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Second Harmonic Frequency Adjustment Strategy for Class-E Amplifier Design

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ABSTRACT- *Class-E* amplifiers are a type of switching amplifiers with an efficiency that approaches 100%. The harmonic frequency is very important in the design of *Class-E* amplifiers. In this study, the second harmonic frequency is considered in the design of a *Class-E* amplifier. The *Class-E* amplifier has been fabricated on FR4 and has demonstrated a power-added efficiency (PAE) of 74.5% at 1.01 GHz. This result shows that the termination of the second-harmonic output is essential for switching amplifiers.

Keywords: Class-E amplifier; High efficiency; Microwave circuit; Wireless power transfer.

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1. INTRODUCTION

Class-E amplifiers, introduced by Sokal and Sokal [1] in the 1970s, are high-efficiency switching-type amplifiers that minimize power loss in transistors. In an ideal scenario, these amplifiers can achieve 100% efficiency. The performance of Class-E amplifiers at high frequencies was theoretically elaborated by Rabb [2]. With the evolution of wireless communication technologies, the demand for low-power, high-efficiency amplifiers has been on the rise [3–8]. However, the adoption of these amplifiers is curtailed by their switching characteristics which necessitate the utilization of nonlinear transistor characteristics, potentially leading to signal distortion.

The field of wireless power transmission systems has been burgeoning, with numerous research studies applying Class-E amplifiers in innovative ways. Notably, [9] utilized a Class-E amplifier for the transmitter of a near-field wireless power transmission system. Chen et al. [10] employed a Class-E amplifier with a remarkable efficiency of 94% that was based on a GaN transistor for wireless power transmission. Strategies for the use of dynamic Class-E amplifiers to prevent efficiency degradation due to load fluctuations in wireless power transmissions were proposed in [11,12]. Furthermore, [13, 14] incorporated a Class-E amplifier into a wireless power transmission system designed to deliver energy to the human body instead of through air. Liu et al. [15] improved efficiency further by deploying a Class-E amplifier that leveraged resonance characteristics at 6.78 MHz for wireless power transmission. Recently, an innovative design technique employing artificial intelligence was introduced to streamline the complex design process of Class-E amplifiers [16].

Table 1. Recent Class-E amplifier research

	Detailed Findings	significance
[10]	Developed a wireless power transfer system that uses a Gallium Nitride (GaN) Class-E power amplifier, achieving a notable efficiency of 94%	Their work emphasized the potential of GaN-based Class-E amplifiers in high-performance wireless systems.
[11]	Proposed a complementary design approach for Class-E amplifiers in wireless power transfer systems.	dynamic configuration of Class-E amplifier for wireless power transfer system is proposed
[12]	Presented a novel design methodology that enhances the efficiency of both current-mode and voltage-mode Class-E power amplifiers.	Introduction to class E amplifier design techniques with constant efficiency despite changes in voltage and current.
[13]	Provided a tailored design and optimization strategy for Class-E power amplifiers used in capacitive coupled wireless power transfer systems for biomedical implants.	Proposed design of a class E amplifier bordering on a capacitor-based wireless power transfer system rather than an inductor.
[14]	Presented a comprehensive modeling and optimization approach for Class-E amplifiers operating at sub nominal conditions, which is particularly useful for biomedical implant applications.	This enhanced the adaptability of Class-E amplifiers in various operating conditions.

The standard design approach for Class-E amplifiers involves modelling transistors as switches and capacitors and maximizing efficiency through the adjustment of harmonic matching circuits. However, accurately modelling transistors with intricate structures using this method is challenging, especially in high-frequency circuits [17,18,19]. In this study, we employed simulations to design various Class-E amplifiers based on the common design method discussed in previous studies. We explored the design of a Class-E amplifier that remains functional even with errors in the transistor model and validated the effect of the designed amplifier. A transistor in a user-friendly package was utilized as the active component, and a standard Class-B amplifier was fabricated to affirm the impact of the Class-E amplifier.

2. THEORY

A switching amplifier, in an ideal scenario, is represented as a perfect switch with an impedance of '0' when the transistor is ON, and 'infinity' when it is OFF. However, the presence of resistance during the ON state of the transistor, along with various parasitic capacitors during both ON and OFF states, results in power loss. This resistance impedes the efficiency of switching amplifiers. Class-E amplifiers are designed to mitigate this issue by targeting the reduction of power loss within these circuits to enhance efficiency. Specifically, Class-E amplifier design concentrates on managing the energy stored in parasitic capacitors which are the key contributors to power loss at high frequencies. The power loss can be calculated as:

$$P_{loss} = V \times I^* \quad (P_{loss} \cong 0 \ at\ Class\ E) \qquad (1)$$

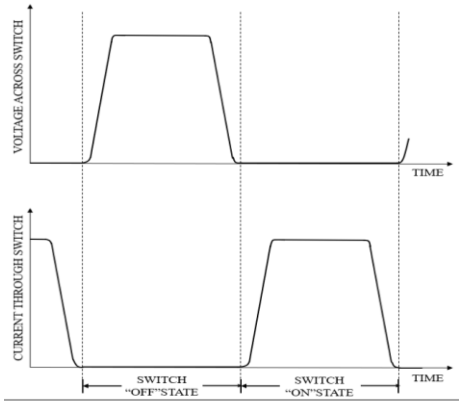


Figure 1: Waveform of voltage and current applied to an ideal Class-E amplifier device; As the waveforms of voltage and current do not overlap, there is no power loss inside the device [1]

The voltage and current waveforms for an ideal Class-E amplifier can be represented by the following equations:

$$v_d(\theta) = V_{DD} + V_{1m}\sin(\theta) + V_{3m}\sin(3\theta) + V_{5m}\sin(3\theta) \cdots \qquad (2)$$

$$I_d(\theta) = I_{DD} - I_{1m}\sin(\theta) - I_{2m}\cos(2\theta) - I_{4m}\cos(4\theta) \cdots \qquad (3)$$

Where
$v_d; Drain\ voltage$
$i_d: drain\ current$
$V_{dd}: DC\ of\ drain\ voltage$
$i_d : DC\ of\ drain\ current$
$\theta: wt$
$Vnm : n^{th}\ harmonic\ voltage$
$I_{nm} : n^{th}\ harmonic\ current$

v_d has a DC component and odd-order harmonic components, whereas i_d has a DC component, an operating frequency component, and even-order harmonic components. Therefore, the goal of a Class-E amplifier design is to eliminate even-order harmonics of the voltage and odd-order harmonics of the current. *Figure 1* shows the transistor voltage and current versus time curves for an ideal Class-E amplifier. The DC bias of the Class-E amplifier is the same as that of the Class-B amplifier. However, unlike Class-B amplifiers, Class-E amplifiers do not have an intersection of voltage and current waveforms; therefore, there is no energy loss inside the transistor.

3. DESIGN

The objective of this section was to design a Class-E amplifier that could attain maximum efficiency at a frequency of 1 GHz with an input power of 0 dBm. The transistor selected for this circuit design was FHX35LG, an HEMT packaged by Fujitsu. This particular device possesses a *Wg* of 280-nm and can operate up to ~18 GHz. Given these characteristics, it was inferred that the selected device would have a sufficiently minuscule parasitic capacitance at 1 GHz. Class-E amplifiers can be designed using a basic switch model [3] and by analyzing the waveforms of voltage and current. However, utilizing a simple switch model to determine the design methodology for a transistor of complex structure poses challenges and is prone to numerous simulation errors due to parasitic capacitors and inductors present because of the transistor device's packaging. Therefore, the Advanced Design System (ADS) - a simulator software popularly used by Keysight, was employed to discern a suitable design method for the chosen active device. Because the large-signal model of the FHX35LG provided by ADS differed from the measurement results offered by *Fujitsu*, the model was remodeled using the large-signal model of the FHX35X, an internal chip of the FHX35LG. The Class-E amplifier design methodology was investigated by segregating each frequency using an ideal filter. Harmonics higher than the 3rd order were not considered for this study. For the operating frequency, the input/output impedance was consistent with that of a Class-B amplifier. For the 2nd harmonic frequency, it was verified that the absolute value of the reflection coefficient of the optimal output impedance (*Figure 2* Γ_l) is '*1*', as reported in another paper [3], and its phase is contingent on the unique characteristics of the transistor (The optimal Γ_l phase for a packaged active device is challenging to define uniformly) Using the design method that was studied, the following amplifiers were designed:

Class-B: The circuit design was optimized to match the ideal input/output impedance, determined through optimization simulations and load-pull.

Class-E: The input and output impedance matched those of the Class-B amplifier at the operating frequency, and the Γ_l of the 2nd harmonic (*Figure 2*) had an absolute value of '*1*'. The phases were set at 45°, 90°,···, 360° (Various circuit designs were employed due to the simulation model's inability to adequately reflect the phase of the actual active element).

A Class-B amplifier was employed as the reference circuit to gauge the effect of adjusting the second harmonic. The Class-E amplifier was designed by fixing l_2 in *figure 2* to 45° at the operating frequency and only altering l_1.

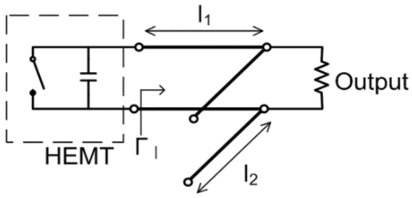


Figure 2: The design of a Class-E amplifier was achieved by fixing the length of l_1 to 45° at the operating frequency and adjusting l_2

4. MEASUREMENT RESULT

The operating frequency of the circuit was analyzed using Keysight's network analyzer N5230A. The S-parameter was measured by adjusting the output power of the network analyzer to 5 dBm in the pinch-off DC bias state of the circuit. All produced circuits demonstrated their maximum dB (S21) at the frequency of 1.01 GHz. At the confirmed operating frequency of 1.01 GHz, the efficiency of the circuit was measured with the equipment setup shown in *figure 3*. To minimize the measurement error, the power loss of cables, couplers, and bias tees at 1.01 GHz was measured in advance and reflected in the efficiency calculation. It was confirmed that the gain measured with the equipment configuration in *figure 3* showed an error of less than 0.5 dB from the value of dB (S21) measured using the network analyzer N5230A. Class-E amplifiers with different phases in the 2nd harmonic showed very different results, as demonstrated in *figure 2*. While there are circuits that exhibit higher efficiency than Class-B circuits, there are also circuits with significantly lower efficiency. These results were predicted in the simulation. *Figure 4* shows the measurement results of the circuits with the highest (Class E_max: $\angle\Gamma l$ @ 2 = 225°) and lowest efficiencies (Class E_min: $\angle\Gamma l$ @ 2 = 135°) and the Class-B amplifier. The efficiency is calculated as follows:

$$PAE = \frac{P_{out} - P_{input}}{P_{DC}} \times 100 \qquad (4)$$

In the optimal case, the efficiency of the Class-E amplifier increased by more than 15% compared with that of the Class-B amplifier [*Fig. 4 (a)*]. In addition, the circuit with high efficiency was also confirmed to have a large output power [*Fig. 4 (b)*]. This result demonstrates the characteristics of the Class-E amplifier, which fundamentally reduce power loss compared to those of the Class-C amplifier, which improves efficiency at the cost of a decrease in output power.

5. CONCLUSIONS

Unlike Class-A amplifiers, Class-B amplifiers leverage the non-linear characteristics of active elements. Therefore, harmonic signals greatly influence their circuit characteristics. A circuit type that utilizes this phenomenon to enhance its efficiency and output power is the Class-E amplifier. In this study, we investigated the design methodology of a Class-E amplifier and fabricated the corresponding circuit. The manufactured circuits only took into consideration the second harmonic; however, they demonstrated the characteristic traits of Class-E amplifiers, managing to increase their efficiency by 15% or more. As for future work, our plan is to extend our investigations beyond the second harmonic. We aim to develop a comprehensive design methodology that can account for the effects of higher-order harmonics. We believe this could further enhance the efficiency and broaden the application of Class-E amplifiers.

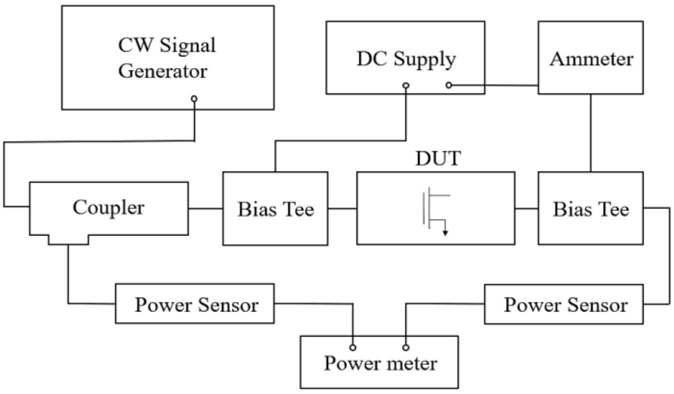
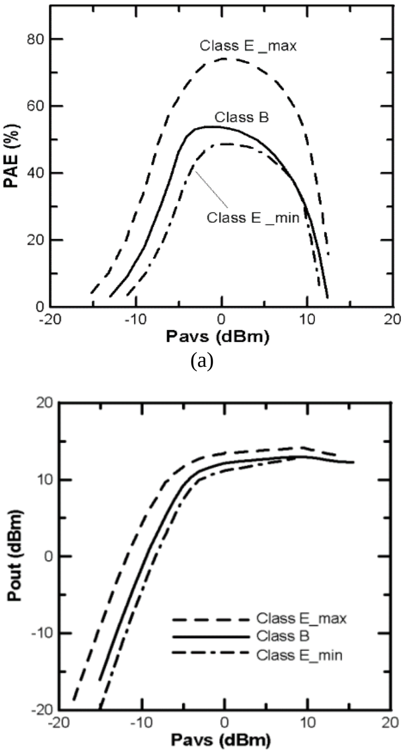


Figure 3: Set-up of laboratory equipment for measuring the efficiency of the amplifier. The power loss that occurs in coupler, bias tees and cables must be corrected



(a)

(b)

Figure 4: Measurement results of the manufactured Class-E and Class-B amplifiers. Efficiency and output power comparisons are according to the phase of the reflection coefficient of the second harmonic output matching circuit (Class E_max: Phase circuit with maximum efficiency,
Class E_min: Phase circuit with minimum efficiency)

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