Multi-octave and Frequency-agile LNAs Covering S-C Band using 0.25 μm GaN Technology

A. Mattamana\textsuperscript{1}, W. Gouty\textsuperscript{1}, W. Khalil\textsuperscript{2}, P. Watson\textsuperscript{1}, and V. J. Patel\textsuperscript{1}

\textsuperscript{1}Air Force Research Laboratory, Sensors Directorate, WPAFB, OH
\textsuperscript{2}The Ohio State University, Columbus, OH

Abstract — This paper reports the design and measured results of a multi-octave low noise amplifier (LNA) and a frequency-agile LNA utilizing a 0.25 μm gallium nitride (GaN) integrated circuit process technology for multi-band receiver applications. The demonstrated broadband LNA covers an instantaneous bandwidth from S- to C-bands (2.2-7.0 GHz), and the frequency-agile LNA cumulatively spans across 3 distinct bands (2.2-2.4 GHz, 4.4-5.0 GHz, and 5.0-6.7 GHz). The measured noise figure (NF), output third order intercept (OIP3), and peak gain of the wideband LNA is 1.0-1.7 dB, 19.0-26.0 dBm, and 10.6 dB with a gain flatness of +/- 0.35 dB respectively at a nominal power consumption of 480 mW across the band. At the same nominal power consumption, the frequency-agile LNA demonstrated a NF of 1.3, 1.4, and 1.2 dB; OIP3 of 23, 27, and 31 dBm; and gain of 13.6, 10.6, and 10.8 dB at 2.3 GHz, 4.7 GHz, and 5.8 GHz, respectively. The performance of the frequency-agile LNA is comparable to that of optimized narrowband LNAs at S- and C-bands. Compared to the multi-octave LNA, the frequency-agile LNA demonstrated better performance in gain and OIP3 at the frequencies of interest.

Index Terms — Frequency-agile, Broadband, Low Noise Amplifier, Receiver, GaN, Telemetry, Multi-band, Multi-functional, Noise Figure, Output Third Order Intercept, CSWaP.

I. INTRODUCTION

The radio spectrum is increasingly becoming a scarce and expensive natural resource as new communication standards evolve to accommodate the growing demand for data rates. With the rapid growth of these standards, spectrum congestion becomes a critical concern as more data are required to fit within the designated bands. A technique to manage the spectrum efficiently is band re-purposing [1], which re-allocates to a frequency band that is less congested.

Traditionally, radio systems are designed to operate solely in their specified band, which are referred to as point designs. As a result of band re-purposing, point designs need to be re-architected to accommodate the newly allocated band, which increases system complexity, design and release times, and cost. A more recent approach to address the band re-purposing is a frequency-agile system capable of accommodating multiple bands of operation while maintaining point design performance [2]. Toward this goal, modern wireless technology is moving to the development of multi-band/multi-functional receiver systems to accommodate larger bandwidths and more flexibility [3, 4].

As an example, telemetry bands that currently operate at L- to lower C-band will be including mid and upper C-bands in the near future [1]. Hence, the telemetry community can benefit from a single radio that operates in L-, S-, or C-band thus supporting new and legacy bands.

One of the critical components of a radio frequency (RF) receiver is the LNA, which is the first active element and sets the overall NF of the receiver. Therefore, an LNA with low noise figure, high gain, and high linearity is desired for high sensitivity and high dynamic range receivers. Different LNA technologies are used in receivers for multi-band functionalities. Conventional receiver architectures use multiple independent LNAs at different frequencies for the multi-band operation with an unavoidable increase in cost, size, and power dissipation (CSWaP) [3, 4]. A concurrent LNA approach utilizes a single LNA that is capable of simultaneous operation at different frequencies for multi-band/multi-function receivers without dissipating large amounts of power or significant increase in cost and size [4]. A wideband receiver with a broadband LNA is also capable of providing multi-band receiver functionalities, but with significant degradation in receiver sensitivity due to the amplification of unwanted signals along with the desired signals [4].

Another approach to develop multi-band receivers is using frequency-agile RF components. This paper reports an integrated frequency-agile LNA in GaN technology for multi-band receivers without dissipating large amounts of DC power or significant increase in cost and footprint. For performance comparison of the frequency-agile LNA, a multi-octave LNA is also designed and reported in this paper. While maintaining low NF and high OIP3, the frequency-agile LNA demonstrates narrowband input and output matching and gain at multiple frequency bands. This paper is organized as follows. Section II describes the GaN technology used for the LNA. A detailed description of the two LNAs is given in section III. Section IV shows the measured small- and large-signal results. Finally, section V summarizes the two LNAs and their performances.
II. GAN TECHNOLOGY

Wide variety of solid state device technologies that offer low noise and high linearity, as well as high output power and efficiency, are available for next generation radar and communication systems. Silicon-based device technologies offer high speed and high levels of integration, whereas GaN technology offers high breakdown voltage, high thermal conductivity, and low noise high-electron-mobility transistors (HEMTs). Also, GaN technology can withstand high amplitude input signals and therefore eliminate the use of limiter circuits before the LNA, which improves the overall NF of the receiver. Fig. 1 shows the cross-section of the GaN technology.

The intrinsic characteristics of the GaN compound semiconductor device provides $\text{NF}_{\text{min}}$s of 0.26 dB and 0.64 dB and associated gains of 21.1 dB and 14.5 dB at 2 GHz and 7 GHz respectively. Input and output matching networks are essential to reduce reflections; minimize NF; maximize the power transfer, linearity, and bandwidth; and to achieve unconditional stability. A small degenerative inductor at the source is used to move the source impedance of the device closer to $\Gamma_{\text{opt}}$ to obtain minimum NF and good input return loss simultaneously with minimal impact on the available gain. As the associated gain decreases with frequency, an inductance in series with the load resistance is used on both amplifiers for bandwidth enhancement and gain improvement at high frequency [8].

III. DESIGN METHODOLOGY

Two microstrip LNA topologies have been explored and designed using the 0.25 μm GaN technology to assess their performance tradeoffs. A device trade-study was performed among available device sizes and bias conditions for optimum noise. Both LNAs utilized a 400 μm periphery GaN HEMT biased at a nominal drain current of 32 mA from a 15 V power supply. Fig. 2 shows the simulated minimum noise figure ($\text{NF}_{\text{min}}$) and the associated gain of the GaN HEMT under the nominal bias condition.

The intrinsic characteristics of the GaN compound semiconductor device provides $\text{NF}_{\text{min}}$s of 0.26 dB and 0.64 dB and associated gains of 21.1 dB and 14.5 dB at 2 GHz and 7 GHz respectively. Input and output matching networks are essential to reduce reflections; minimize NF; maximize the power transfer, linearity, and bandwidth; and to achieve unconditional stability. A small degenerative inductor at the source is used to move the source impedance of the device closer to $\Gamma_{\text{opt}}$ to obtain minimum NF and good input return loss simultaneously with minimal impact on the available gain. As the associated gain decreases with frequency, an inductance in series with the load resistance is used on both amplifiers for bandwidth enhancement and gain improvement at high frequency [8].

A. Multi-octave LNA Design

Traditional broadband LNA topologies are either distributed, feedback, or cascade topologies. Compared to previous broadband LNA designs [10], the proposed LNA consumes less area and has lower power consumption. Furthermore, the LNA design achieves low noise figure and flat gain over the multi-octave frequency range of operation with unconditional stability. The schematic and micrograph of a single stage broadband LNA that covers S- to C-bands are shown in Fig. 3. The multi-octave single stage common source LNA is divided into three sections:
1) wideband LC matching network at the input was optimized to reduce reflection and minimize NF across the band, 2) a small on-chip source degeneration is used to simultaneously match optimum noise and input impedance, and 3) LC matching and shunt peaking network at the output provides flat gain and output impedance match across the band.

B. Frequency-agile LNA Design

The frequency-agile technology is another approach to demonstrate a multi-band LNA to meet the frequency of operation from S- to C-band. Frequency tunability can be achieved either by tunable inductors, varactors, or RF switches [3]. Important performance characteristics for the tunable components are low insertion loss, high quality factor, high power handling capability, and wide tuning range. The schematic and micrograph of a single stage frequency-agile LNA that covers the 3 telemetry bands are shown in Fig. 4. Due to the unavailability of high performance tunable passives in the GaN technology, the LNA design utilizes low-loss RF switches to enable or disable shunt capacitors at the input and output of the amplifier based on the desired frequency band of operation. Note that the only RF switch model available is a 5x100 $\mu$F device and is used in the LNA design for frequency tuning. All switches are controlled by their gate voltages. The switch is ON when the gate bias is set at 0 V, and the OFF-state is achieved when the gate is biased deep into pinch-off at -20 V. Table I shows the switch conditions to achieve the frequency configurability from S- to C-band.

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-band</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
</tr>
<tr>
<td>Mid C-band</td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>High C-band</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
</tr>
</tbody>
</table>

IV. DEMONSTRATED MULTI-OCTAVE AND FREQUENCY-AGILE LNA PERFORMANCE

On-wafer characterization of both LNA designs in a 50 $\Omega$ environment was conducted using an Agilent E8364B performance network analyzer (PNA) for small-signal measurement. Noise figure was measured using an Agilent E4448A performance spectrum analyzer (PSA) with noise figure personality. Maury Microwave load pull system with 50 $\Omega$ input and output tuners and 1 MHz tone spacing at different frequencies across S- to C-bands were used to measure the OIP3 of the LNAs. In order to protect the circuits from excess heat, five dies of each LNA variant were mounted on a high thermal conductivity copper molybdenum heat sink using silver epoxy. With the described setup, both LNAs are unconditionally stable across the frequencies 0.1-50 GHz. Measurements reported in this paper are based on the nominal bias condition of $V_D=15$ V and $I_D=32$ mA at room temperature.

A. Multi-octave LNA

The multi-octave LNA demonstrated a peak small-signal gain of 10.6 dB with a gain flatness of +/- 0.35dB over the entire frequency band from 2.0-7.0 GHz with input and output return losses of < 7.3 dB and < 6.7 dB respectively. Simulated versus measured S-parameter results and NF of the LNA are shown in Fig. 5. The minimum measured NF is 1 dB and the maximum is 1.7 dB across the bandwidth. The measured OIP3 of the LNA is in the range of 19.0-26.0 dBm across the bandwidth.

![Fig. 3. Schematic and micrograph (1.4 mm x 1.8 mm) of a single stage wideband LNA.](image)

![Fig. 4. Schematic and micrograph (2.1 mm x 2.0 mm) of a single stage frequency-agile LNA.](image)

![Fig. 5. Simulated versus measured S-parameters and NF of the single stage multi-octave LNA.](image)
The demonstrated single stage frequency-agile LNA spanning S-band (2.2-2.4 GHz), mid C-band (4.4-5.0 GHz), and high C-band (5.0-6.7 GHz) shows a gain of > 13.0 dB at S-band, > 10.0 dB at mid C-band, and > 10.0 dB at high C-band. Measured input return loss is < 7.0 dB, and output return loss is < 6.0 dB across the three telemetry bands. Simulated versus measured small-signal gain and NF of the LNA is shown in Fig. 6 (a) and (b) respectively. Fig. 7 (a) and (b) display the input and output return losses of the frequency-agile LNA respectively. The LNA also demonstrated > 23 dBm OIP3 across the three bands with measured NFs from 1.2 dB to 1.4 dB.

Table II compares the performance of the LNAs reported in this paper with previously published and commercially available GaN LNAs. The NF, OIP3, and power dissipation are comparable or better than the previously published multi-stage, point design LNAs.

V. CONCLUSION

Two LNA topologies were explored to compare multi-octave LNA versus frequency-agile LNA for multi-band operation. Both LNAs utilized a 400 µm periphery GaN HEMT with nominal power consumption of 480 mW. In terms of linearity, the frequency-agile LNA yielded 5.0-7.0 dB higher OIP3 than the multi-octave LNA. Noise figures of both LNAs are comparable across the bands of interest. In general, our study indicates the frequency-agile LNA has better performance in terms of linearity, gain, and interference suppression than the multi-octave and can be used in multi-band receiver architectures if concurrent frequency operation is not critical.

REFERENCES


<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>[9]</td>
<td>0.25 µm GaN</td>
<td>21, 3-stage</td>
<td>1.2</td>
<td>38</td>
<td>5.95-6.05</td>
<td>2160</td>
</tr>
<tr>
<td>[10]</td>
<td>0.25 µm GaN</td>
<td>22-28, 2-stage</td>
<td>0.9-1.5</td>
<td>32</td>
<td>2.0-6.0</td>
<td>1100</td>
</tr>
<tr>
<td>[12]</td>
<td>* GaN</td>
<td>12-12.5, Balanced</td>
<td>2.5</td>
<td>38.5</td>
<td>2.5-4.0</td>
<td>1920</td>
</tr>
<tr>
<td>Frequency-agile</td>
<td>0.25 µm GaN</td>
<td>13.6, 10.6, 10.8, 1-stage</td>
<td>1.3, 1.4, 1.2</td>
<td>23, 27, 31</td>
<td>2.2-2.4, 4.4-5.0, 5.0-6.7</td>
<td>480</td>
</tr>
<tr>
<td>Multi-octave</td>
<td>0.25 µm GaN</td>
<td>10-10.7, 1-stage</td>
<td>1.0-1.7</td>
<td>19-26</td>
<td>2.0-7.0</td>
<td>480</td>
</tr>
</tbody>
</table>

B. Frequency-agile LNA

The demonstrated single stage frequency-agile LNA spanning S-band (2.2-2.4 GHz), mid C-band (4.4-5.0 GHz), and high C-band (5.0-6.7 GHz) shows a gain of > 13.0 dB at S-band, > 10.0 dB at mid C-band, and > 10.0 dB at high C-band. Measured input return loss is < 7.0 dB, and output return loss is < 6.0 dB across the three telemetry bands. Simulated versus measured small-signal gain and NF of the LNA is shown in Fig. 6 (a) and (b) respectively. Fig. 7 (a) and (b) display the input and output return losses of the frequency-agile LNA respectively. The LNA also demonstrated > 23 dBm OIP3 across the three bands with measured NFs from 1.2 dB to 1.4 dB.

Table II compares the performance of the LNAs reported in this paper with previously published and commercially available GaN LNAs. The NF, OIP3, and power dissipation are comparable or better than the previously published multi-stage, point design LNAs.

![Fig. 6. Simulated versus measured (a) gain and (b) NF of the frequency-agile LNA.](image)

![Fig. 7. Simulated versus measured (a) input return loss and (b) output return loss of the frequency-agile LNA.](image)


