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Efficient Low-Power Recovery Circuits for Bio-implanted Micro-Sensors

Abstract*. This paper presents a modified sub-electronic circuit with low-power recovery circuits to be implemented in implanted micro-sensor used to stimulate the human and animals' nerves and muscles. The system based on ASK modulation techniques operated with 13.56 MHz according to industrial, scientific, medical (ISM). The modulation index is 12.6% to achieve minimum power consumption to avoid the tissue heating. The system consists of external part with modified class-E power amplifier efficiency 87.2%, and internal part consists of a voltage doubling rectifier with self-threshold cancellation and efficient low-dropout voltage regulator based on series NMOST transistor using 0.35 μm technology to offer very stable 1.8 DC V. The produced voltage used to power the sub-electronic implanted device with steady voltage even in any changing with the implanted load resistance. The mathematical model is given. The design is simulated using OrCAD PSpice 16.2 software tools and for real-time simulation, the electronic workbench MULISIM 11 has been used to simulate the class-E power amplifier.*

Streszczenie. *W artykule przedstawiono zmodyfikowany układ pół-elektroniczny do zastosowania w implantowych mikro-czujnikach stymulujących pracę ludzkich i zwierzęcych nerwów i mięśni. Urządzenie posiada obwód odzyskiwania mocy w przypadku obniżonego zasilania w układzie. W proponowanym rozwiązaniu zastosowano modulację ASK o częstotliwości 13.56MHz i indeksie 12.6% w celu minimalizacji zużycia energii. Przedstawiono także model matematyczny urządzenia. Badania symulacyjne przeprowadzono w środowisku OrCAD PSpice 16.2 oraz MULISIM 11 do symulacji w czasie rzeczywistym wzmacniacza mocy klasy E. (****Sprawny układ odzyskiwania mocy w implantowych mikro-czujnikach****).*

Keywords: ASK modulation; Class-E power amplifier; Rectifiers; Bio-implanted devices; Voltage regulators.
Słowa kluczowe: modulacja ASK, wzmacniacz klasy E, prostownik, urządzenia implantowane, regulator napięcia.

Introduction

The biomedical implanted devices are an implanted electronics devices. So far, most of the implanted devices such as, peacemaker, brine peacemaker implants, micro-system stimulator implants powered using weirs penetrates living tissue, and this cases hazards and skin infections. In order to avoid this problmes, researchers developed the implanted devices to be powered using the batteries, and because of the limited time-life of the battery, chemical side effect and large size, researchers find several new methods to power and monitoring the implanted devices such as thermal method, vibration method and coupling links method [1]. Currently most of the implanted devices powered transcutaneously using inductive coupling links. The power recovery system consists of two parts, external part and internal part as shown in figure 1. The external part transfer power inductively to the internal part (implanted devices) which is located inside the body. And because of weak links between the two parts, hence the system needs efficient sub-electronic circuits with low-power consumption and low noise. The external part consists of power supply (battery), ASK modulator and efficient Power amplifier acts as a driver to offer very stable sinusoidal wave to the inductive coupling link [2]. The internal power recovery circuits should be with low power consumptions, small size feasibility and mainly consists of rectifier, voltage regulator and implanted remote electronics circuits. The implanted micro-system stimulators used to stimulate and monitoring the biological signal, such as, muscles signals, nerves signals, intraocular, pressure blood pressure, etc. The modulation technique used in the implanted devices can be an amplitude shift keying ASK, frequency shift keying FSK and phase shift keying PSK. The ASK modulation is widely used due to it is low-power consumption. simplest architecture, and low cost [3]. In this paper, the low-power recovery system provides very stable 1.8 DC voltages was designed and developed, included external and internal parts. The proposed system operated with 13.56 MH$_Z$ with modulation index 12.6%. The design is simulated using OrCAD PSpice 16.2 software tools and for real-time simulation, the electronic workbench MULTISIM 11 has been used to simulate the class-E power amplifier.

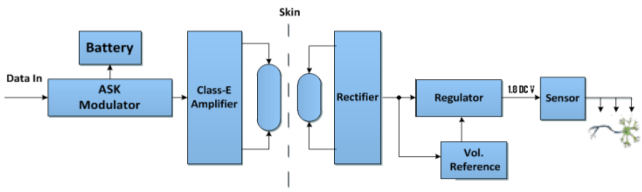

Fig. 1. Power Recovery System for Implanted Micro-system.

System Architecture

The power recovery circuits for the implanted micro-system consist of two parts, external and internal part. The external part located outside the body and consists of power supply (battery) ASK modulator, class-E power amplifier and external RLC circuit act as a transmitter. The internal part located within the body and consists of internal RLC circuit which acts as a receiver, rectifier and low-dropout regulator LOD. One of the main key issues in the implanted devices is the power consumption, and to increase the system efficiency. The power consumption should be decrease as possible. Figure 2 shows the expectable power dissipation and power recovery path, where the main power dissipated was detected in the power amplifier, inductive power link, rectifier and voltage regulator. In this paper, the system efficiency should be developed by using efficient power amplifier, efficient inductive links, voltage doubling rectifier with self-thresholds and voltage regulator based on series NMOST transistor as shown in figure 3. The system uses ASK modulation techniques with operated frequency 13.56 MHz and modulation index 12.6%.

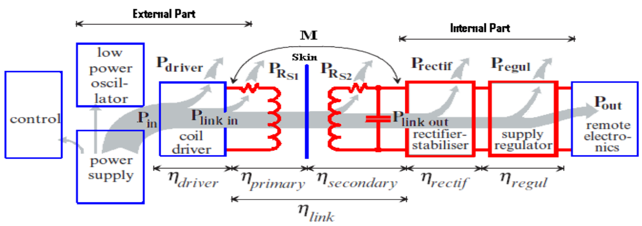

Fig. 2. Power dissipation at implanted devices.

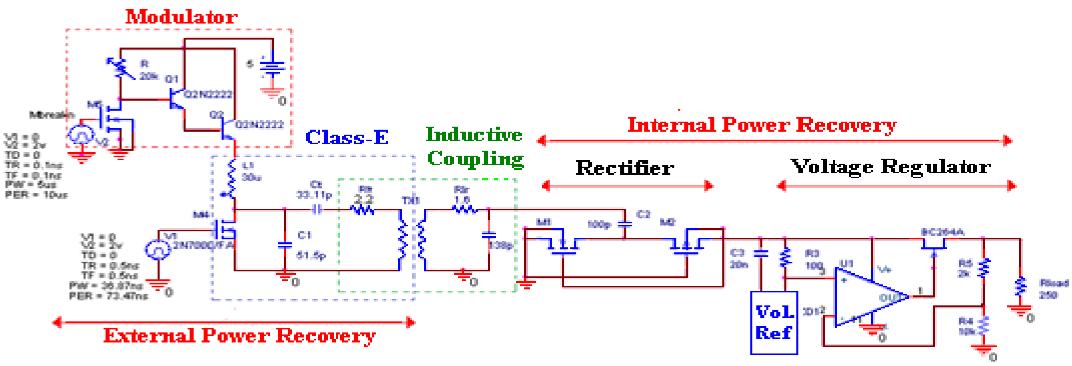

Fig. 3. Full circuit power recovery system for implanted micro-system

External Power Recovery

The external part mainaly, consists of four sub-electro circuits, such as power supply (battery), ASK modulator, class-E power amplifier and external RLC circuits, which act as a transmitted antenna as shown in figure 3. The ASK modulator used to modulate the binary signals, and consists of single-pole fast switching NMOS transistor based on 0.35um technology, two bipolar Q2N222 transistors and adjustable resistor to adjust the modulation index with value 12.6%. The ASK modulator powered with V_{DD}= 5 DC voltages from the external battery. This voltage is higher than the requirement of the class-E power supply 3.3 DC voltages in order to compensate the drop voltage of the modulator and offers 2.7 to 3.7 DC voltages, which are enough to power class-E power amplifier. The third sub-electronic circuit is the class-E power amplifier which is widely used to drive the inductive power links due to its high efficient 90-95% [4]. The supply voltage is 3.3V with 50% duty cycle. The single pole MOSFET transistor was selected type (3TEN-2N7000). The high efficiency of class-E power amplifier can be achieved by reducing the transistor switching losses, otherwise the components of class-E must be calculated from the values that satisfy the transistor fast switching, all class-E component was calculated according to equations as given in [5]. Table 1 shows the component values of class-E. The simulation and results in Figure 4 shows the output waveform, and the Drain-Source voltage (V_{DS} = 0) when the switch is active state (1) and V_{GS}=1 when the switch in the state (0), where this will reduces the power consumption of the power amplifier and gives efficincy 87.2%.

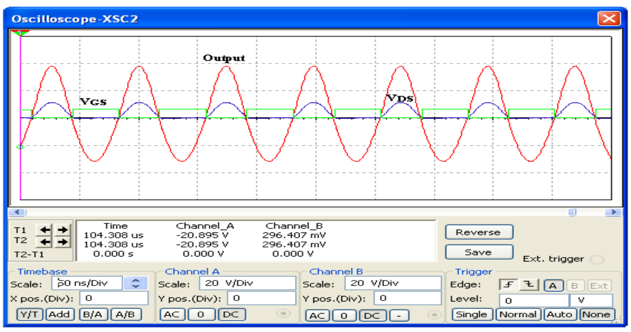

Fig. 4. The Voltage output signal. Drain-Source and Gate-Source in time.

Table 1. Class-E power amplifier values.

	Reson Freq. MHz	RFC Induct. µH	Primar Induct µH.	Load Resis	Primar Capaci PF	Shun Capa PF
Symb	F_0	L_{choke}	L_t	R_t	C_t	C_{shunt}
Value	13.56	30	4.92	2.2 Ω	33.11	51.5

Inductive Coupling Link

In general, the transcutaneous inductive coupling links consist of two resonant RLC circuits, acts as transmitter and receiver respectively. The transmitter coil located outside the human body and driven with high efficient class-E power amplifier. The receiver coil implanted inside the body and powered from external part where, a portion of generated magnetic flux from the transmitter coil part is coupled to the receiver coil and induct voltage [6,7]. The load resistance is assumed to be 250 Ω to 400 Ω. To get better power transfer efficiency, the transmitted coil tuned at series resonance, whereas the receiver coil tuned at parallel resonance. Both coils tuned at the same resonant frequency 13.56 MHz as shown in figure 5. The low-power consumption related to the low modulation index. Hence the transmitted ASK signal is V_{MAX} = 28V and V_{MIN} = 19 V, and the received ASK signal is V_{MAX} = 8 V and V_{MIN} = 6.2 V. With coupling factor 0.3 as shown in figure 6, and according to equation (1), the modulation index at the received coil is 12.6%

$$\text{(1)} \qquad Modulation\ index = \frac{V_{max} - V_{min}}{V_{max} + V_{min}} \times 100\%$$

The inductive coupling link variables as, primary coil inductance L_t, secondary coil inductance L_r, resonant frequency f_0, mutual inductance M are calculated as shown in table 2 [8]. Coupling factor (coupling coefficient K must be 0< K <1), and calculated as given in (2).these variables have a direct effect on the coupling link efficiency.

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

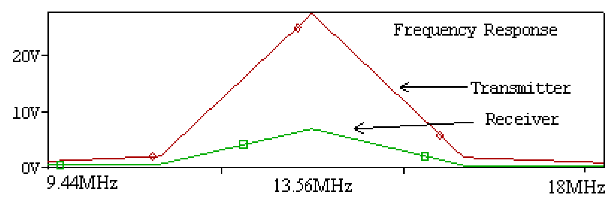

Fig.. 5. The both coils tuned at the same resonance frequency

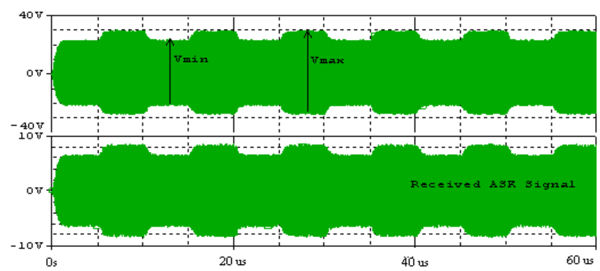

Fig. 6. ASK modulated signal at the primary and secondary coils.

Table 2. Inductive coupling links values.

	Induc μH	Capaci PF	Resis.	No. Turns	Coup. Fact.	QualFact
Transmitter	4.92	33.11	2.2 Ω	30	0.3	190
Recei.ver	1	140	1.6 Ω	8	0.3	53

Internal Power Recovery

The internal power recovery circuits consist of two sub-electronic circuits. The first one is the rectifier, which used to convert the received RF signal into DC signal. One of the main incentives of power consumption and occupies a large area in implanted devices is the rectifiers, due to its switching loss (channel size) and time response, where the received RF signal is low and drop of the output voltage below the threshold voltage. This kind of rectifiers causes to reduce the efficiency of the implanted devices such as Schottky diode rectifier, and full wave rectifier [9]. To improve and develop the rectifier efficiency, the threshold voltage should be considered. In this paper, the voltage doubling rectifier using low-drop voltage with low-leakage CMOS diodes by using self-threshold voltage cancellations techniques will be used [10]. The rectified voltage is stepped down due to its voltage drop as given in (3).

$$V_{rec} = V_{RF} - V_{DROP} \quad (3)$$

The maximum power obtained in voltage doubling rectifier is 2X more than the maximum power obtained in full wave rectifier as given in (4 and 5).

$$P_{rect.bridge(\max)} = C_r(V_{RF} - 2V_{DROP})^2 \times f \quad (4)$$

$$P_{rect.doub.(\max)} = C_r(V_{RF} - V_{DROP})^2 \times f \quad (5)$$

The relationship between drop voltage, thershold voltage and channel size is given in (6).

$$V_{DROP} = |V_{TH}| + \sqrt{\frac{2I_D}{C_{ox}\,\mu\left(\frac{W}{L}\right)}} \quad (6)$$

where $C_{ox}\mu_n\left(\frac{W_n}{L_n}\right)$ presented the process related product for K_n and similar for K_p. and the value $\frac{W_n}{L_n}$ is depended of the rectifier parasitic capacitance and its area consumption and should be increased as to lower voltage drop. The channel size values are considered as Ln=0.35μm, Lp= 0.35μm, Wn=70μm and Wp=130μm, respectively. This structure and channel size values have strongability to reduce the reverse current, whereas maintaining similar forward current.

To improve the rectifier efficiency, the threshold voltage and channel size should be considered. In this paper, a voltage doubling rectifier using low-drop voltage with low-leakage CMOS diodes is developed by using self-threshold voltage cancellations techniques. The developed circuit is used at low band frequency for biomedical implanted devices. The structure design is simple and consists of a small capacitor C_2 which have the same value of the receiver capacitor C_r, one N-MOSFEF and one P-MOSFET. Both gates are connected across the output and ground terminal as shown in figure 3. This structure increases gate-source voltage of both transistors than that of the output voltage that allowed the V_{TH} decreased by the same value to the output DC voltage. The voltage drop V_{DROP} is reduced to decrease the power consumption and increases the average rectified DC voltage that delivered 3 V DC voltages to the input of voltage regulator block. The leakage current must be lower than that of the output load current to hold the capacitor not discharge during the time when the diode is reverse biased.

Finally, the small capacitor used to smooth the output DC voltages. Figure 7 shows the rectified ASK signal, and figure 8 shows the smoothed signal with 3 DC V with minimum ripple. As a result, the threshold voltage proximity equals zero, and the V_{DROP} is depended on channel size as given in Eq. (7).

$$V_{DROP} = \sqrt{\frac{2I_D}{C_{ox}\,\mu\left(\frac{W}{L}\right)}} \quad (7)$$

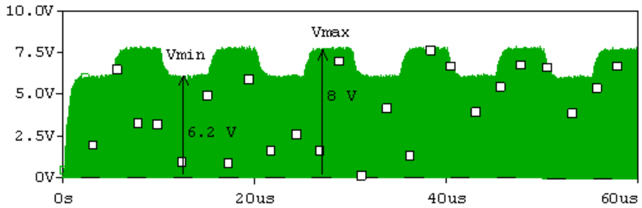

Fig. 7. The ASK rectified signal.

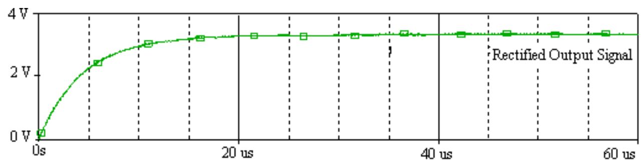

Fig. 8. The smoothed rectified signal.

The second sub-circuit is the low-dropout voltage regulator. Conventional low-dropout regulator (LDO) [11] was shown in figure 3. In this paper, a voltage regulator based on transconductance operational amplifier is used with series-pass NMOSFT transistor [12]. The on-chip voltage regulator is connected across the rectifier output to generate a stable and fixed low-power supply of 1.8 V and 2 mA depending on the transmitted power from the transmitter coil to the receiver coil. This structure consists of two-stage error-amplifiers M_1 to M_7 which offers a fast transient response, adjusts the get drive of NMOSFET load current and keeps the output voltage at a fixed level [13,14]. Thus, the conventional resistors R_4 and R_5 are replaced by the M_9-M_{12} MOSFETS as shown in figure 9. NMOSFET transistor M_8 presents the adjustable series-pass transistor to deliver the required load current and keep the output voltage at fixed value and allow the reference voltage to be one-quarter of the required output voltage, whereas consuming a very small amount of power. The small feedback capacitor 3PF is connected between the series-pass transistor gate and the drain to increase and ensure the system stability. This regulated voltage is used to power the remote of the implanted device with steady regulated voltage 1.8 V_{DD}, regardless of any possible change occurs in the resistance of implanted devices or current drawn by the load as shown in figure 10. This proposed structure has high DC gain, low current consumption and low noise.

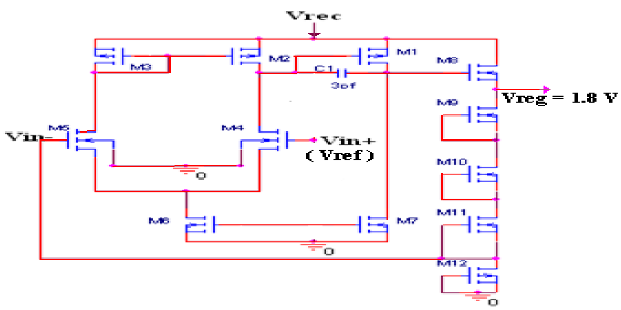

Fig. 9. Voltage regulator with series-pass NMOSFET

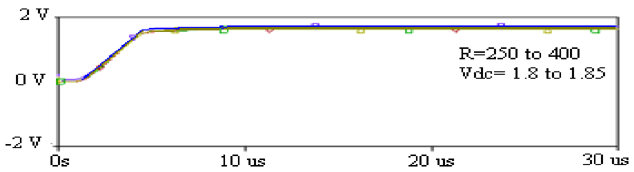

Fig. 10. The output regulated voltage with varies load resistance

Results and Discussion

This paper presents the low-power recovery system design for implanted biomedical micro-system. The proposed system consists of two parts, external part and internal part as shown in figure 3, where the external part consists of power supply (battery), ASK modulator and class-E, power amplifier included transmitted coil to transmit the power and data. Whereas the internal part consists of received coil, the voltage doubling regulator with self-cancellation threshold voltage and voltage regulators based on a series-pass NMOST transistor to step down the rectified ASK signal to fix 1.8 DC voltages without ripple voltage to power other parts of the implanted device. The system operated with a low-frequency band 13.56 $MH_{Z,}$ according to the ISM band to avoid the tissue damage. The ASK modulator used to modulate the input signal and provide 2.7 to 3.7 DC voltage to power the class-E power amplifier. The class-E, power amplifier operated with 13.56 MHz which is designed with minimum switching losses, low-power consumption. The output waveform, and the Drain-Source voltage (V_{DS} = 0) when the switch is active state (1) and V_{GS}=1 when the switch in the state (0), and offer stable sinusoidal wave signal to the transmitted coil as shown in figure 4. The asset value of the power amplifier was calculated as given in table 1. The transmitted coil act as an antenna to transmit the modulated ASK signal with V_{MAX}=28 V and V_{MIN}=22 V as. The received coil in the internal part receives the ASK modulated signal inductively with valoes V_{MAX}=8 and V_{MIN}=6.2 V with modulation index 12.6% as shown in figure 6. Because of weak coupling between the external and internal coils, then the inductive coupling links should be designed to be able to transmit the power at high efficiency according to the values given in table 2. For the internal power recovery, the proposed voltage doubling rectifier with self-cancellation threshold voltage used to rectify the ASK signal with low-drop voltage as shown in figure 3. And offer a stable rectified 3 DC voltage, which smoothed with small capacitor C_3 with very small ripple voltage as shown in figures 7 and 8. The rectify signal was stepped down and regulated using proposed voltage regulator based on a series-pass NMOST transistor to provide very fixed and stable 1.8 DC voltages as shown in figure 9, which satisfied the requirement of the implanted device even in any changing at the implanted load resistor as shown in figure 10. The power efficiency is 66% where from the simulation, the input power is 250 mw and the output power is 165 mW. This system may be used for implanted micro-system devices to stimulate the nerves and muscles.

Conclusion

In this paper, the design of the low-power recovery system for implanted micro-system is presented. The system operated with ISM low-band frequency 13.65 MH_Z and simulated using OrCAD PSpice 16.2 software tools and electronic workbench MULISIM 11. The high efficient class-E, power amplifier 87.2% and efficient inductive links 66% were used to transmit the ASK signal to the implanted device. The proposed voltage doubling rectifier using low-drop voltage with low-leakage CMOS diodes by using self-threshold voltage cancellations techniques rectifier and voltage regulator based on series NMOST transistor was used to offer low-power supply 1.8 DC voltages to power the implanted sensor. The total power efficiency is 66% with modulation index 12.6%. This design is may be suitable for implanted sensors with resistance 200-400 Ω.

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