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Wireless Energy Transmission High-Efficiency DC-AC Converter Using High-Gain High-Efficiency Two-Stage Class-E Power Amplifier

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Abstract

In this paper, a high-efficiency DC-AC converter is used for wireless energy transmission. The DC-AC convertter is implemented by combining the oscillator and power amplifier. Given that the conversion efficiency of a DC-AC converter is strongly affected by the efficiency of the power amplifier, a high-efficiency power amplifier is implemented using a class-E amplifier structure. Also, because of the low output power of the oscillator connected to the input stage of the power amplifier, a high-gain two-stage power amplifier using a drive amplifier is used to realize a high-output power DC-AC converter. The high-efficiency DC-AC converter is realized by connecting the oscillator to the input stage of the high-gain high-efficiency two-stage class-E power amplifier. The output power and the conversion efficiency of the DC-AC converter are 40.83 dBm and 87.32 %, respectively, at an operation frequency of 13.56 MHz.

Key words: Wireless Energy Transmission, DC-AC Converter, High-Gain High-Efficiency Power Amplifier, Class-E, Drive Amplifier.

Ⅰ. Introduction

In recent years, there has been increasing interest in the research and development of wireless energy transmission technology capable of eliminating the "last cable". The large number of battery-operated consumer electronics, such as laptops, cell phones, PDAs, etc., and the associated tangle of wall-wart chargers has generated interest in designing a single, convenient charging system. Wireless energy transmission systems would permit many different devices equipped with receiving coils to be charged and would cut the last wire of portable wireless devices [1]~[3].

Wireless energy transmission technology can be categorized as a transmitter, resonator, and receiver. The transmitter consists of a DC-AC converter realized by combining the oscillator and power amplifier. Therefore, improving the efficiency of the power amplifier is important for realizing a high-efficiency transmitter. Also, because of the low output power of the oscillator connected to the input stage of the power amplifier, increasing the power amplifier's gain is important for realizing a DC-AC converter with a high output power.

In this paper, a class-E amplifier structure is adopted to achieve the high-efficiency power amplifier. Also, the drive amplifier is connected to the input stage of the power amplifier in order to increase the power amplifier's gain. Essentially, a two-stage class-E power amplifier is used to realize a high-gain high-efficiency power amplifier. Finally, the wireless energy transmission high-efficiency DC-AC converter is implemented by connecting the oscillator to the input stage of the high-gain high-efficiency two-stage class-E power amplifier.

Ⅱ. Principles of a Class-E Power Amplifier

As first proposed by Sokal, in theory, a class-E power amplifier is 100 % efficient. A class-E power amplifier is more efficient than other classes of amplifier as a result of its lower power consumption. A class-E power amplifier using the same operation frequency, output power, and transistor consumes 2.3 times less power than a conventional class-B or class-C power amplifier. Fig. 1 shows the circuit of a class-E power amplifier. Fig. 2 shows the ideal voltage and current waveforms of transistor in the class-E power amplifier. The transistor is operated like the ideal switch in the switch-mode power amplifier. The voltage and current waveforms of the transistor must not overlap if the power consumption of the transistor is to be minimized, and the high-efficiency property of the power amplifier is obtained by switching the transistor between its "ON" and "OFF" states.

As shown in Fig. 2, when switching to the "ON" state, the voltage approaches 0 V, and the current is

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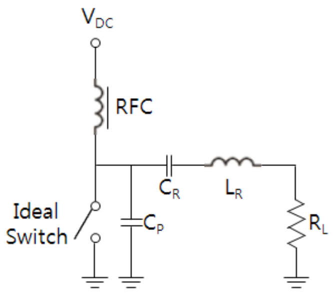


Fig. 1. Circuit of a class-E power amplifier.

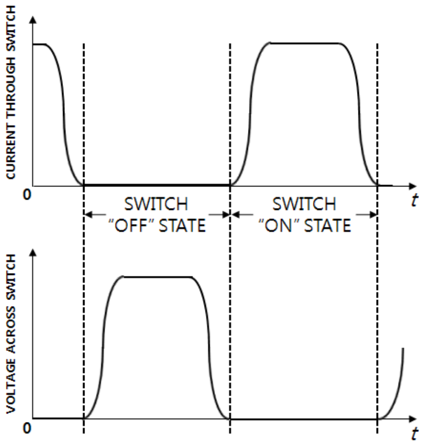


Fig. 2. Voltage and current waveforms of the transistor of a class-E power amplifier.

high as a result of it being operated as if it had low impedance. On the other hand, when switching to the "OFF" state, the voltage is high, and the current approaches 0 A since it is operated as though it has high impedance [4]~[8].

Ⅲ. Simulation Results for a Two-Stage Class-E Power Amplifier

Fig. 3 shows the circuit for a two-stage class-E power amplifier consisting of a drive amplifier and a class-E power amplifier. As shown in Fig. 3, the two-stage structure using the drive amplifier is adopted to obtain the high-gain property, and the class-E power amplifier structure is adopted to obtain the high-efficiency property. The target application of our work is in magnetic resonance.

The two-stage class-E power amplifier is designed using Freescale's MRF282S LDMOSFET and a Taconic's TLC substrate with a dielectric constant of 3.2 and a thickness of 31 mils. The same transistor is used in the drive amplifier and power amplifier stages. The load impedance of the power amplifier depends on the antenna coil. In our work, the wireless energy transmission using

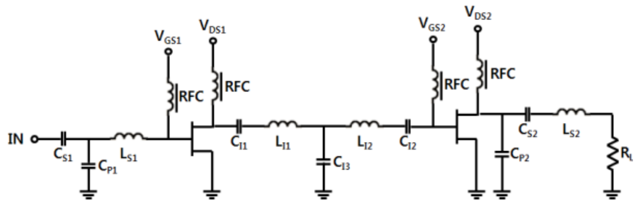
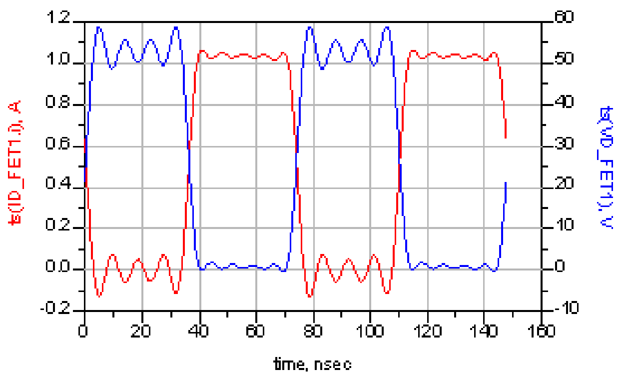


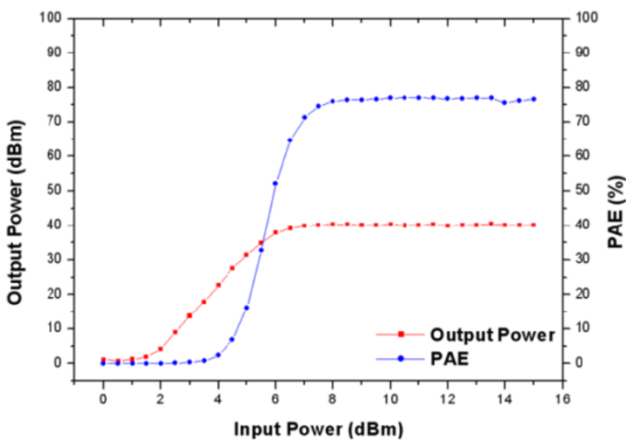
Fig. 3. Circuit for a two-stage class-E power amplifier.

the single transmitter and single receiver was considered as a fixed distance between the receiver and transmitter. Namely, the load impedance of the DC-AC converter was not changed in our work. The input impedance of the antenna coil is 50 Ω, therefore, the output port of the power amplifier was matched at 50 Ω. In the circuit schematic in Fig. 3, C_{S2}, L_{S2}, and C_{P2} are 10 nF, 1.2 nH, and 0.5 pF, respectively.

Fig. 4 shows the simulated drain voltage and current waveforms, and output power and power-added efficiency (PAE) versus the input power of the high-gain high-efficiency two-stage class-E power amplifier. The operation frequency of the two-stage class-E power amplifier is 13.56 MHz for the wireless energy transmi-



(a) Drain voltage and current waveforms



(b) Output power and PAE vs. input power

Fig. 4. Simulation results for a two-stage class-E power amplifier.

ssion. The gate and drain voltages at the drive amplifier stage are 2.6 V and 22 V, respectively. The gate and drain voltages at the power amplifier stage are 4.4 V and 26.5 V, respectively. As shown in Fig. 4 (a), the drain voltage and current waveforms do not overlap, which results in reduced power consumption. Therefore, efficiency is improved at the same operation frequency and output power. As shown in Fig. 4 (b), the simulated output power and PAE of the two-stage class-E power amplifier are 40.332 dBm and 76.955 %, respectively, at an input power of 10 dBm. The high-gain of about 30 dB was obtained by the two-stage structure using the drive amplifier, and a high-efficiency of about 77 % was achieved by the class-E power amplifier structure. Because an output power of about 10 W and a PAE of about 77 % were obtained at an input power of 10 dBm, the high-efficiency DC-AC converter can be implemented by connecting the oscillator with the output power of 10 dBm to the input stage of the two-stage class-E power amplifier.

Ⅳ. Fabrication and Measurement Results of the Two-Stage Class-E Power Amplifier

Fig. 5 shows the fabrication of the two-stage class-E power amplifier using Freescale's MRF282S LDMOSFET and a Taconic's TLC substrate with a dielectric

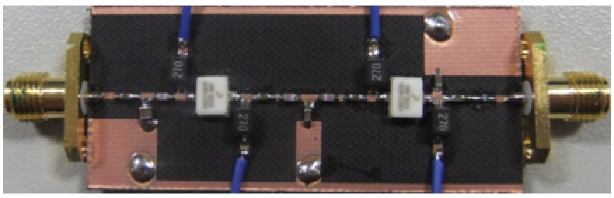


Fig. 5. Fabrication of the two-stage class-E power amplifier.

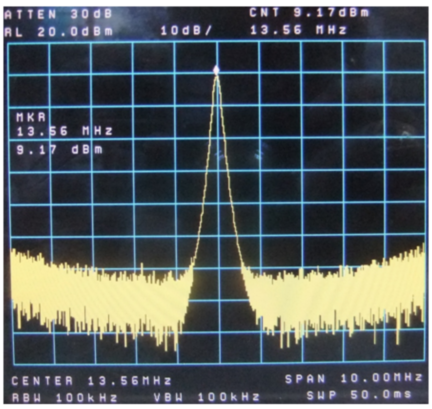
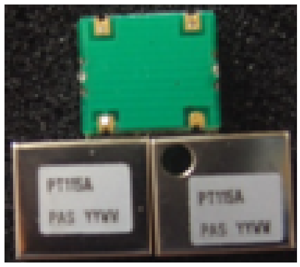
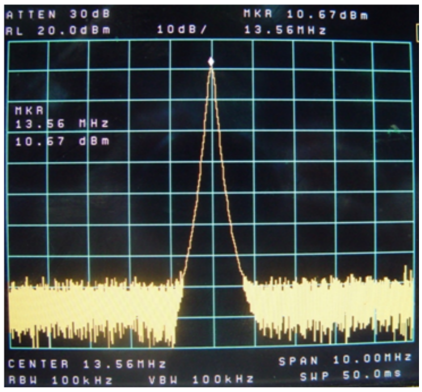


Fig. 6. Measured output power of the two-stage class-E power amplifier.



(a)



(b)

Fig. 7. (a) Oscillator used to realize the DC-AC converter, (b) Measured output power.

constant of 3.2 and a thickness of 31 mils. The gate and drain voltages of the drive amplifier stage are 2.6 V and 22 V, respectively, and the gate and drain voltages at the power amplifier stage are 4.4 V and 26.5 V, respectively, as in the simulation. Fig. 6 shows the measured output power of the two-stage class-E power amplifier. As shown in Fig. 6, the measured output power is 40 dBm at an operation frequency of 13.56 MHz and an input power of 10 dBm. Given that the attenuation property of the attenuator connected to the output stage of the two-stage class-E power amplifier for the measurement of the output power is −30.83 dB, the output power of 40 dBm was measured through an output power of 9.17 dBm, as in Fig. 6. The drain currents at the drive amplifier and power amplifier stages are 9 mA and 463 mA, respectively, therefore the PAE is 80.13 %. The gain is 30 dB. Compared to the simulation results, the output power fell by about 0.3 dB, but the drain current also fell by about 50 mA. Therefore, the PAE increased by about 3 %. In general, the measurement results are similar to the simulation results. Because an output power of about 10 W and a PAE of about 80 % were obtained at an input power of 10 dBm, the high-efficiency DC-AC converter can be implemented by connecting the oscillator with the output power of 10 dBm to the input stage of the two-stage class-E power amplifier.

Ⅴ. Fabrication and Measurement Results for the High-Efficiency DC-AC Converter

A high-gain high-efficiency two-stage class-E power amplifier with an output power of about 10 W and a PAE of about 80 % at an operation frequency of 13.56 MHz and an input power of 10 dBm and with an oscillator output power of 10 dBm at an operation frequency of 13.56 MHz were used to realize the high-efficiency DC-AC converter. The oscillator used to realize the high-efficiency DC-AC converter was a PT115A TCXO (Temperature-Compensated Crystal Oscillator). Fig. 7 shows the oscillator used to realize the DC-AC converter and the measured output power of the oscillator. As shown in Fig. 7, the current and output power of the oscillator are 20 mA and 10.67 dBm, respectively, at an input voltage of 5 V and an operation frequency of 13.56 MHz. Fig. 8 shows the fabrication of a high-efficiency DC-AC converter realized by connecting the oscillator to the input stage of the high-gain high-efficiency two-stage class-E power amplifier. Fig. 9 shows the measured output power of the high-efficiency DC-AC converter. As shown in Fig. 9, the output power of the DC-AC converter is 40.83 dBm at an operation frequency of 13.56 MHz. Because the attenuation property of the attenuator connected to the output stage of the DC-AC converter for the measurement of the output power is −30.83 dB, the output power of 40.83 dBm was measured through the output power of 10 dBm, as shown in Fig. 9. The input voltage of the oscillator is 5 V. The gate and drain voltages of the drive amplifier stage are 2.6 V and 18 V, respectively, and those of the power amplifier stage are 4.395 V and 26.983 V, respectively, in the two-stage class-E power amplifier. The current of the oscillator is 42 mA. The gate and drain currents at the drive amplifier stage are 6 mA and 18 mA, respectively, and those at the power amplifier stage are 15 mA and 491 mA, respectively, in the two-stage class-E power amplifier. The voltage and current of the drive amplifier changed due to the optimization and the difference in the fabrication error between the power amplifier and the DC-AC converter. Therefore, the DC-AC conversion efficiency of the DC-AC converter is 87.32 %. The efficiency of the DC-AC converter is better than that of the two-stage class-E power amplifier. The reason being that the 27 V drain voltage of the power amplifier in the DC-AC converter is optimized relative to the 26.5 V in the two-stage class-E power amplifier. The measured performances of the high-gain high-efficiency two-stage class-E power amplifier, the oscillator used to realize the DC-AC converter, and the high-efficiency DC-AC converter are summarized in Table 1.

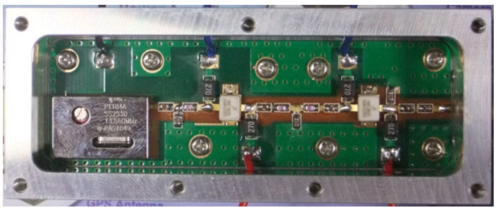


Fig. 8. Fabrication of the high-efficiency DC-AC converter.

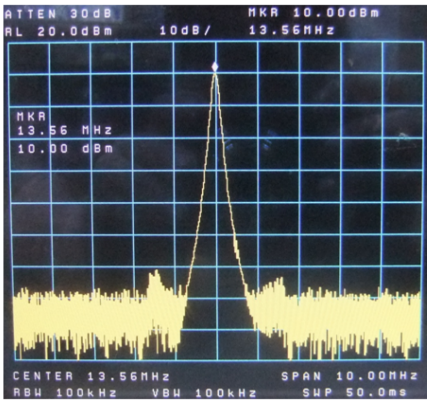


Fig. 9. Measured output power of the DC-AC converter.

Table 1. Measured performances of the two-stage class-E power amplifier, oscillator, and DC-AC converter.

Performance	Units	Oscillator	Two-stage class-E PA	DC-AC converter
Operation frequency	MHz	13.56	13.56	13.56
Input power	dBm	-	10	-
Output power	dBm	10.67	40	40.83
Gain	dB	-	30	-
Power consumption	W	0.1	12.4675	13.8642
PAE	%	-	80.13	-
DC-AC conversion efficiency	%	-	-	87.32

Ⅵ. Conclusion

In this study, a high-efficiency DC-AC converter is implemented for wireless energy transmission. The DC-AC converter is implemented by combining the oscillator and power amplifier. Because the conversion efficiency of the DC-AC converter is strongly affected by the efficiency of the power amplifier, the high-efficiency power amplifier is implemented by using a class-E amplifier structure. Also, because the output power of the oscillator connected to the input stage of the power amplifier is low, a high-gain two-stage power amplifier using a drive amplifier is implemented to realize the high-output power DC-AC converter. The high-efficiency DC-AC converter is realized by connecting the oscillator to the input stage of the high-gain high-efficiency two-stage class-E power amplifier. The output power and conversion efficiency of the DC-AC converter are 40.83 dBm and 87.32 %, respectively, at an operation frequency of 13.56 MHz.

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References

[1] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljacic, "Wireless power transfer via strongly coupled magnetic resonances," *Science*, vol. 317, pp. 83-86, Jul. 2007.

[2] A. Karalis, J. D. Joannopoulos, and M. Soljacic, "Efficient wireless non-radiative mid-range energy transfer," *Annals of Physics*, vol. 323, no. 1, pp. 34-48, Jan. 2008.

[3] B. L. Cannon, 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 Transactions on Power Electronics*, vol. 24, no. 7, pp. 1819-1825, Jul. 2009.

[4] S. C. Cripps, *RF Power Amplifiers for Wireless Communications*, Artech House, 1999.

[5] A. Grebennikov, N. O. Sokal, *Switchmode RF Power Amplifiers*, Newnes, 2007.

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

[7] N. O. Sokal, "Class-E high-efficiency power amplifiers, from HF to microwave," *IEEE MTT-S International Microwave Symposium Digest*, vol. 2, pp. 1109-1112, Jun. 1998.

[8] F. H. Raab, "Idealized operation of the class-E tuned power amplifier," *IEEE Transactions on Circuits and Systems*, vol. 24, no. 12, pp. 725-735, Dec. 1977.

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Reference to Journal of The Korean Institute of Electromagnetic Engineering and Science, vol. 5, no. 4, pp. 204-207, Dec. 2005.