Analytical Investigation of Thermal Effects on Outphasing Power Amplifiers

Keith Finnerty, John Dooley and Ronan Farrell
Callan Institute, Dept. Electronic Engineering,
Maynooth University
Maynooth, C.o. Kildare, Ireland
kfinnerty@eeng.nuim.ie

***Abstract*—The outphasing amplifier has alternative linearity requirements when compared with traditional amplifier technology. As a relatively new architecture for mobile communications the physical and electrical causes of nonlinearity have not yet been fully identified. In this work the effect of thermal variations on the characteristic operation of the outphasing amplifier architecture is investigated. More specifically the impact that gain and phase variations which result from a change in device temperature affect the characteristic performance of the outphasing amplifier. Amplifier biasing circuits commonly account for changes in temperature, a process which will result in a shift in characteristic performance. The result demonstrates a shift in characteristic outphasing angle of as much as 2.4 degrees and a reduction in dynamic range greater than 20 dB.**

Keywords— Outphasing; LINC; Thermal; GaN; Cheriex;

I. INTRODUCTION

Modern wireless communications standards have traded system efficiency for spectral efficiency. To meet the demand of data through put on wireless networks through increased user demands and the advent of smart phone technology, more spectrally efficient modulation schemes are required. Such modulation schemes require information to be encoded on both the amplitude and phase components of the signal. Fundamentally power amplifier efficiency is linked to the amplitude of the output signal, as spectral efficiency is increased the average signal power is reduced, in turn reducing power amplifier efficiency. A range of power amplifier architectures using load modulation are designed to improve the efficiency associated with modulated signals with lower average output powers. The Doherty [1], Envelope tracking [2] and outphasing [3] amplifiers have the potential to greatly improve amplifier efficiency and therefore transmitter efficiency, however some linear concerns exist for both the Envelope tracking and outphasing PA’s.

The linearity of the outphasing amplifier is outlined in [4], as the robustness of the architecture to amplitude and gain offsets is analysed and quantified. Typically these offsets are a result of variations in the signal generation equipment and the characteristic behaviour of the amplifiers. Currently the calibration or correction algorithms are implemented as static function’s, however this paper proposes that long term memory, generated as a result of thermal variation in the amplifier active devices will result in significant amplitude and gain variations [5], resulting in non-ideal signal recombination. Outphasing amplifiers while still an active area of research have been recently demonstrated to work for current communication standards [6] [7]. This achievement has been enabled by current leaps in technology, however further progress is needed to achieve more efficient architectures. As such the operational issues associated with the architecture is not fully understood. The remainder of this paper is organised as follows: in Section II we introduce the outphasing PA architecture. Next we simulate the effects of thermal changes in the context of an outphasing PA. Section IV investigates the sensitivity of the outphasing architecture to thermal variations and the possible issues with current temperature controlled bias circuits.

II. OUTPHASING POWER AMPLIFIERS – LINEARITY

The outphasing power amplifier first introduced by Henri Chireix in 1935 [3] as a method to improve both efficiency and linearity in amplitude modulation transmitters. In 1974 the concept was later revised by Cox [8] with the concept of LINC (Linear amplification using Non-linear Components). This work demonstrated how highly non-linear yet efficient devices could be arranged to provide a linear output. The concept of the outphasing amplifier is illustrated in Figure 1.

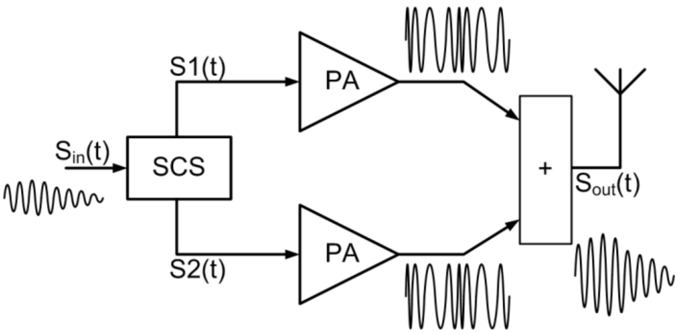

Figure 1 Concept of outphasing amplification

The principle of operation is relatively simple; the amplitude modulated signal is converted to a pair of phase modulated signals with constant amplitude. These signals are then amplified by identical saturated linear PA's or switch mode PA's. The constant envelope amplified signals are then re-combined in the power combiner stage, resulting in an amplified version of the amplitude modulated input signal. Efficient operation is achieved as both amplifiers are operating with constant output power close to or at peak efficiency, reducing the losses in the transistor. The key to efficient operation is the signal component separator more precisely; the amplitude to phase modulation process allows the PA's to operate at constant output amplitude. Operating the amplifiers at constant amplitude does not remove their non-linear input-output power characteristics; however, in theory, the recombination of these two signals will result in a linear output. This architecture allows the system to employ highly efficient PAs in the two signal paths while maintaining a linear output, provided the input signal component separator and the output power combiner are linear.

There are three individual operations that occur during outphasing amplification, signal component separation, amplification and re-combination. Signal component separation involves de-constructing a quadrature modulated signal by transforming it to a pair of complementary constant envelope signals with the amplitude information encoded as a phase difference. Where *A(t)* is the amplitude modulated component of the signal and *ϕ(t)* is the phase modulated component of the signal. The input signal processed by the SCS now consists of two constant amplitude signals an additional phase modulation component *ρ(t)* is used to encode the amplitude *A(t)*.

$$S(t) = A(t)cos[\omega t + \phi(t)] \quad 0 \leq A(t) \leq A_{max} \tag{1}$$

$$S_1(t) = \frac{A_{max}}{2} exp[j\omega t + \phi(t) + \rho(t)] \tag{2}$$

$$S_2(t) = \frac{A_{max}}{2} exp[j\omega t + \phi(t) - \rho(t)] \tag{3}$$

The outphasing angle *ρ(t)* is a function of the recombining circuit, for ideal outphasing recombination the SCS function is denoted as

$$\rho(t) = acrsin(\frac{A(t)}{A_{max}}) \quad 0 \leq \rho(y) \leq \frac{\pi}{2} \tag{4}$$

For an ideal recombination an arc-cosine function provides linear amplitude to phase mapping. However for a Chireix combiner this is not always the case, specifically in the case of a load compensated Chireix combiner, the additional reactive components change the phase angle at which minimum and maximum magnitude is achieved. For linear operation the combiner must be characterized fully, failing to perform this will limit the dynamic range achievable by the outphasing system.

The PA's dynamic range is defined as the ratio between the largest and the smallest possible output power. In the case of power amplifier system it is classified as the normalized output power which represents zero magnitude of a modulated signal. Within the outphasing amplifier there are many properties which can limit this value. This results in non-linear operation at low output powers, the effect of this is visible as wideband noise in the frequency domain, greatly reducing the adjacent channel power ratio (ACPR) of the modulated signal. The effects of which are demonstrated in Figure 2. The effects of limited dynamic range in outphasing transmitter have been widely studied [4], in which the author quantifies the impact of both gain and phase mismatch on dynamic range and ACPR. Many publications have considered imbalances due to drift in the small signal generation or variation in frequency of operation. In this paper analysis will be carried out on the impact of thermal variations of the transistors within the outphasing topology amplification stages..

III. SIMULATION – IDEAL OUTPHASING PA

To analyse the effects of thermal variation on a Chireix outphasing architecture an amplifier design was implemented in Keysight advanced design systems (ADS). To achieve this, a transistor capable of modelling thermal variations must be used. A 10W Cree GaN HMET (CGH40010) device was chosen, the broadband packaged device will simplify the design process, in addition the comprehensive model provided is capable of a full range of analytical simulations including harmonic balance and S-parameter simulations while accounting for the variability of thermal effects. Outphasing amplifiers achieve efficient amplification through load modulation of constant envelope, phase modulated signals. As a result the amplification stages are designed to achieve maximum efficiency at peak output power, while providing a wide passband to accommodate outphasing signals which experience bandwidth expansion [2]. As such Class B amplifiers were used for this application.

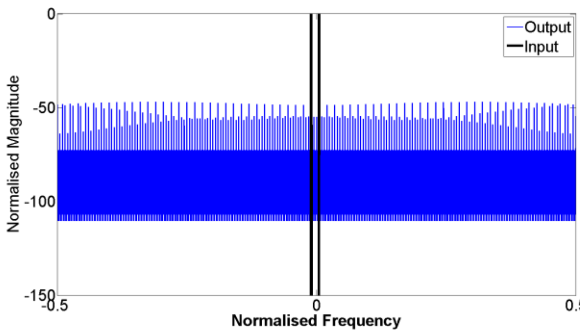

Figure 2 Infinite harmonic distortion resulting from limited dynamic range of a two tone signal.

A. Saturated Class B

A saturated Class B design was implemented in ADS, the amplifier is designed with an input and output impedances of 50 ohms. Load pull analysis was carried out on the transistor in order to determine the optimum load impedance, a design compromise between maximum output power and maximum power added efficiency was chosen. The load impedance chosen delivered a 42 dBm of power to the load at a power added efficiency of 75.6%. Input and output matching circuits were designed using single poll stub matching. The biasing network is also included in the matching circuit, quarter wavelength transmission lines proved the required inductance to achieve isolation between the transistor pads and supply rails. The source impedance of the amplifier was measured at *5 + 0j* ohms, therefore a real impedance transformation is require to match the active device to 50 ohm input, the chosen network can be seen in Figure 3. As an impedance transformation does not require any reactive components the circuit is designed without any stubs. The load impedance chosen was 20 + 23j, a single pole L matching network preforms the impedance transformation to a 50 ohm output as seen in Figure 4.

B. *Outphasing Combiner*

The Chireix combiner is chosen for its efficiency at back-off output power. The topology of the combiner is outlined in Figure 5 the combiner consists of three quarter wavelength transmission lines. Ideal reactive functions are used to provide load compensation, enabling the efficiency gains at back off output powers. Choosing 50 ohm impedance for load matching for both the class B amplifier and the output of the combiner greatly reduced the complexity of the combiner design. Equation 5 describes the relationship between the branch transmission line impedance's *Z1* and the output impedance and characteristic impedance *Z0* when the inputs and output of the combiner are the same.

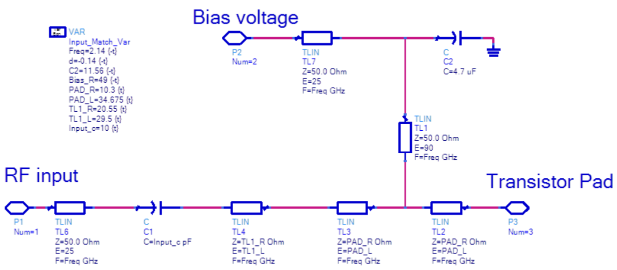

Figure 3 Saturated Class B input match.

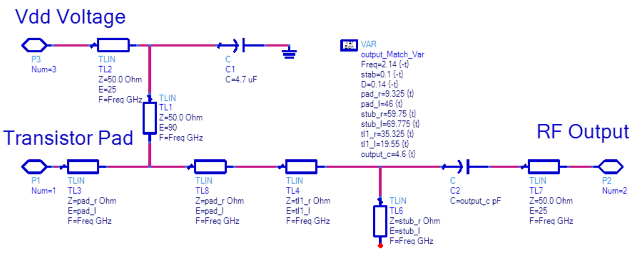

Figure 4 Simulated Class B output network.

$$Z1 = Z0\sqrt{2} \tag{5}$$

$$B = \frac{sin(2\pi\phi)}{2Z_L} \tag{6}$$

Load compensation is calculated by equation 6, where the impedance Z_L is the load impedance of the amplifier input to the combiner circuit and the outphasing angle is ϕ. The design choose to optimize the outphasing angle to achieve a maximum drain efficiency at 6 dB power back off. Following some system tuning an outphasing angle of 22.5 degrees is chosen. The resulting amplifier performance is presented in Figure 6, peak drain efficiency of 75% is the same as the class B amplifier however the additional efficiency in back off means a 64% drain efficiency at 6 dB back off or at 0.5 output magnitude.

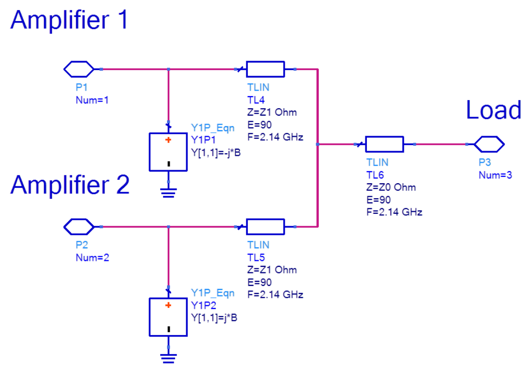

Figure 5 Ideal outphasing combiner, admittance equations are used to provide load compensation for increased back off efficiency

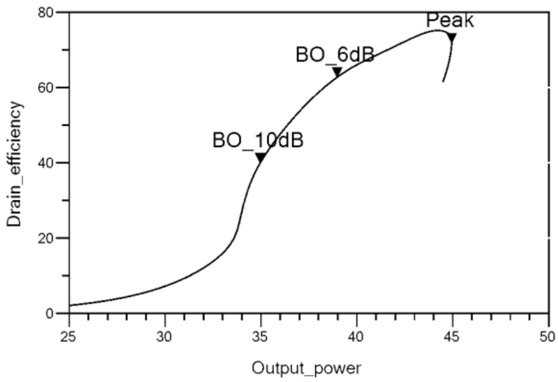

Figure 6 Drain efficiency of saturated class B outphasing amplifier.

IV. Effects of Thermal Variation on Outphasing Topology

Power amplifier thermal stability impacts not only device longevity, it significantly contributes to the characteristic operation of the amplification circuit. Variations in transistor temperature affect the internal resistance, R_{th} on, resulting in an impact to amplifier gain. This effect can result in a memory effect which is referred to as an electro thermal memory effect. Depending on device properties and method of amplifier operation, in either pulsed power operation or carrier wave operation the effect can result in long or short term memory. In traditional amplifier structures, particularly ones which rely on pre-distortion for linear operation, the electro thermal memory effect can impact ACPR and error vector magnitude (EVM). In [4] the authors present analysis and subsequently a thermal model for a power amplifier which experience both long and short term thermal memory effects, accounting for amplifier temperature, output gain and absolute phase shift with device temperature.

A. Class B PA Thermal Characteristics

Thermal variations are simulated through modifying the transistor package temperature of the device model. Harmonic balance analysis is carried out demonstrating the relative effects on the amplifier structure. Figure 7 demonstrates the impact of a 10 degree swing above and below the nominal operating value. In a typical amplifier structure the variance demonstrated will almost be undetectable, the gain is reduced by 0.15 dB for each 10 degree step, while apparent in a variation in output power however will not result in a significant non-linearity unless the amplifier is operating on the edge of compression and attempts to compensate for the variation. The absolute phase shift is approximately 1 degree which would remain undetectable in the amplifiers output. These variations will have a greater impact on the outphasing structure which depends on constant branch gain and phase for a linear output.

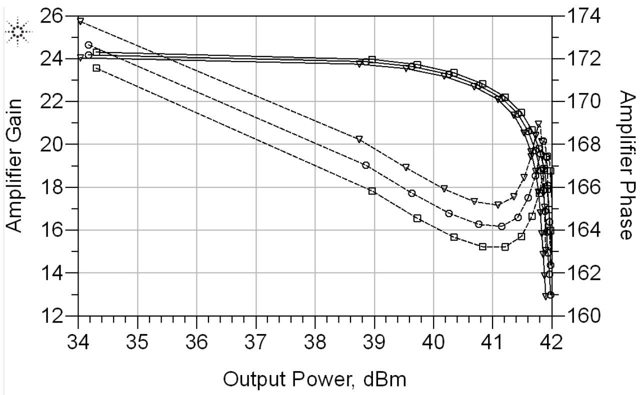

Figure 7 Thermal Variations of class B amplifier, Solid line = amplifier gain, Dashed line = amplifier phase. Square delta temp -10 degrees C, Circle delta temp 0 degrees C, Triangle delta temp +10 degrees C.

B. Outphasing Amplifier Thermal Considerations

In contrast to the class B amplifier the outphasing amplifiers output power is determined by the outphasing angle between the combiners input paths, as described in equations 1-3. The thermal variation effectively results in an impedance change at the output of the amplifier. The load impedance of the outphasing amplifier is fixed and the output impedance of the amplification stage has been modified, therefore equation 5 is no longer true. As a result the input return loss between the amplification stages and the combiner varies, resulting in a gain imbalance. In addition the outphasing phase angle experiences a shift in accordance with the variation demonstrated in Figure 7. The effect on the relationship between outphasing angle and output power is demonstrated in Figure 8. The most notable impact is on the dynamic range achievable by the outphasing amplifier. A reduction of greater than 20 dB can be seen, limiting the total outphasing dynamic range to 44.5dB

V. THERMAL STABILITY THROUGH ACITIVE BIAS CONTROL

Active biasing circuits are common in many modern power amplifier modules. They aim to provide a constant quiescent current through the drain supply by gate bias voltage control. The quiescent current is directly related to the conducting angle of the power amplifier, achieving a constant quiescent current will result in constant amplifier gain and equivalent amplifier linearity characteristics. In addition active bias control can account for electro thermal effects, given that device temperature directly effects R_{th} on, it will result in a variation in current through the device. A comprehensive overview of biasing circuits for GaN pHEMT devices is presented in [9].

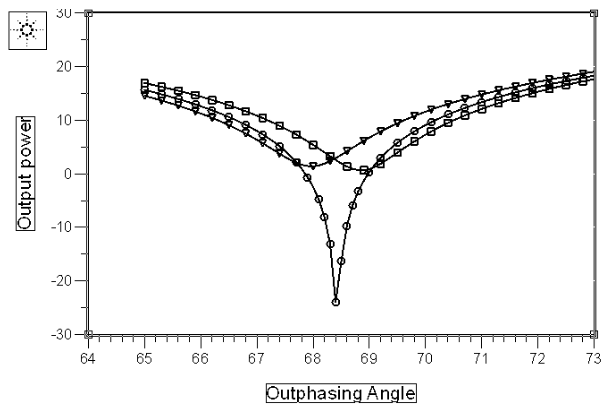

Figure 8 Effect of temperature variation on minimum achievable output power. Square delta temp -10 degrees C, Circle delta temp 0 degrees C, Triangle delta temp +10 degrees C.

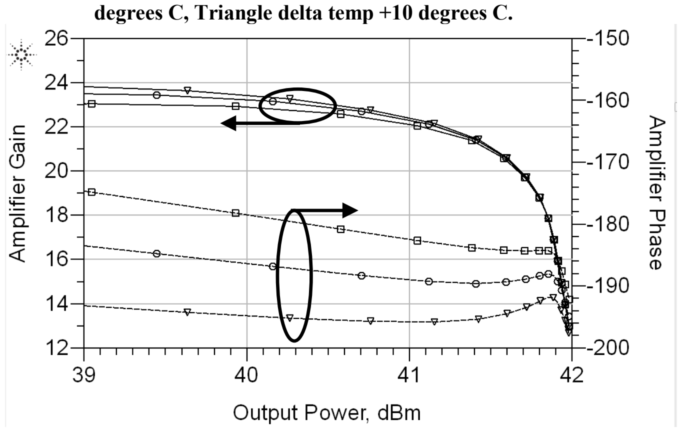

Figure 9 Various Bias Values for class B amplifier, Solid line = amplifier gain, Dashed line = amplifier phase. Square -3.4V, Circle -3.2 V, Triangle -3V.

First let's investigate the effects on varying the bias voltage of the class B amplifier. From the theory of operation, the bias voltage controls the conducting angle of the amplifier. A change in the conducting angle varies the gain and as result the output power of the amplifier. This is demonstrated in Figure 9, as the amplifier gain outside of compression reduces with the bias voltage, the amplifier phase however experiences a much larger change of approximately 10 degrees for every 0.2 volt step.

Bias voltage manipulation can restore the relationship between the combiner load impedance and the output impedance of the amplification stage. However as demonstrated in Figure 10, the outphasing function which describes the outphasing phase angle and the amplifier output power has been significantly changed. By comparing the original outphasing function in Figure 8 to the new optimal outphasing function at a bias voltage of -3.4 volts the outphasing angle has shifted 2.4 degrees. As demonstrated in [4] variations in outphasing angle and/or magnitude input to the combiner will result in an increase to ACPR and signal EVM.

VI. CONCLUSIONS

From simulated analysis carried out in this paper it is clearly evident that thermal variations on the power transistor die and package influences the operation of outphasing topology a great deal more than standard amplifier architectures. In section IV the thermal effects heavily impact on the amplifier dynamic range and outphasing function. The thermal drift modifies the resistance of the transistor in its low impedance state, the resulting amplifier output impedance and hence the input impedance to the Chireix combiner is modified.

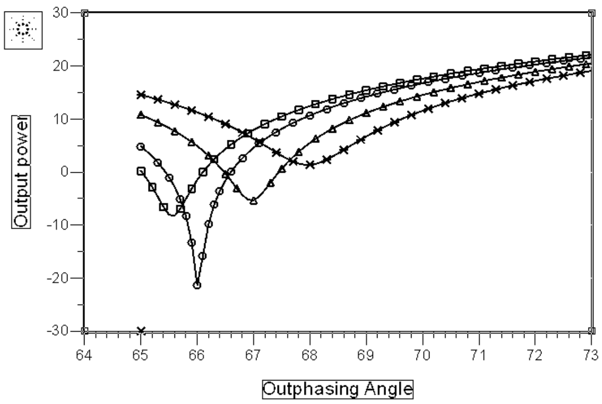

Figure 10 Effect of bias variation on temperature variation of +10 degrees C. Square -3.6V, Circle -3.4 V, Triangle -3.2V and the Cross = -3V.

Modern amplifier biasing circuits include temperature control. This enables the amplifier to achieve a constant output gain and maintain amplifier stability. As demonstrated in section V varying the bias value to compensate for temperature effects can restore amplifier dynamic range it will result in a significant change in the outphasing amplitude to phase function. This will result in limited dynamic range and non-linear operation if not accounted for in signal generation.

From this work it is evident that thermal effects are a significant concern in outphasing systems. In static or carrier wave characterisation a signal with comparable output power to the desired transmission standard must be used for system characterisation. This can either be a multi-tone signal or a pulsed carrier wave of equivalent pulsed output power.

In order to fully combat thermal effects on the outphasing amplitude to phase translation a continuous closed loop two path pre-distortion algorithm would be required. Alternatively the inclusion of the thermal effects in calculating the outphasing function and a feedback of a thermal model of the amplifier increased linearity can be achieved. A combined outphasing angle and amplifier bias control function could offer long term stability and linearity.

ACKNOWLEDGMENT

This material is based upon works supported by Science Foundation Ireland under Grant No. 10/CE/I1853 and by HEA under PRTLI5 and is being co-funded by the Irish Government and the EU under Ireland's Structural Funds Programmes 2007-2013: Investing in your future. The authors gratefully acknowledge this support.

VII. REFERENCES

[1] B. Kim, J. Kim, I. Kim and J. Cha, “The Doherty power amplifier,” *Microwave Magazine,* vol. 7, no. 5, pp. 42,50, Oct 2006.

[2] J. Staudinger, B. Gilsdorf, D. Newman, G. Norris, G. Sadowniczak, R. Sherman and T. Quach, “High efficiency CDMA RF power amplifier using dynamic envelope tracking technique,” in *Microwave Symposium Digest*, 2000.

[3] H. Chireix, “High Power Outphasing Modulation,” in *Radio Engineers, Proceedings of the Institute of*, 1935.

[4] J. Fritzin, A. Alvandpour, P. Landin and C. Fager, “Linearity, intermodulation distortion and ACLR in outphasing amplifiers,” in *Microwave Symposium Digest (IMS)*, Seattle, WA, 2013.

[5] S. Boumaiza and F. Ghannouchi, “Thermal memory effects modeling and compensation in RF power amplifiers and predistortion linearizers,” *Microwave Theory and Techniques, IEEE Transactions on* , vol. 51, no. 12, pp. 2427,2433, 2003.

[6] M. van der Heijden, M. Acar, J. Vromans and D. Calvillo-Cortes, “A 19W high-efficiency wide-band CMOS-GaN class-E Chireix RF outphasing power amplifier,” in *Microwave Symposium Digest (MTT), 2011 IEEE MTT-S International*, Baltimore, 2011.

[7] J. Qureshi, M. Pelk, M. Marchetti, W. Neo, J. Gajadharsing, M. van der Heijden and L. C. N. De Vreede, “A 90-W Peak Power GaN Outphasing Amplifier With Optimum Input Signal Conditioning,” *Microwave Theory and Techniques, IEEE Transactions on,* vol. vol.57, no. no.8, pp. pp.1925,1935, Aug 2009.

[8] D. Cox, “Linear Amplification with Nonlinear Components,” *Communications, IEEE Transactions on* , vol. 22, no. 12, pp. 1942-1945, 1974.

[9] J. Bellantoni, “Bias Techniques for GaN and pHEMT Depletion Mode Devices,” TriQuint, 2014.