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RF and Microwave Power Amplifier and Transmitter Technologies — *Part 1*

By Frederick H. Raab, Peter Asbeck, Steve Cripps, Peter B. Kenington, Zoya B. Popovic, Nick Pothecary, John F. Sevic and Nathan O. Sokal

With this issue, we begin a four-part series of articles that offer a comprehensive overview of power amplifier technologies. Part 1 covers the key topics of amplifier linearity, efficiency and available RF power devices

RF and microwave power amplifiers and transmitters are used in a wide variety of applications including wireless communication, jamming, imaging, radar, and RF heating. This article provides an introduction and historical background for the subject, and begins the technical discussion with material on signals, linearity, efficiency, and RF-power devices. At the end, there is a convenient summary of the acronyms used—this will be provided with all four installments. Author affiliations and contact information are also provided at the end of each part.

1. INTRODUCTION

The generation of significant power at RF and microwave frequencies is required not only in wireless communications, but also in applications such as jamming, imaging, RF heating, and miniature DC/DC converters. Each application has its own unique requirements for frequency, bandwidth, load, power, efficiency, linearity, and cost. RF power can be generated by a wide variety of techniques using a wide variety of devices. The basic techniques for RF power amplification via classes A, B, C, D, E, and F are reviewed and illustrated by examples from HF through Ka band. Power amplifiers can be combined into transmitters in a similarly wide variety of architectures, including linear, Kahn, envelope tracking, outphasing, and Doherty. Linearity can be improved through techniques such as feedback, feedforward, and predistortion. Also discussed are some recent developments that may find use in the near future.

A power amplifier (PA) is a circuit for converting DC input power into a significant amount of RF/microwave output power. In most cases, a PA is not just a small-signal amplifier driven into saturation. There exists a great variety of different power amplifiers, and most employ techniques beyond simple linear amplification.

A transmitter contains one or more power amplifiers, as well as ancillary circuits such as signal generators, frequency converters, modulators, signal processors, linearizers, and power supplies. The classic architecture employs progressively larger PAs to boost a low-level signal to the desired output power. However, a wide variety of different architectures in essence disassemble and then reassemble the signal to permit amplification with higher efficiency and linearity.

Modern applications are highly varied. Frequencies from VLF through millimeter wave are used for communication, navigation, and broadcasting. Output powers vary from 10 mW in short-range unlicensed wireless systems to 1 MW in long-range broadcast transmitters. Almost every conceivable type of modulation is being used in one system or another. PAs and transmitters also find use in systems such as radar, RF heating, plasmas, laser drivers, magnetic-resonance imaging, and miniature DC/DC converters.

This series of articles is an expanded version of the paper, "Power Amplifiers and Transmitters for RF and Microwave" by the same authors, which appeared in the the 50th anniversary issue of the *IEEE Transactions on Microwave Theory and Techniques*, March 2002. © 2002 IEEE. Reprinted with permission.

No single technique for power amplification nor any single transmitter architecture is best for all applications. Many of the basic techniques that are now coming into use were devised decades ago, but have only recently been made practical because of advances in RF-power devices and supporting circuitry such as digital signal processing (DSP).

2. HISTORICAL DEVELOPMENT

The development of RF power amplifiers and transmitters can be divided into four eras:

Spark, Arc, and Alternator

In the early days of wireless communication (from 1895 to the mid 1920s), RF power was generated by spark, arc, and alternator techniques. The original RF-power device, the spark gap, charges a capacitor to a high voltage, usually from the AC mains. A discharge (spark) through the gap then rings the capacitor, tuning inductor, and antenna, causing radiation of a damped sinusoid. Spark-gap transmitters were relatively inexpensive and capable of generating 500 W to 5 kW from LF to MF [1].

The arc transmitter, largely attributed to Poulsen, was a contemporary of the spark transmitter. The arc exhibits a negative-resistance characteristic which allows it to operate as a CW oscillator (with some fuzziness). The arc is actually extinguished and reignited once per RF cycle, aided by a magnetic field and hydrogen ions from alcohol dripped into the arc chamber. Arc transmitters were capable of generating as much as 1 MW at LF [2].

The alternator is basically an AC generator with a large number of poles. Early RF alternators by Tesla and Fessenden were capable of operation at LF, and a technique developed by Alexanderson extended the operation to LF [3]. The frequency was controlled by adjusting the rotation speed and up to 200 kW could be generated by a single alternator. One such transmitter (SAQ) remains operable at Grimeton, Sweden.

Vacuum Tubes

With the advent of the DeForest audion in 1907, the thermoionic vacuum tube offered a means of electronically generating and controlling RF signals. Tubes such as the RCA UV-204 (1920) allowed the transmission of pure CW signals and facilitated the transition to higher frequencies of operation.

Younger readers may find it convenient to think of a vacuum tube as a glass-encapsulated high-voltage FET with heater. Many of the concepts for modern electronics, including class-A, -B, and -C power amplifiers, originated early in the vacuum-tube era. PAs of this era were characterized by operation from high voltages into high-impedance loads and by tuned output networks. The basic circuits remained relatively unchanged throughout most of the era.

Vacuum tube transmitters were dominant from the late 1920s through the mid 1970s. They remain in use today in some high power applications, where they offer a relatively inexpensive and rugged means of generating 10 kW or more of RF power.

Discrete Transistors

Discrete solid state RF-power devices began to appear at the end of the 1960s with the introduction of silicon bipolar transistors such as the 2N6093 (75 W HF SSB) by RCA. Power MOSFETs for HF and VHF appeared in 1974 with the VMP-4 by Siliconix. GaAs MESFETs introduced in the late 1970s offered solid state power at the lower microwave frequencies.

The introduction of solid-state RF-power devices brought the use of lower voltages, higher currents, and relatively low load resistances. Ferrite-loaded transmission line transformers enabled HF and VHF PAs to operate over two decades of bandwidth without tuning. Because solid-state devices are temperature-sensitive, bias stabilization circuits were developed for linear PAs. It also became possible to implement a variety of feedback and control techniques through the variety of op-amps and ICs.

Solid-state RF-power devices were offered in packaged or chip form. A single package might include a number of small devices. Power outputs as high as 600 W were available from a single packaged push-pull device (MRF157). The designer basically selected the packaged device that best fit the requirements. How the transistors were made was regarded as a bit of sorcery that occurred in the semiconductor houses and was not a great concern to the ordinary circuit designer.

Custom/Integrated Transistors

The late 1980s and 1990s saw a proliferation variety of new solid-state devices including HEMT, pHEMT, HFET, and HBT, using a variety of new materials such as InP, SiC, and GaN, and offering amplification at frequencies to 100 GHz or more. Many such devices can be operated only from relatively low voltages. However, many current applications need only relatively low power. The combination of digital signal processing and microprocessor control allows widespread use of complicated feedback and predistortion techniques to improve efficiency and linearity.

Many of the newer RF-power devices are available only on a made-to-order basis. Basically, the designer selects a semiconductor process and then specifies the size (e.g., gate periphery). This facilitates tailoring the device to a specific power level, as well as incorporating it into an RFIC or MMIC.

3. LINEARITY

The need for linearity is one of the principal drivers in the design of

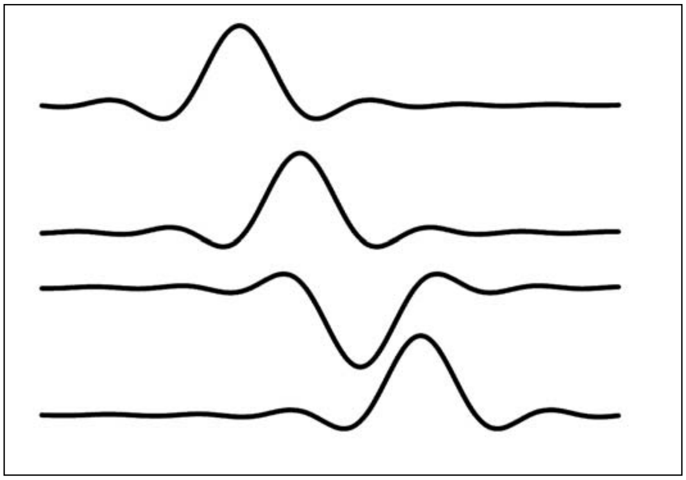

Figure 1 · SRRC data pulses.

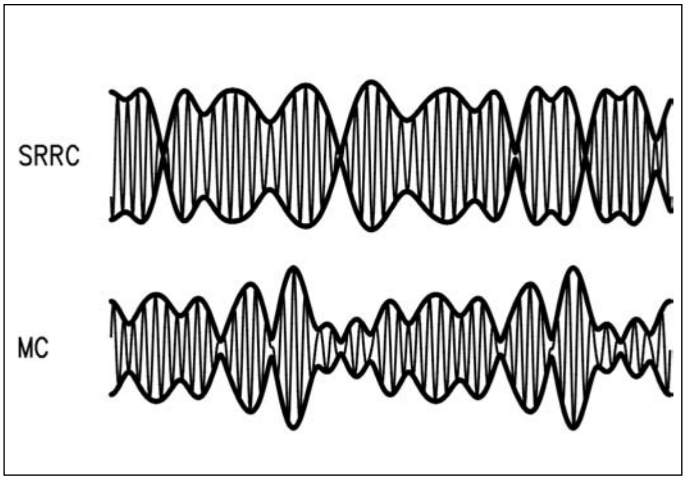

Figure 2 · RF waveforms for SRRC and multicarrier signals.

modern power amplifiers. Linear amplification is required when the signal contains both amplitude and phase modulation. It can be accomplished either by a chain of linear PAs or a combination of nonlinear PAs. Nonlinearities distort the signal being amplified, resulting in splatter into adjacent channels and errors in detection.

Signals such as CW, FM, classical FSK, and GMSK (used in GSM) have constant envelopes (amplitudes) and therefore do not require linear amplification. Full-carrier amplitude modulation is best produced by high level amplitude modulation of the final RF PA. Classic signals that require linear amplification include single sideband (SSB) and vestigal-sideband (NTSC) television. Modern signals that require linear amplification include shaped-pulse data modulation and multiple carriers.

Shaped Data Pulses

Classic FSK and PSK use abrupt frequency or phase transitions, or equivalently rectangular data pulses. The resultant RF signals have constant amplitude and can therefore be amplified by nonlinear PAs with good efficiency. However, the resultant sinc-function spectrum spreads signal energy over a fairly wide bandwidth. This was satisfactory for relatively low data rates and a relatively uncrowded spectrum.

Modern digital signals such as QPSK or QAM are typically generated by modulating both I and Q subcarriers. The requirements for both high data rates and efficient utilization of the increasingly crowded spectrum necessitates the use of shaped data pulses. The most widely used method is based upon a raised-cosine channel spectrum, which has zero intersymbol interference during detection and can be made arbitrarily close to rectangular [4]. A raised-cosine channel spectrum is achieved by using a square-root raised-cosine (SRRC) filter in both the transmitter and receiver. The resultant SRRC data pulses (Figure 1) are shaped somewhat like sinc functions which are truncated after several cycles. At any given time, several different data pulses contribute to the I and Q modulation waveforms. The resultant modulated carrier (Figure 2) has simultaneous amplitude and phase modulation with a peak-to-average ratio of 3 to 6 dB.

Multiple Carriers and OFDM

Applications such as cellular base stations, satellite repeaters, and multi-beam “active-phased-array” transmitters require the simultaneous amplification of multiple signals. Depending on the application, the signals can have different amplitudes, different modulations, and irregular frequency spacing.

In a number of applications including HF modems, digital audio broadcasting, and high-definition television, it is more convenient to use a large number of carriers with low data rates than a single carrier with a high data rate. The motivations include simplification of the modulation/demodulation hardware, equalization, and dealing with multipath propagation. Such Orthogonal Frequency Division Multiplex (OFDM) techniques [5] employ carriers with the same amplitude and modulation, separated in frequency so that modulation products from one carrier are zero at the frequencies of the other carriers.

Regardless of the characteristics of the individual carriers, the resultant composite signal (Figure 2) has simultaneous amplitude and phase modulation. The peak-to-average ratio is typically in the range of 8 to 13 dB.

Nonlinearity

Nonlinearities cause imperfect reproduction of the amplified signal, resulting in distortion and splatter. Amplitude nonlinearity causes the instantaneous output amplitude or

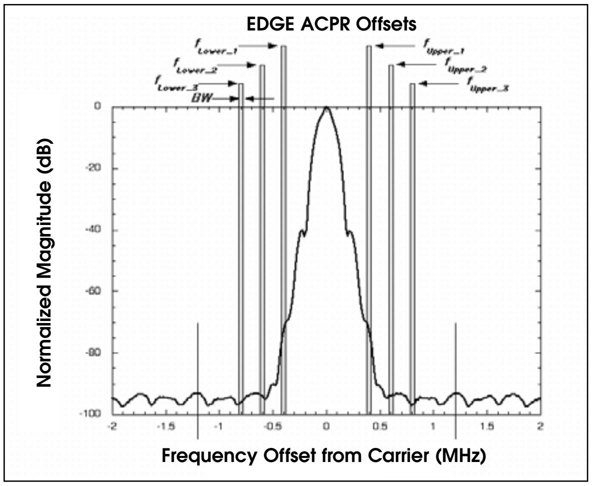

Figure 3 · ACPR offsets and bandwidths.

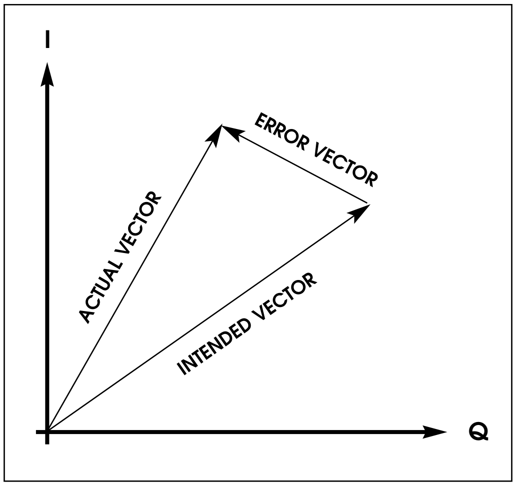

Figure 4 · Error vector.

envelope to differ in shape from the corresponding input. Such nonlinearities are the variable gain or saturation in a transistor or amplifier. Amplitude-to-phase conversion is a phase shift associated with the signal amplitude and causes the introduction of unwanted phase modulation into the output signal. Amplitude-to-phase conversion is often associated with voltage-dependent capacitances in the transistors. While imperfect frequency response also distorts a signal, it is a linear process and therefore does not generate out-of-band signals.

Amplitude nonlinearity and amplitude-to-phase conversion are described by transfer functions that act upon the instantaneous signal voltage or envelope. However, memory effects can also occur in high-power PAs because of thermal effects and charge storage. Thermal effects are somewhat more noticeable in III-V semiconductors because of lower thermal conductivity, while charge-storage effects are more prevalent in overdriven BJT PAs.

Measurement of Linearity

Linearity is characterized, measured, and specified by various techniques depending upon the specific signal and application. The linearity of RF PAs is typically characterized by C/I, NPR, ACPR, and EVM (defined below).

STANDARD	Offset 1	Offset 2	BW (kHz)	Integration Filter	EVM (peak/rms)
NADC [JS5]	±30 kHz –26 dBc	±60 kHz –45 dBc	32.8 kHz	RRC α=0.35	25%/12%
PHS [JS6]	±600 kHz –50 dBc	±900 kHz –55 dBc	37.5 kHz	RRC α=0.50	25%/12%
EDGE [JS7]	±400 kHz –58 dBc	±600 kHz –66 dBc	30 kHz	None	22%/7.0%
TETRA [JS8]	25 kHz –60 dBc	50 kHz –70 dBc	25 kHz	RRC α=0.35	30%/10%
IS-95 CDMA [JS9]	885 kHz –45 dBc	1980 kHz –55 dBc	30 kHz	None	N/A
W-CDMA (3G-PP) [JS10]	5.00 MHz –33 dB	10.0 MHz –43 dB	4.68 MHz	RRC α=0.22	25%/N/A

Table 1 · ACPR and EVM requirements of various systems.

The traditional measure of linearity is the carrier-to-intermodulation (C/I) ratio. The PA is driven with two or more carriers (tones) of equal amplitudes. Nonlinearities cause the production of intermodulation products at frequencies corresponding to sums and differences of multiples of the carrier frequencies [6]. The amplitude of the third-order or maximum intermodulation distortion (IMD) product is compared to that of the carriers to obtain the C/I. A typical linear PA has a C/I of 30 dB or better.

Noise-Power Ratio (NPR) is a traditional method of measuring the linearity of PAs for broadband and noise-like signals. The PA is driven with Gaussian noise with a notch in one segment of its spectrum. Nonlinearities cause power to appear in the notch. NPR is the ratio of the notch power to the total signal power.

Adjacent Channel Power Ratio (ACPR) characterizes how nonlinearity affects adjacent channels and is widely used with modern shaped-pulse digital signals such as NADC and CDMA. Basically, ACPR is the ratio of the power in a specified band outside the signal bandwidth to the rms power in the signal (Figure 3). In some cases, the actual power spectrum $S(f)$ is weighted by the frequency response $H(f)$ of the pulse-shaping filter; i.e. (eq. 1)

$$ACPR_{lower} = \frac{\int_{f_c - f_o - BW/2}^{f_c - f_o + BW/2} \left|H(f)\right|^2 S(f)\,df}{\int_{f_L}^{f_U} \left|H(f)\right|^2 S(f)\,df}$$

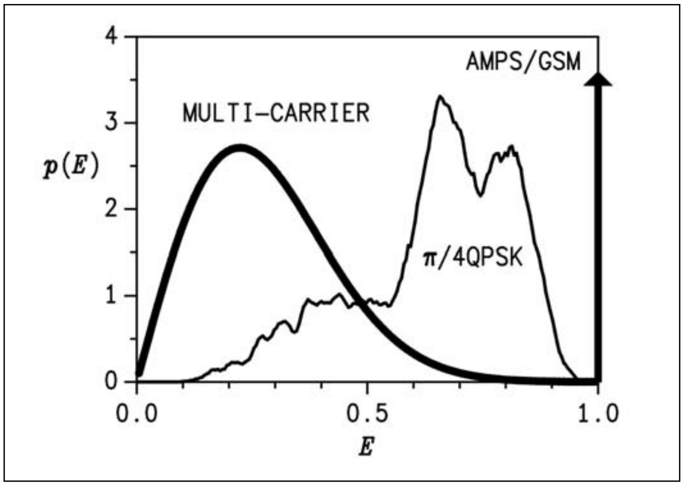

Figure 5 · Envelope PDFs.

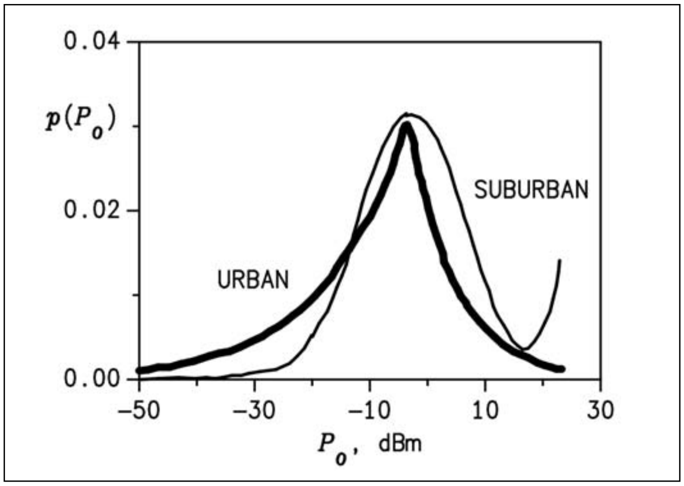

Figure 6 · Power-output PDFs.

where f_c is the center frequency, B is the bandwidth, f_o is the offset, and f_L and f_U are the band edges. The weighting, frequency offsets, and required ACPRs vary with application as shown in Table 1. ACPR can be specified for either upper or lower sideband. In many cases, two different ACPRs for two different frequency offsets are specified. ACPR2, based upon the outer band, is sometimes called "Alternate Channel Power Ratio."

Error Vector Magnitude (EVM) is a convenient measure of how nonlinearity interferes with the detection process. EVM is defined (Figure 4) as the distance between the desired and actual signal vectors, normalized to a fraction of the signal amplitude. Often, both peak and rms errors are specified (Table 1).

4. EFFICIENCY

Efficiency, like linearity, is a critical factor in PA design. Three definitions of efficiency are commonly used. Drain efficiency is defined as the ratio of RF output power to DC input power:

$$\eta = P_{out}/P_{in} \qquad (2)$$

Power-added efficiency (PAE) incorporates the RF drive power by subtracting it from the output power; i.e. $(P_{out} - P_{DR})/P_{in}$. PAE gives a reasonable indication of PA performance when gain is high; however, it can become negative for low gains. An overall efficiency such as $Pout/(P_{in} + P_{DR})$ is useable in all situations. This definition can be varied to include driver DC input power, the power consumed by supporting circuits, and anything else of interest.

Average Efficiency

The instantaneous efficiency is the efficiency at one specific output level. For most PAs, the instantaneous efficiency is highest at the peak output power (PEP) and decreases as output decreases. Signals with time-varying amplitudes (amplitude modulation) therefore produce time-varying efficiencies. A useful measure of performance is then the average efficiency, which is defined [7] as the ratio of the average output power to the average DC-input power:

$$\eta_{AVG} = P_{outAVG}/P_{inAVG} \qquad (3)$$

This concept can be used with any of the three definitions of efficiency.

The probability-density function (PDF) of the envelope gives the relative amount of time an envelope spends at various amplitudes (Figure 5). Also used is the cumulative distribution function (CDF), which gives the probability that the envelope does not exceed a specified amplitude. CW, FM, and GSM signals have constant envelopes and are therefore always at peak output. SRRC data modulation produces PDFs that are concentrated primarily in the upper half of the voltage range and have peak-to-average ratios on the order of 3 to 6 dB. Multiple carriers [8] produce random-phasor sums much like random noise and therefore have Rayleigh-distributed envelopes; i.e.,

$$p(E) = 2E\,\xi\exp(-V_2\,\xi) \qquad (4)$$

Peak-to-average ratio ξ is typically between 6 and 13 dB.

The average input and output powers are found by integrating the product of their variation with amplitude and the PDF of the envelope. Two cases are of special interest. When the DC input current is constant (class-A bias), the DC input power is also constant. The average efficiency is then η_{PEP}/ξ. If the DC input current (hence power) is proportional to the envelope (as in class-B), the average efficiency is $(4/\pi)^{1/2}\,\eta_{PEP}$, for a Rayleigh-distributed signal. Thus for a multicarrier signal with a 10 dB peak-to-average ratio, ideal class-A and B PAs with PEP efficiencies of 50 and 78.5 percent, respectively, have average efficiencies of only 5 and 28 percent, respectively.

Back-Off

The need to conserve battery power and to avoid interference to other users operating on the same frequency necessitates the transmission of signals whose peak amplitudes well below the peak output power of the transmitter. Since peak power is needed only in the worst-case links, the "back-off" is typically in the range of 10 to 20 dB.

For a single-carrier mobile transmitter, back-off rather than envelope PDF is dominant in determining the average power consumption and average efficiency. The PDF of the transmitting power (Figure 4) depends not only upon the distance, but also upon factors such as attenuation by buildings, multipath, and orientation of the mobile antenna [8], [9], [10]. To facilitate prediction of the power consumption, the envelope and back-off PDFs can be combined [11].

5. RF POWER TRANSISTORS

A wide variety of active devices is currently available for use in RF-power amplifiers, and RF-power transistors are available in packaged, die, and grown-to-order forms. Packaged devices are used at frequencies up to X band, and are dominant for high power and at VHF and lower frequencies. A given package can contain one or more die connected in parallel and can also include internal matching for a specific frequency of operation. Dice (chips) can be wire-bonded directly into a circuit to minimize the effects of the package and are used up to 20 GHz. In MMICs, the RF-power device is grown to order, allowing its size and other characteristics to be optimized for the particular application. This form of construction is essential for upper-microwave and millimeter-wave frequencies to minimize the effects of strays and interconnects. Virtually all RF power transistors are npn or n-channel types because the greater mobility of electrons (vs. holes) results in better operation at higher frequencies.

Bipolar Junction Transistor (BJT)

The Si BJT is the original solid-state RF power device, originating in the 1960s. Since the BJT is a vertical device, obtaining a high collector-breakdown voltage is relatively simple and the power density is very high. Si BJTs typically operate from 28 V supplies and remain in use at frequencies up to 5 GHz, especially in high-power (1 kW) pulsed applications such as radar. While Si RF power devices have higher gain at high frequencies, their fundamental properties are basically those of ordinary bipolar transistors. The positive temperature coefficient of BJTs tends to allow current hogging, hot-spotting, and thermal runaway, necessitating carefully regulated base bias. Since RF power BJTs are generally composed of multiple, small BJTs (emitter sites), emitter ballasting (resistance) is generally employed to force even division of the current within a given package.

Metal-Oxide-Silicon Field-Effect Transistor (MOSFET)

MOSFETs are constructed with insulated gates. Topologies with both vertical and later current flow are used in RF applications, and most are produced by a double-diffusion process. Because the insulated gate conducts no DC current, MOSFETs are very easily biased.

The negative temperature coefficient of a MOSFET causes its drain current to decrease with temperature. This prevents thermal runaway and allows multiple MOSFETs to be connected in parallel without ballasting. The absence of base-charge storage time allows fast switching and also eliminates a mechanism for subharmonic oscillation. An overdriven (saturated) MOSFET can conduct drain current in either direction, which is very useful in switching-mode operation with reactive loads.

Vertical RF power MOSFETs are useable through VHF and UHF. Gemini-packaged devices can deliver up to 1 kW at HF and 100s of watts at VHF. VMOS devices typically operate from 12, 28, or 50-V supplies, although some devices are capable of operation from 100 V or more.

Laterally Diffused MOS (LDMOS)

LDMOS is especially useful at UHF and lower microwave frequencies because direct grounding of its source eliminates bond-wire inductance that produces negative feedback and reduces gain at high frequencies. This also eliminates the need for the BeO insulating layer commonly used in other RF-power MOSFETs.

LDMOS devices typically operate from 28-V supplies and are currently available with power outputs of 120 W at 2 GHz. They are relatively low in cost compared to other devices for this frequency range and are currently the device of choice for use in high-power transmitters at 900 MHz and 2 GHz.

Junction FET (JFET)

JFETs for power applications are often called Static Induction Transistors (SITs). Impressive power and efficiency have been obtained from RF JFETs based upon Si, SiGe, and SiC at frequencies through UHF. However, the JFET has never become as popular as other RF-power FETs.

GaAs MEtal Semiconductor FET (GaAs MESFET)

GaAs MESFETs are JFETs based upon GaAs and a Schottky gate junction. They have higher mobility than do Si devices and are therefore capable of operating efficiently at higher frequencies. GaAs MESFETs are widely used for the production of microwave power, with capabilities of up 200 W at 2 GHz and 40 W at 20 GHz in packaged devices. These devices have relatively low breakdown voltages compared to MOSFETs or JFETs and are typically operated from supply voltages (drain biases) of 5 to 10 V. Most MESFETs are depletion-mode devices and require a negative gate bias, although some enhance-mode devices that operate with a positive bias have been developed. Linearity is often poor due to input capacitance variation with voltage; the output capacitance is also often strongly bias- and frequency-dependent.

Heterojunction FET (HFET) / High-Electron-Mobility Transistor (HEMT)

HFETs and HEMTs improve upon the MESFET geometry by separating the Schottky and channel functions. Added to the basic MESFET structure is a heterojunction consisting of an n-doped AlGaAs Schottky layer, an undoped AlGaAs spacer, and an undoped GaAs channel. The discontinuity in the band gaps of AlGaAs and GaAs causes a thin layer of electrons (“two-dimensional electron gas or 2-DEG”) to form below the gate at the interface of the AlGaAs and GaAs layers. Separation of the donors from the mobile electrons reduces collisions in the channel, improving the mobility, and hence high-frequency response, by a factor of about two.

AlGaAs has crystal-lattice properties similar to those of GaAs, and this makes it possible to produce a potential difference without lattice stress. The GaAs buffer contributes to a relatively high breakdown voltage. Their fabrication employs advanced epitaxial technologies (Molecular Beam Epitaxy or Metal Organic Chemical Vapor Deposition) which tends to increase their cost.

The GaAs HEMT is known in the literature by a wide variety of different names, including MODFET (Modulation-Doped FET), TEGFET (Two-dimensional Electron-Gas FET), and SDFET (Selectively Doped FET). It is also commonly called an HFET (Heterostructure FET), although technically an “HFET” has a doped channel that provides the carriers (instead of the heterojunction). The acronyms “HFET and “HJFET” (HeteroJunction FET) appear to be used interchangeably.

GaAs HEMTs/HFETs with f_T as high as 158 GHz are reported. PAs based upon these HEMTs exhibit 15-W outputs at 12 GHz with a power-added efficiency (PAE) of 50 percent. Outputs of 100 W are available at S band from packaged devices.

Pseudomorphic HEMT

The pseudomorphic HEMT (pHEMT) further improves upon the basic HEMT by employing an InGaAs channel. The increased mobility of In with respect to GaAs increases the bandgap discontinuity and therefore the number of carriers in the two-dimensional electron gas. The lattice mismatch between the GaInAs channel and GaAs substrate is also increased, however, and this limits the In content to about 22 percent.

The efficiency of PAs using pHEMTs does not begin to drop until about 45 GHz and pHEMTs are useable to frequencies as high as 80 GHz. Power outputs vary from 40 W at L band to 100 mW at V band. While pHEMTs are normally grown to order, a packaged device pHEMT has recently become available.

InP HEMT

The InP HEMT places an AlInAs/GaInAs heterojunction on an InP substrate. The lattices are more closely matched, which allows an In content of up to about 53 percent. This results in increased mobility, which in turn results in increased electron velocity, increased conduction-band discontinuity, increased two-dimensional electron gas, and higher transconductance. The thermal resistance is 40 percent lower than that of a comparable device built on a GaAs substrate.

The InP HEMT has higher gain and efficiency than the GaAs pHEMT, with the PA efficiency beginning to drop at 60 GHz. However, it has a lower breakdown voltage (typically 7 V) and must therefore be operated from a relatively low drain-voltage supply (e.g., 2 V). This results in lower output per device and possibly loss in the combiners required to achieve a specified output power. Nonetheless, the InP HEMT generally has a factor-of-two efficiency advantage over the pHEMT and GaAs HEMT.

InP HEMTs have been fabricated with fmax as high as 600 GHz (0.1 µm gate length), and amplification has been demonstrated at frequencies as high as 190 GHz. The efficiency does not begin to drop until about 60 GHz. Power levels range from 100 to 500 mW per chip.

Metamorphic HEMT (mHEMT)

The mHEMT allows channels with high-In content to be built on GaAs substrates. The higher electron mobility and higher peak saturation velocity result in higher gain than is possible in a pHEMT. mHEMTs are generally limited to low-power applications by their relatively low breakdown voltage (<3 V). However, an mHEMT capable of 6-V operation and a power output of 0.5 W has been recently reported.

Heterojunction Bipolar Transistor (HBT)

HBTs are typically based upon the compound-semiconductor material AlGaAs/GaAs. The AlGaAs emitter is made as narrow as possible to minimize base resistance. The base is a thin layer of p GaAs. The barrier is created by heterojunction (AlGaAs/GaAs) rather than the doping. The base can therefore be doped heavily to minimize its resistance. Base sheet resistance is typically two orders of magnitude lower than that of an ordinary BJT, and the frequency of operation is accordingly higher. The current flow is (in contrast to a MES-

FET) vertical so that surface imperfections have less effect upon performance. The use of a semi-insulating substrate and the higher electron mobility result in reduced parasitics. The DC curves are somewhat similar to those of a conventional BJT, but often contain a saturation resistance as well as saturation voltage. Currently available AlGaAs/GaAs HBTs are capable of producing several watts and are widely used in wireless handsets, GaAs HBTs are also widely used in MMIC circuits at frequencies up to X band and can operate in PAs at frequencies as high as 20 GHz.

SiGe HBT

The use of SiGe rather than Si in the base of the HBT both increases the maximum operating frequency and decreases the base resistance. However, they are generally less efficient than GaAs HBTs and can have lower breakdown voltages. One experimental SiGe HBT is capable of delivering over 200 W at L band.

InP HBT

The use of InP in an HBT further boosts mobility and therefore the high frequency response. In addition, InP HBTs have lower turn-on and knee voltages, resulting in higher gain and efficiency. InP HBTs for RF-power applications incorporate two heterojunctions (AlInAs/GaInAs and GaInAs/InP). The InP in the collector increases the breakdown voltage, allowing higher output power. To date, outputs of about 0.5 W at 20 GHz have been demonstrated, but it is anticipated that operation to 50 or 60 GHz will be possible.

SiC MESFET

The wide band gap of SiC results in both high mobility and high breakdown voltage. An SiC MESFET can therefore have a frequency response comparable to that of a GaAs MESFET, but breakdown voltages double that of Si LDMOS. This results in power densities of 10 W/mm, which is ten times that of a GaAs MESFET. The high thermal conductivity of the SiC substrate is particularly useful in high-power applications. The higher operating voltage and associated higher load impedance greatly simplify output networks and power combining. SiC MESFETs typically operate from a 48-V supply. Devices with outputs of 10 W are currently available, and outputs of 60 W or more have been demonstrated experimentally. The cost of SiC devices is at presently about ten times that of Si LDMOS.

GaN HEMT

GaN offers the same high breakdown voltage of SiC, but even higher mobility. Its thermal conductivity is, however, lower, hence GaN devices must be built substrate such as SiC or diamond. While the GaN HEMT offers the promise of a high-power, high-voltage device operating at frequencies of 10 GHz or more, it is still in an experimental state. Power outputs of 8 W at 10 GHz with 30 percent efficiency have been demonstrated.

Monolithic Microwave Integrated Circuit (MMIC)

MMICs integrate RF power devices and matching/decoupling elements such as on-chip inductors, capacitors, resistors, and transmission lines. The proximity of these elements to the RF-power devices is essential for input, output, and interstage matching at microwave and millimeter-wave frequencies.

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Acronyms Used in Part 1

AC	Alternating Current
ACPR	Adjacent-Channel Power Ratio
BJT	Bipolar-Junction Transistor
C/I	Carrier-to-Intermodulation
CDF	Cumulative Distribution Function
CDMA	Code-Division Multiple Access
CW	Continuous Wave
DC	Direct Current
DSP	Digital Signal Processing
EVM	Error-Vector Magnitude
FET	Field-Effect Transistor
FSK	Frequency-Shift Keying
GMSK	Gaussian Minimum Shift Keying
GSM	Global System for Mobile communication
HBT	Heterojunction bipolar transistor
HEMT	High Electron-Mobility Transistor
HFET	Heterojunction FET (also HJFET)
IC	Integrated Circuit
JFET	Junction Field-Effect Transistor
LDMOS	Laterally Diffused MOS (FET)
MESFET	MEtal Semiconductor FET
mHEMT	Metamorphic HEMT
MMIC	Microwave Monolithic Integrated Circuit
MOSFET	Metal-Oxide-Silicon Field-Effect Transistor
NADC	North American Digital Cellular
NPR	Noise-Power Ratio
NTSC	National Television Standards Committee
OFDM	Orthogonal Frequency-Division Multiplex
PA	Power Amplifier
PAE	Power-Added Efficiency
PDF	Probability-Density Function
PEP	Peak-Envelope Power
pHEMT	Pseudomorphic HEMT
PSK	Phase-Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
SRRC	Square-Root Raised Cosine
SSB	Single SideBand

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