ELECTRONICALLY TUNABLE CLASS-E POWER AMPLIFIER

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ABSTRACT

The 20-W class-E power amplifier (PA) described here is electronically tunable from 19 to 31 MHz (ratio 1.67). This PA employs a single RF-power MOSFET and operates from 25 V. The output-tuning network employs fixed inductors and high-voltage MOSFETs for variable capacitors. The PA achieves an efficiency of 61 to 71 percent and has nearly constant output power across the band. It has excellent amplitude-modulation linearity for Kahn-technique transmitters, with two-tone IMDs at -40.4 dBc.

1. INTRODUCTION

The generation of power at radio frequencies (RF) is required in a number of applications, including not only the well-known radio/cellular/PCS communications, but also RF heating, plasma generation, RF lighting, and magnetic-resonance imaging (MRI). High efficiency in the PA lowers the cost of operation, reduces size and weight, and increases operating (talk) time.

RF power can be generated efficiently by amplifiers operating in classes D, E, and F [1]. Which class is best depends upon the required power output, frequency band, and other aspects of the application. Common to all three classes is the need for a tuned output filter to reject harmonics and to match to the load impedance. Broadband linear amplifiers such as class A and B offer a large bandwidth, but at the cost of lower efficiency.

Broadband filters somewhat mitigate the bandwidth limitations of the output filter. However, such filters have inherent trade-offs between bandwidth and the maximum in-band mismatch, hence efficiency. Switched elements can also be used to provide a range of tuning. However, there is again an inherent trade-off between the number of switched elements and the quality of the match. Such tuning networks tend to become physically

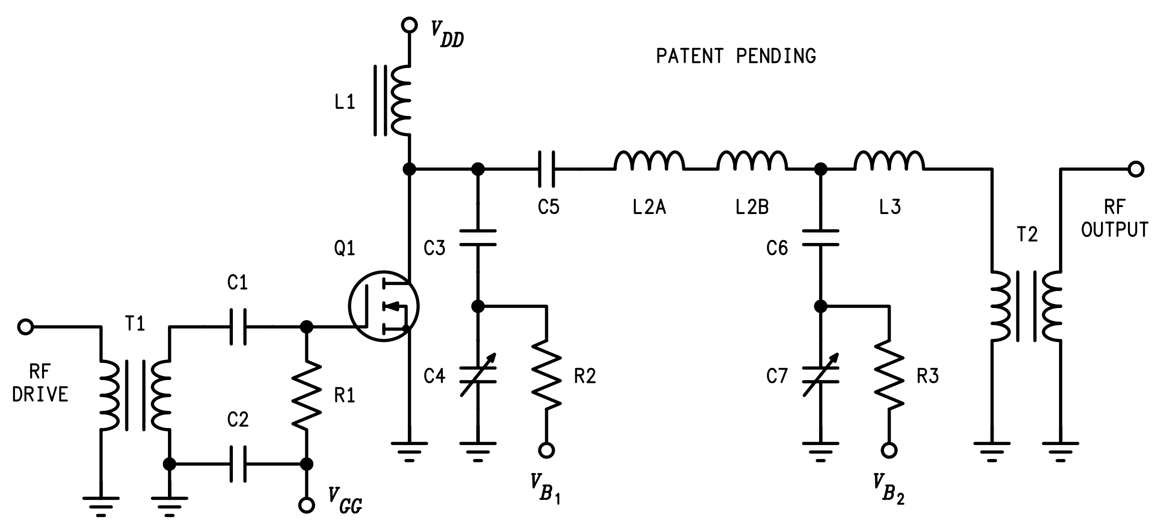

Fig. 1. Simplified circuit of electronically tunable class-E PA.

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large and difficult to implement for large numbers of switched components.

Electronic tuning of a PA [2] is continuous and rapid. This enables the use of efficient power amplifiers in applications for which they were previously unsuitable. The prototype described here is designed for operation over a large range of frequencies. Similar circuits can be used to match variable loads or for efficient, wideband amplitude modulation.

2. CLASS-E POWER AMPLIFIER

Class-E amplification is based upon a single-ended power amplifier (PA) (Fig. 1) whose transistor is operated as a switch. High efficiency is achieved because the drain capacitance is discharged at the time of switching and power losses associated with charging and discharging the drain capacitance (as in class D) are eliminated. This allows class-E PAs at HF to use relatively low-cost MOSFETs that would otherwise not be suitable for RF operation because of their large capacitances [3],[4],[5]. It also makes possible high-efficiency PAs at frequencies as high as X band [6],[7],[8].

The prototype PA uses a Polyfet SQ741 with both MOSFETs connected in parallel. The on-state resistance of the SQ741 is about 1 Ω and the drain capacitance is about 34 pF at 25 V. A 12.5-Ω load line allows efficient operation and production of a 25-W output with a supply voltage of 25 V. The peak drain voltage is below the 120-V rating when the PA is properly tuned (3.56 V_{DD}). The output transformer is a Guanella type that produces a 12.5-Ω drain-load line with an SWR less than 2 for frequencies up to 152 MHz.

The drive input is based upon a Guanella transformer terminated by a gate-swamping resistor. This provides an essentially resistive load to the driver for frequencies up to 132 MHz. The gate is biased at the threshold of conduction (about 3.5 V). Capacitors C1, C2, C3, C5, and C8 are for dc blocking or RF by-pass.

3. TUNING

Optimum class-E operation requires a total drain-shunt susceptance (drain plus added capacitance) of $B = 0.1836/R$ and a load series reactance of $X = 1.152R$. While the transformer provides a constant load resistance over frequency, suitable values of B and X must be maintained by the tuning network. The output tuning network must also provide a high impedance to all harmonics.

The tunable output network (Fig. 1) is divided into two parts. The first part (C4) is a variable capacitance shunting the drain. Adjustment of this capacitance provides the shunt susceptance B required for optimum class-E operation at the desired frequency. The total required capacitance varies from 117 pF at 20 MHz to 78 pF at 30 MHz, 34 pF of which is supplied by the drain capacitance.

The second part of the tunable output network (L2B, L3. and C7) is a T filter, which can be regarded as two back-to-back L networks and designed according to Table 3-3.1 of [1]. The second inductor and half of the capacitance transform the load to a higher intermediate resistance; the first inductor and the other half of the capacitance transform the intermediate resistance back down to the original load resistance. The input inductor provides a high impedance to the harmonics. For a class-E PA, a Q of 3 is sufficient to keep the amplitude second-harmonic current below one tenth of that of the fundamental.

For a minimum $Q = 3$ at 20 MHz, L2B and L3 are 289 nH. An additional 109 nH (L2A) provides the reactance of 1.15R at the middle of the band (25 MHz). This allows approximately optimum class-E operation at all frequencies in the band of operation. Capacitance C6 must vary from 191 pF at 20 MHz ($Q = 3$) to 90 pF at 30 MHz ($Q = 4.5$).

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Electronically variable capacitances are conveniently provided by APT ARF446/7 RF-power MOSFETs. The drain capacitance of these devices varies with dc bias according to the classical abrupt-junction formula. Bias voltage V_B must be sufficiently large so that the drain voltage of the ARF446 does not swing negative and turn on the intrinsic diode in the MOSFET. It must also not be so large that the RF peak exceeds the 900-V breakdown voltage of the MOSFET. The range of 100 to 800 V provides about a 2.4:1 variation in capacitance. The tuning range of the filter is then approximately $2.4^{1/2} \approx 1.55$:1.

The ARF446s are installed with the gate grounded to ensure stability. One ARF446 is used to control the drain shunt capacitance, and a pair (ARF446 and ARF447) connected in parallel are used to vary the capacitance in the T filter. Bias is applied through a large resistor with high-voltage chip capacitors for by-pass.

4. PERFORMANCE

The drain-voltage waveforms for maximum-efficiency tuning (Fig. 2) are basically those of a conventional class-E PA. The transients are due to ringing of the lead between the drain and output filter when the MOSFET switches off. The transients push the peak drain voltage very close to the 120-V rating of the MOSFET when operating at full power at 20 MHz.

The variations of power output and efficiency with frequency are shown in Fig. 3 for adjustment of both bias voltages for maximum efficiency. The power output is somewhat lower (20 W vs. 25 W) than for tuning with conventional capacitors, and the efficiency is slightly lower (61 to 71 percent vs. 71 to 74 percent) as well. However, a nearly constant output power is maintained across the entire band of 18.75 to 31.25 MHz (factor of 1.67).

Bias V_{B1} ranges from 70 V at 17.5 MHz to 800 V at 32.5 MHz. Bias V_{B2} ranges from 30 V

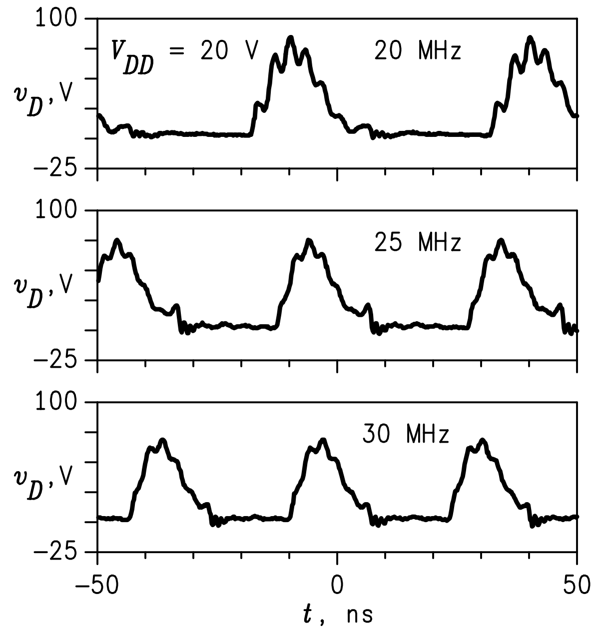

Fig. 2. Drain-voltage waveforms.

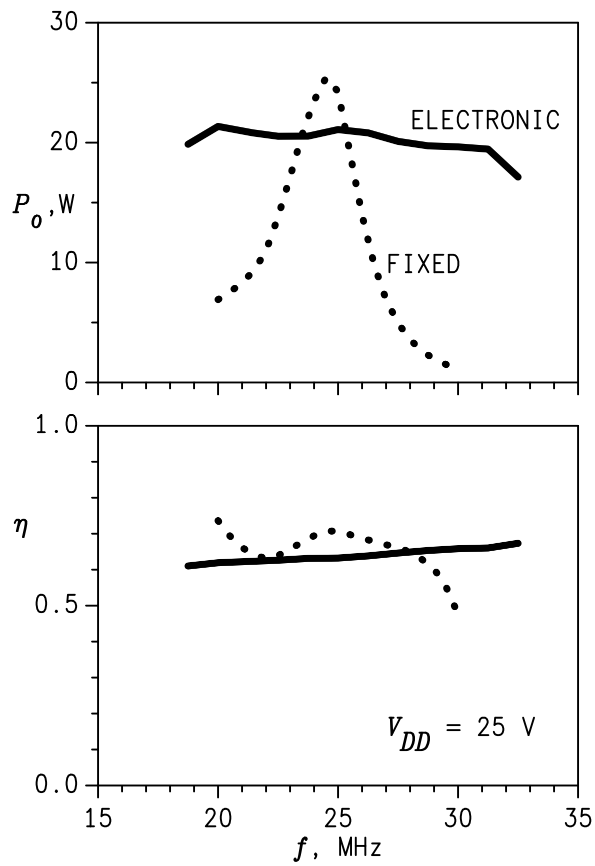

Fig. 3. Power output and efficiency.

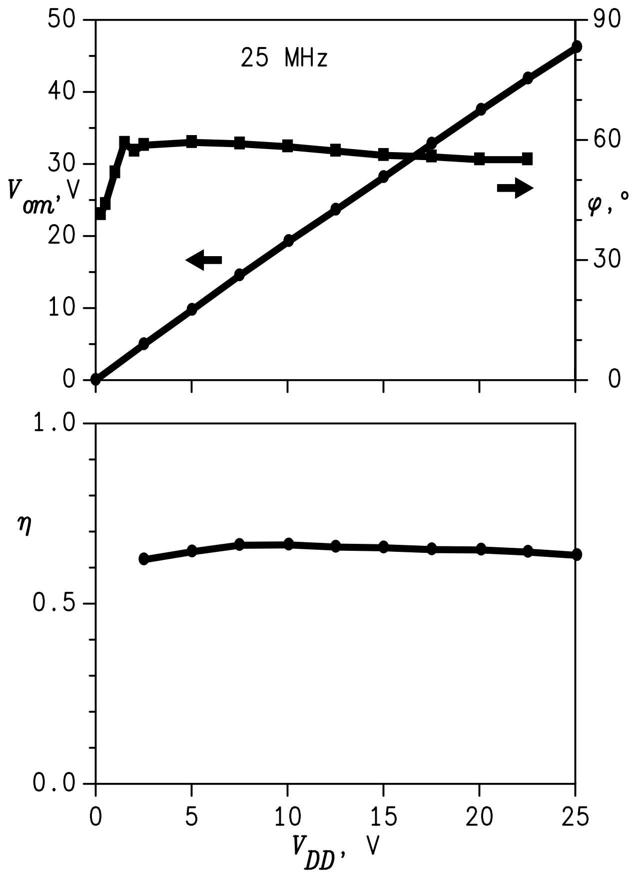

Fig. 4. Amplitude-modulation characteristics.

at 17.5 MHz to 325 V at 32.5 MHz. Dc-supply voltage V_{DD} affects the tuning, especially at lower frequencies for which the bias voltage is lower. Consequently, obtaining maximum efficiency requires readjusting V_{B2} when V_{DD} is changed.

The characteristics (Fig. 4) for use in a Kahn EER transmitter [9] are based upon biasing the PA for maximum efficiency at PEP and then varying V_{DD} to control the output voltage. The amplitude variation deviates from a straight line by an rms error of only 0.7 percent and the phase varies only 4.3° in the top 20 dB of the dynamic range. The corresponding two-tone IMD level is -40.4 dBc. The efficiency is essentially constant (62 to 65 percent) over the whole dynamic range.

The second and third harmonics in the output are 21 and 51 dB below the fundamental, respectively. The relatively high level of the second harmonic is the result of having only a single pole of filtering between output and the voltage-variable capacitance in the T filter. For applications such as RF heating, these levels are satisfactory. For communication systems, passive filtering can be added.

5. REFERENCES

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