INTERNATIONAL JOURNAL of ENGINEERING SCIENCE AND APPLICATION
A. S. Ahmed et al., Vol.7, No.3, September 2023

Broadband Power Amplifier for Cellular Base Station Application

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Received: 31.05.2023 Accepted:18.09.2023

Abstract-With increased data traffic and RF transmission, the most demanding component for a base station transceiver in a sophisticated cellular communication system is power amplifier. The base-station transceivers require power amplifiers with increasingly high efficiency, low operational cost and wider bandwidth. The challenges of meeting all these requirements simultaneously motivated the design, simulation and evaluation of a Power Amplifier (PA) for base-station application. Advanced Design System (ADS) software was used to simulate broadband PA based on the ATF13786 Gallium Arsenide (GaAs) transistor, across the 850 MHz to 3GHz frequency range. The simulated small and large signal results of the PA revealed a saturated output power of 25.19dBm with a 1-dB compression point at 26.425 dBm output power level, a Power Added Efficiency (PAE) of 32.41 percent and maximum gain of 11.938dB. The input return loss S11 and output return loss S22 are both less than –10 dB over the whole functioning frequency ranges. The minimal values of the computed and simulated Rollett and Bodway stability factors were 1.1751 and 0.092, respectively. However, the simulated PA is unconditionally stable within a fraction of the proposed frequency band; that is 850MHz – 1.7GHz. Given the wide frequency range, the simulated results show that the input and output matching networks perform well over the operating frequency range. The results of simulated BPA compared favorably with those of available designs and their results meet the operational requirements.

Keywords: Broadband power amplifier (BPA), Gallium Arsenide (GaAs), Advance Design system (ADS), Power Amplifier (PA), Power Added Efficiency (PAE).

1. Introduction

There are a lot of broadcasting signals out there waiting to be picked up. Each of these signals can be conveyed with the help of a power amplifier. All electrical amplifiers, regardless of whether they are described as broadband, narrowband, low noise, high power, or otherwise, have the same characteristics of giving limited positive power gain at the frequency or range of frequency of interest [1]. A power amplifier (PA) is an electrical circuit that increases the magnitude of power of a given input signal's. The input signal's is boosted to a level that can drive a large number of output devices. A radio frequency power amplifier (RFPA) is an electrical amplifier that boosts the power of a low-power radio frequency signal into a higher power level [2]. RFPA are typically used to drive a transmitter's antenna. A base station is a transceiver that connects networking devices and is capable of sending and receiving wireless signals. The base station is in charge of maintaining communication between the network and the users, as well as between users [3]. The transistor used as the power device and most important component of an RFPA circuit. Today, laterally diffused metal oxide semiconductor (LDMOS), gallium arsenide (GaAs), and heterojunction bipolar transistor (HBT) transistors are widely adopted as commercial power devices for base station applications [4]. The feature of a broadband power amplifier design is evaluated by its ability to reach maximum power gain across the required frequency bandwidth, under stable operating conditions, with minimum amplifier stages, and the requirement for the high efficiency or linearity can be considered where it is needed. BPA applications span a wide range of areas, which includes the base station transceiver of Global System Mobile (GSM) [5]. In RFPA circuits, broadband signal amplification is of great demand [6].

In recent years, the research community has been focused on BPA design. Numerous studies have been done by researchers towards building RFPA that provides the best possible performance in terms of stability, output power, bandwidth, gain, linearity, efficiency, and cost effectiveness. "Ref. [7] used Sequential Harmonic Characterization to design a broadband RFPA. Simulation results of the proposed PA show that adopting sequential trajectory leads to a 12 percent increase in efficiency at in-band frequencies. However, due to low output current, this design is mainly appropriate for low-power applications". "Ref. [8] concentrated on the creation of novel designs that may overcome the bandwidth restrictions of traditional PAs. The bandwidth constraint issues of a traditional Doherty power amplifier (DPA) design are reported in particular. The bandwidth of a traditional DPA is limited. As a result, conventional DPA cannot match the bandwidth need of a modern base station, though the linearity and power output criteria were met". "Ref. [9] developed a broadband gallium nitride (GaN) power amplifier with 1.2- and 2.4-mm diameters. The goal was to investigate the bandwidth and performance of a Class AB, biased, 1.2-mm HEMT power amplifier that was designed to maximize bandwidth, output power, and PAE over the 2-to-8-GHz range. The bandwidth extension design technique was only used on 6W transistors in the modified circuits and may not be applicable at higher power levels. As a result, it should be used for high-power active devices, such as those used in pico-cell base-stations". "Ref. [10] proposed the design of a Broadband Power Amplifier (BPA) over a 2900 MHz bandwidth, from 1.1 GHz to 3 GHz, which cover the mainstream communication standards running in L and S bands. Furthermore, the proposed BPA reached a maximum gain of 14.89 dB, and a saturated output power of 17.14 dBm with 20% of maximum PAE. However, there is need to improve the observed linearity of the design". "Ref. [11] suggested a GaAs Heterojunction Bipolar Transistor based on fully integrated broadband power amplifier for long term Evolution A (LTE-A) Application, with the help of the broadband matching networks employed in the proposed 3-stage power amplifier topology that operate from 1.8GHz to 2.5 GHz frequency. The bandwidth of this design is insufficient for broadband Application". "Ref. [12] Used two design techniques, namely; Doherty power amplifier and Envelope tracking (ET) to optimize the power amplifier performance of class AB for maximum bandwidth and the spots for best efficiency and linearity from the 6W GaN. The proposed PA architecture, appears to be suitable for pico-cell base station application. Based on the recorded findings the bandwidth extension design technique was only used on 6W transistors in the modified circuit and may not be applicable at higher power levels". "Ref. [13] proposed a large signal modeling of GaN HEMTs that took into consideration the charge carrier trapping memory effects. It was created using Agilent's standard EEHEMT1 model. Effect that were not captured by Agilent conventional EEHEMT1 model, were measured and investigated. To ascertain the relationship between variation of the current and the operating point, pulsed I-V characteristics were measured at varying quiescent points. Time constants of trapping effects due to diverse trap origins in the device were monitored. In the frequency domain, the effect with the least time constant was measured, resulting in a kink in the S22-plot with a corner frequency in the MHz region".

Implementation of broadband power amplifier based on balance architectures, distributed configuration and many matching approaches such as the real frequency technique (RFT), resistive matching circuits and reactive filter synthesis has also been presented [14]. Resistive matching and reactive filter synthesis methods do not give good return loss over a wide frequency range and both have some limits in terms of increasing the power amplifiers bandwidth. On the other hand, RFT has distinct advantages in terms of return loss and bandwidth. There is need for improved design of RF power amplifier with better stability, output power, bandwidth, gain, linearity and efficiency at good cost. This need prompted the simulation of Broadband Power Amplifier (BPA) design with simple circuitry and ease of practical implementation.

2. Materials and Method

2.1 Materials

In order to obtain an optimal design and simulation, the materials used to build and model the Broadband Power Amplifier include a variety of components and software include: GaAs FET Transistor, Computer set, 4GB RAM with Advanced Design System (ADS) 2019 version software installed.

The ADS software provides the load-pull and source pull simulation tool to find the suitable load impedance and source impedance for the selected transistor to achieve linearity and high efficiency [15].

2.2. Method

The design and simulation of BPA is divided into three (3) stages as follows:

i. Selection and biasing of an appropriate transistor that meet all of the specifications of the desired power amplifier design.

ii. Simulation of RF power amplifier with the input and output matching network with the use of ADS.

iii. Verification of the results of the single-stage power amplifier performance characteristics such as:

- DC bias
- Stability
- Level of match
- Efficiency and
- Linearity

(a) RF power device Selection

To achieve the appropriate levels of power and frequency performance while maintaining heat transport across the device and preventing device failures, high-power RF devices require the proper selection of semiconductor materials [16]. RF power devices are generally made of III-V semiconductors like Gallium Nitrite (GaN), compound silicon (SiC), Gallium Arsenide (GaAs) and group IV materials like silicon (Si) and germanium (Ge), especially in commercial applications [16]. Wide-band gap materials like Gallium Arsenide (GaAs) have recently attracted a lot of attention in research and development.

The choice a transistor with the desired frequency from an array of components is aided by a datasheet from the manufacturer. The Hewlett-Packard ATF-13786 transistor was employed in this project to design the proposed BPA due to its low-cost, surface- mount Gallium Arsenide schottky barrier gate field effect transistor with plastic packaging. and it has high gain hence; it does not easily cause oscillation when used for PA design. According to the datasheet, the GaAs transistor can operate at up to 60 GHz and can deliver 100 W of output power, (Output Power at 10 GHz up to 10 dBm) [17].

(b) DC Biasing

The second step of the design is to determine the transistor's DC bias via simulation as shown in “Fig.1”. According to the datasheet, the gate-source threshold voltage for GaAs ranges from 0V to 4.0V, with a recommended drain-source value of 3V.

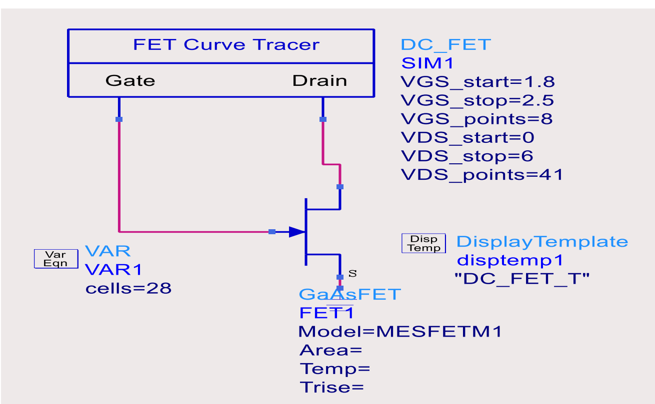


Fig. 1. The DC bias of GaAs

Therefore, the simulation is set up with the drain-source voltage from set 0V to 6V, and the gate-source voltage set over the specified range (1.8 – 2.5V). The current – voltage (I – V) characteristics obtained by running the set - up is shown in “Fig.2.” The DC bias condition of the amplifier was determined using the transistor's I-V curve. The result is shown in “Fig.2”.

(c) Input and Output Matching networks:

To ensure that the BPA's small-signal gain meets the requirement, the series capacitor shields the shunt resistor from an excessive current. Proper connection of the capacitor to the transistor's drain increases the frequency. For both the input and output matching networks, optimal input and output impedances were used. The major one is implemented using lumped elements, resulting in significantly improved stable zones for both the supply and the load.

A single-section cable was used in the output matching networks used in this study. In source-pull simulations, the source stability circle and the load stability circle of the GaAs transistor were simulated and performed for optimum source impedance at the fundamental frequency. At the bias point (VDS = 3V, VGS = 2.2V), the extracted optimum source impedance is ZSource = 10+j*25, with a drain current of 25 mA at 3 GHz. Then, with the same bias point at fundamental frequency, load-pull simulations are run to find the best load impedances for output power and efficiency. The result is as presented in “Fig.3., & 4”.

(d) Verification of Performance Parameters

i. *S-Parameter (Small Signal) Simulation*

The RF performance of the proposed BPA is determined using small signal, two port S-parameter simulation. The S-parameter simulations are done in Common Source, ZO = 50 Ω, VDS = 3.750 V, IDS = 40 mA. Basic S-parameter simulations are small signal, and consist of measuring transmitted, reflected and incident waves. Small signal gain S21, input return loss S11, output return loss S22 and isolation coefficient S12 are simulated using Advanced Design System (ADS) simulation software (Simulated results are presented in Fig.7., & 8). From the simulated input reflection data S11, a complex conjugate of the small-signal impedance is obtained.

Large signal parameters such as power added efficiency, gain and linearity of the BPA were also verified and the simulation results are presented in section below (Fig.9 to 12)

ii. *Stability*

Stability is important design criteria that should be considered in the amplifier design. In two-port systems, oscillations may occur when input or output resistance ports are negative [18]. This negative resistance corresponds to input and output reflection coefficient greater than unity. K factor and the auxiliary condition B factor were simulated with the use of ADS software and the stability conditions were determined from the plot shown in “Fig 5., & 6”.

3. Result and Discussion

i. DC Analysis

The DC bias condition of the amplifier was determined using the transistor's I-V curve. The bias condition set at drain –source voltage (VDS) of 3.750V, the gate –source voltage VGS = 2.200V and drain –source current of 0.187mA are seen in the graphs in “Fig.2”. This shows that the GaAs transistor's acceptable operating points that will produce a high output power while achieving a high drain efficiency.

The simulated transfer characteristic of the transistor shown in “Fig.2” denotes the connection between the VDS and the DC power consumption. The plot shows direct proportionality between the two parameters confirming proper DC biasing.

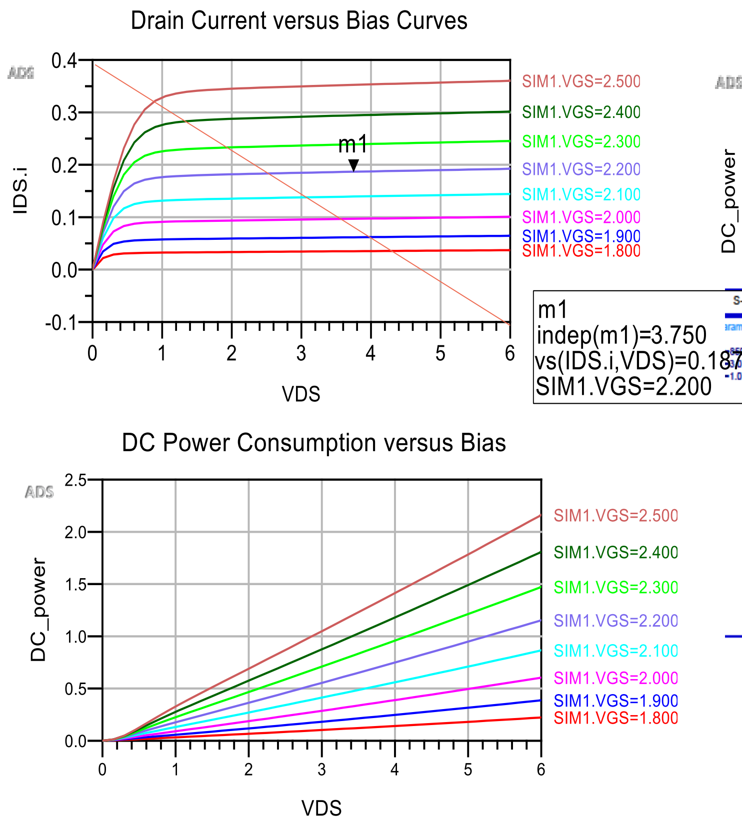


Fig. 2. DC biasing of the desired Transistor output characteristics

ii. *Input and Output Matching Network of BPA*

To boost efficiency, this design used an equalizer in the input matching network as well as dynamic bias circuits and BPA feedback mechanisms to balance the power gain. The input matching network's (IMN) primary function is to convert the optimum source impedance to a system level impedance of 50 Ohm for maximum power transmission from the source to the transistor's gate. An input matching network can also be utilized to increase the power amplifier's overall gain. The ideal input impedance of transistors is found using a source-pull simulation (Fig.3) after the stability circuit is added to the input matching network.

The major purpose of this design is to make BPA more linear across the entire frequency range. The optimal linearity at the center frequency of a PA can be achieved either by finding the optimum output impedance (Ropt) for maximum output power of the specified active device using a two tone load-pull technique or by using bias point optimization to localize the linear operating region of a PA (minimum IMD3 point). However, Ropt may have an impact on the output power and efficiency trade-off [19]. Hence, the second method was employed in this design. Figure 4 shows the power and PAE elliptical output contours in steps of 0.5 dBm and 32 percent. " At an output impedance of Zoutput = 0.115 + j*2.55, the PAE contours provided a 32 percent efficiency.

The Smith chart's location of optimum output power and optimum PAE is slightly off.

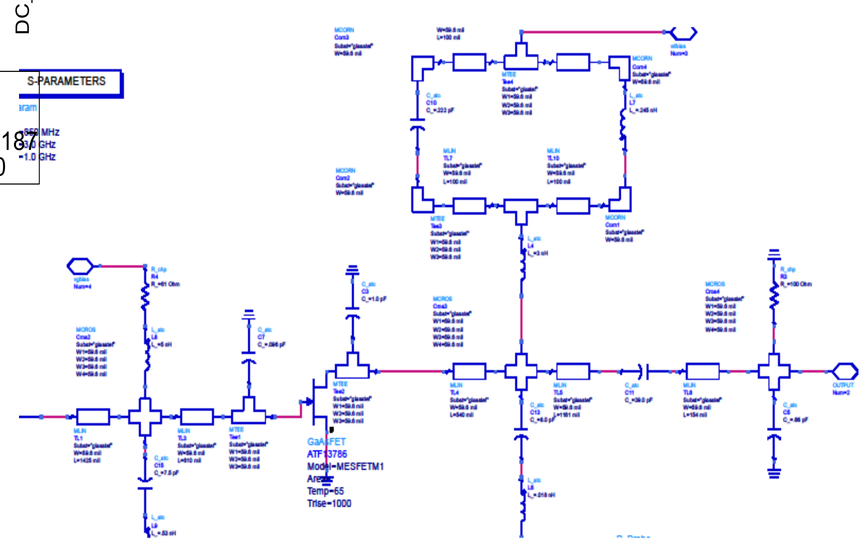


Fig. 3. Matching Networks of Design BPA.

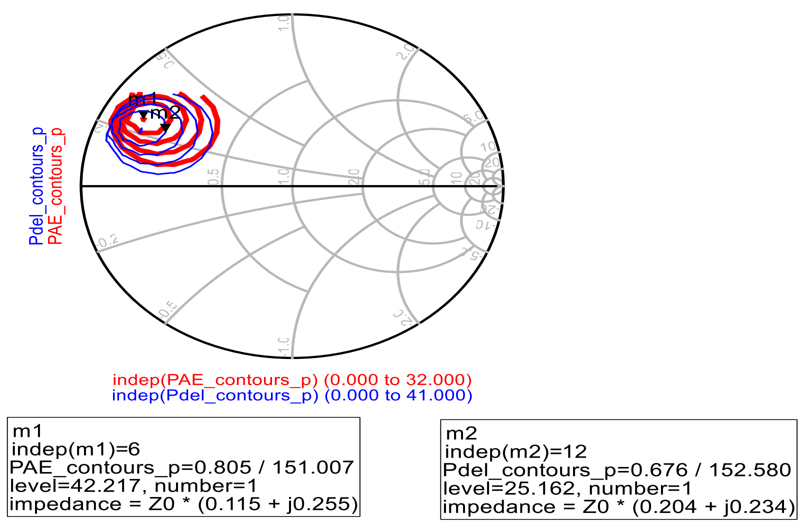


Fig. 4. PAE and Power output contours Smith Chart

iii. *Stability Analysis*

"Figures 5" shows that within the proposed frequency range of 850MHz – 3GHz, K is always greater than one (k > 1), however, the Bodway stability plot in "Fig.6" shows that

Δ<1 only from 850MHz – 1.7GHz frequency range after which the values began to fluctuate. Hence the proposed PA can be said to be unconditionally stable within the 850MHz – 1.7GHz frequency range. This implies that within these band, any source or load can be connected to the BPA's input or output without causing instability or oscillations.

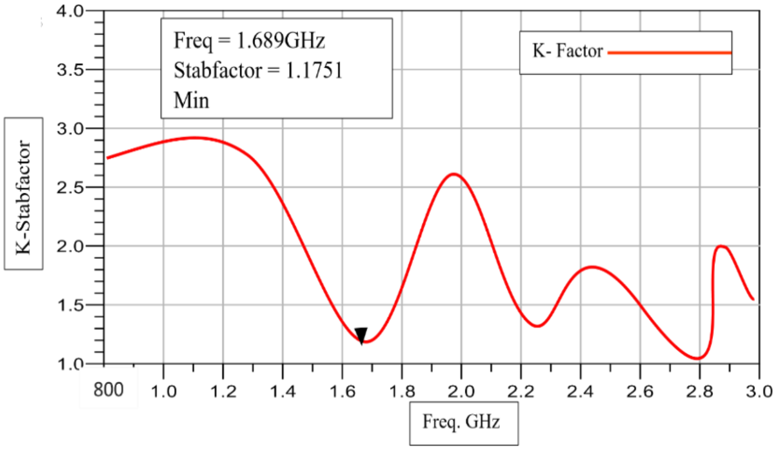


Fig. 5. Simulated K factor

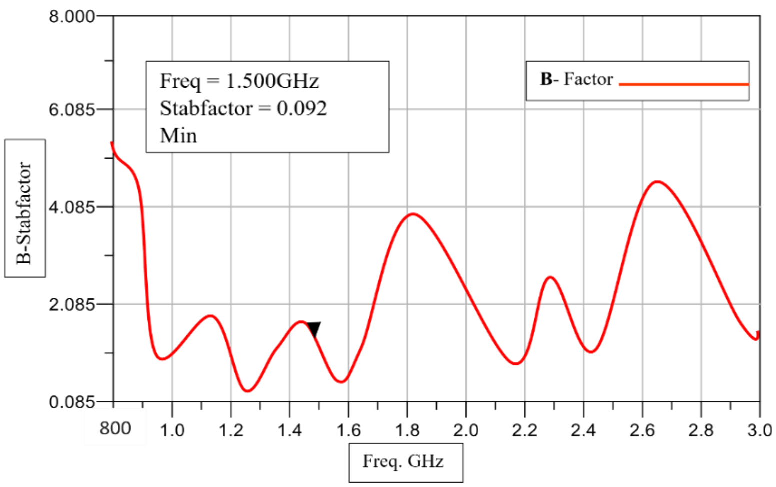
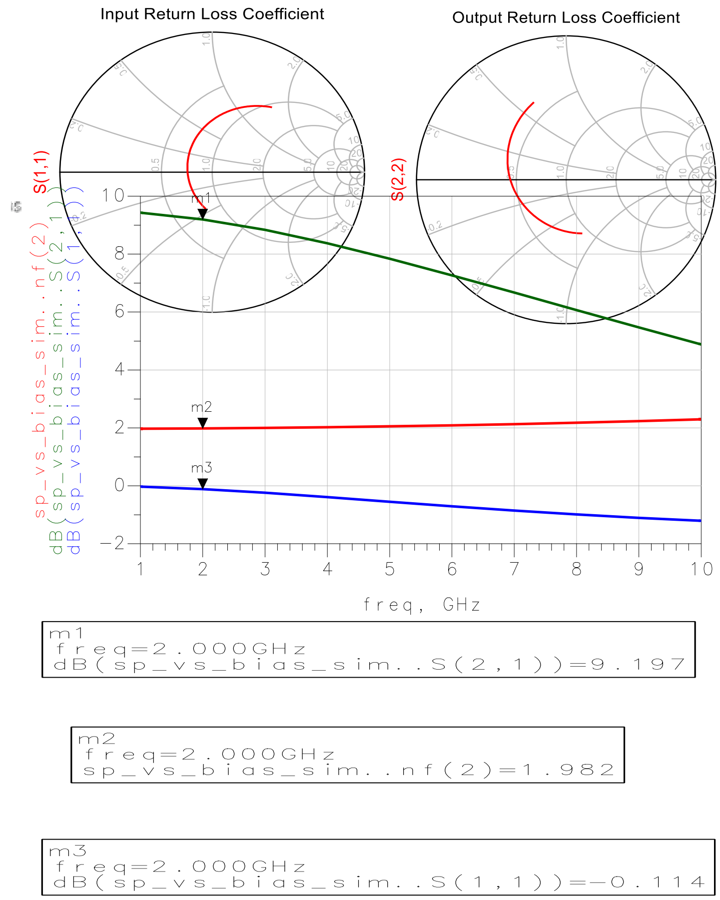


Fig. 6. Simulated B factor

iv. S-Parameter (Small Signal) Simulation

The red line inside the Smith charts in "Fig.7" illustrates the input Return loss coefficient and Output Return loss coefficient. Over frequency from 850 MHz to 3 GHz, input return loss, S11, ranges between -10.057 dB and -35.948 dB as shown in an input return loss chart while the output return loss, S22, varies between -9.849 dB and -25.631 dB over the specified band. The simulated results show that the input and output matching is good over the operating bandwidth, implying that very little power is "returned" to the source from the input or to the load from the output.

Fig. 7. Input and Output return loss



The Small Signal Simulation S-parameters for this power amplifier in the frequency band of 850 MHz – 3 GHz is shown in "Fig.8". A small-signal gain, S21 varies between a minimum value of about 8.9 dB to 9.5 dB within the operating frequency range.

Fig. 8. Small Signal Simulation and Reverse Isolation at 2 GHz

The magnitude of Reverse Isolation, S12, which reflect the input and output matching of this amplifier circuit is about 2.0dB. In order to operate a functional power amplifier, S12 must be as minimal as possible, because the smaller the reverse isolation value, the greater the degree of isolation between the output and input, as well as the degree of stability of a given stage.

v. Large signal simulation

The simulated Load reflection coefficient indicates how dissimilar the amplifier's impedance is from the standard impedance (50Ω). “Figure 9” shows the simulated Load reflection coefficient, which ranges from -0.966 to -0.234 and represents how different the load resistance is from the transmission line characteristic impedance. “Figure 9” also shows that the simulated maximum output power was delivered at 25.19 dBm, resulting in a 32.41 percent power added efficiency. This reveals how much source input power is transform to RF output power in the power amplifier.

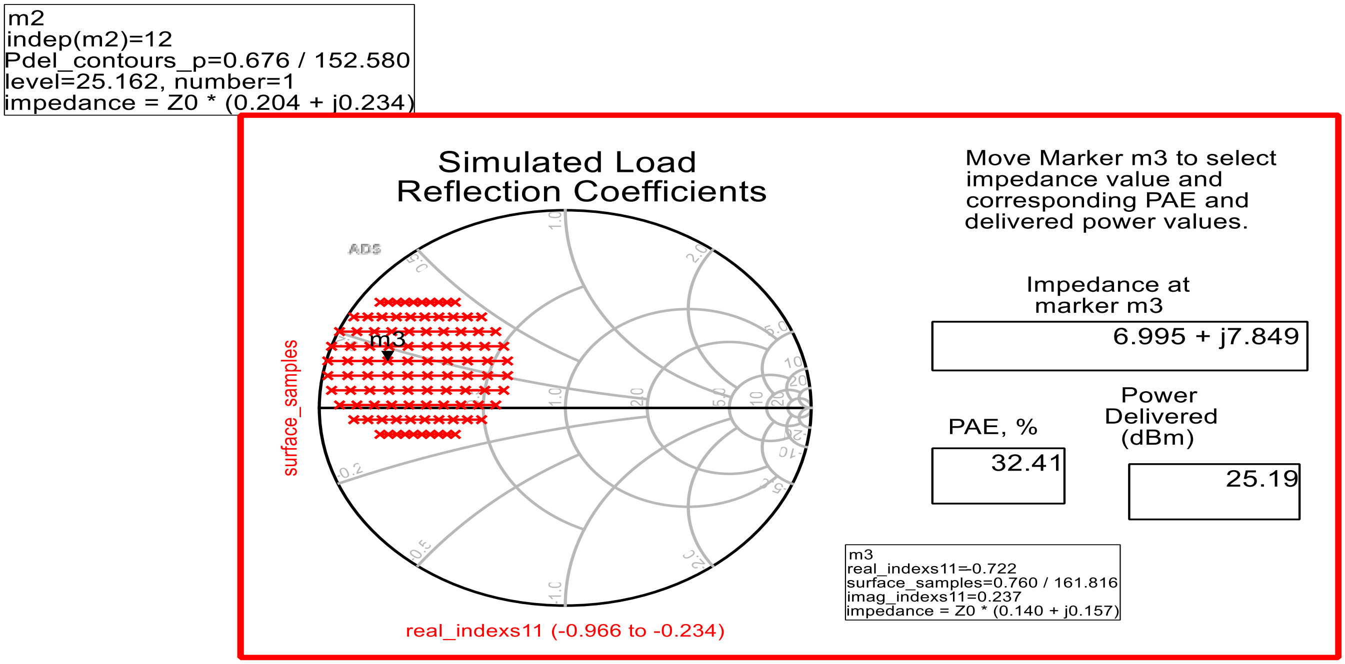


Fig. 9. Simulated load Reflection coefficient.

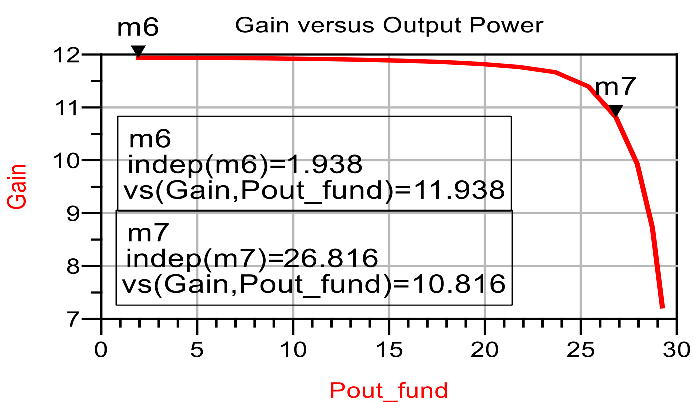


Fig. 10. Gain versus power output

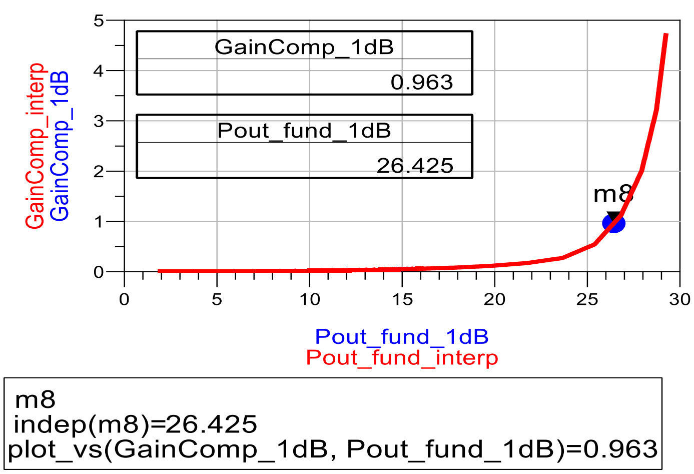


Fig. 11. Gain Compression versus 1dB

From the data sheet specification for ATF 13786, the typical value of power at 1dB gain compression (P1dB) is given as 16.5dBm. The simulated P1dB value of 26.425dBm presented in "Fig.11" is an improvement; which is confirmed by the constant gain at varying output shown in "Fig.10"., The relationship between Power amplifier gain and power output shows that the power amplifier has the ability to increase the magnitude of an input signal without reducing the gain.

"Figure 12" shows a plot of third harmonics versus source power. Third harmonic usually appears with a negative coefficient, resulting lesser distortion. The plot reveals that output power Po increases with increase in output power level of third order harmonics P3o. It was observed that at higher input power values the difference between the two parameters lessens suggesting lower intermodulation distortion (IMD3) and better linearity.

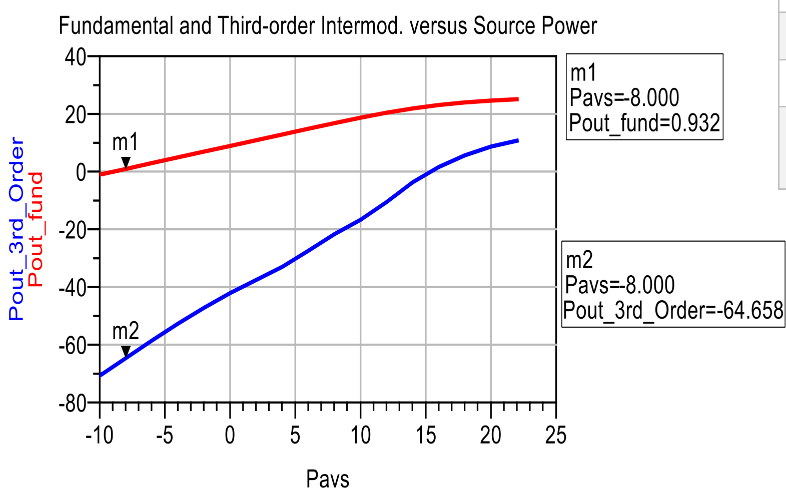


Fig. 12. Third harmonic distortion versus Source power.

When compared to related previous works on broadband PA design, as shown in "Table 1", the proposed broadband matching approaches are clearly useful, and the simulated BPA achieves an exceptional bandwidth with good matching and linearity across the operational frequency ranges.

Table. 1. Performance comparison with Previously designed power amplifier.

RF Devices	Freq. (GHz)	Power (dBm)	Gain (dB)	PAE/DE (%)	Author
Si-LDMOS	1.75 – 2.15	8	10	--	**‘’[4]**
LDMOS	1.2	50	40	20	**‘’[5]**
GaN HEMT	2.11 – 2.17	37	12.6	52.8	**‘’[10]**
LDMOS	0.55 – 0.75	316	4	>46	**‘’[11]**
GaN HEMT	1.8 – 2. 8	28	25	6.1	**‘’[13]**
GaN	2.15– 2.66	13.5	2.5	65-76	**‘’[14]**
GaAs	1.9 – 2.6	28.1	11	13.7	**‘’[15]**
LDMOS	0.1 – 0.5	30	0.6	52 – 63	**‘’[19]**
SiGe HBT	1.8	28	13	51	**‘’[20]**
LDMOS	0.002 – 0.8	40	2	25 - 35	**‘’[21]**
GaAs	**850MHz – 3GHz**	**25.19**	**11.938**	**32.41**	**This work**

4. Conclusion

A Broadband power amplifier for base station applications in the 0.85 - 3GHz frequency spectrum is presented. Extensive simulations were run in ADS with an exact device and component model to achieve the optimum maximum gain of 11.938 dB across the entire frequency range, as well as improved PAE for the specified bandwidth. The simulation findings show that the BPA has a fairly good linearity and high efficiency considering the wide frequency range. The performance characteristics obtained such as high gain, outstanding bandwidth, good output power, good matching across working bandwidth, and simple circuitry makes this PA an excellent choice for cellular base station application.

Acknowledgements

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References

[1] C. P. Huang, "A Multimode 5–6 GHz SiGe BiCMOS PA Design Powers Emerging Wireless LAN Radio Standards, in 2017", IEEE Bipolar/BiCMOS Circuits and Technology Meeting (BCTM), pp. 38-41, 2017.

[2] S. R. Balanethiram, A. D'Esposito, S. Chakravorty, Fregonese, and T. Zimmer, "Extraction of BEOL Contributions for Thermal Resistance in SiGe HBTs",

IEEE Transactions on Electron Devices, vol. 64, no. 3, pp. 1380-1384, 2017

[3] Simbase, Electronics Tutorials/Amplifier/Frequency Response, https:// www. Electronic tutorial, 4 June 2019 Revol No. 07.

[4] A. Rachakh, L. El Abdellaoui, J. Zbitou, A. Errkik, A. Tajouati, and M. Latrach. "A Novel Configuration of a Microstrip Microwave Wideband Power Amplifier for Wireless Application", Telkomnika, Vol.16, No.1, pp.2014-2031, 2018

[5] N. Rostomyan, M. Ozen, P. Asbeck, "28 GHz Doherty Power Amplifier in CMOS SOIWith 28% Back-Off PAE". IEEE Microw., Wirel. Compon. Lett. 28, 446–448, 2018.

[6] M. M. Tarar and R. Negra, "Design and Implementation of Wideband Stacked Distributed Power Amplifier in 0.13-μm CMOS Using Uniform Distributed Topology", IEEE Transactions on Microwave Theory and Techniques, vol. 65, no. 12, pp. 5212-5222, 2017.

[7] M. Iqbal, "Advanced High Efficiency and Broadband Power Amplifiers Based on GaN HEMT for Wireless Applications". PhD thesis, 2017.

[8] J.E. Pen, "1.2- and 2.4-mm Gallium Nitride (GaN) Power Amplifier Designs. Sensors and Electron Devices Directorate", ARL 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302 2016.

[9] S. C. Cripps, "RF Power Amplifiers for Wireless Communications", 2nd ed. Norwood, MA: Artech House, 2006.

[10] D. Gustafsson, C. M. Andersson, and C. A. Fager, "Modified Doherty power amplifier with extended bandwidth and reconfigurable efficiency". IEEE transactions on microwave theory and techniques, 61(1), 533-542, 2019.

[11] M. M. Tarar and R. Negra, "Design and Implementation of Wideband Stacked Distributed Power Amplifier in 0.13-μm CMOS Using Uniform Distributed Topology", IEEE Tra nsactions on Microwave Theory and Techniques, vol. 65, no. 12, pp. 5212-5222, 2018.

[12] N. Giovannelli, "A 250W LDMOS Doherty PA with 31% of Fractional Bandwidth for DVB-T Applications", IEEE MTT-S Int. Microw. Symp., Tampa Bay, FL, USA, pp. 1– 4, june 2014.

[13] K. Li, T. Shi, S. Di and W. Yin, "A 40W ultra broadband LDMOS power amplifier," 2015 IEEE MTT-S International Microwave Symposium, Phoenix, AZ, USA, 2015, pp. 1-4, doi: 10.1109/MWSYM.2015.7166842.

[14] Chun-Q, M. Chen, Z. Hao, Z. Li, and Y. Hao, "A 1.8–2.8GHz Highly Linear Broadband Power Amplifier for LTE-A Application", Progress. In Electromagnetics Research C, Vol. 66, 47–54, 2016

[15] N. Tuffy, A. Zhu, and T.J. Brazil, "Novel Realisation of a Broadband High-Efficiency Continuous Class-F Power Amplifier", European Microw. Integr. Circuits Conf., Manchester, UK, pp. 120–123, October 2011.

[16] M. Golio, "RF and Microwave Semiconductor Device Handbook", CRC Press, Boca, USA, ISBN: 978-08493-1562-6, pp. 340, 01/February/2003

[17] Keysight Technologies, S-parameters Measurements, Basics for High speed Digital Engineers published in USA. June 2019, 5991 – 3736EN: http: www.keysight.com.

[18] L. Wu, "Design of Radio Frequency Power Amplifiers for Cellular Phones and Base", IEEE Microwave and Wireless Components Letters, Vol.28, No.1, pp.37-39, 2009.

[19] S. A. Mohadeskasaei, "A Systematic Approach for Design of Broadband, High Efficiency, High Power RF Amplifiers", ETRI Journal, Volume 39, Number 101, https://doi.org/10.4218/etrij.17.0116.0440, February 2018.

[20] J. Inchan, "A Study on Design Methodologies of Power Amplifiers using SIGE HBT BICMOS Technologies", A Dissertation School of Electrical and Computer Engineering. Georgia Institute of Technology, 2019.

[21] B. Francois, and P. Reynaert, "Highly linear fully integrated wideband RF PA for LTE-advanced in 180-nm SOI", IEEE Transactions on Microwave Theory and Techniques, Vol. 63, No.3, pp. 649–658, 2015.