



DESIGN AND IMPLEMENTATION AN EFFECTIVE ENERGY TRANSFER SYSTEM FOR POWERING THE REMOTE IMPLANTABLE BIOMEDICAL DEVICES

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ABSTRACT

This paper introduce the designand implementation of an efficient electronic circuit to power and transfer data to the internal implantable biomedical devices. The proposed system is designed and implemented using ASK modulation techniques at 10 MHz operated frequency with 11.6 % of modulation index. The system involves a modified ASK modulator, a proposed efficient self-tuning Class-E coil driver with 92.14% of efficiency and self-threshold cancellation voltage-doubling rectifier to generate a constant 1.8 DC voltage to power the implanted sub-electronic circuits. The OrCADPspice 16.2 software using spectre simulation with edit 0.35um CMOS technology is used to validate the design. Whereas, the simulation results of the self-tuning Class-E coil driver is simulated with NI MULTISIM 11. For further testing and validation, an experimental hardware simulation is alsopresented using National Instruments NI circuits design suit (Virtual ELVIS 11) compatible with NI LabVIEW.

Keywords: class-E amplifiers, implanted devices, inductive coupling links, rectifiers, ASK modulator.

1. INTRODUCTION

In the previous years, the weirs penetrate the human tissue is used to power most of the bio-implantable devices and this causes tissue infections and risks. To overcome the above problems, batteries were used to power the remote bio-implanted devices. However, due to the large size, chemical side effect, limited time-life of the battery and battery replacement which causes patient discomfort. Hence, currently, the wireless energy transfer systems are commonly used to transfer power (energy) and information to the bio-implanted devices [1]. Currently the inductive coupling links is widely used to power the remote implanted circuits [2].

Usually, the bio-implanted devices which powered inductively consist of two parts, external part placed outside the human body and internal part implanted within the human tissue [3]. Due to the weak coupling links between the two parts, the system requires an efficient sub-electronic circuit with small size as possible. Three modulation techniques have been used to transfer data to the implanted devices; these techniques are Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK) and Phase Shift Keying (PSK). The ASK modulation techniques are commonly used due to its simplest architecture design, low-power consumption and low cost [4].

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 [5]. Many studies focused on developing an efficient transcutaneous Energy Transfer System by designing transmission system with efficient frequency-controlled Class-E technique [6-8]

An auto-tuned transcutaneous energy system is tuned by capacitors to a specific resonant frequency of the transmitter coil and receiver coil [9]. 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 [10]. The same approach is also used by [11], both systems given in [10] and [11] suffered from the losses in the overall efficiency due to the DC-DC converter. However, the various fractal geometries might be adopted to gain both size reductions with similar power handling as compared with the traditional structures [12-16].

In this paper, the energy transfer system is proposed as shown in the block diagram given in Figure-1. It consists of modified ASK modulator, self-tuning Class-E coil driver with 92.14% of efficiency, doubling rectifier with self-threshold cancellation to generate stable 1.8DC v. The OrCADPspice 16.2 software using specter simulation with edit 0.35 um CMOS technology is used to validate 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.

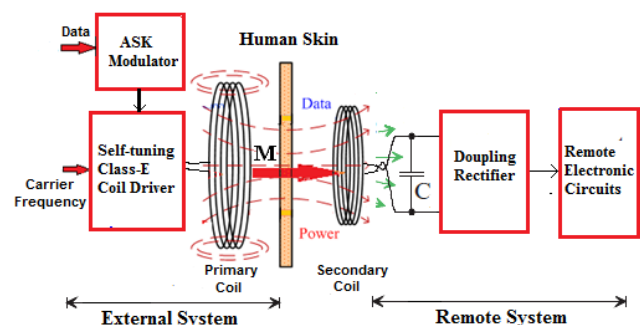


Figure-1. Block diagram of the wireless energy transfer system.



2. SYSTEM DESIGN

Generally, the transcutaneous energy system involves of the external part situated outside the body and internal part implanted within the tissue. The proposed system is insulated in Figure-2, the external part architecture consists of data generator; ASK modulator and efficient self-tuning Class-E coil driver. The internal part situated inside the human body and involves of

internal RLC circuit, which behaves 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 ASK signal is rectified by the doubling rectifier with self-threshold cancellation to power the internal implanted circuits with stable low-power supply 1.8 DC voltages and read out the received data.

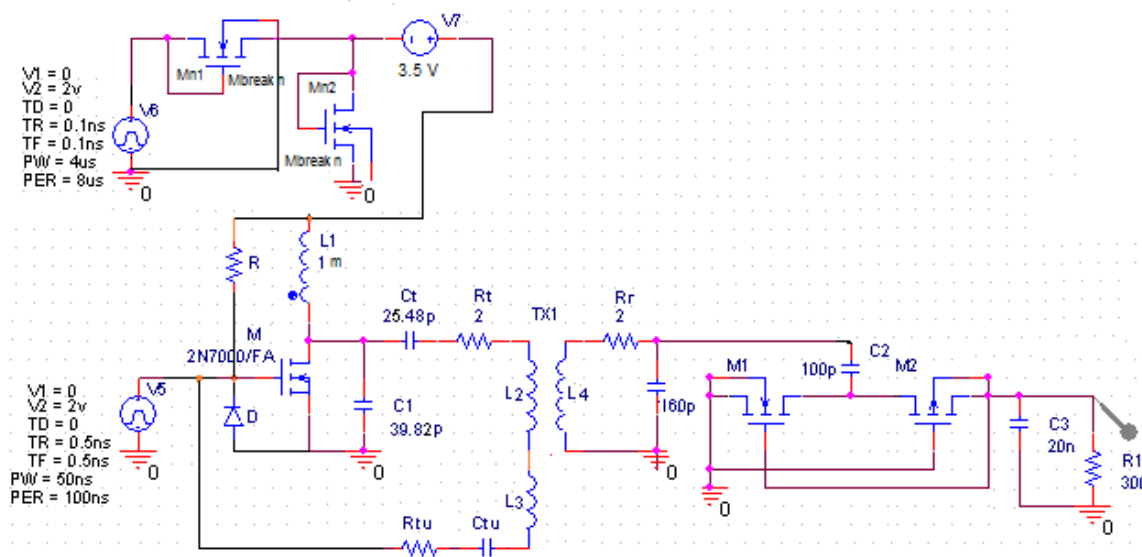


Figure-2. The block diagram of the proposed wireless energy transfer system.

3. EXTERNAL CIRCUIT DESIGN

The major part of the external circuits is the data generator; ASK modulator and efficient self-tuning class-E coil driver amplifier.

3.1 ASK modulator design

The proposed block diagram of the developed ASK modulator is demonstrated in Figure-3. This ASK modulator involves pulse generator to generate a fixed binary sequence. Two similar edited N-MOSFET (Mn1, Mn2) 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 amplitude levels, V_{max} and V_{min} as given in (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 adapted to generate the desired serial digital signals with $T_{bit} = 1\mu s$.

$$Modulationindex = \frac{V_{max}-V_{min}}{V_{max}+V_{min}} \times 100\% \quad (1)$$

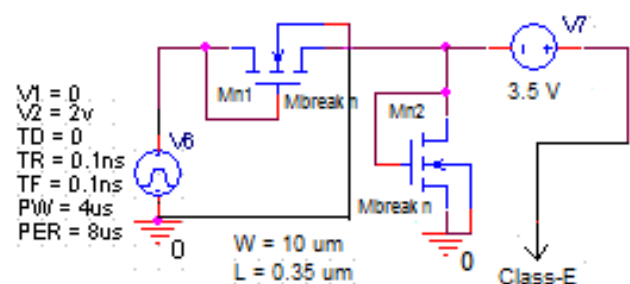


Figure-3. The proposed ASK modulators based on NMOSFET technology.

3.2 Self-tuning class-e coil driver with resonant network design

The Class-E coil driver is extensively used in the biomedical 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 [17]. In this paper, 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 driver is introduced by Fig. 4. In this design, the method presented by [18] and [19] 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 C1, 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 C1 is determined to make this voltage not only reach zero but also have zero slope at this instant. The shunt capacitor C1 Calculated by (2) and Ct calculated as given in (3) respectively.

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

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

In general, the efficiency of any amplifier is called the power-conversion efficiency and defines the ratio of output power (P_{out}) to the supply power (P_s) and calculated as given in (4)

$$\eta = \frac{P_{out}}{P_s} 100 \% \quad (4)$$

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

$$\eta_d = \frac{P_{out}}{P_{DD}} = \frac{P_{out}}{P_{DC}} \quad (5)$$

Then overall Class-E efficiency can be found by

$$\eta_{\text{all}} = \frac{P_{\text{out}}}{P_{\text{DC}} + P_{\text{in}}} \quad (6)$$

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

The coupling link in this circuit is presented by the transcutaneous transformer, L2 and L4, are coupled with a 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 produces a frequency offset which tracks the spectral location corresponding to the absolute maximum power transfer efficiency. In this way, an automatically tuned power amplifier for maximum power transfer with varying separation-distance between the two coils of a transcutaneous amplifier is realized. The self-tuning class-E coil driver element values are given in Table-1.

Table-1. The values related to the self-tuning Class-E coil driver elements.

Operated freq.	L1(mh)	C1(Pf)	Ct(Pf)	L2(μh)	L3(μh)	Rt(Ω)	R _{tw} (Ω)	C _{ut} (Pf)	P _{DC} (mW)	P _{out} (mW)	η%
10MHz	1	39.82	25.48	14.12	1.85	2	1.5	2.8	229	211	92.14

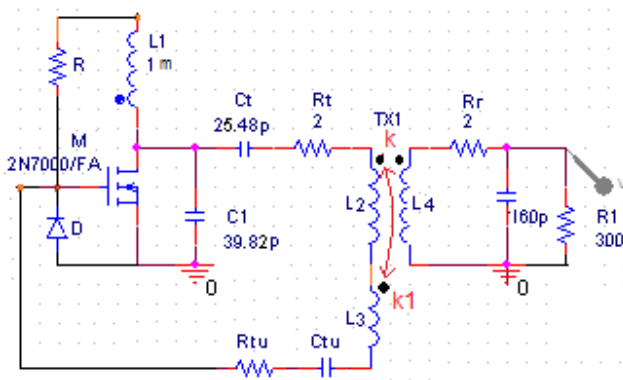


Figure-4. A self-tuning class-E coil driver at 10 MHz.

4. INDUCTIVE COUPLING LINK

Nowadays, the inductive coupling techniques are widely used for short range energy wireless communication systems such as implanted devices. The coupling consists of two resonant RLC circuits, the transmitter coil (primary) situated outside the body and receiver coil (secondary) implanted within the human body. The transmitter coil is driven by 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 induces voltage [20] and [21]. For efficient power transfer, both primary and secondary coils tuned to the same resonant frequency 10MHz. The topology serial- parallel is used in this design where the transmitted coil tuned at series resonance and the receiver coil tuned at parallel resonance. From the simulation results is observed that the maximum transmitted modulated ASK signal is $V_{\text{MAX}} = 60 \text{ V}$ and the minimum transmitted modulated ASK is $V_{\text{MIN}} = 47.5 \text{ V}$, whereas, the maximum received ASK signal is $V_{\text{MAX}} = 8 \text{ V}$ and minimum received ASK signal is $V_{\text{MIN}} = 6.3 \text{ V}$ to achieve 11.6 % of modulation index as given in Eq. (1).

5. INTERNAL POWERING CIRCUITS DESIGN

The process of the digital signal processing within the human body is more complicated than outside. Since signal permits the body, therefore many limitations should be consider in the design of electronic circuits that achieve a stable dc voltage to power the implantable remote sub-electronics circuits. This requires 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. Because of the fast response and low-power consumption, the MOSFET transistors so it is widely used in the wireless and biomedical applications than the Bipolar Junction Transistors (BJT) [22]. The topologies of the RF-DC MOSFET full wave rectifiers are widely used in the biomedical applications such as gate cross-coupled rectifiers and fully cross-coupled rectifiers [23]. These topologies suffer from slow time response where the received signal is low and drop of the output voltage below the threshold value causing reduced the data rate speed and reduce the total efficiency of the implanted devices. In addition, due to the switching loss transistor and threshold voltage these topologies consume power. The maximum output power for the full wave rectifier and the maximum output power for voltage doubling rectifier can be explained in (7) and (8) respectively. It can be seen that the maximum power achieved in voltage doubling rectifier is 2X more than the maximum power obtained in full wave rectifier.

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

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

Where V_{RF} represents the reference voltage and V_{DROP} is the dropped voltage.

Hence, the major motivation for voltage drops in MOSFET rectifiers is the channel size (width W and length L) and a threshold voltage V_{TH} as given in (9) and (10), respectively.

$$V_{rect} = V_{RF} - V_{DROP} \quad (9)$$

$$V_{DROP} = |V_{TH}| + \left(\frac{2I_D}{C_{ox}\mu \left(\frac{W_n}{L_n} \right)} \right)^{\frac{1}{2}} \quad (10)$$

Where $C_{ox}\mu_0 \left(\frac{W_n}{L_n} \right)$ represents the process related product for K_n

The threshold voltage and channel size need to be considered to overcome the above disadvantages and enhance the rectifier efficiency. In this paper, 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 [24]. The structure design is simple and involves of two devices such as N-MOSFET (M1), P-MOSFET (M2) and small capacitor C_2 as shown in Figure-5. The transistors gates connected to the output and ground terminal. In this structure the gate-source voltage of both transistors will be

increases 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 paper produces a very stable 1.8 DC V to power the implantable internal 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} depends on the channel size as given in (11).

$$V_{DROP} = \left(\frac{2I_D}{C_{ox}\mu \left(\frac{W_n}{L_n} \right)} \right)^{\frac{1}{2}} \quad (11)$$

The MOSFET channel size values were edited as $L_n = 0.35\mu m$, $L_p = 0.35\mu m$, $W_n = 70\mu m$ and $W_p = 130\mu m$, respectively. Where L_n and W_n represents the width and length of the transistor M_1 respectively, while L_p and W_p represents the width and length of the transistor M_2 respectively. The proposed structure and channel size values have robust ability to reduce the reverse current, while keeping similar forward current, resulting in higher data rate speed and faster time response.

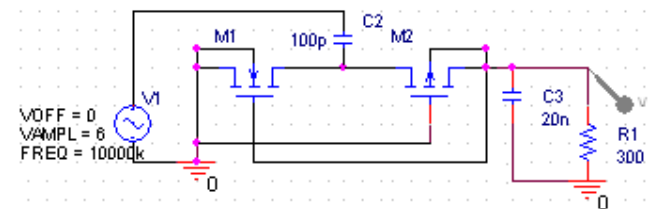


Figure-5. The proposed voltage-doubling rectifier with self-threshold cancellation.

6. EXPERIMENTAL DESIGN AND RESULTS 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 Figure-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 are presented in section results and discussions.



Figure-6. (a) The NI ELVIS 11 breadboard (b) the NI ELVIS 11 breadboard with the virtual ELVIS 11.

7. RESULTS AND DISCUSSIONS

This paper deals with design and implementation of an efficient wireless energy transfer system to power the sub-electronic implantable biomedical devices with stable 1.8 DC. V. Even though frequency variation. Taking into consideration simple design as possible and achieve less power consumptions. The proposed transcutaneous transfer system consists of two parts, external part and internal part operated with 10 MHz frequency as shown in Figure-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. On the other hand, the internal part consists of receiving coil, voltage doubling regulator with a self-cancellation threshold voltage.

The ASK modulator offer modulation and required DC voltage to power the self-tuning Class-E coil driver. Figure-7 (a) shows the binary data generated by data generator with amplitude 2V with risetime 0.1 ns. Figure-7(b) shows the ASK modulator output power up to 3.5 V to power the proposed self-tuning Class-E P/AMP operated at 10MHz with zero transistor switching to achieve 92.14% of efficiency as shown in Figure-8 and Table-1.

The transmitted resonance RLC circuits in the Class-E act as an antenna to transmit the maximum modulated ASK signal with $V_{MAX}=60$ V and minimum $V_{MIN}=47.5$ V. The RLC circuits in the implanted part receives the ASK modulated signal inductively with values $V_{MAX}=8$ V and $V_{MIN}=6.3$ V with modulation index 11.6% as shown in Figure-9 (a) and. 9 (d) respectively. Both RLC network tuned to the same resonance frequency 10 MHz to achieve acceptable coupling links efficiency as shown in Figure-10 (a) and (b) respectively.

To test and verify the performance of the voltage-doubling rectifier with self-threshold cancellation, a separated block is designed using OrCADPspice 16.2 software as given in Figure-5. The results of this design are compared with two simulated topologies of rectifiers such as gate cross-coupled rectifiers and fully cross-coupled rectifiers [16]. The results given in Figure-11 show that the proposed design has a better performance

where no ripples and produce very stable DC voltage to power the implantable remote electronic circuits. In that way, no need for a voltage regulator with gap references and thermal protection circuits. After above testing, the proposed rectifier is connected to the overall system and driven 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 Figure-12.

Finally, to verify and validate the proposed design, the National Instruments NI circuits design suite (Virtual ELVIS 11) compatible with NI LabVIEW is used to implement the external part and the measured results at 10MHz are reported. Figure-13 shows the experimental results; it can be seen the zero MOSFET transistor switching and transmitted ASK modulated signal where compatible with the simulated results.

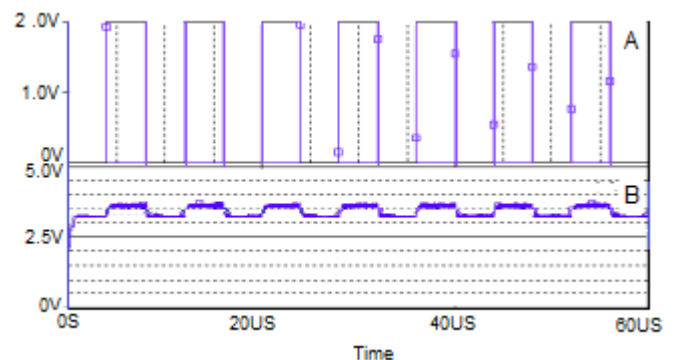


Figure-7. (a) Binary signals and (b) the required Class-E power supply.

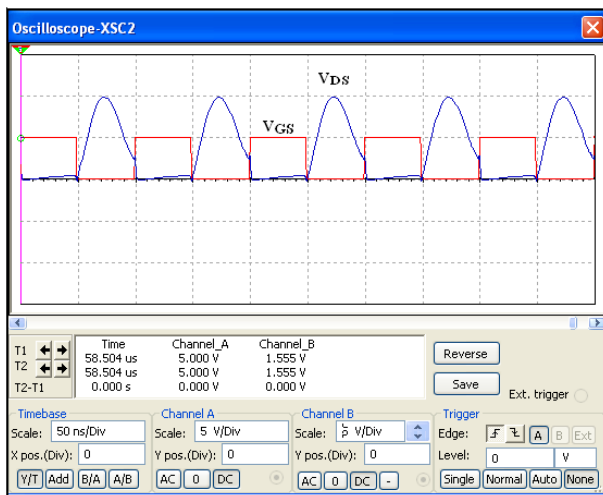


Figure-8. The MOSFET transistor (2N7000/FA) drain-source and gate-source switching in time.

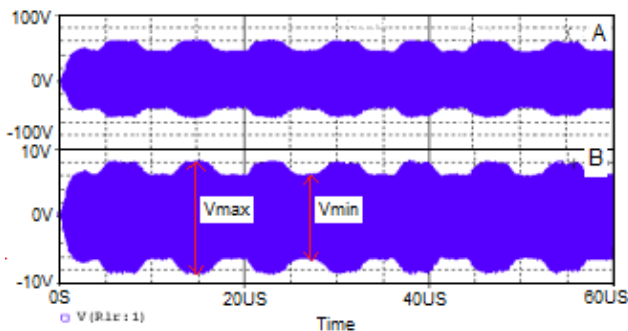


Figure-9. ASK modulated signal (a) transmitted coil (b) received coil.

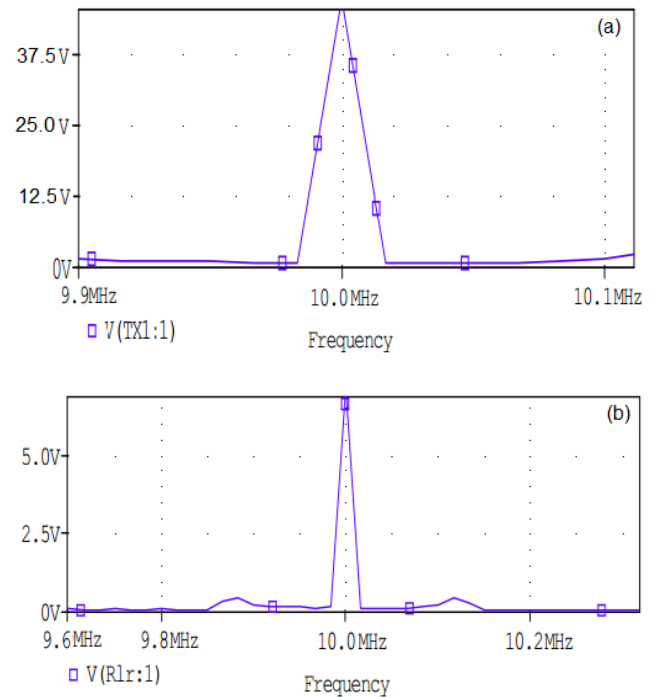


Figure-10. The transmitter coil (a) and the receiver coil (b) tuned at the same frequency 10 MHz.

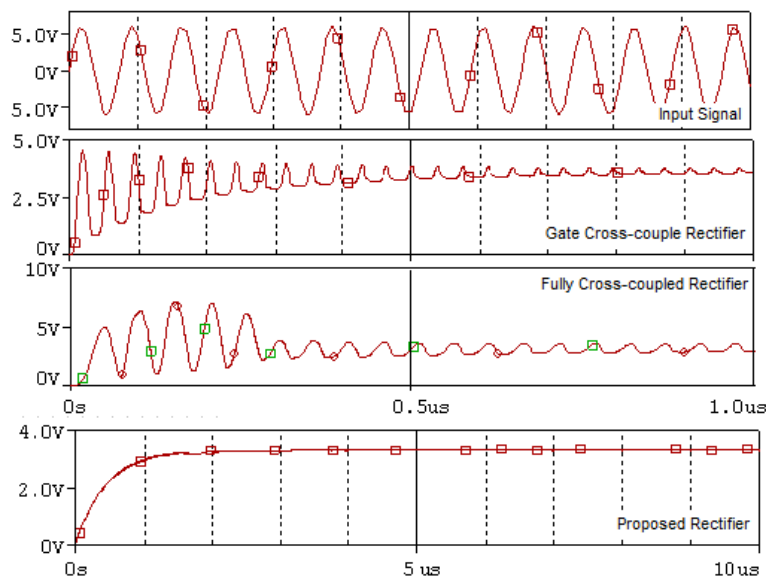


Figure-11. The output signal of the proposed rectifier compared with others design.

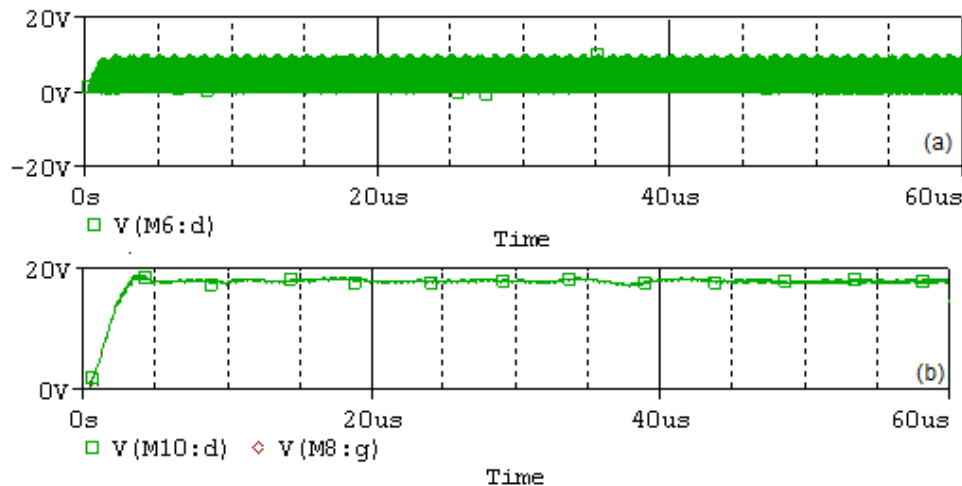


Figure-12. The rectified ASK modulated signal (a, b).



Figure-13. The experimental measured results using the National Instruments NI circuits design suite.

8. CONCLUSIONS

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 with resonant network and Self-threshold Cancellation Rectifier. The system operated with low-band frequency 10 MHz with 11.6% of modulation index and 92.14% of self-tuning Class-E efficiency, inductive coupling link and doubling rectifier to produce stable 1.8 DC.V to power the implantable circuits. To test and validate the system, a simulation and measured results were presented by using OrCAD-Pspice 16.2 software using spectre 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 further 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 bio-implantable devices such as cochlear and retinal implants and nerves stimulator.

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