Design of a Low Noise Amplifier for C-band Receivers using pHEMT

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***Abstract*—** Antenna is the first element at the receiver of a satellite communication system. It receives information signals of very low strength added with unwanted noise signals. A Low Noise Amplifier (LNA) is an electronic amplifier that is used to amplify such signals by introducing only a minimum amount of noise. The design of an LNA requires a trade-off between many important characteristics such as Gain, Noise Figure, Stability, Bandwidth and Bias conditions. This work proposes the design of a two-stage LNA using the pHEMT transistor ATF-34143 for 3-5 GHz frequency range in which most of the satellite receiver systems operate. The design includes usage of Inductive source degeneration concept to make the LNA unconditionally stable and Radial stubs to isolate the DC sources from AC signals. This work demonstrates a design which provides gain > 20 dB and a noise figure < 1.5 dB over the entire bandwidth using the electronic simulation tool Advanced Design System (ADS) 2016.

***Keywords*—** *pHEMT, Stability, Source degeneration, Bias, Radial Stubs, Gain, Noise-figure*

I. INTRODUCTION

Satellites have many uses in the modern world and have aided innovation in countless ways. Communication satellites primarily use C-, X-, Ku- and Ka-band frequencies. Though the C-band antennas are large in size, this band allows for wide area coverage and in extremely resilient to severe weather conditions. They play an important role not only in civilian communications but also in Navigation, Military and Space exploration. To amplify the very small signals received from these satellites, a low noise amplifier is required. It is usually located very close to the detection device to minimize the losses in the feed line. It is the key component in the front-end of any receiver system. All receivers require an LNA with sufficient sensitivity to detect the residual signal from the surrounding noise and interference, in order to reliably extract the embedded information. With the increasing wireless data speed and with the extended link distance, requirements on the sensitivity of LNA are becoming stringent. Its main function is to provide gain while adding as little noise as possible. Apart from this, an LNA should accommodate large signals without distortion.

Selection of the active device is the crucial stage in LNA design. Early microwave amplifiers relied on tubes, such as klystrons and traveling-wave tubes, or solid-state reflection amplifiers based on the negative resistance characteristics of tunnel or varactor diodes. However, due to the dramatic improvements and innovations in solid-state technology which have occurred since the 1970s, most RF and microwave amplifiers today use transistor devices such as Si BJTs, GaAs or SiGe HBTs, Si MOSFETs, GaAs MESFETs, or GaAs or GaN HEMTs. The most popular active devices used in LNAs are based on GaAs pHEMTs and SiGe BiCMOS process technologies [1]. In this work is a pHEMT (pseudomorphic high electron mobility transistor) ATF-34143 has been used.

Common−source, common−gate, and cascode are three prevailing LNA topologies. The goal of this paper is to design a wideband LNA with the lowest noise figure, gain as high as possible. For this purpose, a two-stage design using the common-source topology was implemented. The first stage is used to optimize the noise figure while the second stage is used to increase the overall gain.

TABLE I. COMPARISON OF DIFFERENT LNA TOPOLOGIES

Characteristic	Common-Source	Common-Gate	Cascode
Noise Figure	Lowest	Rises rapidly with frequency	Slightly higher than Common-Source
Gain	Moderate	Lowest	Highest
Linearity	Moderate	High	Potentially Highest
Bandwidth	Narrow	Fairly Broad	Broad
Stability	Often requires compensation	Higher	Higher
Reverse Isolation	Low	High	High
Sensitivity to process variation, Temperature, Power supply, Component tolerance	Greater	Lesser	Lesser

II. DESIGN PROCEDURE

A. *Selection of device*

Transistor selection is the first and most important step in an LNA design. It involves choosing the right package, having an adequate current rating, gain and noise figure which meet the requirements of the intended application. A first step for the choice of transistor is to decide the frequency range, because it may affect other specifications [2]. Transistor data sheets help selecting and using the RF devices for intended application. These data sheets describe the transistor's behavior at RF frequencies. Parameters found in the device data sheet typically are: S-parameters, MAG (Maximum Available Gain), and Noise Figure.

Avago's ATF-34143 is a high dynamic range, low noise PHEMT housed in a 4-lead SC-70 (SOT-343) surface mount plastic package. Based on its featured performance, ATF-34143 is ideal for the first stage of base station LNA due to the excellent combination of low noise figure and high linearity. It is operable in the frequency range from 450 MHz to 10 GHz. Its S-parameters are available for four bias conditions of 3V-20mA, 3V-40mA, 4V-40mA and 4V-60mA. From the datasheet, it was found that the gain was highest at the 4V-60mA bias point with only a slight variation of 0.06 dB in its noise figure compared to the other bias points. Hence this bias point was chosen for the design.

B. *DC Biasing*

Biasing a transistor amplifier is the process of setting the dc (Biasing) operating voltage and current to the correct level so that any ac input signal can be amplified correctly by the transistor. S-parameters are a specific to particular bias values. Hence an S-parameter model of the selected transistor does not require biasing where as a practical non-linear model requires biasing. Biasing networks are of two types: Passive biasing (or self-biasing) and Active biasing. Passive biasing uses resistive networks and it has poor temperature stability. Active biasing uses additional active components like BJTs or FETs to provide bias to the main active device. These networks are more complex and require more power consumption [3].

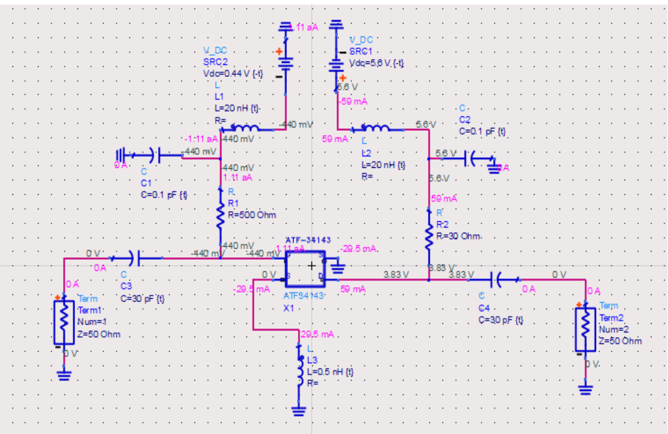

Fig. 1: ATF-34143 non-linear model with biasing circuit

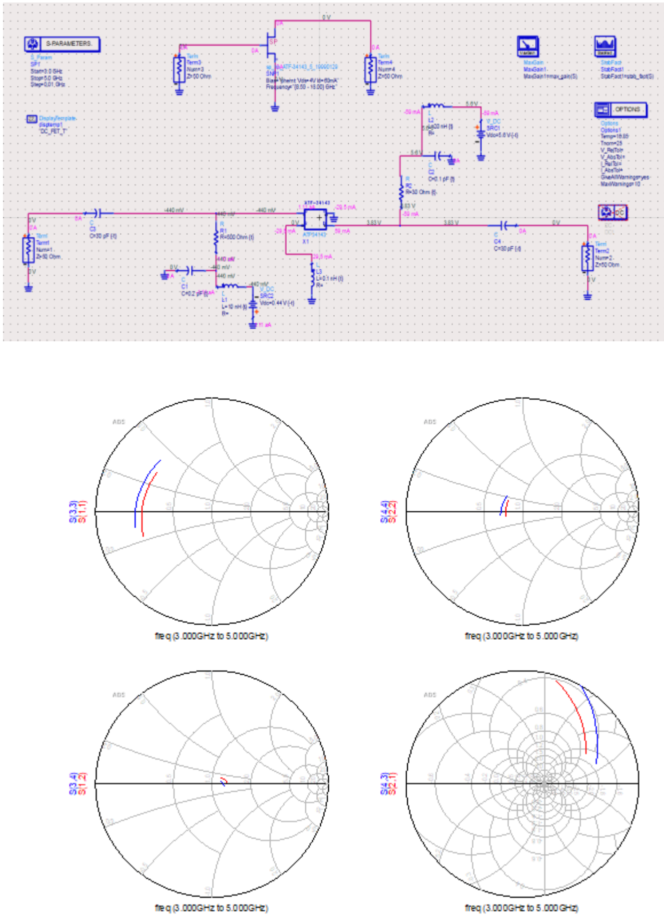

Fig. 2: Comparison of S-parameters after biasing the non-linear model

In order to keep the DC source isolated from the AC signals, radial stubs can be implemented. This can be achieved using a radial stub after the λ/4 high impedance biasing line, which helps to achieve the proper isolation at the desired frequency [4]. The input impedance of radial stub is more consistent and suitable for broadband application. The effect of quarter-wave microstrip line is cancelled by a quarter-wave radial stub reactance. This helps to achieve proper isolation at desired RF frequency, no matter what component is added after λ/4 long bias line. The radial stub approach is especially useful at high frequencies since low frequencies and low dielectric constant will make the quarterwave lines and radial stubs very long. Also Blocking capacitors were used at the input & output to resist the dc power from entering into the transistor.

C. *Stability*

Stability or resistance to oscillation in a microwave circuit can be determined by the S-parameters. Oscillations are possible in a two-port network if either or both the input and output port have negative resistance. This condition occurs when the magnitude of the input or output reflection coefficients is greater than one: $|\Gamma in|>1$ and $|\Gamma out|>1$. There are two types of amplifier stability conditions –unconditionally stable and conditionally stable. The stability test should be done for every frequency in the desired range.

In terms of reflection coefficients, the necessary conditions for unconditional stability at a given frequency are:

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12} \cdot S_{21}|} > 1$$

$$|\Delta| = |s_{11} \cdot s_{22} - s_{12} \cdot s_{21}| < 1$$

When K >1 the circuit will be unconditionally stable for any combination of source and load impedance and when K < 1, the circuit is potentially unstable and oscillation may occur within a certain combination of source and/or load impedance presented to the transistor. Hence this test presents a quick check for stability at a given frequency and a given bias condition.

One of the important characteristics of an amplifier design is unconditional stability. In this work, inductive degeneration technique was adopted to provide unconditional stability to the circuit. Inductive degeneration is the addition of an inductor of appropriate value between the source and the ground in order to get a real input impedance [5]. Source degeneration introduces negative series feedback and reduces the gain of the amplifier. Hence inductive reactance should be as small as possible so that gain would be maximum. The other methods of improving stability are resistive loading of input or output and introducing RLC feedback between gate and drain of the transistor [3]. However, addition of a resistor will greatly increase the noise figure which is of utmost importance for a low noise amplifier and hence Inductive degeneration is of particular interest because it does not introduce noise.

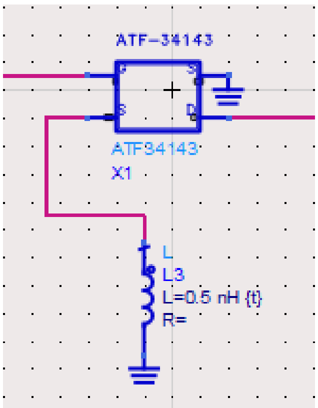

Fig. 3: Source Inductive degenerate Inductor to improve Stability

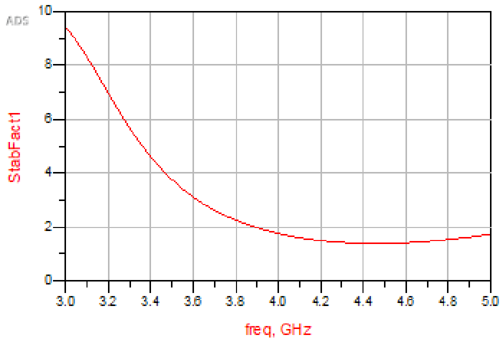

Fig. 4: Unconditional Stability after including Source inductor

Initially, the stability factor at 4 GHz was 0.769 and after adding the source inductor, the stability factor was > 1 for the entire frequency range.

D. Matching Networks

Input and Output matching networks are important for LNA design. The available matching networks are – LC matching network, Stub matching network, T and ∏ matching networks. These matching networks can be designed by some methods such as lumped components, stubs, quarter-wave transformers or using general transmission lines [6]. This work uses stub matching network.

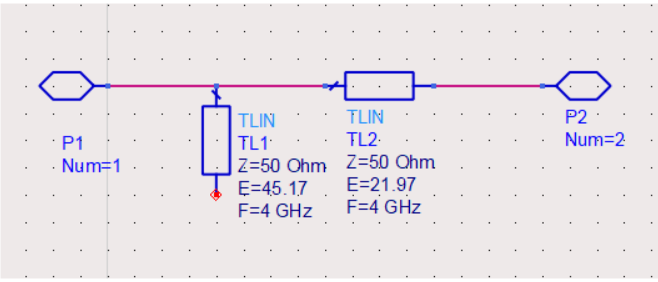

Fig. 5: Input matching circuit

The input matching network is mainly designed to obtain optimum noise figure since the noise figure of the whole amplifier is mainly decided by the first stage amplifier. The output matching network is designed to achieve maximum gain. Also as the number of stages increase, the gain also increase and inter-stage matching networks are required to ensure maximum power transfer between each stage.

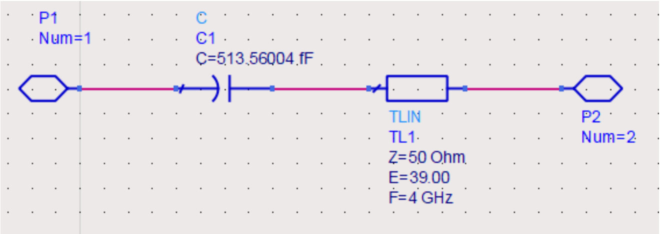

Fig. 6: Inter-stage matching circuit

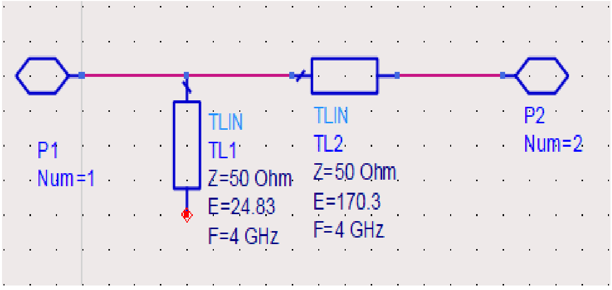

Fig. 7: Output matching circuit

To design the input matching circuit, gain and noise circles have been plotted. The center of Gain circles indicates Γ_{opt} for achieving maximum gain. As the radius of these gain circles increases, gain decreases. Similarly, center of noise circles indicates Γ_{opt} for minimum noise figure. As the radius of these noise circles increases, the noise also increases. Since the goal is to design a low noise amplifier, gain is compromised to achieve least possible noise figure and thus Γ_{opt} for minimum noise is selected to design the matching network [9].

The intermediate stage can be designed by matching S_{11} of second stage to S_{22}* of first stage, but this can introduce slight change in the noise figure. Hence instead, S_{22}* has been matched to the input impedance point which is common to all the noise circles to design the intermediate stage. After designing the input and intermediate matching networks, S_{22} is plotted on smith chart and its impedance at 4 GHz is matched to the 50 ohm load to design the output matching network.

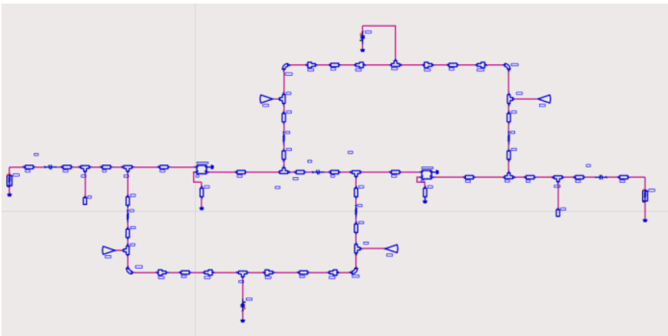

Fig. 8: Overall schematic of the Low Noise Amplifier

III. NON-LINEAR MEASUREMENTS

Linearity is the criterion that defines the upper limit of detectable RF input power and sets the dynamic range of the receiver. It is a key requirement in the design of an LNA because the LNA must be able to maintain the linear operation in the presence of a large interfering signal. The linearity of an amplifier is described in terms of 1-dB compression point (P1-dB) and third-order inter-modulation product (IP3). The saturation effect begins once the main component of the output signals stops following the input signal with ideal ratio. This is known as 1-dB compression point and is defined as the level at which the gain drops by 1-dB. For IP3, the inter-modulation products will increase in amplitude by 3 dB when the input signal is raised by 1 dB. Generally, the third order intercept point is 10 dB above the 1 dB compression point [10].

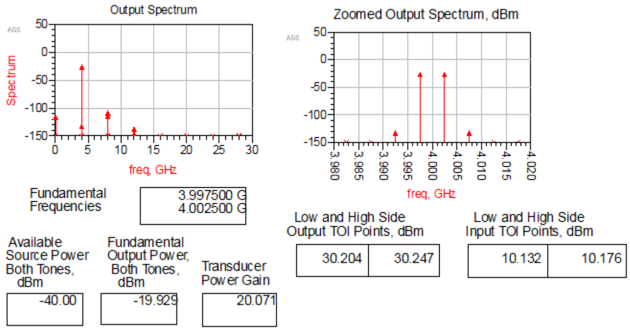

Fig. 9: Input and Output IP3 values

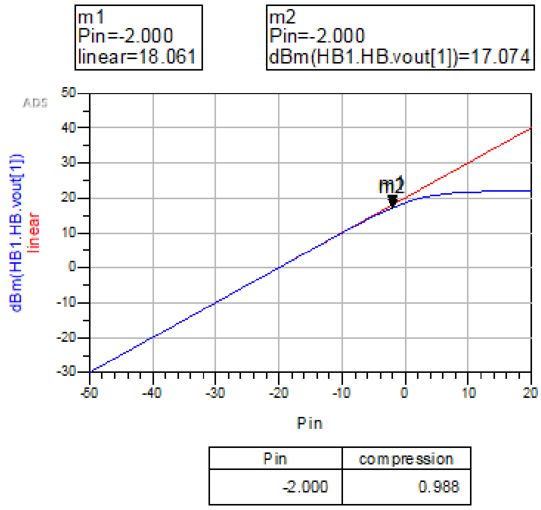

Fig. 10: Output power (in dBm) at 1 dB Compression point

IV. RESULTS

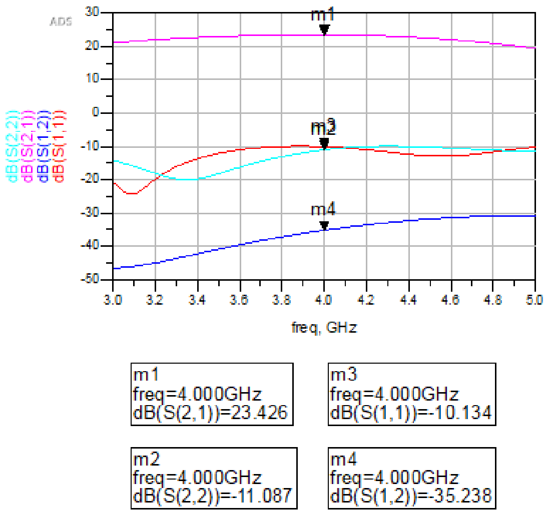

Fig. 11: S-parameters of the final schematic

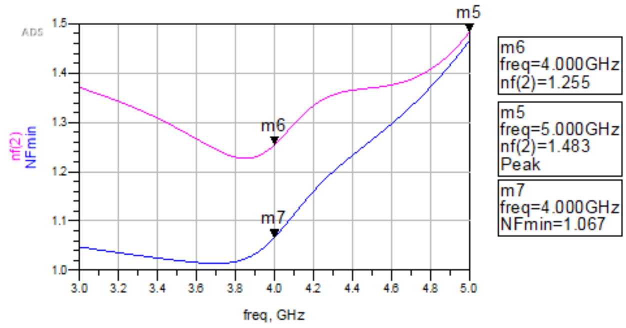

Fig. 12: Minimum noise figure (NFmin) and nf(2) for the final schematic

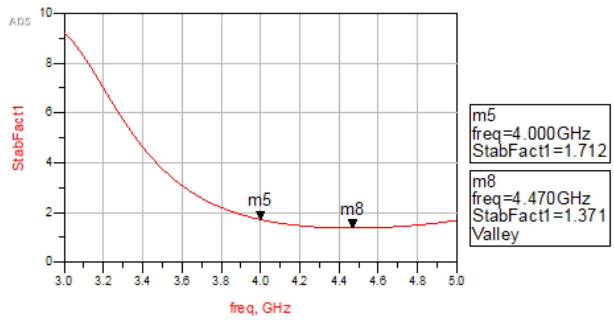

Fig. 13: Stability factor

TABLE II. COMPARISON OF S-PARAMETER AND ADS MODEL FOR SINGLE-STAGE AND TWO-STAGE DESIGNS

Characteristic	Single-stage using S-parameter model	Single stage using ADS model	Two-stage using S-parameter model	Two-stage using ADS model
S21(dB)	11.222	11.928	22.056	23.426
S11(dB)	-25.834	-17.013	-12.953	-10.134
S22(dB)	-13.653	-13.373	-13.148	-11.087
S12(dB)	-15.612	-17.146	-29.519	-35.238
NFmin	0.78	0.85	0.746	1.067
K without source inductive degeneration	0.891	0.769	0.831	0.83
K with source inductive degeneration	1.07	1.098	1.231	1.712
VSWR1	1.1	1.4	1.581	2.1
VSWR2	1.58	1.45	1.564	2.35
P1 dB	NA	19.016	NA	17.074
IIP3 (dBm)	NA	21.143	NA	10.132
OIP3 (dBm)	NA	33.082	NA	30.204

V. CONCLUSIONS

In this work, a Low noise amplifier centered at 4 GHz with a band of operation from 3 to 5GHz has been designed. It provided a gain of > 20 dB and a noise figure of NFmin and nf(2) < 1.5dB. Unconditional stability was met using the Source Inductor degeneration technique and Radial stubs were used to isolate DC sources from the AC signals. A two-stage amplifier design provided greater Gain than a single stage amplifier.

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