Choosing the Proper RF Amplifier Based on System Requirements

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Abstract

In order to properly configure a radio transceiver, designers must understand the performance parameters and tradeoffs of the RF amplifiers being used. A multitude of system requirements must be considered to choose an optimal amplifier from the many devices available by suppliers in the marketplace. Amplifier choices have greatly increased for RF designers since early days where only GaAsFET and Silicon Bipolar technologies were available. Performance tradeoffs of GaAs MESFET, InGaP HBT, and GaAs HFET technologies targeted at wireless and wireline basestation driver amplifier applications are discussed. Measured ACPR and PAE performance is shown for ½-, 1-, and 2-Watt amplifiers utilizing the various process technologies.

Introduction

In a standard base-station transmitter application, the various types of RF amplifiers used in the chain can be broken up into three categories: small-signal buffer amplifier stages, driver amplifier stages, and power amplifier stages (Figure 1). Although the main focus of this paper is with driver amplifier stage applications, key parameters are fundamentally similar for RF designers looking to choose a device to amplify a signal.

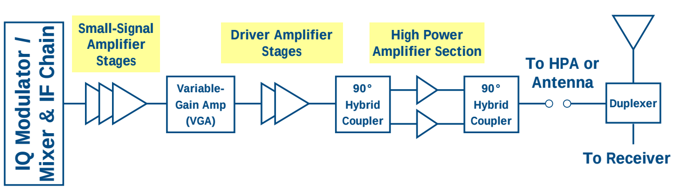

Figure 1. Simplified Base Station Transmitter Block Diagram

Obviously, the small-signal RF performance such as gain and return loss is what most engineers will look for with an RF amplifier – especially for the small-signal amplifier stages. Then depending on where the amplifier is used in the chain and whether the amplifier is used in the Rx/Tx path, device linearity, compression, and noise figure would be the key parameters. For digital radio applications, linearity can be described as spectral regrowth of the modulated (as ACPR, ACLR, or EVM) signal rather than the traditional figure of merit with third order intercept point (OIP3) which is ideally independent of output signal level. Because these characterizations are dependent upon the signal output power level, graphs with respect to output power are often shown on suppliers' datasheets rather than a direct numerical value.

Other RF performance parameters that designers often consider are the device's operational bandwidth, gain flatness across the frequency of operation, RF stability, the amplifier's performance over temperature, and depending on the application, power added efficiency (PAE). All other things being equal, subtle considerations designers often make are with the reliability of device (also known as MTTF) and the ease of designing or matching with the device.

With cost-reduction design cycles becoming shorter and shorter, obviously the price competitiveness of the devices becomes important – especially with the purchasing engineer. Subtle factors engineers can consider to lower the overall cost of the system are the feasibility to re-use the same amplifier in other parts of the system chain. For example, a high linearity device with low noise figure performance can be used in both the Rx/Tx chains. Another aspect affecting the overall system cost is parts count. Certain amplifier configurations are fairly complex and may require many external components to properly bias and tune.

Small-Signal Amplifier Stages

The small-signal buffer amplifier stages in the RF, IF, TX, & LO sections of a system are the simplest amplifiers for designers to consider in the design of their system. The main purpose is to provide amplification of low level RF signals while being very low in cost. Darlington-pair HBT gain blocks are probably the most common devices in the marketplace. These types of devices are designed internally using resistive matching and thus are inherently broadband and easy to use.

Because of their simplicity, designers have a wide variety of choices for gain blocks from various suppliers and with many different process technologies - Silicon Germanium (SiGe), Aluminum Gallium Arsenide (AlGaAs), or Indium Gallium Phosphide (InGaP) HBTs. HBTs were initially pushed into the market using AlGaAs technology, but may engineers have steered away from using AlGaAs because of reliability concerns. SiGe and InGaP HBTs are seen to be the process technologies of choice from a price competitiveness and reliability standpoint. Unfortunately for higher power applications, increased power densities force SiGe HBTs to operate on the borderline limits of reliability and RF stability.

During the early design stage of offering Darlington-pair HBTs into the market, WJ Communications considered the various tradeoffs between various process technologies. While SiGe HBTs offer a very price competitive solution for designers for low power applications, it was determined that InGaP HBTs offer much increased reliability and flexibility for usage with higher power applications. WJ offers RF designers many choices with an offering of AG and EC Series gain blocks that are broken up into various gain levels between 11 and 21 dB, Output IP3 (OIP3) levels between 20 and 40, and output 1-dB compression (P1dB) levels between 6 and 24 dBm. Figure 2 lists an example of the gain blocks available by WJ Communications where the devices are listed with respect to increasing compression levels.

Product Model #	Freq. (GHz)	Gain 1 GHz	P1dB 1 GHz	OIP3 1 GHz	NF (dB)	Device Bias (V)	Id (mA)
AG201	DC-6.0	11	6.5	19.5	4.4	4	20
AG202	DC-6.0	15	7.5	19.5	3.5	4.1	20
AG203	DC-6.0	20	8.0	21	3.1	4.1	20
AG302	DC-6.0	15.5	13.5	26	3.2	4.2	35
AG303	DC-6.0	21	14	26	3.0	4.2	35
ECG001	DC-6.0	20	12.5	25	3.7	3.4	30
ECG004	DC-6.0	16.2	13.5	28	3.2	3.4	35
ECG002	DC-6.0	20	15.5	29	3.8	3.9	45
ECG006	DC-6.0	15	15	32	4.0	3.9	45
AG503	DC-6.0	20.5	16	29	2.9	5	45
AG402	DC-6.0	15	17	32.5	3.7	4.9	60
AG403	DC-6.0	20.5	18	31.5	3.0	4.9	60
ECG005	DC-5.0	19.5	18	34	3.3	4.8	65
ECG040	DC-6.0	15	18	35	5.5	4.8	70
ECG055	DC-6.0	20	18	34	4.3	4.8	65
AG602	DC-6.0	14.5	18.5	33	4.4	5.2	75
EC1119	DC-6.0	15	18.6	36	5.5	4.8	80
AG603	DC-6.0	19	19.5	33	3.9	5.2	75
AG604	DC-6.0	21	19.5	33	3.5	5.2	75
ECG050	DC-5.0	18.5	19	34	4.0	5	70
EC1019	DC-5.0	18.5	19	34	5.5	5	70
EC1078	DC-3.5	19.5	21	37	4.4	5.6	96
ECG003	DC-6.0	20	24	39	3.4	7.2	110
ECG008	DC-6.0	15	24	40	4.6	7.3	120

Figure 2. WJ Communications' InGaP HBT Gain Blocks

GaAs MESFETs Used for Driver Amplifier Applications

RF designers looking for driver amplifier stages in a transmit application with compression levels between 20 to 33 dBm also look for similar RF characteristics as with the small-signal amplifiers such as gain, return loss, OIP3, and P1dB. Because of the larger power requirements though, Darlington-pair gain blocks are not suitable and not available for these applications. Designers do have a variety of choices between MMIC and discrete devices of various competing technologies: GaAs MESFET, GaAs HBT, InGaP HBT, GaAs HFET, GaAs HEMT, and e-PHEMT, etc. For the purposes of this paper, performance characterizations of InGaP HBT, GaAs HFET, and InGaP HBT process will be explored.

Gallium Arsenide Metal Effect Semiconductor Field Effect Transistor (GaAs MESFET) technology is widely used for small-signal and driver amplifier applications. This technology allows amplifiers to combine low noise characteristics with high linearity allowing for usage in both Rx/Tx system designs. WJ has incorporated the mature GaAs MESFET technology in their array of products over the past 15 years. While depletion mode MESFETs have historically required negative voltages to control the gate, WJ's MESFET process was designed to have devices operating reliably at 100% Idss. In other words, only a signal positive voltage is required for operation.

A key feature of MESFET amplifiers are the suitability for very broadband amplifier designs. Operational bandwidths of greater than 5 octaves can be achieved with few external matching circuit components. Very flat performance across the 50 to 1500 MHz bandwidth with high linearity (Figures 3 and 4) is achieved with the WJ AH101 ½-Watt Gain Block without the requirement for any external matching components. For applications where designers are attempting to create a unique circuit design for all three major mobile infrastructure frequency bands at 900, 1900, and 2140 MHz with a ½-Watt driver amplifier, the AH102A would be more suitable. In the case of the AH102A, only two input matching components are required. Performance charts and values are given in Figure 5 and 6. More details regarding these devices and related application notes can be found on the WJ website at http://www.wj.com.

Freq (MHz)	Gain (dB)	OIP3 (dBm)	P1dB (dBm)
50	13.6	45	26.1
450	13.8	46	26.5
900	13.5	44	26.4
1500	12.7	46	25.1

Figure 3. AH101 ½-Watt MESFET Measured Performance

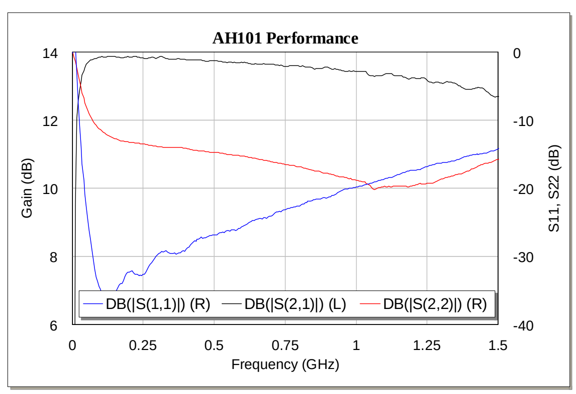

Figure 4. AH101 Small-Signal Performance

Freq (MHz)	Gain (dB)	OIP3 (dBm)	P1dB (dBm)
900	13.9	+45.5	+26.1
1800	12.8	+45.0	+26.1
1900	12.6	+43.9	+25.8
2140	12.6	+43.5	+25.6

Figure 5. AH102A ½-Watt MESFET Measured Performance

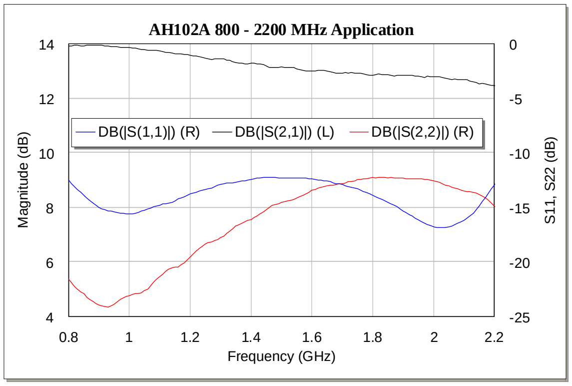

Figure 6. AH102A Small-Signal Performance

The WJ MESFET process has been specifically optimized for driver applications where high linearity is required. Suppression of intermodulation products of multi-tone signals allows for very high linear figure of merit (LFOM) values. This figure of merit is often used by designers as a measure of the linearity efficiency of the amplifier. The LFOM is defined as the difference in OIP3 and the P1dB. Typical values for other process technologies are typically around 10 dB for HEMTs and 15 dB HBTs, while the WJ MESFETs have LFOMs of approximately 20 dB. Another optimization achieved with WJ's MESFET technology allow for the optimal required load impedance for linearity and compression at 50 ohms while concurrently keeping the output load impedance of the amplifiers around 50 ohms. Thus from a designer's standpoint, the output return losses for WJ's MESFET devices are intrinsically better than 14 dB and do not require any additional external matching to optimize for return loss, linearity, or compression.

GaAs HFETs Used for Driver & Power Amplifier Stages

GaAs Heterostructure Field Effect Transistors (HFETs) are also widely used for driver or power amplifier applications. HFET I-V characteristics offer the ability to achieve higher power levels than MESFETs with higher P1dB efficiency. High breakdown voltages make this process technology ideal for designs operating under large signal conditions such as output power stages for ultra-small repeater applications. But similar to other depletion mode FET devices, HFETs require the usage of a negative power supply. In addition, HFETs offer slightly lower LFOMs compared to MESFET devices. This translates into slightly lower OIP3 values for HFET devices with comparable compression values as devices from other process technologies. It will be shown though later in this paper that the ACP performance for wireless basestation or repeater applications is about the same or better than devices from other process technologies.

Similar to MESFET devices, HFETs can easily be tuned for broadband applications. As shown in Figure 8, only two input matching components along with a feedback R-C network are required to design an broadband VHF amplifier from 130 – 900 MHz with less than 0.1 dB gain flatness. The ½-Watt FP1189 device offers high linearity while achieving 46% P1dB efficiency.

Freq (MHz)	Gain (dB)	OIP3 (dBm)	P1dB (dBm)
150	13.9	+32	+26.8
350	13.9	+41	+26.6
550	13.9	+40	+26.4
750	13.9	+40	+26.4

Figure 7. FP1189 ½-Watt HFET Performance

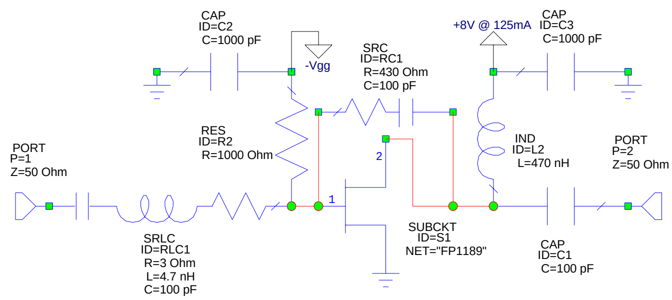

Figure 8. 130 – 900 MHz FP1189 Reference Design

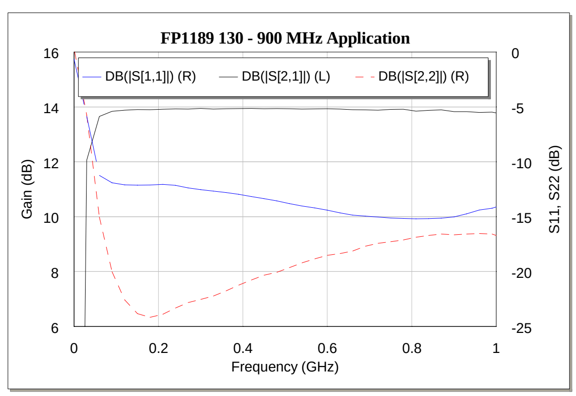

Figure 9. FP1189 Small-Signal Performance

InGaP HBTs for Driver & Power Amplifier Stages

Operation of devices utilizing GaAs MESFET and HFET technologies for driver amplifier applications above ½ Watt require biasing voltages above 8 Volts. Thus the use of these types of devices can sometimes be undesirable for designers constrained to +5V regulators in their system. InGaP HBT devices resolve this issue by operating directly off of a +5V rail while offering designers high power-added efficiencies and linearity. In addition, oftentimes HBT devices are also configured so that designers can set the bias of the amplifier for optimization in Class A or Class AB operation.

While the much similar GaAs HBT technology has been in the marketplace for some time, reliability limitations have left the primary applications for GaAs HBT's to handsets. Components targeting wireless and wireline basestation infrastructure are often biased on constantly and must be orders of magnitude more reliable. This is often defined by reliability engineers as mean time to failure (MTTF). WJ has minimum requirements for any amplifiers released into the market to have a MTTF exceeding 1 million hours (over 100 years) at the maximum recommended operating case temperature. To illustrate the robustness of WJ's HBT process technology, the AH and ECP InGaP HBT product families are unmatched in the industry in terms of reliability with 10^{10} hours MTTF at junction temperatures of 150˚ C.

While HBTs do offer several advantages over other process technologies, there are some tradeoffs that designers must consider. Oftentimes, the optimal load impedance required for maximum linearity and compression is very low in value. Thus this can lead to output matching being configured for HBT amplifiers to not have the preferred 14 dB minimum return loss designers often prefer. In addition, this limits HBT amplifiers to be used only for narrowband applications; designs typically are not ideal for greater than 100 MHz bandwidth. While not being a major concern for transmit power applications, HBTs will have higher noise figures compared to GaAs MESFET and HFET technologies.

Comparison of Devices from Various Process Technologies

The previous sections of this paper have gone through the benefits and tradeoffs that GaAs MESFET, GaAs HFET, and InGaP HBTs have to offer. With the understanding that designers have different requirements for their various applications, WJ Communications has devices available in the market for ½-, 1-, and 2-Watt applications utilizing the various technologies. Figure 10 displays a table of the component names sorted by P1dB and process technology. To illustrate the performance tradeoffs of the technologies, Figure 11 lists the RF and DC characteristics for ½-Watt devices configured for operational in the cellular band of 900 MHz. As discussed earlier and shown in Figure 11, the major performance differences can be seen with the noise figure, OIP3, and P1dB efficiency values between GaAs MESFETs / HFETs and InGaP HBT devices.

	½ Watt	1 Watt	2 Watt
GaAs MESFET	AH102A	AH201	
GaAs HFET	FP1189	FP2189	FP31QF
InGaP HBT	AH115, AH116, ECP050, ECP052, ECP053	AH215, ECP100, ECP103	AH312, ECP200, ECP203

Figure 10. List of WJ components sorted in terms of process technology and P1dB

Model	**AH102A**	**FP1189**	**AH116**
Type	MESFET	HFET	HBT
Gain (dB)	13.9	17.5	17.5
NF (dB)	3.1	2.7	7
P1dB (dBm)	+27	+27.4	+28.7
OIP3 (dBm)	+46	+40	+43
Bias Voltage	+9V	+8V, $-V_G$	+5V
P_{diss} (W)	1.8	1	1.25
P1dB Efficiency	28%	55%	59%
Bandwidth	Wideband	Narrowband	Narrowband
Effective BW @ 1 GHz	400 MHz	100 MHz	100 MHz

Figure 11. Comparison of RF and DC parameters for various ½-Watt amplifiers at 900 MHz

Further performance plots for power-added efficiency vs. output power for ½-, 1-, and 2-Watt amplifiers are displayed in Figures 12 to 14. The plots show that HFET and HBTs behave fairly similar for efficiency, while MESFETs perform slightly worse.

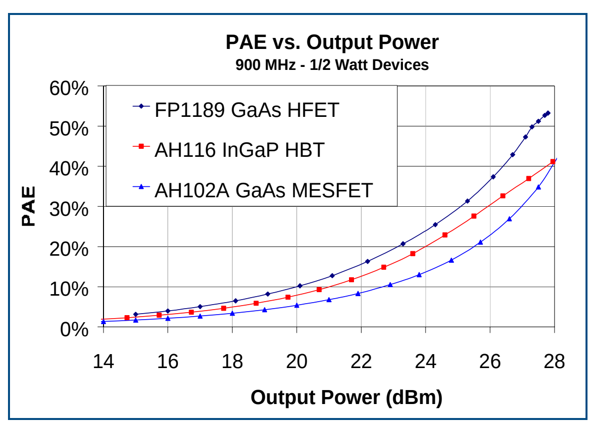

Figure 12. PAE vs. Output Power Plot (½-Watt devices)

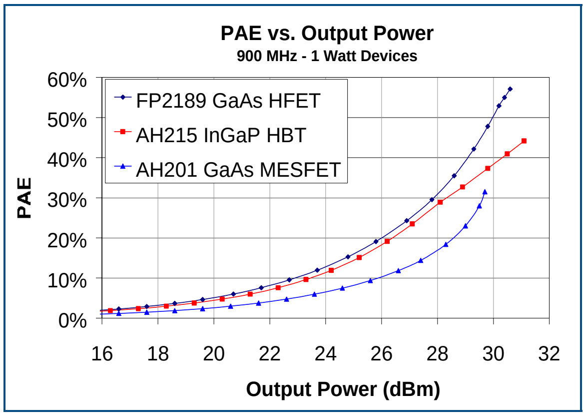

Figure 13. PAE vs. Output Power Plot (1-Watt devices)

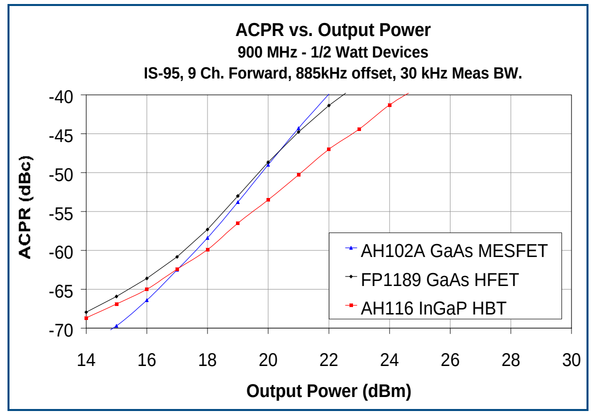

Figure 15. ACPR vs. Output Power Plot (½-Watt devices)

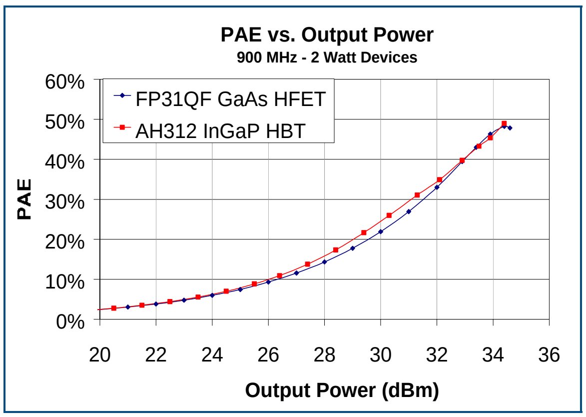

Figure 14. PAE vs. Output Power Plot (2-Watt devices)

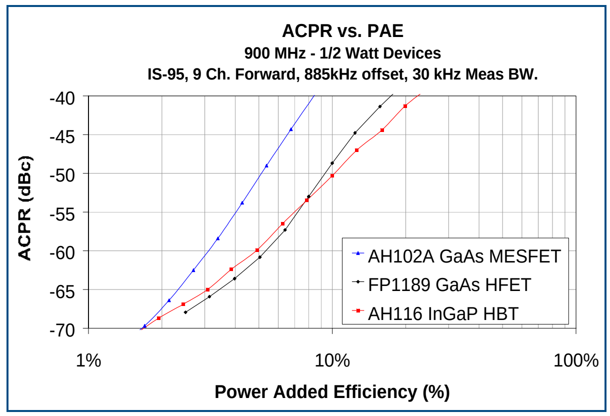

Figure 16. ACPR vs. PAE Plot (½-Watt devices)

Finally, Figures 15 through 20 illustrate the true linearity performance for the amplifier used in a realistic system environment. ACPR performance using a standard IS-95A signal is examined in terms of output power and efficiency for various ½- to 2-Watt devices available from WJ. Figure 15 shows that a designer must also take into account of the targeted operating power level when looking for an amplifier with the highest linearity. Assuming a designer is constrained to choose between ½-Watt amplifiers from various process technologies, the AH102A is ideal for driver amplifier applications up to output power levels of about 17 dBm while the AH116 is more suitable for power levels between 17 and 21 dBm. Of course, the acceptable ACPR level within the system for the particular amplifier socket will be dependent upon the overall chain analysis. Based on these observations, it should be noted that the stated OIP3 values given on amplifiers may not always state to true linearity characteristics of how the device perform in a true modulated signal environment.

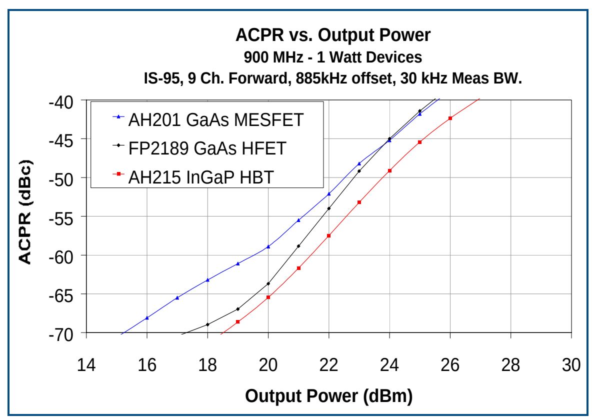

Figure 17. ACPR vs. Output Power Plot (1-Watt devices)

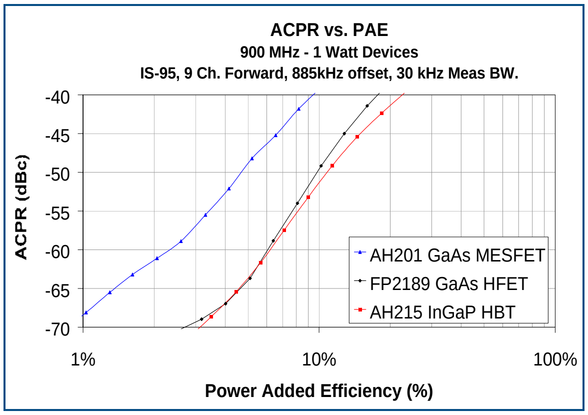

Figure 18. ACPR vs. PAE Plot (1-Watt devices)

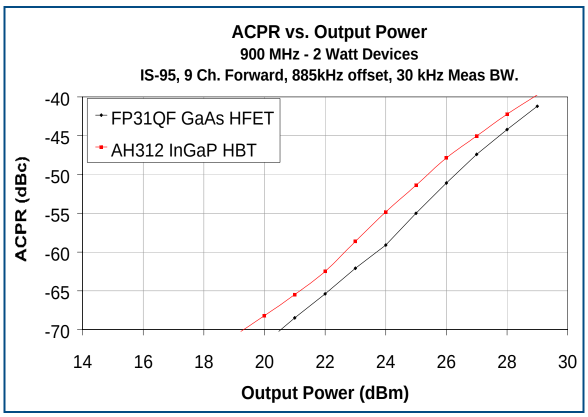

Figure 19. ACPR vs. Output Power Plot (2-Watt devices)

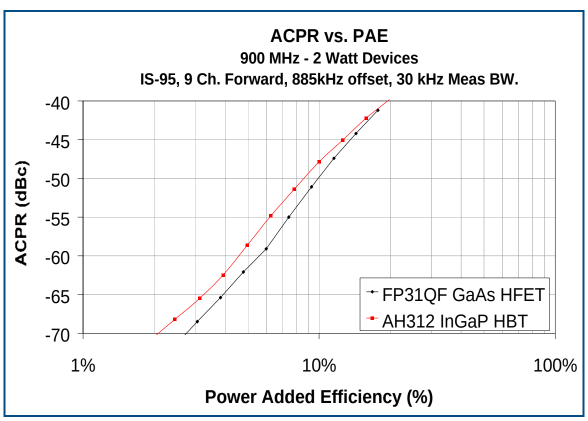

Figure 20. ACPR vs. PAE Plot (2-Watt devices)

Summary

In today's environment, RF designers have a multitude of options when it comes to choosing an RF amplifier in their system. Many RF performance characteristics should be considered that extend past the gain, P1dB, and OIP3 parameters typically shown on a datasheet. Modulated signal linearity performance as well as other subtle characteristics such as ease of use, bandwidth, and cost competitiveness can also guide designers toward making their device and process technology decisions for driver amplifier applications.

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