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The CMOS design of a high-efficiency transcutaneous power and data system

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Abstract

This paper presents a proposed design for transcutaneous inductive powering links with “suspended-carrier”. The design used to transfer power and data to the implanted devices.This work describes the implementation of a 0.35µm CMOS integrated circuit using 3.3v supply dedicated to cochlear prosthesis. In the wireless biomedical implants the carrier frequency, which represent the resonant frequency of the power amplifier is limited to a few tens of megahertz because of the incremental tissue loss and risk of tissue damage at higher frequencies. The system uses synchronous frequency-shift-keyed (FSK) modulation, with 5/10 MHz carrier frequencies, based on the class E power oscillator. The Class-E power oscillator has been identified as a highly-efficient transmitter circuit for use as a means of transferring power to an implant. Although the high-Q nature of this topology makes rapid modulation difficult, it is feasible to use synchronous frequency-shift-keyed (FSK) modulation of the Class-E circuit thereby combining an efficient power transmitter with a high speed data link. Using this method, the transmitter can be modulated on a cycle-by-cycle basis with little to no additional power loss.

Keywords: cochlear prosthesis, class E power oscillator, FSK modulation, “suspended-carrier”.

1. Introduction

Cochlear prostheses shows in figure 1 are electronic apparatus permitting to remedy to total or deep deafness, where conventional prostheses were inefficient. These systems can be divided into four major blocks: the external stage for speech processing, the power and data transmission system, the clock, data and power recovery system and the stimulator of electrodes (figure 2).

In this paper, we present only the conception for radiofrequency transmitter system shows in figure 3. Which consist of a high-rate frequency shift keying (FSK) data transfer protocol and a Class-E power oscillator.

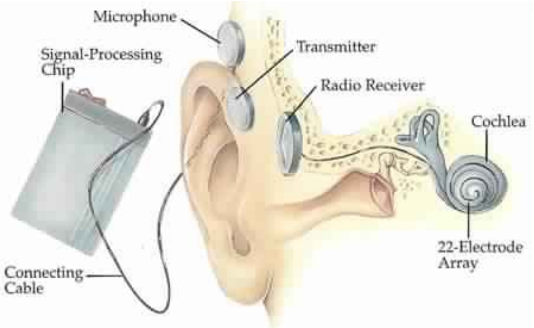

Fig. 1 Cochlear prostheses

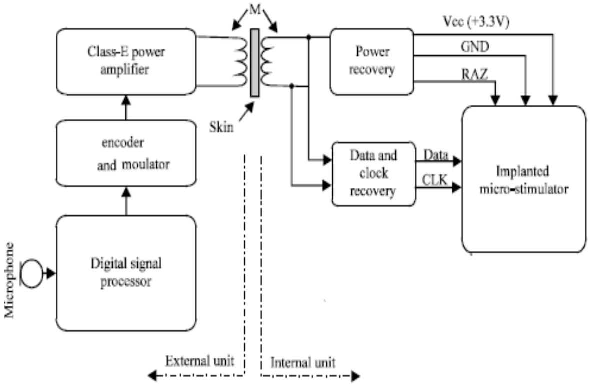

Fig. 2 Bloc diagram of cochlear implant

The transcutaneous link performs two functions: first, it provides power to the implant by inductive coupling; second, it provides a means to send data to the implant for purposes of stimulation. In this work, the power is generated by a class E power amplifier driving by a numeric synchronous signal FSK. The Class-E power oscillator has been identified as a highly-efficient transmitter circuit for use as a means of transferring power to an implant. Although the high-Q nature of this topology makes rapid modulation difficult, it is feasible to use synchronous frequency shift keyed (FSK) modulation of the Class-E circuit thereby combining an efficient power transmitter with a high speed data link. Using this method, the transmitter can be modulated on a cycle-by-cycle basis with little to no additional power loss [4].

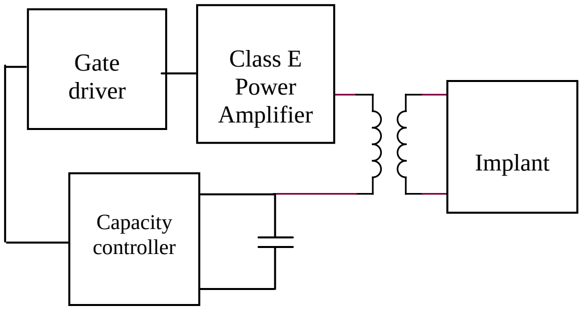

Fig. 3 bloc diagram of power and data transmission

Driving large currents into high- Q coils has historically been problematic when using pushpull type drivers. The Class-E topology [1] resolves this issue by utilizing a multi-frequency resonant network. The power loss within the single-transistor active driver can be sufficiently reduced so that the low-resistance of the high-Q transmitter coil becomes the dominant loss. In fact, for Class-E transmitters it is desirable to use as large of a circuit Q as possible. One serious problem with Class-E circuits is maintaining operation at the precise Class-E frequency. For each circuit, there is only one combination of operating frequency, duty-cycle, and coil-Q that will produce the Class-E conditions. Automatically maintaining the Class-E frequency, for transcutaneous coil drivers has been demonstrated through the use of voltage-mode [2] and current-mode [3] feedback. These techniques convert the Class-E converter into a power oscillator whose frequency is established by the closed-loop control circuit and the characteristics of the Multi-frequency network.

For the Class-E circuit, without closed-loop control, shifting of the Class-E frequency away from that of the input drive signal will result in almost instantaneous destruction of the transistor driver. Using the closed-loop Class-E power oscillator approach, the frequency of the transmitter automatically shifts to compensate for the changes in the transmitter coil characteristics, maintaining the low-loss Class-E operation. The result is a transmitter in which transmitter-coil currents of several amperes can he produced with relatively low transmitter power-supply currents. A disadvantage to using the closed-loop Class-E power oscillator is that the transmitter frequency is riot constant. Since the internal clock of the implanted neural prosthesis is typically recovered directly from the transmitter frequency, the implant’s clock frequency is also variable. Therefore, it is necessary to use the variable frequency of the transmitter as the overall system’s master clock [5], [6], [7], [13].

Both of these techniques are limited by the natural response of the transmitter’s high-Q circuitry, and can be used for data rates which are not much higher than 1/10 the transmitter frequency [4], [8],[9].

An altemative method of Class-E transmitter amplitude modulation is the “suspended-carrier” method; it permits the transmitter to be placed in a “suspended” state in which all of the energy contained within the converter’s multifrequency network is contained in the resonant capacitors. While in this suspended state the energy loss is minimal. Resumption of normal operation can be near-instantaneous, producing 100% modulation. Using this technique the transmitter current can be turned-on for as little as one cycle, and can be turned-off for an arbitrary period of time. While highly efficient for the transmitter, there are two disadvantages to this technique: First, for high-current transmitters, the method requires using a high-voltage, low-on-resistance, and Iow- capacitance FET modulating switch witch is an uncommon combination of parameters. Secondly, as the link is used to its data-speed capacity, the transmitter is turned off 50% of the time, thus reducing the available transcutaneously-coupled power for the implant [4], [14], [12]. We have used in this paper a method of modulating the Class-E circuit that uses FSK modulation. In this approach, both disadvantages of the suspended-carrier method are eliminated. Continuous power transfer is combined with rapid (cycle-by-cycle) data modulation.

2. Data transmission protocol

The new data transmission design is represented on figure 8 It consist of Manchester coder, VCO oscillator, tow counter, three ring oscillator and some logics gates and latch.

The coding circuit design of the data is made more complex by the light variations of the duration of a bit modulated according to the coupling between the antennas: the coder must be obligatorily synchronous with the emission clock.

Manchester coding proves to be most suitable with our application because it allows the recovery of the data and the clock. Moreover more the type of the implants (urinary, visual, Cochlear...) used this coding. Indeed, the Manchester coder integrates the clock signal in the data transmitted of the external controller towards the implant.

With this type of coding, there is always at least a transition from the signal by transmitted bit; what makes it possible to provide a signal of synchronization for the generator of clock. Beside, this coder eliminates the component continues and consequently a logical level "1" cannot be confused with this continuous level. It is simple to realize. That is justified on figure 4.

We associate with the Manchester coder a numeric control unit figure 8. This entity makes it possible to synchronize the retarded Manchester coded signal with the numeric signal of the output of VCO. This is important for the control of the class-E oscillator that will be detail next.

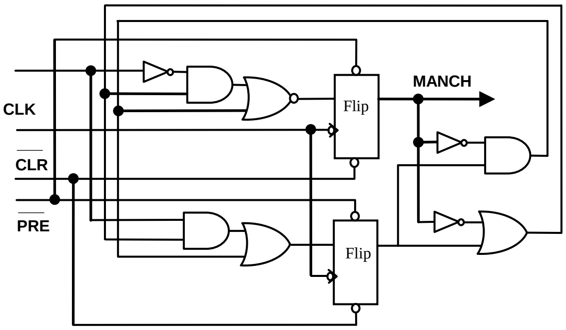

Fig. 4 Manchester encoder

The data received from the DSP would be coded in Manchester coding type. This signal makes it possible to generate the two clock signals for both counters. The first counter figure 7 has a clock signal (clk1) with frequency equal to weakest value of the two frequencies of the VCO (5 MHz) generated by the first ring oscillator (osc1) figure 6 adjusting with the high level of retarded Manchester signal. The second counter figure 7 has a clock signal (clk2) with frequency equal to largest value of the two frequencies of oscillation of the VCO (10 MHz) generated by the two other rings oscillators (osc2, osc3) associated to the low level of the retarded Manchester signal. What allows to represent each modulating bit by two cycles at one operating frequency followed by two cycles at the other operating frequency and to encode a modulating bit "0" in code "10" after tow period of clk1 and a modulating bit "1" in code "01" after tow period of clk2 (figure 5).

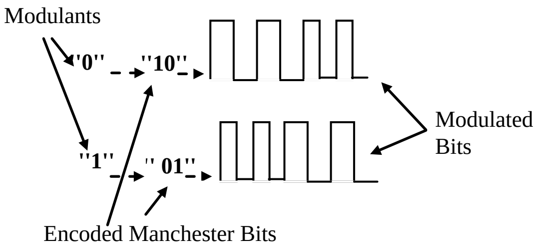

Fig. 5 Coding and modulated signals

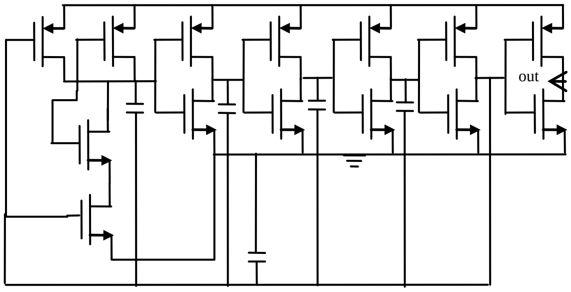

Fig. 6 Ring oscillator

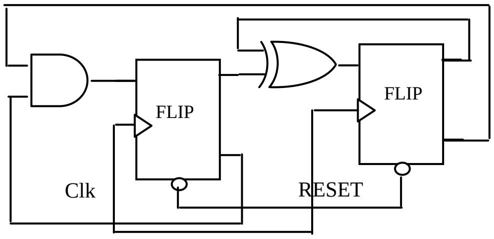

Fig. 7 counter design

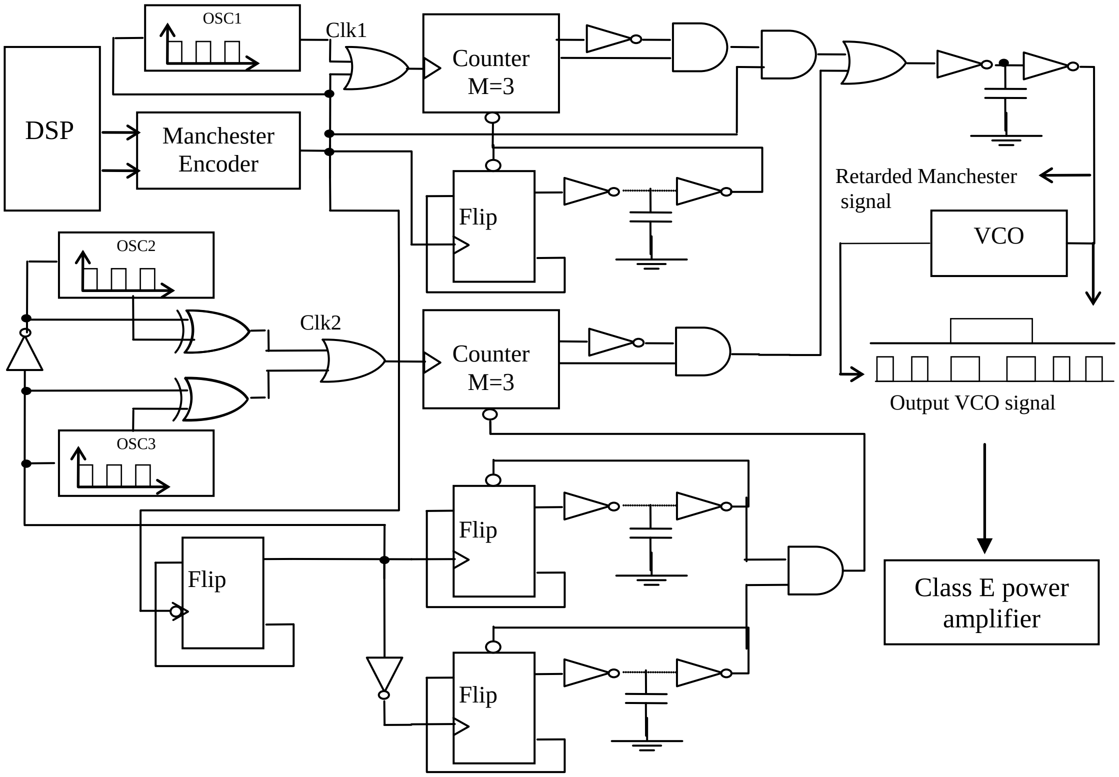

Fig. 8 data transmission design with numerical control unit

The following figure represents a CMOS design of positive edge-triggered D flip-flop with preset and clear inputs using in our system.

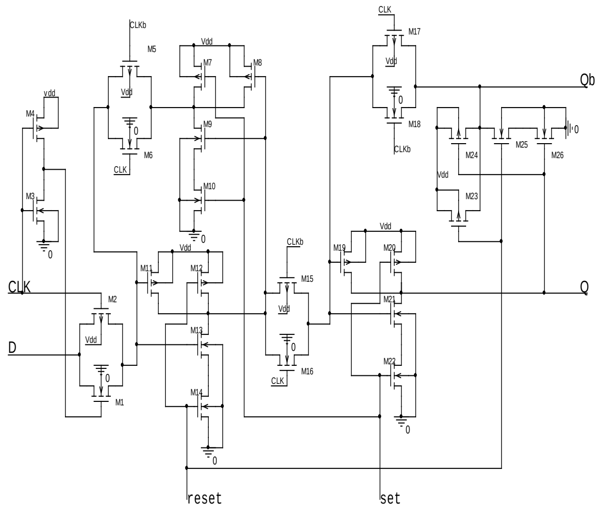

Fig. 9 D flip-flop design

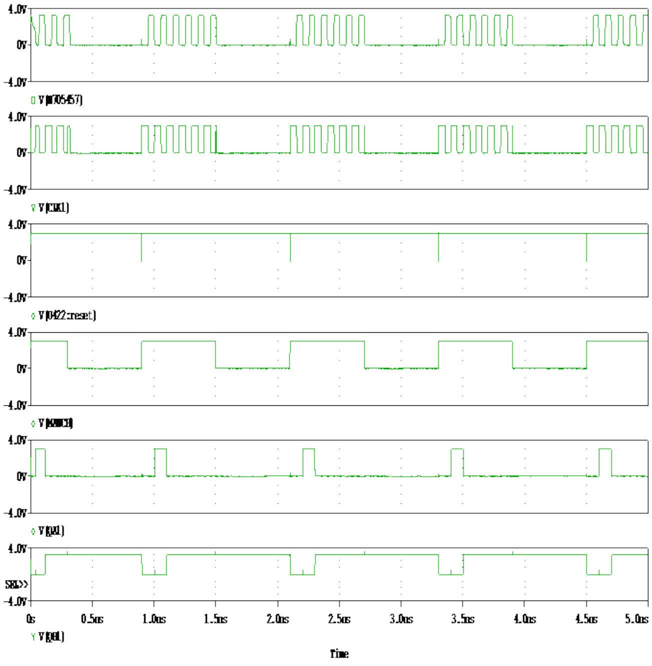

Fig.10 simulation result of first counter

Fig. 10 shows the resulting simulation waveforms of the first counter. From top to bottom, trace-1 shows the output of the oscillator, second trace represents the counter's clock, 3rd trace represents reset signal of the counter, after we find the Manchester's signal. Finally, 5th and 6th signals show outputs of the counter.

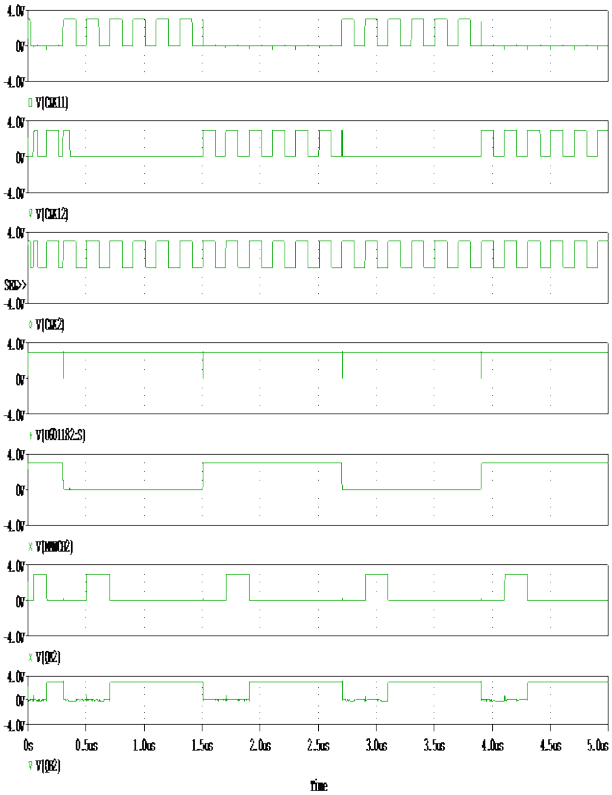

Fig. 11 simulation result of the second counter

Figure 11 shows the resulting simulation waveforms of the second counter. From top to bottom, trace-1 shows the output of the oscillator 2, second trace represents the output of the oscillator 3, then the counter's clock, 4th trace represents reset signal of the counter, after we find the Manchester's signal with a frequency divided by tow. Finally, 6th and 7th signals show outputs of the counter.

The VCO figure 12 employs cells with simple delay. The control of the frequency is achieved by direct control of the current generated by NMOS transistors placed in series with the various inverter cells of the ring oscillator.

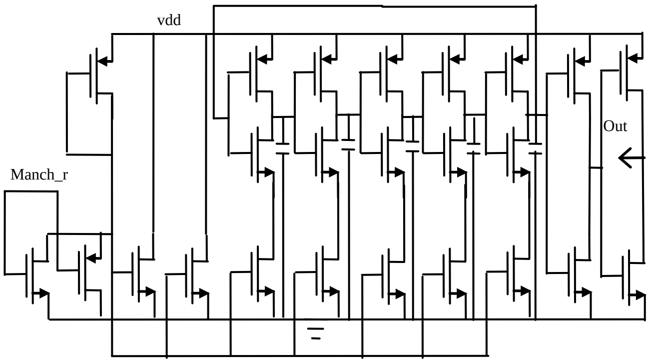

Fig . 12 Numerical VCO circuit

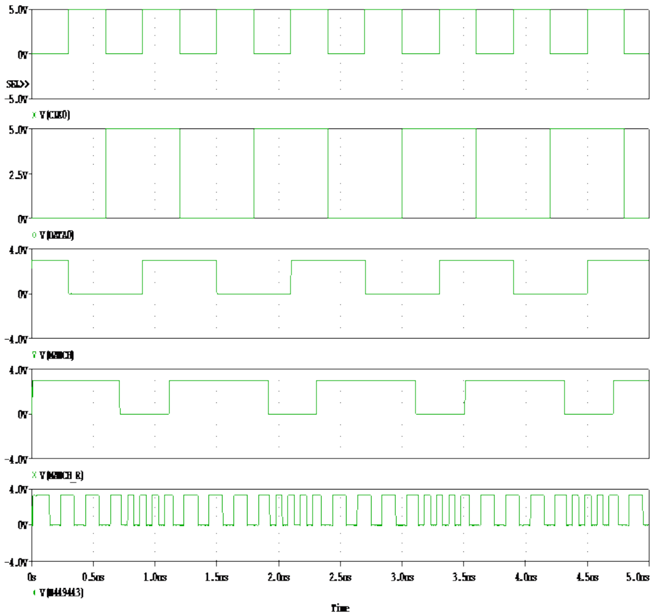

Fig.13 Digital unit result

In this simulation we represent from top to bottom: clock, data, Manchester signal, retarded Manchester signal and VCO output signal. We prove that each modulating bit (Manchester signal) is represented by two cycles at one operating frequency followed by two cycles at the other operating frequency and to encode a modulating bit "0" in code "10" after tow period of clk1 and a modulating bit "1" in code "01" after tow period of clk2. Moreover, the synchronization between retarded Manchester signal and VCO output signal is also demonstrated.

The VCO signal obtained is used to control the class-E oscillator with the retarded Manchester signal. Therefore these two signals must be synchronized that will be demonstrated in the simulation of the data transmission design figure 13.

Figure 14 shows the simulated frequency domain spectrum of the proposed VCO at 5 MHz and 10 MHz.

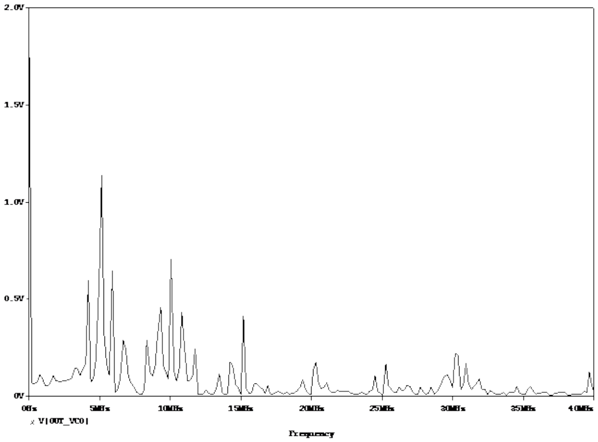

Fig. 14 Frequency domain spectrum of VCO

3. Transcutaneous power transmission

Figure 15a shows the basic circuit topology for the Class-E transmitter. Figure 15b shows the suspended-carrier topology. For simplicity, the oscillator feedback control is not shown. The MOSFET modulation switch, placed in series with the transmitter coil, is used to interrupt the coil current at the point in the cycle for which the coil current crosses zero and all the circuit's energy is stored on the resonant capacitors. When in the suspended mode, the modulation switch must be charged to the sum of the resonant capacitor voltages. For transmitters that use large coil currents, and large inductors, the voltage across the modulation switch can reach several hundred volts. Since the drain-to-source capacitance of the switch is charged to this same voltage, the energy stored on the intrinsic MOSFET capacitance is lost (from the circuit) each time the modulation switch is turned on. Therefore it is desirable for this intrinsic MOSFET capacitance to be as small as possible. Furthermore, when the modulation switch is turned on, it carries the full resonant circuit current. Therefore it must have low conduction losses. This combination of several-hundred-volt breakdown, low capacitance, and low on-resistance, is very difficult to achieve in a MOSFET device. Therefore, for high-power transmitters, use of the suspended-carrier method becomes a compromise design [7],[11].

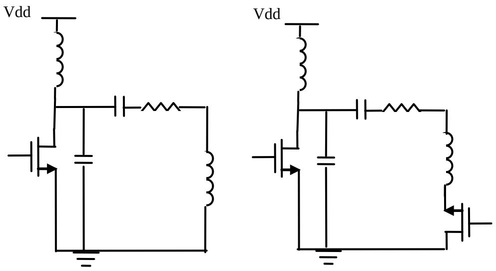

Fig. 15a. Basic Class-E topology, b. Suspended-carrier topology

In examining the operation of the suspended-carrier circuit, it can be seen that when the modulation switch is open the converter would not actually go into the suspended state, as expected. Rather, due to the capacitance of the modulation switch, the circuit would oscillate a new (much higher) frequency. In practice, one must place an RC snubber network across the modulation switch in order to prevent the circuit from oscillating at the higher frequency. This secondary oscillation effect can be exploited in devising a circuit that shifts frequency, rather than going into the suspended state [4], [14].

Figure 16 shows the basic concept of the FSK-modulated Class-E converter. By purposefully placing a capacitor across the modulation switch, the frequency of the converter can be changed on a cycle-by-cycle basis. For minimum power loss, the switch should be closed, or opened, when the voltage across the FSK capacitor is at zero. Since the size of the voltage across FSK capacitor is typically ~1/10 the value of the combined resonating capacitors (for ~10% modulation) the peak voltage across the modulation switch is considerably less than for the suspended-carrier topology.

And since the FSK capacitor is in parallel with the intrinsic capacitance of the MOSFET, it becomes feasible to use a large-area, low-resistance, MOSFET for the modulation switch. As was the case for the suspended-carrier approach, toggling of the modulation switch must occur synchronously with the transmitter clock at precisely the correct point in the cycle for which the voltage across the MOSFET is zero [4], [7],[12],[10].

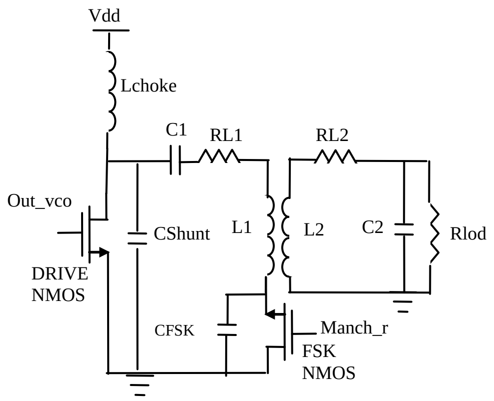

Fig. 16 Class-E FSK transmitter topology

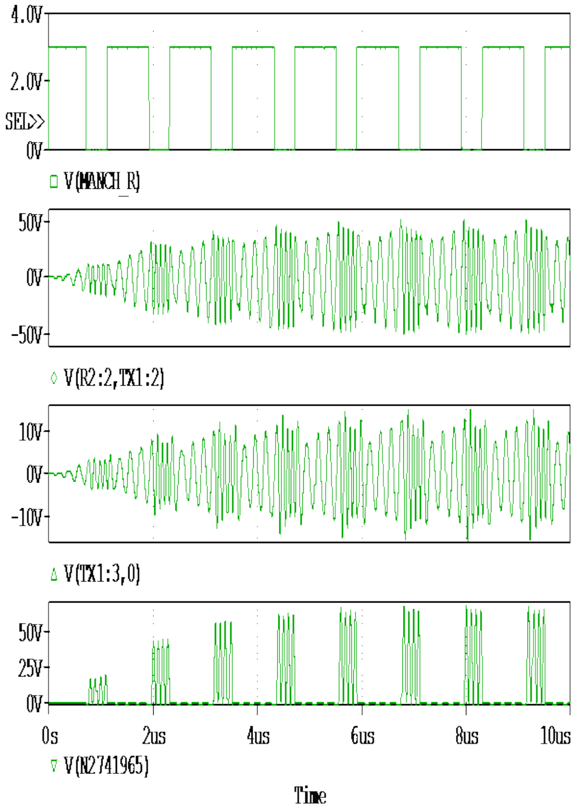

Fig. 17 Result of power transmission

Figure 17 represent the result of power transmission and recuperation. The first signal represent the retarded Manchester signal, the second represent Voltage across the transmitter coil, the third represent Voltage across the receiver coil and finally the last represent voltage of the FSK capacitor.

Figure 18 shows the simulated frequency domain spectrum of transmitter coil, receiver coil and FSK capacitor

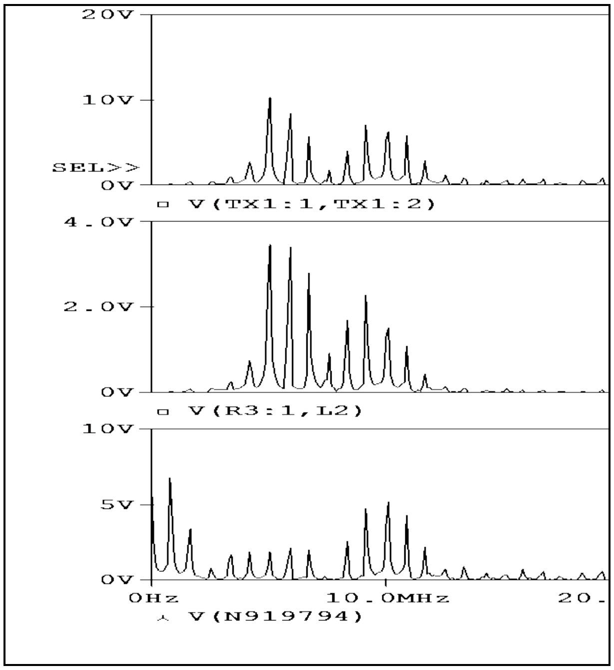

Fig. 18 frequency domain spectrum of transmitter coil, receiver coil and FSK capacitor

The value's parameters of our design are shown below in TABLE 1.

Table1: Inductive link specifications.

Parameters	**Values**
Operating frequencies	5/10 MHz
Supply voltage	Vdd= 3.3V
Primary coil	L1 = 5 µH
secondary coil	L2 = 1.7 µH
Parasitic resistance of the transmitter coil	RL1= 2.12 Ω
Parasitic resistance of the receiver coil	RL2= 1.63 Ω
Load resistance	RL= 320 Ω
Coupling factor	k = 0.25
Primary capacitor	C1= 202 pF
Secondary capacitor	C2=167pF
C_{FSK} capacitor	CFSK=67.6 pF
C_{Shunt} capacitor	C_{shunt}=900 pF
RF choke inductor	L_{choke}=12 µH
Drive NMOS transistor W/L	2000/0.35 µm
FSK NMOS transistor W/L	1000/0.35 µm

4. Conclusion

This work proposes and discusses a possible solution to the problem of powering and providing communication with the implant. The coding circuit design of the data is made more complex by the light variations of the duration of a bit modulated according to the coupling between the antennas: the coder must be obligatorily synchronous with the emission clock and retarded Manchester signal must be synchronized with the output signal of VCO.

The Class-E power oscillator has been identified as a highly-efficient transmitter circuit for use as a means of transferring power to an implant. The design of a high-efficiency transcutaneous power and data system is facilitated by FSK modulation of the Class-E power oscillator.

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