A Novel High-Efficiency Linear Transmitter Using Injection-Locked Pulsed Oscillator

Young-Sang Jeon, *Student Member, IEEE*, Hoe-Sung Yang, and Sangwook Nam, *Member, IEEE*

***Abstract*—This letter presents a novel high-efficiency linear transmitter using pulse-width modulation (PWM). An envelope of radio frequency (RF) input signal is modulated by the PWM. The modulated signal is applied to the gate bias of a class F injection-locked power oscillator and switches it on and off. By filtering the pulsed oscillating output signal of the injection-locked oscillator using high-Q bandpass filter, the input signal is restored. This technique enables the transmitter to have high efficiency with good linearity. Also, there is little distortion near saturation point of an active device. The measured results show efficiency of 54.6% and very good linearity in PCS band at 26.4-dBm output power.**

***Index Terms*—Injection-locked oscillator, power amplifier, pulse-width modulation (PWM), pulsed oscillator.**

I. Introduction

EFFICIENCY is very important factor for power amplifiers in that it has dominant effects on sizes of battery cells in mobile terminals and performances of power amplifiers due to the thermal effects in high power systems. There are some high-efficiency techniques. Switching amplifiers such as class E/F amplifiers have high efficiency, and amplifiers using mode-locking have good efficiency due to overdriving effects [1], [2]. Although the switching and the mode-locking power amplifiers have high efficiency, the amplifiers have nonlinear characteristics. Unfortunately, many modern communication systems such as cellular, PCS, and satellite systems require linear amplification.

Various techniques have been proposed and studied for linear power amplification with good efficiency. Envelope elimination and restoration (EER) is one of the most efficient linear radio frequency (RF) power amplification systems and its efficiency is ideally 100%. However, as a dc–dc converter is required in the EER system, it has narrow bandwidth and large size [3]. Furthermore, the efficiency of it generally decreases as the input signal decreases. An improved EER transmitter architecture which does not require a dc–dc converter was proposed [4], [5]. This technique enables the transmitter to have high efficiency without strict limitation of bandwidth. However, many components such as limiter, mixer, and drive amplifier are required to restore the input signal.

In this letter, a novel high-efficiency transmitter using an injection-locked pulsed oscillator is suggested. An envelope of RF input signal is modulated by PWM. Simultaneously a class F injection-locked power oscillator is locked by the RF input signal. By applying the pulse-width modulated envelope signal to the injection-locked oscillator, the oscillator is switched on and off. And by filtering the output of the injection-locked pulsed oscillator, input signal can be restored. Since this proposed transmitter does not use a dc–dc converter, there is no strict limitation of bandwidth and no degradation of efficiency at low input level. Furthermore, by only filtering the injection-locked pulsed oscillator output, the high-efficiency linear transmitter is implemented very simply.

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The authors are with the Applied Electromagnetic Laboratory, School of Electrical Engineering and Computer Science, Seoul National University, Seoul 151-742, Korea (e-mail: junys72@chollian.net).

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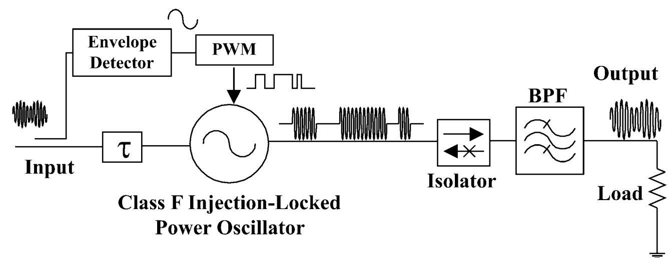

Fig. 1. Block diagram of a proposed high-efficiency linear transmitter using PWM and injection-locked technique.

II. High-Efficiency Linear Transmitter Architecture

Fig. 1 shows the block diagram of the proposed high-efficiency linear transmitter using PWM and injection-locked technique. A part of the RF input is coupled and detected by an envelope detector. And the detected low-frequency envelope is modulated by PWM. On the other hand, the RF signal connected to the though port of the coupler is delayed and then locks the class F power oscillator. The pulse-width modulated envelope signal is applied to the gate of the class F power oscillator and switches it on and off. If a rising time for the oscillator to reach a steady state is very short compared to the period of the switching of the PWM, the output of the oscillator can be assumed to be a pulse train of RF signal. Finally after filtering the RF pulse train by a high-Q bandpass filter, the amplified RF input is restored with high efficiency.

Notice that the isolator in Fig. 1 is required for stability and protection of the power oscillator. Although some power loss exists due to the isolator, practically the loss is not severe compared to the case without isolator. In case of without isolator, the reflected power by the high-Q bandpass filter exists and reenters into the power transistor, where it is dissipated into heat.

III. Analysis of Efficiency of the Proposed Transmitter

Fig. 2 shows the time domain waveform of the pulsed oscillator. In this case, the rising time (T_r) of the oscillator is as-

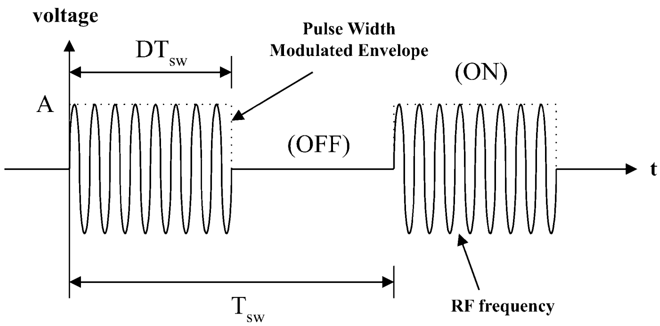

Fig. 2. Time domain waveform of a pulsed oscillator.

sumed to be very small compared to the switching period $(T_{\rm sw})$ of PWM. D and A in this figure are the duty ratio of the PWM and voltage amplitude of the pulsed oscillator, respectively. If the RF carrier frequency is ω_c, the pulsed oscillation output voltage is shown as in

$$v(t) = \left[D + \sum_{n=1}^{\infty}\left(\frac{\sin(2\pi Dn)}{n\pi}\cos\frac{2\pi n}{T_{\rm sw}}t + \frac{1-\cos(2\pi Dn)}{n\pi}\sin\frac{2\pi n}{T_{\rm sw}}t\right)\right]\cos\omega_c t. \quad (1)$$

In (1), $D \cdot \cos\omega_c t$ is the desired signal, and the others are mixing signals. Therefore, efficiency of the proposed transmitter is expressed as

$$\begin{aligned}\eta &= \frac{\frac{1}{2}D^2}{\frac{1}{2}D^2 + \frac{1}{2}\sum_{n=1}^{\infty}\left(\frac{1-\cos(2\pi Dn)}{n^2\pi^2}\right)}\eta_{\text{class } F} \\ &= \frac{D^2}{D^2 + \frac{1}{\pi^2}\left(\sum_{n=1}^{\infty}\frac{1}{n^2} - \sum_{n=1}^{\infty}\frac{\cos(2\pi Dn)}{n^2}\right)}\eta_{\text{class } F} \\ &= D\eta_{\text{class } F}. \end{aligned} \quad (2)$$

$\eta_{\text{class } F}$ in (2) represents efficiency of a class F power oscillator. There are three types of class F oscillators. While the maximum efficiency of a class $F1$ oscillator is 88.4%, $F2$ and $F3$ are 100% ideally.

Fig. 3 shows the ideal instantaneous efficiency of the proposed power amplifier and other traditional power amplifiers. The proposed amplifier can be designed using either class $F1$ or $F2$ injection-locked oscillator. Efficiency of the proposed power amplifiers is higher than class B amplifier, but lower than Doherty amplifier. In the viewpoint of the usable capacity of power amplifiers, the proposed amplifier has an advantage over the traditional amplifiers. Though class A, B, and Doherty amplifiers operate practically up to a few decibals backed off point from a saturation point of an active device, the proposed power amplifier can operate linearly up to a saturation point of an active device.

IV. Design of Class F Injection-Locked Pulsed Power Oscillator

A Class F Injection-locked power oscillator was designed for fundamental locking. Generally, for the injection-locked oscillators, the oscillator output power is a function of the injection amplitude [6]. This effect can be minimized during the design procedure, or eliminated by inserting a limiter between the injection signal and the injection-locked oscillator.

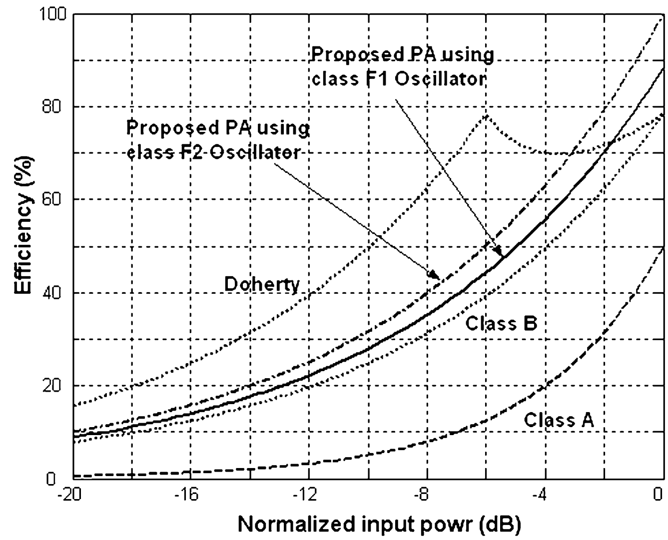

Fig. 3. Ideal instantaneous efficiency of the proposed power amplifier using class $F1$ oscillator or $F2$ oscillator, and other various traditional power amplifiers.

Locking range of the injection-locked oscillator was about 10 MHz at −10-dBm injection power. And minimum injection power for stable locking is −30 dBm. The measured efficiency of the injection-locked oscillator was about 64% at 1.865 GHz, when the oscillator is on.

Generally, rising time (T_r) of an oscillator depends on Q of it. In case of a high Q, the oscillator has large rising time. But, in spite of the high-Q bandpass filter, the proposed oscillator has short rising time due to the effect of the isolator in Fig. 1. Furthermore, the rising time is much shorter if an external input is injected to the oscillator. Simulation results show the rising time of the injection-locked oscillator is very short. It is less than 3 ns at various input level. Also, settling time of the oscillator is very short due to the effects of the isolator and the injection locking. The short rising time and settling time enable the proposed transmitter to have a good linearity.

A switching frequency of the PWM is to be selected in order that the switching period of the PWM is very large compared to the rising time of the injection-locked oscillator. Generally, the switching frequency must be at least ten times larger than the bandwidth of baseband signals for PWM. A 8-MHz switching frequency ($T_{\rm sw} = 125$ ns) is selected. In this case, the approximation to RF pulse train, when the oscillator is on and off, is reasonable because of $T_{\rm sw} \gg T_r$. The bandwidth of baseband signal, however, is limited to about 0.8 MHz.

V. Measured Performance

Fig. 4 shows overall performances of measured and calculated results of the proposed transmitter. Measured efficiency is 54.6% when duty ratio is 100%, and decreases as duty ratio decreases. Though the efficiency of the injection-locked oscillator

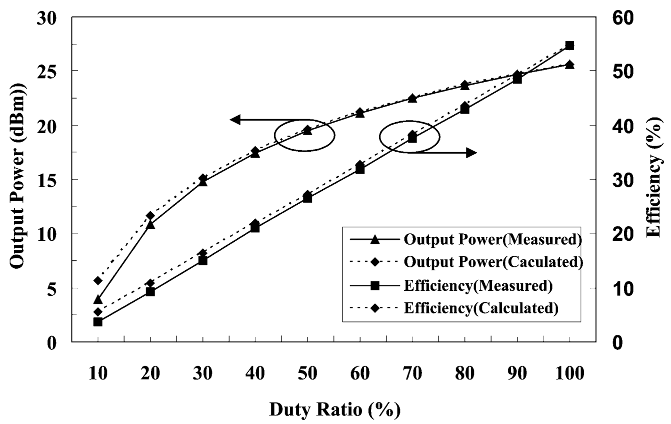

Fig. 4. Measured and calculated efficiency and output power of the proposed transmitter.

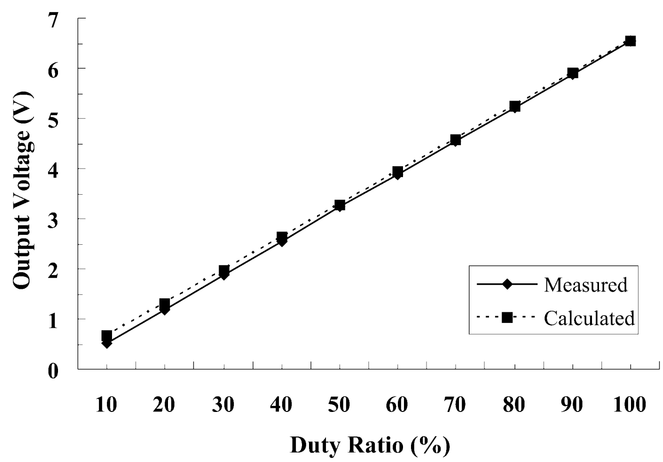

Fig. 5. Measured and calculated output characteristics of the proposed transmitter.

itself is over 64% at on-state, loss of the bandpass filter and the isolator in the transmitter lowers the overall efficiency. Total loss of the bandpass filter and the isolator is about 0.7 dB.

The measured efficiency versus duty ratio is in good agreement with the calculated one except that there exist some error at low duty ratio. In case of low duty ratio that is corresponding to the low input signal, the rising time is not small enough compared to duration of on-time. Therefore, the approximation in Section III is not valid any more at very low input signal. Similarly, the measured output power is in good agreement with the calculated one except at low duty ratio.

Because, the output voltage of the proposed transmitter is determined only by on-time of the injection-locked oscillator, it has ideally perfect linearity independent of an active device. Fig. 5 shows the measured and calculated output characteristics of the proposed transmitter. The measured result is good agreement with the calculated one which is perfectly linear.

Unlike other conventional linear transmitter, the proposed one is more linear as output power increases. The reason is that the duration of on-time of the oscillator is large enough compared to the rising time of the injection-locked oscillator at high output power level. Measurement of error vector magnitude (EVM) has been performed in order to measure the linearity. As predicted, EVM was improved as the output power increased. EVM of the offset quadrature phase-shift-keying (OQPSK) signals was about 4.3% at 20 dB back-off level, but decreased to 3.1% at the highest output power level.

VI. Conclusion

A novel high-efficiency linear transmitter using injection-locked pulsed oscillator is presented. An envelope of RF input signal is modulated by PWM, and switches a class F injection-locked power oscillator on and off. After filtering the pulsed oscillation output by bandpass filter, the input signal is restored. The output voltage of the proposed transmitter is determined only by duration of on-time of the injection-locked oscillator, which enables the transmitter to have high efficiency with good linearity. Furthermore, the thermal effect and back-off for linearity are not needed to be considered any more in this technique.

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