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Abstract

Design approach of wideband envelope termination for high efficiency RF power amplifiers (PAs) is discussed, considering power loss subject to design constraints including envelope bandwidth, inductor quality factor, and transistor output impedance. Analysis shows that the optimum envelope termination topology depends on the design constraints. For LTE-Advanced transmission with 80-MHz channel bandwidth, a novel wideband envelope termination is designed using an AC-terminated third order LC filter (LCF-ET), providing 3-dB envelope impedance bandwidth of 150 MHz. Measured results demonstrate 1.75- dB envelope power loss and -39.2-dB normalized root-mean-square error (NRMSE) with the LTE envelope signals. For the LTE signal with 10.3-dB peak-to-average power ratio (PAPR), the average power efficiency of an ideal Class-A RF PA with the LCF-ET prototype is calculated as 33.4% from the measured 1.75-dB envelope power loss, which exceeds the 4.7% and 24.0% average power efficiency of conventional Class-A and Class-B PAs without envelope termination.

Electronics Letters

Design considerations on wideband envelope termination for high efficiency RF power amplifiers

SungWon Chung, Rui Ma and Koon Hoo Teo

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Introduction: Envelope injection and termination (EIT) technique for Class-A RF power amplifiers (PAs) improves average power efficiency by dynamically modulating PA supply voltage using a passive envelope termination [1]. Compared to envelope tracking systems [2], which require an additional envelope amplifier for PA supply modulation, EIT technique provides comparable average power efficiency with reduced complexity and low cost. Envelope termination can be also used with Class-AB PAs, Doherty PAs [3], and outphasing PAs [4] for additional efficiency enhancement.

This letter presents key design considerations on wideband envelope termination for high efficiency RF PAs using EIT technique. It is shown that, with a proper selection of inductors subject to design requirements on envelope bandwidth and power transistor output impedance, *envelope termination with an AC-terminated LC filter (LCF-ET)* [5] overcomes both the bandwidth and the efficiency limitation of the *conventional envelope termination with a parallel LC-resonator (PR-ET)* [1]. We also show that PR-ET is preferred over LCF-ET when power transistors have a high output resistance.

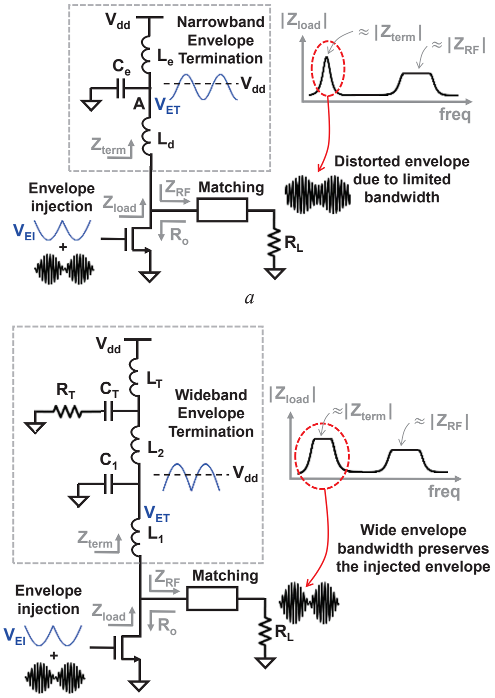

Fig. 1 *Envelope injection and termination (EIT) RF power amplifiers (PAs)*
a using envelope termination with a parallel LC-resonator (PR-ET)
b using envelope termination with an AC-terminated LC-filter (LCF-ET)

Envelope termination with a parallel LC-resonator (PR-ET): Fig. 1*a* shows a conventional PR-ET for EIT RF PAs. The envelope signal V_{EI} is injected to the PA (e.g., power field-effect transistor) input. For the envelope signal, the RF choke inductor L_d is chosen to provide short circuit impedance whereas the LC resonator (L_e and C_e) provides high envelope termination impedance Z_{env}. The node A is modulated by the injected envelope signal V_{EI}, providing a dynamically modulated supply voltage V_{ET} to the PA and thus improving power efficiency. When the low and high cut-off frequencies of a PR-ET are given as ω_l and ω_h with low frequency large-signal transistor output resistance R_o, we find that the LC resonator can be designed as

$$L_e = \frac{R_o\left(\sqrt{\omega_h/\omega_l} - Q/(1+Q^2)\right)}{\sqrt{\omega_l\omega_h}},\ C_e = \frac{1}{\omega_l\omega_h L_e} \tag{1}$$

where Q is the quality factor of the inductor L_e. When Q is high, the inductance L_e can be approximated as R_o/ω_l.

For a design example, with $f_l = \omega_l/2\pi = 1$ MHz and $R_o = 25\ \Omega$, the resonator will consist of a 4-μH inductor. For 100-MHz RF channel bandwidth, PR-ET needs around 200-MHz bandwidth [6], which is typically beyond the self-resonance frequency (SRF) of a 4- μH inductor. Hence, PR-ET has been used with EIT PAs with RF channel bandwidth below 10 MHz [1].

The power loss of the PR-ET is the sum of the envelope power loss and the DC power loss introduced by the envelope termination, which can be estimated in decibel (dB) unit as

$$\begin{aligned} L_{PR} &= 10\log_{10}\left(1+\frac{R_o}{R_{term}}\right) + 10\log_{10}\left(1+\frac{R_{term}}{R_o(1+Q^2)}\right) \\ &= 10\log_{10}\left(1+\frac{1}{Q}\sqrt{\frac{\omega_h}{\omega_l}} + \frac{\sqrt{\omega_h/\omega_l}}{(1+Q^2)\sqrt{\omega_h/\omega_l} - Q}\right) \end{aligned} \tag{2}$$

where R_{term} is the envelope termination impedance at the resonance of the LC tank, which is given as $L_e(\omega_h\omega_l)^{0.5}(1+Q^2)/Q$ with a simple inductor model [7]. This result confirms that the power loss of PR-ET increases as the bandwidth increases. 3-dB loss occurs with the previous design example, if Q is 15, which is challenging to achieve with 4 μH at 200 MHz.

Envelope termination with an AC-terminated LC filter (LCF-ET): Fig. 1*b* shows an LCF-ET based on a third-order LC low pass filter [8] consisting of L_1, L_2, and C_1. AC-termination is made by R_T and C_T for frequency $\omega_l > 1/(R_T C_T)$ while the supply is isolated by the choke L_T. The fundamental advantage of LCF-ET compared to PR-ET is that inductors with a smaller inductance and a higher Q can achieve the same bandwidth. For 200-MHz envelope bandwidth, the inductors L_1, L_2 are below 150 nH, which can provide Q over 200 at 200 MHz, allowing low power loss.

The power loss of the LCF-ET in decibel (dB) unit is obtained as

$$\begin{aligned} L_{LCF} &= 10\log_{10}\left(1+\frac{QR_o}{\omega_h(L_1+L_2)+QR_T}\right) \\ &\quad + 10\log_{10}\left(1+\frac{\omega_h(L_1+L_2)+QR_{DC}}{QR_o}\right) \end{aligned} \tag{3}$$

where R_{DC} is the DC resistance of the choke L_T and the quality factor Q of the two inductors L_1, L_2 is assumed to be same.

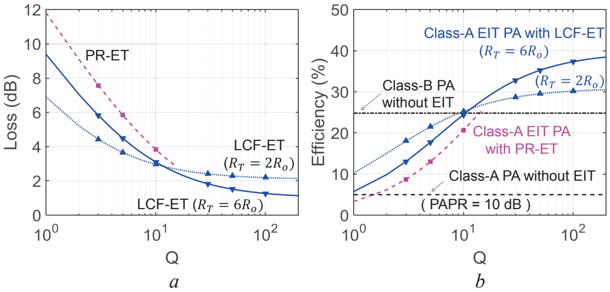

Fig. 2 *Comparison of envelope termination with 200-MHz 3-dB bandwidth by analysis (solid and dashed lines) and circuit simulation (dots)*
a Power loss
b Average power efficiency of an ideal Class-A EIT PA

Power Loss Optimization of Envelope Termination: Fig. 2*a* shows the power loss of PR-ET and LCF-ET with a 3-dB envelope bandwidth of 200 MHz from the analysis (2)–(3) and circuit simulation, assuming 2-Ω DC resistance of a choke and 25-Ω FET transistor output resistance. The average power efficiency of an ideal Class-A EIT PA using the two envelope terminations (Fig. 2*b*) is predicted for modulated signals with 10-dB peak-to-average power ratio (PAPR) and normal distribution of envelope amplitudes. A large AC-termination resistance R_T reduces envelope power loss, but increases DC power loss since a large R_T in turn increases L_1 and L_2. When the ratio of R_T to R_o is between 2 and 6, envelope power loss and DC power loss are reasonably balanced, achieving up to 5-15% higher average efficiency than ideal Class-B PAs. Fig. 2 shows that the optimum ratio depends on inductor Q.

For a large envelope bandwidth with a low transistor output resistance, as exemplified in Fig. 2 with 200-MHz bandwidth and 25-Ω R_o, LCF-ET provides a higher efficiency. On the contrary, with a high transistor output resistance, which in turn requires a large inductance with LCF-ET, it can be shown from the analysis (2)–(3) that the envelope power loss of PR-ET may become smaller than LCF-ET.

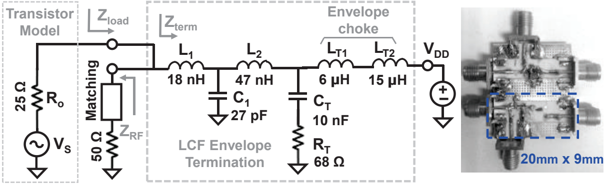

Fig. 3 *Prototype envelope termination: LCF-ET for 80-MHz bandwidth LTE*

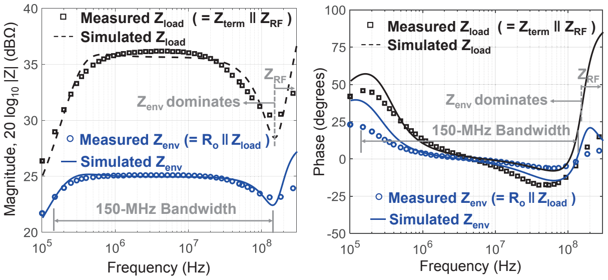

Fig. 4 *Measured frequency response with the LCF-ET prototype*

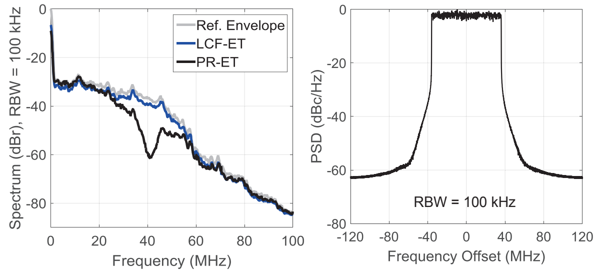

Fig. 5 *Measured LTE envelope spectrum with the LCF-ET prototype for a wideband envelope reference signal (left). The envelope reference signal is obtained from LTE transmission with 80-MHz channel bandwidth (right)*

Measured Results: Fig. 3 shows an experimental LCF-ET prototype fabricated on a Rogers RO4350 substrate with 20-mil thickness. The LCF-ET prototype is designed for LTE transmission with 80-MHz channel bandwidth. The inductors L_1 and L_2 are from Coilcraft 1206CS series, which have Q higher than 70 at 200 MHz. A 6-µH BCR-652JL broadband conical inductor cascaded with a 15-µH chip inductor is used as an envelope choke. Fig. 4 shows the measured envelope impedance Z_{load}, which is the envelope termination impedance Z_{term} in parallel with Z_{RF} from PA output matching. The measured 3-dB bandwidth of overall envelope impedance Z_{env} $(= R_o \parallel Z_{RF} \parallel Z_{term})$ is 150 MHz.

The LCF-ET prototype is tested with modulated signals. The measured envelope spectrum is shown in Fig. 5. The reference envelope signal is obtained from LTE-Advanced transmission with 80-MHz channel bandwidth and 10.3-dB PAPR with which complementary cumulative distribution function (CCDF) is 0.01%. An envelope spectrum with a PR-ET, which has 3-dB envelope impedance bandwidth of 23-MHz, is compared to exhibit the impact of bandwidth limitation. The gain and DC offset of the measured envelope are corrected by a least-mean-square (LMS) method for comparison with the reference signals (Fig. 6). The LCF-ET prototype achieves -39.2-dB normalized root-mean-square error (NRMSE). The measured average envelope power loss is 1.75-dB, which well matches the prediction in Fig. 2*a* based on the analysis (2)–(3). For the LTE signal with 10.3-dB PAPR, the average efficiency of an ideal Class-A RF PA with EIT technique using the LCF-ET prototype is 33.4%, which is calculated from the measured envelope power loss, exceeding the 4.7% and 24.0% average efficiency of conventional Class-A and Class-B PAs.

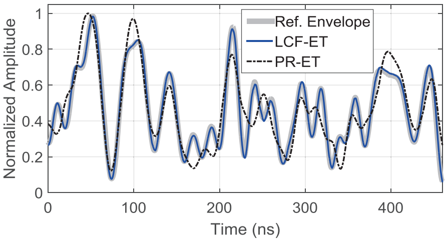

Fig. 6 *Measured transient LTE envelope signals with the LCF-ET prototype after the correction of gain and DC offset*

Conclusion: This article presents design considerations to minimize the power loss of wideband envelope termination. These considerations facilitate RF PAs with envelope injection and termination (EIT) technique to enhance average power efficiency with reduced complexity and low cost for challenging wideband RF applications.

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