An Optimal Design of High Output Power CMOS Class E Power Amplifier with Broadband Matching for RFID Applications

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Abstract. In the radio frequency frontend the power amplifiers are most essential block for reliable wireless communication. Power amplifiers are used for amplification and enhance the input signal to the desired power level at output. The class-E power amplifiers are used in many RF portable electronic devices that need low power consumption, high gain, and high efficiency. In this article, we present an optimum design of a complementary metal-oxide semiconductor (CMOS) class-E power amplifier (PA) that achieves high efficiency and high gain simultaneously for RF based electronic article surveillance (EAS) system. The simulated analysis and implementation of a class-E RF power amplifier with an appropriate output impedance matching network are presented. The proposed CMOS class-E PA has 41.7 dBm output power with 63% of power efficiency at frequency of 7.7 MHz to 8.7 MHz.

Keywords: Class-E PA; High efficiency; CMOS PA; RFID; RF-EAS; Power amplifier; Broadband matching.

1. Introduction
A power amplifier is the main section of a transmitter, that’s why it has been comprehensively studied for several decades [1-3]. Typically, a power amplifier is used for amplification of input signal to the required power level with less consumption of DC power. In modern communication systems, a high data transmission rate is used with high spectral efficiency. Because of advanced signal formats and new standards defined in modern communication, two major challenges are mostly considered for designing PA namely as effective and adequate amplification with high peak to average power ratio (PAPR) and the support of multi-carrier and wide BW.

In recent years, wireless communications systems are experiencing an expeditious growth due to the evolution in complementary metal-oxide-semiconductor technology (CMOS) [4-5], because CMOS technology has more advantages than the Gallium Nitride (GaN) and Gallium Arsenide (GaAs) technologies. The CMOS PA is an encouraging solution for modern communication devices based on low cost and low power. Over the last few decades, CMOS power amplifiers have been extensively used in several wireless communication applications, such as TV transmission, Radio Frequency Identification (RFID), phones, home automation, medical instrument, and industrial consumer electronics [6-8]. CMOS anticipating the integration of analog/digital/RF functions on a single chip at a very low cost [9-11].

An RF transmitter includes on digital to analog converter (DAC), a phase lock loop (PLL) / mixer, a local oscillator, a power amplifier (PA), and a band pass filter (BPF) [12-14] as shown in Figure 1.
The power amplifier is the most important module among all of these modules, because the performance of PA can significantly affect the overall performance of the RF transmitter [15-17].

2. Proposed Design of RF-PA

To increase the output power of an efficient PA, it is necessary many active devices used in parallel or push pull configuration. Push pull configuration provides the increased values of impedances at input and output. The balanced active devices with common emitter configuration can be provided good circuit symmetry. In this paper, a new design of class-E RF-PA which uses a combination of some different techniques proposed. The proposed schematic of high efficiency and high output power CMOS class-E PA with broadband output power matching network is depicted in Figure 2.

For the first transistor the current equation will be as;

\[ i_{c4} = \begin{cases} +I_c \sin(\omega t) & 0 \leq \omega t < \pi \\ 0 & \pi \leq \omega t < 2\pi \end{cases} \]  

For the second transistor the current equation will be as;

\[ i_{c3} = \begin{cases} 0 & 0 \leq \omega t < \pi \\ -I_c \sin(\omega t) & \pi \leq \omega t < 2\pi \end{cases} \]  

Two separate gate drive circuit is an advantageous approach in terms of switching time synchronization and controllability enhancement. Complementary MOSFET (Q1, Q2) performs RF signal amplification forming an efficient switching RF power amplifier followed by the LC broadband output power matching network for 50 \( \Omega \) load impedance. RF choke is used to isolate the applied VDD.
and RF signals it allows only the DC to pass through it block the RF frequency AC. \( V_{DD} \) at \( R_5 \) provides the gate drive voltage to CMOS adjusted by \( R_5 \) and \( R_4 \) voltage divider, using this voltage divider approach we eliminated the separate source for gate voltage. \( D_1 \) and \( D_2 \) are the protective diodes which act as an open switch for current when reverse biased and vice versa. The amplified signal through \( R_2 \) and \( R_3 \) is then finally matched to the load of 50 \( \Omega \) impedance producing our desired power output waveforms.

For obtaining a specifically required frequency response (S21 of the network) filters are used, which are generally described as linear networks. Filters are classified on the basis of their topology, nature, dissipation etc. Some important classifications of filters are analog/digital, lumped/distributed, reflective/absorbing, and low pass/high pass/band pass/notched/comb. After figuring out the suitable output matching network approach to achieve our targeted output, the calculation of lumped elements to design a passive bandpass matching network has to be carried out. In the bandpass filter type output matching approach we can transform the low-pass LC calculations into geometrically centered bandpass design this can be done by transforming the poles and zeros of the network and by frequency transformation having complex calculations. The basic and complex transformation functions are discussed briefly by various designers and authors [22-23] therefore we can discuss the transformation results used for the calculations of LC values for the required bandpass matching network step by step.

\[
\Omega_n = \frac{\omega_{SB} - \omega_{PB}}{\omega_{PB} - \omega_{PB}} \tag{3}
\]

\[
f_r = \sqrt{f_1 \cdot f_2} \tag{4}
\]

\[
T_{SB}(dB) = -10 \log_{10} \left( 1 + [\varepsilon^2 \Omega_n]^2N \right) \tag{5}
\]

\[
\Omega_{bp} = \frac{BW}{f_r} \tag{6}
\]

\[
L_{1n} \rightarrow L_{1b} = \frac{L_{1n}}{\Omega_p} ; \quad C_{1b} = \frac{C_1}{\Omega_p} \tag{7}
\]

- First, calculate the normalized stopband frequency \( \Omega_n \) as shown in equation (3) where \( \omega_{SB} \) and \( \omega_{PB} \) represent the stopband and passband frequency points.
- Calculate the resonant frequency \( f_r \) for wide band case which is the geometric mean of upper cutoff \( f_1 \) and lower cutoff \( f_2 \) frequencies equation (4).
- Find the stopband attenuation \( T_{SB} \) which is the attenuation of the power output at frequency other than the required band it can be calculated in dB as shown in equation (5) where \( N \) is the order of the LC sections in matching network.
- Select the normalized approximation values for LC \( (L_nC_n) \) at the required \( N \).
- Now evaluate \( \Omega_{bp} \) the normalize bandpass frequency variable value from low pass frequency variable equation (6).
- Take the approximated low-pass LC values \( (L_nC_n) \) and apply its transformation to bandpass LC sections by normalizing it with bandpass frequency variable \( \Omega_{bp} \) as shown in equation (6), so that first parallel \( C_n \) will transform into a shunt \( L_bC_b \) pair and a series \( L_n \) transform into series \( L_bC_b \) pair.
- Finally, denormalize the value of each element by the factor “\( 2\pi f_r \)” and by the required matching impedance (i.e. 50 \( \Omega \)).

### 3. Results and Discussions

The characteristics of class-E PA can be determined by finding its steady-state drain and current waveforms. The factor which contributes to decreasing the power amplification efficiency is the overlapping of drain voltage and current waveforms. The passive load network is designed to maximize efficiency by reducing the overlapping of the voltage and current waveforms. The drain of MOSFET \( (Q_2) \) is connected with supply voltage \( (V_{DD}) \) through an RF choke with high reactance at the fundamental frequency. The remarkable characteristic of our design is the complementary MOSFET synchronize switching from which we can obtain full cycle output, positive from N-MOSFET and
negative from P-MOSFET, in Figure 3 we can compare the current and voltage waveforms of an ideal class E amplifier and the final I-V waveforms of our complementary MOS PA. Final voltage and current waveforms has no phase overlapping assuring the maximum efficiency of the power amplifier.

![Waveform Images](a) (b)

**Figure 3.** (a) Ideal class E I-V waveforms. (b) Final full cycle I-V waveforms of our CMOS PA design.

After promising the proper functioning of our amplifier design satisfying the conditions for higher efficiency, the output signal which is the amplified RF signal is considered. RF and microwave engineers face problems in generating the desired amplified output because a good amplification pattern in case of high frequencies is challenging. In this work to obtain the required band with stable power, we must first assure the amplification performance of the power amplifier without proper matching. Figure 4 and Figure 5 depicts the output amplification performance at the desired central frequency (i.e. 8.2 MHz).

![Graph Images](a) (b)

**Figure 4.** Output power vs supply voltage. **Figure 5.** Supply voltage vs initial drain efficiency.

Filters with different responses around the transition between pass and stop bands are available for multiple applications, the most popular ones being Bessel, Butterworth, Gaussian, Chebyshev, and Elliptic. Our final design with an output impedance matching network has expected output results to be a stable waveform with -3dB band. It is expected to have the power waveform with a stable power range of around 15 watts within the required bandwidth of 1.4 MHz (7.5 MHz – 8.9MHz) with 0.1-0.5 Watt band tolerance. The power and its stability are especially under consideration for this design in order to fulfill the EAS system design requirements. Some important characteristics which define the performance of filter are Insertion loss (in-band signal attenuation), Phase linearity/group delay (quality of the phase response across the passband) Input/output impedance and VSWR (characteristic impedance and reflectivity of signals transmitted and rejected). It can be seen from Figure 6 the insertion loss for an ideal bandpass matching is near 0.1 dB insertion loss which indicates the best and efficient performance of the band matching. As shown in Figure 7 the final output is the same as the expected output. The final achieved output satisfied the requirements of our project and final design.
4. Conclusion
The designed power amplifier with a complementary MOS technique is a unique approach for the EAS system to make it more efficient and more accurate in the detection process. The stable power output level has been achieved with better efficiency. The complete implementation with design analysis, simulations, and PCB layout of the RF power amplifier for RF-based EAS systems has been made. The final outputs achieved and satisfied the requirement as desired. In future investigations hardware fabrication and its testing can be made to check the system performance and assurance. The designed RF power amplifier can be re-design with more features added in it such as band switching. We may apply some modifications in the recent design to introduce the switched band functionality which enables to match the power level for two different frequency bands so that it can be used in a variety of other applications as well.

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