70–116-GHz LNAs in 35-nm and 50-nm Gate-Length Metamorphic HEMT Technologies for Cryogenic and Room-Temperature Operation

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Abstract—In this paper, the room-temperature and cryogenic performance of two low-noise amplifier (LNA) modules in the frequency range from 70 to 116 GHz is presented and analyzed. The investigation is based on LNA millimeter-wave integrated circuits using 35-nm and 50-nm gate-length metamorphic high-electron-mobility transistor technologies. At room temperature, the WM-2540 waveguide modules demonstrate an average noise temperature of 214 and 247 K over the 70–116-GHz frequency range. The lowest achieved noise temperatures are 171 and 196 K. When cooling the LNA modules to an ambient temperature of 6 K, the average noise temperatures improve to 30.2 and 31 K. The lowest achieved noise temperatures are 20.7 and 19.2 K. To the best of the authors’ knowledge, the demonstrated LNAs yield the lowest published average noise temperatures at room temperature over the 70–116-GHz frequency range. Furthermore, the achieved cryogenic noise performance is among the best results published so far.

Index Terms—Cryogenic, High-electron-mobility transistors (HEMTs), low-noise amplifiers (LNAs), millimeter-wave integrated circuits (MMICs), E-band, W-band.

I. INTRODUCTION

Low-noise amplifiers (LNAs) are essential building blocks in a multitude of applications, such as radio astronomy, wireless communication, radar, imaging, radiometric systems, or earth observation. Due to an atmospheric window, the W-band is a highly-used frequency range. For instance, wireless-communications applications start at frequencies of 71 to 95 GHz (E-band communication) and comprise frequency bands of up to 109.5 GHz. Apart from room-temperature (RT) applications, in general, the lowest noise temperatures over large bandwidths are required by radio-astronomy receiver systems, such as the Atacama Large Millimeter/submillimeter Array (ALMA) where band 2 and 3 cover a combined frequency range of 67 to 116 GHz.

The best-published RT results of packaged LNAs demonstrate noise temperatures of 230 to 413 K over the full band [1] or 240 to 300 K over a smaller bandwidth [2]. For cryogenic conditions, the best results obtain a noise temperature between 18.6 and 33.3 K [1], [3].

Thus, this work demonstrates two LNA waveguide modules for applications in the frequency range from 70 to 116 GHz. The investigations comprise RT small- and large-signal results as well as detailed measurement results at cryogenic conditions. On basis of the achieved RT and cryogenic results, the utilized 35-nm and 50-nm gate-length metamorphic high-electron-mobility transistor (mHEMT) technologies are compared and discussed.

II. LOW-NOISE AMPLIFIER MODULE

The two LNAs use millimeter-wave integrated circuits (MMICs) with a total chip dimension of (1.5 × 1) mm². LNA 1 and LNA 2 are based on the Fraunhofer IAF 35-nm and 50-nm gate-length mHEMT technologies [4], [5], respectively. Both LNAs use four stages in common-source configuration with source lines as inductive source degeneration for a simultaneous noise and power input matching. LNA 1 (35-nm mHEMT) utilizes transistors with a gate width of 4 × 10 µm. LNA 2 (50-nm mHEMT) uses transistors with a gate width of 4 × 12 µm. The MMICs are designed in a grounded coplanar waveguide environment with a ground-to-ground spacing of 50 µm. Resistors are used in the gate and drain paths of the latter stages to achieve stable operation. In order to achieve maximum comparability of the two mHEMT technologies, the designs and layouts of both MMICs are realized as similar as possible. A detailed description of the utilized LNA MMICs, including chip photographs and schematic, is given in [6].

The MMICs are packaged in WM-2540 (formerly WR-10) waveguide gold-plated brass modules. $E$-plane transitions are used at the input and output of the MMICs for a connection to the waveguide. The $E$-plane transitions are fabricated on 50-µm-thick quartz substrates. An interior view of an assem-
bined LNA module, including dc and RF wire bonds, is given in Fig 1. The dc supply boards comprise additional parallel 1-kΩ resistors and capacitors as electrostatic protection.

III. MEASUREMENT RESULTS AND DISCUSSION

A. Room-Temperature Measurements

The two LNA modules are measured in WM-2540 waveguide setups. The S-parameters are measured using Keysight waveguide extensions and a Keysight PNA-X. The noise setup uses an ELVA-1 waveguide noise diode and a waveguide down-conversion mixer. The measurement results are corrected for the contribution of the down-converter noise. The room-temperature measurement results are depicted in Fig. 2 for noise-optimized biasing conditions. LNA 2 is biased with a drain voltage \( V_d \) of 0.7 V and 250 mA/mm, respectively. This results in a total power consumption of the module of 36.3 mW. The S-parameters are measured from 67 to 115 GHz (limits of the S-parameter setup) and yield an average small-signal gain of 22.2 dB (19.5 to 24.7 dB). The average input and output reflection coefficients are \(-8.2\) dB (\(-15\) to \(-5.8\) dB) and \(-15\) dB (\(-21\) to \(-9\) dB), respectively. In the frequency range from 70 to 116 GHz (limits of the noise setup), the noise temperature is 196 to 291 K with an average of 247 K. This results in a noise figure of 2.2 to 3 dB (average: 2.6 dB).

LNA 1 is biased (on transistor level) with \( V_d = 0.6 \) V and \( j_d = 250 \) mA/mm (first stage). The other stages are biased with \( V_d \) and \( j_d \) of 0.8 V and 250 mA/mm, respectively. Hence, the total power consumption of the module is 58.6 mW. LNA 1 achieves an average small-signal gain of 22.6 dB (19.6 to 24.6 dB). The average input and output reflection coefficients are \(-9.3\) dB (\(-26\) to \(-7.5\) dB) and \(-11.9\) dB (\(-17\) to \(-9.8\) dB), respectively. The noise temperature is between 171 to 283 K with an average of 214 K. The resulting noise figure is 2.2 to 2.9 dB (average: 2.4 dB). Assisted by Monte Carlo analysis, the measured noise temperature of the amplifiers includes an uncertainty of about \( \pm 25\) K (2\( \sigma \)).

In Fig. 3, the continuous-wave output-power \( (P_{out}) \) performance of both LNA modules is illustrated for noise- and power-optimized biasing conditions. The low-noise bias of the LNAs is as stated above for S-parameter and noise measurements. The power bias equals \( V_d \) at transistor level of \( 1 \) V and \( j_d \) of 300 mA/mm. For a noise-optimized bias, LNA 1 and LNA 2 exhibit an average \( P_{out} \) at 1-dB gain compression \( (P_{1\text{dB}}) \) of \(-0.6\) and \(-1.6 \) dBm. \( P_{out} \) at \( P_{1\text{dB}} \) increases to 3.8 and \( 1.5 \) dBm when using a power-optimized bias. For low-noise and power biasing conditions, a saturated output power \( (P_{sat}) \) is achieved for an input power of \(-15\) and \(-13\) dBm. LNA 1 demonstrates an average \( P_{sat} \) of 2.9 and 6.2 dBm, whereas LNA 2 yields an average \( P_{sat} \) of 2.2 and 5.1 dBm.

B. Cryogenic Measurements

At cryogenic temperatures, the noise measurement setup is based on the Y-factor method with a heated load. The hot and cold states are 50 and 20 K, respectively. The mixer at the output of the DUT for the down conversion of the test signal is outside the cryostat at room temperature. The measured noise performance is corrected for the contribution of the down-converter noise, but includes the losses of the waveguide at the output of the DUT and the vacuum window. Thus, the measured gain is slightly lower than the actual gain of the

\[
\text{S-Parameters (dB)} = 2 \text{ to } 283 \text{ K with an average of } 214 \text{ K.}
\]

The resulting noise figure is 2.2 to 2.9 dB (average: 2.4 dB). Assisted by Monte Carlo analysis, the measured noise temperature of the amplifiers includes an uncertainty of about \( \pm 25\) K (2\( \sigma \)).
LNAs. The measurements are performed over the entire 70–116-GHz frequency range.

In Fig. 4, the measured noise temperature and gain versus operating frequency are depicted at an ambient temperature of 6 K for noise-optimized biasing conditions. Additionally, Fig. 4 shows the average noise temperature for ambient temperatures of 6, 11, 15, and 18 K for the same values of $V_d$ and $j_d$. In the first stage, LNA 2 is biased with a $V_d$ and $j_d$ of 0.4 V (on transistor level) and 146 mA/mm, respectively. The other stages are biased with the same $j_d$, whereas $V_d$ is 0.7 V. The total power consumption of the LNA module is 28.8 mW. For an ambient temperature of 15 K, the obtained average noise temperature is 32.5 K (20.6 to 40.1 K) with a minimum noise temperature of 20.6 K at 71 GHz. The corresponding gain is between 21.8 and 27.7 dB with an average of 24.8 dB. When cooling down to an ambient temperature of 6 K, the measured noise temperature is reduced to an average value of 31 K (19.2 to 38.5 K) with a minimum noise temperature of 19.2 K at 71 GHz. For the measurements versus ambient temperature, LNA 2 exhibits a linear slope (noise temperature per ambient temperature) of 0.17 K/K, whereas the gain remains almost constant.

LNA 1 is biased, in all stages similarly, with a $V_d$ (on transistor level) and $j_d$ of 0.5 V and 137.5 mA/mm, respectively. The total power consumption of the LNA module is 17 mW. For an ambient temperature of 15 K, the achieved average noise temperature is 32.2 K (23.0 to 41.9 K) with a minimum noise temperature of 23 K at 76 GHz. The corresponding gain is between 19.1 and 28.0 dB with an average of 23.1 dB. When cooling down to an ambient temperature of 6 K, the measured noise temperature is reduced to an average value of 30.1 K (20.7 to 39.0 K) with a minimum noise temperature of 20.7 K at 76 GHz. LNA 1 yields a linear slope of 0.24 K/K when varying the ambient temperature from 6 to 18 K. As for LNA 2, the gain of LNA 1 stays almost constant. The measured cryogenic noise temperature of the amplifiers includes an uncertainty of about ±1.4 K (2σ).

For a comprehensive comparison of the utilized mHEMT technologies, gain and noise of the two LNAs are measured for various biasing conditions. In Fig. 5, contours of the obtained noise temperature and gain are given for an ambient temperature of 15 K. Black circles indicate measurements over the 70–116-GHz frequency range. The gain of the LNAs versus bias behaves very similarly. As already illustrated in Fig. 4, the average noise temperature for an optimized bias is almost identical. LNA 2 tolerates a wide area of biasing conditions. However, the noise contour of LNA 1 indicates that the 35-nm gate-length mHEMT technology is slightly more flexible in biasing the amplifier. For instance, $V_d$ can be varied from 0.25 to 0.8 V and a wide range of drain currents with still an average noise temperature of less than 36 K.

C. Discussion

The comparison of the achieved room-temperature and cryogenic performance of LNA 1 and LNA 2 exhibits an improvement of average noise temperatures, when cooling the amplifiers, by a factor of 71 and 8, respectively. It can be observed that, at lower frequencies, the cryogenic noise...
temperature of both LNAs improves more than at higher frequencies.

In Table I, the performance of the presented LNAs is summarized and compared to state-of-the-art results. The performance at cryogenic temperatures of the LNAs in this paper compares very well to previously-published results where only [1], [3] demonstrate lower average noise temperatures over a similar frequency range. To the best of the authors’ knowledge, the presented LNAs demonstrate the lowest published average noise temperature at room temperature over the 70–116-GHz frequency range. LNA 1 yields an average noise temperature of 214 K (noise figure: 2.4 dB).

TABLE I
STATE-OF-THE-ART W-BAND LNAs

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Techn.</th>
<th>$T_{\text{amb}}$ (K)</th>
<th>Freq. (GHz)</th>
<th>Gain (dB)</th>
<th>$T_{\text{n}}$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1]</td>
<td>100-nm InP HEMT</td>
<td>16</td>
<td>65–116</td>
<td>19.3–25.8</td>
<td>24.7 (18.6–33.3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>295</td>
<td></td>
<td>22–28</td>
<td>330 (230–413)</td>
</tr>
</tbody>
</table>

In this paper, the comparison of two WM-2540 70–116-GHz LNA modules is presented. The utilized MMICs are based on 35-nm and 50-nm gate-length mHEMT technologies. Both LNAs exhibit an excellent gain and noise performance at room temperature and cryogenic conditions. At room temperature, LNA 1 and LNA 2 obtain an average gain of 22.6 and 22.2 dB and an average noise temperature of 214 and 247 K (noise figure: 2.4 and 2.6 dB), respectively. The lowest-achieved noise temperatures are 171 and 196 K (noise figure: 2 and 2.2 dB). To the best of the authors’ knowledge, the presented LNAs obtain the lowest average noise temperatures at room temperature over the 70–116-GHz band. Simultaneously, LNA 1 and LNA 2 yield average cryogenic noise temperatures of 30.1 and 31 K with a minimum value of 20.7 and 19.2 K at 76 and 71 GHz, respectively. Thus, the achieved cryogenic noise performance of the LNAs is among the best noise temperatures published so far. Furthermore, the results demonstrate that mHEMT and InP HEMT technologies achieve comparable noise performances.

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REFERENCES