

Class-E Self-Oscillation for the Transmission of Wireless Power to Implants

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Abstract

This paper develops the concept of Class-E self oscillation for wireless power delivery to implantable sensors with the comparison of several topologies. Power amplifiers and oscillators are considered as two separate blocks in wireless power transmission. By combining these topologies into a self-oscillating power transmitter, greater efficiency can be achieved. Various topologies are compared with measured hardware results, determining that a crystal feedback network provides both accuracy and high power output. A new crystal feedback Class-E self oscillator has been implemented by transmitting power through 2cm-thick biological tissue. The paper includes a second order modelling and design process that can be used to design a Class-E self oscillator as an inductive power transmitter as well as measured results.

Keywords: class-e, self-oscillator, inductive power, implantable devices

1. Introduction

Wireless power transmitters form an important role in supplying energy to implanted electronic devices and biosensors. Inductive coupling was introduced to biomedical implants to recharge implanted batteries for devices such as pacemakers in order to avoid periodic surgery to replace flat batteries.

As biomedical implant technology progresses with developments such as cochlear and retinal prosthesis, attention is increasingly being focused on the supply of constant wireless power within tight space and power constraints [1, 2]. As space restrictions tighten, so does the allowable size of components in the implanted environment. This naturally translates to higher frequency designs, in that as frequency increases, circuit components generally decrease in size. However, the transfer of energy to implanted devices becomes less

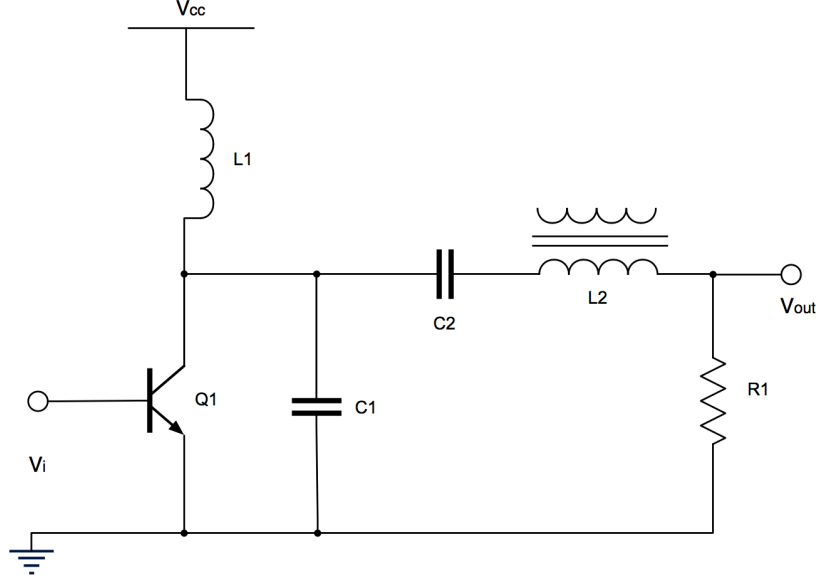


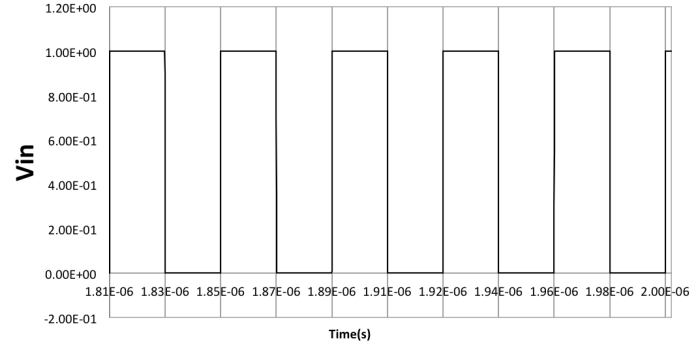
Figure 1: The Class-E amplifier [7]

efficient as the frequency of transmission increases [3]. The design of highly efficient higher frequency power transmitters is therefore an important challenge.

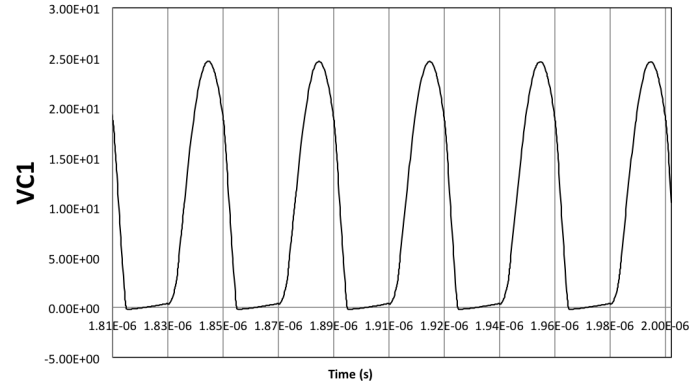
The concepts behind inductive power transfer may be understood by considering a weakly coupled transformer, with a primary coil from which energy is transmitted and a secondary coil at which energy is received [4]. The core of this transformer is a combination air and several layers of human tissue all existing between the two coils. Once the energy is received at the secondary coil, it is rectified and regulated as a DC supply for the implanted electronics and biosensors. The primary coil, which is external to the body is driven by a power transmitter.

Given that space restrictions cause a natural progression towards smaller coils and therefore higher transmission frequencies, power transmitters have been developed to operate at higher frequencies. One particular field of interest has been switching power amplifiers. They operate efficiently at higher frequencies, which is why the Class-E power amplifier has been widely adopted as the means by which energy is inductively transferred to implanted devices [5, 6].

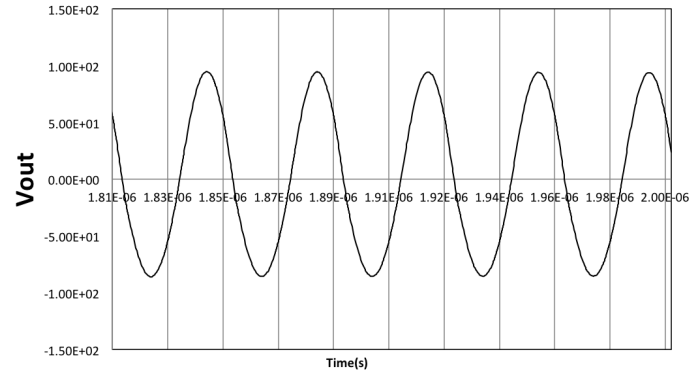
Shown in Fig. 1, the Class-E amplifier comprises an inductor L_2 . This



(a)



(b)



(c)

Figure 2: Class-E amplifier timing diagrams at 27MHz (a) v_{in} (b) v_{C_1} and (c) v_{out} .

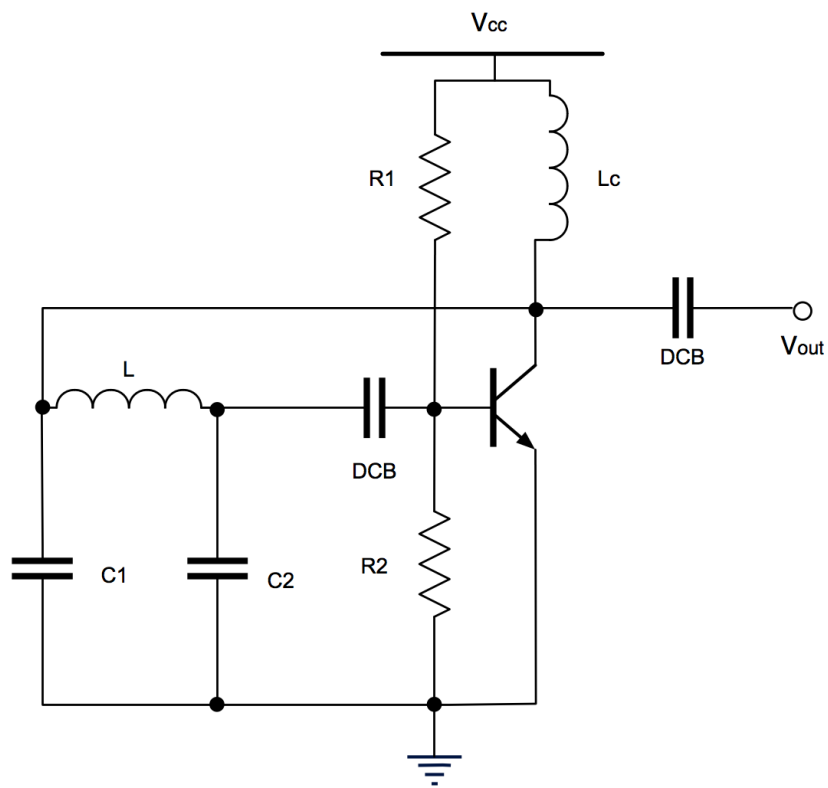
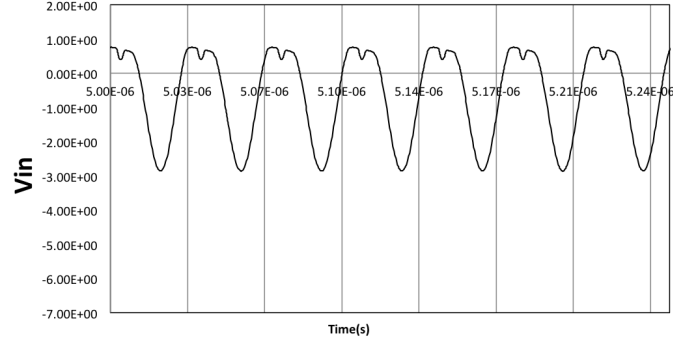
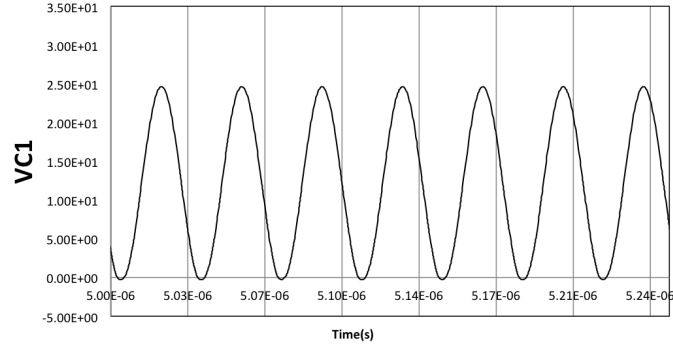


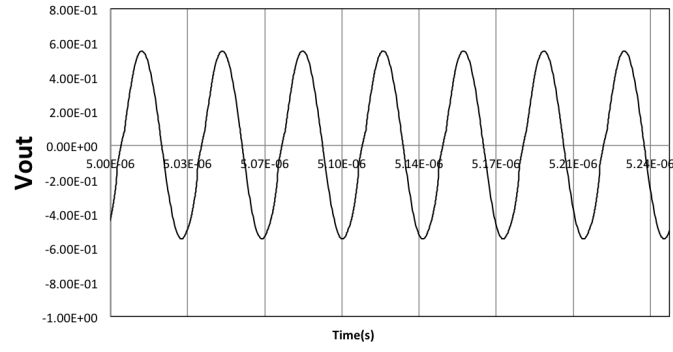
Figure 3: A common emitter colpitts oscillator.



(a)

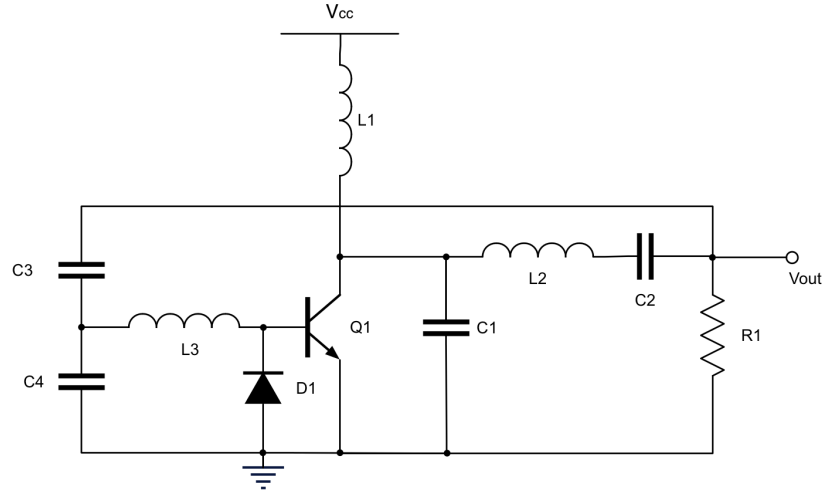


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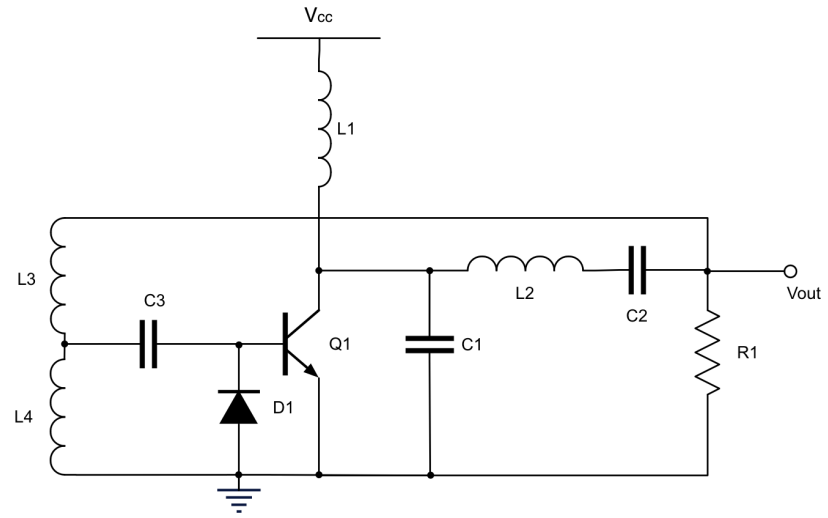


(c)

Figure 4: Colpitts oscillator timing diagrams at 27MHz (a) v_{in} (b) v_{C1} (c) v_{out}

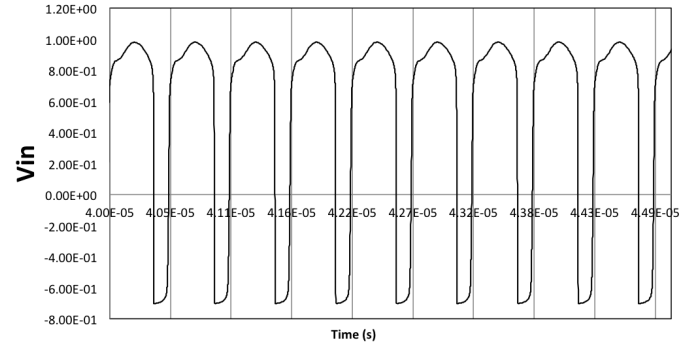


(a)

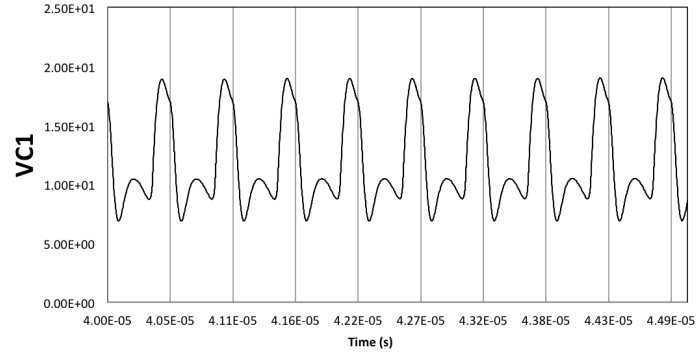


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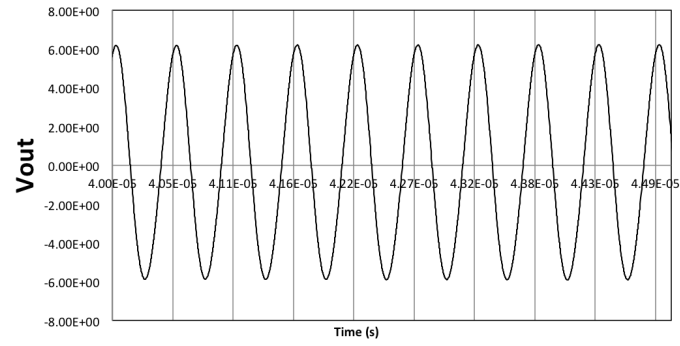
Figure 5: (a) The Class-E oscillator with a Colpitts network [8], (b) with a Hartley feedback network



(a)



(b)



(c)

Figure 6: Class-E oscillator timing diagrams based on [8] (a) v_{in} (b) v_{C1} and (c) v_{out} .

inductor represents the primary coil for the transmission of wireless energy to an implanted device. The amplifier's efficiency at high frequencies is attributed to its ability to hold zero charge across the terminals of the transistor while it is switching. Not only is the voltage designed to be zero, but so is the rate of change of voltage (dv/dt) according to [7, 9]. A simulated timing diagram of a 27MHz Class-E amplifier is presented in Fig. 2, with the input clock signal v_{in} , voltage across C_1 (v_{C_1}) and load voltage v_{out} . An observation of v_{C_1} shows that after a transistor delay, the voltage drops prior to switching according to the principles of the Class-E amplifier. This allows for a power amplifier which efficiently transmits energy across L_2 according to the switching frequency supplied by the input voltage v_{in} . The capacitor C_1 also absorbs parasitic capacitance that exists between transistor terminals, which becomes increasingly significant at higher frequencies where design parameters are in the order of parasitic impedances [7, 10, 9].

The Class-E amplifier works efficiently at high frequencies, however the fact that it is a switching power amplifier means that it requires a high frequency square-wave input in order to operate effectively. This efficiency does not consider the energy that is required to produce the square-wave input using a dedicated oscillator, be it a crystal or LC oscillator.

One example of an LC oscillator is the Colpitts oscillator, shown in Fig. 3. It is designed by selecting an inductor-capacitor combination that resonates at a specified design frequency. The output signal of the oscillator is 180° out of phase with the input signal. The feedback network then shifts the signal's phase by another 180° for the input of the transistor. Simulated timing diagrams of a Colpitts oscillator are shown in Fig. 4. The input signal v_{in} and feedback signal v_{C_1} are 180° out of phase, all sinusoidal. In order to use the Colpitts oscillator as an input to a switching power amplifier, the output must pass through an inverter in order to produce a square signal.

Generally speaking, the purpose of an oscillator is to generate a stable oscillating signal at a specific frequency. Similarly, the purpose of a power amplifier is to use a pre-existing square-wave signal and boost its power level. In most literature regarding the design of wireless power transmitters for implantable devices, these two blocks are considered separate as indicated in Fig. 7, yet both are necessary for the supply of inductive power. The combination of both an oscillator and power amplifier may reduce the complexity and increase the overall efficiency of a power transmitter. An example of such a circuit is presented in literature as a Class-E oscillator as shown in Fig. 5(a) [8, 11, 12, 13].

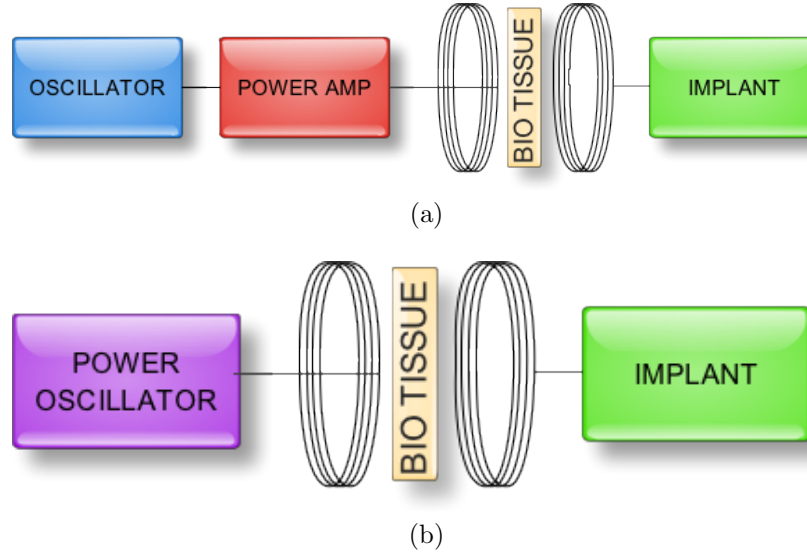


Figure 7: Block diagrams indicating (a) separate power amplifier and oscillator blocks, and (b) combined power oscillator blocks.

Additional circuit elements have been added to the Class-E amplifier of Fig. 1 to form the Class-E oscillator of Fig. 5(a), namely the feedback elements C_3, C_4 and L_3 . It was designed by Ebert et al. to constructively shift the phase of the feedback point of the oscillator [8]. The diode D_1 is placed at the input of the transistor in order to clip the input signal such that it appears as a square wave, satisfying the requirement of the Class-E circuit to have a square-wave input. A simulated timing diagram of the Class-E oscillator [8] is shown in Fig. 6 with the input, feedback and output signals v_{in} , v_{C_1} and v_{out} respectively. Comparing the timing diagrams of the Class-E amplifier and Colpitts oscillator, it is possible to identify that the Class-E oscillator can be considered as a combination of these two circuits. The feedback network of the Class-E oscillator is similar to that of the Colpitts oscillator. It is also interesting to consider implementing a Hartley feedback Class-E oscillator, conceptualised in Fig. 5(b).

Low power consumption is advantageous in biomedical systems, so rather than implementing oscillators and Class-E power amplifiers for wireless power transmission it may be advantageous to consider a Class-E self-oscillator [5]. Similar to the power amplifier, the Class-E self-oscillator would transmit energy through L_2 . This idea will be investigated in subsequent sections of

this paper, including a measured comparison of different topologies, circuit design and modelling and an example of inductive wireless power transfer using a Class-E self-oscillator.

2. Comparison of Class-E Topologies

The Class-E amplifier is currently a popular choice in transmitting wireless inductive power, however the use of Class-E self-oscillators is a potential improvement. In this paper a number of different Class-E circuits are compared using laboratory measurements. The circuits include a Class-E amplifier, Class-E self-oscillator with LC feedback, and a Class-E self-oscillator with a crystal feedback link.

In order to determine whether using a Class-E oscillator is advantageous over a Class-E amplifier, similarly designed circuits have been constructed and tested with the main circuit elements chosen to be as similar as possible. The transistor used for all of the five circuits is BC547B from Fairchild Semiconductors. The elements of the Class-E circuits have been determined according to [9], and all of the circuits are supplied with a 3V supply. The inductor L_2 is in fact a spiral inductor, forming the primary coil for the transfer of inductively transferred power.

The first power transmitter circuit uses the Class-E amplifier, as shown in Fig.8. The 27-MHz clock input signal to the amplifier is produced a separate oscillating block, a crystal oscillator ACHL-27MHZ-EK. Small 1Ω measurement-resistors R_{meas} have been positioned in the combined connection to ground and after L_2 in order to measure the total current and current through the transmission coil respectively, such that the input and output power can be calculated. The 27MHz frequency of transmission is selected because it is in the allowable limits of the Industrial, Scientific and Medical (ISM) band.

The power used by this circuit is 77mW (18.9dBm), which is determined by multiplying the supply voltage with the r.m.s. value of the total current. The output power of 11.2dBm is calculated by multiplying the r.m.s. voltage and current across and through the inductor L_2 . This corresponds to an efficiency of 17%, which is quite low however not surprising considering that a crystal oscillator circuit was powered to supply the square-wave input signal to the amplifier.

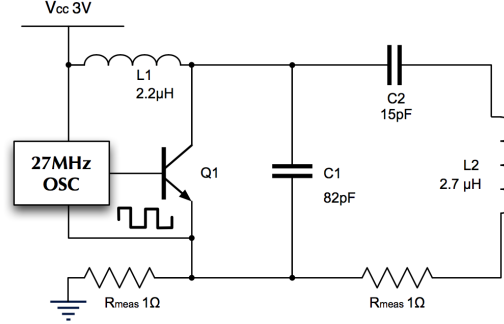


Figure 8: A 27MHz Class-E amplifier constructed in hardware, driven by a crystal oscillator.

2.1. Class-E Oscillators biased with Resistors

The next step of the comparison involves the construction of the Class-E self-oscillator circuit, shown in Fig.9. This differs from the Class-E oscillator shown in Fig. 5(a) in that the load is represented by the inductor L_2 rather than a resistor. Other proposals involve using a capacitor as a feedback network [14], however the feedback point in this experiment is taken between the L_2 and C_2 component of the Class-E amplifier, and consists of an LC pair in order to reverse the phase difference that is incurred at the point across L_2 to increase efficiency. The element between the base and emitter of Q_1 is a $100k\Omega$ biasing resistor. The power used by this circuit is 35mW (15.5dBm) and 11.4dBm is transmitted, corresponding to an efficiency of 39%. While this is much higher than the efficiency of the Class-E Amplifier of Fig.8, the 34MHz frequency of the output is higher than the desired 27MHz value. This is due to the fact that the accuracy of the circuit's frequency is controlled solely by the accuracy of its individual inductor and capacitor values.

A variant of this circuit has been implemented by inserting a 27MHz crystal (Citizen America CS1027.000MABJ-UT) as the feedback network in order to create a stable frequency. This crystal is not an oscillator itself, but an accurate impedance that ensures the input frequency to the transistor is 27MHz. The schematic of this circuit is shown in Fig.10, with the base-emitter element being $100k\Omega$ resistor. The power used by the circuit has been measured to be 112mW (20.5dBm) and the output power is also 20.5dBm, which corresponds to a measured efficiency of 100%. This is attributed to negligibly small losses in the biasing circuit of the amplifier and zero-switching conditions at the collector of the transistor.

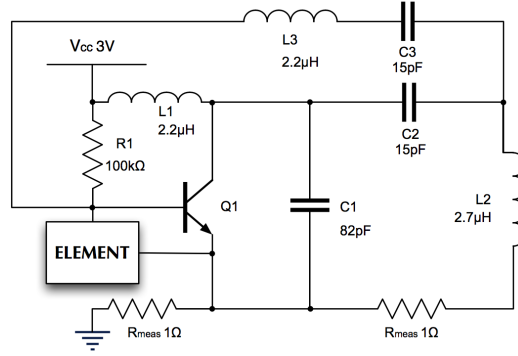


Figure 9: Schematic diagram of a Class-E oscillator with an LC feedback network and element between the transistors base and emitter terminals, being either a 100k Ω resistor or a Schottky diode.

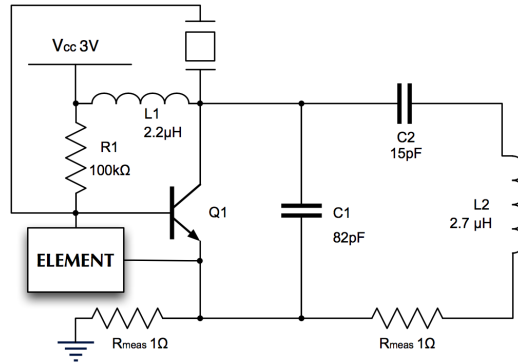


Figure 10: Schematic diagram of a Class-E oscillator with a 27MHz Crystal feedback network and element between the transistors base and emitter terminals, being either a 100k Ω resistor or a Zener diode.

Table 1: Comparisons between Class-E Circuits

Class-E Circuit	B/E Element	f	S_{used}	V_{L2pp}	S_{out}
Amplifier of Fig.8		27MHz	18.9 dBm	1.6 V	11.2 dBm
Oscillator with LC feedback, Fig.9	100k Ω	34MHz	15.5 dBm	0.9 V	11.4 dBm
Oscillator with Crystal Feedback, Fig.10	100k Ω	27MHz	20.5 dBm	7.0 V	20.5 dBm
Oscillator with LC feedback, Fig.9	Schotky Diode	34MHz	16.2 dBm	1.2 V	9.9 dBm
Oscillator with Crystal Feedback, Fig.10	Zener Diode	27MHz	18.0 dBm	6.7 V	18.7 dBm

2.2. Class-E Oscillators biased with Diodes

Class-E oscillators presented in literature have employed Schottky diodes across the base and emitter of the circuit's transistors [8]. This is usually done to clip the input signal such that it approximates a square-wave input, which is preferred as the transistor continues to operate as a switch.

The LC feedback Class-E oscillator of Fig.9 has been implemented using a Schottky diode from Fairchild Semiconductors (MBR0520L) as a biasing element, which is the same diode used in [8]. The power used by this circuit is 42mW (16.2dBm) and an output power of 9.9dBm is produced, corresponding to an efficiency of 23%, which is considerably lower than the 39% efficiency achieved with a 100k Ω resistor in place of the diode. Zener diodes are a more suitable option than the Schottky diode used, however the voltage level of the output is not high enough to switch the transistor.

A 3V Zener diode (NXP-BZX384-C3V0) has been implemented as the element between the base and emitter of Q_1 in the Class-E oscillator based on Fig.10. The circuit works in that the feedback voltage is high enough to drive the transistor and Zener diode. The circuit's power usage has been recorded as 63mW (18dBm), with an output power of 18dBm. This mathematically corresponds to 100% efficiency, and is attributed to negligibly small losses in the biasing circuit of the amplifier and zero-switching conditions at the collector of the transistor.

The results of these experiments are summarised in Table 1. The first

significant point of note is that using a feedback network in the Class-E circuit improves the efficiency of the transmitter, in that a dedicating oscillating unit is no longer required.

Another significant point is that including a crystal in the feedback network allows the frequency of the transmitter to be controlled, rather than relying on the accuracy of individual inductors and capacitors, which may cause unstable or inaccurate transmission frequencies.

The use of zener diodes on the base of the circuit's transmitter makes little difference on the performance of the amplifier, however it may be an important to regulate the output of the transmitter in the case that the feedback voltage becomes too high.

3. Modelling the Class-E Oscillator

It is determined that the Class-E self-oscillating circuit with the crystal feedback link is the most efficient and stable of the three options presented in Section 2. A higher-powered version of Class-E self-oscillator circuit of Fig. 10 is shown in Fig.11. This circuit may be further understood by viewing it in its signal model shown in Fig. 12. The load network at the collector of the transistor is of particular interest. The quartz crystal consumes very little current in comparison to the load network, making it negligible in the determination of Z_L . The choke inductor L_1 can also be large enough to ignore with respect to the load network of the oscillator such that Z_L becomes:

$$Z_L = \frac{1}{sC_1} \parallel \left(\frac{1}{sC_2} + L_2 + R_L \right) \quad (1)$$

If the output of the circuit is seen as the voltage across the transmitting inductor L_2 and R , the output voltage of the signal becomes:

$$v_{out} = \beta i_b \frac{sL_2 + R_L}{sL_2 + R_L + \frac{1}{sC_2}} Z_L \quad (2)$$

and the transfer function becomes:

$$\frac{v_{out}}{v_{in}} = K \frac{sL_2C_2 + R_LC_2}{s^2L_2C_1C_2 + sR_LC_1C_2 + s(C_1 + C_2)} \quad (3)$$

where K is a scalar related to the transistor's βi_b base-emitter resistance r_{be} and input voltage v_{in} .

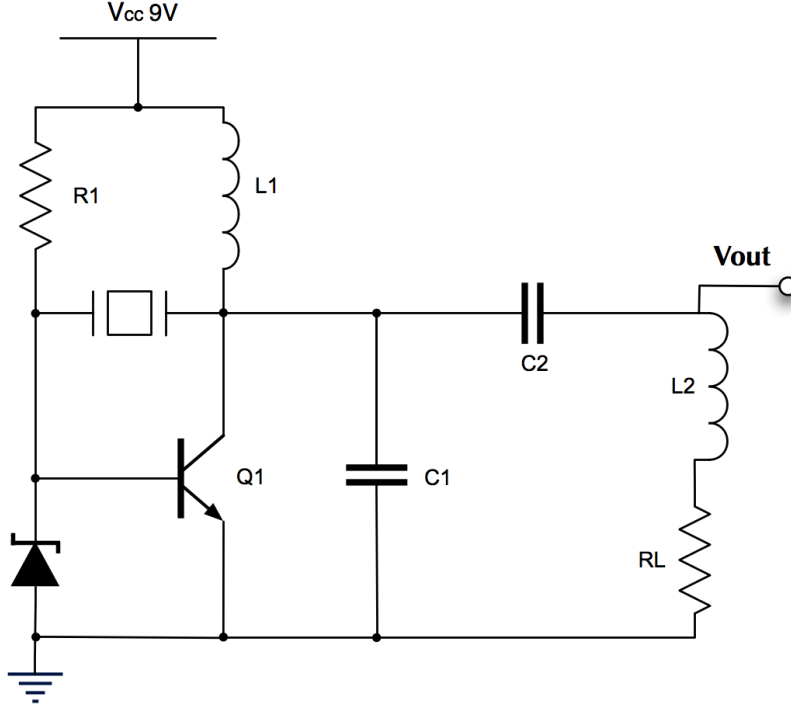


Figure 11: Schematic diagram of a Class-E oscillator with a 27MHz Crystal feedback network and element between the transistors base and emitter terminals, being either a $100\text{k}\Omega$ resistor or a Zener diode [15].

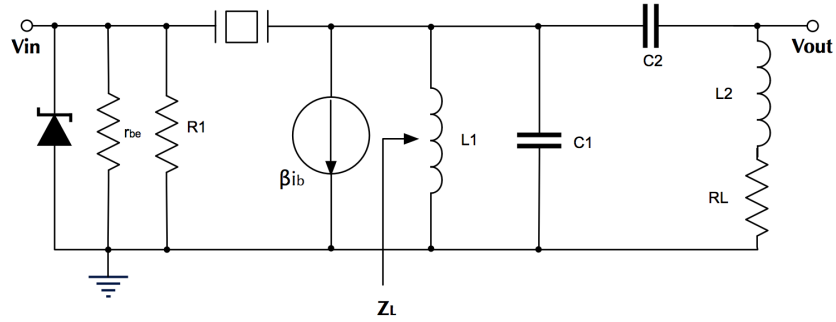


Figure 12: A small signal model of the Class-E self-oscillator of Fig. 11

This presents a second order system, the circuit elements of which may be determined by manipulating the transfer function's resonant frequency ω and damping factor ζ . Based on (3) these terms are determined by:

$$\omega = \frac{1}{\sqrt{L_2 C_1 || C_2}} \quad (4)$$

$$\zeta = \frac{R_L}{2} \sqrt{\frac{C_1 || C_2}{L_2}} \quad (5)$$

Given that the intended resonant frequency ω is known, and that the coil's properties L_2 and R_L have been determined, it is possible to determine expressions from the simultaneous equations (4) and (5) to determine expressions for ζ and $C_1 || C_2$ as (6) and (7) respectively.

$$\zeta = \frac{R_L}{2\omega L_2} \quad (6)$$

$$C_1 || C_2 = \frac{2\zeta}{R_L \omega} \quad (7)$$

Once $C_1 || C_2$ has been calculated, the next step involves the selection of individual capacitor values C_1 and C_2 . If C_1 is larger than C_2 , it will charge and discharge quicker. This implies that the voltage across C_1 will drop to zero quicker as charge enters the larger capacitor C_2 . It is important that this voltage drops before the transistor switches states so as to avoid discharge losses.

4. Wireless Power Transfer

The oscillator of Fig. 11 is used to transmit wireless power to a harmonics-based implantable telemetry device based on [16]. The transmission coil represented in Fig. 11 as L_2 and R_L is in fact a square planar spiral of 8 turns in an area of 100 x 100mm. The feedback input signal to the Class-E self-oscillator is shown in Fig. 14 and v_{C_1} in Fig. 15. The voltage across the output inductor L_2 is shown in Fig. 16(a).

In order to test the operation of the Class-E self-oscillator in biological tissue, the experiment is constructed such that the Class-E self-oscillator transmits wireless power through lean beef, 2cm in thickness as shown in Fig. 13.

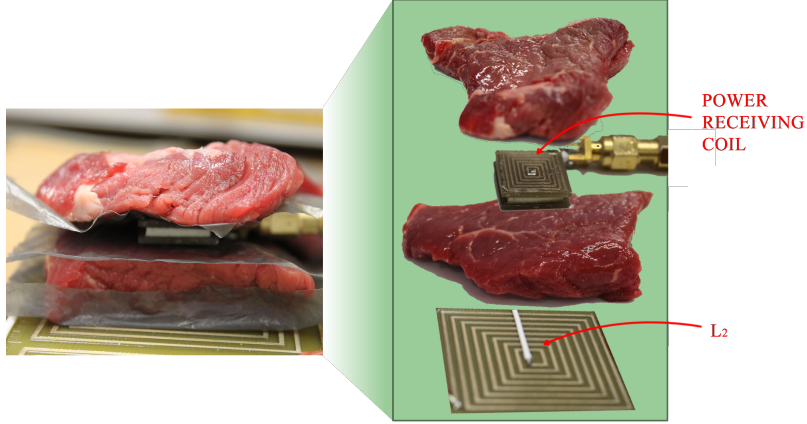


Figure 13: Experimental set up with the transmission coil, lean beef, stacked spiral receiving coil and meat.

The receiving coil is a stacked spiral coil from [15]. Stacking planar spiral inductors increases parasitic capacitance, which allows the stacked spiral coil to operate at a lower self-resonant frequency compared with an equivalent planar spiral. The stacked spiral is contained within a 10mm x 10mm x 4.5mm volume and the voltage across the coil after the wireless transfer through meat is shown in Fig. 16(b).

The power sent by the Class-E oscillator is 27.5dBm, and the received power on the stacked spiral 20.6dBm, implying that a path loss of just 6.9dB occurred.

5. Conclusion

This paper proposes the use of Class-E oscillators of a particular topology as inductive power transmitters for implanted telemetry devices that transmit information read by biosensors. In most literature regarding inductive power transfer for biodevices, power amplifiers and oscillators are considered as two separate blocks. By combining these topologies into a self-oscillating power transmitter, greater efficiency can be achieved. Several Class-E self-oscillator topologies were compared with the commonly used Class-E amplifier. The Class-E oscillators were determined to be more efficient when considering the power used by the input signal to the amplifier.

Different feedback options are compared amongst Class-E oscillators, and it is proposed that a crystal feedback network ensures a more efficient circuit

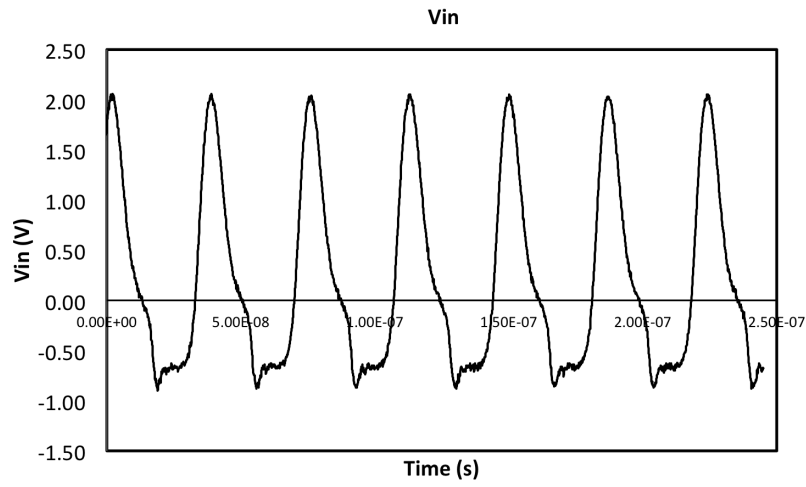


Figure 14: Input signal of the Class-E Self-Oscillator of Fig. 11

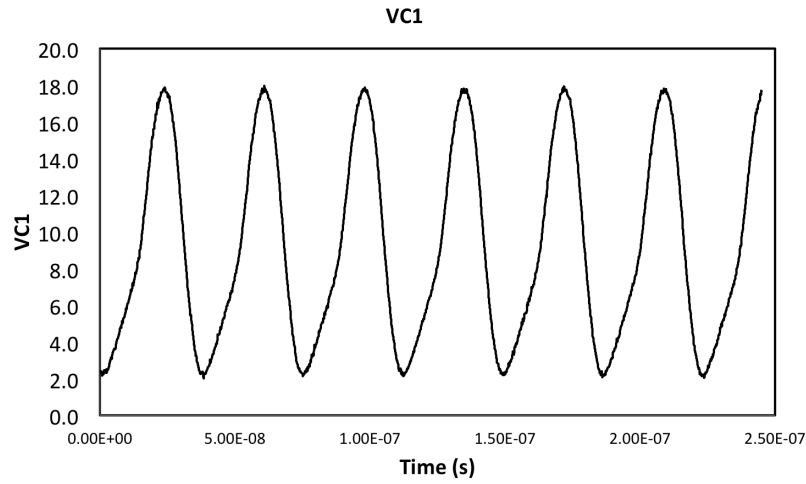
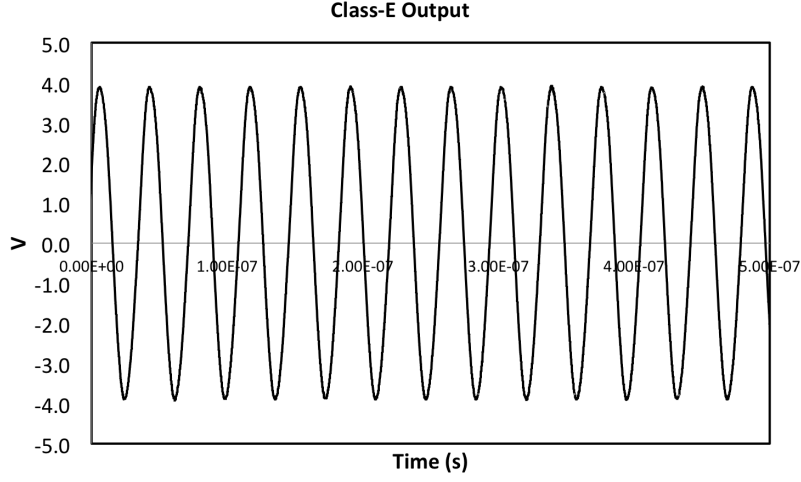
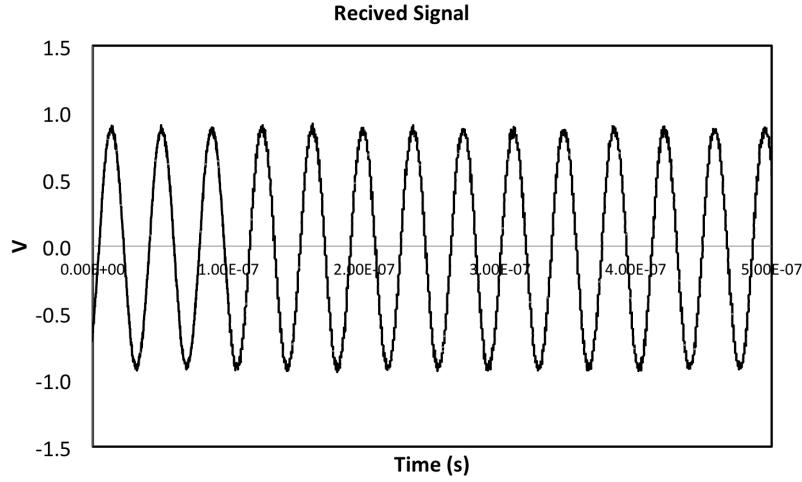


Figure 15: Voltage across C_1 in the Class-E Self-Oscillator of Fig. 11



(a)



(b)

Figure 16: Voltage signals across (a) the transmission coil of he Class-E self-oscillator of Fig. 11, and (b) the receiving coil after the biological tissue.

with a more stable and better controlled frequency. The use of Zener diodes at the input of the oscillator is determined to be advantageous when operating at higher input voltage levels, in that the input is clipped to the diode's voltage rating, allowing the Class-E load to operate as designed.

The Class-E load network was modelled as a second-order system, which allowed for a straightforward design process based on second order variables.

A higher-power Class-E oscillator was implemented based on the results of the circuit comparisons, and used to transmit power through a biological muscle environment using 2cm thick beef. The received power successfully powered the telemetry device implanted in biological tissue.

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