidal wave signal to the transmitted coil.

Table (1) displays the value for the class-E power amplifier. The transmitted coil L1 presents the exterior loop for the inductive connection and presents it as an antenna to transmit the modulated ASK signal with VH=27 V and VL=21 V with modulation index 12,5%. In the case of received coil in the interior section, it receives the ASK modulated signal inductively with values VMAX=6 and VMIN=4.65 V with modulation index 12.5% as shown in Figure 4.
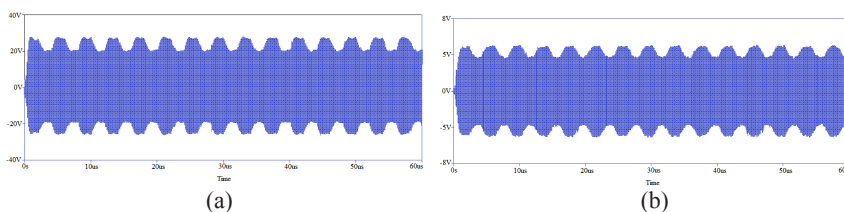

(a)   (b)

Figure 4. (a) The transmitted ASK signal; (b) the received ASK signal

The weak coupling between the exterior and interior coils is because of the constrained size of coils utilised in the embedded section. Hence, the inductive coupling connections ought to have the capacity to transfer the power at high efficiency as indicated by the values given in Table 2

The rectified signal is smoothed by stabiliser capacitor 20 nf to get a non-regulate DC signal. The non-regulated DC voltage must be constant. Therefore, the voltage reference for power recovery is intended to produce a level voltage VREF that is 900mV, half of the required value on the yield voltage regulator with an extremely stable DC voltage as shown in Figure 5(a) and 5(b). Therefore, the proposed voltage regulator is utilised to produce exceptionally stable 1.8 V VDD, notwithstanding the embedded device resistance altered from 250 Ω up to 2.5 kΩ as seen in Figure 6.
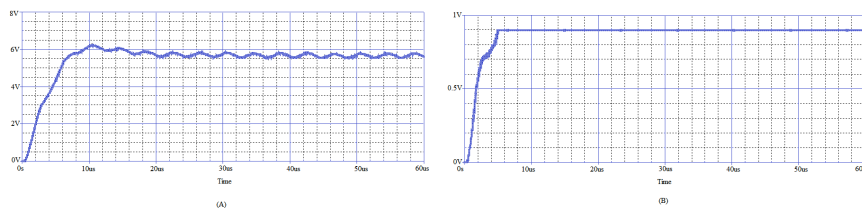

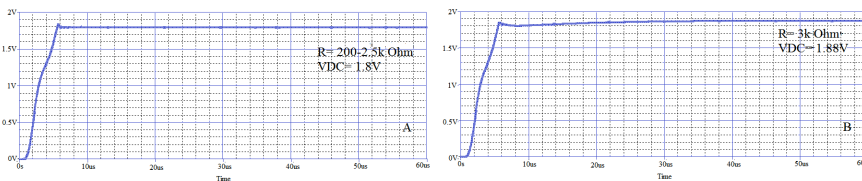Figure 5. (a) The rectified ASK signal; (b) Reference voltage output signal

Figure 6. The constant regulated VDD =1. 8 with various load resistances

CONCLUSION

An adapted design for low-power recovery framework using an embedded micro-system was presented in this paper. The proposed system utilised operating frequency 6.78MHz ISM band. The class- E power amplifier had high efficiency of 94.5% and proficient inductive connections up to 74.4% were used to transmit power and data to the embedded device. The embedded section which is exemplified by power recovery section comprises half wave voltage rectifier utilising low-leakage CMOS diodes rectifier, multi stage voltage reference to produce independent voltage 900mV and voltage regulator was utilised to offer low-power supply 1.8 DC voltage to power the embedded sensor. This design is simulated using electronic workbench MULISIM 11 and OrCAD PSpice 16.6 software. The design is suitable for embedded micro system device to invigorate the nerves and muscles.

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