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Cryogenic Low Noise MMIC Amplifiers for U-Band (40-60 GHz)

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***Abstract*—In this work, we describe monolithic millimeter-wave integrated circuit (MMIC) Low Noise Amplifier (LNA) and mixer designs for U-Band, also known as the WR19 waveguide band (40-60 GHz). The LNAs were fabricated in NGC's 35 nm InP HEMT MMIC process. The MMICs were packaged in WR19 waveguide housings and tested for noise, both at room temperature and cryogenically. We present the results, including a comparison to the state-of-the-art, and discuss applications for amplifiers in this frequency range. To date, these are the first cryogenic 35 nm InP MMIC results covering the 40-60 GHz range. We achieved a noise temperature less than 30 K over the 40-60 GHz range, when the amplifiers were cryogenically cooled. These results are comparable with other results in the literature, and we believe are the lowest reported for MMICs in the 50-60 GHz range.**

Keywords—MMIC, cryogenic LNA, InP, HEMT, WR19, U-band.

I. INTRODUCTION

In this work, we describe monolithic millimeter-wave integrated circuit (MMIC) low noise amplifier and mixer designs suitable for use in U-band (40-60 GHz), also known as the WR19 waveguide band. Many of the applications for low noise amplifiers in this frequency range are in astrophysics, or atmospheric sounding and remote sensing. The Jansky Very Large Array, and the future next generation Very Large Array are examples of telescopes that need detectors in the 1-50 GHz or 1-115 GHz ranges. Observing from 50-70 GHz from the ground is difficult due to atmospheric absorption. However, some molecular lines which are of interest to the astrophysics community are detectable from space, outside the atmosphere, and it is these applications for detection and mapping of such molecules as redshifted Carbon Monoxide (CO) outside our galaxy, that we address here. In addition, the atmospheric attenuation which makes astrophysical observations difficult from the ground is useful for oxygen and water vapor sounding, such as in the High Altitude MMIC Sounding Radiometer (HAMSR) [1], an airborne instrument at JPL with a radiometer in the 50-60 GHz range.

Prior MMIC work in this frequency range has mainly covered 30-50 GHz (Ka and Q-Band) [2-5], as well as higher frequencies such as V-Band (60-80 GHz) [6]. Commercial MMIC LNAs exist, though at narrower bandwidth. In addition, several excellent results on MIC amplifiers have also been reported [7-10]. This work seeks to fill a technology gap for full waveguide-band WR19 MMIC cryogenic LNA and mixer designs, with useful applications in astrophysics and earth science.

II. DESIGNS

A. *Low Noise Amplifier MMICs*

The LNA chips were designed using NGC's 35 nm gate length InP HEMT MMIC technology [11]. They were fabricated onto a 50 μm thick InP substrate with through-substrate vias, thin film resistors, and metal-insulator-metal (MIM) capacitors on-chip. Two LNA designs were chosen for optimization. This involved fabricating each design with different transistor sizes while keeping the same passive microstrip structures in the layouts.

The first LNA design, or LNA1, was a two-stage chip with separated gate and drain lines for each transistor stage. The first stage used a single source via for increased source inductance with an air-bridge across the transistor, while the second stage used two source vias on either side of the transistor. Devices having 2 gate fingers, each either 45 μm, 50 μm, 55 μm, or 65 μm in total gate width, were inserted in each of the two stages for the four separate chips. Portions of the circuit were simulated using the electromagnetic simulator Sonnet to obtain better accuracy. A photograph of one of the LNA1 chip variations is shown in Fig. 1.

The second LNA design, or LNA2, is shown in Fig. 1. It was also designed with two transistor stages and had two source vias connected to each HEMT. Three versions of LNA2, with three different transistor sizes were also compared: 2 gate fingers with 40 μm, 50 μm, and 60 μm total gate width were used. Both the LNA1 and LNA2 versions were packaged into WR19 waveguide housings using alumina probe transitions with wire bonds to the MMIC. A photo of one of the packaged LNAs is shown in Fig. 2.

This work was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, for the National Aeronautics and Space Administration.

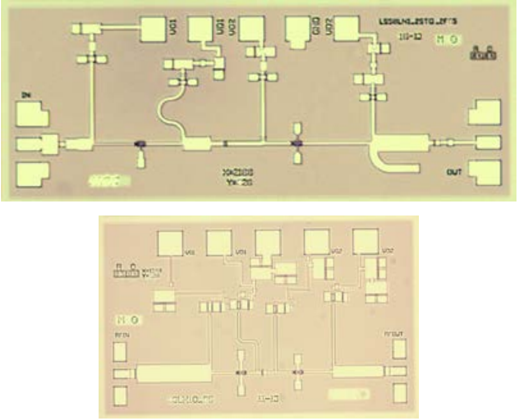

Fig. 1. Chip photos of the two LNAs described here. Top: LNA1 with 2F65 variation. Bottom: LNA2 with 2F60 variation.

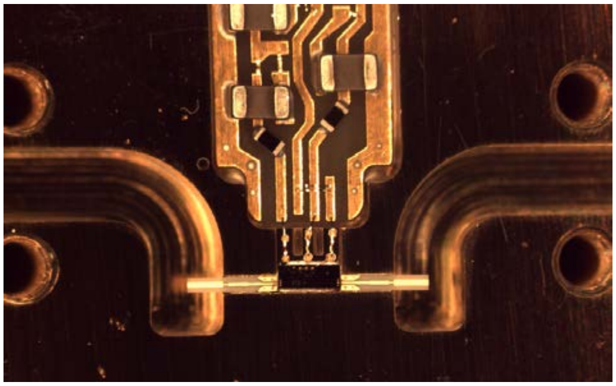

Fig. 2. Top: Interior of WR19 LNA module, showing waveguides, alumina probe transitions, and MMIC LNA (center) with DC bias board above the chip.

B. *Mixer MMICs*

For the mixer MMICs, very few mixer chips exist commercially in U-band. We wanted to have a full bandwidth mixer chip, and designed a subharmonic I-Q mixer chip for this purpose to cover the 40-60 GHz frequency range. The design was similar to those presented in [12]. We utilized United Monolithic Semiconductor's (UMS) GaAs Schottky diode process for the mixer fabrication. A photograph of one of the mixer chips is shown in Fig. 3. We packaged the mixer chip into a WR19 waveguide housing, with separate connections for the two in-phase (I) and quadrature (Q) IF ports, and a LO port, in addition to the WR19 RF port. A photograph of the mixer block is shown in Fig. 4.

III. RESULTS

A. *S-Parameters*

LNA designs packaged in a WR19 housing were tested for *S*-parameters at room temperature in the 40-70 GHz frequency range. In order to perform vector network analyzer measurements on the blocks, we had to use two experimental setups since we could not cover the full measurement band simultaneously. The LNAs were first tested from 40 to 50 GHz with a coaxial setup, and then from 50 to 70 GHz with a WR15 waveguide setup. The room temperature *S*-parameters for all the variations of LNA1 are shown in Fig. 5, and for LNA2 in Fig. 6. Some of the chips exhibited slight differences in *S*-parameters between test sets, which may be due to calibration accuracy at the band edges, or slightly different biasing conditions in the two measurement setups. Simulated results for the two chip variations are also shown in the figures.

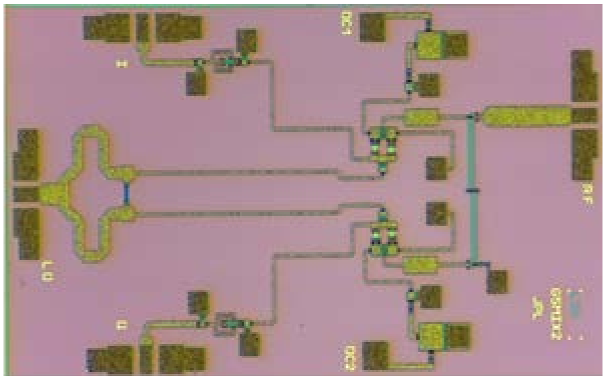

Fig. 3. Mixer chip designed for 40- 60 GHz, and fabricated at United Monolithic Semiconductor (UMS).

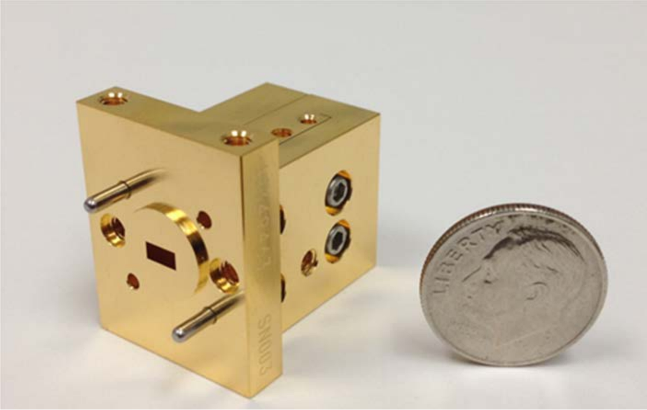

Fig. 4. Mixer waveguide housing, shown with a U. S. dime for size.

From Fig. 5, it can be observed that the best variations of LNA1 are for the 2F45 and 2F50 HEMT sizes. In the 40-60 GHz range, 2F45 features a gain of 16.5±4 dB, with input return losses better than 6 dB and output return losses better than 7 dB. Variation 2F50 has a gain of 17±4 dB, input return losses better than 5 dB, and output return losses better than 6 dB. There is reasonable agreement with the simulations in terms of the bandpass and magnitude of the return loss, and especially in the trends with increasing HEMT device size, however there are still some differences in the measured shape of *S21*. In Fig. 6, we observe that the LNA2 variations have a slightly higher and flatter gain than LNA1. For instance, the 2F60 variation has a gain of 22±2 dB, with input return losses better than 5 dB, and output return losses better than 7 dB; and 2F50 has a gain of 20±3 dB, with input return losses better than 8 dB, and output return losses better than 7 dB. Gain is higher than predicted at the lower frequencies – this may be a function of bias conditions. All of the LNAs were biased at a drain current of ~200-250 mA/mm of gate width, per stage.

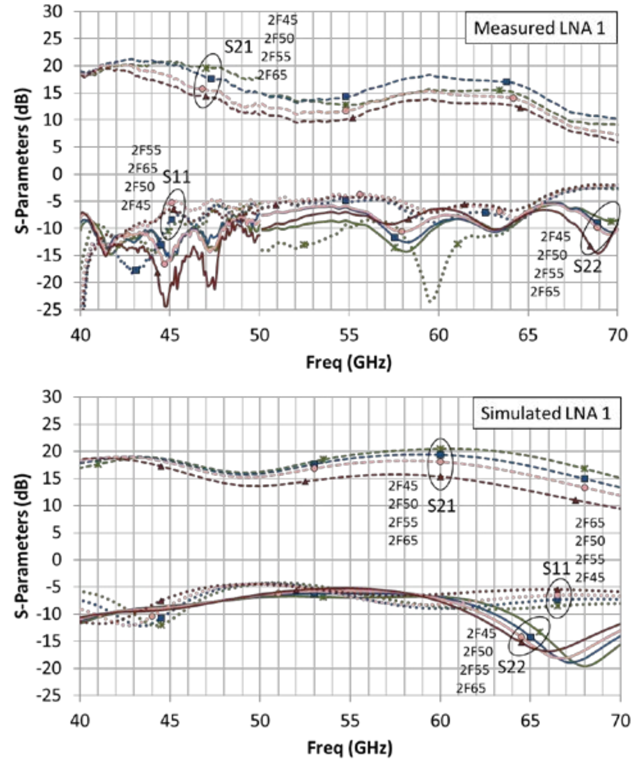

Fig. 5. Top: Measured S-parameters of the LNA1 designs with 4 different chip variations according to HEMT device size (2F45 to 2F65). Dashed lines correspond to S21, dotted lines correspond to S11, and solid lines correspond with S22. The reverse gain (S12) is better than 35 dB from 40 GHz to 70 GHz. Bottom: Simulated S-parameters for the same four variations.

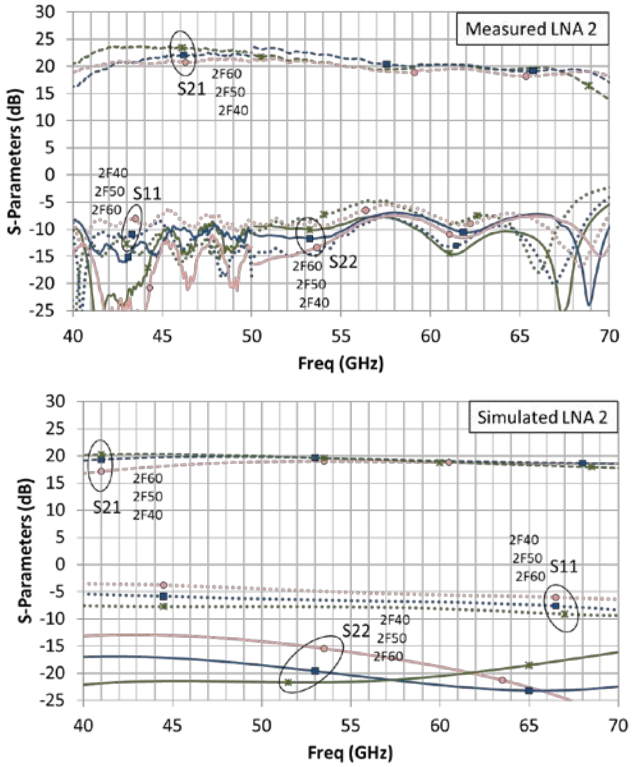

Fig. 6. Top: Measured S-parameters of the LNA2 designs. Dashed lines correspond to S21, dotted lines correspond to S11, and solid lines correspond with S22. The reverse gain (S12) is better than 35 dB from 40 GHz to 70 GHz. Bottom: Simulated S-parameters for the same three variations.

B. Noise

We tested the LNAs for noise at room temperature using the Y-factor method. A 77 K “cold” load and a room temperature “hot” load were used. The power emitted by the hot/cold loads was collected by a WR19 rectangular horn attached to the DUT, then a second LNA to minimize backend noise, followed by our custom mixer block (section 2.b) to down-convert the RF signal into the IF range, and IF amplifiers and filters to adapt the signal to the input frequency range of the power meter. By measuring the IF power generated by the cold/hot loads it was possible to calculate the noise temperature of the receiver under test. Then, by measuring and applying a correction for the backend’s noise contribution, the noise of the LNA DUT was calculated. The noise of the best LNAs tested at room temperature is shown in Fig. 7. Amplifier noise temperature of 160-200 K was observed for one of the designs from 40-60 GHz. Below 42 GHz, the mixer chip had high conversion loss, which made the noise correction less accurate than at the other frequencies. Simulated noise is also plotted, assuming 0.5 dB package loss.

After testing the LNAs at room temperature, they were inserted into a Dewar and cryogenically cooled to 30 K using a closed cycle refrigerator. The Dewar contained a 3.5 mil mylar vacuum window, which allowed application of the Y-factor method with external loads of 77 K and 295 K.

The LNAs were inserted into a test receiver similar to the one described in the previous paragraph for the room temperature tests, and a correction for the backend LNA and mixer noise contributions was applied; no correction was applied for the loss of the horn and the mylar window. The noise of the best three measured LNAs is shown in Fig. 8. We biased the LNAs for a drain current *Id* between 50-90 mA/mm of gate periphery per stage, approximately half (or less) of the room temperature bias conditions, in order to obtain the lowest possible noise. The best chip exhibited less than 30 K noise from 42-60 GHz with 21 K at 48 GHz.

IV. COMPARISON TO STATE-OF-THE-ART

In Table I the best LNAs described in this work are compared to the state-of-the-art devices in the 40-60 GHz frequency range. Prior work has included InP HEMT and mHEMT technology with several different gate lengths. It can be observed that the performance of the LNAs reported in this work are comparable to the best MMIC LNAs in the 40-50 GHz frequency range. Many of the prior reported results were cooled to 15-20 K ambient temperature, and we would expect further improvements in our noise results with additional improvements to our cryogenic system. Furthermore, not many LNAs have been developed in the 50-60 GHz frequency range, and according to Table 1, the LNAs described in this work would set a new state-of-the-art noise performance in this 50-60 GHz subrange.

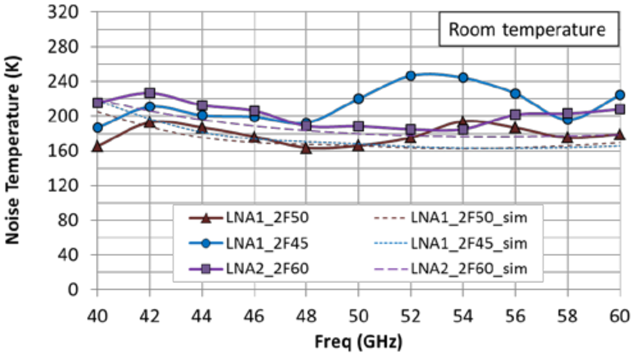

Fig. 7. Noise temperature of the best three LNAs, measured at 295 K ambient temperature. Simulated noise represented with dashed lines.

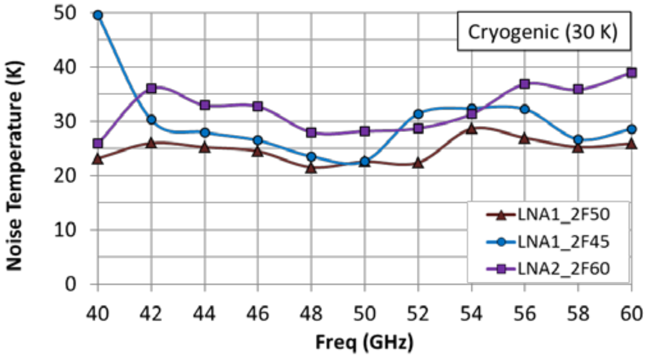

Fig. 8. LNA noise temperature of the best three LNAs, measured at 30K ambient temperature.

TABLE I. COMPARISON OF THIS WORK WITH OTHER STATE-OF-THE-ART LNAS PREVIOUSLY REPORTED

Freq. Range [GHz]	**Gain (room temperature) [dB]**	**Noise (room temperature) max - min [K]**	**Noise (cryogenic temperature) max - min [K]**	**Process**	**MIC/MMIC**	**Work Reference**
30 - 50	19.8	345 - 500	23 - 38 @ 16 K	0.15 um GaAs mHEMT	MMIC	[2]
32 - 50	29.5	262 - 390	not reported	0.15 um GaAs mHEMT	MMIC	[3]
37 - 53.2	32.5	315 - 375	not reported	0.15 um GaAs mHEMT	MMIC	[3]
35.5 - 41.5	26	not reported	18 - 30 @ 20 K	100 nm InP HEMT	MMIC	[4]
30 - 50	27.5	124 - 169	not reported	50 nm GaAs mHEMT	MMIC	[5]
35 - 46	31	< 180	< 50 @ 80 K	100 nm InP HEMT	MIC	[7]
53 - 69	31	< 300	< 80 @ 80 K	100 nm InP HEMT	MIC	[7]
33 - 52	35	not reported	9 - 25 @ 20 K	60-80-100 nm InP HEMT	MIC	[8]
40 - 48	33	not reported	8 - 16 @ 18 K	100 nm InP HEMT	MIC	[9]
40 - 60	17	163 - 194	21 - 28 @ 30 K	35 nm InP HEMT	MMIC	This work, LNA1 (2F50)
40 - 60	22	184 - 226	28 - 39 @ 30 K	35 nm InP HEMT	MMIC	This work, LNA2 (2F60)

V. CONCLUSION

In this work, we have designed and measured LNAs and mixers to cover the 40-60 GHz U-band frequency range. We performed cryogenic testing of the LNAs, and the best results achieved below 30 K noise over nearly the full WR19 waveguide band, with a minimum noise of 21 K at 48 GHz, when cooled to 30 K ambient. Such LNAs may be useful for the next generation of the Very Large Array, or future instruments for astrophysics or earth remote sensing.

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