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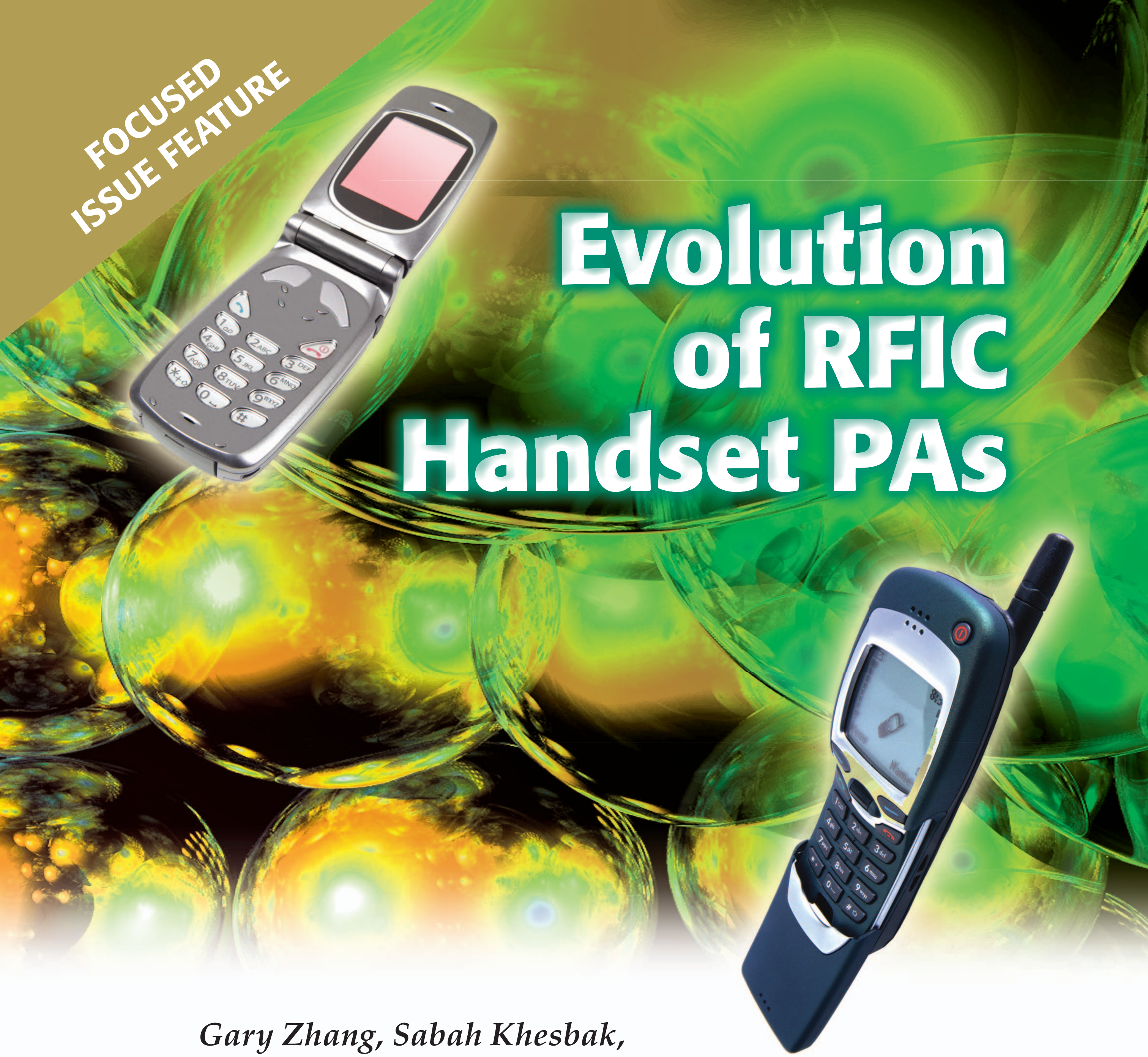

Evolution of RFIC Handset PAs

Gary Zhang, Sabah Khesbak, Anil Agarwal, and San Chin

The first official shift in communication systems from fixed-location devices to portable/mobile devices happened in 1973 when Martin Cooper, general manager of Motorola's Communications Systems Division at the time, placed the first mobile call from a New York street using AT&T's network. Four years later, the first cell phone was made in Chicago with free trials offered to more than 2,000 people. The first commercial handset to receive FCC approval was Motorola's DynaTAC in 1983 [1], which was made available to the public a year later. This 1.13 kg (2.5 lb) phone that

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cost consumers US$3,500 was only able to achieve approximately 35 minutes of talk time and took almost 15 years to develop with the cost totaling US$100 million.

The first generation (1G) of cell phone technology was purely analog using the advanced mobile phone system (AMPS) as the cellular interface standard. It was followed by some digitizing of the control signals, such as the one used in the Narrowband AMPS (NAMPS) air interface. Then came a major step forward in standardizing cell phone systems when the Cellular Technology Industry Association (CTIA) was created in 1988, paving the way for the needed infrastructure and organization to spur the development of next-generation technologies. This led to a noticeable shift in technology in the 1990s from analog to digital systems, resulting in new digital standards such as the global system for mobile communications (GSM) and code division multiple access (CDMA) systems, which are known as the second-generation (2G) networks.

The new digital systems not only increased efficiency of the phone but also enabled the addition of new features such as short message service (SMS) text messaging and downloadable content. With the increasing demand for data transmission in addition to voice usage, third-generation (3G) networks were established, with emphasis on higher data transfer capability. These networks (and their successors) conform to the International Mobile Telecommunications-2000 (IMT-2000) standards that set data transfer rates over the air. Several different 3G standards have emerged, such as CDMA2000, evolution data only (EVDO), wideband CDMA (WCDMA)\high-speed packet access (HSPA), and long-term evolution (LTE).

Today, the use of mobile communication devices is widespread and has become an essential part of daily life. From heads of states to farmers in the remotest part of China, the reliance and addiction to services such as texting, enterprise e-mail, internet access (for e-mail, banking, sharing of photos, etc.), navigation, and video downloads are ever increasing with no end in sight. This is pushing the technology at a faster rate than ever before and is driving the pace at which new networks and features are being added to meet and enhance user experience. This is clearly demonstrated by the handset unit growth/estimated growth between 2002 and 2013 shown in Figure 1, with a breakdown between different air standards (see also [2]).

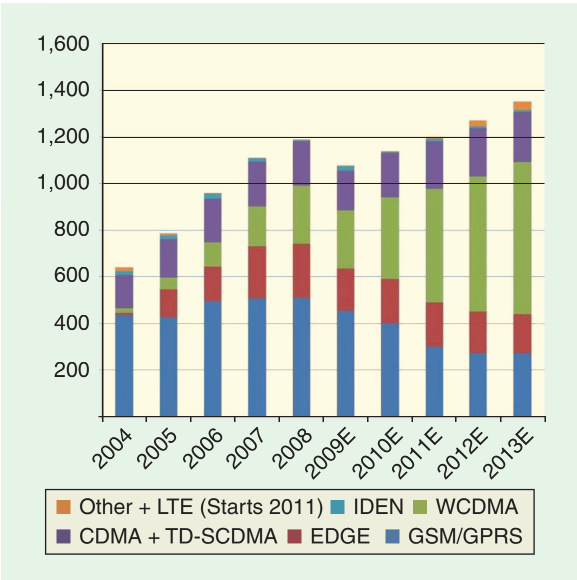

Figure 1. *Cell phone handset unit growth year over year forecast worldwide (in millions). (Courtesy of Skyworks, used with permission.)*

The use of mobile communication devices is widespread and has become an essential part of daily life.

Requirements for Power Amplifiers

The power amplifiers (PAs) in cell phones are the major gating devices for ensuring a flawless connection between the handset and the base station (hence, the other connected party). Being forefront of the active elements in a phone, they guarantee the power to satisfy the requirements of the air interface. There are several types of PA designs that are used, depending on the frequency of operation, the requirements of the standard (linear/saturated), and the generation of the phone (2G/3G). The trend toward size and power consumption reduction to ensure a smaller and lighter phone with a longer talk time puts a lot of pressure on the handset PA, which must be designed to deliver the same output power with much smaller size and much higher efficiency than previously. The PA has changed from large, power hungry, single transistor chain for 1G handsets to a small, highly integrated, very efficient radio frequency integrated circuit (RFIC) for 3G handsets. To cover more than one generation at a time, the current tendency of PAs is to move into multigeneration 2G/3G devices so that the same handset can support the new, upcoming technology while keeping backward compatibility with the lapsing generation.

Semiconductor Technologies for RF Integrated Circuit Handset PAs

Two main semiconductor technologies are available for PA applications: III-V-compound-based technologies and silicon-based ones. The former includes metal-semiconductor field-effect-transistor (MESFET), pseudomophic high electron mobility transistor (pHEMT), and hetrojuction bipolar transistor (HBT). The devices used for PA design are compared in [3]. MESFET technology was the most mature technology and a good candidate as a power device during the early stages of cell phone technology. As the pHEMT technology matured, it became a better choice for PAs. The pHEMTs demonstrate good RF performance with high gain, high linearity and good power added efficiency (PAE), especially at high frequencies (30 GHz or above). At cellular radio frequencies, it has shown to be the best PAE performance for linear handset PAs. However, its yield is not very attractive, leading to a higher cost structure. Gallium arsenide (GaAs) HBTs, on the other hand, are very robust devices. They have high breakdown voltage, high gain, good linearity, enhanced PAE, and high yield. All types of GaAs HBTs meet the essential requirement, which make them very attractive for low-cost handset PAs. Their improved PAE for linear PA applications is getting very close to pHEMT devices [4]. Their very good linearity performance is explained in reference [5]. GaAs HBT is also the dominating technology for saturated PA applications in handsets. Main handset PA suppliers, such as Skyworks, RFMD, Triquint, Avago, and Anadigics, all use GaAs HBT as their backbone technology for their product lines.

Silicon-based technologies, such as silicon-complimentary metal-oxide-semiconductor (CMOS), bipolar junction transistor (silicon-BJT), and SiGe-HBT, are penetrating the GaAs world and are trying to take market share away from GaAs HBT. The unique advantages of silicon-based technologies for PA applications are their low cost and technology compatibility with other handset integrated circuit (IC) building blocks. Silicon-based technologies for PAs could lead to the integration of RF front-end, RF transceiver, and phone baseband into a single IC chip. However, they are still playing a catch-up role in closing in on the performance of GaAs HBT technology in handset PAs. Lower power gain, worse linearity, and poorer PAE by nature are the main performance issues associated with silicon-based technologies, especially silicon-CMOS. In addition, the low breakdown voltage is their main drawback for PA applications, and some unique PA architectures need to be applied to resolve this issue [6], [7]. This may lead to circuit design complexity and higher cost.

Nevertheless, many research activities and industrial efforts have been carried out to improve the silicon-based PA performance and displace the dominance of GaAs HBT PAs in the handset market. Recent data is more promising for CMOS GSM PAs [8] and SiGe HBT linear PAs [9]. Samsung and Amalfi are currently sending samples of saturated GSM and linear

TABLE 1. Different operating class power amplifier performance comparison.

Class	Modes	Device Conduction Angle	Output Power	Maximum Efficiency	Linearity
A	Current Source	360	Moderate	50%	Excellent
AB		180–360	Moderate	50–78.5%	Good
180		180	Moderate	78.5%	Moderate
C	Switch	<180	small	100%	Poor
D		180	large	100%	Poor
E		180	large	100%	Poor
F		180	large	100%	Poor

CMOS PAs to handset original equipment manufacturers (OEMs). Axiom, recently acquired by Skyworks, has shipped millions of GSM/general packet radio services (GPRS) quad-band PAs to the handset market. The PA is fully integrated on a single 0.13 μm CMOS die with low price and decent PAE performance. Though this does increase the hope for silicon-CMOS technology used for saturated PAs, these devices still need more work for linear handset PAs. SiGe HBT technology, on the other hand, shows good potential for linear handset PAs that compete with GaAs HBTs. In the lower frequency bands (below 1 GHz), the main PA performance parameters, such as gain, linearity, and PAE, are comparable with HBTs. If the performance would catch up for higher frequency bands, SiGe HBT PAs may well position themselves to take some of the handset market share.

Generic Features for Traditional Power Amplifiers Operating in Different Classes

PAs operating in different classes have different trade-offs between their efficiency and linearity, as shown in Table 1. When a saturated PA is designed, where linearity is not a concern, it is usually selected to operate at class D, E, or F. In these cases, the PA active device functions as a switch. A detailed description and features of switching mode class D, E, and F can be found in [10]. Generally, at high RF frequencies, it is very difficult to realize the PA device as an ideal switching element. However, if a high-speed CMOS FET or a SiGe/GaAs HBT is used, saturated PAs will provide a sufficiently fast switching speed when heavily overdriven. By carefully controlling the input (gate/base) and output (drain/collector) device bias voltages and RF drive level, these devices can be made to behave very much like a fast switch. GSM/GPRS PAs for handset application are usually realized in class E to maximize their PAE. Linear handset PAs, on the other hand, may not be operated at switching mode due to their stringent linearity requirement. If no linearization techniques are used, linear PAs are usually selected to operate at class AB, which has better PAE than class A and better linearity than class B.

Handset Power Amplifier Design Methodologies and Architectures

Saturated Power Amplifier Design Methodologies and Architectures

Power Amplifier Design Methodology

GSM/GPRS PAs for handset applications are usually operated in saturated classes to make use of the constant envelope nature of the modulation [Gaussian mean-shift keying (GMSK)], and are able to operate into compression for PAE enhancement. GMSK can be thought of as a type of digital FM in which information is encoded onto a constant envelope waveform in terms of its phase transitions. Most currently available

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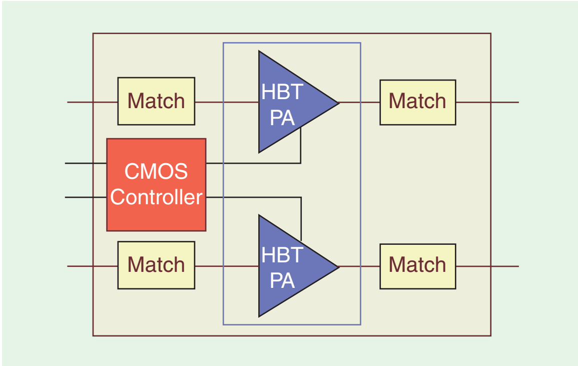

Figure 2. *Block diagram of a quad-band GSM/GPRS power amplifier. The CMOS controller provides dc bias, logic control, and power control for the two parallel HBTs. Impedance matching circuits are used at the input and output of the amplifier. (Courtesy of Skyworks, used with permission.)*

GSM/GPRS PAs are able to operate over four (quad) bands covering worldwide wireless handset services: GSM850 and extended GSM (EGSM), digital cellular system (DCS), and personal communication services (PCSs). A simplified block diagram is shown in Figure 2. The typical PA output power requirement into a 50 Ω load is about 35 dBm for the GSM850/EGSM bands, and about 32 dBm for the DCS/PCS bands.

These PAs are usually designed using three gain stages, as shown in Figure 3, to satisfy the high gain (greater than 30 dB) requirements. For this particular type of design, the first stage provides linear gain, while the second stage provides enough power to drive the third stage for saturated-mode operation. The third-stage device is the most important element and is directly related to the PA performance,

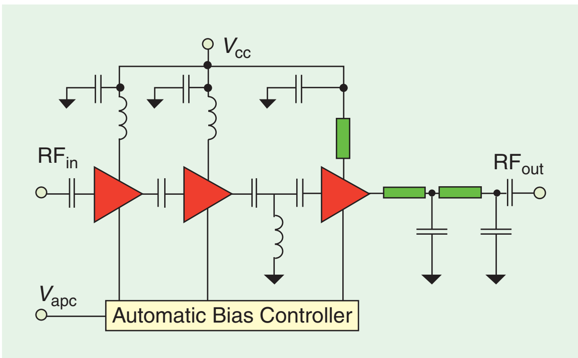

Figure 3. *Block diagram of a three-stage power amplifier. The first stage provides linear gain and the second stage provides enough power to drive the third stage for saturated-mode operation. From [13].*

PAs are also required to operate with high efficiency even down to very low output power levels.

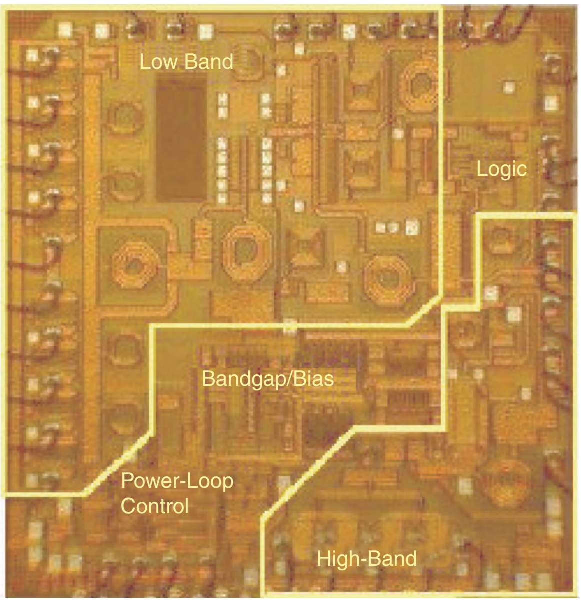

Figure 4. *Die micrograph of a quad-band SiGe HBT power amplifier. This design integrates the control stages and the amplification stages on one chip. From [12].*

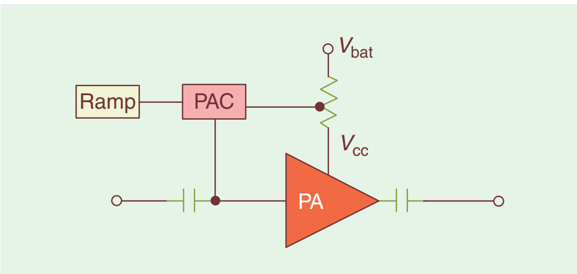

Figure 5. *Current-controlled, variable-gain circuit. The gain is adjusted by changing the biasing by sensing the current in the output stage. Ramp is the external voltage supply to control the power amplifier control (PAC). (Courtesy of Skyworks, used with permission.)*

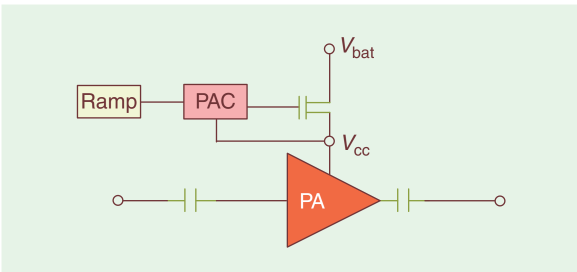

Figure 6. *Voltage-controlled, variable gain circuit. The voltage on the collector is sensed, and the series FET gate voltage is adjusted to set the collector voltage. (Courtesy of Skyworks, used with permission.)*

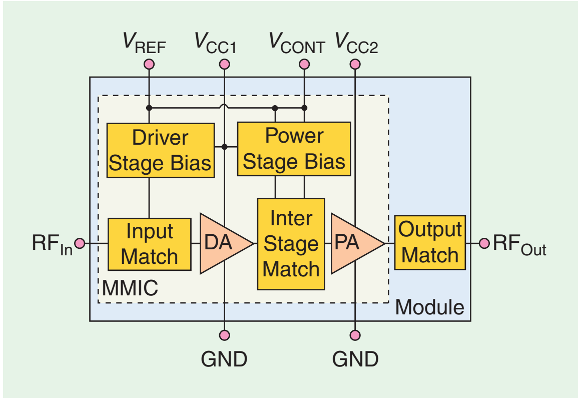

Figure 7. *Simplified two-stage handset linear power amplifier block diagram. The first stage consists of a driver amplifier (DA), followed by the power stage amplifier (PA). (Courtesy of Skyworks, used with permission.)*

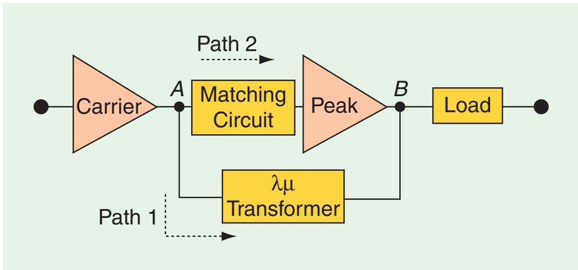

Figure 8. *Simplified structure of a series-type Doherty power amplifier. The output carrier signal is split and fed through Path 1 and Path 2 and combined at the load. From [23].*

especially PAE. This stage is typically designed to operate in class E switching mode for further PAE enhancement [11]. For SiGe HBT or GaAs GSM PAs, the third-stage device must be robust enough to handle high voltage swings arising from the high power level and high voltage standing wave radio (VSWR) at the output [12], [13]. Figure 4 [12] illustrates a die layout that integrates the PA stages and the control circuits of a SiGe HBT PA. A silicon-CMOS GSM PA, on the other hand, requires different design approaches to overcome the low breakdown voltage issue associated with the device itself. Transformers are usually applied to stack the last stage device in series so that each device cell shares the voltage swing equally.

Saturated Power Amplifier Design Architectures

Two main architectures are used in GSM PAs; one is a variable-gain and the other is a fixed-gain architecture. In the variable-gain architecture, [14] the PA has fixed input power, usually from a voltage controlled oscillator (VCO), and the output power is changed by varying the gain of the PA through biasing control. The biasing control can be achieved by sensing the current in the output stage, as shown in Figure 5, and adjusting the base bias accordingly. These are called *current controlled PAs*. Another method for output power control is via collector voltage control. This method senses the voltage at the output transistor collector [15] and adjusts the series FET gate voltage to set the collector voltage for desired power level, as shown in Figure 6. These are called *collector voltage-controlled PAs*. Newer architecture combines both approaches for greater flexibility in optimizing the PA. In the fixed gain architecture, the output power is adjusted by adjusting the input power of the PA from the preceding RFICs feeding the PA.

The rule of thumb is that a higher load impedance is required for lower output power levels to get good PAE.

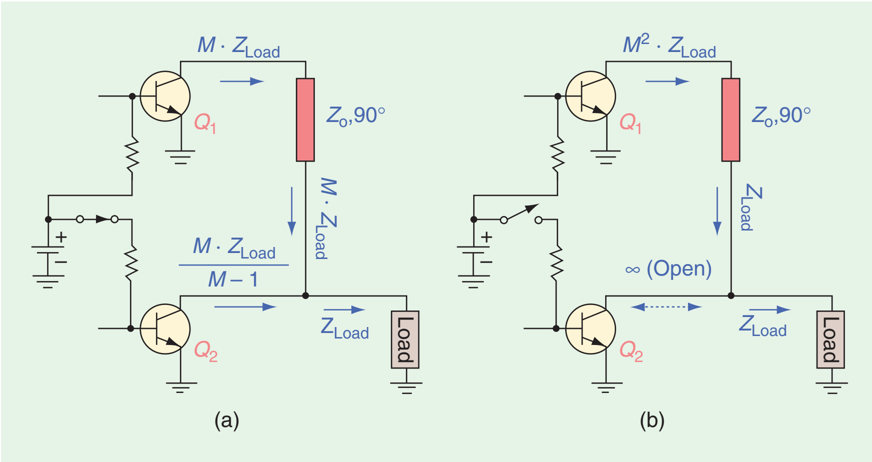

Figure 9. *A simplified structure of a switched Doherty power amplifier. (a) High-power mode. (b) Low-power mode. From [22].*

Current technology allows for GSM PAs to be extended to work with Enhanced Data Rates for Global Evolution (EDGE) modulation [16]. The two main architectures for EDGE are the polar architectures [17], where separated phase and amplitude information of the modulation are applied to the PA input and collector voltage of the PA, respectively and the direct launch architecture [18], where phase and amplitude modulated RF Carrier is supplied to the input of the PA directly.

Linear Power Amplifier Design and Its Architecture

3G digital mobile communication systems require PAs with both high PAE and good linearity, not only at peak power level but also at backed-off power levels. At higher power levels, PAs consume the majority of handset battery power, and efficiency is important for thermal consideration. At lower power levels, where 3G handsets spend most of the time, every few milliamps counts toward talk time optimization. Therefore, PAs are also required to operate with high efficiency even down to very low output power levels. The high linearity of the PA is needed, especially at higher output power levels, due to the high peak-to-average-power ratio of signals such as the HSDPA

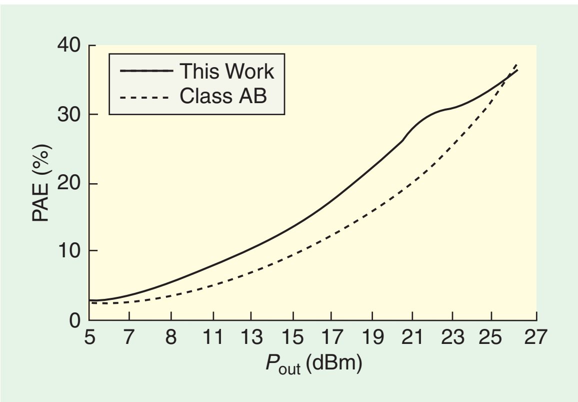

Figure 10. *The measured power added efficiency of a series-type Doherty power amplifier (solid line) as compared with a typical Class AB power amplifier (dashed line). From [23].*

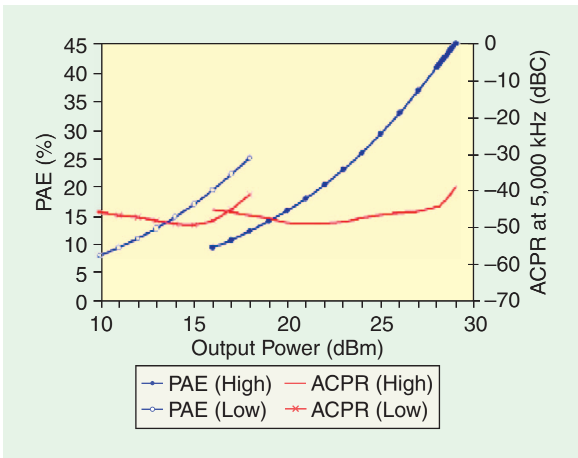

Figure 11. *Measured power added efficiency (PAE) and adjacent channel power ratio (ACPR) at a 5 MHz offset using a wideband code-division multiplexing access scheme (WCDMA 3GPP rel.99). The carrier frequency is 836.5 MHz. "High" refers to the higher frequency band and "Low" refers to the lower frequency band used in the WCDMA cell phone standard. From [22].*

Some phone manufacturers have started using limited multiband PAs while working with PA vendors to develop multimode devices.

and/or HSUPA configuration applied in 3G mobile systems. Generally, PAE and linearity work against each other. In other words, improvement of the PAE of a PA usually happens at the cost of linearity, and vice versa. For a linear handset PA in 3G and beyond, a certain level of linearity is a prerequisite. A PA designer has to squeeze out PAE with just enough linearity margin at each power level.

A linear handset PA typically uses two stages, a driver stage amplifier and a power stage amplifier, as shown in Figure 7. With the PA set to operate in class AB, the PAE can be optimized by controlling bias points and load impedances at both stages. A variety of papers have been published for PAE improvement at backed-off power levels using dynamic bias control [19], [20]. The enhancement of the PAE at backed-off power levels is usually achieved by lowering the quiescent current at these levels. If the optimum load impedance can be set according to the output power requirement, the PAE can be optimized at different power levels. The rule of thumb is that a higher load impedance is required for lower output power levels to get good PAE. Doherty PA architectures fall in this category [21]–[23]. The basic idea of Doherty PA operation is to set a high load impedance at the back-off power levels and lower the output impedance as the output approaches the peak-power level. This is achieved by a combination of the active load modulation effect of the peak amplifier and the impedance inverting effect of the quarter-wavelength transmission. Figures 8 and 9 show two types of Doherty architectures adapted for handset PA application. The uniqueness of both types is the overall size reduction, which is important for mobile devices—especially handsets. The PAE improvement from both structures is shown in Figures 10 and 11.

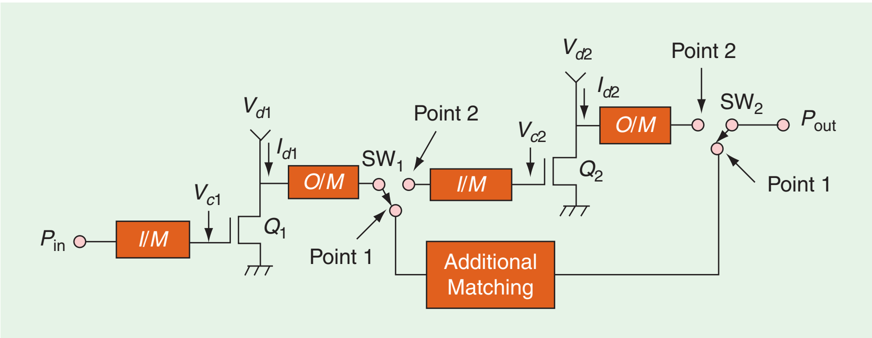

Figure 12. *Block diagram of stage bypass power amplifier. A switch is used to change the power amplifier device periphery. I/M: input matching. O/M: output matching. From [24].*

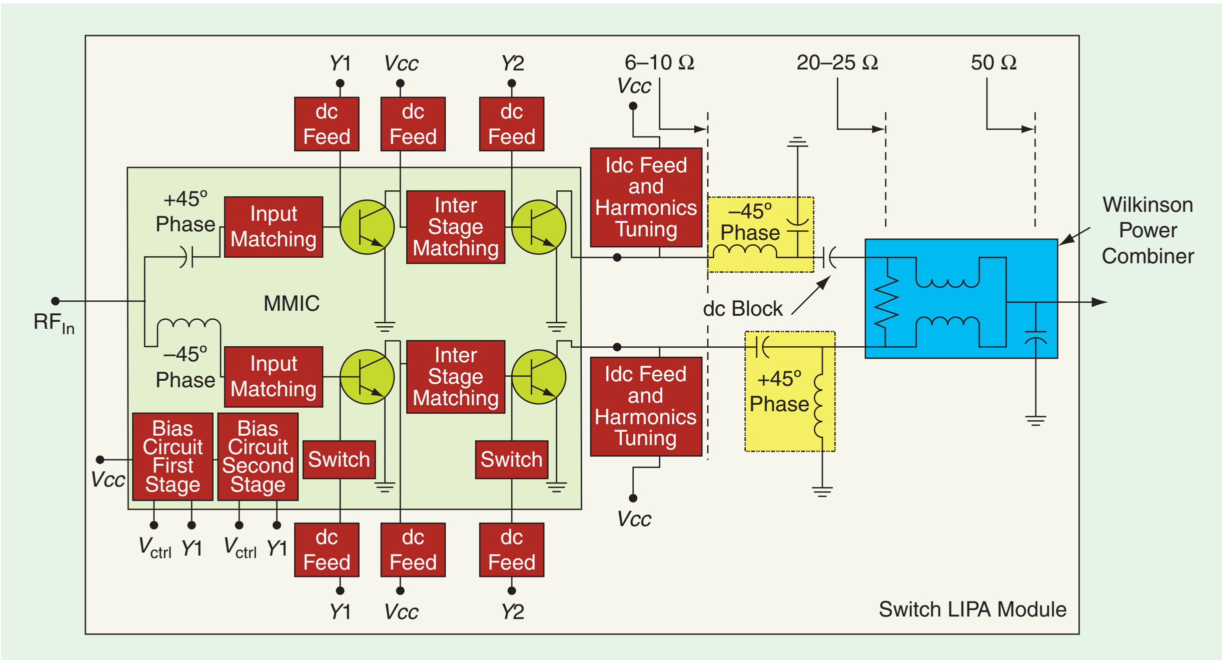

Figure 13. *Schematic of a switched load insensitive power amplifier (LIPA). The device periphery is changed by partially turning off the output cells. The output array size is optimized individually for different power levels. From [25].*

In addition to the bias point optimization and load modulation, changing the device periphery according to required output power level is another way to optimize the PAE at lower power levels. The following PA architectures represent output PA device periphery change through complete turning-off (bypassing) of the output stage, as shown in Figure 12 [24], or partially turning-off the output cells, as shown in Figure 13 [25]. The output array size optimization for different power levels can also be realized by selecting the output array size independently to avoid any loading effect from each other [26]. Improvement in PAE is shown in Figure 14 for partially turning-off the array size. In Figure 15, we show a schematic of a parallel PA that independently selects different output array sizes. The gain and PAE for this circuit are shown in Figure 16.

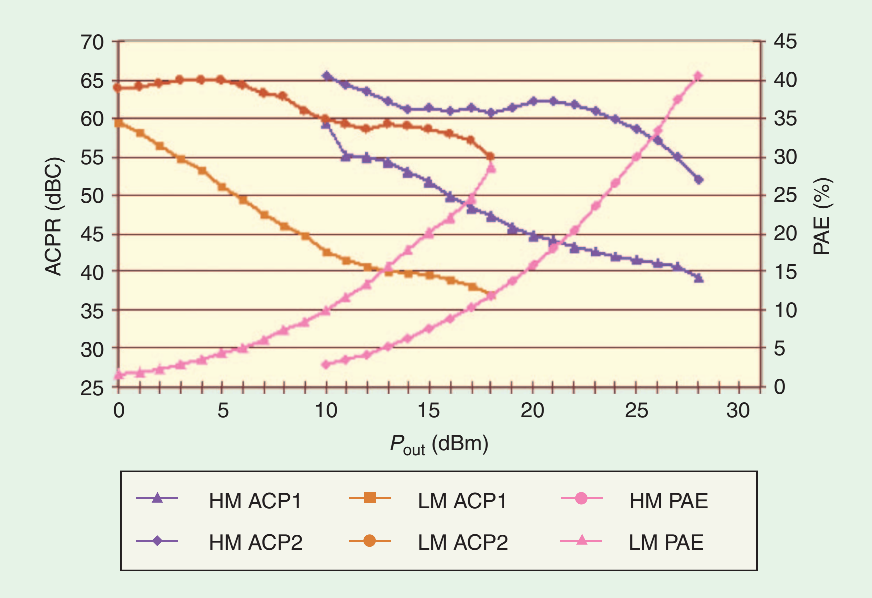

Figure 14. *Measured ACPRI and ACPR2 and PAE for low (LM) and high (HM) power mode at a carrier frequency of 1880 MHz for a stage bypass power amplifier. (Courtesy of Skyworks, used with permission.)*

Future Handset PAs

Multimode and Multiband PAs

As the usage and demand for mobile devices increases and existing available spectrum becomes more crowded, more frequency bands have been made available for cellular networks. This has caused the PAs to evolve from a single band PA with limited frequency span to multiband PAs with wide frequency span. Also, with the existence of multiple standards 2G/2.5G/3G and the ever-increasing requirement of domestic and international roaming, carriers are forced to cover more than one standard on their networks. This brought a new reality to the world of handset PAs, which is the need for multistandard PAs such as CDMA/WCDMA, GSM/WCDMA and others. Even though the phone vendors are currently using multiple PAs to cover multiple bands/standards, the push is very real for multimode (multiband/multistandard) PAs in the near future. In fact, some phone manufacturers have started using limited multiband PAs while working with PA vendors to develop multimode devices.

Moving into multimode PAs creates new challenges. One main challenge is related to the wider frequency band that the PA needs to cover. Another is related to the output power of the PA, where some

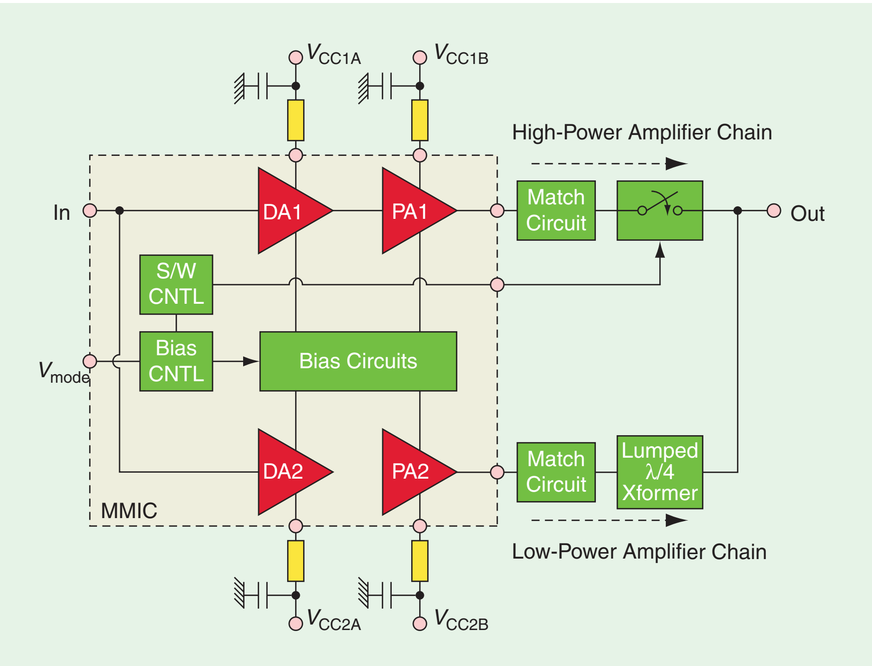

Figure 15. *Schematic of a parallel power amplifier. From [26].*

Silicon-based technologies provide a good solution for single chip integration.

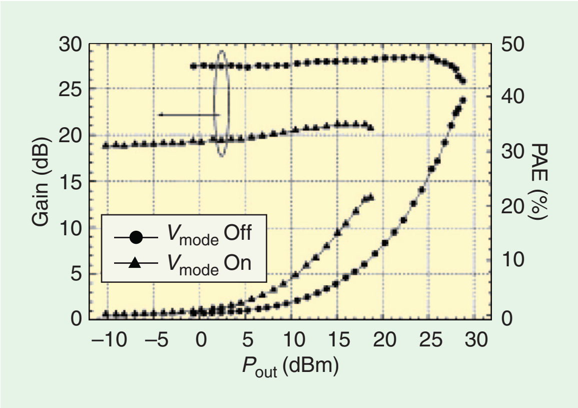

Figure 16. *Measured gain and power added efficiency (PAE) for low and high power mode at a carrier frequency of 1880 MHz for the circuit shown in Figure 15. From [26].*

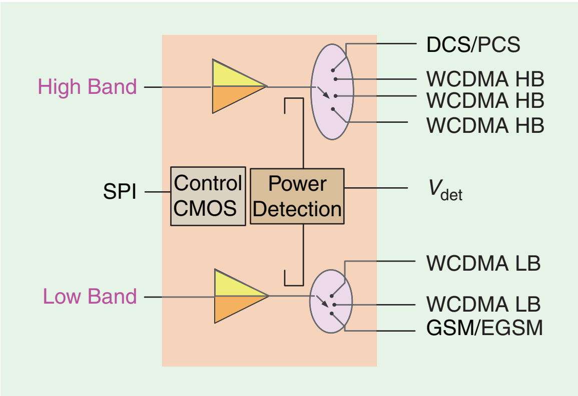

Figure 17. *Single path architecture for multimode power amplifiers. A switch is used to change between different demodulator circuits (SPI: serial port interface). (Courtesy of Skyworks, used with permission.)*

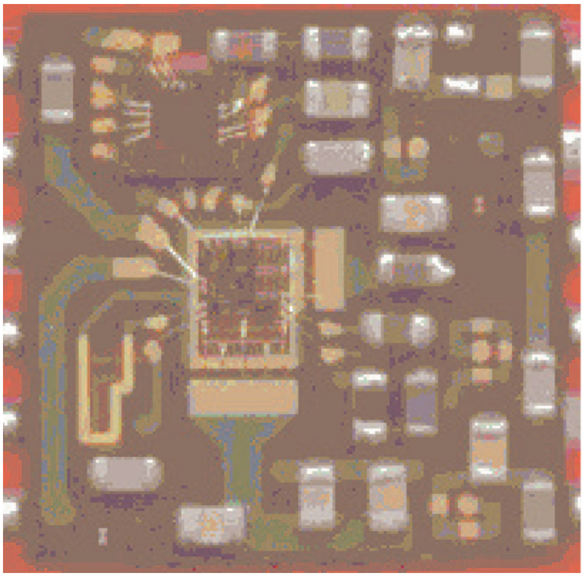

Figure 18. *GSM PA module (6 mm × 6 mm). (Courtesy of Skyworks, used with permission.)*

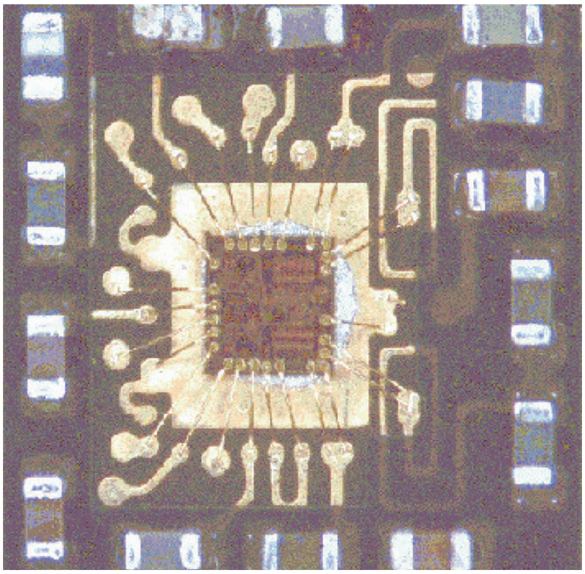

Figure 19. *WCDMA PA module (4 mm × 4 mm). (Courtesy of Skyworks, used with permission.)*

of the 2G standards are at a higher power than the 3G PAs. The fact that the filtering circuitry before the antenna is frequency selective for 3G system adds another difficulty to the tray because additional switching is necessary that reduces the efficiency of the system—hence the talk time.

Two main architectures are currently in development in the industry: The single-path architecture shown in Figure 17 combines all the modes in a single path while using an additional external component, such as a Dc-Dc converter, to mitigate the challenges and shortcomings associated with single-path design. The multiple-path PA, in which the 2G (GSM) mode is separated from the 3G mode at the output of the amplifier, reduces the mode switching penalty on the GSM path and allows for independent optimization of different modes with more flexibility.

Both types use the same design methodology and technology that is used by single mode PAs, with the main focus being on smaller size and higher efficiency. Multimode PAs are expected to be in production at the end of 2010, opening the path for higher and higher integration while providing a path toward a cognitive PA that can support reconfigurable software and cognitive radios of the future.

Summary

Because PAs used in cell phone handsets operate with a battery supply, a high PAE is essential for battery life. It is also important for thermal management on the handset. Linearity is critical for 3G applications or beyond. In addition, cost, size, and reliability are also very important to consider. Higher and higher on-chip integration using various semiconductor technologies is the key to make handset PAs smaller and more cost-effective, enabling more features on the phones. III-V compound technologies are still dominant in today's handset market due to their superior performance such as PAE, linearity, and ruggedness. Most of the handset PAs using III-V compound technologies are delivered in an over molded multichip module (MCM) package. The physical integration inside the MCM for a GSM PA is shown in Figure 18 and one for a WCDMA PA is shown in Figure 19.

Silicon-CMOS technologies are playing catch-up. Further performance improvement and more novel design approaches are needed to displace the dominance of the III-V compound technologies. Silicon-based technologies provide a good solution for single chip integration. Silicon-CMOS multimode/multi-band hand-set PAs may provide phone vendors with the lowest cost, smallest size, and most functionality. The PA may eventually be integrated with transceiver and baseband chips to further reduce size and cost.

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