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A wireless-power and data-transfer using inductive RF link and ASK modulation

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ABSTRACT

This paper aims to present a novel trans-cutanaeous, wireless and an efficient radio frequency (RF) inductive power and data link (IPDL) based on amplitude shift key (ASK) - modulator with an efficient 'Class-E'– RF 'power amplifier' that is applicable to implantable medical devices (IMDs). The IPDL system comprises an external device placed on exterior to human skin to transmitting power and data to IMDs like implantable micro-systems (cardiac pacemakers, cochlear implants, retinal implants, deep brain stimulators) to excite and monitor respective neural and muscular system. The entire system is designed to operate with a 'low-band-frequency' of 4 MHz by avoiding the problem of tissue heating. A practical model for the IPDL with results is presented. Various graphs such as frequency vs primary coil/secondary coil output are plotted and shown. Typical specifications of the exterior device, namely, the modulation-index (MI) and the modulation-rate (MR) are 40% and 4.3% respectively with a data rate of 172 Kbps. The design is simulated with electronic workbench MULTISIM 12.0 and TINA Ver 9.

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1. INTRODUCTION

The implantable medical devices (IMDs) are electronic-devices like and similar to 'pace makers', 'retinal implants', 'cochlear implants', and 'micro-system stimulator implants. The 'micro-system stimulators' are utilized for stimulating and monitoring nerve's signaling, muscular signaling, blood pressure, and intra-ocular pressure [1]. Some implantable medical devices (IMDs) are power-charged by use of battery, and due to its limited life-time and chemical effects, several findings identifies fresh approaches to power-up and monitor IMDs [2]. At present, most of the IMDs are applied power with transcutaneous means using RF inductive coupling links. The developed inductive power and data link (IPDL) system comprises an external device for transferring data and powering in inductive manner to the internal device (IMD) placed beneath and interior to human within the body. Being not a robust radio frequency (RF) inductive links in between external and internal devices, the system deserves an efficient external-part that has a battery, modulator and power amplifier [3]. Out of modulation methods for IMDs like 'amplitude shift keying (ASK)', 'frequency shift keying (FSK)' and 'phase shift keying (PSK)', while 'ASK modulation' is being in wide use owing to its simplicity, as less power consumption and lower costs as mentioned in literature review [4]–[6].

An improved ASK modulator is addressed with a base band of 86.2 kHz and an efficacious 'Class-E' power-amplifier which operates with a 'low-band' carrier frequency of 4 MHz without tissue heating according to the industrial, scientific and medical (ISM) band [7], with modulation-index (MI) of 40% to achieve

172 Kbps at the primary exterior device. The inductive power and data link (IPDL) is designed with an assumption, so that the implantable electronic device load is 150-300 Ω with variable coupling factor K. The 180 nm fabricated complementary metal oxide semiconductor (CMOS) technology may be suitable to design the system. The design used simulation with 'OrCADP Spice 16.2 Software Tools', and the electronic work-bench 'MULISIM 12' and 'TINA Ver 9' are used, for real-time simulation.

The section 2 addresses the overview of system architecture, key elementary devices and corresponding parameters which were deployed in the system. ASK modulator is discussed in section 3. The design of 'Class-E' power-amplifier including computed parameters and values are dealt in section 4. The inductive-coupling link based on mathematical model is explained in section 5. Complete simulation and practical results are shown and illustrated in sections seven and eight respectively followed by the conclusion in section eight.

2. WIRELESS POWER AND DATA TRANSFER

The hardware functional block-diagram of power and digital data-transmission wirelessly for IMDs is shown in Figure 1. The IPDL system comprises two sections: external or primary device placed externally and comprises power supply, base-band 'data generator', 'ASK modulator', 'Class-E power amplifier', and transmit (Tx) coil. The internal or secondary part comprises the received (Rx) coil as 'antenna', 'rectifier' to recover Tx data and converts 'RF signal' into DC voltage, 'voltage regulator' to cater stable DC voltage to IMD and ASK demodulator to demodulate Rx signal. The inductive link involves two 'RLC circuits' tuned at the same resonant frequency of 4 MHz [8]. The primary circuit is tuned at series resonant at 4 MHz to provide a lower impedance load and the secondary circuit is tuned at parallel resonant at 4 MHz to obtain 'higher power transfer' efficiency [9]. An efficient 'Class-E power amplifier' is used to achieve efficient transmission around 90% [10]. The primary circuit is in Figure 2.

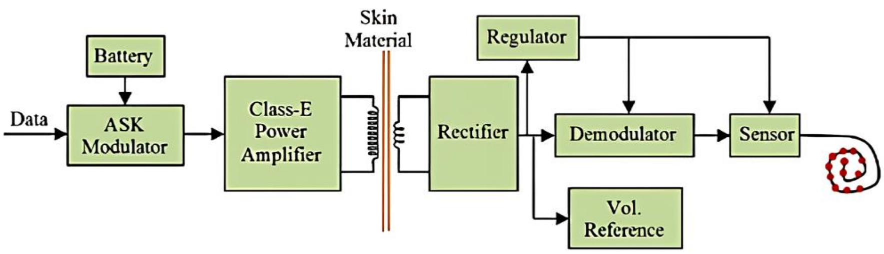


Figure 1. Functional block-diagram of inductively linked wireless power and data transmission

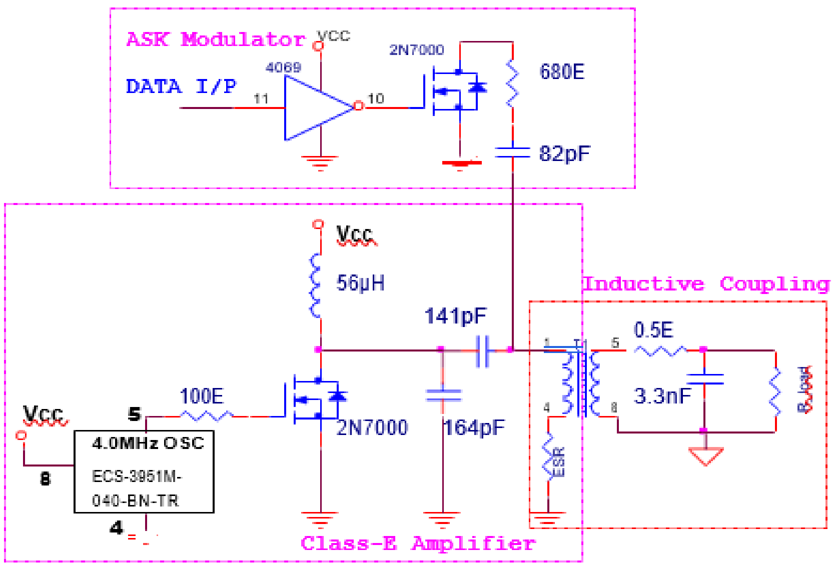


Figure 2. Primary circuit diagram of Class-E power amplifier with ASK modulator

3. ASK MODULATOR

The baseband binary data signal as the modulating signal is applied as input to the modulator electronics. In general three digital modulation methods are applicable for biotelemetry operation in IMDs, namely, ASK, FSK, and PSK with merits and demerits for every method. In the present work ASK method of modulation is preferred as it is a simple logic, offers low power consumption and low cost. The speed of transmission may be improved by modifying the circuit in a suitable manner. Figure 2 shows the ASK modulator that comprises 2N7000 switching MOSFET, resistor-Rm and capacitor-Cm. The Rm (680 Ohms) and Cm (82 pF) are for depth of modulation (40%). The baseband data signal with Tbit=5.8 µs is generated using the Pspice function for generating serial digital-data signals in accordance with the configurations setforth using MULTISIM 12/TINA Ver 9 software tools. The ASK modulator is powered with +5 V. The binary-data signal for the 'ASK modulator' with values '1' and '0' is shown in Figure 3 (top). The ASK-modulated signal at the transmitter coil with Vmax=28.0 V and Vmin=12.0 V is shown in Figure 3 (middle). Modulation index (MI) and modulation rate (MR) are according to the equations given in (1) and (2). Received ASK signal is at the receive coil antenna with Vmax=4.8 V and Vmin=2.0 V is in Figure 3 (bottom). It is identified that MI for Tx and Rx coils is almost the same. Modulation rate $M.R$ is the ratio of data rate to operated frequency:

$$M.R = \frac{DataRate}{Operated\ Frequency} * 100\% \quad (1)$$

$$Modulation\ Index = \frac{Vmax - Vmin}{Vmax + Vmin} * 100\% \quad (2)$$

where V_{max} and V_{min} are the maximum and minimum for ASK signal.

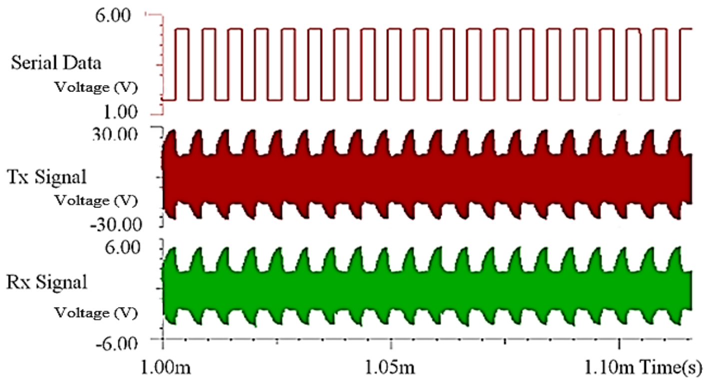


Figure 3. Binary/modulation signals of serial data (top), ASK Tx (middle), and ASK Rx (bottom) signals

4. CLASS-E POWER AMPLIFIER

'Class-E' RF power amplifier provides significant high efficiency (90-95%) than that of conventional 'Class-B' or 'Class-C' amplifiers and are widely in use in all biotelemetry applications as well as in external/primary part of IMDs because of the simplest (one switching transistor), high-energy transmission and consumes power when used as a modulator [11]. The architecture of a Class-E power amplifier comprises an RF choke (3 to 10 times primary coil inductance) with very small resistance to reduce power supply loss. The presented 'Class-E' RF power amplifier is operated with low ISM band-frequency (4 MHz) without tissue damage [12]. The mathematical model is given below:

Assuming power out-Pout as 150 mW, carrier frequency fo as 4 MHz, Vdd as +5 V, R_l (load resistor) is 150 Ω, and the transistor is switched at 50% duty-cycle. For optimum power of 'Class-E' amplifier, optimum resistance RL. Opt is to be found. The (3) is used to calculate the optimum resistance. According to (4) and (5) are used to find values of 'Class-E' components as in diagram in Figure 4, Cs=141 pf is the primary series tuning capacitor, Cp=164 pF is the primary parallel tuning capacitor, L_1=9 µH is the primary coil inductance.

$$\mathrm{p}_{out} = \frac{2}{1+\frac{\pi^2}{4}} * \frac{Vcc^2}{\mathrm{R}_{l.out}} \quad (3)$$

$$\mathrm{C}_s = \frac{1}{\omega^2 L_1} \quad (4)$$

$$C_P = \frac{C_S}{(L_1 C_S \omega^2 - 1)} \tag{5}$$

Peak efficiency is based on maximum Q ('quality factor') and consistently the required band-width. A higher value of Q of the inductive coil should lead to the output nearer to the ideal-sinusoidal signal shape. But very high Q decreases the effective band width of the system [13]. Hence the choice of Q must be as realistic as possible to (6) and Q is found as 27.

$$Q = \frac{\omega L}{R} \tag{6}$$

The higher-efficiency of 'Class-E' RF power amplifier [14] mitigates 2N7000 transistor-switching loss. The 2N7000 MOSFET transistor is turned 'ON' when gate voltage is high (logic'1') reducing the 'turn ON' loss as the drain to source resistance is very small. At the same time 'drain voltage' also increased from zero whenever gate voltage is low (logic'0') without losing the efficiency. Figure 5 shows VGS (4 MHz clock signal and VDS) drain switching voltage in Figure 5(a) together indicating that VDS is almost zero when VGS is high and VDS becomes a positive half-sine signal when VGS is low. Both signals are from 'Class E-power amplifier simulation output signals with TX coil signal in Figure 5(b)

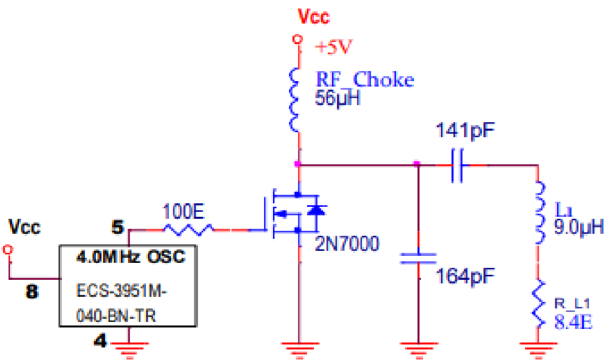


Figure 4. Class E power amplifier

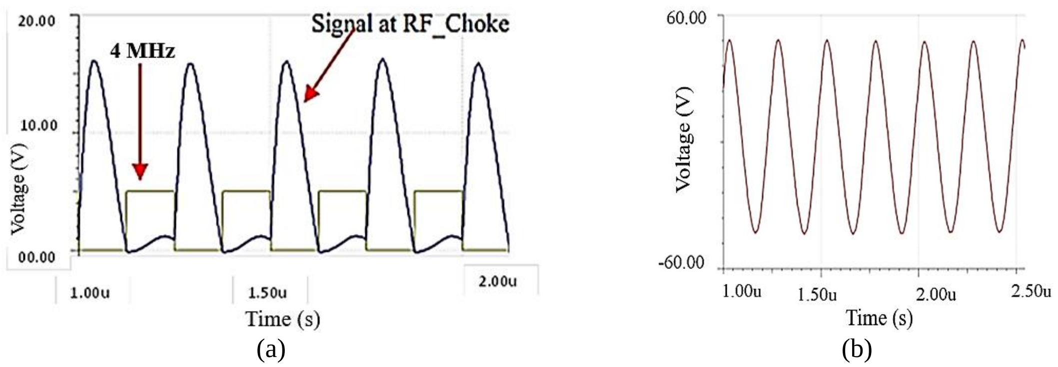


Figure 5. Clock/RF-Choke/Tx coil signals (a) 4 MHz clock/RF-choke signal and (b) Tx coil signal

5. INDUCTIVE RF LINKS

The majority of IMDs are getting power inductively to transfer power and data for shorter ranges between Tx and Rx coils. The IPDL comprises two resonating RLC circuits, namely, primary and secondary are as given in Figure 6 [15]. The primary one is placed externally and is called as external unit/device driven by an efficient 'Class-E' RF-power amplifier [16], while the other one is placed internally within the human body called as internal unit/device, supplied power from the exterior device in which some part of 'generated magnetic flux' from the exterior/primary unit (Tx coil) is coupled with internal part (Rx coil) that generates an inductive voltage as Rx coil which act as an antenna. To achieve higher power transfer efficiency, Tx and Rx coils are synchronized at point of same resonance frequency (4 MHz). The IPDL parameters such as primary coil-inductance Lt, secondary coil-inductance Lr, resonance frequency f0, mutual inductance M, and coupling factor K (0< K <1), have a direct effect on the coupling link efficiency. The coupling factor K, is the main factor used to determine the amount of power that can be delivered to the IMDs [17]–[19].

This section deals with analysis between the voltage gain V_{gain} and other variables such as coupling coefficient K and resistive load R_{load} (simulated Implanted devices load). The mathematical model for IPDL is calculated as given below the coupling factor is:

$$K = \frac{M}{\sqrt{Lt*Lr}} \tag{7}$$

the primary capacitance Ct is given in section 4 as (4), and the secondary capacitance Cr, is given as in (8).

$$Cr = \frac{R_{Load} + \sqrt{R_{Load}^2 + 4L_r^2\omega^2}}{2\omega^2 R_{Load} L_r} \tag{8}$$

Where, R_{load} is implanted device load [20], and it should be greater than 2ωLr.

Figure 7 graphs (frequency vs primary voltage in Figure 7(a) and frequency vs secondary voltage in Figure 7(b)) depict results of simulation values that both coils tuned at the same resonance frequency of 4 MHz and the inductive link acts as band pass filter (BPF). The simulation graphs in Figure 8, show the relationship between the constant load resistor at value 250 Ω with different coupling factors (K=0.5, K=0.6, K=0.7, K=0.8, K=0.9, K=1.0) where the best voltage gain is achieved when K=0.5.

Figure 9 shows the relationship between constant coupling factor K=0.5 and variable load resistors (R_{load}=100 Ω, R_{load}=150 Ω, R_{load}=200 Ω, R_{load}=250 Ω, R_{load}=300 Ω). The results have shown that this design best fits to powered implantable units/devices load with resistance load 150 Ω to 450 Ω and the value of the implanted resistance R_{load} acts as a function of the amplitude of the Rx voltage at the secondary coil, and higher voltage corresponds to more power consumptions.

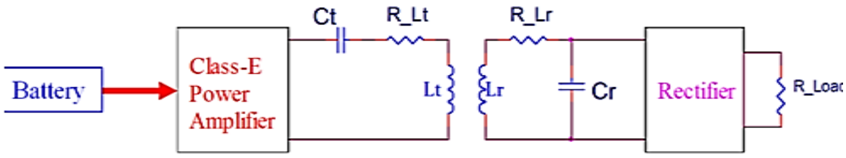
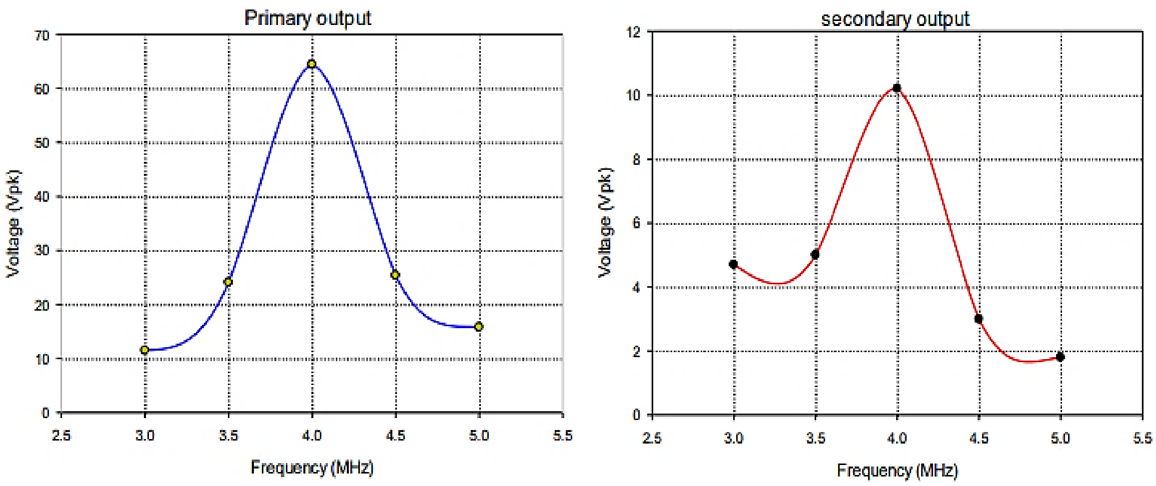


Figure 6. Simplified functional block-diagram of trans-cutaneous inductive coupling link



(a) (b)

Figure 7. Primary/secondary coils volt vs freq. graphs - (a) freq. vs primary coil voltage and (b) freq. vs secondary coil voltage

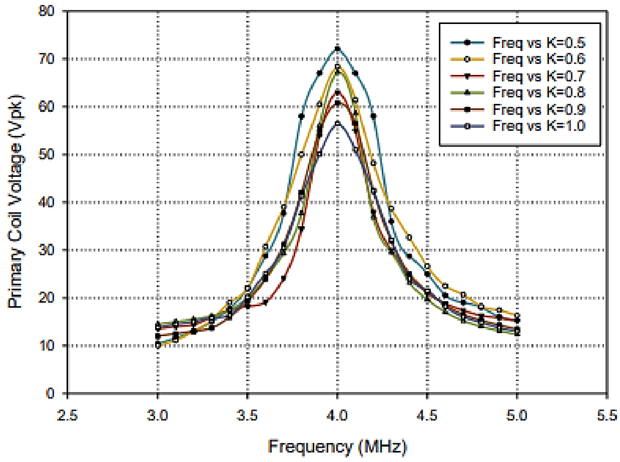


Figure 8. Relationship between the constant load resistor at value 250 Ω with different coupling factors (K=0.5, K=0.6, K=0.7, K=0.8, K=0.9, K=1.0)

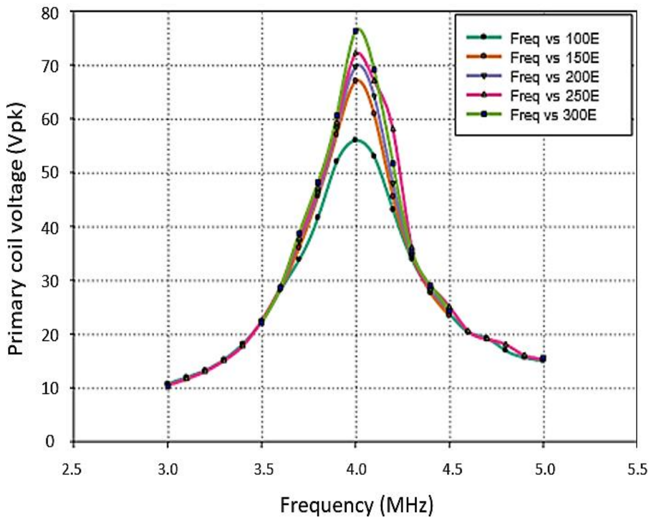


Figure 9. Freq. vs voltage gain with constant coupling factor K=0.3 and variable load resistor

6. SIMULATION RESULTS

Electronic workbench MULISIM 12.0/TINA Ver 9 software is utilized to simulate the IPDL. Figure 3 shows the binary data signal with "1" and "0" values provided to ASK modulator with frequency 86 kHz, the ASK modulated Tx signal on the transmitter coil with Vmax=28 V and Vmin=12 V, and the ASK modulated Rx signal at the received coil with Vmax=4.8 V and Vmin=2.0 V, both transmitted and received signal have modulation index 40% and modulation rate 4.3%. Figure 5 shows simulation results for a 4 MHz RF carrier frequency clock with a 50% duty cycle to drive 2N7000 NMOS transistor on and off so that when V_{GS}=0 the drain-source voltage V_{DS} in maximum value and V_{DS}=0 when gate-source voltage V_{GS} in maximum value and show the output signal of the power amplifier a stable sinusoidal signal to the inductive coupling link to increase the system efficiency to 90% approximately.

7. PRACTICAL MODEL AND RESULTS

Figure 10 shows a practical set-up for microcontroller-based inductively coupled power transmission system. The transmitter is designed based on high-speed 8-bit microcontroller (89C420) with modulating signal data as hex bytes serially transmitted at 172 Kbps using ASK modulation via inductively coupled 4 MHz RF link to receiver [21]–[23]. The receiver is also designed based on a high-speed8-bit microcontroller (89C420) with the reception of ASK modulated signal data as hex bytes via an inductively coupled 4 MHz RF link

[24], [25] as shown in Figure 10. An experimental inductive link with primary TxLitz coil coupled to secondary Rx Pt-Ir coil is shown in Figure 11.

Hex data bytes transmitted are displayed on a hex display interfaced to µC at the transmitter side as well as at the receiver side after receiving through the link [26]–[29]. The top two waveforms in Figure 12 correspond to serial data bits transmitted and the ASK transmission signal. The bottom two wave forms in Figure 12 are the respective receive data bits and ASK received signal.

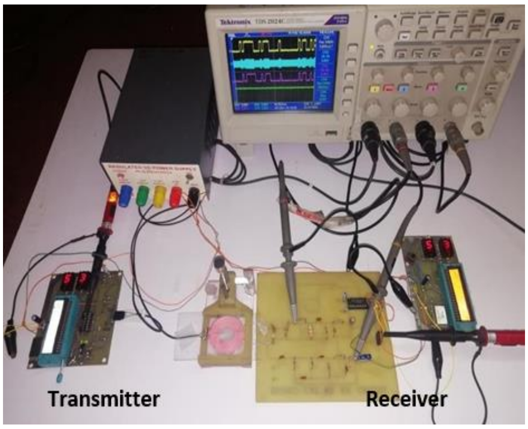


Figure 10. Practical set-up microcontroller-based inductively coupled power transmission system

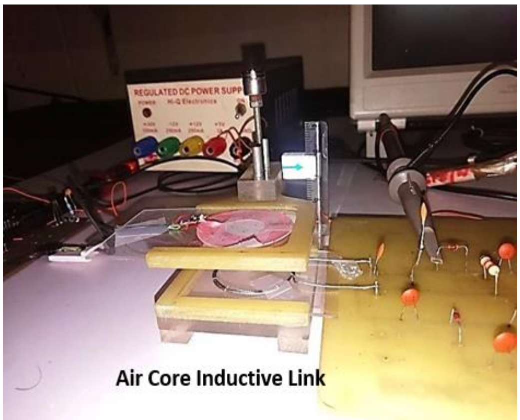


Figure 11. Practical inductive link with Litz Cu Coil as primary and LizPt-Ir Coil as secondary coil

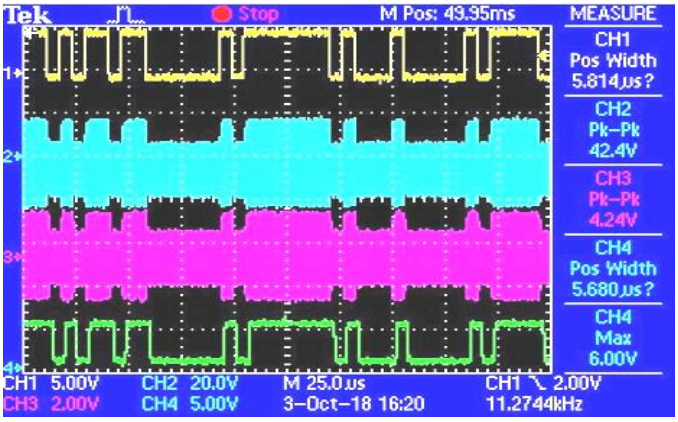


Figure 12. Wave forms of serial data transmit and receive signals with ASK signal wave forms

8. CONCLUSION

The ‘wireless power’ and ‘data transfer’ using inductively coupled transcutaneous-link design for the external/primary part to applicable implanted devices with 4 MHz RF using the ‘ASK modulation technique’ has been presented. The comprising three units/parts of the external/primary system (IPDL) are designed and simulated with MULTISIM 12 software. The results have shown that the system can transfer with efficient power to the implanted devices with data rate of 172 Kbps and a modulation index of 40%. The inductive link is best fit for micro-system implants such as cochlear and retinal implants.

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