

A 99%-efficiency GaN converter for 6.78 MHz magnetic resonant wireless power transfer system

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Abstract: The authors developed a high-efficiency gallium-nitride (GaN) Class-E converter for a 6.78 MHz magnetic resonant wireless power transfer system. A negative-bias gate driver circuit made it possible to use a depletion mode GaN high-electron-mobility transistor (HEMT), and simplified the converter circuit. As the depletion mode GaN HEMT with very small gate-source capacitance provided almost ideal zero-voltage switching, the authors attained a drain efficiency of 98.8% and a total efficiency of 97.7%, including power consumption of a gate driver circuit, at a power output of 33 W. In addition, the authors demonstrated a 6.78 MHz magnetic resonant wireless power transfer system that consisted of the GaN Class-E converter, a pair of magnetic resonant coils 150 mm in diameter with an air-gap distance of 40 mm, and a full-bridge rectifier using Si Schottky barrier diodes. The system achieved a dc-dc efficiency of 82.8% at a power output of 25 W. The efficiencies of coil coupling and the rectifier were estimated to be ~ 94 and 90%, respectively.

1 Introduction

Inductively coupled wireless power transfer (WPT) systems have been used for power supply and battery charging of mobile electronics and home appliances. Magnetic resonant coupling (MRC), reported in 2007, has attracted attention in the research community because MRC provides high coupling efficiency even if the transmitting coil and receiving coil are widely separated [1]. An industrial alliance of MRC recently legislated for a practical specification [2]. However, there are drawbacks of low efficiency for a total magnetic resonance WPT system including dc-ac and ac-dc converters, because a high frequency within the industrial, scientific and medical (ISM) band must be selected under radio regulations to meet coil size requirements for mobile equipment [3].

To increase the total efficiency of an MRC WPT system, many kinds of dc-ac converter have been studied as transmitters. Gallium-nitride (GaN) high-electron-mobility transistor (HEMT) fabricated on a silicon substrate is the most promising candidate for high-power and high-frequency transistors. Switching converter topologies using Class-D and Class-E amplifiers have been studied because of their inherent high efficiency (theoretically 100%). As frequency stabilisation using Class-D amplifiers is difficult in the ISM band, Class-E amplifiers are desirable for both high efficiency and precise frequency tuning [4, 5]. Chen *et al.* [5] demonstrated a Class-E converter using an enhancement mode GaN HEMT with a drain efficiency of 93.6% at a power output of 26.8 W, and system efficiency of 73.4% at a frequency of 13.56 MHz. However, there is a large scope to increase the efficiency of Class-E converters and MRC WPT systems in the ISM band.

We have developed a high-efficiency Class-E converter using a depletion mode GaN HEMT with a drain efficiency of 98.8% at a frequency of 6.78 MHz and demonstrated an MRC WPT system with a dc-dc power transfer efficiency of 82.8%, which consisted of a Class-E converter, a pair of transmitting and receiving coils with an air-gap distance of 40 mm and a full-bridge rectifier. To our knowledge, this is the highest efficiency Class-E converter for MRC WPT systems at a frequency of 6.78 MHz reported to date.

2 Experimental results

Fig. 1 shows a schematic circuit diagram of Class-E converter using a depletion mode GaN HEMT. Although enhancement mode GaN HEMT has been studied for switching devices to achieve highly

efficient converter, we adopted a depletion mode GaN HEMT (prototype of Mitsubishi Electric Co.) to idealise zero-voltage switching (ZVS) operation because of its very small gate-source capacitance of 34 pF, low drain-source on-resistance of 69 m Ω , and high drain voltage rating of above 200 V. The use of a negative-bias gate driver circuit made it possible to simplify the converter circuit, because a cascade design combined with, for example, an Si metal-oxide semiconductor field effect transistor was not suitable for low-power application of <50 W. A shunt capacitance C_1 of 445 pF and a choke inductance L_2 of 1.8 μ H were integrated in the vicinity of the GaN HEMT. In the experiment, we designed a load resistance (RL) of 31 Ω , which was close to the maximum output impedance of the following demonstration of an MRC WPT system.

Fig. 2 shows waveforms of the negatively biased gate pulses and the GaN drain voltage in Fig. 2a, and waveforms of the drain voltage and output voltage at the load resistance RL in Fig. 2b. The drain voltage waveform shows almost ideal Class-E operation, and the output voltage waveform at load resistance was a sinusoidal wave with very small distortion. However, a small phase difference between the start point of the drain voltage off state and peak point of the negative output voltage was observed because the fall time of the gate pulse voltage was delayed due to the influence of the rippled gate voltage, and the phase difference caused a decrease in the drain efficiency.

The drain efficiency and total efficiency, including the power consumption of the gate driver circuit, are shown in Fig. 3. A drain efficiency >95% was maintained over the wide range of the

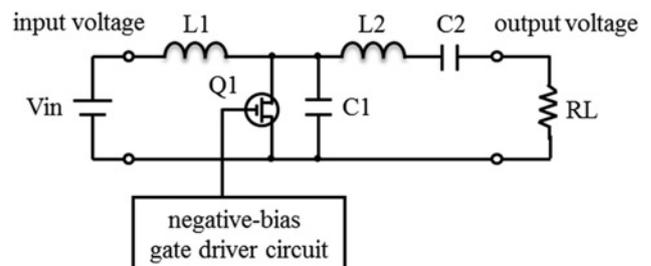


Fig. 1 Schematic circuit diagram of Class-E converter, where depletion mode GaN HEMT was operated by negative-biased pulses from the gate driver circuit

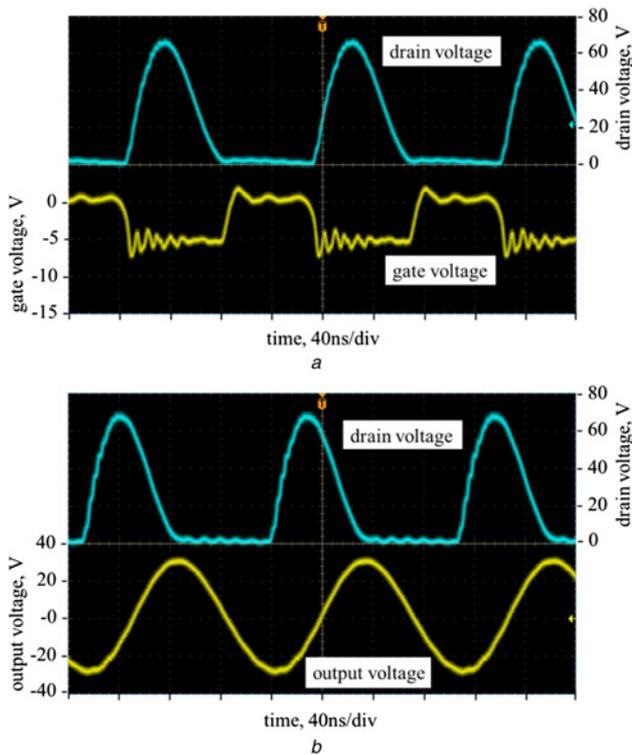


Fig. 2 Waveforms of Class-E converter as follows
 a Drain voltage and gate voltage
 b Drain voltage and output voltage at the load resistance R_L

power output from 5 to 36 W. The highest drain efficiency of 98.8% and the total efficiency of 97.7% were attained at a power output of 33 W. As the power output was measured with an oscilloscope in the experiment, a certain small error was probably included due to distortion of the output voltage waveforms.

Fig. 4 shows the schematic circuit diagram of a 6.78 MHz MRC WPT system using the GaN Class-E converter. A photograph of the test set is shown in Fig. 5. Assuming desktop battery charging application, we designed a pair of helical coils with a diameter of 150 mm at a coil distance of 40 mm, where the coils were made of Litz wire with a length of 1.9 m and a diameter of 3 mm. Air-gap variable capacitors were adopted at both ends of the coils to precisely tune the resonant frequency and to achieve a monopole frequency response. The series compensation on the primary side with the capacitor

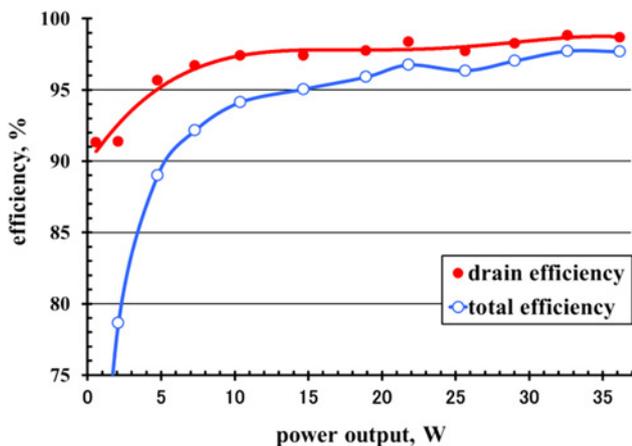


Fig. 3 Drain efficiency (solid circles) and total efficiency including power consumption of the gate driver circuit (open circles) as a function of power output

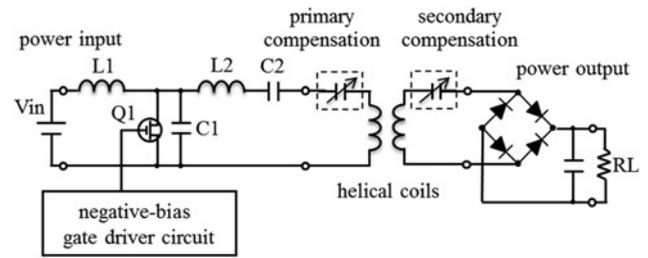


Fig. 4 Schematic circuit diagram of magnetic resonant WPT system using GaN Class-E converter, with series-series compensating design at both sides of the coils and full-bridge rectifier with Si Schottky barrier diodes

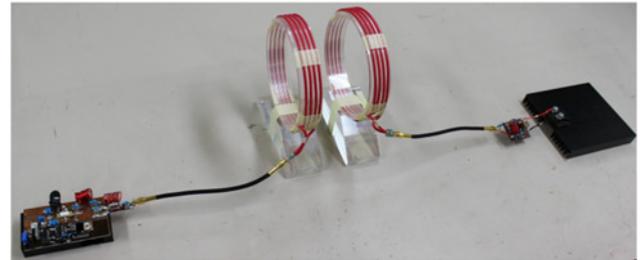


Fig. 5 Photograph of MRC WPT system

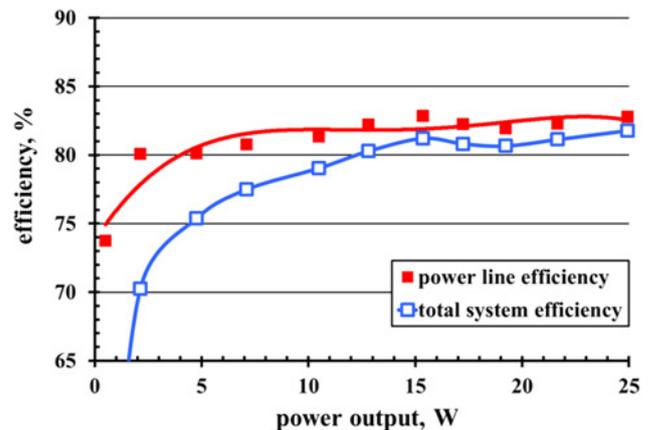


Fig. 6 Power line efficiency (solid squares) and total system efficiency of WPT system, including power consumption of gate driver circuit (open squares), as a function of power output

reduced high-voltage stress to the GaN HEMT, and the series compensation on the secondary side was empirically selected to increase the efficiency. To increase the rectifier efficiency, Si Schottky barrier diodes with very small forward voltage of 0.5 V and total capacitance of 30 pF were applied. The variable capacitors were precisely tuned to decrease the power reflection from the rectifier.

A power line efficiency and total system efficiency, including power consumption of the gate driver circuit, are shown in Fig. 6. The system efficiency from the dc input to the dc output was 82.8% at a power output of 25 W, and the corresponding efficiencies of coil coupling and the rectifier were estimated to be ~94 and 90%, respectively. A decrease in power reflection from the rectifier appeared to increase the rectifying efficiency, rather than a secondary higher rectifying mode effect [6].

3 Conclusion

We have developed a high-efficiency GaN Class-E converter and the prototype of an MRC WPT system using the converter at a

frequency of 6.78 MHz. As the depletion mode GaN HEMT with very small gate-source capacitance provided an almost ideal ZVS, we attained a drain efficiency of 98.8% and a total efficiency of 97.7%, including power consumption of the gate driver circuit at a power output of 33 W. In addition, the dc-dc efficiency of the total MRC WPT system was 82.8% at a power output of 25 W. The efficiencies of coil coupling and the rectifier were estimated to be ~94 and 90%, respectively.

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5 References

- [1] Kurs A., Karalis A., Moffatt R., Joannopoulos D.J., Fisher P., Soljacic M.: 'Wireless power transfer via strongly coupled magnetic resonances', *Science*, 2007, **317**, pp. 83–86, doi: 10.1126/science.1143254
- [2] Tseng R., Novak B., Shevde S., Grajski K.A.: 'Introduction to the alliance for wireless power loosely-coupled wireless power transfer system specification version 1.0'. Proc. 2013 IEEE Wireless Power Transfer Conf., 2013, pp. 79–83, doi 10.1109/WPT.2013.6556887
- [3] Shoki H.: 'Issues and initiatives for practical deployment of wireless power transfer technologies in Japan'. Proc. IEEE, 2013, vol. 101, pp. 1312–1320, doi: 10.1109/JPROC.2013.2248051
- [4] Calder R.J., Lee S., Lorenz R.D.: 'Efficient, MHz frequency, resonant converter for sub-meter (30 cm) distance wireless power transfer'. Proc. 2013 IEEE Energy Conversion Congress and Exposition, 2013, pp. 1917–1924, doi: 10.1109/ECCE.2013.6646942
- [5] Chen W., Chinga R.A., Yoshida S., Lin J., Chen C., Lo W.: 'A 25.6 W 13.56 MHz wireless power transfer system with a 94% efficiency GaN Class-E power amplifier'. Proc. 2012 IEEE MTT-S Microwave Symp., 2012, pp. 1–3, doi: 10.1109/MWSYM.2012.6258349
- [6] Kusaka K., Itoh J.: 'Experimental verification of rectifiers with SiC/GaN for wireless power transfer using a magnetic resonance coupling'. Proc. 2011 IEEE Ninth Int. Conf. Power Electronics and Drive Systems, 2011, pp. 1094–1099, doi: 10.1109/PEDS.2011.6147394