

Design and Simulation of an X-BAND Balanced Power Amplifier for Linear Applications

Majid Lorestani¹, Ali Mir²

1- Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan, Iran

Email: m.lorestani@ec.iut.ac.ir

2- Department of Electrical and Computer Engineering, Lorestan University, Khorramabad, Iran

Email: mir.a@lu.ac.ir

Received: July 2014

Revised: September 2014

Accepted: October 2014

ABSTRACT

In this paper, a GaAs pHEMT class A balanced power amplifier with a 3-dB bandwidth of 4.5 GHz at the center frequency of 9 GHz is presented. Our amplifier yields to an input/output-matching better than -15 dB over this frequency band. Also, the realization of impedance matching network using microstrip line and lumped component is carried out. At the end, simulation results for the broadband impedance matching network are presented and analyzed

KEYWORDS: GaAs pHEMT; Power Amplifier; Negative Feedback; Broadband Matching; Balanced Amplifier.

1. INTRODUCTION

High Power amplifiers (HPAs) are used in the final stages of radar and radio transmitters to increase the radiated power level. Typical output powers may be on the order of 100-500 mW for mobile voice or data communications systems, or in the range of 1-100 W for radar or fixed point radio systems. Also, the Broadband Power Amplifiers (BPAs) are used for multi-frequency base-station transmitter applications. Generally, power amplifiers (PAs) are categorized according to different classes (A, B, AB, C, D, E, F)[1-4]. The classes of operation differ in the method of operation, efficiency and linearity. Depending on the linearity and efficiency requirements, the operation classes of amplifiers can be divided into two groups: the first covers linear amplifiers such as PAs in mobile communication applications, and the second belongs to efficient amplifiers such as high PAs in satellite applications.

Our work presents the design of a linear BPA (the first group mentioned above) with a minimum output power of 10W at 1dB power compression point. Since class A amplifier is ideally linear, it is suitable for this work and so, small signal S-parameters analysis is applicable.

Also, as one of the main concerns of the design of a (BPA) is its stability and transistors are potentially unstable within large bandwidths, we use a variation of negative feedback for improving the stability and reducing the variation in the transistor maximum gain.

Another essential problem is the Voltage Standing-Wave ratio (VSWR) due to power match instead of a

conjugate match [5-6]. One of the main approaches for improving VSWR is to use balanced amplifiers for obtaining a BPA with flat gain and good input/output VSWR. This type of circuit is more complex than a single-stage amplifier since it requires two hybrid couplers and two separate amplifier sections, yet it has a number of interesting advantages [5-6]:

- The individual amplifier stages can be optimized for gain flatness or noise figure, without concern for input/output matching.
- Reflections are absorbed in the coupler terminations, improving input/output matching. As well as the stability of individual amplifiers.
- Bandwidth can be an octave or more, primarily limited by the bandwidth of the coupler.
- Balanced amplifier units are easy to cascade with other units, since each unit is isolated by the coupler.

In spite its impact of on the performance of BPA's the VSWR parameter is not appreciated fully [7-9]. In this paper, for improving VSWR, a GaAs pHEMT class A balanced power amplifier with a 3-dB bandwidth of 4.5 GHz at the center frequency of 9 GHz is presented which yields to input/output-matching better than -15 dB over this frequency band(VSWR lower than 1.5). Also, the realization of impedance matching network using microstrip line and lumped component is carried out. At the end, simulation results for broadband impedance matching network are presented and analyzed.

2. DESIGN ISSUES AND CONSIDERATIONS

The first step in designing a BPA is to choose a suitable transistor for this purpose. Our goal in this work is to design a linear BPA with a minimum output power 10 W at 1dB power compression point. The amplifier should cover the frequency range of 7 to 11GHz with a gain greater than 10 dB and satisfy linearity requirements of class A operation. To meet these requirements, a GaAs pHEMT transistor (TGF2021-08) would be suitable, because (Psat>39dBm Nominal), high Power Added Efficiency (59% Maximum PAE), high temperature operation capability, good frequency range (from DC to 12 GHz) and high power gain (11 dB Nominal Power Gain).

3. NEGATIVE FEEDBACK

Next, we check the stability of the transistor. Since instabilities begin at low signal level, small signal S-parameters can be used for this purpose. Stability is especially important for power amplifiers, as high power oscillations can easily damage active devices [5].

Using the small signal S-parameters model from Triquint(S2P file), stability and gain analysis has been performed using the Advanced Design System (ADS) from Agilent. For class A operation, the bias point for this transistor is 12V/600 mA. Fig. 1 shows a snapshot of the circuit diagram used for stability and gain analysis.

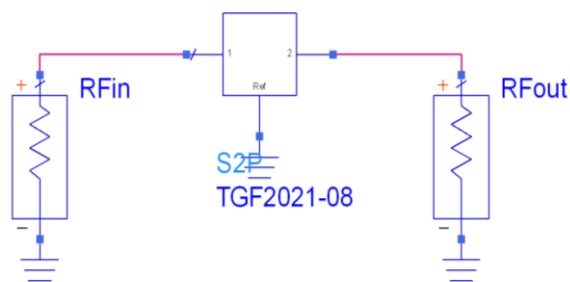


Fig. 1. Circuit diagram used for stability and gain analysis

Fig.3 shows that TGF2021-08 is not unconditionally stable at 7 to 11GHz frequency range and fig.4 shows its maximum gain is greater than 10dB at this frequency range and also reduce 6dB at end this frequency range (at frequency that transistor is not unconditionally stable maximum gain is equal to Maximum Stable Gain (MSG) and for unconditionally stable case is equal to Maximum Available Gain (MAG)).To improve the stability, four choices of resistive loading of transistor are given in [6]. Resistive loading at the input is usually not used since it produces a significant deterioration in the noise performance of

the amplifier. A series resistor at the output is also not so popular since it can dramatically reduce the gain of the amplifier.

Consequently, we use the RLC shunt feedback which improves the stability of the transistor and also reduces variations of the transistor maximum gain. This method, also defined as a lossy match, uses shunt feedback between the gate and the drain of the transistor. A full implementation of the feedback path typically consists of three elements: Resistor (R_fb), Inductor (L_fb) and Capacitor (C_fb). The value of R_fb controls the gain and the bandwidth of the amplifier, and L_fb can be used to extend the bandwidth. C_fb prevents a DC current flowing through the shunt resistor, reduces the total DC power consumption and protects the resistor R against large currents. On the other hand, to ensure a good RF performance of the power amplifier, resistors of surface mount device (SMD) from US Microwaves Company are used, which have very small dimensions and High power dissipation while could operate to GHz frequencies. We also used a thin microstrip line for realization of the L_fb in the feedback path. This is accomplished through a substrate (RO5880) from Rogers Company with a thickness of 0.787 mm and a relative permittivity $\epsilon_r = 2.22$. "Equation (1)" gives the length of the microstrip line to realize an inductor of value L.

$$L = \frac{\lambda_e}{2\pi} \tan^{-1} \left(\frac{\omega L}{Z_0} \right) \quad (1)$$

In "Equation (1)" λ_e is the effective wavelength and Z_0 is the characteristic impedance of the microstrip line. Similarly, a thick microstrip line can be used to realize capacitors.

However, this technique is not very effective for realizing large values of DC-blocking and Bypass capacitors. Therefore, to ensure the good DC-blocking performance of the C_fb in the feedback path, broadband microwave Millimeter-wave (SMT) capacitors from American Technical Ceramics Company should be used, which have very small dimensions, low insertion loss and high self-resonant frequency. Manufacturers usually measure and provide S-parameters of capacitors as a function of frequency in the form of S2P file which import in ADS, by using the this method SMT capacitor has been defined in ADS software. After the negative feedback has been added, stability and gain analysis for TGF2021-08 has been performed using the ADS software.

The TGF2021-08 with the negative feedback as shown in Fig. 2.

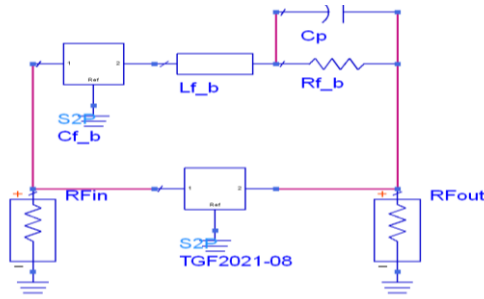


Fig. 2. TGF2021-08 with the negative feedback

In Fig. 2 the capacitor C_p that parallel with the SMD resistor is the parasitic Capacitance of this device. Fig. 3 shows the stability factor (K) of TGF2021-08 with and without the negative feedback versus frequency and also Fig. 4 shows the Maximum Available Gain (MAG) of TGF2021-08 with and without the negative feedback versus frequency.

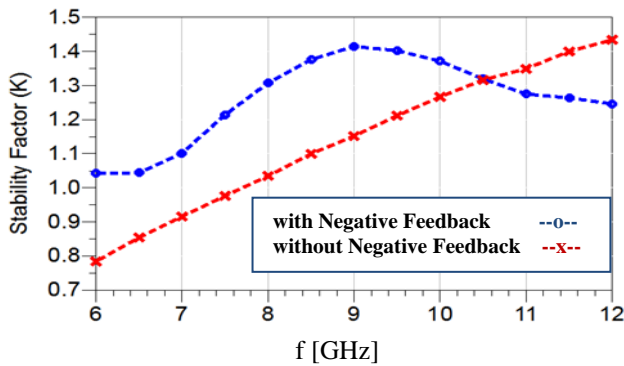


Fig. 3. Stability Factor of the TGF2021-08 with and without the Negative Feedback versus frequency

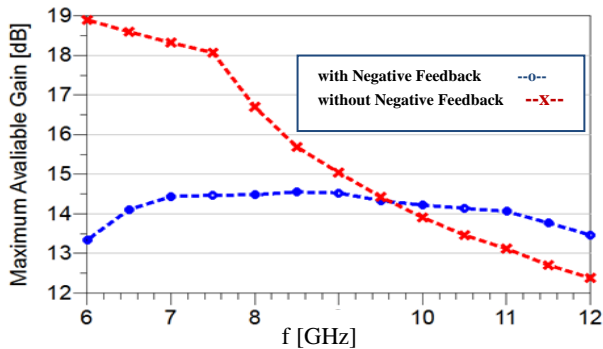


Fig. 4. Maximum Available Gain (MAG) of the TGF2021-08 with and without the Negative Feedback versus frequency

As shown the Fig. 4 the stability factor for TGF2021-08 after inserting the negative feedback is greater than one and $|\Delta|$ is less than one. Therefore, the transistor is

unconditionally stable at 6 to 12GHz frequency range. As shown in Fig. 4, negative feedback structure reduces variations of the MAG and simplifies the design of the input/output impedance matching network.

4. BROADBAND MATCHING

Broadband matching is a procedure to transform the extracted optimum input/output impedance to 50ohm. Since $K > 1$ and $|\Delta| < 1$, the transistor is unconditionally stable and maximum gain occurs in the simultaneous conjugate match. The impedance of power transistor are far from 50ohm, therefore for broadband high power design, we need to keep the Q low for best matching over a broad frequency range, where Q on the smith chart is given in Figure.5.

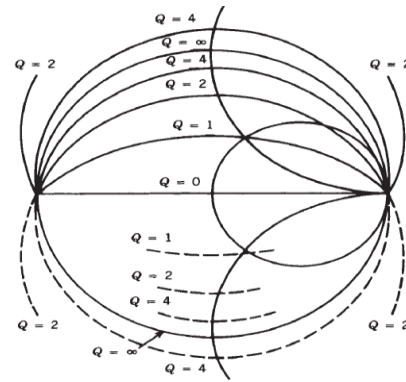


Fig. 5. Smith chart Q plots [10]

We used multiple LC section approach for input/output impedance matching networks. The matching elements are chosen so that the matching network has a low Q . Fig. 2 shows the graphical technique to find the values of inductances and capacitances while avoiding the higher Q regions on the Smith chart.

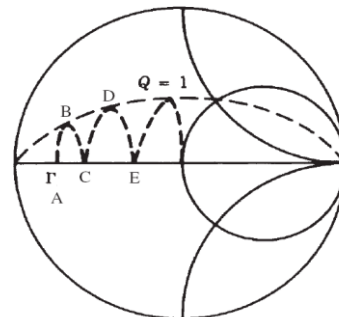


Fig. 6. Broadband matching avoiding high Q region [10]

To design a broadband matching network for a given frequency band from f_1 to f_2 , the value of Q for 3dB bandwidth is given by

$$Q = \frac{\sqrt{f_1 f_2}}{f_2 - f_1} \tag{2}$$

In Fig.6 each hop from the real axis to the constant Q contour and back to the real axis adds a LC section. The number of hops required to reach a Γ of 50Ω point decides the number of LC section required for the impedance matching network. Multiple LC sections matching networks are designed using the graphical method and optimized using Agilent ADS software for 6 to 12GHz frequency band. Fig.7 shows the amplifier with two LC section matching networks and Fig. 8 shows the S-parameters performance of amplifier versus frequency.

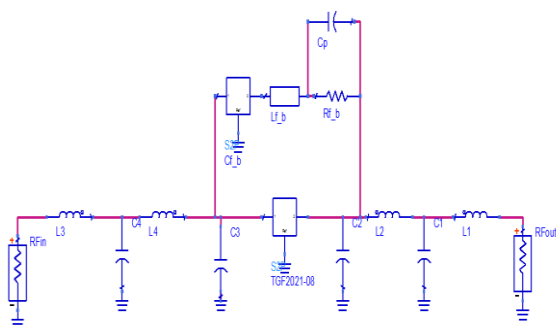


Fig. 7. Amplifier with two LC section impedance matching network

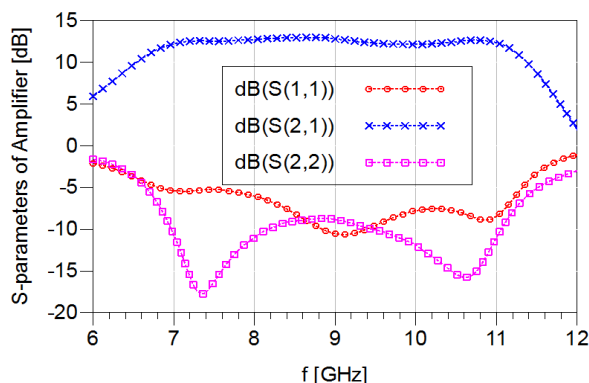


Fig. 8. S-parameters of Amplifier with two LC section impedance matching networks versus frequency

As it is shown in Fig. 8, the gain of amplifier is greater than 10dB from 7 to 11GHz frequency band, but the input/output ports of the amplifier is be poorly matched, this problem has been solved by balanced amplifier structure in the next section.

5. BALANCED AMPLIFIER

A matching network produces the desired match at only one frequency and matching degradation occurs in other frequencies. [11] has derived a complete set of integrals that predict the gain- bandwidth restrictions for lossless matching networks terminated in an arbitrary load impedance. For some example given in [11] the best Γ that can be achieved over a frequency range is restricted by

$$\int_0^\infty \ln \left| \frac{1}{\Gamma} \right| \leq \frac{\pi}{RC} \tag{3}$$

“Equation (3)” implies the fact that the area under the curve $\ln|1/\Gamma|$ is not greater than π/RC . Therefore, if matching is required over a certain bandwidth, it could be obtained at the expense of less power transfer (i.e., the input/output ports of the amplifier will be poorly matched). The use of balanced amplifier is a practical method for implementing a broadband amplifier with a flat gain and good input and output match (i.e., low input/output VSWR). The most popular arrangement of a balanced amplifier, (shown in Fig. 9) uses two 3-dB hybrid coupler.

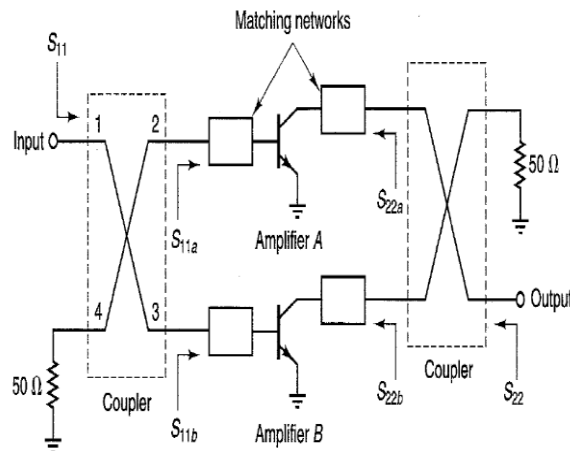


Fig. 9. Balanced amplifier configuration [12]

The magnitude of the S-parameters of a balanced amplifier could be given as follows [12].

$$|S_{11}|=0.5 \cdot |S_{11a}-S_{11b}| \tag{5}$$

$$|S_{21}|=0.5 \cdot |S_{21a}+S_{21b}| \tag{6}$$

$$|S_{12}|=0.5 \cdot |S_{12a}+S_{21b}| \tag{7}$$

$$|S_{22}|=0.5 \cdot |S_{22a}-S_{22b}| \tag{8}$$

If the two amplifiers are identical, then $S_{11}=0$ and S_{22} and gain S_{21} (also S_{12}) are equal to the gain of one side

of the coupler. The bandwidth of the balanced amplifier is limited by the bandwidth of the coupler. The disadvantage of structure is that the unit uses two amplifiers, thus consumes more dc power with a bigger size. Also, in practice there is a finite insertion loss associated with the amplifiers [13-15].

As it is mentioned the bandwidth of the balanced amplifier is limited by the bandwidth of the coupler, therefore we used the wideband 3dB branch-line coupler given in [16]. We modified the coupler at the center frequency of 9 GHz by the RO5880 substrate (with a thickness of 0.787 mm and a relative permittivity $\epsilon_r = 2.22$). We also, used the coupler in input/output port of final structure. Then for realizing the inductors of the impedance matching networks based on "(1)" and capacitors, we employed the thin microstrip line and 45° open circuit microstrip line respectively. Fig. 10 shows the S-parameters performance of balanced amplifier.

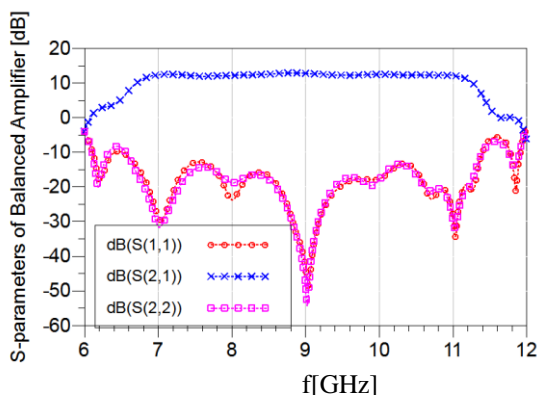


Fig. 10. S-parameters of the balanced amplifier versus frequency

As shown in Fig. 10 the gain of the balanced amplifier is greater than 10dB from 7 to 11GHz frequency range and input and output-matching better than -15dB have been achieved over this frequency band.

6. CONCLUSION

This work presented a broadband microwave power amplifier covering the frequency range from 7GHz to 11GHz using GaAs pHEMT Transistors. Small signal performance analysis has been applied and discussed over the whole frequency band. A small signal gain of 11 ± 1 dB and input/output return losses of less than -15dB were achieved within the specified bandwidth.

REFERENCES

- [1] E.S., Mengistu, "Large-Signal Modeling of GaN Device for Linear Power Amplifier Design", *Doctoral Thesis, University of Kassel, Kassel, Germany*, 2008.
- [2] M., Yanagihara, Y., Uemoto, T., Ueda, T., Tanaka, and D., Ueda, "Recent Advances in GaN

Transistors for Future Emerging Applications." *Phys. Status. Solidi*, Vol. 206, No. 6, pp.1221-1227, 2009.

- [3] A. Z., Markos, "Efficiency Enhancement of Linear GaN RF Power Amplifiers Using the Doherty Technique", *Doctoral Thesis, University of Kassel, Kassel, Germany*, 2008.
- [4] A., Jarndal, "Large-Signal Modeling of GaN Device for High Power Amplifier Design", *Doctoral Thesis, University of Kassel, Kassel, Germany*, 2006.
- [5] D.M., Pozar, "Microwave Engineering", Wiley., Fourth edition, pp. 570-573, 2011.
- [6] G., Gonzalez, "Microwave transistor amplifiers," *Second edition, Prentice Hall Inc.*, New Jersey, pp. 323-340, 1997.
- [7] R., Kopru, H., Kuntman and B.S., Yarman, "A Novel Method to Design Wideband Power Amplifier for Wireless Communication," *IEEE International Symposium on Circuits and Systems (ISCAS)*, pp. 1942 - 1945, Beijing, May 2013.
- [8] R., Kopru, H., Kuntman, B.S., Yarman, "2W wideband microwave PA design for 824-2170 MHz band using Normalized Gain Function method," *8th International Conference on Electrical and Electronics Engineering (ELECO)*, pp.344-348, Bursa, Nov 2013.
- [9] A., Zokaei, M.A., Boroujeni, F., Razaghian and J., Alvankarian, "A 3-5 GHz Ultra Wideband Common-Gate Low Noise Amplifier," *IEEE International Conference on Circuits and Systems (ICCAS)*, pp. 98 - 102, Kuala Lumpur, Oct 2012.
- [10] G.D., Vendelin, A.M., Pavo and U.L., Rohde, "Microwave Circuit Design Using Linear and nonlinear Techniques," Wiley, pp. 247248, 2005.
- [11] R.M., Fano, "Theoretical Limitations on the Broadband Matching of Arbitrary impedances," *Journal of the Franklin Institute.*, vol.249(1,2), pp. 57-83 and 139-154, Jan 1950.
- [12] G., Gonzalez, "Microwave transistor amplifiers," *Second edition, Prentice Hall Inc.*, New Jersey, pp. 327-331, 1997.
- [13] F., Golcuk, O.D., Gurbuz and G.M., Rebeiz, "A 0.39–0.44 THz 2x4 Amplifier-Quadrupler Array With Peak EIRP of 3–4 dBm," *IEEE Trans. Microw. Theory Tech.*, Vol.61, No.12, pp. 4483 - 4491, 2013.
- [14] H.L., Lee, D.H., Park, M.Q. Lee and J.W., Yu, "Reconfigurable 2, x, 2 Multi-Port Amplifier Using Switching Mode Hybrid Matrices," *IEEE Microwave and Wireless Components Letters.*, Vol. 24, No. 2, pp. 129 - 131, 2014.
- [15] U., Schmid, H., Sledzik, P., Schuh, J., Schroth, M., Oppermann, P., M. Bruckner, F.V., Raay, R., Quay and M.S., Eggebert, "Ultra-Wideband GaN MMIC Chip Set and High Power Amplifier Module for Multi-Function Defense AESA Applications," *IEEE Trans. Microw. Theory Tech.*, Vol. 61, No. 8, pp. 3043 - 3051, 2013.
- [16] W., A. Arriola, J. Y., Lee, and I. S., Kim, "Wideband 3 dB branch line coupler based on $\lambda/4$ open circuited coupled lines," *IEEE Microw. Wireless Compon. Lett.*, Vol. 21, No.9, pp. 486-488, Sept 2011.