

## 1.25 GHz – 3.3 GHz broadband solid-state power amplifier for L and S bands applications

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### Article Info

#### Article history:

Received Dec 25, 2018

Revised Apr 9, 2019

Accepted Apr 20, 2019

#### Keywords:

Broadband power amplifier

GaAs

Impedance matching

L and S bands

Solid state

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### ABSTRACT

The research of a single stage broadband solid-state power amplifier based on ATF13876 transistor, which operates in the frequency ranging from 1.25 GHz ~3.3 GHz is presented in this paper. To achieve the broadband performance of the operating bandwidth, a multi-section quarter wave impedance transformer and an approximate transformation of previously synthesized lumped elements into transmission lines are adopted. With neatly design of broadband matching networks and biasing circuit, excellent matching performances and unconditionally stability are achieved over the whole operating bandwidth with a maximum gain of 17.2 dB. The large signal simulation shows that the proposed circuit reaches a saturated output power of 18.12 dBm with a maximum PAE of 27.55% and a 1-dB compression point at 5 dBm input power level. Considering the wide frequency coverage, the features of the proposed design compares favorably with the contemporary state-of-the-art.

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## 1. INTRODUCTION

In today's communication age, almost every communication device-be it a radio of Global System Mobile (GSM), Universal Mobile Telecommunications System (UMTS), Long Term Evolution (LTE), or a device of Worldwide Interoperability for Microwave Access (WiMAX), Wi-Fi or Bluetooth-has some sort of transceiver, and inherently a power amplifier operating in one of the following bands (defined by IEEE Standard 521-1984): L-S-C-X or Ku Bands. [1-5].

Therefore, in Radio Frequency (RF) and microwave electronics circuits, the power amplification is one of the most critical and essential circuit functions [6-8], playing a key role in the realization of many RF and microwave systems, among which, avionics, induction heating, magnetic resonance imaging (MRI), medical microwave imaging and radar applications represent just a few examples [9-11].

Given such enormously diversified fields, RF Power Amplifier (PA) specifications may significantly differ in operating, design and technological requirements. As a result, a broad assortment of PA realizations results from microwave heating tubes to amplifiers composing hyperthermia systems, and from travelling wave tubes amplifiers in satellite payloads to solid-state amplifiers for personal wireless communication handsets [12-16].

Regardless of its physical configuration, all RF PAs have in common the defining characteristic of increasing the power level of the signal at its input up to a predefined level at its output, in a given frequency

band. On other hand, the PA design requires an accurate active device-mostly a Radio Frequency Transistor -, stability in operation, impedance matching technique that depends on the operating frequency band, and a simple configuration for practical realization purpose. The active device bias conditions-that are commonly different for efficiency or linearity improvement – depend on the active device technology and the operating class of the PA [17-18].

Consequently, the PA design is a result of a trade-off, trying to accomplish several conflicting requirements such as: broad bandwidth vs gain, high output power vs low distortion, or linearity vs efficiency. Likewise, the design approach depends on the available technology of the active device, the operating frequency band, application requirements (modulated CW or pulsed signal; mobile, fixed or satellite communications, etc.) and many other factors.

However, for many microwave applications that running in L and S bands such as SRAN (Single Radio Access Network) for wireless communication, would it not be better if we had one PA that can cover at the same time 2G, 3G and 4G bandwidths? Such device is the Broadband Power Amplifier (BPA) which can significantly reduce the hardware research & develop costs due to the compatibility for the old and new wireless standards [19].

Indeed, the need for broad bandwidth besides of the increasing demand for higher data rates are the main driver in the BPA design. As a result, the BPA implementation and architecture has expanded to correlate through the ever changing application requirements, latterly with the extensive adoption of Doherty configuration in order to improve the back-off efficiency in linear applications, mainly in the base stations [20], but this configuration shows some limitation in term of performance when the bandwidth requires more than octave. Up to present, many design and realization of BPAs have been implemented using various circuit topologies such as balanced configurations or distributed structures with several matching techniques including shunt or series resistive feedback, reactive/resistive matching and reactive filter synthesis [21].

The BPAs that purely reactively matched uses lumped inductors and capacitors or transmission lines within its reactive matching circuits at the input and output of the active device. This technique shows good noise figure and power performance, whereas it gives a moderate bandwidth. The reactive/resistive matching circuits present weak points in requiring more matching elements to implement broadband bandwidth and shows poor VSWR and gain flatness.

This work introduces a novel and simple BPA configuration which cover the mainstream standards running in L and S bands from 1.25 GHz to 3.3 GHz. In order to achieve the broadband performances of the proposed BPA, we adopt two broadband matching techniques which are a multi-section quarter wave impedance transformer and an approximate transformation of previously designed lumped elements into transmission lines. The proposed BPA is based on ATF13876 which is a GaAs transistor, and implemented on FR4 substrate.

This paper is organized as follows. In section 2, the proposed BPA circuit design is presented including the deployed broadband matching techniques and the synthesized biasing circuit. The simulation results are presented in section 3, and finally, the concluding remarks are summarized in section 4.

## 2. THE PROPOSED BROADBAND POWER AMPLIFIER CIRCUIT DESIGN

Regardless of its classification as broadband, narrowband, high efficiency, low noise, high power or otherwise, the task of a RF power amplifier is to increase the power level of the signal at its input up to a predefined level at its output in a given frequency band, in other words, providing a finite positive power gain at the operating bandwidth. However, the BPA design is basically the result of a trade-off, trying to satisfy a broad and often conflicting requirements including but not limited to broad bandwidth vs power gain, high output power vs low distortion or linearity vs efficiency.

Referring to Figure 1, the simplest single stage microwave power amplifier consists of a single active device, connected through an input and output matching circuits to a source and load respectively, having the system characteristic impedance  $Z_0$ , and DC supplied through a DC bias circuit. After accurate active device is chosen, the subsequent step resides in the adoption of the preliminary PA architecture required to accomplish the design specifications.

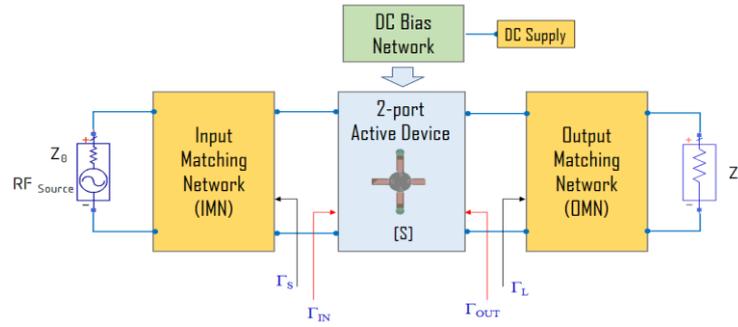


Figure 1. Single-stage microwave power amplifier block diagram

**2.1. Biasing circuit design**

At high frequency, the active device performance depends significantly on the DC biasing conditions, as a consequence, the biasing circuits design is an important part of power amplifier design, and must be synthesized neatly to avoid low frequency oscillations due to low substrate resistivity, high capacitance and high device gain, as well as to contribute a great deal to the performance and the stability of the whole power amplifier circuit.

There are several schemes available to provide a proper DC biasing condition for a power amplifier. In this work, the biasing circuitry is realized by using an RF choke terminated by a radial line section as shown in Figure 2. The active device of the proposed BPA is supplied with a single supply voltage VCC of +4V. The RF choke role is to prevent the microwave signal from leaking into the bias port. This biasing scheme is smaller in size and provides better bandwidth that  $\lambda/4$  open circuited stub. In addition, it becomes an integrated part of the power amplifier circuitry.

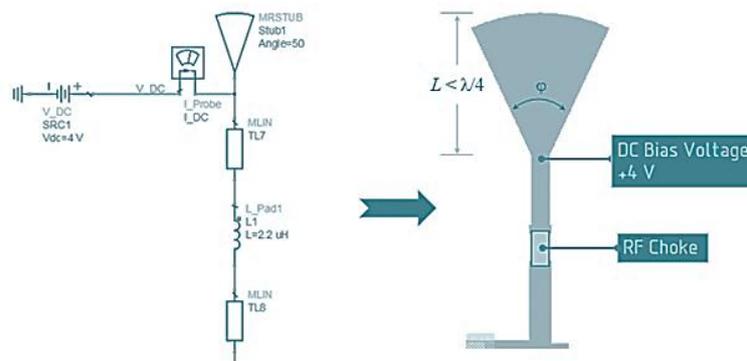


Figure 2. Biasing circuit for the proposed BPA

**2.2. Broadband matching circuits design**

Owing to the broadband design approach, the broadband impedance matching circuits are usually difficult and tedious to design. Thus, it takes a major part in the design process of the overall BPA circuitry. In general, the active device is mismatched with the load and source impedances, and this led to the loss of RF energy, because the RF power available from the source is not properly delivered to the load.

To resolve this mismatch, an accurate matching circuit should be designed at the interface between two sections having mismatched impedances, if not, a portion of the electrical signal propagated inside the PA circuit will be reflected. In a broad sense, to provide a maximum power transfer of the RF power from the input port to RF transistor, from the RF transistor to the output port, or between devices, a matching circuit that transforms a given mismatched impedance into a desired impedance must be synthesized.

There are several matching techniques that can be used to accurately design matching networks (MNs), a crucial requirement for successful BPAs design, but the selection of the appropriate technique might not always be clear. However, in the design process of MNs, the following parameters must be considered: frequency bandwidth, circuitry complexity and ease of implementation.

In this work, we combine a variety of matching techniques in order to reach the broadband performance of the proposed matching circuits. The first technique used is the Binomial Transformer, which is a multi-section quarter wave transformer that transforms the load impedance  $Z_L$  to the characteristic impedance of the feed line  $Z_0$ , by using discrete sections of transmission lines having dissimilar characteristic impedances, but the same electrical length,  $\beta l = \theta$ . Commonly, the electrical length will be  $\lambda/4$  at the band center frequency  $f_0$ . The schematic of a multi-section quarter wave transformer is shown in Figure 3. While Figure 4 shows Four-Section binomial transformer.

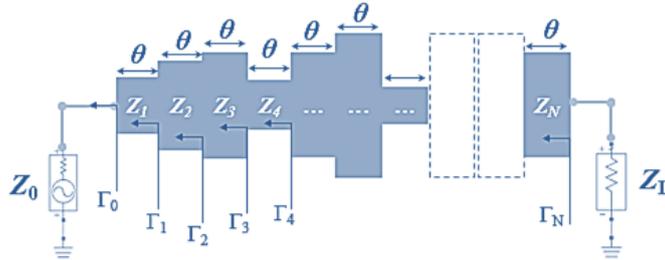


Figure 3. Multi-section quarter-wave transformer. N = Number of sections

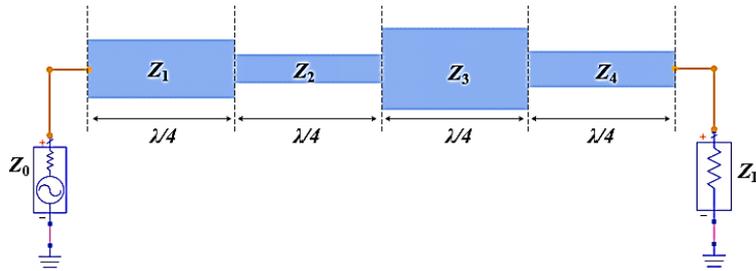


Figure 4. Four-Section binomial transformer

A schematic diagram of a four-section binomial transformer is illustrated in Figure 4. The impedances of the sections can be approximately calculated as:

$$\ln \frac{Z_{n+1}}{Z_n} = 2\rho_n = 2^{-N} C_n^N \ln \frac{Z_L}{Z_0} \quad \text{Where: } C_n^N = \frac{N!}{(N-n)!n!} \quad (1)$$

$C_n^N$  are the binomial coefficients.  $Z_n$  and  $Z_{n+1}$  are the impedances of the  $n$ th and  $(n+1)$  th sections respectively, and  $\rho_n$  is the reflection coefficient at the junction between  $Z_n$  and  $Z_{n+1}$ .

Excepting an MMIC, it is generally difficult to implement a matching circuit based on lumped element on a PCB. Thus, the second technique used in this work is an approximate transformation of the previously synthesized lumped elements into transmission lines, which are easy to implement on a PCB substrate. Figure 5 shows an approximate transformation of lumped elements into transmission lines.

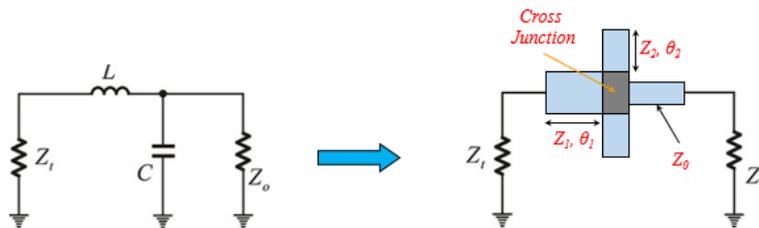


Figure 5. Conversion of lumped elements MN into transmission lines MN

The series inductor  $L$  can be considered as a transmission line having characteristic impedance  $Z_1$  and length  $\theta_1$ , while the shunt capacitor  $C$  can be considered as two parallel connected open transmission line stubs with characteristic impedance  $Z_2$  and  $\theta_2$ . The approximated values of  $Z_1$ ,  $\theta_1$ ,  $Z_2$  and  $\theta_2$  can be calculated as:

$$X_1 = Z_1 \tan(\theta_1) \approx \omega L \tag{2}$$

$$X_2 = \frac{Z_2}{2 \tan(\theta_2)} \approx \omega C \tag{3}$$

Since the variables are  $Z_1$  and  $\theta_1$  in (2), it is worth noting that there are two degrees of freedom in implementing the value of an inductor. In addition, those two degrees of freedom are also true for (3). By using the concepts mentioned above, the proposed BPA schematic is presented in Figure 6.

### 3. RESULTS AND ANALYSIS

#### 3.1. Stability considerations

At microwave frequencies, every power amplifier with power gain can be ready to oscillate by applying an external positive feedback. These oscillations are due to the unavoidable parasitic effects that are usually sufficient to provide oscillations if care is not taken in the design of the power amplifiers. However, design techniques can be deployed to build in confidence of stability. For BPAs, the unconditional stability is more required out of band where there are no system specifications of component impedances.

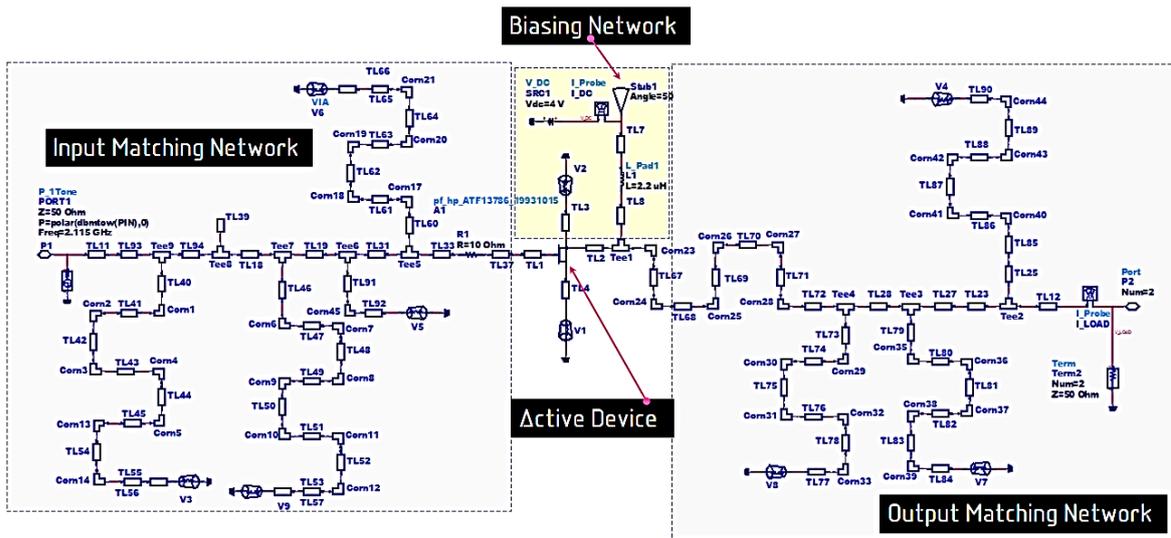


Figure 6. The proposed BPA schematic

The unconditional stability is achieved when the following (4) is validated [22]:

$$k = \frac{1 + |\Delta|^2 - |S_{11}|^2 - |S_{22}|^2}{2|S_{12}S_{21}|} > 1 \tag{4}$$

where  $k$  is the Rollet Stability Factor.

From a practical standpoint, when  $k > 1$  and  $S_{22} < 1$ , the PA circuit is unconditionally stable. Nevertheless, Rollet Stability factor by itself is not sufficient to ensure stability, and an additional parameter must be fulfilled. One such parameter is the Bodway stability factor  $B_1$  or stability measure which must be greater than zero. Bodway stability factor is given by the following (5) and (6):

$$B_1 = 1 + |S_{11}|^2 + |S_{22}|^2 - |\Delta|^2 > 0 \tag{5}$$

$$\Delta = S_{11}S_{22} - S_{12}S_{21} \tag{6}$$

As we can see in Figure 7, the unconditional stability for the proposed BPA is established over the operating frequency.

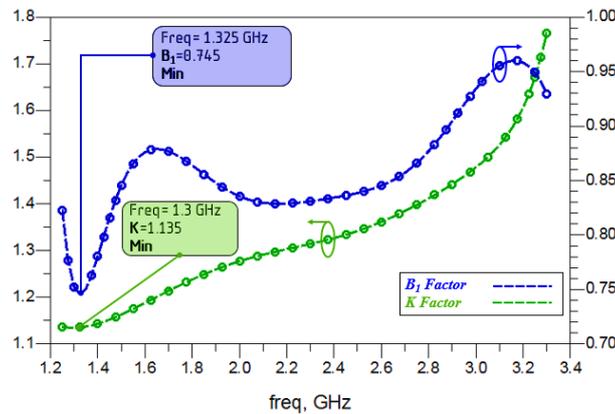


Figure 7. Curves of rollet and bodway factors versus frequency

**3.2. Small-signal analysis**

At high frequency, it's so difficult to measure directly the voltage and currents. However, with a resistive termination, the scattering parameters (S-parameters) defined from incident and reflected waves can be measured. Basically, S-parameters are linear complex coefficients that describe the behavior of a two-port network in terms of input and output reflected waves as well as input and output incident waves at the network ports, when it is terminated on its characteristic impedance  $Z_0$ . The source and load impedances used in this work is  $50 \Omega$ .

The simulated small signal S-parameters are shown in Figures 8 and 9. That it can be see, this Broadband PA has an input return loss  $S_{11}$  varies between a maximum value of -10 dB and a minimum value of -17 dB, while the output return loss  $S_{22}$  changes between -10 dB and -28 dB. It also reaches an excellent reverse isolation of less than -18 dB over the operating frequency ranging from 1.25 GHz to 3.3 GHz. We note that, the  $S_{12}$  parameter represents the internal feedback from the output to the input of a two-port circuit. From a practical standpoint, the smaller value of  $S_{12}$  the greater is the degree of stability and isolation between the output and output of a given stage. From Figure 9, the power gain  $S_{21}$  changes between a maximum value of 17.2 dB and 8.16 dB over the operating frequencies.

The small signal S-parameters simulation shows satisfying achievement in terms of matching impedances, reverse isolation and power gain over a wide bandwidth from 1.5 GHz to 3.3 GHz. Thus, for the whole circuit, we can clearly assume that the broadband impedances matching is fulfilled, the unconditional stability is achieved with good power gain performance over the entire bandwidth.

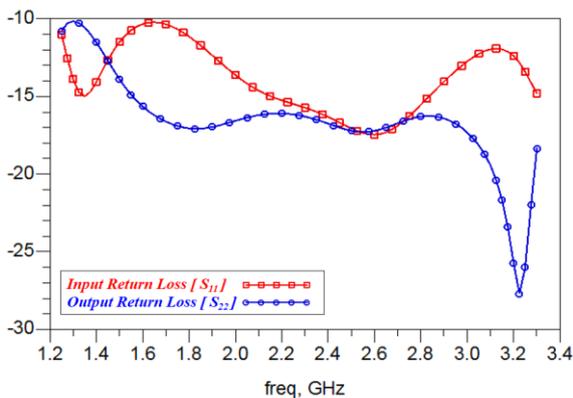


Figure 8. Curves of input and output return loss versus frequency

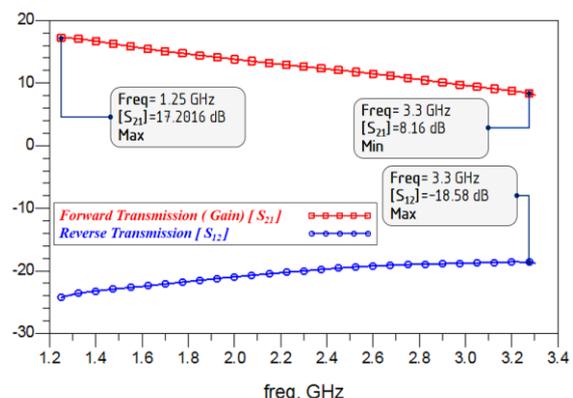


Figure 9. Curves of gain and reverse transmission coefficient versus frequency

**3.3. Large-signal performances**

The large-signal performances of the proposed Broadband PA have been simulated at 2.115 GHz with 50Ω input and output loads. The output power P<sub>out</sub> given by the (7) is defined as the power delivered to the external load at a specified frequency f, or in a frequency band B = [f<sub>Low</sub>, f<sub>High</sub>].

$$P_{out} = P_{out}(f) = \frac{1}{2} \text{Re}\{V_{out} \cdot I_{out}^*\} \quad f \in [f_{Low}, f_{High}] \quad (7)$$

However, while the input power is increased, we ultimately achieve a point where the output power can no longer keep increasing linearly with the input power. This point is called the 1dB compression point, in which, the output power of a PA deviates from the linear region by -1dB. The 1dB compression point is usually used to define the range of input power levels for which the output power is linearly proportional to the input power. In other words, it is used to define the dynamic range of PAs.

The simulated output power and the 1dB compression point are depicted in Figure 10. The proposed BPA reaches a saturated output power of 18.12 dBm, thus leading to 64.86 mW, with an output 1dB compression point of 5 dBm of input level.

From energetic standpoint, a power amplifier may be regarded as a device qualified to convert the DC power from supplies into RF power at a specified frequency or range of frequencies. The effectiveness of this conversion process is commonly evaluated by means of Power Added Efficiency (PAE), which is the ratio between the added power and the supplied DC power:

$$\eta_{add} = \frac{P_{add}}{P_{DC}} = \frac{P_{out} - P_{in}}{P_{DC}} \quad (8)$$

Where:  $P_{DC} = V_{bias} \frac{1}{T} \int I_{bias}(t) dt$  (9)

Figure 11 shows the simulated Power Added Efficiency of the proposed BPA. At 2.115 GHz, this BPA reaches a maximum PAE of 27.55%.

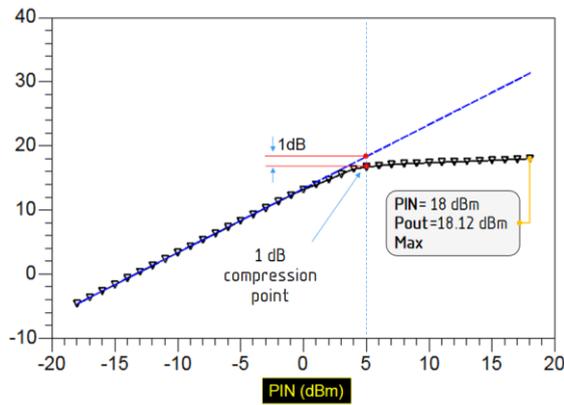


Figure 10. Output power versus input power with the 1dB compression point

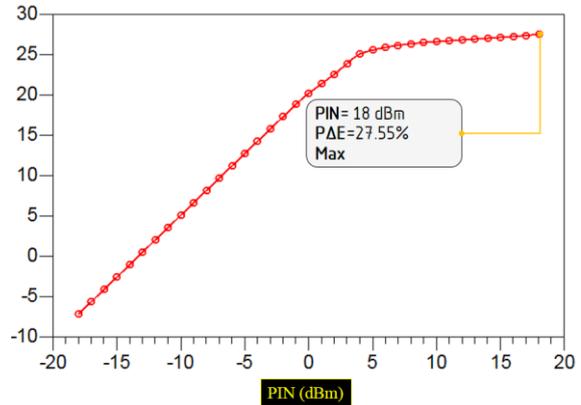


Figure 11. PAE versus input power

In Table 1, the proposed Broadband Power Amplifier and the state-of-the-art BPAs are compared. To author’s best knowledge, we can clearly remark that the matching techniques deployed in this work are very sufficient and allows to reach a wide bandwidth. By comparing the simulated results of the proposed BPA with the similar contemporary state-of-the-art BPAs, the proposed topology exhibits good output power with good PAE, excellent bandwidth, high gain and excellent impedance matching as well as simple circuitry.

Table 1. Performance comparison between the proposed BPA and state – of –the art BPAs

PAs	Freq [GHz]	Gain [dB]	Psat [dBm]	PAE[%]	S11[dB]	S22[dB]	Supply[V]
[23] 2015	1.9 – 2.7	11	28.1	13.7	-	-	2.5
[24] 2016	1.8 – 2.8	28	25	6.1	-12   -25	-9   -19	5
[6] 2017	1 – 4	12.15	14.8	20	-9   -24	-8   -18	3.5
[25] 2018	1.75 - 2.15	-	8	11.7	-11   -22	-13   -19	12
[7] 2018	1.1 - 3	14.9	17.14	14.9	-10   -35	-10   -25	3
This Work	1.25 - 3.3	17.2	18.12	27.55	-10   -17	-10   -28	4

#### 4. CONCLUSION

In this paper, we introduce a broadband power amplifier operating in the frequency ranges from 1.25 GHz to 3.3 GHz and covering the mainstream applications running in L and S bands. With carefully synthesized impedance matching and biasing networks, excellent input and output matching are established with unconditionally stability over the whole operating bandwidth. The design effectiveness was verified using the simulation results. At 2.115 GHz, the large signal simulation shows that the proposed BPA achieves a maximum output power of 18.12 dBm, that leading of 64.86 mW, with a maximum PAE of 27.55% and output 1-dB compressed point of 5 dBm input power level.

A power Amplifier with those features is more suitable for many RF applications operating in L and S bands among which: medical applications (imaging, hyperthermia, radiometry, ...), cellular communication standards, digital television broadcasting, electronic warfare, avionics and navigation applications represent just a few examples.

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