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A Class E Power Oscillator for 6.78-MHz Wireless Power Transfer System

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Abstract – A class E power oscillator is demonstrated for 6.78-MHz wireless power transfer system. The oscillator is designed with a class E power amplifier to use an LC feedback network with a high-Q inductor between the input and the output. Multiple capacitors are used to minimize the variation of the oscillation frequency by capacitance tolerance. The gate and drain bias voltages with opposite characteristics to make the frequency shift of the oscillator are connected in a resistance distribution circuit located at the output of the low drop-out regulator and supplied bias voltages for class E operation. The measured output of the class E power oscillator, realized using the co-simulation, shows 9.2 W transmitted power, 6.98 MHz frequency and 86.5% transmission efficiency at the condition with 20 V V_{DS} and 2.4 V V_{GS}.

Keywords: Class E, LC feedback network, Power oscillator, Wireless power transfer system

1. Introduction

Wireless power transfer system is a system that supplies energy wirelessly to electronic devices or power systems. It solves the difficulty of constructing electric power facilities due to the use of environment constraints. It also has advantages such as elimination of electric shock factor due to the use of electric power lines, prevention of deterioration of aesthetic appearance, and provision of charging convenience. In recent years, mobile phones equipped with a wireless charging function have been commercialized, and applications have been broadened by various products such as charging electric vehicles and powering large-capacity white goods, such as washing machines and refrigerators [1].

Wireless power transmission can be classified into three categories: magnetic induction (tightly coupled method), self-resonance (loosely coupled method), and radiative transfer (RF transmission) [2]. In contrast to the magnetic induction method in which electric power is transmitted and received by the electromagnetic induction phenomenon, the self-resonance method can have directivity in the power transmission due to the self-resonance occurring between adjacent coils designed at the operating frequency. And it is also an advantageous technique for wireless power transmission to a plurality of terminals [2, 3].

A self-resonant wireless power transfer system largely consists of a transmitter that generates power signals, a receiver that collects the signals, and a coupling that connects the transmitter and the receiver. It is important for the transmitter to supply sufficient power required in the receiver by generating the signals in the frequency specification of the wireless power transmission.

Because the power conversion loss in the transmitter causes heat generation which may hinder the operation stability of the system, it is also important to obtain high-efficiency high-power transmission characteristics in the system [4]. In the conventional self-resonant wireless power transfer system, a frequency signal generator and a high output amplifier are implemented in each [5]. The transmitter using intrinsic circuits is suitable for accurate frequency signal generation and highly efficient and high-power signal transmission with in a predetermined band, but it has a serious disadvantage of increasing the complexity of the system configuration [6]. In wireless power transmission applications which do not require high frequency accuracy compared to the commercial wireless communication systems, a power oscillator can be useful because it can lower the complexity of the whole system and bring the overall power conversion efficiency of the transmitter to a high level.

In this paper, a class E power oscillator using an LC resonant feedback network between the input and the output of the class E power amplifier is proposed. The power oscillator can generate the desired signal frequency by adjusting values of the components in the feedback path and bias voltages of the switching transistor while maintaining a high-efficiency high-power transmission characteristics of a class E power amplifier [5, 7]. The oscillator module for the 6.78-MHz wireless power transfer system is designed using an electromagnetic (EM) circuit co-simulation process, considering the parasitic effects of interconnections on PCB. The fabricated power oscillator module shows 6.96 MHz output frequency, 9.2 W transmitted power and 86.5% overall power conversion efficiency at the drain-source voltage of 20 V and the gate-source voltage of 2.4 V.

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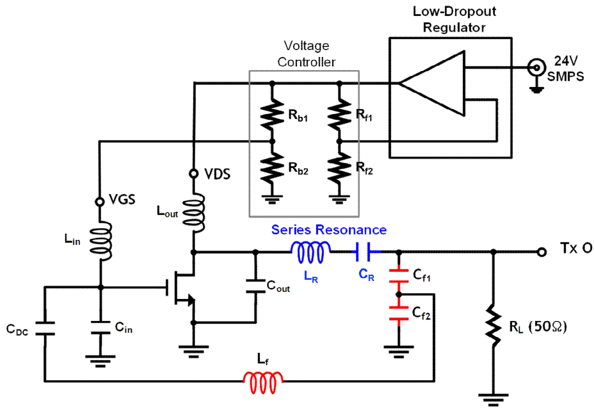


Fig. 1. Schematic of the proposed class E power oscillator

2. Design of the Class E Power Oscillator

Fig. 1 shows the schematic diagram of the proposed class E power oscillator. The 24 V supply voltage through a switching-mode power supply (SMPS) is applied to the drain-source voltage (V_{DS}) of the switching power transistor using a low drop-out (LDO) regulator. The V_{DS} can vary from 12 V to 24 V depending on the ratio of the feedback resistors R_{f1} and R_{f2} in the regulators as follows:

$$V_{DS} = 1.240 \times (1 + \frac{R_{f1}}{R_{f2}}) \tag{1}$$

The gate-source voltage (V_{GS}) of the switching transistor is changed by the ratio of resistances R_{b1} and R_{b2} in the distribution circuit designed with a voltage variation of 2.1 V to 4.2 V. A class E power oscillator provides the desired frequency signal by feeding back the output signal of the class E power amplifier with an LC series resonator, consisting of L_R and C_R, at the output to the gate of the transistor using an LC resonant network. If the frequency shift due to the parasitic elements is not taken into consideration, the output frequency f_{osc} of the power oscillator can be expressed using the inductor L_f and capacitors C_{f1} and C_{f2} in the network and the overall impedance Z_g at the gate node of the transistor as follows:

$$f_{osc} = \frac{1}{2\pi\sqrt{L_f C_T}} \tag{2}$$

$$C_T = \frac{C_f Z_g}{C_f + Z_g} \tag{3}$$

where C_f is obtained by the ratio between the feedback capacitances C_{f1} and C_{f2}. To improve the transmission efficiency and the transmitted output power in the oscillator operating in class E mode, high-Q inductors are used in the bias path to supply the V_{DS} of the transistor, the network to decide the oscillation frequency and the series resonator to filter out harmonics in the output signal. The capacitances in the oscillator are obtained from multiple capacitors to minimize the variation of the oscillation frequency by capacitance tolerance.

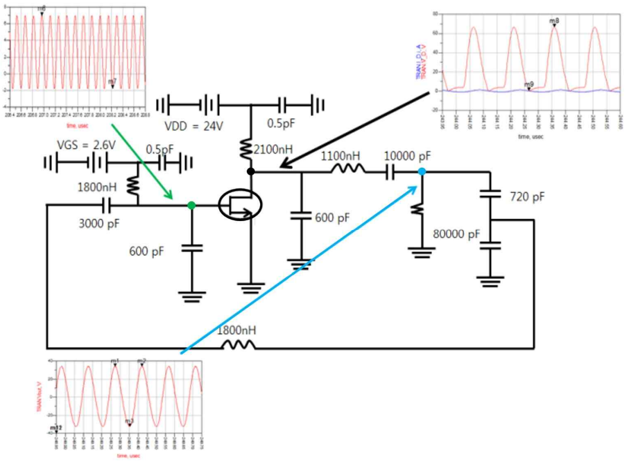


Fig. 2. Transient waveforms in the circuit simulation of the class E power oscillator

2.1 Electromagnetic circuit Co-simulation

The class E power oscillator shown in Fig. 1 is designed using Keysight ADS circuit simulation tools. The device characteristics of the switching transistor and capacitors are applied in the circuit design using the simulation models provided by the manufacturer. The inductors with parasitic resistances are considered in the simulation because the output performances of the oscillator are greatly affected by the quality factors of the inductors [5]. In the circuit simulation in Fig. 2, the class E operation is shown from the waveforms at each node of the oscillator. At 24 V V_{DS} and 2.6 V V_{GS}, the oscillation frequency in the circuit is simulated to be a 6.78 MHz signal. The transmitted power and the dc-to-ac conversion efficiency are obtained to be 11.1 W and 96.2% at the frequency in the simulation.

The wireless power transfer system is a high-Q system that operates in the narrowband, and the output frequency generated by the power oscillator should be designed to have an accurate and constant value. In particular, parasitic elements of passive components used in the oscillator module and transmission lines implemented on PCB can have important influences on the oscillation frequency and the output performances in the high-power oscillator. Since the error of the device is caused by the characteristics of the device itself, the influences thereof cannot be completely eliminated. However, it is possible to reduce the influences on the output characteristics by optimizing layout design and using low-tolerance devices. Multiple capacitors with a tolerance of 1% are used to reduce the effect of the error in the oscillator design. The parasitic elements on the FR4 PCB are extracted from the layout design of the power oscillator module, and they are applied

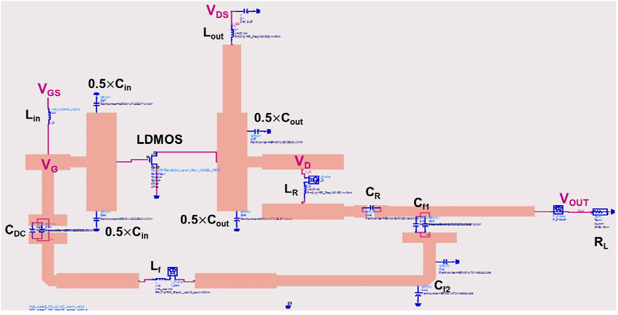
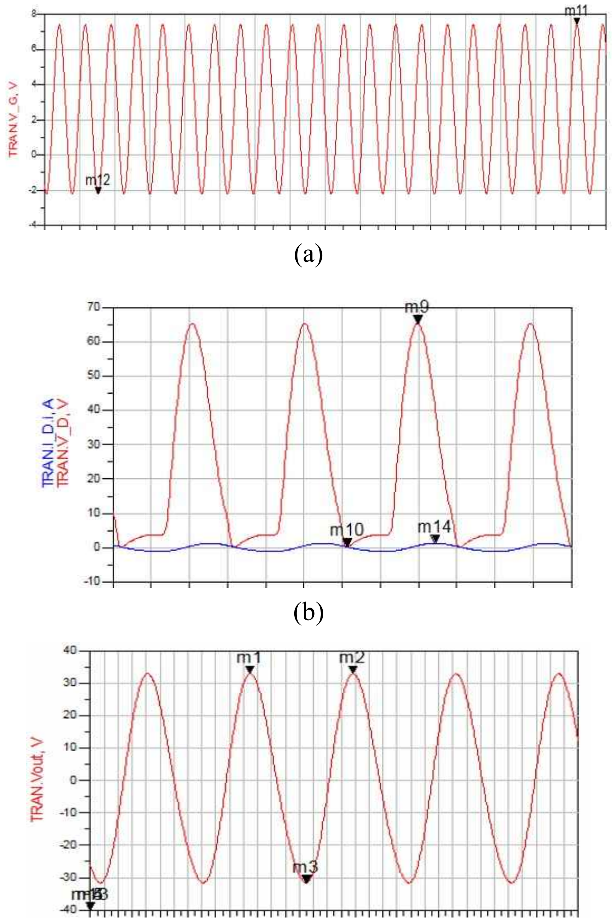


Fig. 3. Schematic for EM circuit co-simulation of the class E power oscillator considering the effects of the layout design on PCB



(a)

(b)

(c)

Fig. 4. Transient waveforms using EM circuit co-simulation in each node of the power oscillator. (a) At the gate node, (b) the drain node of the transistor and (c) the output port connected to the 50-Ω reference impedance

to the circuit simulation of the oscillator. This process is called EM circuit co-simulation. Fig. 3 shows the schematic diagram for the co-simulation of the class E power oscillator. The simulation may not converge if the layout design area for the co-simulation is widened. In the consideration of simulation accuracy and convergence, the layout design for the part in generating the oscillation signal in the circuit is only applied to the co-simulation. This approximation is valid if it is assumed that the components in the feedback loop and layout design near the loop are dominant factors to determine oscillation characteristics.

The transient voltage-current waveforms in Fig. 4 are obtained by the co-simulation. From the voltage waveform at the drain node of the transistor in Fig. 4(b), it can be seen that the power oscillator operates in the class E mode. Fig. 4(c) shows the output voltage waveform of the oscillator when the oscillator is connected to the wireless power transfer network with a reference impedance of 50 Ω. A 6.78-MHz signal can be easily seen from the sine waveform in Fig. 4(c) because harmonics at the output terminal of the oscillator are diminished by the series resonant LC circuit. The output power and the transmission efficiency at the same bias conditions as the circuit simulation are 10.4 W and 89.4% in the co-simulation. The simulation results show that the parasitic elements have effects on the output performances of the oscillator. The capacitances in the feedback loop should be changed in the co-simulation to obtain the same oscillation frequency as the circuit simulation because of the effects. The changes of the capacitances to generate the 6.78-MHz oscillation frequency in both simulations are summarized in Table 1. It shows that additional capacitances by the transmission lines affect the design of the power oscillator. And the results also show that design parameters should vary depending on layout design. The proposed oscillator module has the layout design with long transmission lines which can make the additional capacitances in the feedback loop due to the size of the high-Q inductors and the interconnection between the input and the output. It is the reason that the value of the capacitors constituting the

Table 1. Comparison of the capacitances in the feedback loop designed to generate the 6.78-MHz oscillation frequency in both simulations

	C_{DC} (nF)	C_{f2} (nF)
Circuit simulation only	3.3 nF	80 nF
EM circuit co-simulation	2.5 nF	66 nF

Table 2. Design parameters of the power oscillator in Fig. 1

Components	Value	Manufacturer
L_{in}	1800 nH	Coilcraft Inc.
L_{out}	2100 nH	Core Electronics Co., Ltd.
L_R	1100 nH	
L_f	1800 nH	
C_{DC}	2.5 nF	Murata Manufacturing Co., Ltd.
C_{in}	600 pF	
C_{out}	600 pF	
C_R	10 nF	
C_{f1}	720 pF	
C_{f2}	66 nF	

feedback network is greatly reduced in the design using the co-simulation. Therefore, it is necessary to minimize the design error by shortening the length of the transmission line in the feedback loop as short as possible. It is also possible to improve the design accuracy by using the multiple capacitors because the various capacitances needed to generate the desired frequency can be implemented more accurately in the oscillator. The final design parameters considering the co-simulation results are summarized in Table 2.

2.2 Fabrication of the power oscillator module

The oscillator module in Fig. 5 including an LDO regulator, a resistance distribution circuit for controlling the V_{GS} and a plug for connecting 24 V SMPS is realized on FR4 PCB using the switching LDMOS transistor made by NXP Semiconductors. High-Q inductors used in the oscillator are specially designed taking into account the magnitude of the current flowing in each path. In wireless power transfer system, it is not generally considered that the impedance to the input of the wireless power transmission network is fixed to the reference impedance since the positions of the transmitting and the receiving coils are not fixed [8]. A wideband output matching is one of methods that can reduce the influence of the impedance mismatch, but it is also difficult to realize the characteristics in the high-power oscillator design with high efficiency. Assuming that the variation in the impedance of the wireless power transmission network caused by changing receiver locations can be ignored for the overall transmission efficiency in the system, the oscillator can be designed in consideration of the output impedance of the 50-Ω reference impedance [9]. As impedance mismatch increases, the reflected signal increases at the output of the oscillator, and the heat of the oscillator gets higher. The rise of the internal temperature of the oscillator is the main reason for the change in output characteristics such as the efficiency degradation and the frequency shift of the oscillator. To minimize the effect of high temperatures at the output, a 15-mm metal heat sink and a cooling fan are installed under the PCB. The overall size of the module is 35 mm (width) × 65 mm (length) × 30 mm (height) shown in Fig. 5. The height of the module excluding the metal heat sink and the cooling fan is about 10 mm due to the size of inductors.

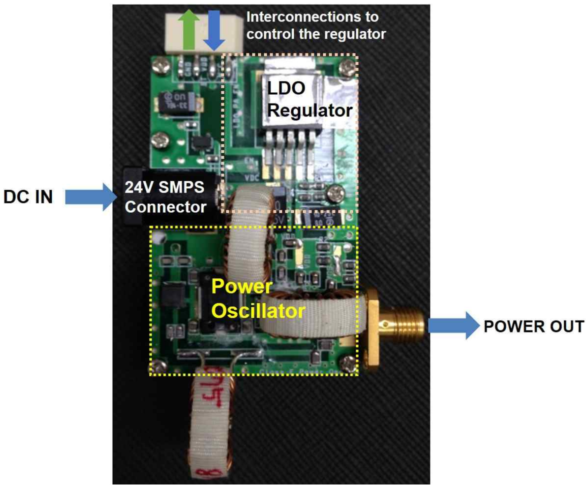


Fig. 5. Proposed class E power oscillator module. The overall size of the module is 35 mm (W)×65 mm (L)×30 mm (H) including a LDO regulator, a SMPS connector, a metal heat sink, a cooling fan, and interconnections to BLE module, which can be used to control the regulator operation

3. Measurement Results

The output frequencies of the oscillator module without a LDO regulator are measured to obtain the frequency variable range depending on the bias voltages which are the V_{DS} and the V_{GS}. Fig. 6 shows measurement results obtained by varying the V_{GS} and the V_{DS}, respectively, based on the bias voltages using in the EM circuit co-simulation. The fundamental oscillation frequency increases as increasing the V_{DS} at the gate voltage of 2.6 V, but the frequency decreases as increasing the V_{GS} at the drain voltage of 24 V. The measurement results in Fig. 6 shows that the frequency shift of the proposed oscillator can be limited by the variation of the bias voltages because the resistance distribution circuit is connected to the V_{DS} with the V_{GS} at the output of the regulator. Because the V_{DS} is determined by the required power of the wireless power transfer system and the voltage-to-frequency conversion ratio is obtained to be 0.05 MHz/V from the measurement results, the oscillator can be used to generate the fixed

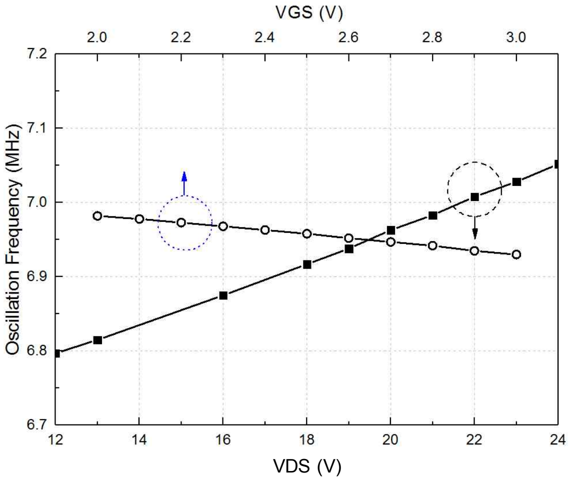


Fig. 6. Measured fundamental oscillation frequencies of the power oscillator depending on the bias voltages, which are the V_{GS} (an opened circle line) and the V_{DS} (a closed box line)

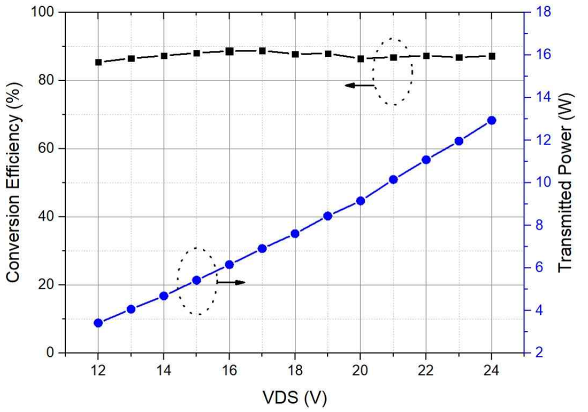


Fig. 7. Measured power conversion efficiency and transmitted power of the power oscillator depending on the V_{DS} at 2.4 V V_{GS}

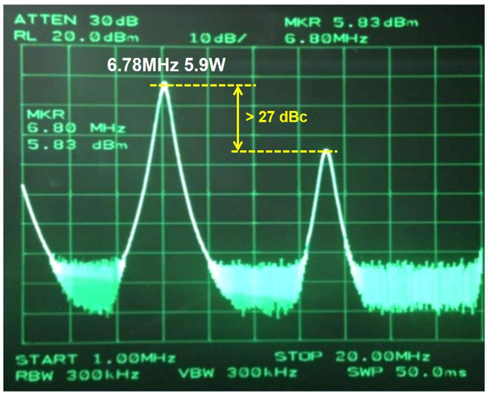


Fig. 8. Output power spectrum of the power oscillator with 30 dB attenuator

frequency in the wireless power transfer system.

Measurement results are shown in Fig. 7 for the case where the gate bias of the transistor is 2.4 V, which are the optimum value for high efficiency. At 20 V drain-source voltage, the 6.96-MHz oscillation frequency is measured with 86.5% power conversion efficiency. The transmitted power at the same bias conditions is 9.2 W. The oscillation frequency designed by the EM circuit co-simulation is changed from 6.78 MHz because the inductors used in the oscillator have a tolerance of 5%.

The 6.78-MHz wireless power transmission frequency is measured using the spectrum analyzer and 30 dB attenuator at 17 V V_{DS} and 3.8 V V_{GS} as shown in Fig. 8. The 2 dB assembly losses are calibrated using the reference signal generator. The output power of the oscillator is measured to be 5.9 W due to the decrease in the V_{DS}. The dc-to-ac power conversion efficiency including the regulator is measured to be 81.5%. The power conversion efficiency of the oscillator is estimated to be 88.6% with the assumption of 92% efficiency of the regulator. The harmonics are measured to be less than −27 dBc as shown in Fig. 8, but the value can be acceptable in the wireless power transfer system because the wireless power transfer network reduces the effects of the harmonics in the system [4]. Table 3 shows the comparisons of the class E oscillator in the MHz range.

Table 3. Comparisons of the class E oscillator in the MHz range

Reference	Oscillation Frequency [MHz]	Output Power [W]	Efficiency [%]
This work	6.98	9.2	86.5
[10]	2	3	95
[11]	0.8	0.953	82
[12]	1.97	2.8	89.7

4. Conclusion

A power oscillator is provided for 6.78-MHz wireless power transfer system. The oscillator operates in class E mode with a series LC resonator, and the oscillation frequency is determined by bias voltages of the switching transistor and an LC feedback network which is located between the input and the output nodes in the class E amplifier. The EM circuit co-simulation is used in the design of the oscillator to obtain design parameters considering the effect of the parasitic elements on PCB. In the measurement, the oscillator including a low drop-out regulator achieves 6.98 MHz oscillation frequency, 9.2 W output power and 86.5% conversion efficiency at 20 V drain-source and 2.4 V gate-source voltages. A 6.78-MHz signal for wireless power transfer system is generated with 5.9 W at 17 V drain-source and 3.8 V gate-source voltages. The measurement results show that the oscillator is suitable for high-efficiency and high-power signal transmission in the wireless power transfer system.

Acknowledgements

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