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DESIGN AND ANALYSIS OF CLASS-E POWER AMPLIFIER: A 4GHZ BAND FOR MOBILE APPLICATION

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Abstract

Power amplifier (PA) is the most important component used for overall RF transmitter efficiency, because it consumes the largest portion of dc power in the transmitter. Highly efficient PAs are necessary to improve overall efficiency. A class-E power amplifier is nonlinear amplifier, in the sense that variations in input signal amplitude will not reproduced at the output in any acceptable form. In this research efficient class-E power amplifier was designed by using 180nm technology. The 37.4mW Class-E power amplifier design was achieved and tested in the laboratory. The IRF540 MOSFET was used in the design of the amplifier. The calculation 100%, simulation98.42% and experimental90.34%design of Class-E power amplifier with load network and single transistor was carried out, the overall efficiency were achieved with 1.8V dc power supply. The amplifier was operated at band frequency of 4GHz and 50% duty cycle for a stable sinusoidal signal. Performance parameters relationships with Class-E power amplifier were observed and analyzed in respect to the load and duty cycle. In comparison to wireless communication devices application, this designed Class-E power amplifier gave good performance and high efficiency at low power consumption by reducing the input dc power level. Theoretical calculations, simulation and experimental results for optimum operation using selected component values were compared with other work. The results can assist for the efficient design for Wi-Fi applications.

Keywords: Class-E amplifier, RF-transmitter, Power amplifiers (PA), Band frequency, duty cycle

1.0 INTRODUCTION

Mobile equipment demands highly efficient RF transmitters to conserve battery life. The power amplifier(PA) is the most important component used to determine overall RFtransmitter efficiency because it consumes the largest portion of dc power in the transmitter. Thus, highly efficient PAs are necessary to improve overall efficiency. A class-E PA is adaptable for a high-efficiency transmitter due to its high efficiency and simplicity. A class-E amplifier with a shunt capacitor was introduced in [1] and was examined in [2] in an analysis of idealized operation. The expensive development of wireless communication systems during the last decade has particularly put the design of Radio Frequency Power Amplifiers in focus. Efficiency and linearity are opposing requirements in the power amplifiers design and much research is focused on how to improve the efficiency of power amplifiers circuits while still satisfying the linearity requirements of a given system [3,4].The need for linear power amplifiers arises in many radio frequency applications. At present, most linear power amplifiers designed for portable devices, employ a class A output stage and exhibit efficiencies around 30% to 40% [5]. In this range of frequency, class- E amplifier has shown to exhibit efficiency as high as 96% [1]. To achieve a higher efficiency, it is possible to begin with a nonlinear power amplifier and apply linearization techniques to the circuit. A power amplifier is an amplifier, which is capable of providing a large amount of power to the load such as loudspeaker, or motor. It is essential in almost all electronic systems where a large amount of power is supplied to the load. The PA is more commonly known as audio amplifier [6].The power is fed to the load. The type of ac power developed at the output of a power amplifier is controlled by the input signal. Thus it is said that power amplifier is a dc to ac power converter whose action is controlled by the input signal. The power amplifiers are also known as large signal amplifiers [7].

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The proposed system is designed for achieving low power consumption for wide bandwidth and also to improve efficiency of PA by decreasing the input DC power Level using 180nm technology [8]. Class E amplifiers have been shown to be usable at higher frequencies and useful for wireless communications. Also they have been shown to have much better performance and efficiency than other classes of power amplifiers at lower supply voltages [9].

2.0 THEORETICAL BACKGROUND

The conventional ideal class EPA topology is depicted in Figure 1. For this PA circuitry [10]. The transistor is considered as a switch and capacitor C_I is connected in parallel with it if the transistor switch is turn on, the current flows entirely through the switch drain and source, the voltage is zero. The current can be expressed as

$$isw(t) = Idc[1 + a\sin(wt + \emptyset)] \quad (1)$$

When the switch is turned off, the current flows entirely into the capacitor which is charged simultaneously. During this off state interval, the voltage on this parallel capacitor is given by:

$$Vsw(t) = \frac{1}{C_I}\int_o^t isw\,(t^I)\,dt^I \qquad = \frac{Idc}{WC_I}\,[1 + a(\cos(wt + \emptyset)] \quad (2)$$

There are two boundary conditions for the ideal class E operation [11] referred as zero voltage switching (ZVS) and zero voltage derivative switching (ZVDS) condition.

Assume the switch is turned off at t=0 and turned on at $t = \frac{T}{2}$, those two conditions are given by

$$Vsw\ (t = 0\ ) = 0$$

$$\frac{\partial Vsw}{\partial t}\ (\ t = \frac{T}{2}) = 0 \quad (3)$$

Where T denotes the time period of one class E duty cycle. The ZVS condition prevents simultaneous non zero voltage and current across the switch device, the ZVDS enforce the current to start flowing after the voltage has reached zero.

The value of$a$ and $\emptyset$ can be determined uniquely by applying these two constraints leading to

$$a = \frac{\sqrt{1+\pi^2}}{4} \quad (4)$$

$$\emptyset = \arctan\frac{2}{\pi} \quad (5)$$

Consequently, there is no overlap between the transient drain current and voltage, which leads to a zero dc power dissipation and 100% drain efficiently. Using Fourier series expansion [12] the optimal fundamental load, yielding perfect class E operation, can be determined by:

$$Z_{E,f_o} \ = \frac{0.28}{Wc_I}e^{49^\circ} \quad (6)$$

This impedance present inductive, which is illustrated, see figure 2 In deal class E mode, the total current through the combined switch capacitor tank is a pure sinusoidal wave, and the harmonics are entirely due to the voltage. The ideal impedances at higher order harmonic frequencies are infinite with relation given by:

$$Z_{E,nf_o} = \infty, \quad n \geq 2 \quad (7)$$

3. METHODOLOGY

The Class-E PAs are classified into different types depending upon the input and output matching network. Figure 1 shows a block diagram of the proposed Class-E power amplifier in this work.

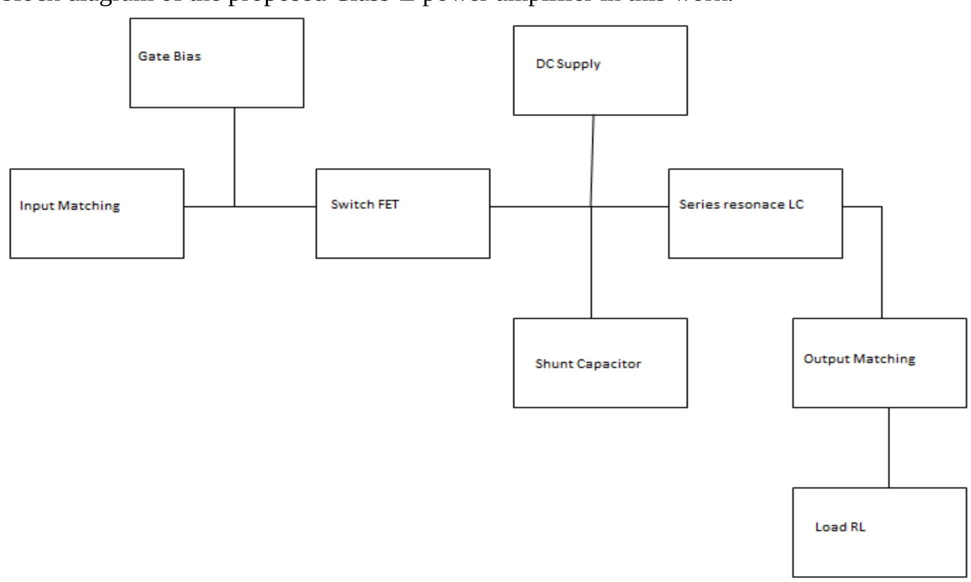

Figure 1. Block Diagram of the proposed Class-E Power amplifier

Narrowband amplifier design was chosen in this work for matching network. Narrow band or band pass amplifiers are devices whose frequency response characteristics is determined by resonant LC or RC circuit. The series LC resonator has a limited frequency response. Resonant LC circuits are placed in the base and collector circuits of Class-E PA to provide the spectrum-shaping properties of the amplifier. The resultant bandwidth is dependant on the sharpness of the tuned circuit and the load R_L. The more tuned circuit loaded, the broader its frequency characteristic becomes [13].The assumptions of theClass-E Power Amplifier circuit are quite similar to the one that is presented in[1]. Theanalysis of the Class-E power amplifier of Figure1 was carried out under the following assumptions:

i. The MOSFET and diode form an ideal switch whose on-resistance is zero, off-resistance is infinity, andswitching times are zero.
ii. The choke inductance is high enough so that its ac component is much lower than the DC component ofthe input current.
iii. The loaded quality factor Q of the L, C and RL series-resonant circuit is high enough so that the current Ithrough the resonant circuit is sinusoidal.
iv. Duty cycle, D = 50%

Designed Specifications

In this work, few parameters were determined prior to the simulation. The pre-determined specifications are as follows:

Table 1. Pre-determined specifications of class E power amplifier

Specification	Values
Output power P_o	37.4mw
Input voltage v_i	1.8v
Duty cycle D	0.5
Frequency F	4GHz
Quality factor Q	1.2

Based on the parameters, some other values were determined. The values of tank circuit werecalculated from the following equations:

$$f= \frac{1}{2\pi\sqrt{L_2C_2}} = \frac{1}{2*3.142\sqrt{2.3*10^{-9}*0.69*10^{-12}}} = 4\text{GHz} \quad (8)$$

$$L_2 = \frac{\pi Vd\,d^2}{2WP_{out}}\frac{\pi^2-4}{\pi^2+4} = \frac{3.142\,(1.8)^2}{2*2.5*1010*0.0374}\frac{(3.142)^2-4}{(3.142)^2+4} = 2.3\text{nH} \quad (9)$$

$$w = \frac{1}{\sqrt{L_2C_2}} = \frac{1}{\sqrt{2.3*10^{-9}*0.69*10^{-12}}} = 2.51*10^{10}\text{rad} \quad (10)$$

$$L_1 = \frac{3.534R_L}{W} = \frac{3.534*50}{2.51*10^{10}} = 7\text{nH} \quad (11)$$

$$C_2 = \frac{1}{L_2W^2} = \frac{1}{2.3*10^{-9}(2.51*10^{10})^2} = 0.69\text{pF} \quad (12)$$

$$C_1 = \frac{1}{WR_L} = \frac{1}{2.51*10^{10}*50} = 0.8\text{pF} \quad (13)$$

$$\text{DC Input current } I_i = \frac{8}{\pi^2+4} * [\frac{V_i}{R_i}] = 0.577 * \left[\frac{1.8}{50}\right] = 0.0208\text{A} \quad (14)$$

$$\text{Output current } I_o = \frac{I_i\sqrt{\pi^2+4}}{2} = \frac{0.0208*3.725}{2} = 0.039\text{A} \quad (15)$$

$$\text{Peak voltage across capacitor } VC_2 = \frac{I_0}{WC_2} = \frac{0.039}{2.51*10^{10}*0.69*10^{-12}} = 2.25\text{V} \quad (16)$$

Peak voltage across inductor:

$$VL_2 = WL_2I_0 = 2.51 * 10^{10} * 2.3 * 10^{-9} * 0.03 = 2.25\text{V} \quad (17)$$

$$\text{Maximum switch current } I_{ms} = [\frac{\sqrt{\pi^2+4}}{2} + 1] * I_i = 2.86*0.0208 = 0.059\text{A} \quad (18)$$

$$\text{Maximum Voltage across switch } V_{ms} = 3.652V_i = 3.652*1.8 = 6.57\text{V} \quad (19)$$

Based on the theoretical calculation, the efficiency of the overall system was determined by calculating the power input P_i and power output $P_o$based on particular values.

Input power:

$$P_i = V_i * I_i = 1.8 * 0.0208 = 0.0374W \quad (20)$$

$$P_{out\,(\max)} = \frac{0.577Vdd^2}{R_L} = \frac{0.577*(1.8)^2}{50} = 0.0374\text{W} \quad (21)$$

$$Efficiency, \dot{\eta} = \frac{P_{out}}{P_{in}} * 100\% = \frac{0.0374}{0.0374} * 100\% = 100 \quad (22)$$

4. RESULTS AND DISCUSSION

The technology used for this paper is 180nm technology. The maximum power added efficiency achieved in this paper were: 100%, 90.34% and 98.42%. and output power was 37.4mWfor the supply voltage of 1.8V, at frequency 4GHz. The comparison is shown in Table 2. The schematic diagram of proposed class-E power amplifier is shown in Figure2.The transistor characteristic and transient analysis of proposed system is shown in Figure 3showing the output voltage, and Figure 4.

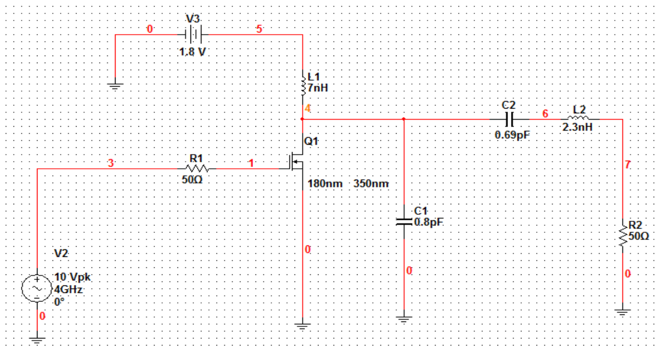

Figure 2.Schematic diagram of the proposed class-E PA

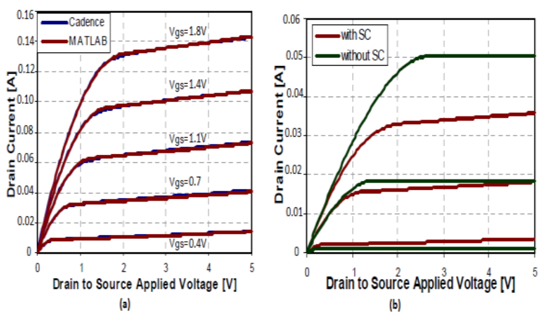

Figure 3. IV Characteristic comparison

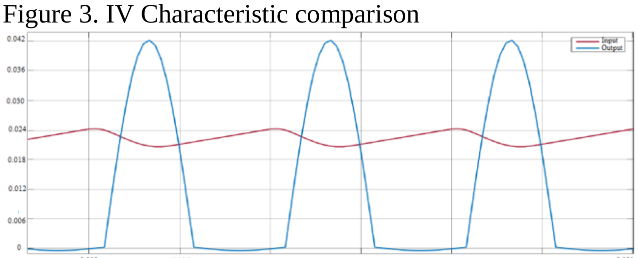

Figure 4. Input and Output currents of the Class-E amplifier

Table 2: Class-E Power AmplifierParameters Comparison

Parameter	Calculated Result	Simulation Result	Experimental Result
R_1 (Ω)	50	50	50
R_2 (Ω)	50	50	50
L_1 (nH)	7	7	7
L_2 (nH)	2.3	2.3	2.3
C1(pF)	0.8	0.8	0.8
C_2 (pF)	0.69	0.69	0.69
$V_{RL\ (peak)}$ (V)	1.933	1.930	1.930
$V_{ds\ (peak)}$ (V)	6.570	6.574	6.574
I_{DC} (A)	0.0208	0.0230	0.0210
$I_{RL\ (peak)}$ (A)	0.039	0.043	0.039
$V_{C\ (peak)}$ (V)	2.25	2.50	2.30
$V_{L\ (peak)}$ (V)	2.25	2.50	2.30
$I_{S\ (peak)}$ (A)	0.059	0.070	0.060
$P_{out\ (a.c)}$ (W)	0.0374	0.0374	0.0374
$P_{i\ (d.c)}$ (W)	0.0374	0.0380	0.0414
η (%)	100	98.42	90.34

Table 3: Comparison of designed system with referred papers

Reference	This work	[16]	[17]	[18]	[19]	[8]
Technology	180nm	180nm	180nm	180nm	180nm	180nm
Supply Voltage	1.8V	1.8V	1.8V	1.8V	3.3V	1.8V
Frequency	4GHz	2.4GHz	1.9GHz	2.4GHz	1.8GHz	2.4GHz
Output Power	37.4mW	22mW	1.6W	20mW	2W	32mW
Efficiency	98.42%	44%	40%	62%	31%	66.11%

DISCUSSION

Based on the design equations and assumptions provided in Section 3, all the circuit parameters were calculated and tabulated in Table 2.The simulations were carried out using Multisim 11.0 beforethe real circuit implemention. In order to validate the simulation results, the experimental work was carried out. IRF540 MOSFET (n channel, enhancement mode) was used as a switching device in the design.Also, based on Table 2, the peak switch voltage and current were 6.57*V* and 0.059*A* respectively. Also, the overall technology, efficiency and band frequency is presented in Table 3 for comparison with other work.According to IRF 540 MOSFET datasheets, the breakdown switch voltage and current were 100*V* and 28*A* respectively. This confirms that the IRF540 MOSFET is suitable to be used for Class-E power amplifier circuit. The voltage and current of the designed amplifier were measured by Digital Multimeter and oscilloscope was used to obtain the waveforms data of the output voltage. The efficiency of the overall system of power input$P_i$to power output,$P_o$based on particular values was determined. It was observed that the efficiency of Class-E simulation circuit and experiment in Table 2differs by 1.58%and 9.66%from the efficiencyof the calculated theoretical values. This situation happened because the value of components used for the simulation was selected as the best value to suit for the zero-voltage switching (ZVS) condition. Beside, Multisim is very sensitive towards decimal points of the values. Therefore, some values were rounded to acceptable ones to make the simulation results firmly presented.

5.0 CONCLUSION

The model of Class-E Power amplifier was designed and presented in this research work. It is proved successful through verification in the Multisim circuit simulator. Deriving an expression to obtain the correct optimal switching condition was donein order to prove this theory correct. The calculation 100%, simulation 98.42% and experimental 90.34% of designClass-E power amplifier with load network, and a single transistor was carried out, the overall efficiency were achieved, powered with 1.8V dc. The amplifier was operated at band frequency of 4GHz and 50% duty cycle for stable sinusoidal signal. Therefore, it can be concluded that the optimum operation can be achieved only at an optimum load resistance, $R_2= R_1$. At $R_2 = R_1$the sinusoidal output voltage will reach nearly to maximum for the tested operating frequency. For future development, in wireless communication devices application, our design Class-E power amplifier will give better performance and high efficiency at low power consumption by reducing the input dc power level.

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