Comparative Analysis of GaAs/LDMOS/GaN High Power Transistors in a Digital Predistortion Amplifier System

Bill Vassilakis, Member IEEE, and Armando Cova, Member IEEE

Corporate R&D, Powerwave Technologies, 1801 E. St. Andrew Pl., Santa Ana CA 92705 USA

Abstract - **Silicon LDMOS transistors have long been employed as the technology of choice for high power amplifiers in cellular infrastructure equipment. With each successive generation, improvements have been achieved in the areas of power, efficiency, linearity and reliability. As device performance approaches ideal, the focus for improvements has shifted to circuit based techniques and alternate device technologies such as GaAs, and lately GaN. Employing these technologies successfully in high power amplifier designs affords unique opportunities and challenges. In addition, as distortion correction techniques migrate towards the digital domain, new algorithms must address the unique properties of each technology. In this paper a comparative analysis of GaAs, LDMOS, and GaN devices are performed in a digitally predistorted amplifier system.**

Index Terms — **amplifier, digital predistortion, microwave power amplifiers, microwave power FETs, high power transmitters, device modeling, MOS devices, Gallium Arsenide, Gallium Nitride**

I. INTRODUCTION

LDMOS transistors were first introduced around 1993 for high power, 1GHz applications. These devices were capable of about 45W P1dB at 1GHz, offered significantly higher gain, and much improved back-off linearity compared to the state of the art bipolar transistors in use at the time. The gain of the LDMOS transistor was about 3 dB higher, and IMD was 10 dB improved compared to the same size (P1dB) bipolar transistor when operated at similar back-off level. By use of die thinning, multiple improvements to the implant geometries and metallization geometries, the electrical and thermal performance continues to improve, ever approaching ideal performance.

Gallium Arsenide (GaAs) devices have long been reported as the technology that will displace the ubiquitous LDMOS. GaAs has been used extensively at higher frequencies, but has not been introduced in large volume in the commonly used wireless frequencies. Recently, high voltage (HV), quasi-enhancement mode devices have been announced. Along with more traditional D-mode pHEMT devices that have been around for a while, these devices offer the system designer the possibility of using advanced circuit techniques such as Doherty combination and class F matching, that promise to offer better than 10-15% efficiency improvements over conventional matching and combining techniques.

Silicon Carbide (SiC) and Gallium Nitride, type III-V semiconductors, have long been thought to be the Holy Grail technology of high power amplifier design. Device properties such as high electron mobility, High Ft, large power handling capability, and high temperature operation would allow for new innovative system architectures. Unfortunately, high die defect densities have limited the availability of high power devices until recently. It has recently become possible to examine side-by-side the properties of approximately equally sized power devices. An additional challenge has been the development of a test system that is able to separate the fundamental characteristics of each device technology.

II. DIGITAL PREDISTORTION LINEARIZATION

Digital predistortion is a linearization technique for microwave power amplifiers (PA's) that employs digital baseband techniques to generate a compensation signal at the input of the PA which after nonlinear amplification reduces the level of output distortion. Less complex than competing feedforward linearization techniques, digital predistortion does not require the use of an error amplifier and allows for high efficiency system operation over moderate bandwidths.

To linearize the PA, the predistorter compares the distorted amplifier output to the modulation input and uses this error information to approximate the inverse of the transfer characteristic of the amplifier. Figure 1 is a basic block diagram of a digital predistortion linearizer that illustrates this process.

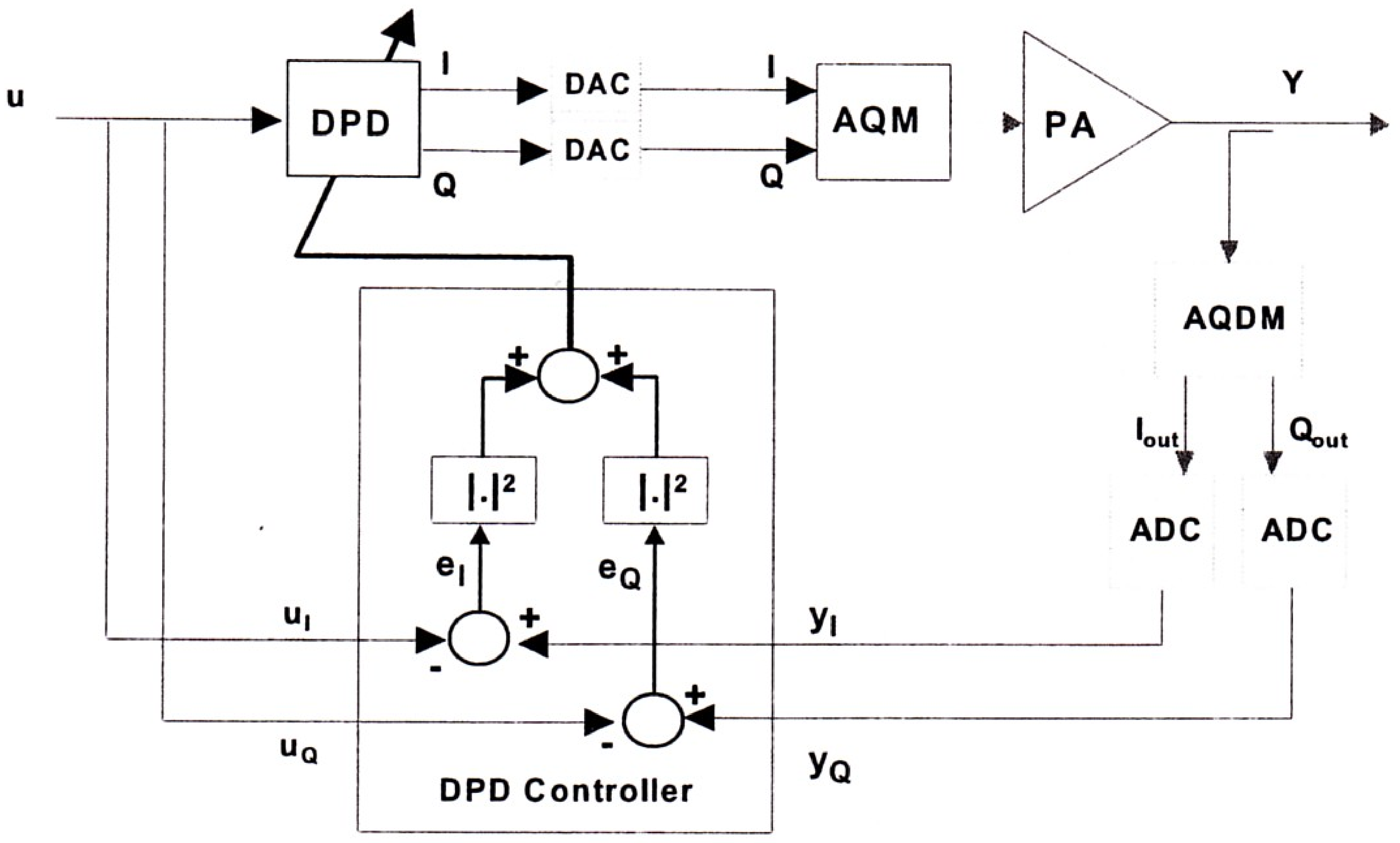


Fig. 1. Basic block diagram of a digital predistorter

The digital baseband input signal ***u*** is nonlinearly processed by the digital predistorter (DPD), converted into analog form via digital-to-analog converters (DAC) and upconverted to RF with an analog quadrature modulator (AQM) to drive the PA with a predistorted version of the input signal. The RF output ***Y*** of the PA is quadrature downconverted with an analog quadrature demodulator (AQDM) and digitized using analog-to-digital converters (ADC) to generate a digital baseband correlate ***y*** of the PA output:

$$y = y_I + jy_Q \qquad (1)$$

The DPD controller periodically updates the parameters of the predistorter to ensure that transmitter linearity is maintained during changes in operating conditions such as changes in modulation format, power level, carrier configuration, temperature variations, component aging, etc. To accomplish this task the controller employs optimization algorithms that seek to minimize metrics of the input-output system error ***e***:

$$e = y - u = (y_I - u_I) + j(y_Q - u_Q) \qquad (2)$$

A commonly used metric is the mean-squared error:

$$MSE = E(e^* e) = E((y_I - u_I)^2 + (y_Q - u_Q)^2) \quad (3)$$

Conventional digital predistortion techniques use look-up-tables (LUT) with complex gain coefficients to approximate the static inverse transfer characteristic of the PA. LUT digital predistortion techniques, despite having been successful in many applications, exhibit performance limitations when trying to linearize highly nonlinear (<25 dB C/I) and highly efficient (>35%) amplifiers. These performance limitations are partly due to the inability of static LUT predistorters to cancel memory effects in the PA. Memory effects are an important factor affecting the “predistortability” of an amplifier in a DPD application. By predistortability we understand the ability of an amplifier to achieve specific linearity and efficiency targets when linearized using digital predistortion. As we will see in the next section this qualitative concept can be objectified in a concrete way through the use of appropriate metrics (predistortability indexes).

III. PREDISTORTABILITY OF POWER AMPLIFIERS

Two major factors affect the predistortability of amplifiers: output back-off (OBO) and memory effects. OBO is an indirect measure of the level of signal clipping introduced by the PA:

$$OBO = P_{sat} / P_{avg} \qquad (4)$$

where P_{sat} refers to the saturated output power of the PA and P_{avg} refers to the average output power of the amplifier. Ideally the level of OBO must be selected such that no clipping occurs because the transfer characteristic of the PA is not invertible in its saturation region and intermodulation distortion (IMD) is very sensitive to clipping of signal peaks. Clipping is avoided when OBO matches the peak-to-average power ratio (PAR) of ***u***:

$$PAR = \frac{PeakPower(u)}{Avg.Power(u)} = \frac{\max(u^* u)}{E(u^* u)} \qquad (5)$$

The second major factor influencing predistortability is memory effects. Memory effects are IMD components that are sensitive to the bandwidth of the modulation input. These effects are particularly strong in high efficiency amplifiers operating at high output power and are difficult to cancel with DPD. Memory effects have electro-thermal and electrical origins [3]. Electro-thermal memory effects are related to device self-heating effects. Electrical memory effects are caused by changes in the biasing and matching circuit impedances across the range of modulation frequencies around the carrier and its harmonics. One convenient method to model memory effects is the memory polynomial expansion [1]-[2]:

$$PA_{out}(n) = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} c_{km} PA_{in}(n-m) \left| PA_{in}(n-m) \right|^k \qquad (6)$$

which can be used to additively segregate the contributions of the static IMD (m=0,k>0) and memory effects ($m \neq 0$,k>0) in the PA output signal. From this description, two figures of merit (static and dynamic predistortability indexes) can be defined to assess the predistortability of the amplifier:

$$SPI = \frac{\text{Avg.Static IMD Power}}{\text{Avg.PA}_{\text{out}}\text{ Power}} \qquad (7)$$

$$DPI = \frac{\text{Avg.Memory Effects Power}}{\text{Avg.PA}_{\text{out}}\text{ Power}} \qquad (8)$$

These indexes were used to evaluate the predistortability of RF PA technologies (LDMOS, GaAs, GaN) as discussed in the following sections.

IV. MATERIALS AND METHODS

Three single stage UMTS Class AB amplifiers (Fc = 2140 MHz) built with GaN, GaAs and LDMOS devices were tested to evaluate their predistortability and compare their performance of with digital predistortion. The amplifiers were driven with a 15 MHz BW, two non-adjacent carrier WCDMA TM1 signal with a 10 MHz carrier separation and a 7.2 dB PAR. Average output power was selected to satisfy OBO=PAR to avoid clipping. Predistortability evaluations were performed with the aid of a DPD evaluation test-bench developed by Powerwave R&D. Predistortion tests were conducted on a DPD amplifier prototype unit developed by

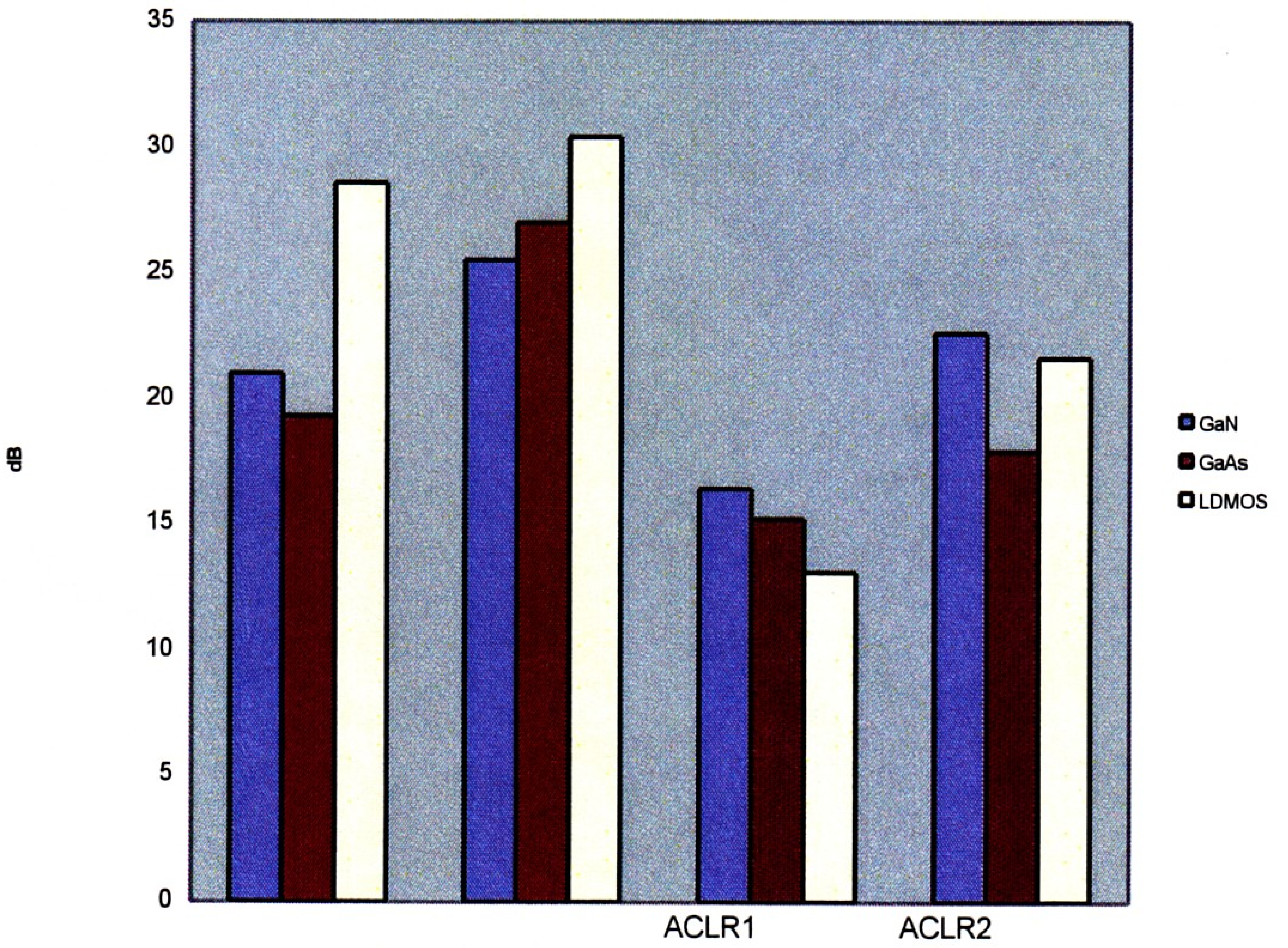
Powerwave R&D that uses proprietary predistortion algorithms to cancel memory effects. All tests were conducted at room temperature. Table 1 summarizes the RF characteristics of the amplifiers tested.

Device	Psat (dBm)	OBO (dB)	Gain (dB)	Idq (A)	Eff (%)
GaN 100W	49.8	7.2	14.2	2.46	25.3
GaAs 90W	49.7	7.2	15	2.52	24.9
LDMOS 100W	51.5	7.2	15.3	3.48	27.3

Table 1. Summary of RF parameters of amplifiers tested

V. EXPERIMENTAL RESULTS

Figure 2 summarizes the results of the predistortability analysis. Of the three device technologies tested, the GaAs amplifier exhibited the strongest static nonlinearity as evidenced by its low (in relative terms) SPI (C/SIMD). The static nonlinearities of the GaN PA were the second strongest among the amplifiers tested.



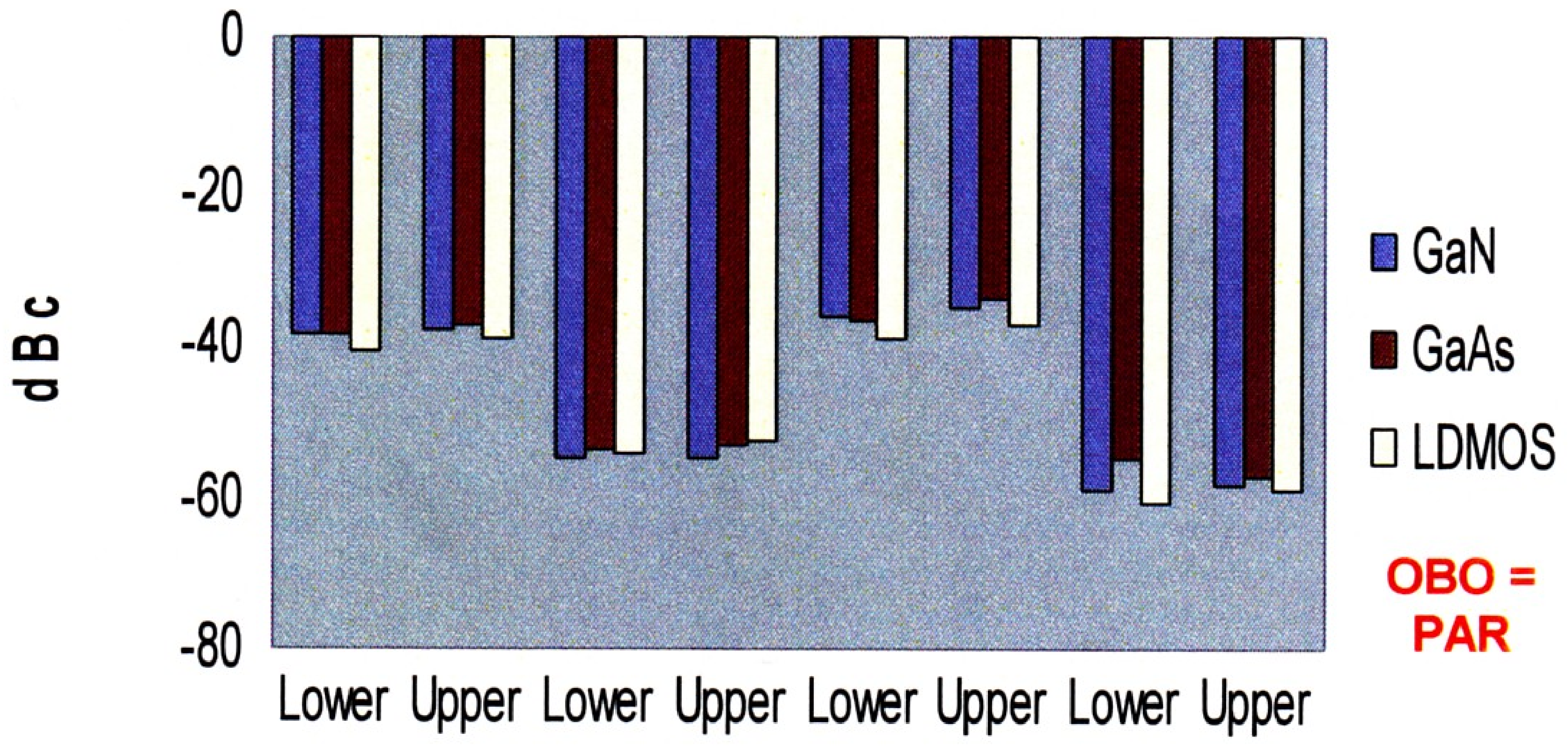
	C/SIMD (dB)	C/DIMD (dB)	ACLR1 Cancellation (dB)	ACLR2 Cancellation (dB)
■ GaN	21	25.5	16.4	22.6
■ GaAs	19.3	27	15.2	17.9
□ LDMOS	28.6	30.4	13.1	21.6

Fig. 2. Predistortability analysis results

The LDMOS amplifier was the most predistortable in the static sense and exhibited the lowest SPI. Memory effects in the GaN amplifier were "stronger" than GaAs and LDMOS, as evidenced by its low (in relative terms) DPI (C/DIMD). Of the three amplifiers tested the GaN PA would be the most difficult to predistort using traditional techniques with limited or no memory effect compensation capabilities.

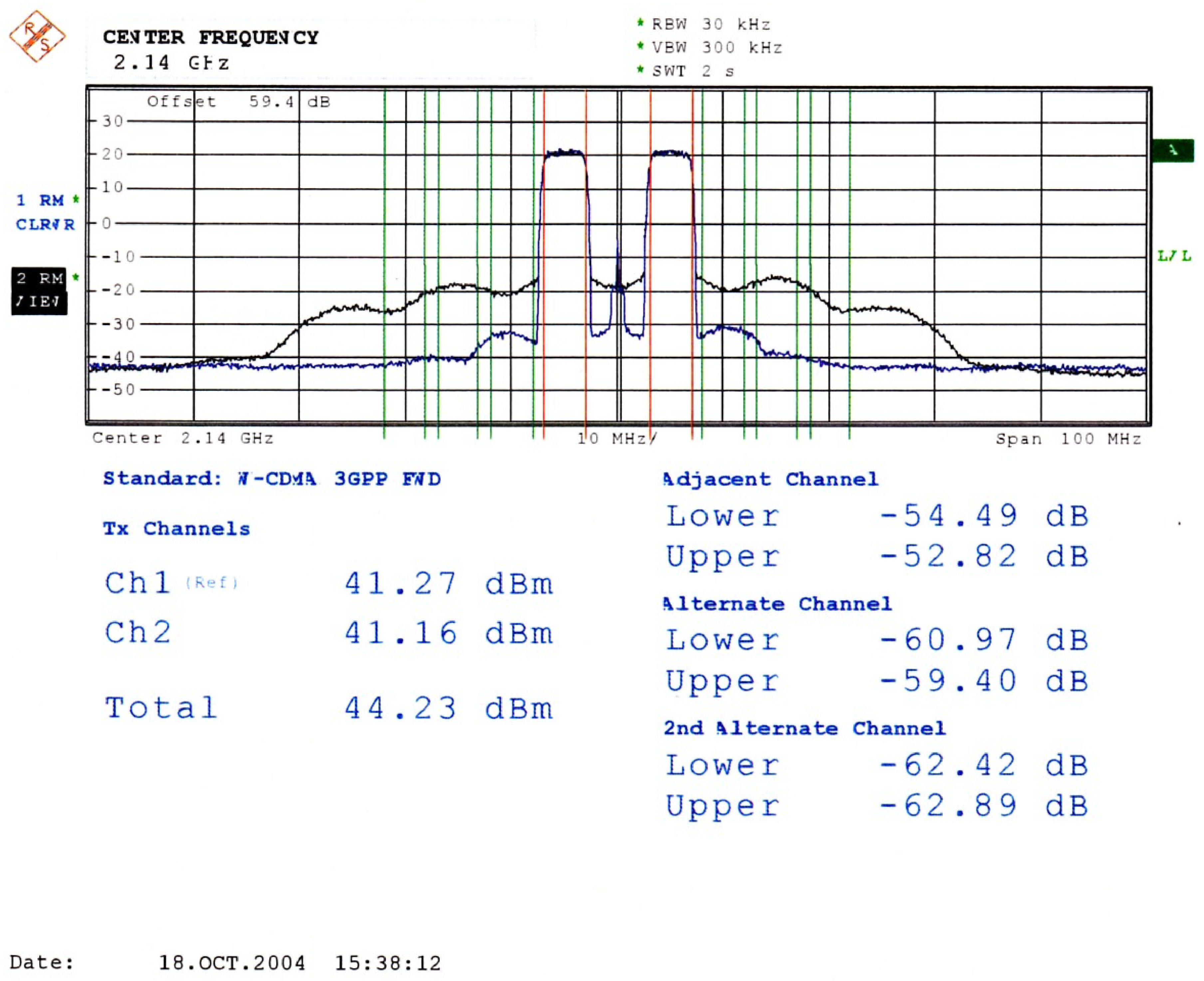
Figure 3 summarizes the results obtained before/after DPD. The ACLR performance of the amplifier with/without DPD was measured per the UMTS specifications. Powerwave's DPD algorithm provides predistorted linearity compliant to UMTS out-of-band emissions spec with margins >= 5dB in all cases irrespective of device technology. Of particular relevance is the ability of the DPD to cancel the strong memory effects of the GaN amplifier, a difficult task for conventional predistortion technologies.

Out of band IMD cancellation levels achieved by the DPD reached 22.6 dB for GaN, 21.6 dB for LDMOS and 17.9 dB for the GaAs amplifier as shown in Figure 2. Plots showing the spectra of the amplifiers outputs with/without DPD are shown in Figures 4-6.



	ACLR1 PA (dBc) Lower	ACLR1 PA (dBc) Upper	ACLR1 MCH (dBc) Lower	ACLR1 MCH (dBc) Upper	ACLR2 PA (dBc) Lower	ACLR2 PA (dBc) Upper	ACLR2 MCH (dBc) Lower	ACLR2 MCH (dBc) Upper
■ GaN	-38.9	-38.5	-55.3	-55	-36.6	-35.2	-59.2	-58.7
■ GaAs	-38.8	-37.8	-54	-53.6	-37	-34.4	-54.9	-57.4
□ LDMOS	-40.9	-39.7	-54.5	-52.8	-39.4	-37.5	-61	-59.4

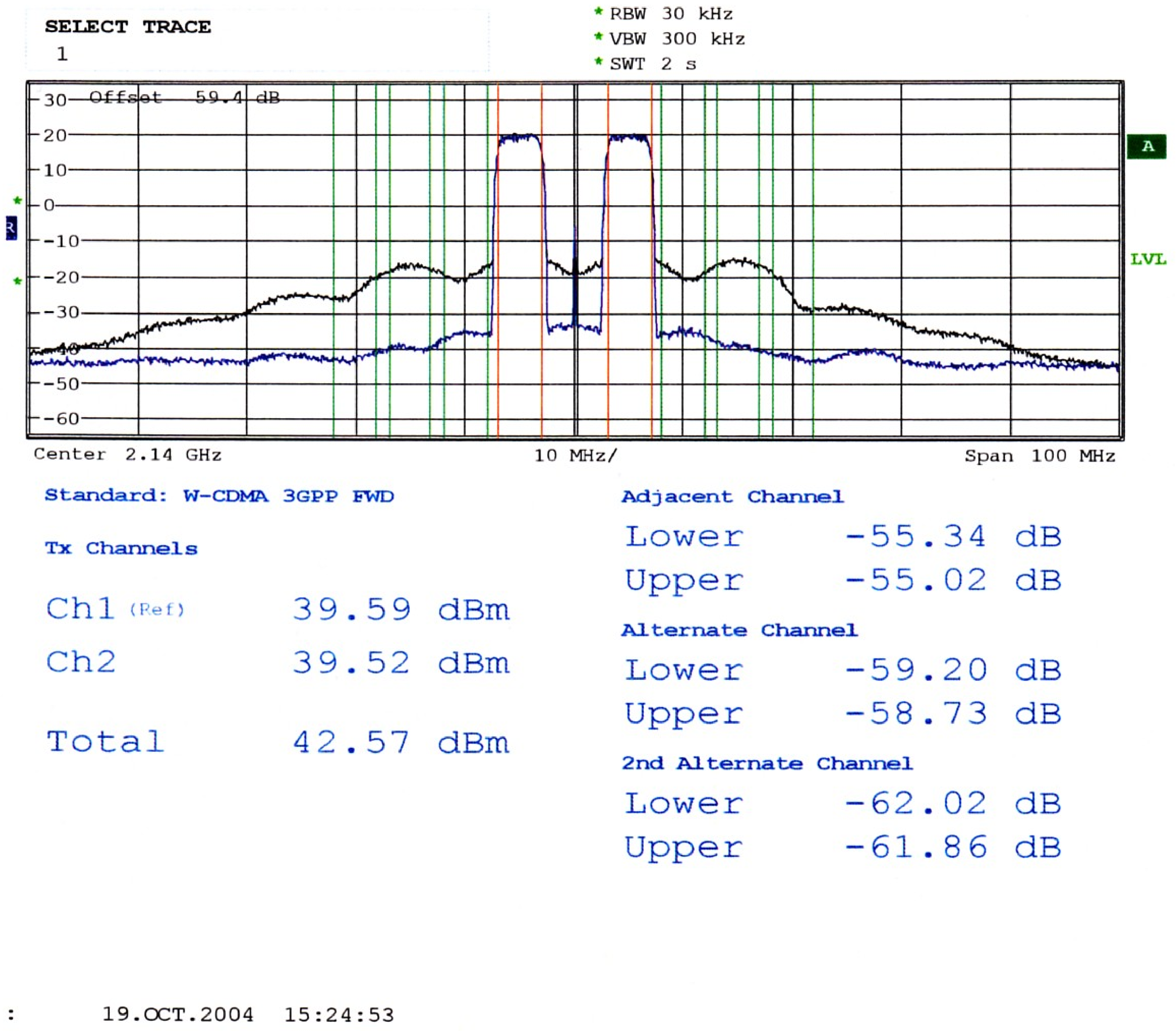
Fig. 3. Results with/without DPD



```
Standard: W-CDMA 3GPP FWD                 Adjacent Channel
                                          Lower      -54.49 dB
Tx Channels                               Upper      -52.82 dB
Ch1 (Ref)        41.27 dBm                Alternate Channel
Ch2              41.16 dBm                Lower      -60.97 dB
                                          Upper      -59.40 dB
Total            44.23 dBm                2nd Alternate Channel
                                          Lower      -62.42 dB
                                          Upper      -62.89 dB

Date:       18.OCT.2004  15:38:12
```

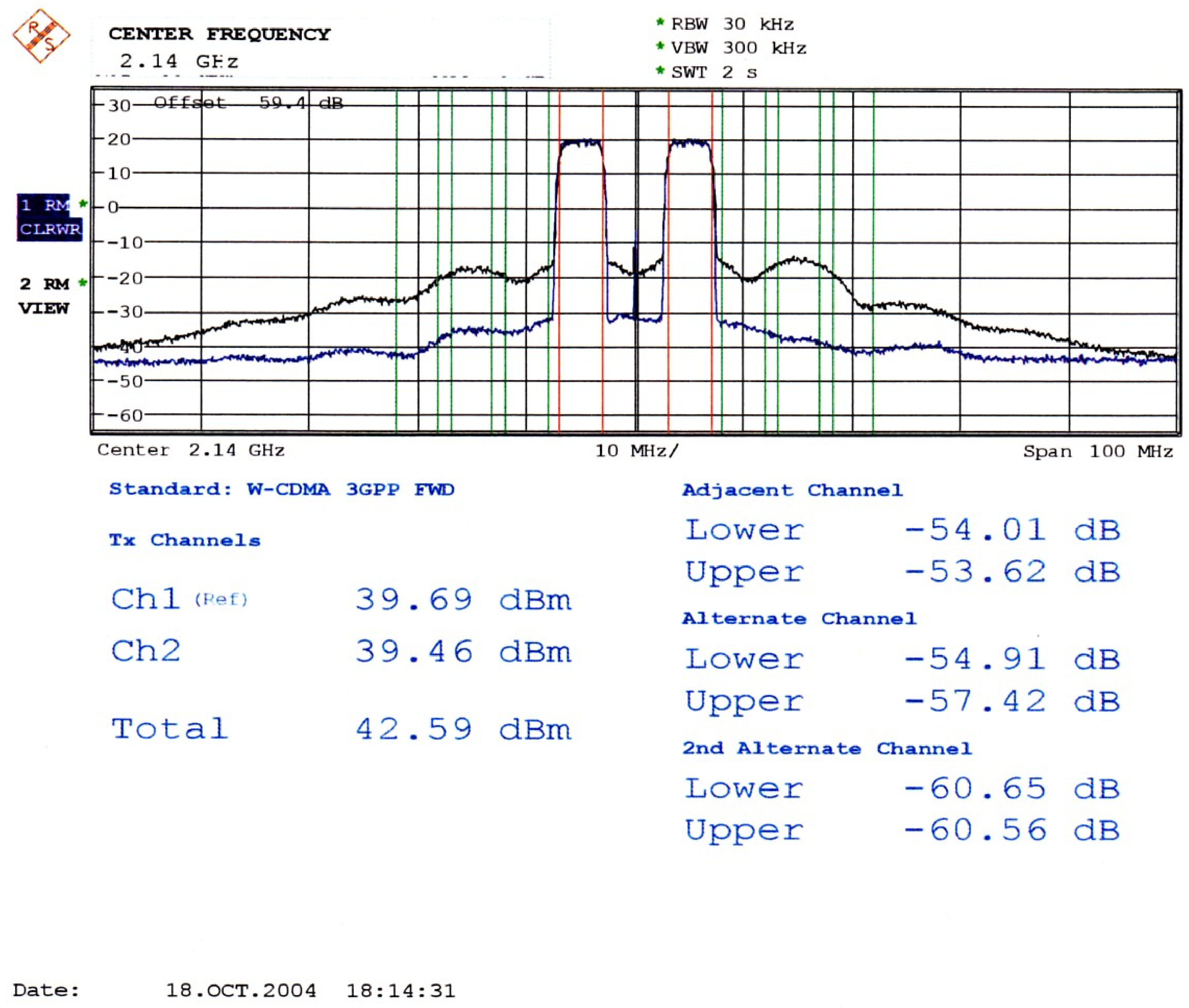
Fig. 4. Output spectrum of LDMOS



```
Standard: W-CDMA 3GPP FWD              Adjacent Channel
                                       Lower      -55.34 dB
Tx Channels                            Upper      -55.02 dB
Ch1 (Ref)       39.59 dBm              Alternate Channel
Ch2             39.52 dBm              Lower      -59.20 dB
                                       Upper      -58.73 dB
Total           42.57 dBm              2nd Alternate Channel
                                       Lower      -62.02 dB
                                       Upper      -61.86 dB

:       19.OCT.2004  15:24:53
```

Fig. 5. Output spectrum of GaN PA



```
Standard: W-CDMA 3GPP FWD                 Adjacent Channel
                                          Lower      -54.01 dB
Tx Channels                               Upper      -53.62 dB
Ch1 (Ref)        39.69 dBm                Alternate Channel
Ch2              39.46 dBm                Lower      -54.91 dB
                                          Upper      -57.42 dB
Total            42.59 dBm                2nd Alternate Channel
                                          Lower      -60.65 dB
                                          Upper      -60.56 dB

Date:       18.OCT.2004  18:14:31
```

Fig. 6. Output spectrum of GaAs PA

VI. CONCLUSION

LDMOS high power transistors remain the technology of choice for high power amplifier transmitters for cellular basestations. The emergence of alternate GaAs and GaN technologies will allow the development of innovative new system architectures and linearization techniques for wireless basestation equipment. Reliability and cost concerns need to be addressed for these technologies before widespread acceptance and use.

ACKNOWLEDGEMENT

The authors would like to acknowledge the contributions of Scott Carichner, Joseph Storniolo and Roel Medina of Powerwave R&D to this paper. As well, historical transistor information from Freescale Semiconductor is appreciated.

REFERENCES

[1] J. Kim and K. Konstantinou, "Digital predistortion of wideband signals based on a power amplifier model with memory," *Electronics Letters,* vol. 37, no. 23, pp. 1417-1418, November 2001.

[2] L. Ding, G. T. Zhou, D. R. Morgan, Z. Ma, J. S.Kenney, J. Kim, and C. R. Giardina, "A Robust Digital Baseband Predistorter Constructed Using Memory Polynomials," *IEEE Trans. Communications*, vol. 52, no. 1, pp. 159-165, January 2004.

[3] S. Boumaiza and F. M. Ghannouchi, "Thermal memory effects modeling and compensation in RF power amplifiers and predistortion linearizers," *IEEE Trans. Microwave Theory & Tech.,* vol. 51, no. 12, pp. 2427-2433, December 2003.