A Power Re-Use Technique for Improved Efficiency of Pulsed Oscillating Amplifiers

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***Abstract*—This letter presents a power re-use technique for pulsed oscillating amplifiers. By rectifying the upconverted switching harmonics of the pulsed oscillating output, some portions of wasted power can be returned to the power supply. The efficiency of the amplifier can be enhanced without degradation of the linearity. The measured results show that the overall efficiency of the amplifier with power re-use is improved up to 22% compared to the pulsed oscillating amplifier without the power re-use at the PCS band.**

***Index Terms*—Injection-locked oscillator, linear power amplifier, power re-use, pulsed oscillating amplifier.**

I. INTRODUCTION

MODERN digital communication systems widely use modulation formats where signal envelopes are not constant. Therefore, linear radio frequency (RF) power amplifiers are required for those applications. Unfortunately, conventional linear power amplifiers such as classes A and AB have poor efficiency. Various techniques have been proposed for improving the efficiency of linear power amplifiers. The author of this letter suggested a pulsed oscillating amplifier (also known as a pulsed "injection-locked" amplifier) [1]. The pulsed oscillating amplifier amplifies the input signal using a class F injection-locked oscillator. The efficiency of the pulsed oscillating amplifier is high due to the class F oscillator. It has good linearity because its output is determined only by the on-time duration of the injection-locked oscillator. Therefore, unlike conventional amplifiers, good linearity can be maintained even at maximum output power. The amplifier, however, has some inherent power loss because of the dissipation of upconverted switching harmonic components in the pulsed oscillating output.

In this letter, a power re-use technique is suggested for improved efficiency of pulsed oscillating amplifiers. Instead of wasting the upconverted switching harmonics generated by the pulsed oscillating output, the unwanted switching harmonics are rectified and returned to the power supply. Since the wasted switching harmonics are recycled as dc power, the efficiency of the pulsed oscillating amplifier can be improved without degradation of the linearity.

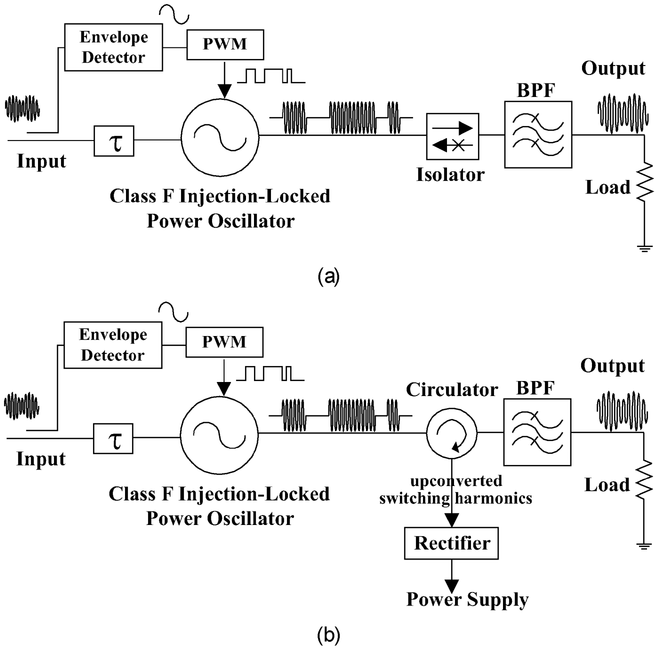

Fig. 1. Block diagram of the (a) pulsed oscillating amplifier and (b) proposed pulsed oscillating amplifier using a power re-use technique.

II. POWER RE-USE IN A PULSED OSCILLATING AMPLIFIER

Fig. 1(a) and (b) shows the block diagram of a pulsed oscillating amplifier and the proposed pulsed oscillating amplifier using a power re-use technique. As shown in Fig. 1(a), a part of the RF input is coupled and is detected by an envelope detector for the pulsed oscillating amplification system. The detected low-frequency envelope is modulated by pulse width modulation (PWM). On the other hand, the RF signal connected to the through port of the coupler is delayed, and then locks the class F power oscillator. The signal of the PWM envelope is applied to the gate of the class F power oscillator, switching it on and off. After the RF pulse train is filtered by a high-Q band pass filter, the amplified RF input is restored with high efficiency. In order to minimize AM/PM of the injection-locked oscillator, a constant-envelope RF input can be injected to it, instead.

Though the isolator in Fig. 1(a) enables the power oscillator to operate stably, the upconverted switching harmonics reflected by the band pass filter are dissipated as heat. In order to reduce power loss, the switching harmonics are recycled as dc power. The reflected switching harmonics enter into the rectifier through the circulator and are recovered back to the dc power supply as shown in Fig. 1(b). Since some portion of power loss from dissipated switching harmonics is reduced, the efficiency

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Manuscript received April 29, 2006; revised June 1, 2006. This work was supported by the University IT Research Center Project of Korea.

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Digital Object Identifier 10.1109/LMWC.2006.882381

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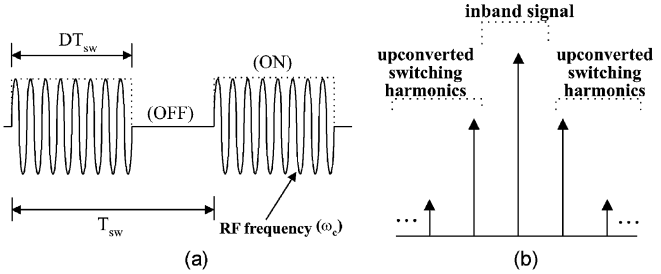

Fig. 2. (a) Time domain waveform and (b) the frequency domain components of the pulsed oscillator output.

of the pulsed oscillating amplifier is improved. The power re-use of the pulsed oscillating amplifier somewhat differs from that of an outphasing amplifier. The pulsed amplifier recycles the upconverted switching harmonics as dc, while the outphasing amplifier recycles combine loss as dc [2], [3].

III. ANALYSIS OF EFFICIENCY OF THE PULSED OSCILLATING AMPLIFIER WITH POWER RE-USE

Fig. 2(a) and (b) shows the time domain waveform and the frequency domain components of the pulsed oscillator output. In this case, the rising time of the oscillating amplifier is very small compared to the switching period $(T_{\rm sw})$ of PWM. D and ω_c in Fig. 2(a) are a duty ratio and a RF carrier frequency of the RF pulse train, respectively. If the upconverted switching harmonic components are recycled as dc, the efficiency of the pulsed oscillating amplifier with power re-use is expressed as in (1) [1]. $\rm P_{out}$, $\rm P_{dc}$, and $\rm P_{re-use}$ in (1) mean the RF output power, the dc bias power from the dc supply, and the recycled power as dc, respectively. Also, $\eta_{\rm rectifier}$ and $\eta_{\rm class\ F}$ represent the efficiency of the rectifier and the class F power oscillator, respectively. The theoretical efficiency of the class F (F1) oscillator is 88.4% [4]

$$\begin{aligned}\eta = \frac{P_{\rm out}}{P_{\rm dc}-P_{\rm re-use}} &= \frac{D^2\cdot\eta_{\rm class\,F}}{D-\sum_{n=1}^{\infty}\left(\frac{1-\cos(2\pi Dn)}{n^2\pi^2}\right)\cdot\eta_{\rm rectifier}}\\ &= \frac{D^2\cdot\eta_{\rm class\,F}}{D^2+(1-\eta_{\rm rectifier})\sum_{n=1}^{\infty}\left(\frac{1-\cos(2\pi Dn)}{n^2\pi^2}\right)}\\ &= \frac{D\cdot\eta_{\rm class\,F}}{D\eta_{\rm rectifier}+1-\eta_{\rm rectifier}}. \qquad (1)\end{aligned}$$

Fig. 3(a) shows the ideal instantaneous efficiency of the pulsed oscillating amplifier without power re-use compared to other traditional power amplifiers. Its efficiency is higher than that of a class B amplifier, but lower than that of a Doherty amplifier. The ideal efficiency of a pulsed oscillating amplifier with power re-use at various rectifier efficiencies $(\eta_{\rm rectifier})$ is plotted against the efficiency of the Doherty amplifier in Fig. 3(b). The $\eta_{\rm rectifier}$ is critical for the efficiency of the amplifier at large back-off point from a maximum power as shown in Fig. 3(b). This is because when a duty ratio is low, the upconverted switching harmonic powers are much larger than the desired inband signal power.

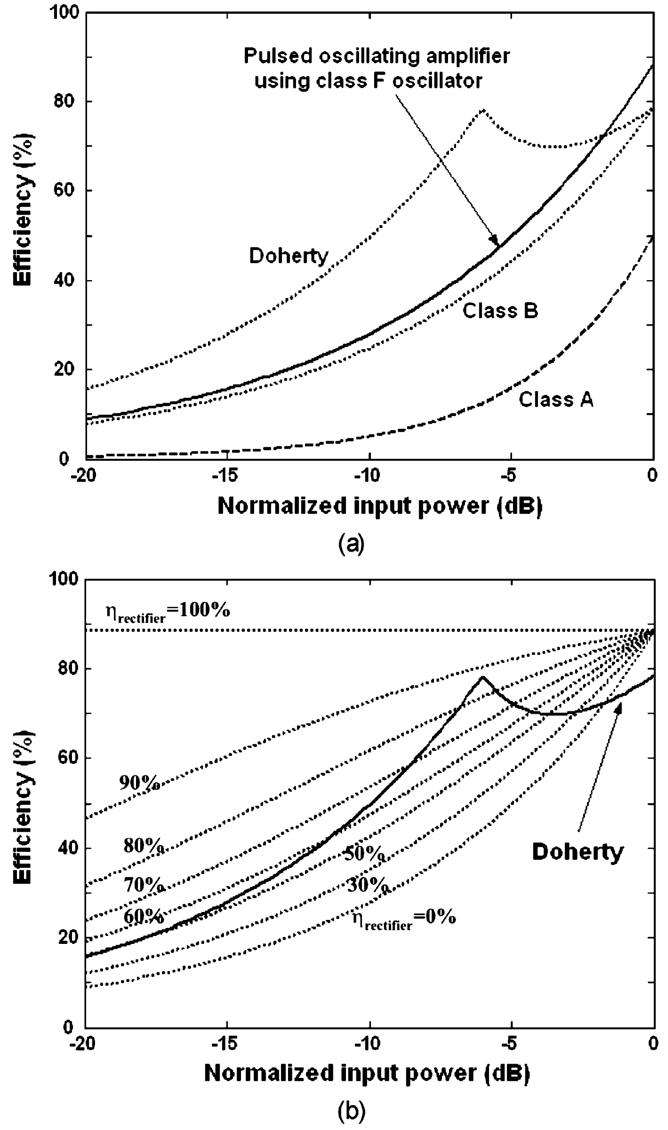

Fig. 3. Ideal instantaneous efficiency of the (a) pulsed oscillating amplifier without power re-use compared to various traditional power amplifiers. (b) Pulsed oscillating amplifier with power re-use technique at various rectifier efficiencies $(\eta_{\rm rectifier})$.

IV. DESIGN OF THE PULSED OSCILLATING AMPLIFIER AND THE RECTIFIER

A Class F injection-locked power oscillator was designed for fundamental locking. The measured efficiency of the injection-locked oscillator was about 64% at 1.865 GHz when the oscillator is on. A GaAs FET device was used to implement the injection-locked oscillator. Its drain bias and dc current are 5.4 V and 124 mA, respectively.

Also, a rectifier for recycling the upconverted switching harmonics was designed. The rectifier is composed of a matching network, a diode, and a low pass filter [5]. RF power enters into the matching network and is clipped by a nonlinear component such as a schottky diode. After filtering the clipped signal by the low pass filter, the RF power can be converted to dc power. The cutoff frequency of the low pass filter must be much lower than

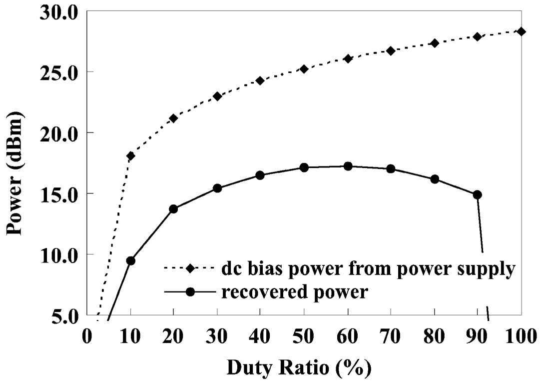

Fig. 4. Measured dc bias power from the power supply and the recovered power by the rectifier.

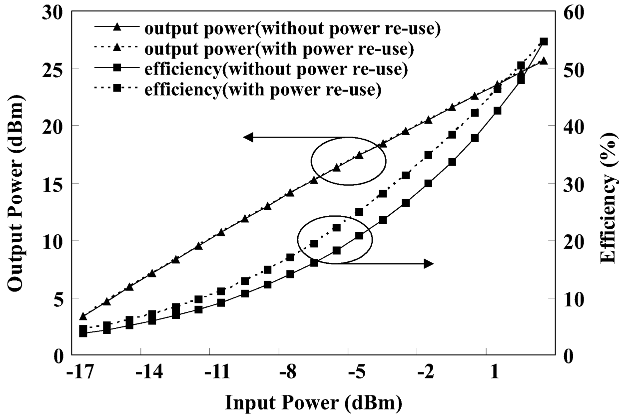

Fig. 5. Measured instantaneous output power and overall efficiency of the pulsed oscillating amplifier with and without power re-use technique.

the switching frequency of PWM in order to eliminate the upconverted switching harmonics. The measured RF–dc conversion efficiency and bandwidth of the rectifier were about 64% and 3% (54 MHz), respectively, at a 1.865-GHz 17-dBm CW input. Because the switching frequency of the PWM is selected to 8 MHz, only several switching harmonic components can be recycled as dc when the upconverted switching harmonics in Fig. 1(b) enter into the rectifier.

Fig. 4 shows the measured dc bias power from the power supply for the oscillating amplifier and the recovered power by the rectifier. The dc bias power from the power supply increases linearly as the duty ratio increases. On the other hand, the recovered power has maximum at duty ratios between 50%–70%. At very high duty ratio, the switching harmonic components in the RF pulse train are small and the dc power converted by the rectifier is small. Also, the recovered power is small at very low duty ratios. The spectrum of the RF pulse train is spread wide at low duty ratio. Therefore, the recovered power is reduced due to the narrow bandwidth of the rectifier. A wideband design of the rectifier can increase the efficiency of the re-use at low duty ratios.

V. MEASURED PERFORMANCE

Fig. 5 shows the measured instantaneous output power and efficiency of the pulsed oscillating amplifier with and without power re-use. Its gain is more than 20 dB due to the positive feedback. In order to maintain stable locking, more than -20 dBm input power was injected. As mentioned above, the measured efficiency of the injection-locked oscillator itself is about 64%. However, considering the loss of the band pass filter and the isolator or the circulator, the overall efficiency of the pulsed oscillating amplifier without the power re-use is about 55%. Its efficiency decreases as input power decrease.

Unlike the recovered power in Fig. 4, the efficiency of the pulsed oscillating amplifier was highly improved at duty ratios between 20%–50%. This corresponds to -10.7 dBm $\sim$ -2.7 dBm input, for which the overall efficiency of the amplifier increases by more than 20%.

VI. CONCLUSION

A power re-use technique for pulsed oscillating amplifiers is presented. Instead of wasting the upconverted harmonic powers generated by the pulsed oscillating output, these are rectified and recovered back to the power supply. Because the wasted switching harmonic power is recycled as dc power, the efficiency of the pulsed oscillating amplifier increases. This technique promises to improve the overall efficiency of the pulsed oscillating amplifier while maintaining its linearity performance.

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