ACPR Design of High-Efficiency Power Amplifiers for Wireless Handset Applications

By Hui Geng, NDK Machida Corporation,
and Yasuaki Hasegawa, NEC Corporation

Commonly, a multi-chip module power amplifer (MCM PA) used for wireless handset application consists of two- or three-stage field-effect transistor (FET) amplifiers. The key point of the design is to achieve a compromise between high efficiency and high linearity. However, as this article will describe, the adjacent channel power ratio (ACPR) of a two-stage power amplifier can be greatly improved by selecting the biasing point and the gain level of the first- and second-stage amplifiers. This 3 to 5 dB improvement result has been verified by experimental investigation.

Although there are many linearization techniques for power amplifiers, this MCM circuit-level technique is the most attractive in terms of achieving a low-cost, good ACPR design. Four things are very important for good ACPR design: biasing points, gain levels of the stages, source inductance of FETs and phase delay between the two stages.

In this design, a new dual-mode MCM PA with a 0.12 cc volume (7.8 × 7.8 × 2.0 mm) for code-division multiple access (CDMA) and time-division multiple access (TDMA) cellular handset applications was developed using this MCM circuit-level linearization technique. This MCM PA uses an enhancement-mode gallium arsenide (GaAs) enhancement heterojunction field-effect transistor (HJFET) developed by NEC Corporation that needs only a single polarity power supply.

The PAE of the two-stage MCM PA is more than 55 percent for TDMA mode (IS-136) at an output power of 30 dBm, with an ACPR of –30 dBc at 30 kHz off-center frequency (ACPR1). For CDMA mode (IS-95), the PAE is more than 45 percent at an output power of 28 dBm, with an ACPR of –50 dBc at 885 kHz off-center frequency. These performances satisfy the requirements of IS-136 DAMPS and IS-95 CDMA cellular communication systems. At 30 dBm output power, the PAE of the last-stage amplifier reached 64 percent, which shows the good practicality of the E-mode HJFET. Design emphasis is on maximizing the output power, power-added efficiency and the ACPR performance.

ACPR design consideration

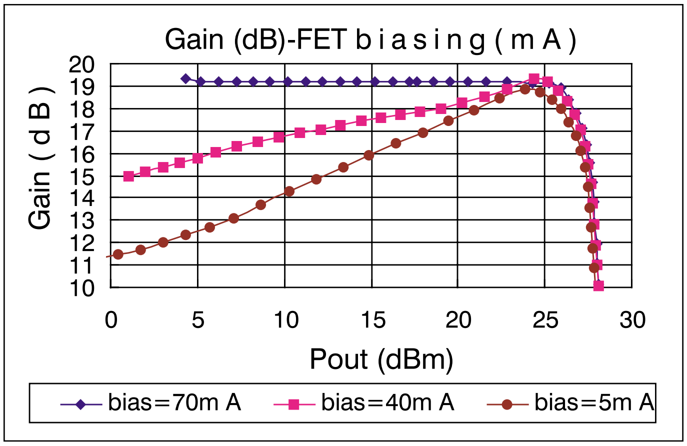
For the IS-136 TDMA signal, the ACPR1 at 30 kHz off-center frequency is caused by third-stage IM products. Therefore, the ACPR1 with an output power at G_c dB point gain compression point may be expressed as:

$$ACPR1 = 20\log\left[\left(10^{\frac{G_c}{20}} - 1\right)/3\right] \qquad (1)$$

For the multitone intermodulation (IMD) to carrier ratio (M-IMR), M-IMR is the ratio of the linear output power per tone to the distortion power of one certain tone in the adjacent channel. It is therefore [2]:

$$M - IMR_{dBc} = IMR_{2dBc} - 10\log(4) + 10\log\left(\frac{n^2}{4N_1(n,r) + M_1(n,r)}\right) \qquad (2)$$

It can be confirmed that the ACPR of the TDMA signal is similar to the spectral regrowth of a two-tone intermodulation component. From the expression of the CDMA signal, the ACPR of



▲ **Figure 1. Measured gain and bias characteristics of a FET.**

the CDMA signal is similar to the distortion of a multi-tone intermodulation component.

According to the definition, the ACPR1 of the IS-95 CDMA is the ratio of the power density at the offset frequency in a 30 kHz bandwidth to the power within 1.23 MHz bandwidth in the carrier channel bandwidth. The ratio of 1.23 MHz to 30 kHz is –16.13 dB. Subtracting –16.13 dB from Equation (2) and substituting Equation (1) into Equation (2), the ACPR1 of CDMA PA with an output power at G_c dB gain compression point can be approximately expressed as:

$$ACPR1 = 20\log\left[\left(10^{\frac{G_c}{20}} - 1\right)/3\right] - 10\log\left[\frac{n^2}{4N_1 + M_1}\right] - 10.18 \tag{3}$$

where n is the number of tones:

$$N = \left(\frac{n-1}{2}\right)^2 - \frac{\varepsilon}{4}, M = \left(\frac{n-1}{2}\right)^2 + \frac{\varepsilon}{4}$$

and ε is the division remainder of

$$\frac{n+1}{2}$$

For $n = 5$, Equation (3) can be expressed as:

$$ACPR1 = 20\log\left[\left(10^{\frac{G_c}{20}} - 1\right)/3\right] - 11.6 \tag{4}$$

Equations (1) and (4) are the compact expressions to relate ACPR1 and gain compression of the power amplifier. From these equations, for the TDMA signal, ACPR1 is about 27.8 dBc at P_{1dB} (1 dB gain compression point). For the IS-95 CDMA signal, ACPR1 is about 39.2 dBc at P_{1dB}. However, this result is for a signal-stage PA. For a multistage PA, the situation becomes complicated because of the AM to AM and AM to PM distortion effects between FETs.

The large-signal RF characteristics of the E-mode HJFET have been reviewed using the load-pull system. For the different gate widths of the E-mode HJFET (with the gate widths 3.5, 5, 17.5 and 21 mm), P_{1dB} with the continuous wave input and ACPR with IS-136 TDMA and IS-95 CDMA signal inputs have been measured at the frequency of 900 MHz. From the measured data, it is shown that at P_{1dB}, the ACPR is about –28 dBc at 30 kHz off-center frequency with IS-136 mode. With IS-95 mode, the ACPR1 of P_{1dB} is about –40 dBc at 885 kHz off-center frequency. The results agreed well with the calculated results using Equations (1) and (4).

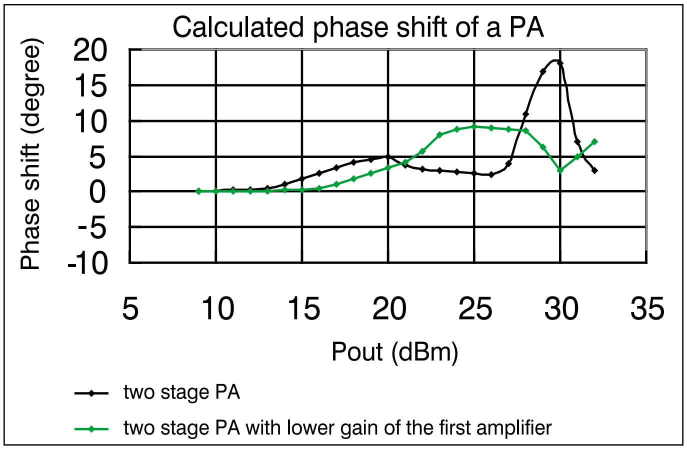
Self-compensated predistortion linearization

This section discusses a self-compensated predistortion method that uses the amplifier to compensate the nonlinearity of the power amplifier. To obtain a distortion-free signal, the predistortion linearization method uses the gain expansion and negative phase deviation responses of the predistorter to compensate for the gain compression and positive phase deviation characteristics of a PA. The first stage of the two-stage PA as a predistorter controls the biasing points and the gain level of the first-stage amplifier. A good design will achieve better ACPR performance at the 1 dB gain compression point of the last-stage FET. That means both ACPR and PAE performances can be achieved at the same time.

AM to AM and AM to PM distortions are the two causes that influence ACPR performance. Figure 1 shows a typical example of the gain-expansive characteristic of a 3.5 mm FET used for the first stage of a MCM PA in dependence of biasing current points. Usually, the second-stage FET shows a gain compressive characteristic because of the relatively high biasing point. By selecting the biasing points of the FETs, the gain performance of PA can be compensated to obtain better AM to AM performance.

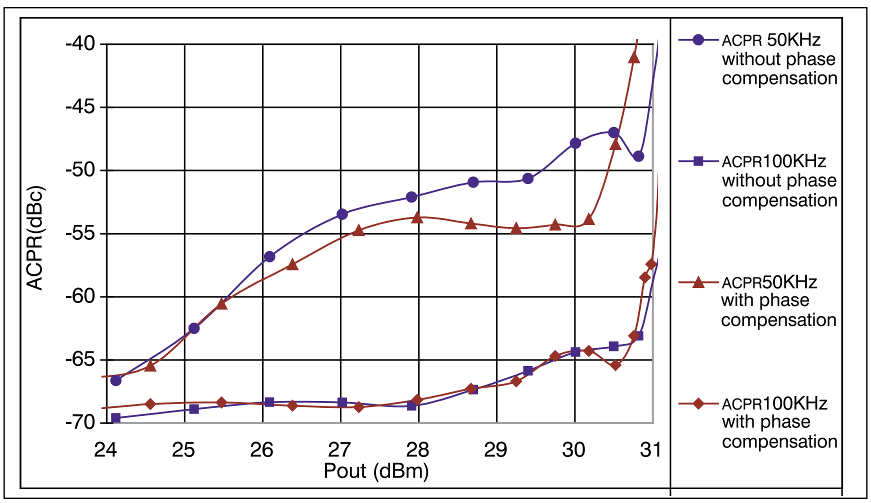
The phase shift of FET is caused mainly by the nonlinearity of Cgs and gm (gm is related to Gds) in the FET equivalent circuitry model. The phase shifts of Cgs and gm depend on their input power level. Difference gain level has a difference phase shift of Cgs and gm. For example, by increasing the gain level of the first-stage amplifier, for a constant output power, large gain level or smaller input power level led to a relatively smaller phase shift of Cgs and gm or smaller overall phase shift.

The phase shift characteristics of Cgs and Gds differ. The phase shift of Gds is increased and the phase shift

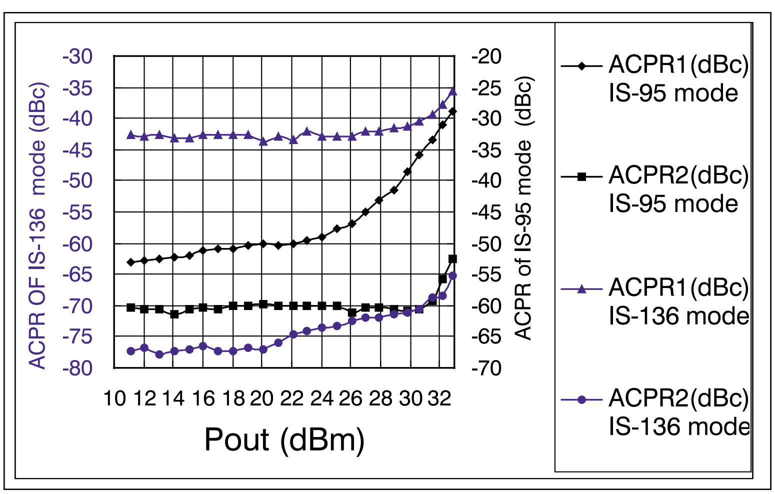


▲ **Figure 2. Calculated phase shift of a two-stage PA.**

of Cgs is decreased with an increasing input power level. Thus, the overall phase shift of the PA changes with the input power level.



▲ **Figure 3. Measured ACPR characteristics of the PA, with and without phase compensation.**



▲ **Figure 4. Measured ACPR performances of the PA.**

Figure 2 shows the simulated phase shifts of a PA. In this figure, the phase shifts of a two-stage amplifier were calculated with two different gain levels for the first-stage amplifier. The overall phase shift of PA with the lower gain level of the first-stage amplifier was improved largely.

Figure 3 shows measured ACPR performances with the Japanese PDC mode signal, depending on the gain level of the first-stage amplifier. The ACPR at an output power of 30 dBm with 50 kHz off-center frequency (ACPR1 of PDC mode) has been improved about 7 dBc by controlling the gain level of the first stage amplifier to compensate for the phase shift of the PA.

Performance of the power amplifier

The basic requirements for this power amplifier are high ACPR and high PAE at both CDMA and TDMA mode input signals. Output power requirements are 30 dBm for TDMA mode and 28 dBm for CDMA mode. From the ACPR analysis and the power load pull measurement result, last-stage E-mode HJFET with the output power of 30.5 dBm at 1 dB gain compression point must be selected. Using this E-mode HJFET, the ACPR requirements both for TDMA and CDMA modes can be satisfied by Equations (1) and (3).

Figure 4 exhibits the measured RF performances of new dual-mode MCM PA with a 0.12 cc volume (7.8 × 7.8 × 2.0 mm) for CDMA and TDMA cellular handset applications using an E-mode GaAs HJFET at 900 MHz frequency band. At 30 kHz off-center frequency, the ACPR requirement for IS-136 DAMPS cellular communication systems is better than 27 dBc. At 885 kHz off-center frequency, the ACPR requirement for IS-95 CDMA cellular communication system is better than 47 dBc. For TDMA-mode (IS-136), the PAE is more than 55 percent at an output power of 30 dBm, with an ACPR of –30 dBc at 30 kHz off-center frequency. For CDMA-mode (IS-95), the PAE is more than 45 percent at an output power of 28 dBm, with an ACPR of –50 dBc at 885 kHz off-center frequency. Those performances satisfied the requirements of IS-136 DAMPS and IS-95 CDMA cellular communication systems.

The last stage of the amplifier achieved a power-added efficiency of more than 64 percent at an output power of 30 dBm, with 10 dB power gain that displays the good practicality of the E-mode HJFET.

Conclusion

It was shown that ACPR is greatly improved by selecting the biasing point and the gain level of the first and second stage amplifiers.

A new-linear, high-efficiency, dual-mode MCM PA for CDMA and TDMA cellular handset applications was developed using E-mode GaAs HJFET. Operating from a 3.5-volt single power supply, this amplifier is targeted at a PAE of 60 percent for TDMA and 50 percent for CDMA applications. The measured results indicate the attractiveness and advisability of the E-mode GaAs HJFET used for cellular handset applications. Final output characteristics validate the proposed ACPR design procedure. The MCM circuit-level linearization technique has realized this E-mode GaAs HJFET PA with good ACPR and PAE performances.

Acknowledgement

The authors would like to thank K. Wasa, N. Iwata and R. Yamamoto of NEC Compound Semiconductor Device Division, as well as T. Watanabe, S. Agu and Y. Fushitani of NDK, for their fruitful discussion and encouragement throughout this work.

References

1. M. C. Jeruchim, et al, *Simulation of Communication Systems*, New York: Plenmu Press, 1990.

2. K. A. Simons, "The Decibel Relationships between Amplifier Distortion Products," *Proceedings of the IEEE*, Vol. 58, No. 7, July 1970.

3. S. Kand and H. Hong, "Effects of a Driver's ACLR on Total ACLR," *Microwave Journal*, October 2000.

4. O. Gorbachov, "Distortions in Cascaded MMIC Power Amplifiers," *Microwave Journal*, October 2000.

Author information

Hui Geng received a bachelor of science degree in electrical engineering from Beijing Polytechnic University, China, in 1982 and an MSEE from Tsinghua University, Beijing, China, in 1984. He completed his Ph.D. in communication engineering from Osaka University, Japan, in 1998 and joined NDK Machida Corporation. Since then, he has been engaged in the research and development of power amplifiers for mobile handset applications. He can be reached via E-mail: kou_ki@lsi.nec.co.jp; or Fax: 81-44-435-1915.

Yasuaki Hasegawa received a bachelor of science degree and a master of science degree in physics from Chiba University, Japan, in 1986 and 1988, respectively. In 1988, he joined NEC Corporation, where he is now a technical manager engaged in the research and development of GaAs devices and RF MCM for mobile phone applications. His research interests include hetero-junction bipolar transistors (HBT) and HBT RF devices for handset applications.