A Low Noise Amplifier with 27 dB Gain and 1.78 dB Noise for Satellite Communications with 0.1 μm GaAs pHEMT Technology

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ABSTRACT

This paper proposes a design of a 38 GHz Low Noise Amplifier (LNA) that uses a three-stage common source inductive degeneration topology with a gain of 27 dB and noise figure of 1.78 dB using 0.1 μm GaAs pHEMT as an active device. The novelty of the design is the usage of inductive load in series with the resistor instead of resistive load, resulting in higher gain performance. A recent pp1010 active device of WIN foundry was explored for this LNA design at the Q band. The high transition frequency offered by this technology succeeded in obtaining competitive results with a minimum number of cells. The designed LNA obtained the lowest noise compared to other recently published LNA designs at the Q band. The total power consumption of this design is 57 mW.

Keywords-pseudomorphic high electron mobility transistor (pHEMT); gallium arsenide (GaAs); low noise amplifier; inductive source degeneration; common source topology; radio frequency (RF)

I. INTRODUCTION

The huge demand of Q, V bands for satellite communications stimulated the design of millimeter wave applications. The low noise amplifier is a critical and essential component of millimeter wave applications of satellite communications [1-3]. BICMOS and MESFET technologies were able to support the MMIC LNA design only up to RF micro meter level (3 to 30 GHz) [4], but the MMIC LNA design at the milli meter level (30 GHz – 300 GHz) is supported only by HEMT technologies [5]. GaAs, GaN, and InP technologies are the mostly used HEMT technologies for RF design. GaAs and InP technologies [6, 7] are preferred for LNA design, whereas GaN technology is ideal for power amplifier designs [8]. However, GaAs technology is significant for LNA design in obtaining low noise figure with low productive cost and less fragile nature.

EM waves travel through longer distances before reaching the base station. These signals get degraded and attenuated during their travel. Hence satellite communication demands a high sensitive receiver at the base station to detect very weak signals received from satellites. As LNA is the first block of satellite communication receiver, the entire system performance depends on the gain and noise of LNA. From the past research it is observed that most of the LNA designs are of CS configuration [9, 10]. Very few designs were identified with other topologies like common gate [11], self-bias [12], current reuse [13] and cascoded [14] topologies. From the past works, it is noticed that other than CS topologies obtained less gain. This is the motivation behind the selection of CS topology for the proposed design. However, the three-stage common source topology LNA [15] with resistive load resulted in low gain. Hence, the proposed LNA used common source topology with inductive load in series with the resistor to obtain more gain. Three-stage LNA with common source topology using 0.15 μm GaAs HEMT technology [16] obtained gain of 23 dB and 3.8 dB noise figure. Using 0.1 μm GaAs HEMT technology obtained better performance than [16]. Features like highest transition frequency and maximum oscillation frequency of HEMT from the WIN foundry also enhanced the performance of the proposed work.

II. TECHNOLOGY

Pp1010 is the selected HEMT for the LNA design. In order to obtain low noise and high gain, the device has to be biased at 10 percent of IDSS. The selected pp1010 is biased with Vgs of

-0.4 V and Vds of 1V, obtained gain of 9.546 dB and 1.3 dB noise figure. This pHEMT can be operated up to maximum drain bias of -4V with gate to drain breakdown voltage of 9.6V. The pp1010 used in the design of LNA has a gate length of 0.1 μm and was generated using the E beam process with substrate thickness of 50 μm. Channel is made up of InGaAs for this particular HEMT with maximum drain bias of 4V. HEMT is fully passivated using nitride as a dielectric for fully passivated Metal Insulator Metal (MIM) capacitors. The inter connections have high density and two thick metal air bridges. At maximum transconductance of 750 mS/mm, the maximum drain current is 760 mA/mm with Vgs of -0.5 V.

III. CIRCUIT DESIGN

The most important key factors in designing an LNA at Q band are: 1) The HEMT performance and 2) the circuit design to obtain low noise, high gain, and good stability. The first factor is attained by selecting 0.1 μm GaAs pHEMT and the second factor is attained by using source inductive degeneration in all three stages with common source configuration. However, the usage of high value inductors at the source for high stability degrades the gain value. Hence, there is a trade-off between stability and gain.

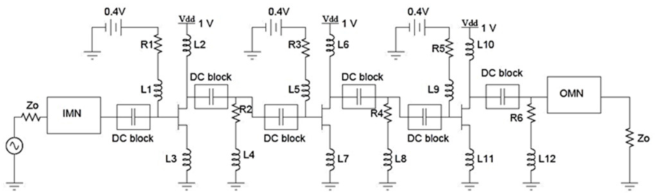

Fig. 1. 38 GHz three stage Q band LNA.

The LNA design starts from selecting the transistor with maximum transition frequency and low noise figure. pp1010 satisfies these features in 0.1 μm GaAs pHEMT technology. The proper gate width and number of fingers give a tradeoff between maximum gain, minimum noise, and Rollet stability factor. For the selected device size of 2×50 μm and bias values of Vgs = -0.4 V and Vds=1V, the pp1010 HEMT offers maximum gain of 9.54 dB and, low noise of 1.3 dB. The schematic block diagram of a 38 GHz three stage Q band LNA is shown in Figure 1. The three-stage Q band LNA was designed by cascading the three single stages. All the three individual single stages are applied with the same value of inductive source degeneration. Each individual single stage obtained a gain of 9.2 dB and 1.56 dB noise figure. Concentrating on maximum gain of the system requirement, we opted the three-stage cascaded common source configuration. Focusing on low noise figure, we selected all the three stages with device periphery of 2×50 μm. With these alignments, finally the cascaded three stages obtained a gain of 27.45 dB and1.78 dB noise.

IV. DESIGN ANALYSIS

Stability check of LNA at millimeter wave frequencies is compulsory because of mismatch conditions. The Rollet factor (*k*) is the measure of stability of a two port network. The necessary and sufficient conditions for stability are:

$$k > 1$$

$$1 - |s_{11}|^2 > |s_{12}s_{21}| \quad (1)$$

$$1 - |s_{22}|^2 > |s_{12}s_{21}| \quad (2)$$

where:

$$k = \frac{1 - |s_{11}|^2 - |s_{22}|^2 + |\Delta|^2}{2|s_{12}s_{21}|}$$

$$\Delta = s_{11}\, s_{22} - s_{12}\, s_{21}$$

where s_{11}, s_{22}, s_{12}, and s_{21} are the *s* parameters of the LNA.

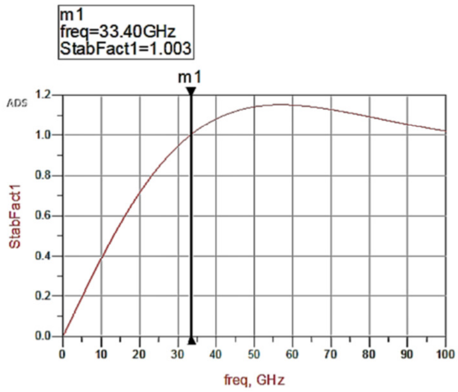

Fig. 2. Stability curve of the pp1010 HEMT.

From the stability curve it is observed that the pp1010 HEMT is unstable from 0 to 33.4 GHz. The stability at low frequency can be analyzed from the frequency stability model.

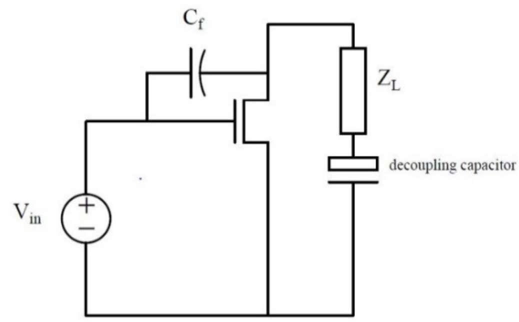

Fig. 3. Low frequency stability.

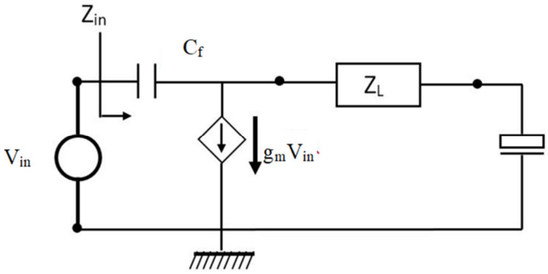

Fig. 4. Small signal equivalent.

V_{in}

From the small signal equivalent circuit, the assumed output is fully decoupled and the input impedance is given by:

$$Z_{in} = \frac{Z_L + \frac{1}{j\omega C_f}}{1+g_m Z_L} \quad (3)$$

For $Z_L = jwL$ and if $\frac{1}{j\omega C_f} > jwL$ then:

$$Z_{in} = \frac{1}{(1+g_m wL)^2}\left(\frac{1}{jwc_f} - \frac{g_m L}{c_f}\right) \quad (4)$$

Similarly, the assumed input is fully decoupled and the output impedance is given by:

$$Z_{out} = \frac{Z_L + \frac{1}{jwL}}{1+g_m Z_L} \quad (5)$$

For $Z_L = R + jwL$:

$$Z_{out} = \frac{R(1+g_m R) - \frac{g_m L}{c_f}}{(1+g_m R)^2 + g_m w^2} \quad (6)$$

By assuming $g_m R > 1$ and $R^2 > \frac{L}{C}$, the Z_{out} will be positive.

From the analysis section, the following changes are performed in the proposed design.

A. *The Proposed Design*

Selecting large series bias inductance values will reduce the negative resistance component at all frequencies. This is a viable case for the input side, as shown in Figure 5. But selecting large bias inductor at the output side does not work out, since the modulated current flows through the output side. The proposed design used an inductor connected in series with the shunt resistor to avoid gain degradation of in-band frequency range, as shown in Figure 6. For a given source impedance, it is trivial to read out the noise figure and the available gain of a two port network. The trade-off between them becomes intuitive in a Smith chart. An appropriate tradeoff is obtained while selecting the source impedance of 26.302+ j27.822 Ω.

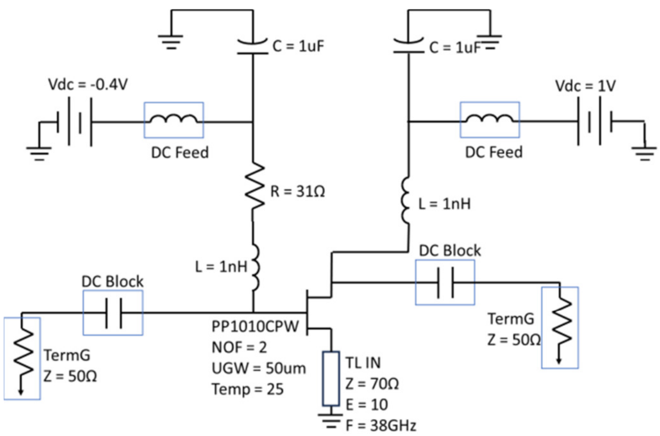

Fig. 5. Schematic diagram after adding *R*, *L* at the input side.

Figure 7 shows the schematic of common source inductive degenerate LNA with matching networks at the input and output side. Matching networks are designed with matching stubs at gate and drain side. The obtained source impedance is 26+j 27 Ω. A stub matching network is introduced at the input side to transform 50 Ω to the required impedance. Similarly at the output side, a matching network is introduced, which would transform the output *Zout* to 50 Ω. Source degeneration is obtained by connecting an inductor at the source side. Spiral inductors are used at input and output side for biasing. Low frequency stability obtained by connecting a resistance in series with the spiral inductor at the gate side. The proposed design avoided gain degradation in band frequency by connecting a shunt resistor at the drain side in series with the spiral inductors as shown in Figure 7.

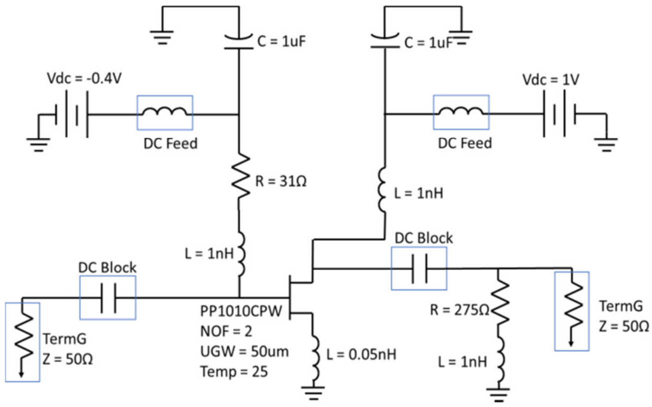

Fig. 6. Schematic diagram after adding a shunt resistor at the output side.

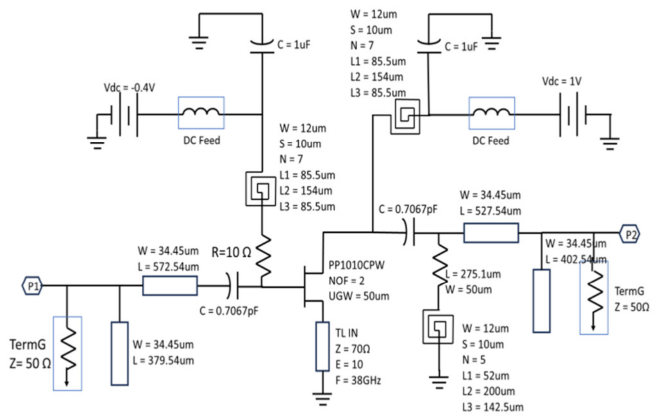

Fig. 7. Schematic diagram after adding matching circuits.

V. RESULTS AND DISCUSSION

The EM simulated gain (S21) behavior of the designed three-stage LNA is shown in Figure 8. The final three stage Q-band LNA achieved a gain of 27.031 dB at 38 GHz and has better performance even when compared to the state of the art performance while meeting the design specifications. The simulated results of the Input Return Loss (IRL) and the Output Return Loss (ORL) of the MMIC Q band three-stage LNA are shown in Figure 10. IRL (S11) of -7.937 dB and a very high ORL (S22) of -31.609 dB are obtained at 38 GHz. With the state-of-the-art performance, this proposed work achieved a very high value of ORL. The simulated noise figure of MMIC

Q band final three stage LNA is shown in Figure 9. A NF of 1.561 dB is obtained at 38 GHz frequency. The obtained noise figure result is very competitive compared to the state-of-the-art (Table I). To the best of our knowledge, most reported works have noise figures around 2 dB. The presented work obtained noise less than 2 dB.

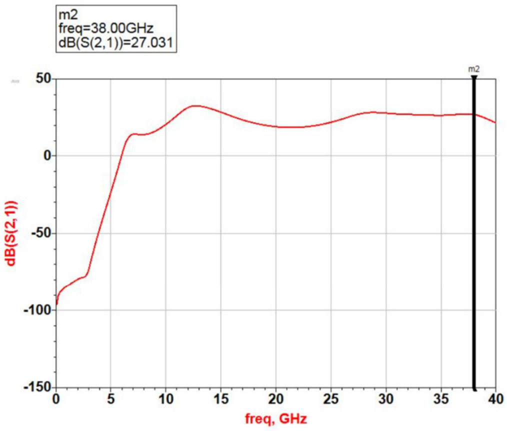

Fig. 8. Gain of 38GHz Q band LNA.

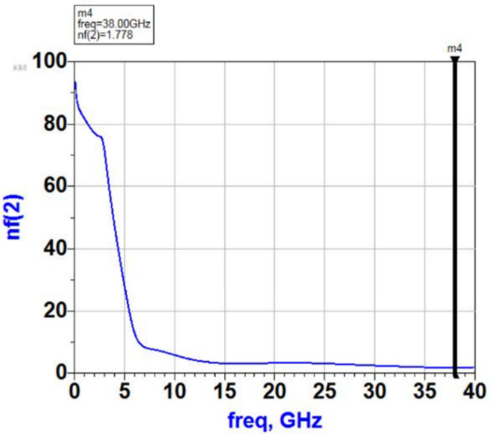

Fig. 9. Noise figure of 38GHz Q band LNA.

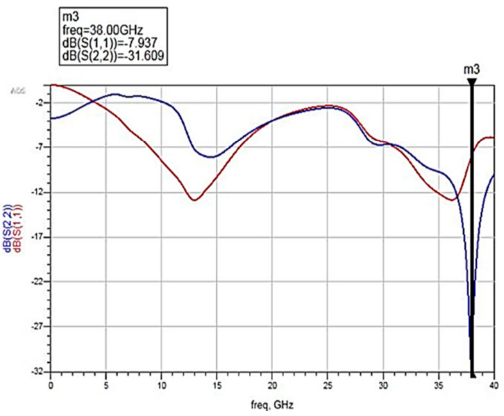

Fig. 10. Input output return losses of 38 GHz Q band LNA.

The final layout of the three-stage LNA is provided in Figure 11. The layout of the MMIC Q band three-stage LNA results in a chip size of 2.5×2.7 mm^2. The chip size is comparable with the state of the art.

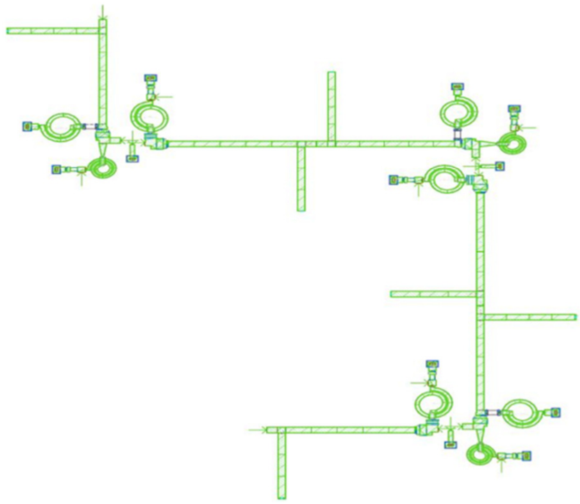

Fig. 11. Layout of the three stage Q band LNA.

Various design solutions of LNA around the Q band are compared with the proposed LNA and the results are shown in Table I. The concerned parameters with the state of the art performance are gain and noise. Compared to the previously reported LNAs, the proposed LNA gives good matching, low output return loss, high gain, and low overall noise figure. Authors in [12, 17] have used a different mHEMT technology but the acquired gain is less compared to the one of the proposed work. The design in [18] using mHEMT obtained a gain almost equal to the proposed work's, but it was designed with four stages of common source configuration, whereas the proposed work obtained the same gain value using three stages. Authors in [16] used the GaAs substrate and acquired comparable gain dimensions but IRL and ORL were not given. Authors in [15] obtained good IRL and ORL but with less gain. Among the cited papers from Table I, the proposed work exhibited better performance in terms of output return loss, noise figure, and gain.

VI. DISCUSSION

The novelty of the design is the usage of inductive load in series with the resistor instead of resistor load. The shunt resistor avoids large voltage drops through load and helps in obtaining a high gain of 27.45 dB. The designed features of the proposed LNA are suitable for satellite communication.

VII. CONCLUSIONS

In summary, a suitable MMIC LNA was realized for a multi gigabit satellite communication receiver. The design strategy used inductive load in series with the resistor for improving the band frequency gain. The designed LNA performance has been compared with the state-of-the-art results. The proposed LNA exhibits a gain of 27.475dB and 1.78 dB noise figure at 38 GHz with a low ORL of -31.609 dB. Noise and output return loss were improved by 10% and 16%, respectively in comparison to the standard design values of 2dB and -12 dB.

TABLE I. COMPARISON SUMMARY

Ref	Technology	Freq (GHz)	Gain (dB)	IRL (dB)	ORL (dB)	Power (mW)	Noise (dB)	Chip area (mm^2)
[16]	0.15µm GaAs pHEMT	28-50	23	-	-	62	3.8	2×1.5
[12]	0.07 µm AlGaAs/ InGaAs mHEMT	42-46	19	-25	-27	40	1.5	3×1.2
[15]	0.1µm GaAs pHEMT	40-51	16.5	-11	-11	80	2	3×1
[17]	0.07µm GaAs mHEMT	47-52	17	-20	-15	-	2	-
[18]	0.05µm GaAs mHEMT	30-50	27.5	-10	-12	240	2	2×1
Proposed	0.1µm GaAs pHEMT	36-40	27.4	-7.937	-31.60	80	1.78	2.5×2.7

From this work, it is evident that 0.1 µm GaAs pHEMT technology can be successfully extended to produce LNA at millimeter wave frequency range for a satellite communication receiver with better performance, provided that appropriate design approach and proper device models are developed.

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