RF and Microwave Power Amplifier and Transmitter Technologies — *Part 2*

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Our multi-part series on power amplifier technologies and applications continues with a review of amplifier configurations, classes of operation, device characterization and example applications

Part 1 of this series introduced basic concepts, discussed the characteristics of signals to be amplified, and gave background information on RF power devices. Part 2 reviews the basic techniques, ratings, and implementation methods for power amplifiers operating at HF through microwave frequencies.

Figure 7 · A single-ended power amplifier.

6a. BASIC TECHNIQUES FOR RF POWER AMPLIFICATION

RF power amplifiers are commonly designated as classes A, B, C, D, E, and F [19]. All but class A employ various nonlinear, switching, and wave-shaping techniques. Classes of operation differ not in only the method of operation and efficiency, but also in their power-output capability. The power-output capability ("transistor utilization factor") is defined as output power per transistor normalized for peak drain voltage and current of 1 V and 1 A, respectively. The basic topologies (Figures 7, 8 and 9) are single-ended, transformer-coupled, and complementary. The drain voltage and current waveforms of selected ideal PAs are shown in Figure 10.

Class A

In class A, the quiescent current is large enough that the transistor remains at all times in the active region and acts as a current source, controlled by the drive.
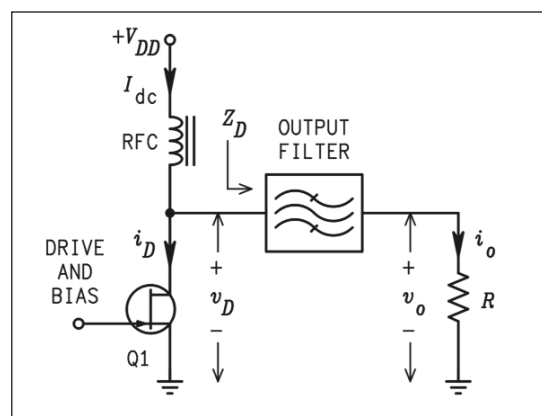
Consequently, the drain voltage and current waveforms are (ideally) both sinusoidal. The power output of an ideal class-A PA is

$$P_o = V_{om}^2 / 2R \qquad (5)$$

where output voltage V_{om} on load R cannot exceed supply voltage V_{DD}. The DC-power input is constant and the efficiency of an ideal PA is 50 percent at PEP. Consequently, the instantaneous efficiency is proportional to the power output and the average efficiency is inversely proportional to the peak-to-average ratio (e.g., 5 percent for x = 10 dB). The utilization factor is 1/8.

For amplification of amplitude-modulated signals, the quiescent current can be varied in proportion to the instantaneous signal envelope. While the efficiency at PEP is unchanged, the efficiency for lower ampli-
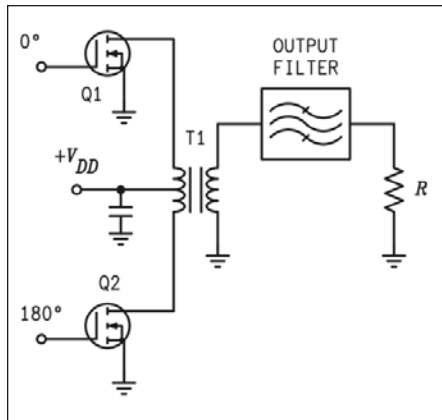
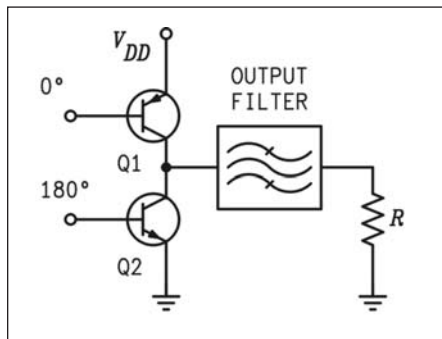**Figure 8 · Transformer-coupled push-pull PA.**

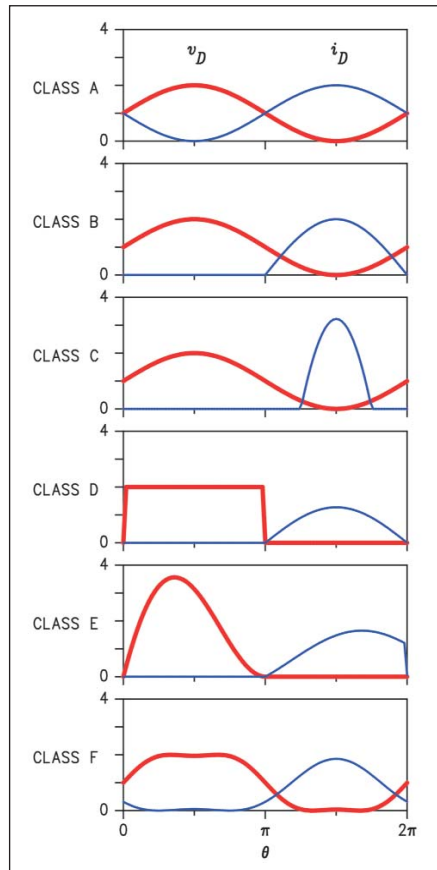
Figure 9 · Complementary PA.

Figure 10 · Wavefroms for ideal PAs.

tudes is considerably improved. In an FET PA, the implementation requires little more than variation of the gate-bias voltage.

The amplification process in class A is inherently linear, hence increasing the quiescent current or decreasing the signal level monotonically decreases IMD and harmonic levels. Since both positive and negative excursions of the drive affect the drain current, it has the highest gain of any PA. The absence of harmonics in the amplification process allows class A to be used at frequencies close to the maximum capability (fmax) of the transistor. However, the efficiency is low. Class-A PAs are therefore typically used in applications requiring low power, high linearity, high gain, broadband operation, or high-frequency operation.

The efficiency of real class-A PAs is degraded by the on-state resistance or saturation voltage of the transistor. It is also degraded by the presence of load reactance, which in essence requires the PA to generate more output voltage or current to deliver the same power to the load.

Class B

The gate bias in a class-B PA is set at the threshold of conduction so that (ideally) the quiescent drain current is zero. As a result, the transistor is active half of the time and the drain current is a half sinusoid. Since the amplitude of the drain current is proportional to drive amplitude and the shape of the drain-current waveform is fixed, class-B provides linear amplification.

The power output of a class-B PA is controlled by the drive level and varies as given by eq. (5). The DC-input current is, however, proportional to the drain current which is in turn proportional to the RF-output current. Consequently, the instantaneous efficiency of a class-B PA varies with the output voltage and for an ideal PA reaches $\pi/4$ (78.5 percent) at PEP. For low-level signals, class B is significantly more efficient than class A, and its average efficiency can be several times that of class A at high peak-to-average ratios (e.g., 28 vs. 5 percent for $\xi = 10$ dB). The utilization factor is the same 0.125 of class A.

In practice, the quiescent current is on the order of 10 percent of the peak drain current and adjusted to minimize crossover distortion caused by transistor nonlinearities at low outputs. Class B is generally used in a push-pull configuration so that the two drain-currents add together to produce a sine-wave output. At HF and VHF, the transformer-coupled push-pull topology (Figure 8) is generally used to allow broadband operation with minimum filtering. The use of the complementary topology (Figure 9) has generally been limited to audio, LF, and MF applications by the lack of suitable p-channel transistors. However, this topology is attractive for IC implementation and has recently been investigated for low-power applications at frequencies to 1 GHz [20].

Class C

In the classical (true) class-C PA, the gate is biased below threshold so that the transistor is active for less than half of the RF cycle (Figure 10). Linearity is lost, but efficiency is increased. The efficiency can be increased arbitrarily toward 100 percent by decreasing the conduction angle toward zero. Unfortunately, this causes the output power (utilization factor) to decrease toward zero and the drive power to increase toward infinity. A typical compromise is a conduction angle of 150° and an ideal efficiency of 85 percent.

The output filter of a true class-C PA is a parallel-tuned type that

bypasses the harmonic components of the drain current to ground without generating harmonic voltages. When driven into saturation, efficiency is stabilized and the output voltage locked to supply voltage, allowing linear high-level amplitude modulation.

Classical class C is widely used in high-power vacuum-tube transmitters. It is, however, little used in solid-state PAs because it requires low drain resistances, making implementation of parallel-tuned output filters difficult. With BJTs, it is also difficult to set up bias and drive to produce a true class-C collector-current waveform. The use of a series-tuned output filter results in a mixed-mode class-C operation that is more like mistuned class E than true class C.

Class D

Class-D PAs use two or more transistors as switches to generate a square drain-voltage waveform. A series-tuned output filter passes only the fundamental-frequency component to the load, resulting in power outputs of $(8/\pi^2)V_{DD}^2/R$ and $(2/\pi^2)V_{DD}^2/R$ for the transformer-coupled and complementary configurations, respectively. Current is drawn only through the transistor that is on, resulting in a 100-percent efficiency for an ideal PA. The utilization factor ($1/2\pi = 0.159$) is the highest of any PA (27 percent higher than that of class A or B). A unique aspect of class D (with infinitely fast switching) is that efficiency is not degraded by the presence of reactance in the load.

Practical class-D PAs suffer from losses due to saturation, switching speed, and drain capacitance. Finite switching speed causes the transistors to be in their active regions while conducting current. Drain capacitances must be charged and discharged once per RF cycle. The associated power loss is proportional to $V_{DD}^3/2$ [21] and increases directly with frequency.

Class-D PAs with power outputs of 100 W to 1 kW are readily implemented at HF, but are seldom used above lower VHF because of losses associated with the drain capacitance. Recently, however, experimental class-D PAs have been tested with frequencies of operation as high as 1 GHz [22].

Class E

Class E employs a single transistor operated as a switch. The drain-voltage waveform is the result of the sum of the DC and RF currents charging the drain-shunt capacitance. In optimum class E, the drain voltage drops to zero and has zero slope just as the transistor turns on. The result is an ideal efficiency of 100 percent, elimination of the losses associated with charging the drain capacitance in class D, reduction of switching losses, and good tolerance of component variation.

Optimum class-E operation requires a drain shunt susceptance 0.1836/R and a drain series reactance 1.15R and delivers a power output of $0.577V_{DD}^2/R$ for an ideal PA [23]. The utilization factor is 0.098. Variations in load impedance and shunt susceptance cause the PA to deviate from optimum operation [24, 25], but the degradations in performance are generally no worse than those for class A and B.

The capability for efficient operation in the presence of significant drain capacitance makes class E useful in a number of applications. One example is high-efficiency HF PAs with power levels to 1 kW based upon low-cost MOSFETs intended for switching rather than RF use [26]. Another example is the switching-mode operation at frequencies as high as K band [27]. The class-DE PA [28] similarly uses dead-space between the times when its two transistors are on to allow the load network to charge/discharge the drain capacitances.

Class F

Class F boosts both efficiency and output by using harmonic resonators in the output network to shape the drain waveforms. The voltage waveform includes one or more odd harmonics and approximates a square wave, while the current includes even harmonics and approximates a half sine wave. Alternately ("inverse class F"), the voltage can approximate a half sine wave and the current a square wave. As the number of harmonics increases, the efficiency of an ideal PA increases from the 50 percent (class A) toward unity (class D) and the utilization factor increases from 1/8 (class A) toward $1/2\pi$ (class D) [29].

The required harmonics can in principle be produced by current-source operation of the transistor. However, in practice the transistor is driven into saturation during part of the RF cycle and the harmonics are produced by a self-regulating mechanism similar to that of saturating class C. Use of a harmonic voltage requires creating a high impedance (3 to 10 times the load impedance) at the drain, while use of a harmonic current requires a low impedance (1/3 to 1/10 of the load impedance). While class F requires a more complex output filter than other PAs, the impedances must be correct at only a few specific frequencies. Lumped-element traps are used at lower frequencies and transmission lines are used at microwave frequencies. Typically, a shorting stub is placed a quarter or half-wavelength away from the drain. Since the stubs for different harmonics interact and the open or short must be created at a "virtual drain" ahead of the drain capacitance and bond-wire inductance, implementation of suitable networks is a bit of an art. Nonetheless, class-F PAs are successfully implemented from MF through Ka band.

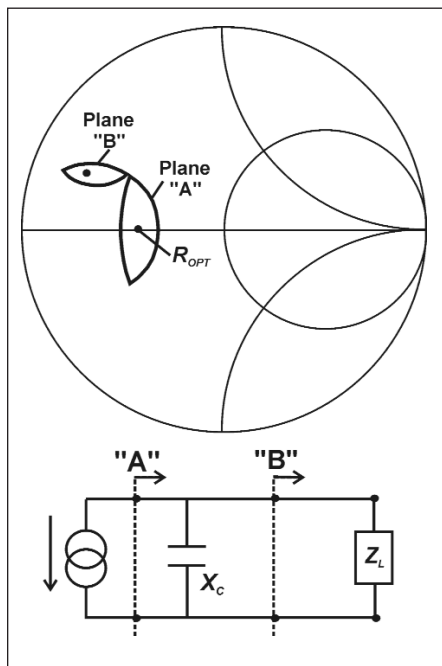A variety of modes of operation in-between class C, E, and F are possi-

Figure 11 · Contant power contours and transformation.

Figure 12 · Example load-pull contours for a 0.5-W, 836 MHz PA. (Courtesy Focus Microwaves and dBm Engineering)

ble. The maximum achievable efficiency [30] depends upon the number of harmonics, (0.5, 0.707, 0.8165, 0.8656, 0.9045 for 1 through 5 harmonics, respectively). The utilization factor depends upon the harmonic impedances and is highest for ideal class-F operation.

6b. LOAD-PULL CHARACTERIZATION

RF-power transistors are characterized by breakdown voltages and saturated drain currents. The combination of the resultant maximum drain voltage and maximum drain current dictates a range of load impedances into which useful power can be delivered, as well as an impedance for delivery of the maximum power. The load impedance for maximum power results in drain voltage and current excursions from near zero to nearly the maximum rated values.

The load impedances corresponding to delivery of a given amount of RF power with a specified maximum drain voltage lie along parallel-resis-
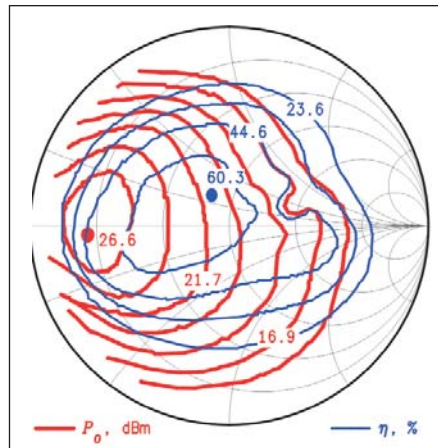
tance lines on the Smith chart. The impedances for a specified maximum current analogously follow a series-resistance line. For an ideal PA, the resultant constant-power contour is football-shaped as shown in Figure 11.

In a real PA, the ideal drain is embedded behind the drain capacitance and bond-wire/package inductance. Transformation of the ideal drain impedance through these elements causes the constant-power contours to become rotated and distorted [31]. With the addition of second-order effects, the contours become elliptical. A set of power contours for a given PA somewhat resembles a set of contours for a conjugate match. However, a true conjugate match produces circular contours. With a power amplifier, the process is more correctly viewed as loading to produce a desired power output. As shown in the example of Figure 12, the power and efficiency contours are not necessarily aligned, nor do maximum power and maximum efficiency necessarily occur for the same load impedance. Sets of such "load-pull" contours are widely used to facilitate design trade-offs.

Load-pull analyses are generally iterative in nature, as changing one

parameter may produce a new set of contours. A variety of different parameters can be plotted during a load-pull analysis, including not only power and efficiency, but also distortion and stability. Harmonic impedances as well as drive impedances are also sometimes varied.

A load-pull system consists essentially of a test fixture, provided with biasing capabilities, and a pair of low-loss, accurately resettable tuners, usually of precision mechanical construction. A load-pull characterization procedure consists essentially of measuring the power of a device, to a given specification (e.g., the 1-dB compression point) as a function of impedance. Data are measured at a large number of impedances and plotted on a Smith chart. Such plots are, of course, critically dependent on the accurate calibration of the tuners, both in terms of impedance and losses. Such calibration is, in turn, highly dependent on the repeatability of the tuners.

Precision mechanical tuners, with micrometer-style adjusters, were the traditional apparatus for load-pull analysis. More recently, a new generation of electronic tuners has emerged that tune through the use varactors or transmission lines switched by pin diodes. Such electronic tuners [32] have the advantage of almost perfect repeatability and high tuning speed, but have much higher losses and require highly complex calibration routines. Mechanical tuners are more difficult to control using a computer, and move very slowly from one impedance setting to another.

In an active load-pull system, a second power source, synchronized in frequency and phase with the device input excitation, is coupled into the output of the device. By controlling the amplitude and phase of the injected signal, a wide range of impedances can be simulated at the output of the test device [33]. Such a

system eliminates the expensive tuners, but creates a substantial calibration challenge of its own. The wide availability of turn-key load-pull systems has generally reduced the application of active load-pull to situations where mechanical or electronic tuning becomes impractical (e.g., millimeter-wave frequencies).

6c. STABILITY

The stability of a small-signal RF amplifier is ensured by deriving a set of S-parameters from using measured data or a linear model, and then establishing the value of the k-factor stability parameter. If the k-factor is greater than unity, at the frequency and bias level in question, then expressions for matching impedances at input and output can be evaluated to give a perfect conjugate match for the device. Amplifier design in this context is mainly a matter of designing matching networks which present the prescribed impedances over the necessary specified bandwidth. If the k factor is less than unity, negative feedback or lossy matching must be employed in order to maintain an unconditionally stable design.

A third case is relevant to PA design at higher microwave frequencies. There are cases where a device has a very high k-factor value, but very low gain in conjugate matched condition. The physical cause of this can be traced to a device which has gain roll-off due to carrier-mobility effects, rather than parasitics. In such cases, introduction of some positive feedback reduces the k-factor and increases the gain in conjugately matched conditions, while maintaining unconditional stability. This technique was much used in the early era of vacuum-tube electronics, especially in IF amplifiers.

6d. MICROWAVE IMPLEMENTATION

At microwave frequencies, lumped elements (capacitors, inductors) become unsuitable as tuning compo-

nents and are used primarily as chokes and by-passes. Matching, tuning, and filtering at microwave frequencies are therefore accomplished with distributed (transmission-line) networks. Proper operation of power amplifiers at microwave frequencies is achieved by providing the required drain-load impedance at the fundamental and a number of harmonic frequencies.

Class F

Class-F operation is specified in terms of harmonic impedances, so it is relatively easy to see how transmission-line networks are used. Methods for using transmission lines in conjunction with lumped-element tuned circuits appear in the original paper by Tyler [34]. In modern microwave implementation, however, it is generally necessary to use transmission lines exclusively. In addition, the required impedances must be produced at a virtual ideal drain that is separated from the output network by drain capacitance, bond-wire/lead inductance.

Typically, a transmission line between the drain and the load provides the fundamental-frequency drain impedance of the desired value. A stub that is a quarter wavelength at the harmonic of interest and open at one end provides a short circuit at the opposite end. The stub is placed along the main transmission line at either a quarter or a half wavelength from the drain to create either an open or a short circuit at the drain [35]. The supply voltage is fed to the drain through a half-wavelength line bypassed on the power-supply end or alternately by a lumped-element choke. When multiple stubs are used, the stub for the highest controlled harmonic is placed nearest the drain. Stubs for lower harmonics are placed progressively further away and their lengths and impedances are adjusted to allow for interactions. Typically, "open" means three to ten times the fundamental-frequency impedance,

and "shorted" means no more 1/10 to 1/3 of the fundamental-frequency impedance [FR17].

A wide variety of class-F PAs have been implemented at UHF and microwave frequencies [36-41]. Generally, only one or two harmonic impedances are controlled. In the X-band PA from [42], for example, the output circuit provides a match at the fundamental and a short circuit at the second harmonic. The third-harmonic impedance is high, but not explicitly adjusted to be open. The 3-dB bandwidth of such an output network is about 20 percent, and the efficiency remains within 10 percent of its maximum value over a bandwidth of approximately 10 to 15 percent.

Dielectric resonators can be used in lieu of lumped-element traps in class-F PAs. Power outputs of 40 W have been obtained at 11 GHz with efficiencies of 77 percent [43].

Class E

The drain-shunt capacitance and series inductive reactance required for optimum class-E operation result in a drain impedance of $R + j0.725R$ at the fundamental frequency, $-j1.7846R$ at the second harmonic, and proportionately smaller capacitive reactances at higher harmonics. At microwave frequencies, class-E operation is approximated by providing the drain with the fundamental-frequency impedance and preferably one or more of the harmonic impedances [44].

An example of a microwave approximation of class E that provides the correct fundamental and second-harmonic impedances [44] is shown in Figure 13. Line l2 is a quarter-wavelength long at the second harmonic so that the open circuit at its end is transformed to a short at plane AA'. Line l1 in combination with L and C is designed to be also a quarter wavelength to translate the short at AA' to an open at the transistor drain. The lines l1 to l4 provide the desired impedance at the funda-
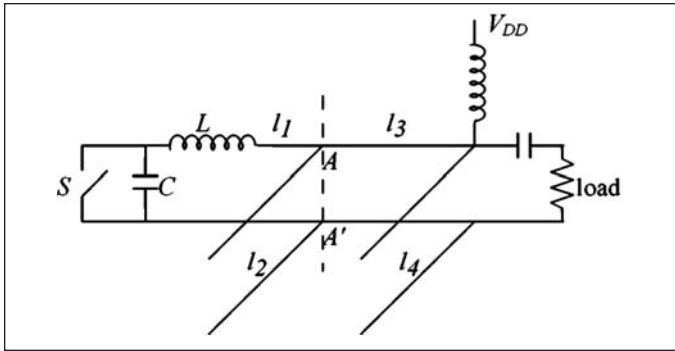
Figure 13 · Idealized microwave class-E PA circuit.

Figure 14 · Example X-band class-E PA.

mental. The implementation using an FLK052 MESFET is shown in Figure 14 produces 0.68 W at X band with a drain efficiency of 72 percent and PAE of 60 percent [42].

Methods exist for providing the proper impedances through the fourth harmonic [45]. However, the harmonic impedances are not critical [30], and many variations are therefore possible. Since the transistor often has little or no gain at the higher harmonic frequencies, those impedances often have little or no effect upon performance. A single-stub match is often sufficient to provide the desired impedance at the fundamental while simultaneously providing an adequately high impedance at the second harmonic, thus eliminating the need for an extra stub and reducing a portion of the losses associated with it. Most microwave class-E amplifiers operate in a suboptimum mode [46]. Demonstrated capabilities range from 16 W with 80-percent efficiency at UHF (LDMOS) to 100 mW with 60-percent efficiency at 10 GHz [47], [48], [44], [49], [50], [51]. Optical sampling of the waveforms [52] has verified that these PAs do indeed operate in class E.

Comparison

PAs configured for classes A (AB), E, and F are compared experimentally in [50] with the following conclusions. Classes AB and F have essentially the same saturated output power, but class F has about 15 percent higher efficiency. Class E has the highest efficiency. Gain compression occurs at a lower power level for class E than for class F. For a given efficiency, class F produces more power. For the same maximum output power, the third order intermodulation products are about 10 dB lower for class F than for class E. Lower-power PAs implemented with smaller RF power devices tend to be more efficient than PAs implemented with larger devices [42].

Millimeter-Wave PAs

Solid-state PAs for millimeter-wave (mm-W) frequencies (30 to 100 GHz) are predominantly monolithic. Most Ka-band PAs are based upon pHEMT devices, while most W-band PAs are based upon InP HEMTs. Some use is also made of HBTs at the lower mm-W frequencies. Class A is used for maximum gain. Typical performance characteristics include 4 W with 30-percent PAE at Ka band [53], 250 mW with 25-percent PAE at Q band [54], and 200 mW with 10-percent PAE at W band [55]. Devices for operation at mm-W are inherently small, so large power outputs are obtained by combining the outputs of multiple low-power amplifiers in corporate or spatial power combiners.

6e. EXAMPLE APPLICATIONS

The following examples illustrate the wide variety of power amplifiers in use today:

HF/VHF Single Sideband

One of the first applications of RF-power transistors was linear amplification of HF single-sideband signals. Many PAs developed by Helge Granberg have been widely adapted for this purpose [56, 57]. The 300-W PA for 2 to 30 MHz uses a pair of Motorola MRF422 Si NPN transistors in a push-pull configuration. The PA operates in class AB push-pull from a 28-V supply and achieves a collector efficiency of about 45 percent (CW) and a two-tone IMD ratio of about –30 dBc. The 1-kW amplifier is based upon a push-pull pair of MRF154 MOSFETs and operates from a 50-V supply. Over the frequency range of 2 to 50 MHz it achieves a drain efficiency of about 58 percent (CW) with an IMD rating of –30 dBc.

13.56-MHz ISM Power Sources

High-power signals at 13.56 MHz are needed for a wide variety of Industrial, Scientific, and Medical (ISM) applications such as plasma generation, RF heating, and semiconductor processing. A 400-W class-E PA uses an International Rectifier IRFP450LC MOSFET (normally used for low-frequency switching-mode DC power supplies) operates from a 120-V supply and achieves a drain efficiency of 86 percent [58, 26]. Industrial 13.56-MHz RF power generators using class-E output stages have been manufactured since 1992 by Dressler Hochfrequenztechnik (Stolberg, Germany) and Advanced
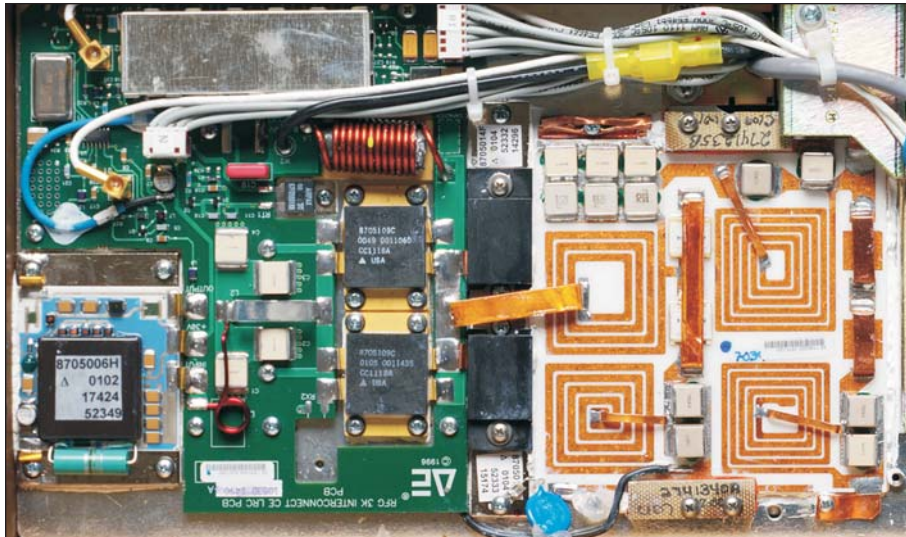
Figure 15 · 3-kW high efficiency PA for 13.56 ISM-band operation. (Courtesy Advanced Energy)

Figure 16 · Output section of a 50-kW AM broadcast transmitter. (Courtesy Harris)

Energy Industries (Ft. Collins, CO). They typically use RF-power MOSFETs with 500- to 900-V breakdown voltages made by Directed Energy or Advanced Power Technology and produce output powers of 500 W to with 3 kW with drain efficiencies of about 90 percent. The Advanced Energy Industries amplifier (Figure 15) uses thick-film-hybrid circuits to reduce size. This allows placement inside the clean-room facilities of semiconductor-manufacturing plants, eliminating the need for long runs of coaxial cable from an RF-power generator installed outside the clean-room.

VHF FM Broadcast Transmitter

FM-broadcast transmitters (88 to 108 MHz) with power outputs from 50 W to 10 kW are manufactured by Broadcast Electronics (Quincy, Illinois). These transmitters use up to 32 power-combined PAs based upon Motorola MRF151G MOSFETs. The PAs operate in class C from a 44-V supply and achieve a drain efficiency of 80 percent. Typically, about 6 percent of the output power is dissipated in the power combiners, harmonic-suppression filter, and lightning-protection circuit.

MF AM Broadcast Transmitters

Since the 1980s, AM broadcast transmitters (530 to 1710 kHz) have been made with class-D and -E RF-output stages. Amplitude modulation is produced by varying the supply voltage of the RF PA with a high-efficiency amplitude modulator.

Transmitters made by Harris (Mason, Ohio) produce peak-envelope output powers of 58, 86, 150, 300, and 550 kW (unmodulated carrier powers of 10, 15, 25, 50, and 100 kW). The 100-kW transmitter combines the output power from 1152 transistors. The output stages can use either bipolars or MOSFETs, typically operate in class DE from a 300-V supply, and achieve an efficiency of 98 percent. The output section of the Harris 3DX50 transmitter is shown in Figure 16.

Transmitters made by Broadcast Electronics (Quincy, IL) use class-E RF-output stages based upon APT6015LVR MOSFETs operating from 130-V maximum supply voltages. They achieve drain efficiencies of about 94 percent with peak-envelope output powers from 4.4 to 44 kW. The 44-kW AM-10A transmitter combines outputs from 40 individual output stages.

900-MHz Cellular-Telephone Handset

Most 900-MHz CDMA handsets use power-amplifier modules from vendors such as Conexant and RF Micro Devices. These modules typically contain a single GaAs-HBT RFIC that includes a single-ended class-AB PA. Recently developed PA modules also include a silicon control IC that provides the base-bias reference voltage and can be commanded to adjust the output-transistor base bias to optimize efficiency while maintaining acceptably low amplifier distortion. over the full ranges of temperature and output power. A typical module (Figure 17) produces 28 dBm (631 mW) at full output with a PAE of 35 to 50 percent.

Cellular-Telephone Base Station Transmitter

The Spectrian MCPA 3060 cellular base-station transmitter for 1840-1870 MHz CDMA systems provides up to 60-W output while transmitting a signal that may include as many 9 modulated carriers. IMD is minimized by linearizing a class-AB main amplifier with both adaptive predistortion and adaptive feed-forward cancellation. The adaptive control
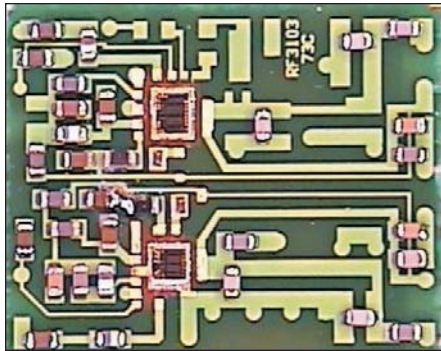
Figure 17 · Internal view of a dual-band (GSM/DCS) PA module for cellular telephone handsets. (Courtesy RF Micro Devices)
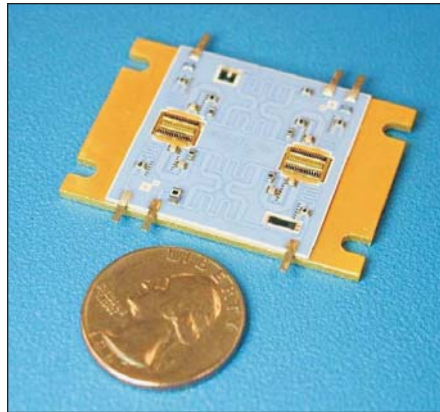

Figure 18 · Thick-film hybrid S-band PA module. (Courtesy UltraRF)

system adjusts operation as needed to compensate for changes due to temperature, time, and output power. The required adjustments are derived from continuous measurements of the system response to a spread-spectrum pilot test signal. The amplifier consumes a maximum of 810 W from a 27-V supply.

S-Band Hybrid Power Module

A thick-film-hybrid power-amplifier module made by UltraRF (now Cree Microwave) for 1805 to 1880 MHz DCS and 1930-1960 MHz PCS is shown in Figure 18. It uses four 140-mm LDMOS FETs operating from a 26-V drain supply. The individual PAs have 11-dB power gain and are quadrature-combined to produce a 100-W PEP output. The average output power is 40 W for EDGE and 7 W for CDMA, with an ACPR of –57 dBc for EDGE and –45 dBc for CDMA. The construction is based upon 0.02-in. thick film with silver metalization.
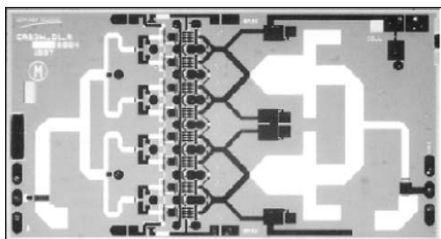

Figure 19 · MMIC PA for X- and K-bands.

GaAs MMIC Power Amplifier

A MMIC PA for use from 8 to 14 GHz is shown in Figure 19. This amplifier is fabricated with GaAs HBTs and intended for used in phased-array radar. It produces a 3-W output with a PAE of approximately 40 percent [59].

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Acronyms Used in Part 2

BJT	Bipolar Junction Transistor
DSP	Digital Signal Processor
IC	Integrated Circuit
IMD	Intermodulation Distortion
MOSFET	Metal Oxide Silicon FET

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Notes

1. In Part 1 of this series (May 2003 issue), the references contained in Table 1 were not numbered correctly. The archived version has been corrected and may be downloaded from: www.highfrequencyelectronics. com — click on "Archives," select "May 2003 — Vol. 2 No. 3" then click on the article title.

2. This series has been extended to five parts, to be published in successive issues through January 2004.