Progress In Electromagnetics Research C, Vol. 35, 13–22, 2013

A CLASS E POWER AMPLIFIER WITH COUPLING COILS FOR A WIRELESS POWER TRANSFER SYSTEM

Jong-Ryul Yang[1, 2, *], Hyeon-Chang Son[1, 2], and Young-Jin Park[1, 2]

[1]Advanced Medical Device Research Center, Korea Electrotechnology Research Institute (KERI), 111, Hanggaul-ro, Sangnok-gu, Ansan-city, Gyeonggi-do 426-910, Korea

[2]Department of Electrical Equipment Information and Communications Engineering, University of Science and Technology, 217, Gajeong-ro, Yuseong-gu, Daejeon 305-350, Korea

Abstract—A class E power amplifier including coupling coils is proposed for application in a wireless power transfer system using magnetic coupling. The proposed amplifier is directly connected to the coils with no discrete components for harmonic filtering and dc feeding, which could cause efficiency degradation of the amplifier. The system with the differential amplifier shows 6.95 W of transmitted power and 44.6% transmission efficiency at 6.8 MHz with 14-cm distant coils. The power-added efficiency of the amplifier is 92.1% with a 14 V supply voltage, excluding the coupling efficiency of the wireless power transfer network.

1. INTRODUCTION

A wireless power transfer (WPT) system transfers and receives electric power wirelessly. It removes the constraint of a power cord from electrical devices, circumvents aesthetic issues related to the cord, and protects against the risk of fire or destruction of electronics due to unwanted short-circuit of the devices [1, 2]. WPT systems are classified into three areas according to frequency range, quality factor of the WPT network, method of transferring the energy, and other factors: use of inductive coupling, resonant coupling, and radiative transmission [3]. Notably, systems using resonant coupling on the HF

Received 9 October 2012, Accepted 21 November 2012, Scheduled 25 November 2012
* Corresponding author: Jong-Ryul Yang (net10226@keri.re.kr).

bands can transfer power over a longer range than those using inductive coupling. They also have higher efficiency than those using radiative transmission [4, 5].

The transmitted power and transmission efficiency are important factors in the WPT system [6]. A class E amplifier is used as the general circuit topology of a power transmitter in a WPT system on the HF bands because it can obtain high output power and theoretically 100% power added efficiency (PAE) with a simple design [7]. However, the PAE is degraded by the switching transistor on-resistance, losses in the output filter and matching network, and discrete components for the dc feed and additional output capacitance [8]. In addition, it is practically difficult to optimize the performance of the amplifier on these bands due to the restriction of the components in high power applications [9].

This paper proposes a class E power amplifier (PA) for use in a WPT system. The amplifier with a WPT network, which is composed of source and load coils and two resonant coils, can eliminate discrete components for harmonic rejection filters and dc feed inductors. The degradation of the PAE is accordingly minimized. The differential amplifier operating at 6.8 MHz is implemented using LDMOS transistors and passive components, which are for input matching and additional output capacitance.

2. ARCHITECTURE OF THE POWER AMPLIFIER WITH A WPT NETWORK

The proposed differential amplifier consists of a passive balun, input matching blocks, power transistors, and the WPT network as shown in Fig. 1. The drain of the transistors is directly attached to the source coil of the network, and the supply voltage is applied to the center of the coil. The output power in each transistor is combined in the coil. The harmonics are decreased in the output without an additional filter because the network can be described as a band-pass filter with a high quality factor in a class E operation. Power loss in the drain node is also decreased in the amplifier. Because of the reduction of the passive components, a highly efficient amplifier is obtained.

The coupling efficiency η can be expressed with S-parameters of the WPT network as

$$\eta = |S_{21}|^2 \times 100. \tag{1}$$

The measured S-parameter of the WPT network cannot be used in the proposed amplifier due to the impedance mismatch between the input and output of the network. The output impedance R_o shown in Fig. 1 is fixed to 50 ohms. The input impedance of the WPT network is defined

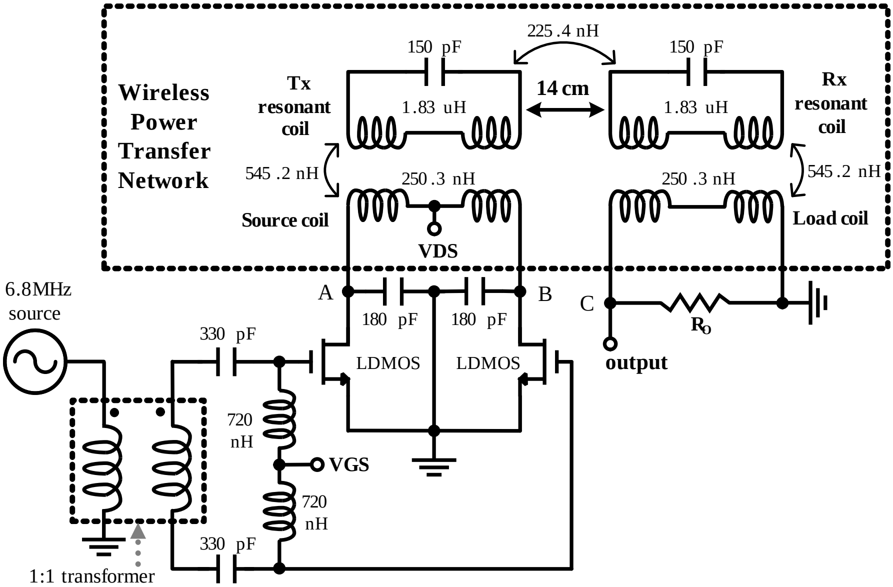


Figure 1. Proposed class E power amplifier with coupling coils for a wireless power transfer system.

by the load condition of the PA due to the direct connection between the drain of the transistor and the network. The coupling efficiency must be calibrated with the modified S-parameter considering different impedances. The load impedance R_L in the class E operation, which is the input impedance of the network, is expressed as in [10]

$$R_L = 1.365 \frac{V_{DD}^2}{P_{out}} \tag{2}$$

where V_{DD} is the supply voltage and P_{out} the output power. When the input and output impedances are different from each other, the S-parameters can be expressed with the Z-parameters as

$$\begin{aligned}
S_{11}^{\circ} &= \frac{(Z_{11} - Z_S)(Z_{22} + Z_L) - Z_{12}Z_{21}}{(Z_{11} + Z_S)(Z_{22} + Z_L) - Z_{12}Z_{21}} \\
S_{12}^{\circ} &= \frac{2Z_{12}}{(Z_{11} + Z_S)(Z_{22} + Z_L) - Z_{12}Z_{21}} \sqrt{Z_S Z_L} \\
S_{21}^{\circ} &= \frac{2Z_{21}}{(Z_{11} + Z_S)(Z_{22} + Z_L) - Z_{12}Z_{21}} \sqrt{Z_S Z_L} \\
S_{22}^{\circ} &= \frac{(Z_{11} + Z_S)(Z_{22} - Z_L) - Z_{12}Z_{21}}{(Z_{11} + Z_S)(Z_{22} + Z_L) - Z_{12}Z_{21}}
\end{aligned} \tag{3}$$

where S°_{ij} represents the calibrated S-parameters, Z_{ij} the measured Z-parameters with the reference load Z_0, Z_S the input port impedance, and Z_L the output port impedance. R_L is the same as Z_S of the network in the amplifier. Using (1) and (3), the calibrated coupling efficiency η° can be expressed as

$$\eta^{\circ} = \eta \times \left| \frac{(Z_{11} + Z_0)(Z_{22} + Z_0) - Z_{12}Z_{21}}{(Z_{11} + Z_S)(Z_{22} + Z_L) - Z_{12}Z_{21}} \frac{\sqrt{Z_S Z_L}}{Z_0} \right|^2 . \tag{4}$$

Therefore, the efficiency of the network must be calibrated by using (4) when R_L is not the same as Z_0 by V_{DD} and P_{out} of the amplifier. The transmission efficiency in the output can be defined as

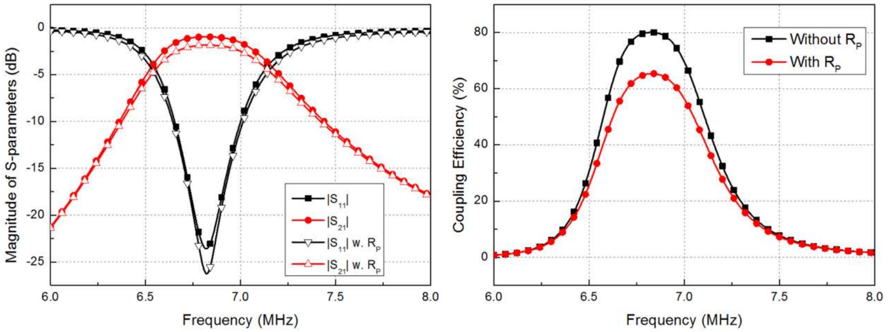
$$\eta_{trans} = \eta^{\circ} \times PAE. \tag{5}$$

The proposed amplifier is designed using the Agilent Advanced Design System (ADS). Freescale LDMOS MRF6VP11KH transistors are used as the switching transistors, and discrete passive components by Murata Manufacturing Co., Ltd. are used for input matching and additional output capacitance. A 1 : 1 transformer, SBT-A1-30G manufactured by RCL Technology is used for the input balun. The network is demonstrated with copper and litz wires to obtain a high quality-factor. The diameter of the source and load coils with one turn is approximately 5.5 cm, and that of the resonant coils with four turns is approximately 11.5 cm. The distance from the source to the load is 14 cm. There is no cooling device in the system except a metal plate incorporated as a heat sink.

3. WIRELESS POWER TRANSFER NETWORK

The WPT network is designed by using [11]. The operating frequency of the system is 6.8 MHz. The simulated data of the WPT network are shown in Fig. 2. The coupling efficiency η is 79.9% using (1). The parasitic resistance in each coil is one of the main factors affecting the efficiency degradation of the network. With a one-ohm additional parasitic resistance R_P in each resonant coil, the efficiency is changed to 65.2% at 6.8 MHz. As shown in Fig. 3, the efficiency has a maximum value as shown in Fig. 3 when the impedance at the input port is 50 ohms. The efficiency degrades rapidly when the impedance is below 30 ohms, but the variation in the efficiency near 50 ohms is small.

Figure 4 shows the measured S-parameter of the WPT network. The magnitude of S_{21} is -2.58 dB at 6.8 MHz. The coupling efficiency η is 55.2%, as determined from the measured data. The differences between the simulations and the measurements can be understood in the observation that the parasitic resistance is more than one ohm in each coil, particularly the resonant coil.



(a) (b)

Figure 2. Simulated data for the wireless power transfer network: (a) S-parameters; (b) Coupling efficiency.

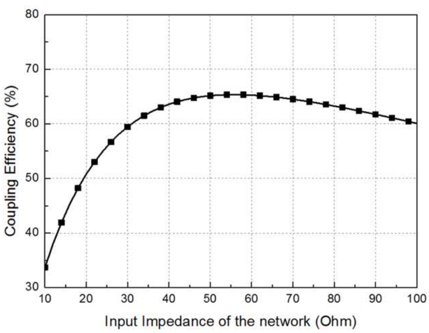


Figure 3. Simulated coupling efficiency with the variation of the input impedance.

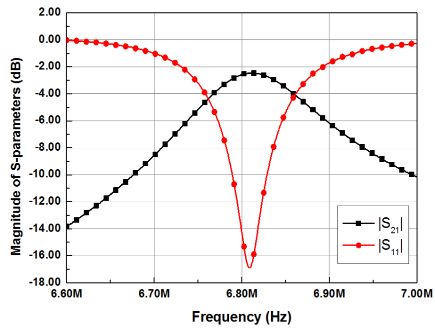


Figure 4. Measured S-parameters for the wireless power transfer network.

4. SIMULATION RESULTS OF THE PROPOSED AMPLIFIER

The class E operation of the proposed amplifier is shown in Fig. 5. The harmonic signals in the output load decreased extremely due to filtering by the WPT network. Fig. 6 shows the output power and efficiencies in the simulation in the case where the input power is 25.5 dBm and the gate bias of the transistor is 1.0 V. The maximum transmission efficiency is 57.7% with a 21 V supply voltage. The variations of all the efficiencies are below 1% depending on the supply voltage from 16 V to 30 V. The black box shown in Fig. 7 represents the coupling efficiency obtained from the power at the drain of the transistor (node A and B at Fig. 1) and the power at the output port (node C at Fig. 1).

The red circle shown in Fig. 7 is the other coupling efficiency obtained from the calibrated S-parameters of the network using (2) and (4). The efficiencies in Fig. 7 are almost the same at a 14 V supply voltage.

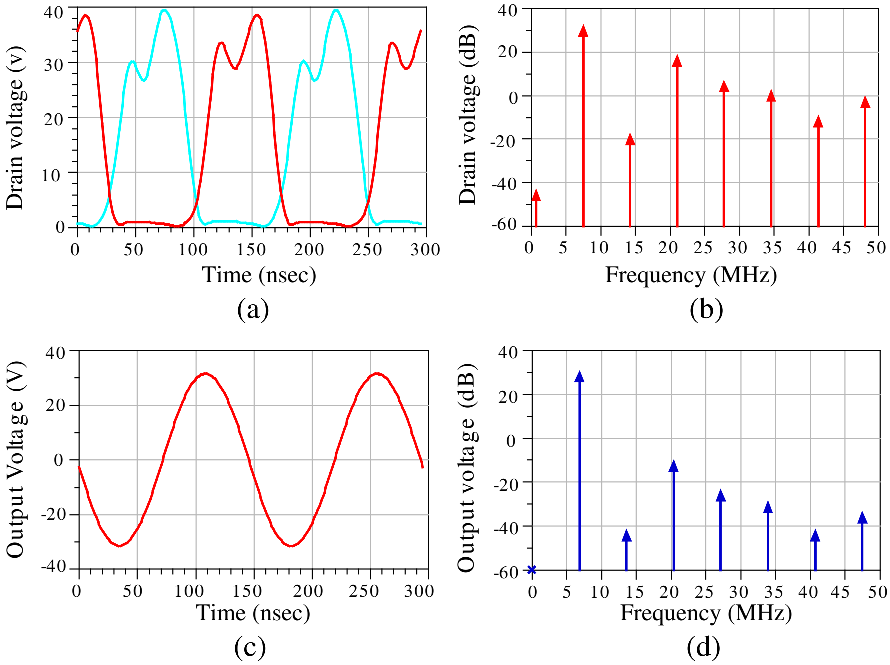


Figure 5. Simulation waveform and spectrum of the proposed amplifier: (a), (b) The drain voltages of the transistors (node A and B in Fig. 1); (c), (d) The output voltage (node C in Fig. 1).

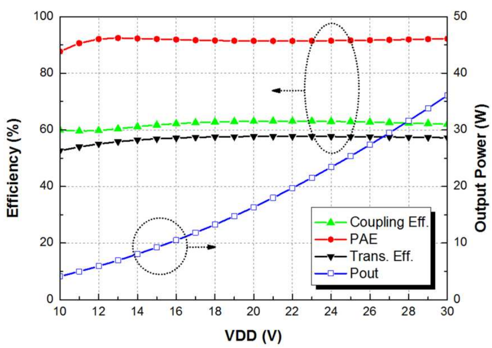


Figure 6. Simulation results of the efficiencies and output power of the wireless power transfer system.

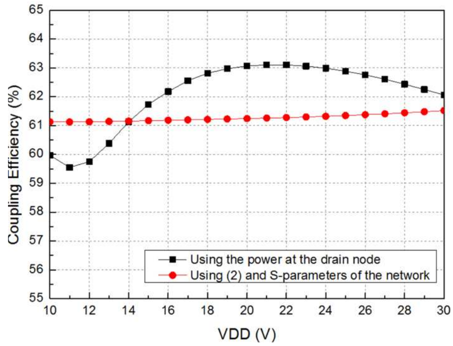


Figure 7. Simulated coupling efficiencies: -■- Using the ratio between the power at the drain node and the output power. -●- Using (2) and the S-parameters of the network.

5. MEASUREMENT RESULTS OF THE PROPOSED AMPLIFIER

The measurement results of the WPT system are shown in Fig. 8 for the case where the input power is 25.5 dBm and the gate bias of the transistor is 1 V, which is the optimum value for high transmission efficiency. With a supply voltage of 14 V, the maximum transmission efficiency is measured at 44.6%, and the transmitted power to the output is 6.95 W. Using (2), the input impedance of the network is 38.2 Ω when the supply voltage is 14 V and the output power is 7 W. The calibrated coupling efficiency is 48.3%, which decreases by 6.9% due to the impedance difference. The PAE of the transistor is calculated as 92.1% using the coupling and transmission efficiencies. All the efficiencies in Fig. 8 change, depending on the supply voltage from 14.5 V. The variations in the efficiencies are similar to the effects on the increase of the drain impedance of the transistor, which is the input impedance of the network. When the supply voltage is increased from 14 V, the coupling efficiency also increases due to the increase in the input impedance of the network, as shown in Fig. 9. However, the transmission efficiency decreases due to the rapid decrease of the PAE, as shown in Fig. 8. These variations are understood by the thermal degradation in the drain node, depending on the output power. The degradation is not shown in the proposed amplifier with an output power of less than 7 W. In other words, the coupling efficiency increases, but the PAE decreases when the input impedance of the network increases due to thermal effects on the impedance of the drain. Therefore, there is an optimum supply voltage for high transmission efficiency in the proposed amplifier depending on the transmitted output power. Because of thermal degradation of the transistors, the transmission efficiency and the transmitted output power decreases to 43.6% and 6.56 W after one hour. However, subsequent performances are not degraded further. All harmonic signals in the output are measured as less than 48 dBc, as shown in Fig. 10.

The performance comparisons are summarized in Table 1. The conventional PA is designed with the same devices as used in the proposed amplifier, but it uses dc feed inductors and an L-type output matching network between the WPT network and the amplifier [10]. The proposed amplifier shows better PAE and transmission efficiency than those of a conventional amplifier under the same bias conditions.

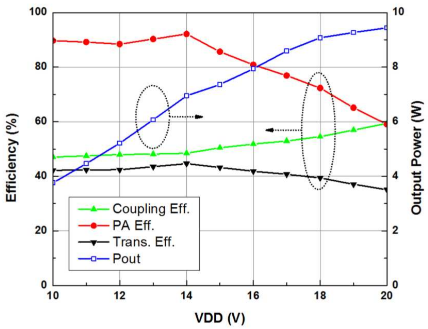


Figure 8. Measured efficiencies and output power of the wireless power transfer system.

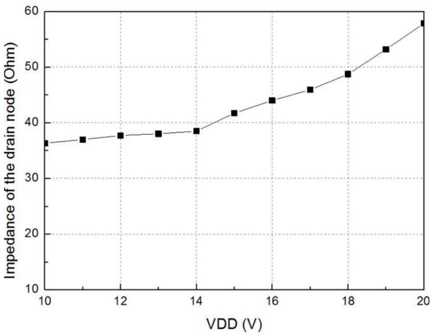


Figure 9. Calculated impedance of the drain node using (2).

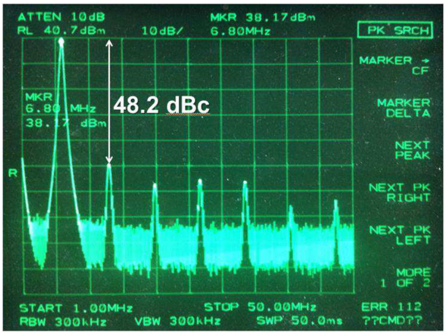


Figure 10. Output power spectrum of the proposed amplifier.

Table 1. Performance comparisons with the conventional class E power amplifier.

$@V_{DD} = 14\,\mathrm{V}$	P_{out} (W)	Power-added efficiency (%)	Coupling efficiency (%)	Transmission efficiency (%)
Conventional Type	6.62	75.7	55.2	41.8
This Work (simulation)	8.05	92.3	61.1	56.4
This Work (measurement)	6.95	92.1	48.5	44.6

6. CONCLUSION

A class E power amplifier with coupling coils is demonstrated for a magnetic induction-based wireless power transfer system. The drain of the transistor in the amplifier links to the source coil of the wireless power transfer network without any devices. The network functions as a harmonic rejection filter and dc feed inductors in the class E amplifier. The optimum supply voltage is determined by obtaining the maximum transmission efficiency because the load impedance in the drain node affects the performance of the network, and thermal degradation by the output power changes the impedance of the drain node. The system with the amplifier shows 6.95 W transmitted power and 44.6% transmission efficiency with a supply voltage of 14 V at 6.8 MHz. Considering the calibrated coupling efficiency of the network, the PAE in the amplifier is 92.1% considering the calibrated coupling efficiency of the network. A highly efficient transmitter of the WPT system can be obtained by using the proposed amplifier with the network designed to consider impedance difference and cooling devices.

ACKNOWLEDGMENT

This work was supported by the Primary Research Program of Korea Electrotechnology Research Institute (grant 12-12-N0101-47).

REFERENCES

1. Peng, L., O. Breinbjerg, and N. A. Mortensen, "Wireless energy transfer through non-resonant magnetic coupling," *Journal of*

Electromagnetic Waves and Applications, Vol. 24, Nos. 11–12, 1587–1598, 2010.

2. Choi, J. and C. Seo, "High-efficiency wireless energy transmission using magnetic resonance based on negative refractive index metamaterial," *Progress In Electromagnetics Research*, Vol. 106, 33–47, 2010.
3. Wei, X. C. and E. P. Li, "Simulation and experimental comparison of different coupling mechanisms for the wireless electricity transfer," *Journal of Electromagnetic Waves and Applications*, Vol. 23, No. 7, 925–934, 2009.
4. Cannon B. L., J. F. Hoburg, D. D. Stancil, and S. C. Goldstein, "Magnetic resonant coupling as a potential means for wireless power transfer to multiple small receivers," *IEEE Trans. Power Elect.*, Vol. 24, No. 7, 1819–1825, Jul. 2009.
5. Jang, B.-J., S. Lee, and H. Yoon, "HF-band wireless power transfer system: Concept, issues, and design," *Progress In Electromagnetics Research*, Vol. 124, 211–231, 2012.
6. Laskovski, A. N. and M. R. Yuce, "Class-E oscillators as wireless power transmitters for biomedical implants," *Proc. 3rd Int. Symp. Appl. Sci. Biomedical and Communication Tech.*, 1–5, Rome, Nov. 2010.
7. Ma, Q., M. R. Haider, S. Yuan, and S. K. Islam, "Power-oscillator based high efficiency inductive power-link for transcutaneous power transmission," *Proc. 55rd IEEE Int. Midwest Symp. Circuits and Systems*, 537–540, Seattle, 2010.
8. Juntunen, E., D. Dawn, S. Pinel, and J. Laskar, "A high-efficiency, high-power millimeter-wave oscillator using a feedback class-e power amplifier in 45 nm CMOS," *IEEE Microw. Wireless Compon. Lett.*, Vol. 21, No. 8, 430–432, Aug. 2011.
9. Jimenez-Martin, J. L., V. Gonzalez-Posadas, J. E. Gonzalez-Garcia, F. J. Arques-Orobon, L. E. Garcia-Munoz, and D. Segovia-Vargas, "Dual band high efficiency class ce power amplifier based on CRLH diplexer," *Progress In Electromagnetics Research*, Vol. 97, 217–240, 2009.
10. Grebennikov, A. V., "Switched-mode rf and microwave parallel-circuit class E power amplifiers," *Int. J. RF and Microw. Computer-Aided Eng.*, Vol. 14, No. 1, 21–35, Jan. 2004.
11. Son, H.-C., J. W. Kim, D.-H. Kim, K.-H. Kim, and Y.-J. Park, "Self-resonant coil with coaxial-like capacitor for wireless power transfer," *Proc. Asia-Pacific Microw. Conf.*, 90–93, Melbourne, 2011.