

ATTENUATOR AND AMPLIFIER ICs AID DIGITAL SYSTEMS

These versatile ICs raise and lower signals to the levels required for digital communications systems.

Digital communications systems require very tight control of output power and intermodulation products at moderate prices. To meet these requirements, designers typically employ discrete power amplifiers or hybrid modules, which increase size and raise costs. Part 2 of this series on integrated circuits (ICs) for digital communications systems show how monolithic ICs offer a cost-effective solution to hybrids in wireless systems.

Linear power amplifiers boost modulated signal levels for transmission by the system antenna. The signal levels can range from less than 1 mW to more than 6 W. As much as 1-W transmitter power is allowed by the Federal Communications Commission (FCC) without licensing in the 900-MHz Industrial-Scientific-Medical (ISM) band. For this requirement, an amplifier should produce 1.25-to-1.50-W output power to allow for losses.

Modern digital systems within this band require less power, typically operating with 100 mW. Also, digital modulation schemes not based on constant-envelope carriers require linear power amplifiers to prevent "spectral regrowth," a phenomenon which occurs when a nonlinear amplifier adds back in modulation sidelobes. Even for constant-envelope carriers, often a linear amplifier is needed to prevent channel-to-channel interference.

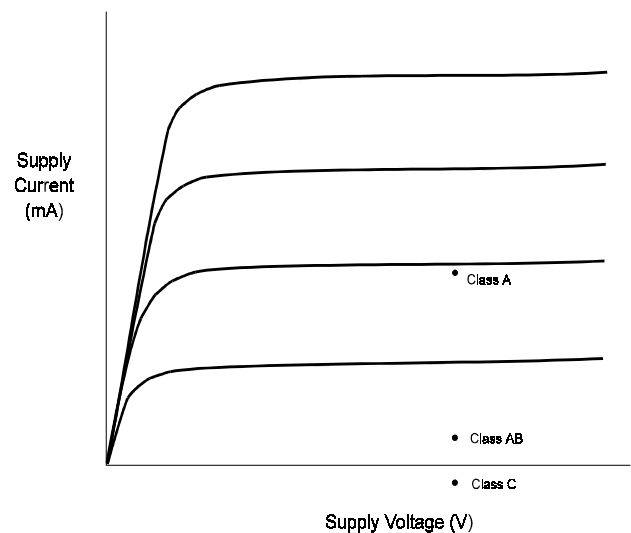
Level control, by means of step or variable attenuators, is desirable when the input signal level is not known or when intelligent protocol allows the receiver to "tell" the transmitter to reduce its transmit power, as in code-division-multiple-access (CDMA) systems. Step attenuators (instruments which switch attenuation at discrete levels) are generally controlled by digital means, while continuously-variable attenuators are controlled by voltage.

Power amplifiers can be fabricated with a variety of technologies, including those based on silicon-bipolar, GaAs MESFET, and GaAs heterojunction-bipolar-transistor (HBT) devices. Modules based on discrete silicon devices tend to be large and consume excessive power since numerous stages are required for adequate power levels. Such modules, which have been used particularly in cellular systems at 900 MHz, have the advantage of a single, positive power supply.

GaAs MESFET power amplifiers are slowly becoming more popular due to the intrinsic performance advantages of GaAs over silicon. GaAs provides high gain and output power with relatively low current consumption. GaAs FETs operate quite well at low

power-supply voltages (3 V) due to the low knee voltage. Also, GaAs is a semi-insulating substrate, which allows incorporation of passive components, such as capacitors and inductors, on-chip for much higher levels of integration. However, GaAs FET amplifiers require a negative voltage supply for the gate-source junction. This is accomplished by an additional battery (in battery-operated systems) or switching regulator. The efficiency and linearity will suffer unless the gate voltage can be held constant.

HBT amplifiers combine the best features of bipolars and MESFETs. Like silicon-bipolar devices, the HBT can be biased with only a positive supply derived from a single battery. Unlike silicon, the HBT can be used at frequencies well into the microwave range.



1. Class A bias conditions provide low distortion amplification and higher current consumption than other bias alternatives.

Power amplifiers are characterized primarily by maximum output power, linearity at the required power level, efficiency, bias supply requirements, size and weight, and packaging. Maximum output power is dependent upon the size of the final power stage, which

determines the level of current which may flow. For Class A operation (Fig. 1), the power density is specified in terms of total transistor channel width:

$$P_{d,max} = [W I_{cc} (V_{cc} - V_{knee})] / 2 \quad (1)$$

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where:

W = the total channel width,
 I_{cc} = the quiescent bias current per unit channel width,
 V_{cc} = the quiescent bias voltage, and
 V_{knee} = the knee voltage.

Therefore, the transistors can be fabricated at sizes according to the required power and available bias. The class of operation affects this result, however. For Class AB devices operated near pinch-off, the bias point changes with the drive power. In this case, the final bias point must be used to determine the optimum power and load. This can be found through load-pull measurements

or can be modeled with a nonlinear simulator such as SPICE. Class A amplifiers provide the optimum linearity, but also provide the lowest efficiency. Class A biased devices have a maximum theoretical efficiency of 50 percent, but are usually closer to 30 or 40 percent.

In this discussion, efficiency is defined as power-added efficiency (η), where:

$$\eta = \frac{(P_o - P_i)/P_{dc}}{(P_o - P_i)/V_{cc}I_{cc}} \quad (2)$$

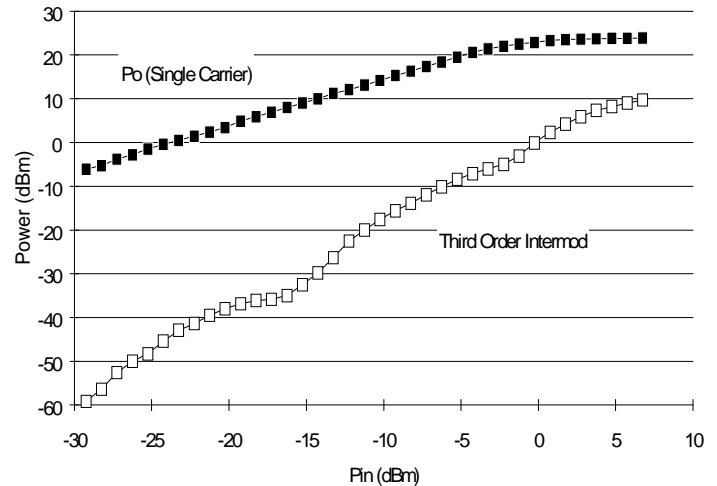
where:

P_o = the output power, and
 P_i = the input power.

This is essentially the ratio of the output power to the total DC power that is supplied. The third-order intermodulation product tends to follow a relatively constant 3:1 slope with respect to input power. Efficiency, however, decreases rapidly with reduced input power due to the current and the voltage swing decreasing together.

To improve efficiency and still maintain sufficient linearity for digital communication systems, the final stage of linear power amplifiers is often biased in Class AB, which is a compromise between maximum efficiency and linearity. For these amplifiers, the third-order product does not follow a true 3:1 slope over its full range but has an inflection point near compression as the bias point begins to shift (Fig. 2).

Efficiency, however, does not roll off at the same rate as a Class A amplifier. Since the quiescent bias point is near voltage pinch-off, the current consumption is reduced as the input power is reduced. Thus, the efficiency rolls off at approximately one-half the rate of the Class A amplifier.



2. Characteristic third-order intermodulation distortion (IMD) for class AB amplifiers rises as a function of input power.

The power amplifier is usually the largest, heaviest, and one of the most expensive active components in the RF section of a portable system, although available amplifier RF ICs are changing this trend. Power amplifiers in plastic SOIC housings help reduce the cost, size, and weight of portable systems.

Generally, a digital RF communications system is in a 50- Ω characteristic impedance. The output of the power transistor, however, tends to be at a very low impedance. For an IC power amplifier, a large cost and performance penalty is paid if the matching transformer is placed on-chip, versus placing the transforming components off-chip on the printed circuit board (PCB). A typical situation may require a transformation from 10 or 20 Ω up to 50 Ω . This can be accomplished with a two-element matching network. The components for terminating the second harmonic are also placed externally, though these are usually limited to a single capacitor, resonated with a package pin.

The power-supply voltage determines the maximum power and efficiency possible from the amplifier. Use of a higher voltage allows use of larger V_{cc} , which from Eq. 1 indicates a higher power capability per unit channel width. As the supply voltage approaches V_{knee} , the required channel width increases as $1/x$, which implies the total current must also follow. This leads to higher

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ohmic losses and lower efficiency, complicating the bias requirements. Obviously, it is much easier to distribute voltage throughout the circuit than current. Also, the required load (R_{load}) changes with the supply voltage as follows:

$$R_{load} = (V_{cc} - V_{knee})^2 / [2(PEP)] \quad (3)$$

where:

V_{cc} = the supply voltage, and
PEP = the peak envelope power.

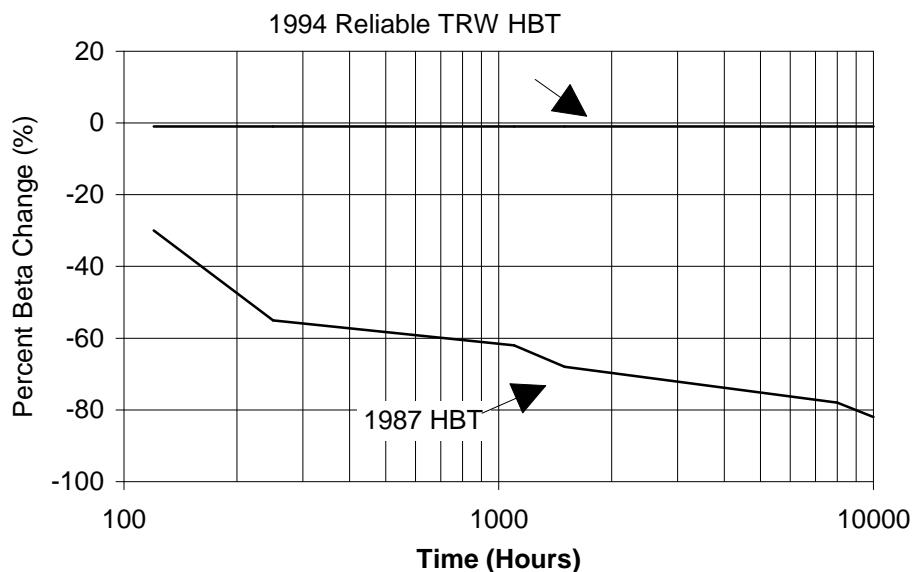
A lower load impedance requires larger transformation ratios to match to 50Ω , so bandwidth is reduced and matching circuit losses are increased. Nonetheless, low-voltage designs are necessitated by the system requirement to reduce the number of battery cells in handheld equipment. Current-generation RF and digital components are generally 5 V designs, but next-generation designs will be around 3 V. For example, the 600 mW, 900 MHz RF2103 HBT power amplifier allows operation from 3.0 to 5.6 V. The load resistance can be optimized since external output matching is used, with the maximum output power adjusted accordingly.

Another factor affecting the performance of power amplifiers is the heat-sink approach. High-power

amplifiers, even those operating with greater than 50 percent efficiency, dissipate significant power. The thermal rise from the ambient temperature to the channel of the transistor affects the reliability and performance of the amplifier. The TRW HBT process (employed for the RF Micro Devices' ICs) uses an enhanced molecular-beam-epitaxy (MBE) technology for which β has been shown not to degrade at a junction temperature of $+252^\circ\text{C}$ for up to 10,000 hours (Fig. 3).

Although the HBT can tolerate high channel temperatures, its performance and reliability will be enhanced if the thermal resistance of the package is kept low. The optimum thermal solution is to eutectically attach the die to a thermally-conductive package base, then solder the package to a suitable heat sink on the PCB.

For some high-power applications, this will be necessary. However, for most medium-power systems (such as battery-operated, hand-held, portable equipment), a higher thermal resistance may be tolerated. For applications that can tolerate plastic-packaged power amplifiers, the RF2103 is available as the RF2103P, the first commercial plastic-packaged HBT power amplifier, as well as a complete line of amplifiers for different frequency bands and output power levels.



3. The TRW HBT process is based on the firm's advanced molecular-beam-epitaxy (MBE) technology.

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Packaging is increasingly moving toward a plastic SOIC format, with emphasis on small size and batch-assembly processing. Several options exist for power applications in SOIC packages. The simplest is to accommodate the higher thermal resistance of a standard SOIC package with a detached die flag. This requires the heat to flow through the plastic, which is generally a poor thermal conductor.

For slightly higher powers, the package may utilize a "fused lead-frame", which ties each ground lead to the die flag, providing a thermal path to external ground through the leads. For higher powers, the die flag may have a "slug" attached to the bottom which extends through the plastic and can be soldered to a heat sink. This slug provides both a thermal path and electrical grounding, eliminating the need for ground pins and enabling use of a smaller outline package. Therefore, an SO-14 using six ground leads, could be reduced to an SO-8. This reduces ground inductance and size while enhancing the performance of the amplifier.

When designing the RFIC, care must be taken to incorporate package parasitics. This requires accurate models for the package and must be robust against assembly variations. Within a 14-lead SOIC package, the corner leads have significantly more inductance than do the center leads, so center leads are often utilized for grounds and series inductance from the corner leads is incorporated into the matching circuit. Not only is the package important, but how the package is mounted also affects the performance as well. Thick boards have higher ground via inductance, and if external components are used, they are also affected by PCB parameters. Use of the amplifier requires care to properly mount the part to the PCB.

Power-down functions are important for power amplifiers. When a time-division duplexed (TDD) system is in receive mode, the transmit side must be powered down, consuming microwatts of DC power in order to conserve battery life. Also, this power-down function should have a well-controlled ramp up and down to control adjacent-channel "splatter." With the HBT amplifiers, the base voltage is controlled to provide the power-down function. This can be controlled with a logic gate, providing ease of implementation.

In addition to power-down control, some additional level of power control is often desirable. This can be accomplished either digitally or continuously. Digital control can be implemented with either an individual

attenuator IC or directly on the amplifier IC. The attenuator will provide better control and resolution, while more limited control on the amplifier may be used. On the input to the amplifier, the level is generally in 10 dB steps over a 30 to 40 dB range. When the power is stepped down, however, the efficiency should not degrade proportionally. This is the case with Class AB amplifiers; however, the quiescent current is still quite high for a 10 dB step in power. To avoid this, the output stage can be bypassed (switched) on-chip and then powered down.

In some cases, analog gain control is required, such as in CDMA systems. This is usually best met with a combination of gain control from the intermediate-frequency (IF) processing section (such as the quadrature modulator) and the RF section (either with an attenuator IC or an integrated solution, such as a gain controlled driver-amplifier/power-amplifier combination). To meet the fine-resolution requirements of these systems, analog control is best utilized, at least for some range, to ensure complete coverage.

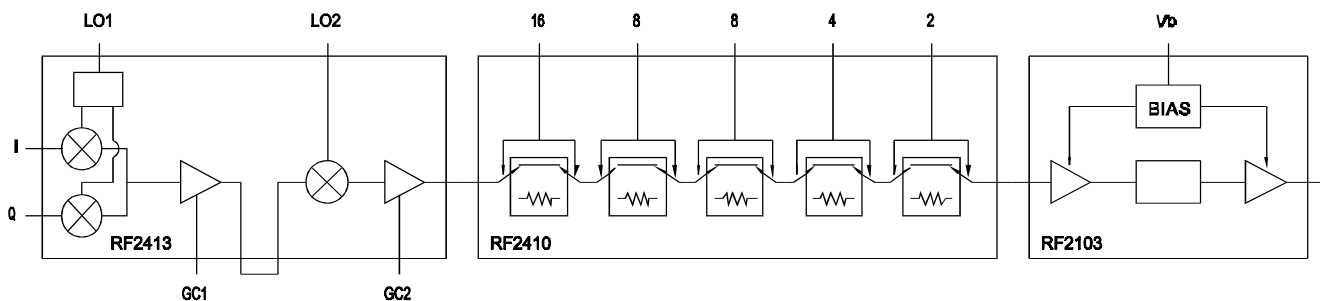
Other applications which require power amplifiers target higher frequencies, for example, at 1.8 and 2.4 GHz. These frequency bands are used for several applications, notably the Digital European Cordless Telephone (DECT) standard, the Japanese Personal Handy Phone System (PHS), the Digital Communication System (DCS-1800), and several new North American Personal Communication Systems (PCS) standards, all around 1.8 - 1.9 GHz.

An attractive approach for these designs is to utilize a single amplifier to cover the 1.8-and 2.4-GHz bands. This could be accomplished either through a broadband or a "dual-band" design. The design approach which utilizes off-chip output matching leaves the choice up to the user while maintaining all of the advantages of a narrowband design. The on-chip driver stage can be designed as broadband to cover both bands without sacrificing efficiency, power, or gain, but the final output stage must be optimized for the specific band of interest.

A current trend in high-frequency systems is toward higher levels of integration. For example, the RF2423 IC incorporates a quadrature modulator with a 100-mW output power amplifier having 25-dB gain control.

A common requirement for power amplifiers is to incorporate a transmit/receive (T/R) switch following the amplifier. This eliminates the need for an external switch

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4. Programmable attenuation (the RF2410 circuit) is critical to the amplitude control required by a CDMA system.

on the board. For the power levels of 100 mW or less, this is easily accomplished. A second switch may be placed in the receive path to provide a diversity function for switching between two antennas.

The attenuator is necessary for those RF systems requiring power control. This versatile component can be digitally-controlled, as in the single-supply RF2410 programmable attenuator IC (Fig. 4), or it may be continuously variable, providing a voltage-controlled attenuation range. Depending upon the application, either type may be optimum. The key parameters are minimum insertion loss, supply requirements, maximum attenuation, flatness vs. frequency, linearity of control, and power handling. GaAs MESFET technology is typically used for attenuators because of its desirable switching properties, ease of implementing passive circuits, and application to CMOS-or TTL-compatible digital control circuits.

Programmable attenuators make use of FETs for switching between a through path and an attenuated path. Alternatively, the FETs can switch between various resistors in a π or T configuration to reduce the losses of the through state. The switches can be controlled by direct application of 0 V and V_{cc} , or in some cases by both positive and negative voltage. Alternatively, digital translators can be incorporated to provide voltage-level translation between standard CMOS or TTL levels to the levels needed by the switches.

The voltage-variable attenuator (VVA) is generally used in a feed-back control loop, such as automatic gain control (AGC). This is due to the inherent lack of precise repeatability in the voltage setting. For these closed-loop applications, the VVA provides a good real-time gain control.

With either type of attenuator, the primary design concern is to minimize VSWR mismatch between sections and for all attenuation states. This reduces the overall error and maintains good match at the input and output. When designing the attenuator, care must be taken to maximize the power-handling ability and minimize loss. Generally, the step attenuators can handle more power than the VVA without distortion.

The next installment in this series on ICs for digital communications system will examine control components, such as switches, and how such components are invaluable in properly routing signals throughout the system.

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