A STUDY ON DRAIN EFFICIENCY OF EDSM/EPWM TRANSMITTER USING CLASS-E AMPLIFIER

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Abstract: Drain efficiency of EPWM (envelope pulse width modulation) transmitter composed of a class-E amplifier is evaluated by circuit simulation, and the pulse modulation method to the constant envelope RF signal by PWM pulses is studied. The class-E amplifier is designed as normal for continuous wave (CW) and constant envelope signals. Each transistor is modeled with an ideal switch and an on-resistor, where the drain-source capacitance is modeled as a linear one together with the shunt capacitor. Simulation results show that the conventional PWM switching method gating the input RF signal produces unnecessary transient responses making the drain voltage rise and the output signal distorted; the efficiency is degraded. Another method that gates the DC supply voltage by the PWM pulses works as expected and intended, and the result shows the drain efficiency is as high as that of a class-E amplifier driven with a CW signal.

1 INTRODUCTION

Linear modulation schemes, band-limited PSKs and multilevel QAM combined with OFDM (Orthogonal Frequency Division Multiplex) are widely used for recent mobile radio communications such as for wireless LANs, and terrestrial digital television broadcasting due to high spectrum efficiency and tolerance to multipath distortion, The modulated radio signal, however, has dynamically varying envelope and high peak power to average power ratio (PAPR). Although power amplifiers of class-B/C/D/E/F can operate with high efficiency especially in saturated region, these nonlinear amplifiers cannot be used for those linear modulation signal due to degradation of modulation accuracy and spectral regrowth at the adjacent channels.

Several techniques using nonlinear amplifiers for linear modulations have been proposed, Doherty (Doherty, 1936), Cartesian loop, feed-forward, and so on (Raab et al., 2002). Among these techniques, Kahn Envelope Elimination and Restoration (EER) (Kahn, 1952) is recently being studied well and its applicability is shown for microwave transmitters (Raab et al., 2002) and the IEEE 802.11a/g wireless LAN systems using QAM with OFDM (Diet et al., 2004). Furthermore for better linearity and efficiency, direct RF modulation techniques by the PWM pulses digitized from the envelope signal have been studied for these ten years (Adachi et al., 2002; Wang, 2003; Taromaru et al., 2007; Yokozawa and Yamao, 2011). This transmitter architecture is called envelope delta-sigma modulation (EDSM)(Dupuy and Wang, 2004), or envelope pulse width modulation (EPWM)(Yokozawa and Yamao, 2011; Takahashi and Yamao, 2010). With the EDSM/EPWM architecture, the direct pulse modulation causes considerable switching spurious or quantization noise at the output of the power amplifier, which should be eliminated with a band-pass filter (BPF). Some experiments or circuit simulation studies have been made for EDSM/EPWM transmitter using class-E (Wang, 2003; Dupuy and Wang, 2004) and class-F (Takahashi and Yamao, 2010; Choi et al., 2007) amplifiers. However, the burst RF mode operation and the transient response due to the pulse modulation are not well studied although the transient response directly affects the drain efficiency.

In this paper, drain efficiency of EPWM transmit-

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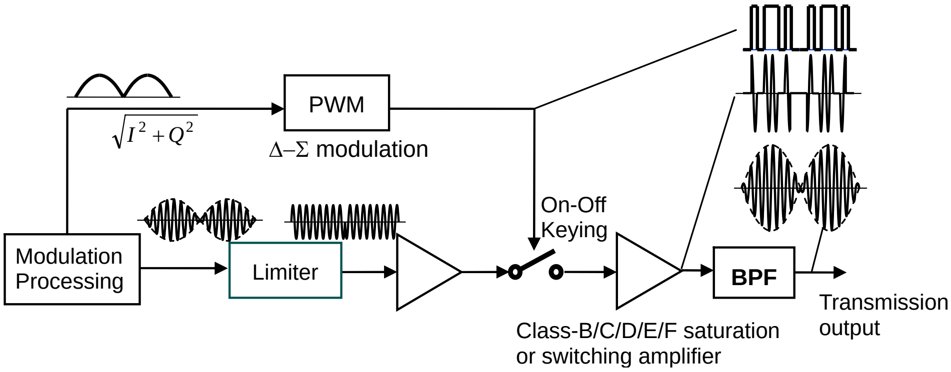

Figure 1: EDSM/EPWM transmitter

ter composed of a class-E amplifier is evaluated by circuit simulation, and the method of pulse modulation by PWM pulses is studied.

2 EDSM/EPWM Transmitter Using Class-E Power Amplifier

2.1 EDSM/EPWM Architecture

Figure 1 shows the block diagram of the EDSM/EPWM transmitter architecture. The left half portion, which is common to conventional EER transmitters, generates digitized PWM pulses of the envelope signal $A(t) = \sqrt{I^2(t)+Q^2(t)}$ and the phase-modulated constant envelope RF signal expressed as $\mathrm{Re}\left[[\{I(t)+jQ(t)\}/A(t)]\exp(j2\pi f_c t)\right]$, where $I(t)$ and $Q(t)$ are the in-phase and quadrature component of the desired modulation respectively, $\mathrm{Re}\,z$ is the real part of complex number z, and f_c is the carrier frequency. In this architecture, the PWM pulse directly drives the RF switch, which is implemented as Gilbert cell mixer or DC bias switching of the amplifier circuit to make the RF signal in burst shape. The burst RF signal becomes amplitude modulated signal whose envelope is proportional to the duty ratio of the PWM pulse through the BPF. With this architecture, all RF amplifiers can be nonlinear ones and free from AM-PM conversion because the amplifiers are driven by a constant envelope signal or zero. Additionally, since the amplitude is controlled by the pulse width, near 100% deep AM can be performed, so long as the isolation of the RF switch is enough.

2.2 Class-E Amplifier

Figure 2 shows the circuit topology of the class-E amplifier. The MOS transistor works as a switch and driven with the RF input signal. The series resonant tank circuit is tuned approximately on but slightly lower than the carrier frequency depending on the resonance Q factor (Albulet, 2001). The shunt capacitance is composed of the external capacitor C_S' and the drain-source capacitance C_{DS}, which is nonlinear.

3 Circuit Simulation

3.1 Circuit Design and Simulation Model

The class-E amplifier is designed normally for continuous wave, for this study. The designed schematics are shown in Figs. 3 and 4. Each transistor is modeled with an ideal switch and an on-resistor where the drain-source capacitance C_{DS} is modeled as a linear one together with the shunt capacitor as $C_S =$

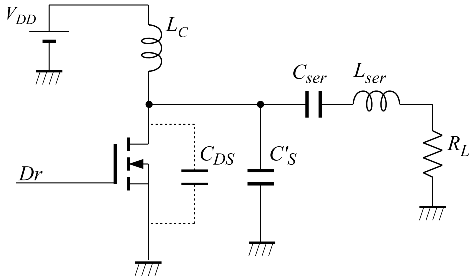

Figure 2: Class-E amplifier.

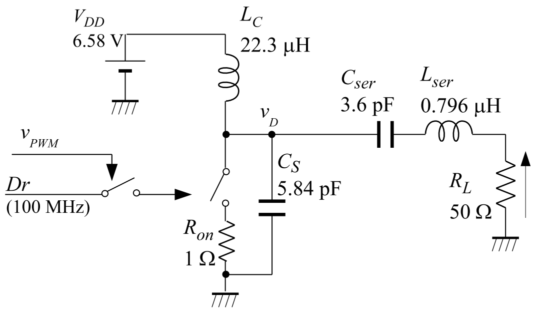

Figure 3: Simulation schematic of RF switching case. PWM pulse modulation is implemented at the RF inputs.

$C'_S + C_{DS}$. The Q factor of the series LC resonator is set to 10, and the carrier frequency is 100MHz. The load impedance $R = 50\,[\Omega]$, and the output power is 27 dBm for CW. All the inductance and capacitance values are designed in accordance with the way described in (Albulet, 2001). The on-resistance of the transistors are assumed $1\,\Omega$. In the case of Fig. 3, the envelope PWM modulation, making the burst switching of RF input, is implemented at the RF inputs as assumed or designed in (Wang, 2003; Dupuy and Wang, 2004), while it is done at the drain DC bias circuits in the case of Fig. 4 as described in (Choi et al., 2007). In this paper, the former and the latter configurations are hereafter called "RF switching" and "DC switching" respectively. Note that in the former case, the RF switching operation of both the transistors stops and they are kept open during each off duration of the PWM pulses, while they continue RF switching all the time. The diode in Fig. 4 at the right side of the PWM switch driven by the PWM pulse v_{PWM} work as a "free wheel diode" and they are turned-on by the current charged in the choke inductor L_C; the DC bias current of drain is somewhat filtered, and the pulsation due to PWM is smoothed.

3.2 Simulation Parameters and Condition

For PSPICE simulation, the input RF signal Dr is defined as rectangular pulses of 100 MHz without phase modulation (CW). The PWM pulse v_{pwm} is assumed to be a couple of the fixed period $T_{PWM} = 0.1,\ 1\,[\mu\text{s}]$, and the drain efficiency is evaluated varying the duty ratio of the PWM pulse. The drain efficiency is calculated from the averaged power consumption at the load R_L and the supplied DC power from the DC sources. It must be mentioned that the output power gradually rises where the time constant is determined by the choke inductance, the on-resistance and etc, so

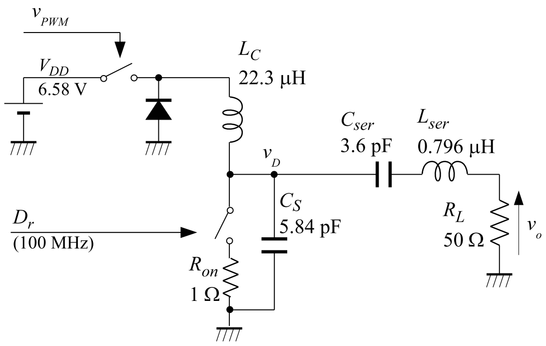

Figure 4: Simulation schematic of DC switching case. PWM pulse modulation is implemented at the drain DC bias circuits.

the power is averaged during the $5\,\mu$s after elapsing $5\,\mu$s.

3.3 Simulation Results

Figure 5 shows the waveforms in the RF switching case, where the duty ratio of PWM is 50%. The upper waveform is the drain voltage of the main amplifier v_S, the lower ones are PWM pulse v_{PWM}, RF input Dr, which is rectangular waveform to drive the transistor modeled as a switch and a on-resistor, and the output signal v_o. Since the CW output is designed 0.5 W and the PWM duty is 0.5, the output power is expected $0.5 * 0.5^2 = 0.125\,\text{W}$; however, It is seen that only 50 mW power is gained and not a few distortion is observed. Therefore, this configuration is unsuitable.

Figure 6 the wave forms in the DC switching case, where the duty ratio of PWM is 20%. The upper waveform is the drain voltage v_D, and the lower ones are PWM pulse v_{PWM}, RF input Dr defined as rectangular wave, and the output signal v_o. In this case, the output power is gained as expected since the root mean square of v_o is seen to be around 2.6 V. It can also be seen that there are little distortion and ripples of the envelope about v_o. The output spectrum is shown in Fig. 7. The spurious due to PWM switching, to apper $100 \pm 10\,\text{MHz}$, is observed to be suppressed by 28 dB to the fundamental component of the carrier. Drain efficiency due to the duty ratio of the PWM pulse is shown in Fig. 8. The efficiency a little degrades in the lower duty region because of the switching loss.

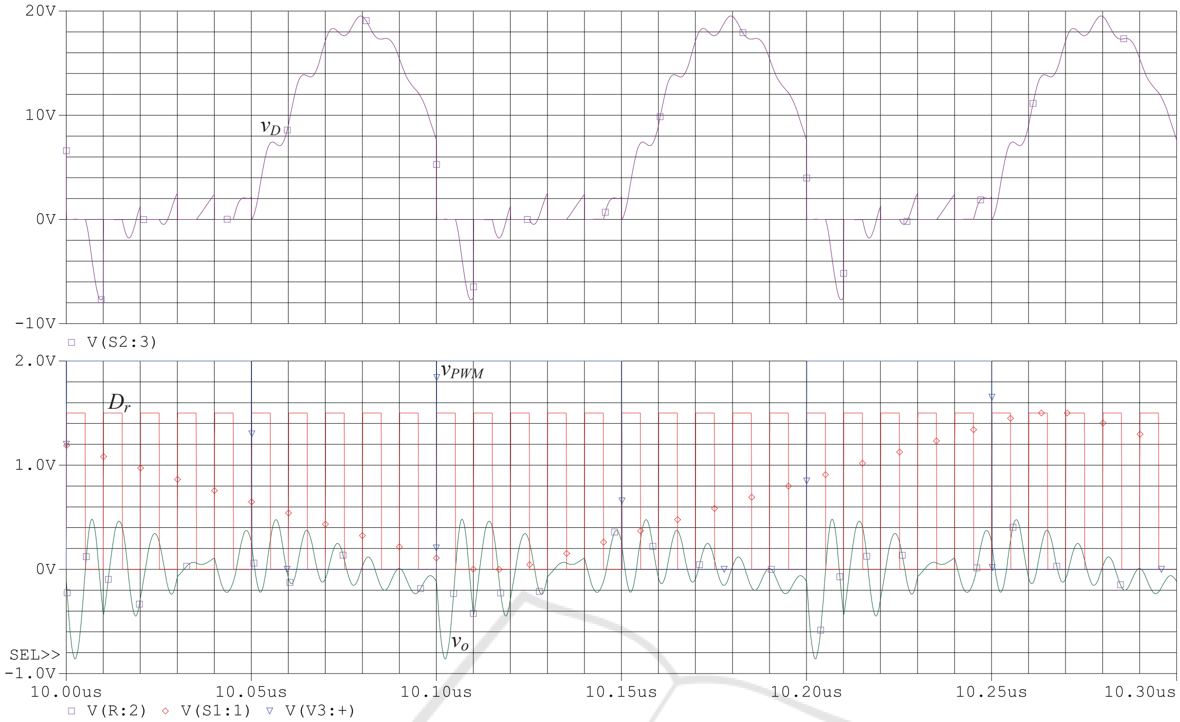

Figure 5: Simulated waveforms of RF switching case.

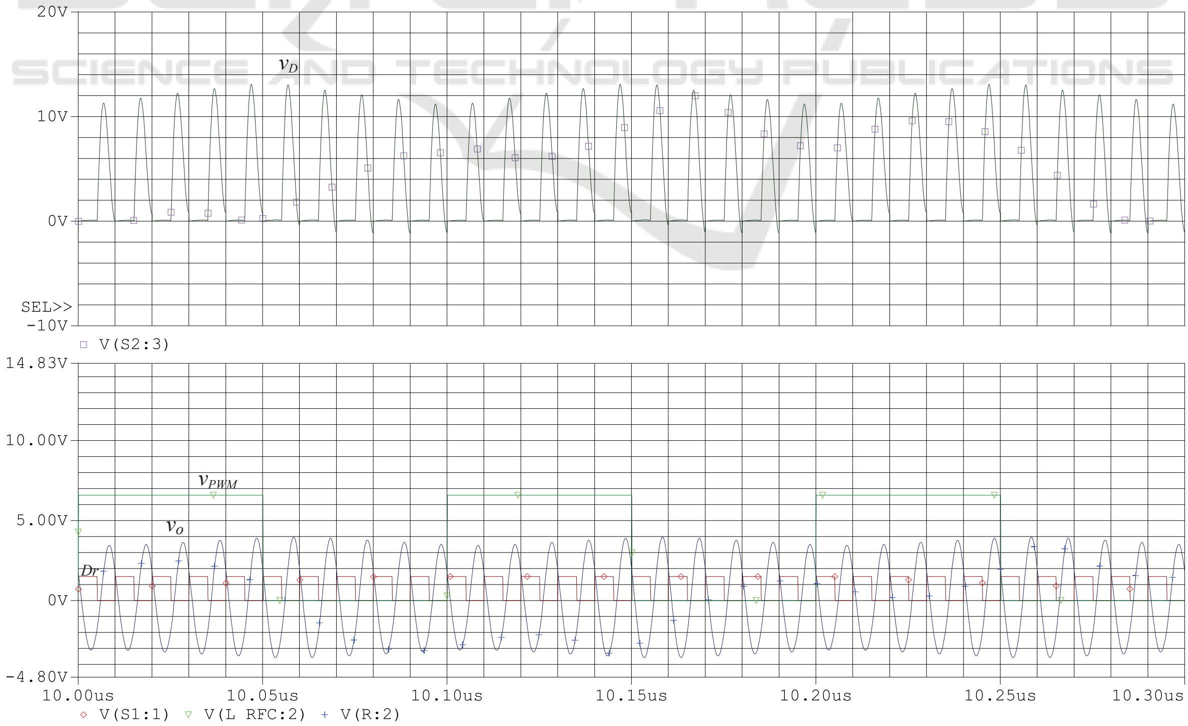

Figure 6: Simulated waveforms of DC switching case.

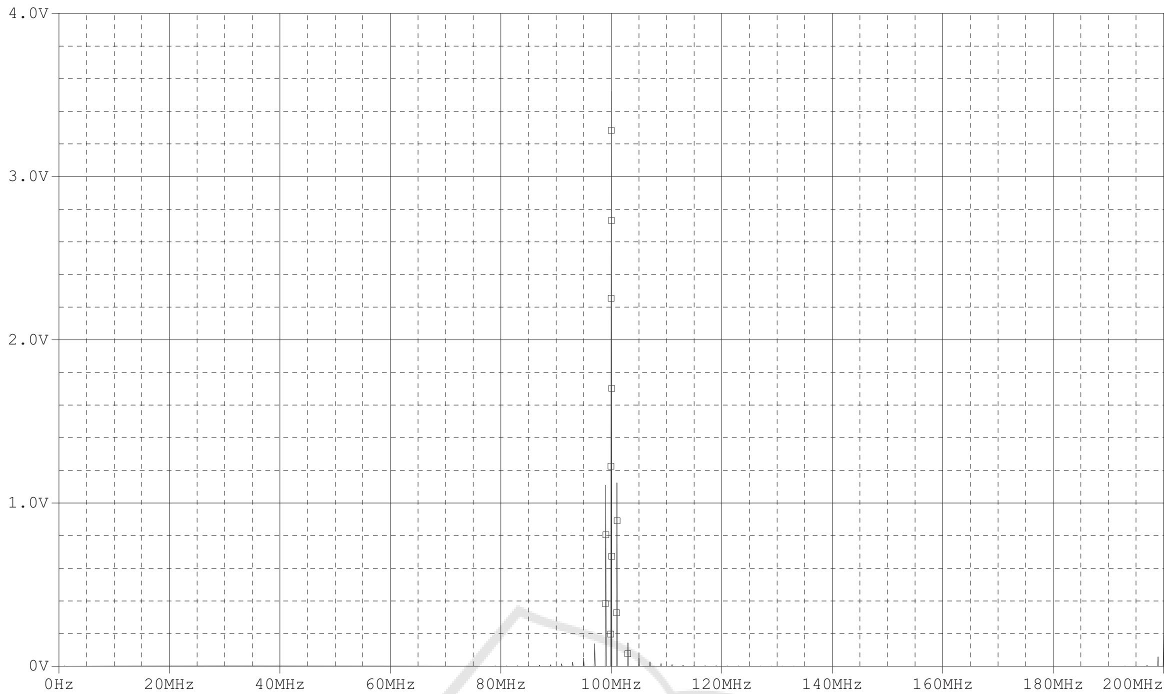

Figure 7: Output spectrum of DC switching case.

3.4 Discussions

Above-mentioned simulation results show that an EDSM/EPWM transmitter using a class-E amplifier should be configured as the DC switching for envelope pulse modulation. However, the PWM signal power to drive the switching device must be higher than the RF switching case and it might not be ignored. The degradation in the RF switching case is clearly caused by transient response after turn-off of every PWM pulse due to the charged current in the drain choke inductors. Note that the choke inductors operate as a low-pass filter to smooth the pulsation of PWM and reduce the PWM spurious or the quantization noise at the output more than the series resonator tank as the BPF where Q is only 10. Therefore, the undesired transient response and loss could be mitigated if the choke components are replaced by LC-resonators or quarter-wavelength stubs as the class-F amplifier case in (Takahashi and Yamao, 2010); however, the filtering effect of the choke inductor cannot be used any more, so the requirement of BPF characteristics becomes severe, sharper cutoff with low insertion loss. Combination of an inductor and a quarter-wavelength stub might be good.

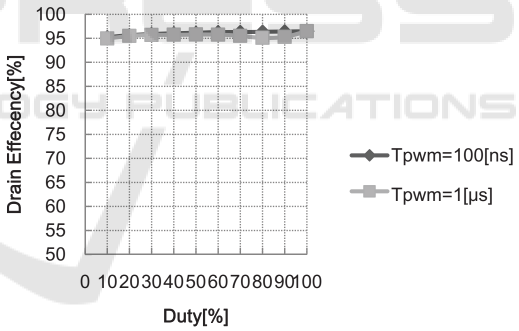

Figure 8: Drain efficiency due to PWM duty (DC switching case).

4 Conclusion

Drain efficiency of EDSM/EPWM transmitter composed of a class-E amplifier is evaluated by circuit simulation, especially on envelope pulse modulation method. Simulation results show that the RF switching method produces unnecessary transient responses and loss, and the output signal distorted, if the drain choke circuits are inductors. Another method that gates the drain DC bias by the PWM pulses works expectedly and the drain efficiency as high as expected; however, it must be noted that the DC switching is done by a transistor and the driving power may not be ignored. This transmitter architecture has to be carefully designed with above-mentioned trade-off.

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