Broadband monolithic S-band class-E power amplifier design

This efficient broadband monolithic class-E power amplifier operates at S-band and employs a 0.3 µm x 1000 µm pHEMT device. The amplifier's measured performance shows a peak power-added efficiency (PAE) of 90% and a peak output power of greater than 23 dBm at 3.25 GHz.

By Reza Tayrani

Highly efficient microwave and RF power amplifiers are required for many commercial as well as defense system applications. These include wireless LANs, cell phones and telecommunication systems as well as advanced airborne active phased array radar systems. The choice of technology, design methodology and manufacturing cycle time are major cost contributors in these systems. A simple and accurate design can be successful for realization of switching mode, class-E high-efficiency power amplifiers in the S band.

The design of class-E amplifiers is based on using a series or parallel resonant load network. The current and voltage time-waveforms at the active device output terminal are optimized in such a way as to minimize the DC power dissipation within. The active device acts as a switch, driven by the RF input signal to on and off conditions. The ideal AC load lines for switching transistors (class D, E, F)

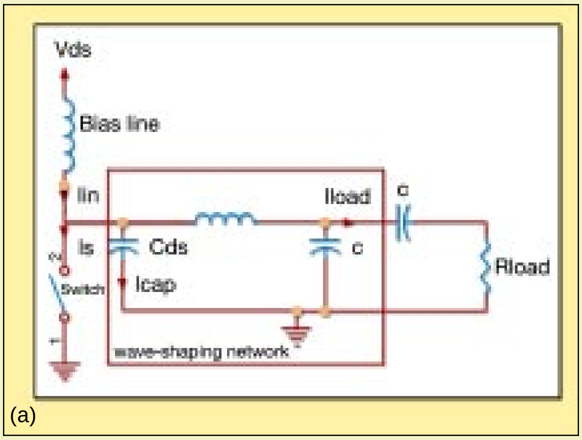
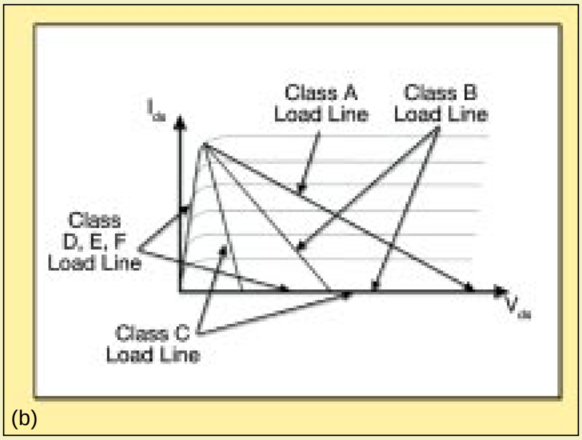


Figure 1. (a) Ideal switching amplifier circuit (shunt load).
(b) Ideal transistor load lines for several classes of operation..



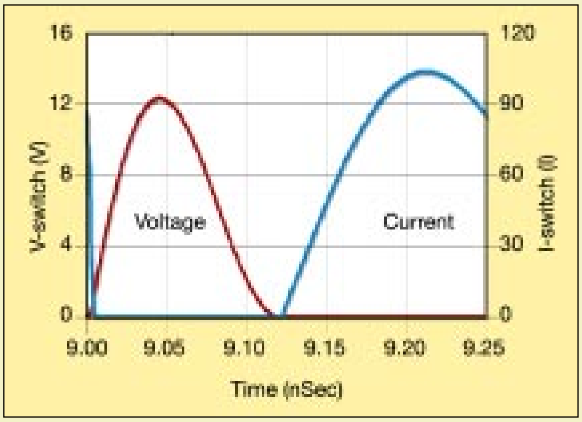


Figure 2. Switch voltage and current waveforms for circuit (1a).

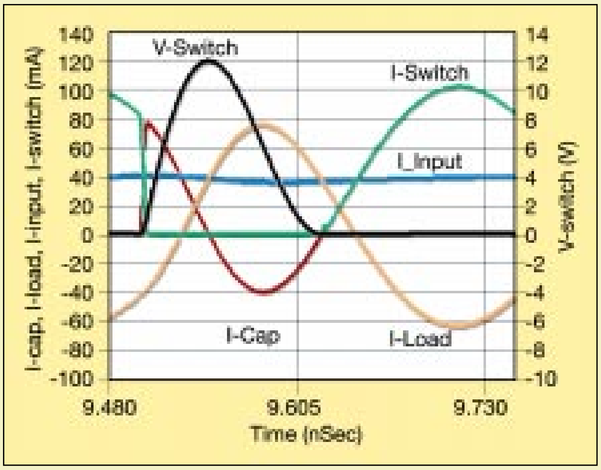


Figure 3. Current-voltage waveforms for circuit (1a).

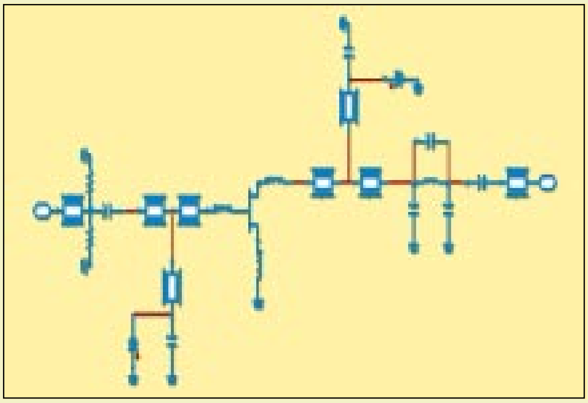


Figure 4. S-band Class-E amplifier circuit.

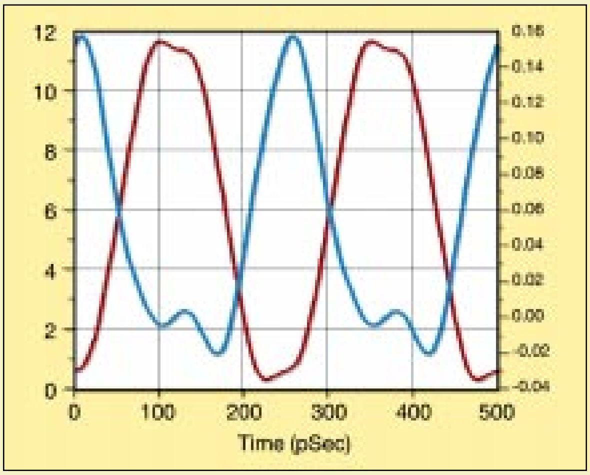


Figure 5. Simulated waveforms of the class-E amplifier.

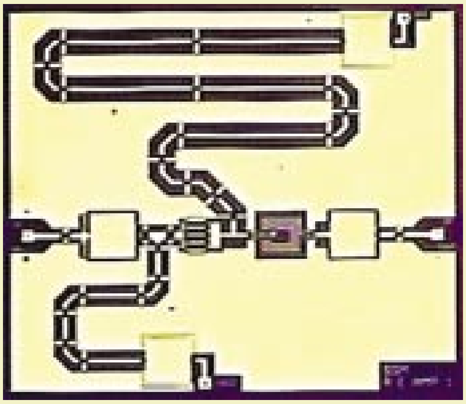


Figure 6. MMIC amplifier chip.

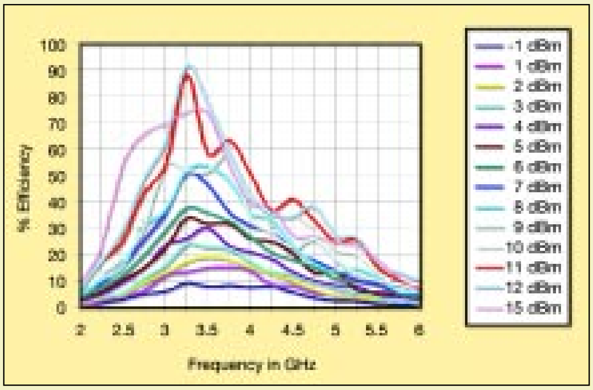


Figure 7. Measured PAE vs. frequency bias (Vds=5V, Vgs=-1V).

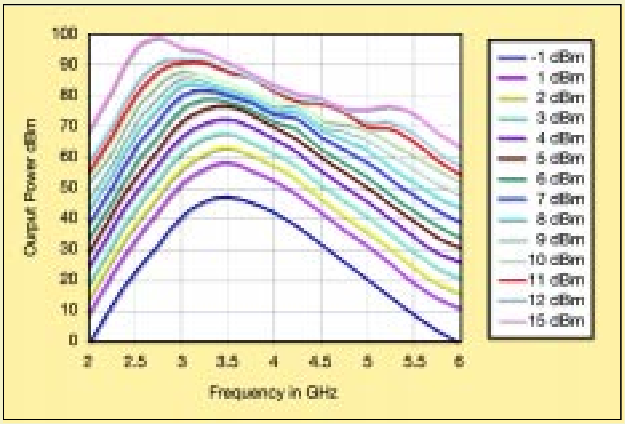


Figure 8. Measured output power, vs. frequency bias (Vds=5V, Vgs=-1V).

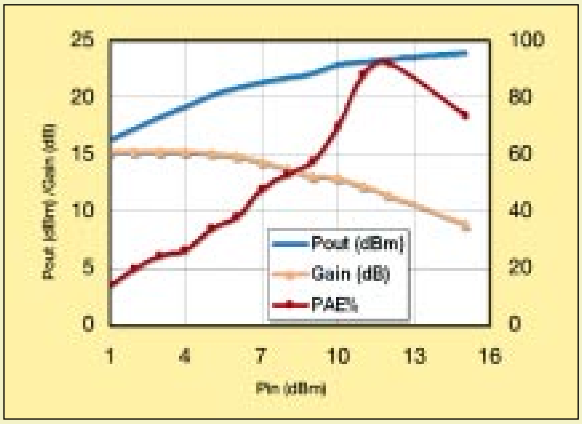


Figure 9. Measured output power, PAE, and gain vs. input power at 3.25 GHz.

are shown in Figure 1(b). It can be seen that the operating point moves along the Vds and Idss axes; i.e. the device is either off (in the saturated region) or on (in the linear region). Under this ideal switching operation, the output voltage and current waveforms at the device output terminal do not simultaneously exist and, therefore, the dissipated energy within the device is zero, leading to 100 percent theoretical power conversion efficiency.

With the advent of active-device performance, non-linear modeling and monolithic circuit technology in the last few years, significant progress has been made toward the development of high-efficiency RF and microwave components. In the case of class-E high efficiency power amplifiers, the circuit designers have pushed the useful operating frequency of these circuits to ever-higher frequencies [1-3].

With this design, we have made a special effort to optimize the amplifier's lumped-element load network in a coplanar waveguide (CPW) environment for the highest PAE attainable while maintaining a minimum of 23 dBm output power. All aspects of non-linear device modeling and circuit simulations, including time domain analysis, harmonic balance (HB) analysis and large signal stability analysis, were performed using Agilent ICCAP and ADS simulators respectively [4].

Design methodology

The detailed analysis and derivation of the ideal load networks for class-E amplifiers are fully discussed elsewhere [1]. Knowing the device drain to source capacitance (C_{ds}) and the drain voltage (V_{ds}), an approximate maximum frequency (f_{max}) for class-E operation can be obtained. Similarly, assuming a load resistance of 50 Ω, approximate values for the circuit elements (L and C) of the shunt load network shown in Figure 1(a) can be obtained by using the following expressions:

$$f_{\max} = \frac{I_{\max}}{56.5 C_{ds} V_{ds}},$$

$$L = \frac{0.28}{\omega^2 C_{ds}} \left[\sin\theta + \cos\theta_0 \sqrt{\frac{\omega_s C_{ds} R}{k_0 \cos\theta} - 1} \right]$$

$$C = \frac{1}{\omega_s R} \sqrt{\frac{\omega_s C_{ds} R}{k_0 \cos\theta_0 - 1}}$$

where $k_0 = 0.28$, $\theta_0 = 49.05°$, $\omega = 2\pi f_{\max}$.

Having obtained the starting values for the load network, a time-domain simulation was performed to optimize the current and voltage waveforms at appropriate terminals of the ideal class-E circuit shown in Figure 1(a).

Figure 2 shows the simulation results for the circuit after optimization of the load network. The voltage waveform across the switch rises slowly at switch-off and falls to zero at the end of the half-cycle. It also has a zero rate of change at the end of half-cycle, thereby ensuring a “soft” turn-on condition. The voltage across the switch when it is off is defined by the integral of the current flowing through C_{ds}. The phase shift introduced by the LC circuit adjusts the point at which the current is diverted from the switch to the capacitor C_{ds}. Therefore, to ensure class-E operation, it is essential that the integral of capacitor current over the half-cycle is zero and that the capacitance current has dropped to zero by the end of the half-cycle. Figure 3 shows that the optimized current and voltage waveforms comply with the aforementioned criteria for the class-E amplifiers.

The majority of the existing non-linear pHEMT models available in the commercial circuit simulators are not suitable for modeling class-E circuits. For accurate modeling of switching mode amplifiers, the model should have the following important properties:

- bias dependency of drain-to-source $C_{ds}(V_{ds},V_{gs})$ and gate-to-drain C_{gd} (V_{ds},V_{gs}) capacitances.
- bias dependency of input channel resistance R_i (V_{ds},V_{gs}).
- bias dependency of output channel resistance $R_{ds}(V_{ds},V_{gs})$.
- a two current generator dispersion model for accurate simulation of R_{ds}.

Any non-linear models that model the dispersive behavior of the output resistance by a simple-series resistor-capacitor network, connected in parallel to the standard output network, should be used with care. In such a case, the loading effect of the series resistor-capacitor network on the output resistance should be removed.

After careful observation of the available non-linear models, we decided on the Eesof GaAs HEMT (EEHEMT) model [1] as a suitable choice for the non-linear simulation of class-E amplifiers. The most distinguishing features of this model for class-E are the ability to model R_{ds}(Vds, Vgs) and its dispersion effect, as well as the bias dependency of the device capacitance.

The design objective was to develop a highly efficient class-E monolithic amplifier operating over 3-5 GHz using a 0.3 µm x 1000 µm pHEMT device. The design process starts by generating the large signal S-parameters of the device over the desired RF input drive and frequency band, while the device stability is assured by conventional circuit techniques. The next stage is to design the input-matching network for the amplifier by providing a conjugate match to the large signal S11 over the frequency band of interest. Figure 4 shows the final circuit of the CPW monolithic microwave IC (MMIC) amplifier.

Figure 5 depicts the simulated voltage and current waveforms at the pHEMT output terminals. The waveforms confirm the switching-mode behavior of the pHEMT, a condition that is necessary for class-E operation of the amplifier.

Measured performance

The completed MMIC amplifier is shown in Figure 6. A primitive layout was used in this first iteration to ensure the accuracy of the complex load. Figure 7 depicts the measured amplifier PAE for different RF input drive levels. PAE of greater than 70% over 3.0-3.7 GHz is obtained for 15.0 dbm input power drive, and a peak PAE of more than 90% is obtained at around 3.25 GHz when the amplifier is driven by only 12.0 dbm of input power.

Likewise, Figure 8 shows the measured amplifier output power for different values of RF input drive levels (-1-12 dBm) over 2-6 GHz. As it can be seen, a broadband output power is obtained indicating the broadband capability of class-E operation. At 3.25 GHz, the output power is more than 23.0 dBm for an input drive level of 12.0 dMm. Figure 9 highlights the measured output power, PAE, and gain vs. input power at 3.25 GHz. A maximum PAE of 92%, and an output power of greater than 23 dBm is obtained at P_{in}=12 dBm. RFD

References

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2. R. Tayrani, “A Monolithic X-band Class-E Amplifier,” IEEE GaAs IC Symposium Digest 2001, pp.205-208.
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4. Agilent Advanced Design Systems (ADS), V.1.7, & Agilent ICCAP, V.5.4.

ABOUT THE AUTHORS

Reza Tayrani received his B.Sc., M.Sc. and Ph.D. degrees in electrical engineering from Kent University, Canterbury, England, in 1974, 1977 and 1985, respectively. He is currently an engineering fellow at Raytheon Microwave Center, Space and Airborne Systems, El Segundo, Calif., engaged in the research and development of GaAs and SiGe MMICs and their related devices. Tayrani has designed and developed many MMICs based on MESFETs, HEMTs, pHEMTs, and HBTs for microwave and millimeter-wave applications. His current areas of interest are high-efficiency switching mode monolithic power amplifiers, advanced SiGe MMICs, broadband sampling circuits and miniature switched filters. Tayrani has published more than 46 technical papers and holds six patents. He can be reached at rtayrani@raytheon.com.