A High-Efficiency Class-E Power Amplifier with Wide-Range Load in WPT Systems

Shuangke Liu, Ming Liu, Minfan Fu, Chengbin Ma and Xinen Zhu*
University of Michigan-Shanghai Jiao Tong University Joint Institute
Shanghai Jiao Tong University, Shanghai, China 200240

***Abstract*—A high-efficiency power amplifier (PA) is important in a Megahertz wireless power transfer (WPT) system. It is attractive to apply the Class-E PA for its simple structure and high efficiency. However, the conventional design for Class-E PA can only ensure a high efficiency for a fixed load. It is necessary to develop a high-efficiency Class-E PA for a wide-range load in WPT systems. A novel design method for Class-E PA is proposed to achieve this objective in this paper. The PA achieves high efficiency, above 80%, for a load ranging from 10 to 100 Ω at 6.78 MHz in the experiment.**

***Index Terms*—Wireless power transfer, Class-E power amplifier, wide-range load, load-pull, impedance transformation**

I. Introduction

WIRELESS power transfer (WPT) makes it possible for people to get rid of messy wires, providing great convenience for users. It can have larger spatial freedom by increasing the system frequency to Megahertz [1], enabling concurrent charging for multiple devices. Usually, such a system is driven by a power amplifier (PA). One significant challenge for the WPT systems is the load variation for PA, which is mainly caused by the changes of coils' positions or the number of loads. For example, in [2], the load seen by PA increases as the number of charging devices increases. Based on such a system, it is promising that the PA can provide increasing output power with the increase of PA's load. Therefore, it is necessary to develop a reliable power amplifier, which can provide adequate power with high efficiency for a wide-range load.

The Class-E PA is first introduced by Sokal and Sokal in 1975 [3]. It is attractive to be used in MHz WPT system for its high efficiency and simple structure [4], [5]. The Class-E PA achieves high efficiency, approaching 100% theoretically, when the circuit satisfies zero voltage switching (ZVS) condition and zero voltage derivative (ZDS) condition [6]. However, the design is only valid for a fixed load. The efficiency decreases quickly once the load deviates from the optimal value and the output power is not proportional to the load. In [7], [8], fixed circuit components are replaced by tunable components to increase the PA efficiency when the load of PA varies. However, it requires additional tuning, detection, and control circuits, which inevitably increases the system complexity. This paper proposes an approach to design a high-efficiency Class-E PA by optimizing the circuit structure and parameters. No control system is required. The efficiency keeps high for a wide-range load and the output power increases with the load of PA increasing. It is believed that this PA is suitable for high frequency WPT applications, especially for those systems with multiple charging devices.

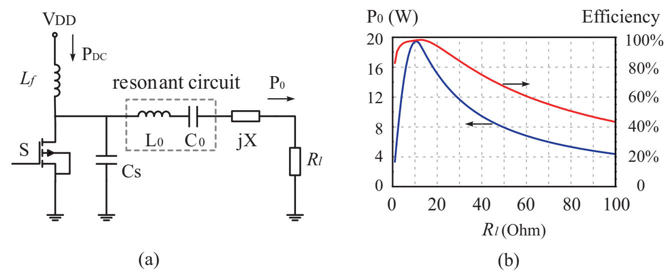


Fig. 1. Basic Class-E power amplifier. (a) Topology of Class-E PA. (b) The output power and efficiency for different R_l

In this paper, a novel design method is proposed to design a high-efficiency Class-E PA working in a wide load range. In Section II, a traditional design for Class-E PA is given and the requirements for PA design are presented. Then in Section III, the circuit tuning methods and impedance transformation network are presented to achieve the objectives based on simulations. Finally, the proposed design method is validated in the experiment in section IV.

II. Class E power amplifier analysis

Fig. 1 (a) shows a general circuit configuration of a Class-E PA. It consists of a DC supply V_{DD}, a RF choke L_f, a switch S, a shunt capacitor C_S, a series resonant circuit L_0C_0, a pure reactance jX and a load R_l. P_0 is the output power of PA and P_{DC} is the input power of DC supply. The PA efficiency equals to the ratio of P_0 and P_{DC}. In order to maximize the PA efficiency, R_l, C_S and X are determined by the following equations (1) - (3), which have been proposed by [6].

$$R_l = \frac{8}{\pi^2+4}\cdot\frac{V_{DD}^2}{P_0} \approx 0.5768\frac{V_{DD}^2}{P_0} \tag{1}$$

$$C_S = \frac{8}{\omega\pi(\pi^2+4)R_l} \approx \frac{0.1836}{\omega R_l} \tag{2}$$

$$X = \frac{\pi(\pi^2-4)}{16}R_l \approx 1.1525R_l \tag{3}$$

A simulation is set up according to Fig. 1 (a). Choose $V_{DD} = 20$ V, $P_0 = 19.2$ W and set the operation frequency 6.78 MHz. The circuit parameters are derived from (1) - (3).

The model of SUD06N10 (N-Channel MOSFET) is used and the inductors and capacitors are ideal in the simulation. Fig. 1 (b) shows the output power and efficiency for different R_l. This PA can only work efficiently within a narrow load range and the output power is not proportional to R_l.

This PA is further analyzed by the load-pull simulation and the results are illustrated on a Smith chart (see Fig. 2). The constant efficiency contours and output power contours are given to provide a overview of PA performance for arbitrary load. The load variation line presents R_l varying from 1 to 100 Ω. Only a small section of this line locates within high efficiency region and the load variation line have two intersection points with some constant output power contours, which are consistent with the results of Fig. 1 (b). If all the loads for PA locates within the high efficiency region, the efficiency will keep high for all these loads. If the all the loads for PA constitute a load variation line, which has no more than one intersection point with each constant power contour and the load increases along the direction of output power increasing, the output power will increase monotonically as the load increases. So a impedance transformation network is required to transform R_l to the desired region.

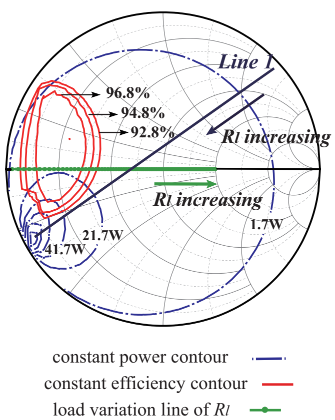


Fig. 2. Constant contours on the Smith chart.

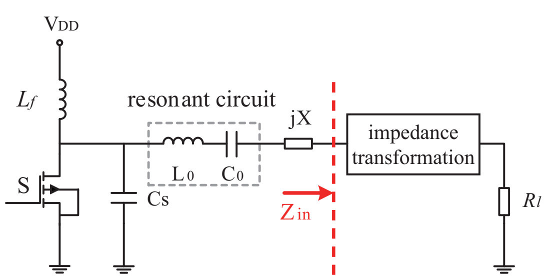


Fig. 3. The Class-E PA with impedance transformation network

As is shown Fig. 3, the input impedance Z_{in} is the equivalent load for Class-E PA and it depends on R_l. If all the Z_{in} locate within the high efficiency region, the PA efficiency will keep high for a wide-range R_l. If all the Z_{in} forms a load variation line like Line 1 in Fig. 2, along which the corresponding R_l increases, the output power will increase monotonically as R_l increases.

The objective of PA design in this paper is to achieve high-efficiency power delivering when R_l varies in a wide range and realize increasing output power with increasing R_l. In order to achieve these goals, two steps are required to achieve this objective:

1) Find a line located within the high efficiency region and having the characteristics of Line 1 by tuning C_S.
2) Design a impedance transformation network to make the load variation line of Z_{in} match the line obtained form step 1 as much as possible.

III. System Realization

A. Tuning the shunt capacitor C_S

After numerous simulations and comparisons, it is noticed that C_S is the most suitable to modulate the constant contours and the line satisfying the requirements. As is shown in Fig 4, the high efficiency region expands and the desired line rotates clockwise when C_S decreases. The output power for the load within high efficiency region decreases. In this paper, C_S is set to be 180 pF and Line 2 in Fig. 5 is selected as the ideal load variation line.

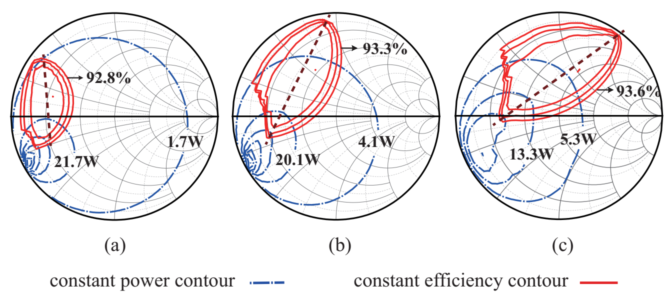


Fig. 4. Constant contours for different C_S. (a) C_S = 358.7pF. (b) $_S$ = 180 pF. (c) C_S = 60 pF.

B. Impedance Transformation

The Π topology is widely used for impedance transformation and it can satisfy the requirements of impedance transformation in this paper. The topology of Π network is shown in Fig. 6 (a). The target of the network design is to make the load variation line of Z_{in} match Line 2 in Fig. 5 as much as possible.

Line 2 can be represented by: $\Gamma_{imag} = 1.86\Gamma_{real} + 1$, $\Gamma_{real} \in (-0.7, 0)$, $\Gamma_{imag} \in (-0.3, 1)$. For the fixed X_1, X_2 and X_3, the reflection coefficient Γ_Z of Z_{in} depends on R_l and the relationship between $\Gamma_{Z,imag}$ and $\Gamma_{Z,real}$ is obtained. X_1, X_2 and X_3 should ensure that the relationship between $\Gamma_{Z,imag}$ and $\Gamma_{Z,real}$ approximates the representation of Line 2 as much as possible when R_l varying from 1 to 100 Ω. The numerical method can provide a prediction for X_1, X_2 and X_3. Further modulation by manual are necessary to ensure the load variation line match Line 2 as much as possible. In this paper, X_1, X_2, X_3 are set to be $-j37$, $j27.2$ and $-j75.7$, respectively.

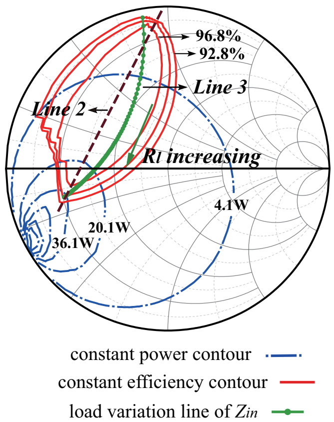
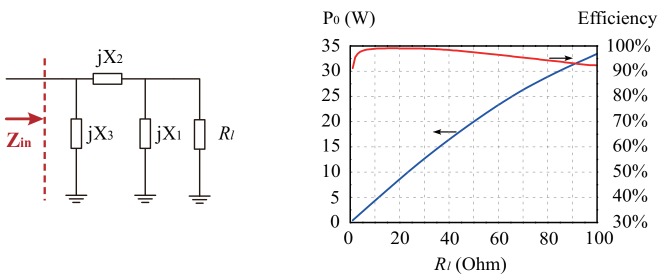


Fig. 5. Constant contours after tuning C_S. Line 2: the ideal load variation line. Line 3: the load variation line for Z_{in}.



(a) (b)

Fig. 6. Adding a Π network. (a) The topology of Π network. (b) The PA performance with Π network.

Line 3 in Fig. 5 is the load variation line of Z_{in}. It locates within the high efficiency region and along it the output power increases with the increase of R_l. The PA performance for the final system is depicted in Fig. 6 (b). The efficiency keeps high for the load varying in a wide range and the output power is approximately proportional to R_l.

IV. Experimental verification

The proposed Class-E PA is fabricated on a FR-4 substrate with thickness of 1.6 mm. The prototype of the fabricated Class-E PA is illustrated in Fig 7. SUD06N10 is used and operates as a switch. The value of components on the board is illustrated in Table I. The driving circuit provides a 6.78 MHz square wave as the driving signal with 50% duty ratio and amplitude of 5 V. V_{DD} is set to be 20 V in the experiment. The test results are shown in Fig 8. The efficiency is not as high as that in the simulation because of the parasitic resistance in circuit. The experiment validates the feasibility of this design method: high efficiency for a wide-range load and increasing output power with increasing load.

V. Conclusion

In this paper a novel design method is proposed to design a high-efficiency Class-E PA working in a wide load range. The design bases on load-pull technique and impedance transformation technique. As a result, the output power of Class-E power amplifier is approximately proportional to the load and the efficiency keeps high even when the load varies in a wide range.

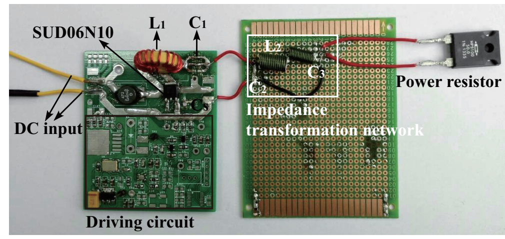
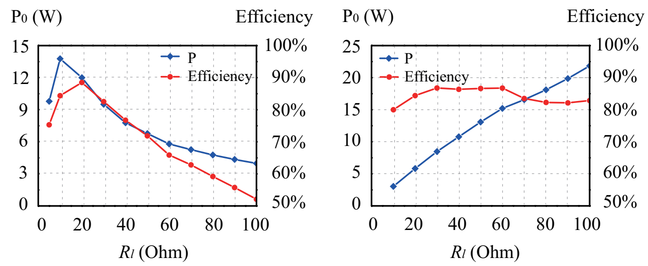


Fig. 7. The prototype of the fabricated Class-E PA

TABLE I
The value for each component on the board

Cs (before tune)	Cs (after tune)	L1	C1	L2	C2	C3
340pF	180pF	2.62μH	240pF	820nH	310pF	490pF



(a) (b)

Fig. 8. Measurement results. (a) Measurement results for traditional Class-E PA. (b) Measurement results for Class-E PA based on the design method of this paper.

References

[1] M. Fu, H. Yin, X. Zhu, and C. Ma, "Analysis and tracking of optimal load in wireless power transfer systems," *Power Electronics, IEEE Transactions on*, vol. PP, no. 99.

[2] T. Zhang, M. Fu, C. Ma, and X. Zhu, "Optimal load analysis for a two-receiver wireless power transfer system," in *Wireless Power Transfer Conference (WPTC), 2014 IEEE*. IEEE, 2014, pp. 84–87.

[3] N. O. Sokal and A. D. Sokal, "Class e - a new class of high-efficiency tuned single-ended switching power amplifiers," *Solid-State Circuits, IEEE Journal of*, vol. 10, no. 3, pp. 168–176, 1975.

[4] P. Srimuang, N. Puangngernmak, and S. Chalermwisutkul, "13.56 mhz class e power amplifier with 94.6% efficiency and 31 watts output power for rf heating applications," in *Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2014 11th International Conference on*. IEEE, 2014, pp. 1–5.

[5] W. Chen, R. Chinga, S. Yoshida, J. Lin, C. Chen, and W. Lo, "A 25.6 w 13.56 mhz wireless power transfer system with a 94% efficiency gan class-e power amplifier," in *Microwave Symposium Digest (MTT), 2012 IEEE MTT-S International*. IEEE, 2012, pp. 1–3.

[6] M. Albulet, *RF power amplifiers*. SciTech Publishing, 2001.

[7] S. Aldhaher, P. C. Luk, and J. F. Whidborne, "Wireless power transfer using class e inverter with saturable dc-feed inductor," in *Energy Conversion Congress and Exposition (ECCE), 2013 IEEE*. IEEE, 2013, pp. 1902–1909.

[8] S. Aldhaher, P. Luk, and J. Whidborne, "Electronic tuning of misaligned coils in wireless power transfer systems," *Power Electronics, IEEE Transactions on*, vol. 29, no. 11, pp. 5975 – 5982.