A Power-Efficient Injection-Locked Class-E Power Amplifier for Wireless Sensor Network

Hyoung-Seok Oh, Taeksang Song, *Student Member, IEEE*, Euisik Yoon, *Member, IEEE*, and
Choong-Ki Kim, *Fellow, IEEE*

***Abstract*—In this letter, we present an injection-locked Class-E power amplifier (Class-E ILPA) suitable for 2.4-GHz wireless sensor network applications where the maximum transmit-power is typically about 10 dBm. In such a low transmit-power application, it is a great challenge to achieve a high transmit efficiency because the driving power and dc power consumption in the previous stage are no more negligible compared with the transmitted signal power. The proposed Class-E ILPA, which is fully integrated in 0.18-μm CMOS technology, achieves the power added efficiency of 44.5% while delivering the output power of 11 dBm with drain efficiency of 49.3% at 1.2-V supply voltage. The measured locking range reaches 300 MHz with the input driving power of −6 dBm.**

***Index Terms*—Class-E power amplifier (PA), injection-locked (IL), power oscillator, wireless sensor network (WSN).**

I. INTRODUCTION

SINCE a wireless sensor network (WSN) consists of many distributed sensor nodes which are expected to operate for years without maintenance, each node requires a highly integrated, low-cost transceiver with low power consumption and high efficiency [1]. The major challenge of transceiver design in WSN applications has been low transmitter efficiency. In conventional high power transmitters, efficiency is largely dominated by that of the power amplifier (PA) itself. But in a low transmit-power application such as WSN, the driving power and dc power consumption in the previous stage are no more negligible and severely degrade the overall transmitter efficiency. Previously reported works [2], [3] tried to reduce power consumption in the previous stage by using a linear PA instead of a switching PA, even though the modulation schemes [i.e., on–off keying (OOK), frequency-shift keying (FSK)] employed do not need linear amplification of the input signal. However, linear PAs suffer from inherent low drain efficiency (DE) which significantly limits the overall transmitter efficiency. Moreover, power dissipation in the preamplifier still occupies a large portion of the total power consumption and lowers the overall efficiency [i.e., power added efficiency (PAE)] by over 10% from DE of PA.

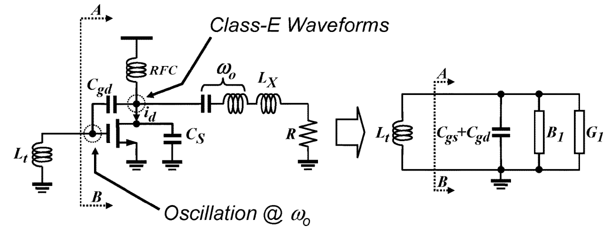

Fig. 1. Class-E power oscillator and its equivalent circuit.

In this letter, we present an injection-locked Class-E PA (Class-E ILPA) suitable for low transmit-power WSN applications. For implementation of the proposed Class-E ILPA, Class-E power oscillator and injection-locking concept are employed. These techniques substantially alleviate the trade-off between the required driving power and DE in a PA. Therefore, we can utilize a Class-E power stage with high DE while minimizing power consumption in the preamplifier stage. As a result, the proposed Class-E ILPA can achieve high PAE as well as high DE. This letter presents the design and analysis of the Class-E ILPA, which is fully integrated in 0.18-μm CMOS 1P6M technology, as well as the measurement results.

II. CLASS-E POWER OSCILLATOR

Fig. 1 shows the proposed Class-E power oscillator which consists of a conventional Class-E load network, feedback capacitor (C_{gd}), and the parallel inductor (L_t). The Class-E power oscillator works as a typical Class-E PA at the drain to achieve a high DE but it also works as an oscillator at the gate to reduce the driving power. First, Class-E operation at the drain is satisfied by the same load network as the classical Class-E PA. Second, oscillation condition at the gate can be derived from the equivalent circuit of Class-E power oscillator (see Fig. 1). The impedance seen into the gate can be expressed by using equivalent capacitance and conductance (G_1) as follows:

$$Y_{AB} = G_1 + j\left[\omega(C_{gs} + C_{gd}) + B_1\right]. \quad (1)$$

For oscillation to occur at a given frequency, the LC-tank including the equivalent capacitance at A–B should be adjusted and its loss be compensated by negative conductance (G_1) which is given by

$$G_1 = \frac{C_{gd} L_X R\omega^2 \left[C_1 C_{gd} R\omega^2 + g_m(C_1 L_X \omega^2 - 1)\right]}{1 - (2C_1 L_X + C_1^2 R^2)\,\omega^2 + C_1^2 L_X^2 \omega^4} \quad (2)$$

where $C_1 = C_{gd} + C_s$. In a simple case where the tank is lossless, from the boundary condition for oscillation ($G_1 = 0$), we

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H.-S. Oh, T. Song, and C.-K. Kim are with the Department of Electrical Engineering, Korea Advanced Institute of Science and Technology, Daejeon 305-701, Korea (e-mail: hyoung-seok.oh@kaist.ac.kr).

E. Yoon is with the Department of Electrical Engineering, University of Minnesota, Minneapolis, MN55455 USA.

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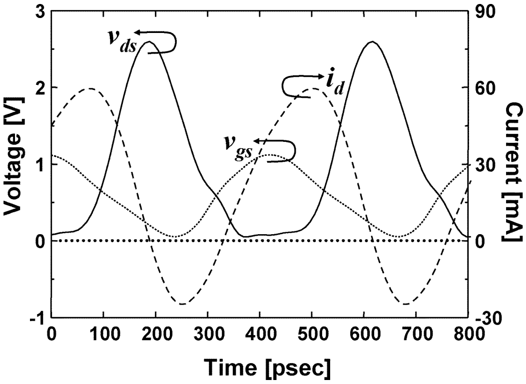

Fig. 2. Simulated waveforms of Class-E power oscillator.

obtain the following relationship between oscillation frequency and circuit components:

$$\omega_o = \frac{K}{\sqrt{C_{gd} + C_s}}, \quad K = \frac{1}{\sqrt{\left(\frac{C_{gd}}{g_m}\right) R + L_X}}. \tag{3}$$

As can be seen in (3), the circuit parameters such as R, L_X, and C_s should be chosen such that the voltage and current waveforms at the drain satisfy the Class-E PA characteristics. And then, the other parameters (i.e., C_{gd}, g_m, and L_t), which are not directly related to the Class-E load network, can be determined for oscillation at the specified operating frequency.

The simulated waveforms of the proposed Class-E power oscillator under dc bias are shown in Fig. 2. The switch transistor size is 600 μm and intrinsic gate-drain capacitance (C_{gd}) is used as a feedback component. Although the gate voltage (v_{gs}) is oscillating, the drain voltage (v_{ds}) and current (i_d) waveforms follow the conventional Class-E PA waveforms. This is because when the transistor is turned off the drain current (i_d) is steered into the shunt capacitor (C_s) and the drain voltage (v_{ds}) increases as the charge stored in C_s increases. At the peak drain voltage, the drain current crosses zero point and flows in reverse direction, which means that the stored charge in C_s is discharging into load (R). When the transistor is turned on, the drain voltage remains near zero voltage which ensures low power loss due to the on-resistance of transistor. The simulation results confirm that the proposed Class-E power oscillator works both as a Class-E PA at the drain and an oscillator at the gate. By using the Class-E power oscillator instead of a conventional Class-E PA, we can minimize the driving power as well as dc power consumption in the preamplifier, while maintaining the power stage fully driven with high DE.

III. INJECTION-LOCKED CLASS-E PA

Class-E power oscillator and injection-locking concept are applied to the implementation of the proposed Class-E ILPA, as shown in Fig. 3. The output frequency of the Class-E power oscillator is locked to the injected signal frequency through the inverter preamplifier. Since the injection-locking requires only small signal input into the Class-E power oscillator, the demand on high driving capability in the preamplifier is substantially relaxed. Also, the proposed Class-E ILPA is immune to interfering signals coming through the antenna because the oscillation node is not directly exposed to the antenna.

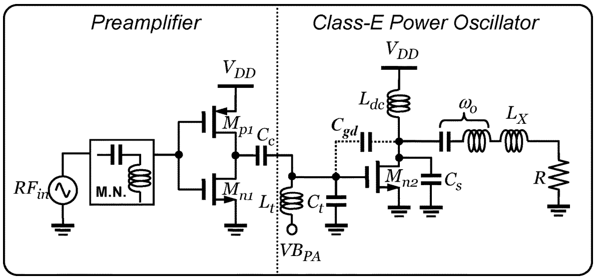

Fig. 3. Proposed IL Class-E PA circuit.

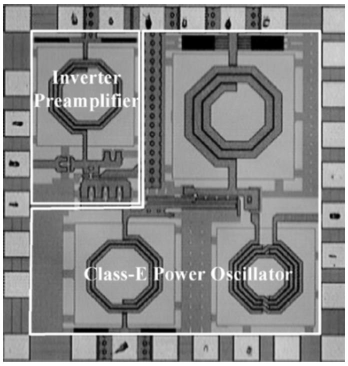

Fig. 4. Microphotograph of the proposed Class-E ILPA.

The injection locking range of the Class-E ILPA can be derived from a general model for an IL oscillator in [4], [5]. Considering the fundamental injection-locking case, the locking range is given by

$$\left|\frac{\Delta\omega}{\omega_o}\right| \leq \left|\frac{H_o}{2Q} V_i \cdot g(V_o)\right|, \quad g(V_o) = \frac{a_1}{V_o} - \frac{3}{4}|a_3| V_o \tag{4}$$

where ω_o is the resonant frequency of LC-tank, $\Delta\omega$ is the frequency offset from ω_o, H_o, and Q are the equivalent parallel impedance and quality factor of LC-tank, respectively, V_i is the input signal amplitude, V_o is the oscillation amplitude of LC-tank, and a_1 and a_3 are the first and third coefficients of nonlinearity in the oscillator. As can be seen in (4), the locking range becomes wider proportional to H_o/Q and the input signal amplitude and inversely proportional to the oscillation amplitude. Since the oscillation amplitude (V_o) is proportional to the equivalent parallel tank impedance (or Q of LC-tank), the filtering characteristic (Q) of LC-tank mainly limits the locking range. In this case, since the oscillation occurs at the gate node of the Class-E power oscillator, the oscillation amplitude should remain at its maximum to obtain higher DE. Therefore, the wide locking range can be achieved by increasing input signal amplitude.

IV. MEASUREMENT RESULTS

Fig. 4 shows the fabricated Class-E ILPA fully integrated in 0.18-μm CMOS technology. The chip size is 1.7 mm^2. Fig. 5 shows the measured output power (P_{out}), DE, and PAE of the fabricated Class-E ILPA at 1-V supply voltage. The injection locking occurs at the driving power as low as -7 dBm. Once the injection locking occurs, the output power is almost constant over the input power changes. Therefore, overdriving of the input power beyond the locking point does not lead to the im-

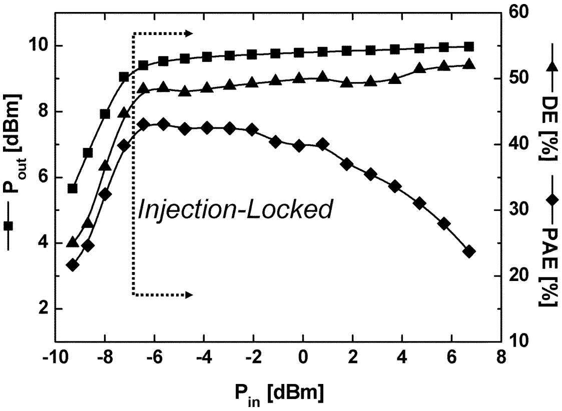

Fig. 5. Measured P_{out}, DE, and PAE versus Pin with 1-V supply voltage.

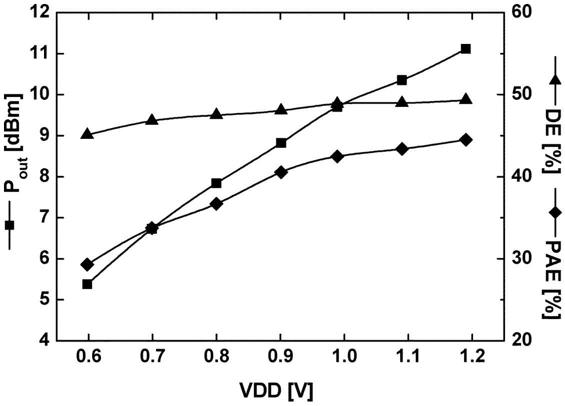

Fig. 6. Measured P_{out}, DE, and PAE versus supply voltage.

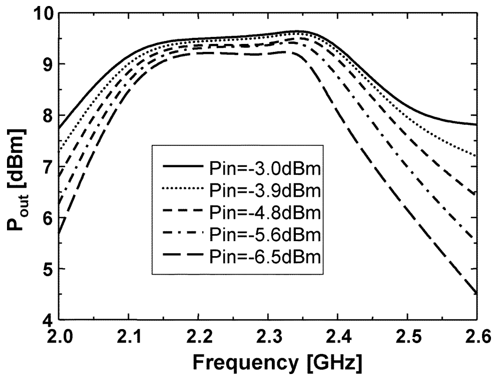

Fig. 7. Measured locking range variation versus P_{in}.

TABLE I
PERFORMANCE COMPARISON OF PA IN WSN

	[2]	[3]	Conventional Class-E**	Class-E ILPA
Frequency	433MHz	1.9GHz	2.4GHz	2.35GHz
CMOS Process	0.5μm	0.13μm	0.18μm	0.18μm
Supply	1.2V	1.2V	1.2V	1.2V
Pout	9.5mW	2.6mW	9.4mW	12.9mW
DE	54%	35%	43%	49.3%
PAE	38.8%*	26%	32%	44.5%
Note	Open drain	Bondwire	Fully integrated	Fully integrated

* Input driving power is not included in calculating PAE.
** This is separately fabricated for comparison with the same preamplifier.

provement of PAE, even though the DE increases slightly. With −6-dBm input power the Class-E ILPA achieves 43% PAE, 48.5% DE, and 9.5-dBm output power at 2.35 GHz. The sum of the driving and dc power consumption (0.27 and 0.54 mW, respectively) in the preamplifier is under 6% of the total power consumption. This is due to the lowered driving power requirement for the Class-E power oscillator. The output power and efficiency are also measured at various supply voltages (see Fig. 6). The output power of 11 dBm, DE of 49.3%, and PAE of 44.5% are achieved at 1.2-V supply voltage. The difference between PAE and DE is only 5% over 1–1.2 V of supply voltage. To investigate the locking range, the output power versus frequency is measured while the input driving power is varied as shown in Fig. 7. The measured locking range reaches 300 MHz with the input power of −6 dBm. As expected in (4), the locking range becomes wider as the input driving power increases. We note that the output power in locking state increases slightly for larger driving power. The reason is that as the driving power increases, the amplitude of LC-tank at the gate also increases to some degree and the inverter preamplifier turns the sinusoidal oscillation waveform into some rectangular shape. But as shown in Fig. 5, the driving power higher than the onset of injection-locking would lower PAE. The desirable input driving power range is −6 dBm to −2 dBm from Fig. 5. Table I shows the summary of measured performances compared with the previously reported works.

V. CONCLUSION

This letter presents the Class-E ILPA suitable for low transmit-power applications such as WSN. Since the employed Class-E power oscillator and injection-locking substantially mitigate the trade-off between the required driving power and DE in a PA, the proposed Class-E ILPA can achieve high PAE as well as high DE. The Class-E ILPA, fully integrated in 0.18-μm CMOS technology, achieves 44.5% PAE, 49.3% DE, and 11 dBm P_{out} at 2.35 GHz with 1.2-V supply voltage.

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