Design of a Highly Efficient Broadband Class-E Power Amplifier with a Low Q Series Resonance

Dang-Duy Ninh · Ha-Van Nam · Hyoungjun Kim · Chulhun Seo[*]

Abstract

This work presents a method used for designing a broadband class-E power amplifier that combines the two techniques of a nonlinear shunt capacitance and a low quality factor of a series resonator. The nonlinear shunt capacitance theory accurately extracts the value of class-E components. In addition, the quality factor of the series resonator was considered to obtain a wide bandwidth for the power amplifiers. The purpose of using this method was to produce a simple topology and a high efficiency, which are two outstanding features of a class-E power amplifier. The experimental results show that a design was created using from a 130 to 180 MHz frequency with a bandwidth of 32% and a peak measured power added efficiency of 84.8%. This prototype uses an MRF282SR1 MOSFET transistor at a 3-W output power level. Furthermore, a summary of the experimental results compared with other high-efficiency articles is provided to validate the advantages of this method.

Key Words: Broadband, Class-E Amplifier, High PAE, Nonlinear Capacitance.

I. INTRODUCTION

Power added efficiency (PAE) was used to validate the performance of the power amplifiers that are required to reduce power consumption with the purpose of maximizing the battery life and increasing the system performance. The switch-mode amplifier structure has been proposed to obtain a high efficiency; however, each class (class-D, -E, -F, and inverse class-F) of switch-mode power amplifiers (PA) has different advantages and disadvantages, which should be carefully considered. The class-D PAs are popular switch-mode PA for audio and RF frequencies; however, this class exhibits a poor efficiency at high frequencies because the parasitic reactance of the device leads to substantial energy loss. The class-F and inverse class-F PAs utilize a method that controls the harmonic components when the device operates in a saturation region to reduce overlapping between current and voltage waveforms, but the number of harmonics should be controlled to improve the efficiency. As a result, the harmonic that controls a circuit becomes complex and large. The switch-mode class-E PAs with a shunt capacitor produced by Sokal and Sokal [1] have an efficiency that theoretically reaches up to 100%. The operation of the linear shunt capacitance MOSFET class-E PA is completely different in a theory than it is in practical use. Because the parasitic drain-to-source capacitance of the switching device, which significantly contributes to the overall shunt capacitance in the operation, is nonlinear, it is necessary to take into account the nonlinear characteristics of this capacitance. The analysis and design of a class-E PA with both a linear and nonlinear shunt capacitance, which was proposed by Suetsugu and Kazimier-czuk [2], included figures and tables that contained the results of the numerical analysis of a design equation. These results

were used to determine the values of the nonlinear shunt capacitance, the linear shunt capacitance, the series reactance of the resonant circuit, and the switch peak voltage; however, in some cases, it is impossible or inaccurate to calculate these parameters on the basis of the table and figures. The numerical analysis of the design equation determined by a program constructed in MATLAB is more exact than the value provided by the table and figures. For this work, the class-E power amplifier circuit was analyzed and designed by relying on the composition of the nonlinear and linear shunt capacitances to satisfy the zero-voltage switching (ZVS) and the zero-voltage-derivative switching (ZVDS) conditions, which ensure zero switching loss and low noise and improve component tolerances [3–5].

The role of a loaded quality factor of a series resonator module in class-E performance was also considered. A high value for the figure of merit is suitable for narrow bandwidth applications in which the harmonic content of the output is important. In contrast, low quality factor circuits are appropriate for applications in which the harmonic suppression of the output is not important. Typical applications include high-efficiency DC/DC converters; a radio-frequency energy supplies for heating, for the generation of plasmas, arcs, or sparks, and for communication jamming; or input drivers of a higher power stage [6]. In designing the class-E, the high quality factor of a resonant network has a limited frequency response. In some studies [7–9], the series LC resonator has been substituted by low pass or band pass matching networks to solve this limitation. Furthermore, the loaded quality factor of the resonant circuit has been reduced sufficiently to extend bandwidth operations and to reduce the sensitivity of amplifier performance to the values of resonator circuit elements [10]. A trade-off between bandwidth and the harmonic content of the output depending on the value of the quality factor is presented in this paper.

II. CURCUIT ANALYSIS AND PARAMETERS

Suetsugu and Kazimierczuk [2] presented a set of design equations for the class-E amplifier composed of both a nonlinear capacitance and a linear capacitance, which can be applied to real design; however, the results provided by the figures and tables in his paper are only considered in some discrete specifications. Therefore, instead of relying on his research results, the MATLAB program was built to solve design equations at our specifications. Furthermore, this study also illustrates the relationship between the frequency and the shunt capacitance in detail.

A circuit of the class-E amplifier is illustrated in Fig. 1, which shows a DC-supply voltage V_{DS}, a DC-feed inductor L_{RFC}, a MOSFET transistor as a switching device, a series resonant filter RLC, a shunt capacitance consisting of a MOSFET
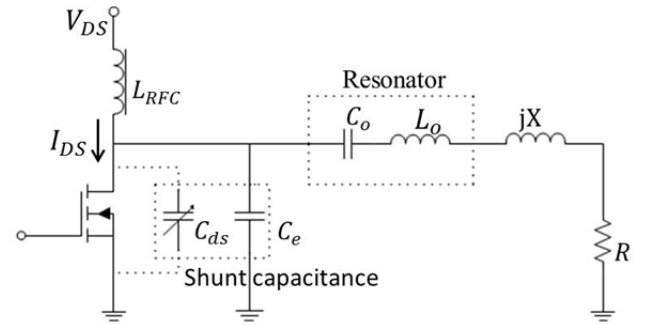

Fig. 1. Class-E power amplifier circuit.

drain-to-source capacitance C_{ds}, and an external linear capacitance C_e. The total shunt capacitance of the class-E power amplifier circuit is described by the following equation:

$$C_{shunt} = C_{ds} + C_e = \frac{C_{j0}}{\sqrt{1+\frac{v_S}{V_{bi}}}} + C_e \tag{1}$$

where C_{j0} is the shunt capacitance at the drain-to-source voltage $v_S = 0$, and V_{bi} is the built-in potential of the MOSFET body diode.

The switch voltage is supposed to satisfy the ZVS condition at the turn-on time. Since the dc component of the voltage dropping across the choke inductor L_{RFC} is zero, the average value of the switch voltage is equal to the dc supply voltage V_{DS}, which is expressed as follows:

$$V_{DS} = \frac{1}{2\pi}\int_0^{2\pi} v_S(\theta)d\theta \tag{2}$$

where v_S is the drain-to-source voltage when the switch is off, i.e. $0 < \theta = \omega t \le \pi$, and it can be extracted from the integration of the drain current equation:

$$\omega\int_0^{v_S}(\frac{C_{jo}}{\sqrt{1+\frac{v_S}{V_{bi}}}}+C_e)dv_S = \int_0^{\theta} i_C d\theta. \tag{3}$$

By partly expanding Eq. (2):

$$\frac{V_{DS}}{V_{bi}} = \frac{\delta}{\pi}[\pi(\delta+\beta\sin\phi\cos\phi+1)+\beta(\frac{\pi^2}{2}+2)\sin^2\phi]$$
$$-\frac{\delta}{\pi}\int_0^{\pi}[\delta^2+2\delta+1+2\delta\beta\sin\phi\cos\phi+2\delta\beta\theta\sin^2\phi$$
$$-2\delta\beta\sin\phi\cos(\theta+\phi)]^{\frac{1}{2}}d\theta \tag{4}$$

where

$$\beta = \frac{V_{DS}}{2\pi f_0 RC_{j0}V_{bi}} \tag{5}$$

$$\delta = \frac{C_{j0}}{C_e} \tag{6}$$
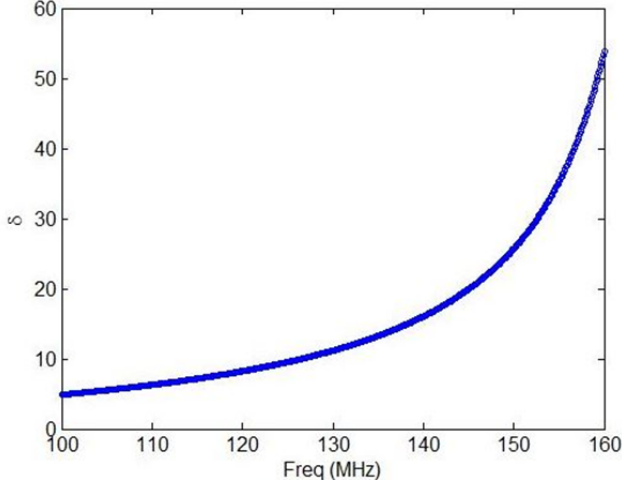
Fig. 2. δ versus f with given parameters of V_{DS} and P_0.

Fig. 3. Completed class-E power amplifier circuit.

ϕ is the phase difference between a sinusoidal input current and a sinusoidal load current.

Because Eq. (4) does not have an analysis solution, a nonlinear function of the optimization toolbox of MATLAB was used to solve this equation. The key function of the MATLAB program used to solve a system of nonlinear equations is "*fsolve*", for which the inputs are a nonlinear function $fun(x)$ and a starting point x_0. It will attempt to solve the equation $fun(x) = 0$ from the starting point x_0. Its output is the solution of the nonlinear equation $fun(x) = 0$. In this work, the nonlinear equation used was Eq. (4) with a variable δ. The inputs of Eq. (4) are parameters including the supply voltage V_{DS}, the output power P_o, and the parameters V_{bi} and C_{j0} of MOSFET which are defined by particular specifications. By sweeping the value of the operating frequency f_0, the results of the MATLAB program will show the relationship between the external capacitance C_e and the operating frequency f_0. The solution is plotted in Fig. 2, which depicts the dependence of δ on the operating frequency f_0 given the supply voltage V_{DS} of 8 V and the output power P_o of 3 W. Particularly, when the frequency increases, the ratio δ will increase corresponding to a reduction of the external capacitance. At the maximum frequency, the ratio δ will be infinite, and the shunt capacitance is solely composed of the nonlinear parasitic capacitance. Based on Fig. 2, the ratio δ at the specific frequency of 155 MHz can easily be determined. Then, the external capacitance C_e can be obtained by calculating the junction capacitance C_{j0}, as shown by the following equation:

$$C_{j0} = (C_{oss} - C_{rss})\sqrt{1 + \frac{V_{spec}}{V_{bi}}} \tag{7}$$

where C_{oss} and C_{rss} are the output capacitance and the reverse transfer capacitance of the transistor, respectively, which are often provided in the catalogs by the manufacturers of power
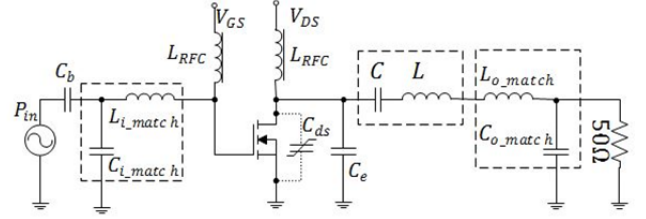
MOSFETs, and V_{spec} is a special value of supply voltage used to measure the value of C_{oss} and C_{rss}. The component values of the class-E circuit in Fig. 1 can be obtained using the following equations:

$$R = \frac{8V_{DS}^2}{(\pi^2 + 4)P_o} \tag{8}$$

$$X = R\tan(\phi + 0.567) \tag{9}$$

$$L = \frac{RQ}{\omega} \tag{10}$$

$$C = \frac{1}{\omega(RQ - X)} \tag{11}$$

$$L_{RFC} = 2(\frac{\pi^2}{4} + 1)\frac{R}{f_0} \tag{12}$$

where Q is the loaded quality factor.

Based on the analysis results, the schematic of the completed class-E PA circuit is modeled in Fig. 3. In this circuit, the output matching network is constructed by L_{o_match} and C_{o_match} to shape the output voltage and current for minimum power loss; L_{i_match} and C_{i_match} constitute the input matching network that only has a slight effect on the overall circuit performance. The voltage current simulation waveforms depicted in Fig. 4 under the optimum operation slightly overlap, which results in a minimized power dissipation on the transistor. The voltage across the switching device is presumed to satisfy the ZVS and ZVDS conditions.

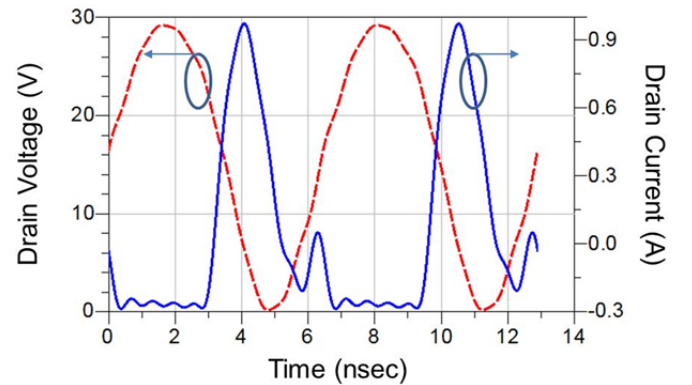In the design of a broadband class-E PA with a shunt capa-

Fig. 4. Drain current and voltage simulation waveforms of class-E power amplifier circuit.

citance, the value of the optimal shunt capacitance changes at different frequencies, whereas the external capacitance is constant. Thus, an optimal state is impossible to obtain at every frequency. In this work, the value of the external capacitor was selected to approximately satisfy the switching conditions for the whole band.

III. BROADBAND CLASS-E PAS WITH A LOW Q RESONANCE

Some studies have investigated the role of quality factor Q in a resonant circuit and filter networks [11], in a gigahertz operation of a CMOS class-E power amplifier [12], and in a common design of an output network power amplifier [13]. In this research, the role of the loaded quality factor has been investigated and validated for the MOSFET class-E with a nonlinear shunt capacitance. This work focused on the relationship between the bandwidth and the quality factor as well as the trade-off between the bandwidth and the harmonic suppression of a series RLC resonant circuit. In a series resonant circuit, the bandwidth measured between 70.7% amplitude points of a series resonant circuit in terms of a loaded quality factor, and the resonant frequency f_c is described by:

$$BW = \frac{f_c}{Q}. \tag{13}$$

A high quality factor resonant circuit has a narrow bandwidth, which is different from a low quality factor. This relationship is expressed in detail in Fig. 5.

The nonlinear shunt capacitance class-E shown in the previous section was optimized for the narrow band design, as the loaded quality factor of the output resonant circuit is high enough that the output current would be considered a sine wave; however, because the loaded quality factor has finite and sufficiently small values with the assumption of harmonic distortion in the output signal, the efficiency increases by several percentage points [12]. As a result, the range of the value of the loaded quality factor is from 5 to 10 to obtain a high efficiency and a linearity at a single frequency [10].

For this work, the operating bandwidth of the MOSFET class-E power amplifier was attempted to be extended by decreasing the value of the loaded quality factor to below the conventional values. In Fig. 6, the simulated output power sweep, containing fundamental, second, and third harmonics, is plotted as a function of the loaded quality factor. This result is based on the conditions of an operating frequency of 155 MHz, a supply voltage of 8 V, a MRF282SR1 MOSFET, an expected output power of 3 W (34.7 dBm), and without matching components. At different values of the low loaded quality factor, the components of the class-E power amplifier were approximately ex-
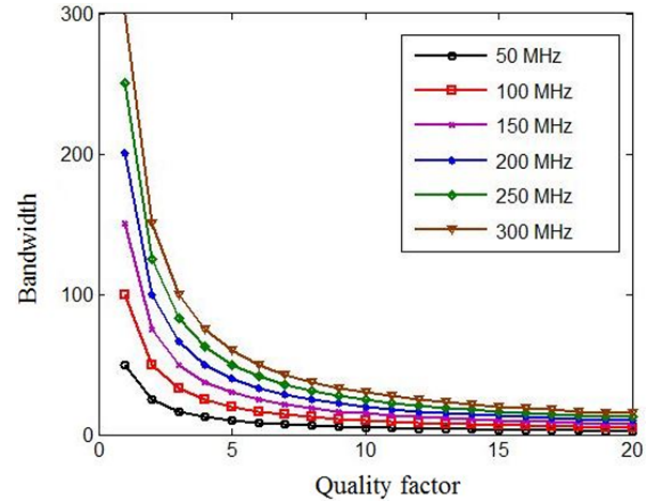

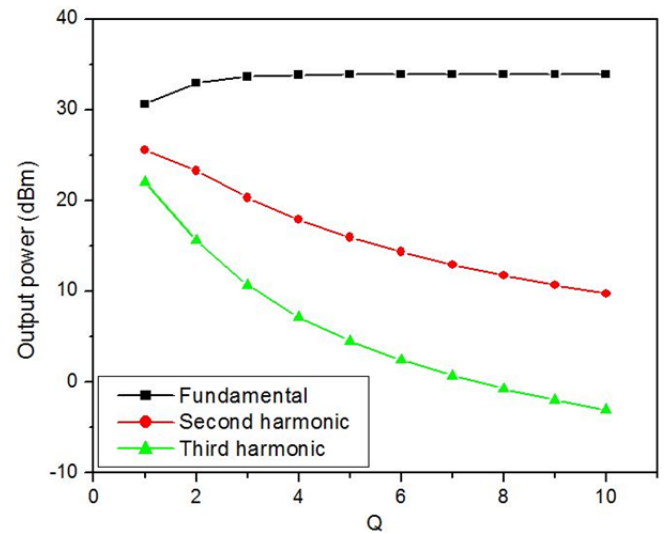Fig. 5. The bandwidth as a function of Q for selected f_c.

Fig. 6. The output as a function of Q.

tracted from Eqs. (8)–(11). As a result, the fundamental output power cannot be achieved as expected at a low Q due to the high harmonics. In addition, the compromise between the bandwidth and the harmonic suppression depends on the specific application.

The topology of the class-E power amplifier for a wide bandwidth is similar to that of a single frequency as shown in Fig. 3; however, a wider bandwidth should be considered for quality factor of the input and output matching networks. A matching high-Q termination leads to narrow bandwidths.

IV. CIRCUIT DESIGN AND MEASUREMENT

The proposed class-E power amplifier circuit was designed using a MRF282SR1 MOSFET transistor. The specifications of this design contain the output power of 3 W or 34.7 dBm and a bandwidth of 130 MHz to 180 MHz, which can be applied for Public and Homelands Security Applications [18].
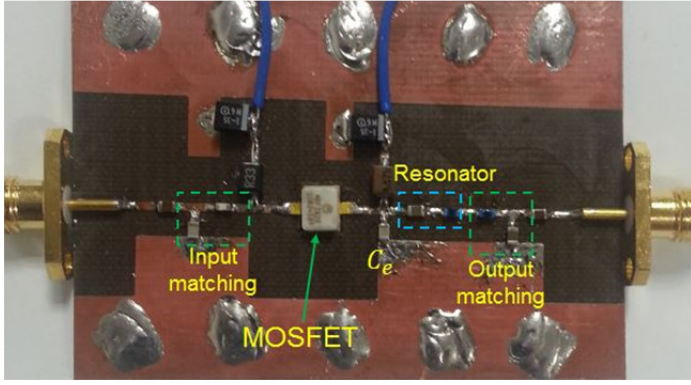
Fig. 7. Photograph of fabricated class-E power amplifier circuit.

Using Eq. (13), the value of the loaded quality factor is equal to 3.2. Based on the analysis in Section II, the calculations, simulations, and measurements of the component values were obtained and are shown in Table 1. The optimized values for accumulating the highest efficiency in the measurements caused the slight difference from the calculated component values. Fig. 7 presents a photograph of the prototype. The output power was measured using an Agilent 8565EC spectrum analyzer, which has a maximum measurement output of 30 dBm. An attenuator of −39.5 dB was added to the end of the circuit. The peak output power and PAE were achieved at 34.3 dBm and 84.8%, respectively, over a bandwidth from 130 MHz to 180 MHz. The drain and gate voltages were set to 8 V and 3.2 V, respectively. The power attenuation of the measured results occurred due to the relatively high harmonic output signal caused by the low loaded quality factor Q of the series resonant circuit. The measured value of Q is also verified by the following formula:

$$Q = \frac{2\pi f_0 L}{R} \tag{14}$$

where R is approximately extracted by Eq. (8) with a measured output power P_o. The calculated, simulated, and measured values of Q are shown in Table 1. The output power and PAE

Table 1. Component values of class-E circuit in calculation theory, simulation and measurement

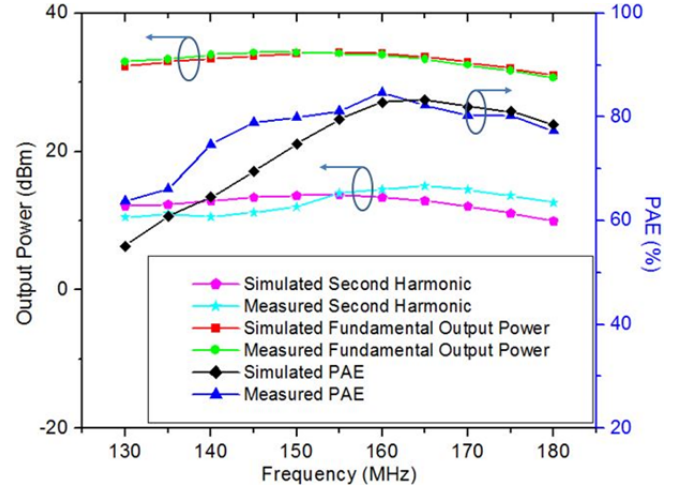| Component	Calculation	Simulation	Measurement
C_e (pF)	1.3	1.3	1.5
C (pF)	46	46	51
L (nH)	38	38	39
L_{RFC} (nH)	450	450	450
L_{o_match} (nH)	-	15	9
C_{o_match} (pF)	-	24	33
L_{i_match} (nH)	-	54	39
C_{i_match} (pF)	-	3.4	3.4
Q	3.2	3.4	3.3

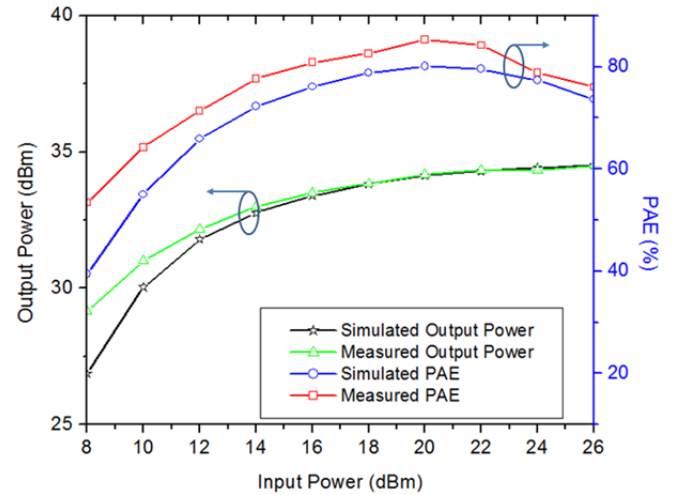Fig. 8. Output power and PAE as a function of frequency at P_{in} = 22 dBm.

Fig. 9. Output power and PAE as a function of input power at f_0 = 155 MHz.

versus the frequency and input power P_{in} are plotted in Fig. 8 and Fig. 9, respectively. The simulated results were obtained using the results in the previous sections without any optimization; however, during implementation, the design was optimized to achieve the best performance. Therefore, the measured results are better than the simulated results. The experimental results compared with other articles are summarized in Table 2.

V. CONCLUSION

This paper has presented a practical broadband class-E PA circuit which was designed using the combination of a nonlinear shunt capacitance and a low quality factor of series resonator. This method showed a high performance in designing broadband PAs for application at the VHF band. The validated design was developed using 130–180 MHz with a peak PAE of 84.8% and a peak output power of 34.3 dBm. Two outstanding

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Table 2. Comparative results

Ref.	Year	Frequency (MHz)	BW (MHz)	P_{out} (dBm)	Efficiency (%)	PAE (%)	Transistor
[14]	1987	130–180	50	37.8	60.0	-	MOSFET
[15]	2001	100–200	100	41.5	70.0	-	MOSFET
[16]	2008	136–174	38	39.0	74.0	-	MOSFET
[17]	2008	135–175	40	38.1	70.0	-	MOSFET
[18]	2010	140–170	30	33.9	-	72.5	GaN HEMT
[19]	2010	134–174	40	37.4	71.0	-	MOSFET
This work		130–180	50	34.3	90.5	84.8	MOSFET

GaN HEMT=gallium-nitride high electron mobility transistor.

advantages of the class-E PA with a shunt capacitance, which are a high efficiency and a simple topology, have been illustrated in this work.

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