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Design and Implementation of Efficient Wireless Power Transfer System to Power the Internal Bio-Implantable Devices

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Abstract: This study deals with the design and implementation of an efficient sub-electronic circuits to power and transfer data to the remote bio-implantable devices. The proposed system is designed and implemented based on ASK modulation techniques operated with 10 MHz with modulation index 11.6%. The system consists of a modified ASK modulator a proposed self-tuning Class-E coil driver with 92.13% of efficiency and voltage-doubling rectifier with self-threshold cancellation to generate a stable 1.8 DC voltage to power the implanted remote electronic circuits. The OrCAD Pspice 16.2 Software using specter simulation with edit 0.35 um CMOS process is used to validated the design. Whereas, the simulation results of the self-tuning Class-E coil driver is simulated with NI MULTISIM 11. For farther testing and validation an experimental hardware simulation is also presented using National Instruments NI circuits design suit (Virtual ELVIS 11) compatible with NI LabVIEW.

Key words: Implanted devices, Class-E amplifiers, inductive links, rectifiers, ASK modulation techniques, sub-electronic

INTRODUCTION

In the earlier decades, most of the bio-implantable devices such as bio-implanted micro-system stimulator powered using weirs penetrate living human tissue and this cases hazards and skin infections. In order to avoid these problems, researchers developed the implanted devices to be powered using the batteries. However, due to the large size, limited time-life and chemical side effect of the battery, cases patient discomfort. Hence, recently, the Wireless Power Transfer (WPT) techniques are commonly used to transfer power and information to the bio-implanted devices (Ghorbel *et al*., 2006). Presently most of the implanted devices powered inductively using inductive coupling links (Mutashar *et al*., 2012).

Normally, the bio-implanted micro-system consists of two parts, external part and internal part. The external part placed outside the human body and the second part implanted within the human tissue (Hmida *et al*., 2007). Due to the weak coupling links between the two parts to the system require an the efficient sub-electronic circuits with small size as possible. Three modulation techniques have been used in the implanted devices such as Amplitude Shift Keying (ASK), Frequency Shift keying (FSK) and Phase Shift Keying (PSK). The ASK modulation techniques is widely used due to its simplest architecture, low-power consumption and low cost (Hannan *et al*., 2012).

In general, most of the implanted devices suffered from many problems such as variation of the operating frequency due to the variation in the separation distance between to coils, carrier frequency and power consumptions power. Many studies focused on developing an efficient transcutaneous energy transfer system by designing transmission system with efficient frequency-controlled Class-E technique (Ma *et al*., 2010; Sira *et al*., 2010; Hannan *et al*., 2014).

An auto-tuned transcutaneous energy system is tuned by a capacitors to specific resonant frequency of the primary and secondary coil (Miller *et al*., 1993). The issue of this design is the resonant frequency of the secondary side is not equal to the switching frequency and extremely sensitive to the coil separation distance. A wireless energy transfer system with a Class-E coil driver is designed to transfer 250 MW of power to a cochlear implant with 65% of efficiency (Wang *et al*., 2008). The same approach is also used by Puers and Vandevoorde (2001) both systems given by Wang *et al.* (2005) and Puers and Vandevoorde (2001) suffered from the losses in the overall efficiency due to the DC-DC converter.

In this study, the energy transfer system is proposed as shown in the block diagram given in Fig. 1. It consists of modified ASK modulator, self-tuning Class-E coil driver with 92.13% of efficiency, doubling rectifier with self-threshold cancellation to the generate stable 1.8 DC v.

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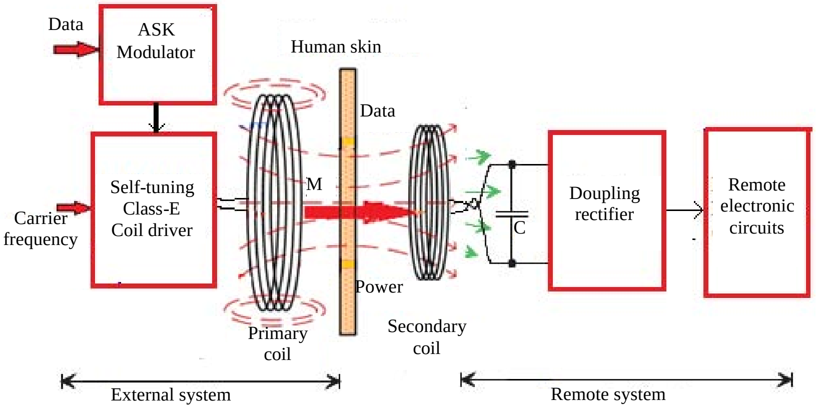

Fig. 1: Block diagram for the transcutaneous energy transmission system

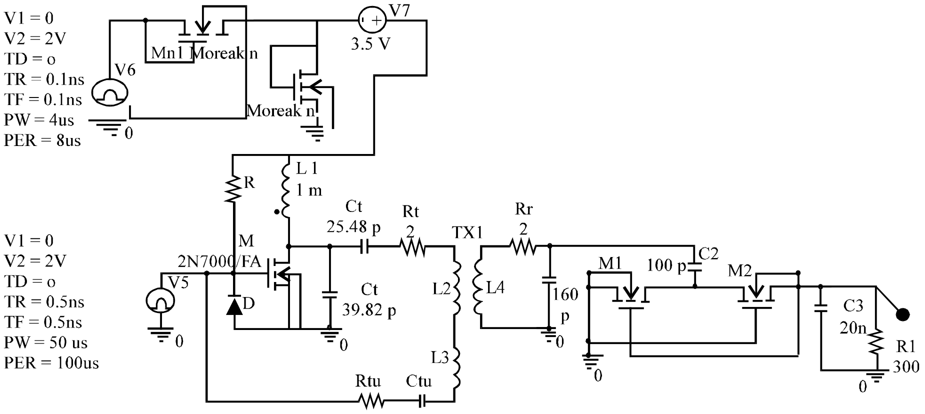

Fig. 2: The proposed energy transfer system architecture

The OrCAD Pspice 16.2 Software using specter simulation with edit 0.35 μm CMOS process is used to validated the design. The proposed design is implemented using National Instruments NI circuits design suit (Virtual ELVIS 11) compatible with NI LabVIEW both simulation and experimental results are reported.

System architecture: In general, the transcutaneous energy system consists of external part located outside the body and internal part implanted within the tissue. The proposed system is insulated in Fig. 2 the external part consists of data generator; ASK modulator, efficient self-tuning Class-E coil diver. The internal part located inside to the human body and consists of internal RLC circuit which acts as a receiver, doubling rectifier with self-threshold cancellation. The power delivered to the remote sub-electronic circuits and data rate speed is one of the main key issues in the implanted devices. The doubling rectifier with the self threshold cancellation rectify to the ASK signal and extract the data and powered the implanted circuits with the stable low-power supply 1.8 DC voltages.

External electronic circuits: The main part for the external circuits is the data generator, ASK modulator and efficient self-tuning Class-E coil diver amplifier. The main parts dealing with date are the digital data generator and modulator.

Ask modulator design: The proposed block diagram of the developed ASK modulator is demonstrated in Fig. 3. This ASK modulator involves pulse generator to generate a fixed binary sequence, two similar edited N-MOSFET (Mn 1, Mn 2) transistors act as the voltage divider resistance to adjust the modulation index to be 11.6% by varies the relation between the maximum and minimum

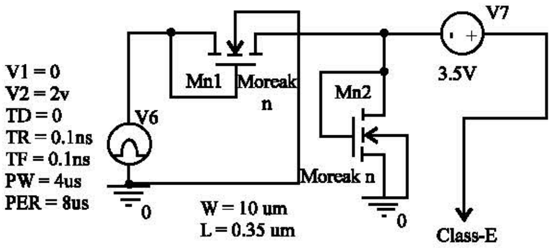

Fig. 3: The proposed ASK modulators based on NMOSFET technology

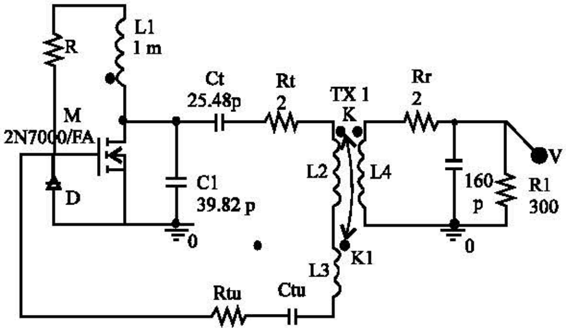

Fig. 4: A self-tuning Class-E coil driver at 10 MHz

amplitude levels, V_{max} and V_{min} as given in Eq. 1. The modified ASK modulator is also used to supply the self-tuning Class-E power amplifier with the required dc Voltage (V7). The digital pulses generator is used to generate the desired digital signals with T_{bit} = 1 µs according to the configuration setting and applications:

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

Self-tuning Class-E coil diver and resonant network design: The Class-E coil driver is widely used in the bio medical applications due to its simplest (single pole transistor) and has a theoretical energy transfer efficiency up to 100% which is mainly due to zero switching losses of its switching transistor (Mutashar and Hannan, 2013). In this study, the ASK modulator powered the self-tuning Class-E coil drivers which can track the separation-distance of the transmitted and received coils for maximum power transfer efficiency. The self-tuning Class-E coil drivers is introduced by Fig. 4. In this design the method introduced by Raab (1978) and Mutashar *et al.* (2014) is chosen for the Class-E coil-driver of the transcutaneous energy transfer system where it is assumed that the quality factor (Q) of the resonant load network is high enough so that the current flowing through it is sinusoidal. This current flows through the MOSFET transistor (2N7000/FA) when it is on. Whereas, when the transistor turns off this current keeps flowing but this time through the capacitor C_1, raising the voltage across it as well as across the transistor. When the direction of the current is reversed, C1 starts supplying this current, reducing the voltage across it. The value for the C_1 is determined to make this voltage not only reach zero but also have a zero slop at this instant. The shunt capacitor C_1 calculated by 2 and C_t calculated as given in Eq. 3, respectively:

$$C_1 = \frac{1}{\omega_0 R_{1.opt}\left[\frac{\pi^2}{4}+1\right]\left[\frac{\pi^2}{2}\right]} = \frac{1}{\omega_0\left(5.447R_{1.opt}\right)} \tag{2}$$

$$C_t \equiv C_1\left[\frac{5.447}{Q}\right]\left[1+\frac{1.42}{Q-2.08}\right] \tag{3}$$

In general, the efficiency of any amplifier is called the power-conversion efficiency and define as the ratio between output power (Pout) to the supply power (Ps) and calculated as given in Eq. 4:

$$\eta = \frac{P_{out}}{P_s}100\% \tag{4}$$

In Class-E design Eq. 4 will be altered specifically by using drain supply power (P_{DD}), then:

$$\eta_d = \frac{P_{out}}{P_{DD}} = \frac{P_{out}}{P_{DC}} \tag{5}$$

Then overall Class-E efficiency can be found Eq. 6:

$$\eta_{all} = \frac{P_{out}}{P_{DC}+P_{in}} \tag{6}$$

Where in Eq. 6 the RF input power (P_{in}) is the very small compared with power supply (P_{DC}) and can be the ignores.

The coupling link in this circuit is presented by the transcutaneous transformer, L2 and L4 are coupled with coupling coefficient of K, they have a coupling with transistor driving coil, L3 for self-oscillation purpose. This coupling is represented by coupling K1 between L2 and L3 coils. The oscillation frequency influenced by the mutual position of the coils. The coupling variation of these coils produce a frequency offset which tracks the spectral location corresponding to the absolute maximum power transfer efficiency. In this way an automatically

Table 1: The self-tuning Class-E coil driver values

Operated Freq.	L1 (mh)	C1 (Pf)	C_t (Pf)	L2 (μh)	L3 (μh)	Rt (Ω)	R_{tu} (Ω)	C_{ut} (Pf)	P_{DC} (mW)	P_{out} (mW)	η (%)
10 MHz	1	39.82	25.48	14.12	1.85	2	1	3	229	211	92.13

tuned power amplifier for maximum power transfer with varying separation-distance between the two coils of a transcutaneous amplifier is realized in Table 1.

Inductive coupling link: Recently, the inductive coupling links used for short wireless communication systems such as implanted devices and involves of two resonant RLC circuits, acts as a primary coil (transmitter) located outside the body and secondary coil (receiver) implanted within the human body. The transmitter coil driven with high efficient self-tuning class-E driver. The implanted coil (receiver) powered from external part where a portion of generated magnetic flux from the primary coil part coupled to the secondary coil and induct voltage (Gervais *et al.*, 2003; Silay *et al.*, 2008). For better power transfer efficiency, both primary and secondary coils tuned at the same resonant frequency 10 MHz, the transmitted coil tuned at series resonance and the receiver coil tuned at parallel resonance. From the simulation results is observed that the transmitted modulated ASK signal is V_{max} = 60 V and V_{min} = 47.5 V. Whereas, the received ASK signal is V_{max} = 8 V and V_{min} = 6.3 V to achieve 11.6 % of modulation index as given in Eq. 1.

Internal powering circuits (rectifier): The process of the digital signal processing within the body is more complicated than outside. Since, signal passes through the body. Therefore, there are many limitations in the design of electronic circuits that achieve a stable dc voltage to power the implantable remote sub electronics circuits. This required an efficient rectifier with lowest power consumption. Since, most of the Bio-implantable devices need to be supplied by Direct Current (DC), this alternating current is required to be converted into direct current by the rectifier block. The topologies of the RF-DC MOSFET full wave rectifiers are widely used in the biomedical applications such as the gate cross-coupled rectifiers and fully cross-coupled rectifiers (Rakers *et al.*, 2001). These topologies suffer from slow time response where the received signal is low and drop of the output voltage below the threshold value resulting reduced the data rate speed and reduce the efficiency of the implanted devices. In additional, these topologies consume power due to switching loss transistor and threshold voltage. The maximum output power for the full wave rectifier can be shows as given in Eq. 7, whereas, the maximum output power for voltage doubling rectifier can be obtain as given in Eq. 8. The maximum power obtained in voltage doubling rectifier is 2X more than the maximum power obtained in full wave rectifier:

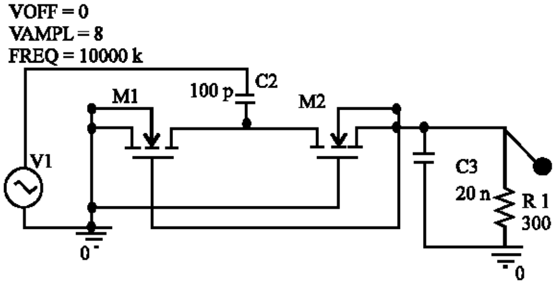

Fig. 5: The proposed voltage-doubling rectifier with self-threshold cancellation

$$P_{rect\,bridge(max)} = C_r\,(V_{RF}-2V_{DROP})^2 \times f \tag{7}$$

$$P_{rect.doub.(max)} = C_r\left(V_{RF}-V_{DROP}\right)^2 \times f \tag{8}$$

Where:

V_{RF} = The represents the reference voltage

V_{DROP} = The dropped voltage

Therefore, the main motivation for voltage drops in MOSFET rectifiers is a threshold voltage V_{TH} and channel size, i.e., width W and length L as given in Eq. 9 and 10, respectively:

$$V_{rect} = V_{RF}-V_{DROP} \tag{9}$$

$$V_{DROP} = \left|V_{TH}\right| + \left(\frac{2I_D}{C_{ox}\mu\left(\frac{Wn}{Ln}\right)}\right)^{\frac{1}{2}} \tag{10}$$

where, C_{oX} μ_0 $[W_n/L_n]$ presented the process related product for K_n. To overcome the above disadvantages and enhance the rectifier efficiency, the threshold voltage and channel size need to be consider. In this study, a voltage-doubling rectifier using low-drop voltage with low-leakage CMOS diodes is developed by using self-threshold voltage cancellation techniques to improve the power efficiency of the implanted devices (Kotani and Ito, 2007). The developed circuit used for low band frequency for biomedical implanted devices. The structure design is simple and involves of a small

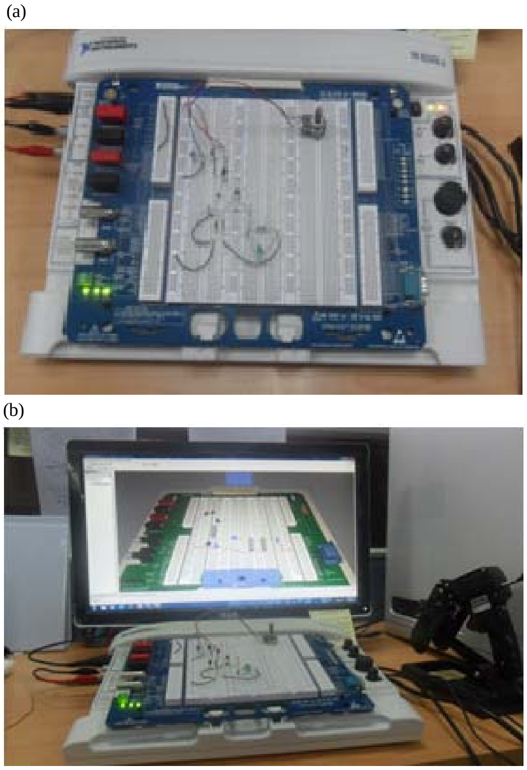

Fig. 6: a) the NI ELVIS 11 breadboard; b) the NI ELVIS 11 breadboard with the virtual ELVIS 11

capacitor C_2, one N-MOSFEF (M1) and one P-MOSFET (M2) as shown in Fig. 5. Both gates connected to the output and ground terminal. 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 of the output DC voltage.

To increase the rectified DC voltage and decrease the power consumption, the voltage drop V_{DROP} should be reduced. 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. The proposed rectifier in this study produce a very stable 1.8 DC voltage to power the implantable remote sub-electronics circuit without using voltage regulators, references voltages and temperature protection circuits. As a result, the threshold voltage proximity equals zero and the V_{DROP} is depending on channel size as given in Eq. 11:

$$V_{DROP} = \left(\frac{2I_D}{C_{ox}\mu\left(\frac{Wn}{Ln}\right)} \right)^{\frac{1}{2}} \tag{11}$$

From Eq. 13 is noted that the relationship between voltage drops and the MOSFET transistor channel size is realized to achieve a desired minimum rising or falling propagation delay. The MOSFET channel size values were edited as $L_n = 0.35$ μm, $L_p = 0.35$, $W_n = 70$ μm and $W_p = 130$ μm, respectively. This structure and channel size values have robust ability to reduce the reverse current, whereas keeping similar forward current, resulting faster time response and higher data rate speed.

Excremental design and measurements: To verify and test the external part, the NI circuit design suit is used to implement the ASK modulator and the self-tuning Class-E coil driver. This instrument consists of LabVIEW and NI ELVIS 11 breadboard to implement the electronic components which can be indicated as a 3D virtual ELVIS 11 on the PC to extract the results as shown in Fig. 6. The implementation is done by using the discrete components proposed in the ASK modulator and the self-tuning Class-E coil driver design.

RESULTS AND DISCUSSION

This study deals with design and implementation if an efficient wireless energy transfer system to power the remote electronic bio-implantable devices with stable 1.8 DC voltage. Even though frequency variation. Taking into consideration achieve less power consumptions and simple design as possible. The proposed transcutaneous transfer system is consists of two parts, external part and internal part operated with 10 MHz of ISM band as shown in Fig. 1. The external part consists of binary data generator a proposed ASK modulator, efficient self-tuning Class-E coil driver included transmitted coil to transmit the power and data. Whereas, the internal part consists of received coil, voltage doubling regulator with self-cancellation threshold voltage.

The ASK modulator offer modulation and required DC voltage to power the self-tuning Class-E coil driver. Figure 7a shows the binary data generated by data generator with amplitude 2 V with rising-time 0.1 ns (Fig. 7b) the required output power from the ASK modulator up to 3.5 V to power the proposed Class-E. The self-tuning Class-E P/AMP operated at 10 MHz with zero transistor switching to achieve 92.13% of efficiency as shown in Table 1 and Fig. 8.

The transmitted resonance RLC circuits in the Class-E act as an antenna to transmit the modulated ASK signal with V_{max}= 60 V and V_{min}= 47.5 V. The received RLC circuits in the implanted part receives the ASK modulated signal inductively with values V_{max} = 8 V and V_{max} = 6.3 V

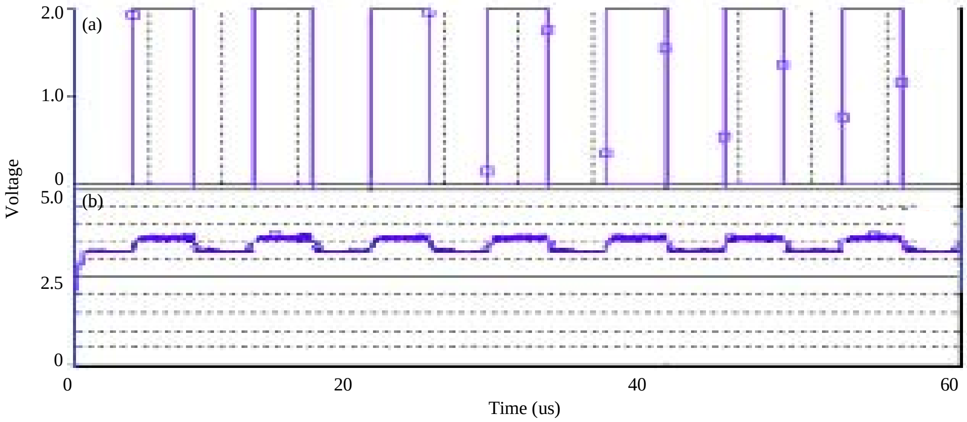

Fig. 7: a) binary signals an; b) the required Class-E power supply

Time	Channel_A	Channel_B
58.504 us	5.000 V	1.555 V
58.504 us	5.000 V	1.555 V
0.000 s	0.000 V	0.000 V

Timebase
Scale: 50 ns/Div
X pos.(Div): 0

Channel A
Scale: 5 V/Div
Y pos.(Div): 0

Channel B
Scale: 5 V/Div
Y pos.(Div): 0

Trigger
Edge: A
Level: 0 V

Fig. 8: The MOSFT transistor (2N7000/FA) Drain-source and Gate-source switching in time

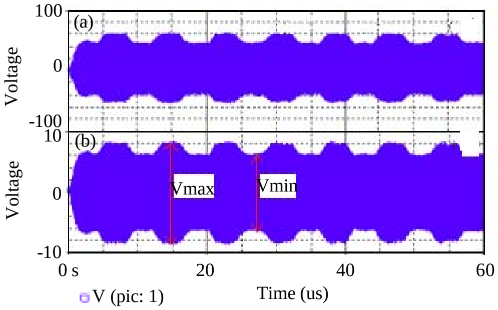

Fig. 9: ASK modulated signal; a) primary coil; b) secondary coils

with modulation index 11.6% based on Eq. 1 as shown in Fig. 9a and b, respectively. Both RLC network tuned at the same resonance frequency 10 MHz to achieve acceptable coupling links efficiency as shown in Fig. 10a and b, respectively.

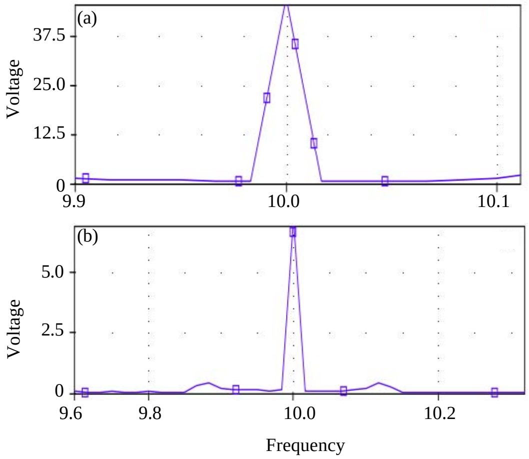

Fig. 10: The primary coil; a) and the secondary coil; b) tuned at the same frequency

To test and verify the performance of the voltage doubling rectifier with self-threshold cancellation a separated block is designed using OrCAD Pspice 16.2 software as given in Fig. 5. The results of this design is compared with tow simulated topologies of rectifiers such as gate cross-coupled rectifiers and fully cross-coupled rectifiers (Silay *et al*., 2008). The results given in Fig. 11 that the proposed design have better performance where no ripples and produce very stable DC voltage to power the implantable remote electronic testing the proposed rectifier is connected to the overall system and divine by the internal RLC circuit (received coil) to extract the rectified ASK modulated signal which smoothed by the capacitor C_3 to produce very stable 1.8 DC V as shown in Fig. 12.

Finally, in order to verify and validate the proposed design, the National Instruments (NI) circuits design suit

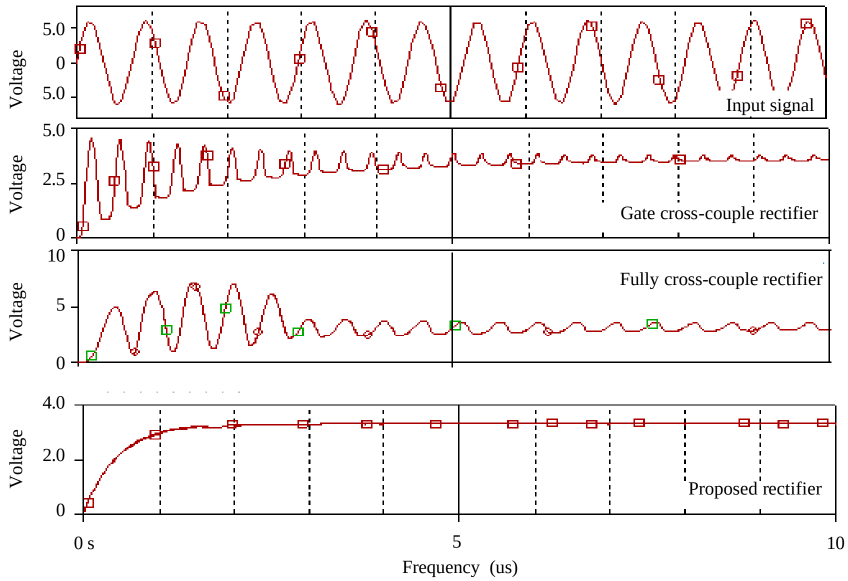

Fig. 11: The proposed rectifier output compared with others design

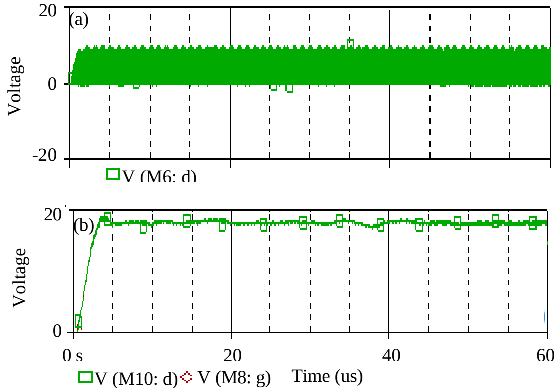

Fig. 12: a, b) The rectified ASK modulated signal

Fig. 13: The measured results using the National Instruments NI circuits design suit

(Virtual ELVIS 11) compatible with NI LabVIEW is used to implement the external part and the measured results at 10 MHz are reported. Figure 13 shows the experimental results, it can be seen the zero MOSFT transisto switching and transmitted ASK modulated signal where compatible with the simulated results.

CONCLUSION

This study, delis to design and implement an efficient energy transfer system to power the remote electronic Bio-implantable Devices. The system involves proposed ASK modulator based on CMOS technology, high efficient self-tuning Class-E power amplifier and Self-threshold Cancellation Rectifier. The system operated with ISM low-band frequency 10 MHZ with 11.6% of modulation index and the 92.13% of the self-tuning Class-E efficiency, inductive coupling link and doubling rectifier to produce stable 1.8 DC voltage to power the implantable circuits. To test and validate the system, a simulation and measured results were presented by using by OrCAD Pspice 16.2 Software using specter simulation with edit 0.35 um CMOS process. Whereas, the simulation results of the self-tuning Class-E coil driver is simulated with NI MULTISIM 11. For farther testing and validation an experimental hardware for the external part is also presented using National Instruments NI circuits design suit (Virtual ELVIS 11) compatible with NI LabVIEW. The proposed system may be useful for the bi-implantable devices such as cochlear and retinal implants and nerves stimulator.

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