A New Microwave One – Port Transistor Amplifier with High Performance for L- Band Operation

A. P. VENGUER, J. L. MEDINA, R. CHÁVEZ, A. VELÁZQUEZ

Departamento de Electrónica y Telecomunicaciones
Centro de Investigación Científica y de Educación Superior de Ensenada
Km. 107 Carretera Tijuana-Ensenada, 22860 Ensenada B. C.
MÉXICO
Phone. 01152 (646)175-0555, FAX: 01152 (646)175-0554,

Abstract: - Results of the research of a new microwave transistor amplifier with high performance at L – Band is presented. This component has been constructed using a new amplification principle based on a one–port reflecting amplifier theory. Experimental results shows that such class of amplifiers using only one transistor provides a very low power consumption, a higher transmission gain and a smaller noise figure in comparison with a conventional single-stage amplifier, making it suitable for amplification at millimetric wave frequencies. Measurements of the amplifier have shown at L-band a 20 dB gain for >2% f_0, a noise figure less than 0.5 dB at ambient temperature (290 K) and a very low power consumption at Dc less than 0.5 mW.

Key words: microwave transistor amplifier; one-port transistor amplifier; reflection amplifier; low noise figure, high efficiency

1 Introduction

Amplification of frequencies in the millimeter wave range, using small signal microwave transistor amplifiers, it is very difficult since at frequencies higher than 30 GHz the transmission gain of a transistor is very low. To obtain a high gain, a high number of amplification stages are required and, as a consequence its own noise is increased.

Literature results have shown that the transmission gain of one-stage amplifier is between 6 and 8 dB in the 50 GHz frequency range [1], [2], and [3]. Since that gain is very small, it is not enough to minimize the noise contribution of the subsequent stages. For reception at frequencies near 100 GHz, a 20 dB gain amplifier requires to use 4 to 6 stages [4], [5], making it very expensive, since cost of transistors sharply grows at higher frequencies, and provides a higher noise figure than a single stage counterpart. To reduce these problems, we have investigated and developed a high performance one-port transistor amplifier (OPTA) working in reflection mode.

Reflection amplifiers for X band operation have been developed at the ends of the 70's by utilizing a circulator and a Gunn diode oscillator, providing 10 dB gain with a noise figure of 15 dB. Another reflection amplifier for the frequency region above 20 GHz, has been developed in 1978, using a field effect transistor and a package resonance as a positive feedback [6]. Experimental results for this amplifier at 23 GHz, have shown a noise figure = 6 dB with a gain = 8 dB.

The proposed amplifier consists of a circulator connected to a one-port circuit that uses a gate connected HJ FET biased in a nonlinear region of the I-V curves to operate in the negative resistance mode. This new type of reflection amplifiers have very good performance, showing a low noise, a very high gain and low power consumption as it is demonstrated by theoretical and experimental results. A low noise OPTA has been developed in the 1.4 - 1.6 GHz frequency band to study the capabilities of this kind of amplifiers resulting in a lower cost and simplified research. Results indicate that research of the proposed OPTA can be extended at higher frequencies making it very interesting for applications at millimeter wave frequencies.

2 Problem Formulation

In general a two-port transistor amplifier working on a specific frequency band is required to amplify an information carrier in form of electromagnetic oscillations, going from a low power level into a higher level. Characteristics of such amplifiers have been very well investigated and basically depend on the scattering and noise parameters of a given transistor. An alternative is to use a transistor amplifier circuit working in reflection mode as shown in Figure 1.

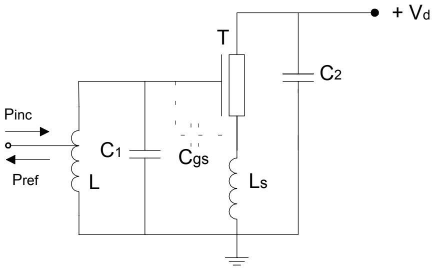

Fig. 1 Basic circuit of the one-port transistor amplifier.

In this configuration a field effect transistor (T) is used as the active element to transform dc current to RF oscillations. A resonant circuit composed by an inductance L_s connected to the transistor source terminal, an internal gate-source capacitance C_{gs}, as well as an additional distributed capacitance C_1 due to the transmission line and matching circuit is used as shown in Figure 1. Ls as is well known [7], [8] is the source impedance acting as a lossless transformer at the transistor input. At low microwave frequencies it is not really true, so this resonant circuit is tuned to the input frequency and the drain terminal of the transistor is grounded through a capacitance C_2. Amplification process for this circuit occurs as follows: An input signal (V_g) is applied to the transistor gate terminal. The signal voltage modulates the conductance of the transistor channel that in turn modulates a constant current through the channel, causing oscillations in the resonant circuit formed by inductance (L_s) and capacitances C_{gs} and C_1. The inductance L_s is the basic element of the resonant circuit providing a strong feedback in contrast to the gate-channel capacitance C_{gs}. The self-induction voltage generated on the source inductance always has an opposite phase related to the input voltage V_g and also depends on the transistor channel transconductance Y_m as follows.

$$V_{Ls} = - \frac{d(VgYm)}{dt} L_s \qquad (1)$$

When L_s is connected to the nonlinear element (gate-channel area of the field effect transistor that has all properties of a Schottky barrier diode), causes an additional increase of the conductance modulation depth. The input signal is transformed into a higher power level through the circulator port. The power gain (G) for such kind of amplifiers as well as for another circuit working on reflection mode, can be defined in function of the input power reflection coefficient ($|\Gamma|^2$) shown in Figure 1 or in function of the incident (P_{inc}) and reflected (P_{ref}) powers:

$$G = |\Gamma|^2 = P_{ref} / P_{inc} \qquad (2)$$

As can be seen in (2), when $P_{ref} > P_{inc}$ we have amplification. More details regarding the definition of gain can be find in [9] and [10]. The main condition for a stable operation of this amplifier is that the phase difference between incident and reflected signals must be equal to 180°, measured at the same reference plane (different from the oscillation condition [11]).

Noise properties for this kind of amplifier was distinguished at [12]. To estimate the noise figure we have proposed the next expression, under the assumption that the main noise sources have a thermal behavior (where influence of another types of noise such as shot noise, flicker effect, i.e. are not included).

$$\mathrm{NF} \cong 1+\frac{Tn}{To}\left(1-\frac{1}{G}\right)-\frac{Tn}{To}\left|\Gamma\right|_{A}^{2}\ (\mathrm{G}-1)+\frac{Tc}{To} \qquad (3)$$

Where T_o is the ambient temperature, T_n is the thermal noise of the active losses, T_c is the noise temperature due to the circulator losses at the input, Γ_A is the input reflection coefficient and G is the gain.

Due to the region where the transistor is biased (low V_{ds} and I_{ds}), a very low consumption is expected, resulting on a very good amplifier efficiency.

3 Experimental Results

Using the theory given in section 2 and the MMICAD computer software, a one-port reflection amplifier has been designed for the 1.4 – 1.6 GHz frequency band as it is shown in Figure 2. The active element chosen is a GaAs Hetero Junction FET with a gate length L_g=0.3µm and a gate width w_g= 280µm. This device has a minimum noise figure = 0.3dB and an associated gain = 19 dB at 1.5 GHz when it is biased at Vds=2V and Ids=10mA (P=20mW).

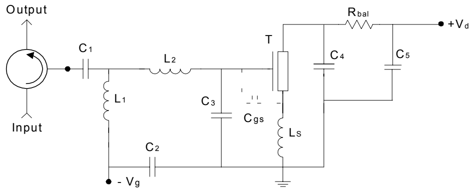

Fig. 2 Schematic of the one-port transistor amplifier.

To calculate the input matching elements of the OPTA circuit we have taken into account the procedure of [8]. The value of the transistor source inductance was calculated to resonate at 1.5 GHz and the matching network has been designed to minimize the noise figure. A picture of the OPTA circuit is shown at figure 3. To separate the incident and reflected signals, a circulator for operation in the 1.47 to 1.55 GHz frequency band has been used. This circulator has insertion losses between -0.17 and -0.25 dB and isolation values better than –20 dB into the operation bandwidth.

Fig. 3 One Port Transistor Amplifier (OPTA)

S-Parameters and gain measurements were performed with a HP8510C network analyzer shown in figure 4 and noise figure was measured using a noise figure meter HP8970A in the 1.4 to 1.6 GHz frequency band.

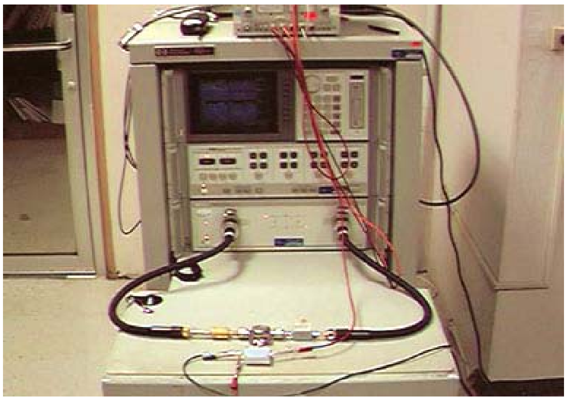

Fig. 4 Network analyzer HP8510C for OPTA S-parameter measurements.

The measurement results for the OPTA can be observed in Figure 5 showing the gain characteristic at specific frequency for V_g = - 0.5 v, I_d = 3 mA bias conditions.

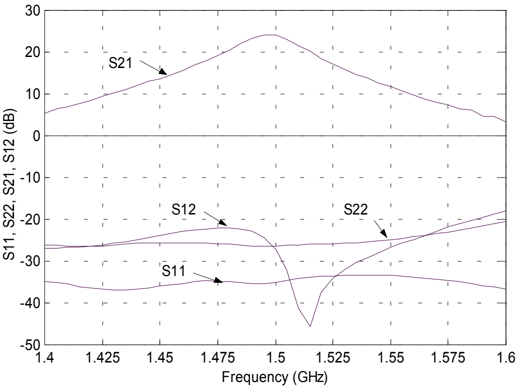

Fig. 5 Measurement results of the OPTA, showing gain characteristics.

It is interesting to note that gain for an OPTA circuit is higher than the gain of a conventional LNA. The maximum value of a stable gain is affected by the value of the circulator isolation.

It is worthy to mention that in order to find the optimum bias conditions to operate the OPTA, we have adjusted the drain current I_d for minimum noise figure and allowed to vary the gate voltage V_g to selected values from –0.33V to –0.7V [12].

Figure 6 shows the gain and noise figure behavior versus frequency for a fixed V_g=-0.5V and different drain currents.

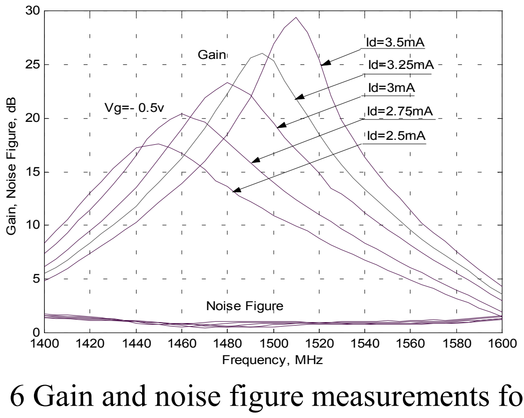

Fig. 6 Gain and noise figure measurements for fixed gate voltage and different drain current

As can be appreciated in figure 6, a very low noise has been obtained for the amplifier due to a partial compensation of its own noise. Once we have selected the optimum gate voltage V_g, the drain current I_d is allowed to vary.

At Figure 7 we can see in detail the noise figure measurements versus frequency for a fixed V_g=-0.5V and different drain currents. As can be seen from this figure, an optimum noise is obtained for I_d=3mA, +V=0.25V and V_g=-0.5V. For these bias conditions a very low power consumption of .75mW is calculated, showing that in this amplifier the transistor work colder than a conventional low noise two-port amplifier.

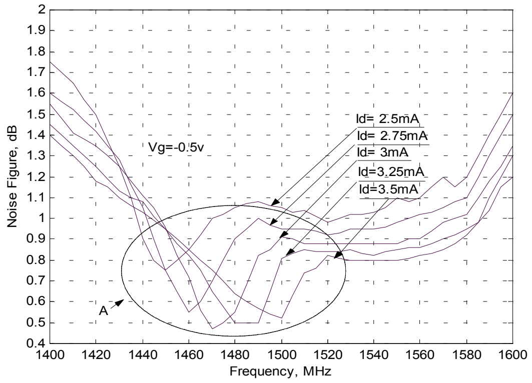

Fig. 7 Drain current dependence of the noise figure.

It is very important to note that noise measurements (NF_{min}=0.47dB) include the circulator losses about –0.2 dB plus the losses of the input-matching network. The effect of an increase on noise figure when drain current is reduced can be attributed to the shot noise in the transistor channel. Area A at Figure 7 is very interesting, showing the effect of noise suppression due to the high gain values as well as to the reflection coefficient of the input matching circuit.

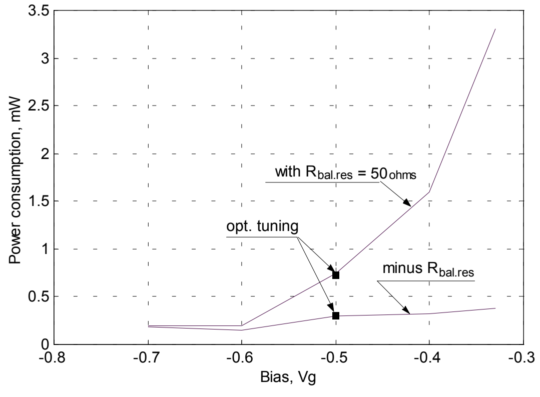

Fig. 8 DC Power consumption of the OPTA

Figure 8 shows measurement results of the DC power consumption, for different V_g and optimal tuning the gain and noise with help I_d. For estimation of the efficiency for DC power consumption, we have used the figure of merit of [13]. It is the ratio of gain (in dB) to power dissipation (in mW). The measured parameters demonstrated a very high performance for the figure of merit (> 65 dB/mW). For comparison, the best result up to date (19.1 dB/mW) at this frequency band was achieved in [14].

Figure 9 illustrates the nonlinear behavior of this amplifier, showing a very high linearity up to –50dBm input power.

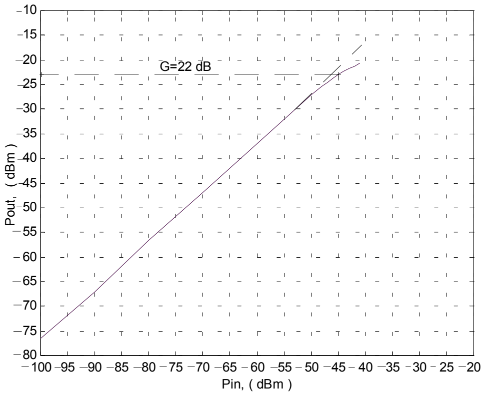

Fig. 9 Nonlinear behavior of the OPTA.

It is worthwhile to mention that in the event of amplifier damage the input signal appears at the circulator output port with very small attenuation dependent from the circulator losses as well as the reflection coefficient of the damaged amplifier [12].

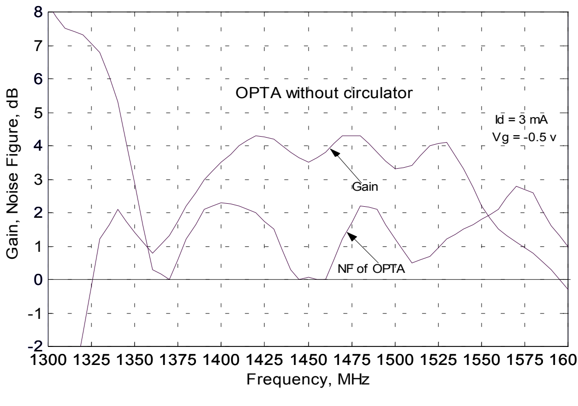

Fig. 10 Basic OPTA parameters without circulator.

An interesting illustration of the OPTA stability is shown on Figure 10, where we can see the basic parameters of the OPTA without the circulator, simply by insertion of a T-joint for measurements. This figure confirms the noise temperature curve at expression (3) and shows that noise suppression occurs with a small amplification gain

An important advantage of the proposed OPTA circuit is its low cost, since it uses only one transistor, a circulator and the appropriate matching circuit. Nevertheless this amplifier has many advantages, some disadvantages exist. For instance, OPTA is a relative narrowband circuit with a 2 to 10 % bandwidth depending strongly of the circulator bandwidth. This problem can be partially solved using several OPTA's in cascade. Another disadvantage for this circuit can be the temperature stability, where the basic source of instability is the power supply. But as this amplifier has very small consumption it strongly simplifies the problem.

4 Conclusions

A new type of one-port reflection amplifier with properties of very low noise, high gain and low power consumption has been presented. Experimental results showed that OPTA circuits using only one transistor, provides a higher transmission gain, smaller noise figure and high power efficiency than a conventional single-stage LNA. A noise suppression effect due to the high gain values as well as to the reflection coefficient of the amplifier input matching circuit has been demonstrated. Experimental results have shown that gain, noise figure and bandwidth for this class of amplifier are strongly dependent from bias conditions. This research can be extended at higher frequencies making it very interesting for applications at millimeter wave frequencies.

5 Acknowledgments

The authors would like to thank CONACYT for partial financial support of this work under grant: 225080-5-35225-A.

References:

[1] M.W.Pospiezalski, W.J.Lakatosh, et al, Q and E band cryogenically-cooled amplifiers using AlInAs/GaInAs/InP HEMT'S, *IEEE MTT-S Int Microwave Symp. Dig*., (1995), 1121.

[2] H.Wang, T.N.Ton, et. al., Low Noise and High Gain 94 GHz Monolithic InP- based HEMT Amplifiers, *IEEE International Electronic Device Meeting Technical Digest*, *Washington D.C*., (1993), 239-242.

[3] H.Wang,R.Lai,Y.C.Chen, et al, A 155–GHz Monolithic InP–Based HEMT Amplifier, *IEEE MTT-S Int Microwave Symp. Dig.*, (1997), 1275.

[4] M.Sholley G. Barber, et al, 119 GHz MMIC Radiometer for the (IMAS) Integrated Multi spectral Atmospheric Sounder, *IEEE MTT-S Int Microwave Symp. Dig., Anaheim,Ca.*, (1999), 479-782.

[5] G.I.Ng, R.Lai, et.al., Fully Passivated ultra low noise W-band monolithic InGaAs/InAlAs/InP HEMT amplifiers, IEEE 1995, *Microwave and Millimeter –wave Monolithic Circuits Symposium Digest, Orlando FL*, (1995), 63-66.

[6] H.Tohyama, H.Mizuno,"23-GHz Band GaAs MESFET Reflection-Type Amplifier", *IEEE Transactions on Microwave Theory and Techniques*, vol.MTT-27, no.5, may, pp.408-411, 1979

[7] Alder van der Ziel, "Noise Source, Characterization Measurement", *Prentice-Hall. Inc., Englewood Cliffs, N.J.*, 1970

[8] R.H.Frater and D.R.Williams, An active "cold" noise source, *IEEE Trans. on Microwave Theory Tech*. 29, (1981), 344-347.

[9]L.G.Gassanov, A.A.Lipatov, V.V. Markov, N.A.Mogilchenko, Solid state devices at Microwave Communication systems, *Radio and Communication*, in russian (1988).

[10] J. Helszain, "Passive and Active Microwave Circuits", , *John Wiley & Sons*, 1978.

[11] John W.Boyles, The oscillator as a Reflection Amplifier: an Intuitive Approach to Oscillator Design, *Microwave Journal,* 29-6, (1986), pp.83-98.

[12] A.P.Venguer,J. L. Medina, R.A. Chavez, A.Velazquez, Low Noise One-Port Microwave Transistor Amplifier", *Microwave and Optical Technology Letters*, to be published on April 20, 2002.

[13] K.W.Kobayashi, A.K.Oki, et al.,"5 mW GaAs HBT Low Power Consumption X – Band Amplifier" *IEEE MTT-S Digest*, pp.17-20, 1994

[14] K.R.Cioffi,"Monolitic L-Band Amplifier Operation at Miliwatt and Sub-miliwatt DC Power Consumption,"in 1992 *IEEE MMMCS Dig.*, pp. 9-12.