High Output Power Low Noise Amplifier Chains at 100GHz

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***Abstract* — Low noise amplifier (LNA) chains at 100GHz were constructed to be used as highly sensitive detectors in the development of the Haystack Ultra-wideband Satellite Imaging Radar (HUSIR). Three separately packaged MMICs are combined to provide a highly sensitive millimeter-wave detector. The LNA chip is a 0.1 micron InP based chip [1]. This is followed by 0.1 micron GaAs based driver and power amplifier MMICs [2]. This combination provides more than 50dB of gain over a frequency range of 90 to 100GHz with 50K noise temperature when measured at 20K ambient temperature. This chain provides enhanced functionality for the Haystack Ultra-wideband Satellite Imaging Radar (HUSIR).**

***Index Terms* — ground based radar, high gain amplifier, direct detector, millimeter waves, InP HEMT LNA, high power GaAs MMICs.**

I. Introduction

The primary function of HUSIR will be to track and image satellites for the U.S. Space Command. To improve the imaging capabilities of HUSIR, wideband and sensitive W-band receivers are required. One of the key-components would be W-band LNAs optimized for these receivers, when cooled to 20K.

The W-band MMIC LNAs [1] and MMIC driver amplifiers [2] that have been used in this study were originally developed for ground-based and space-born radio astronomy. In this study those LNAs and amplifiers were utilized to construct sensitive receiver chains with high gain and low noise temperature. Four LNA chains with comparable performance were characterized. The measured results are presented and guidelines for a safe RF input power range are provided.

II. LNA CHAINS

The LNA chains were tested in a cryostat capable of reaching temperatures below 20K by using two Watts cooling power generated from a closed cycle helium refrigerator. The input and output of the chains were connected to calibrated WR-10 waveguides which include 12.7 micrometer thick vacuum windows made of Mylar. A U-shaped bracket made of copper provided optimal thermal contact to the cold-head. An active temperature controller using calibrated Si-diodes was utilized to keep the temperature variation on the LNA below 0.1K. In order to minimize the thermal conduction of the bias connections, seven duo-twist phosphor bronze wires from Lake Shore, each with 0.127mm diameter and 30cm length, were thermally connected to the 70K stage of the cold-head.

Figure 1 shows a complete LNA chain before it was installed into the cryostat. The noise temperature of the LNA MMIC was less than 50K with more than 20dB gain in the targeted frequency band from 92 to 100GHz at 20K operation temperature.

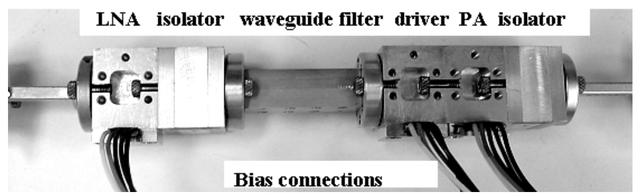

Figure 1: On the left side the input waveguide was attached to the LNA, followed by a WR-10 isolator and a very narrow banded waveguide filter (both made by Millitech). A driver and power amplifier stage provided sufficient system gain. A WR-10 isolator was attached on the output (right side). The total dimensions of the assembled chain were 20x20x160 mm.

A compact and low loss WR-10 isolator was implemented in order to reduce the impedance mismatch between the output of the LNA and the narrow-band WR-10 waveguide filter. Impedance matching at the output was achieved by a second isolator. The bandwidth of the WR-10 filter was designed to cover 92 to 100GHz with 80dB rejection outside the band (Figure 2). The cut-off condition of the waveguide at low frequencies naturally provides for the rejection, but at high frequencies it was necessary to implement a Chebyshev filter with 80dB rejection out of band. Additional rejection at frequencies greater than 103GHz was provided by the roll-off slope of 1.1dB/GHz from the power amplifier when integrated in the LNA chain. Impedance matching at the output was achieved by a second isolator. In Figure 2 the band-pass of the prototype filter is displayed. It was initially tuned too low at room temperature. When the filter was cooled to 20K the band shifted upward by 0.5GHz. In order to properly adjust the bandwidth of the filter an appropriately designed shim was introduced between the two block halves. When shaving off or adding material between the split blocks the first-order effect was that the band-pass could be adjusted and the second-order effect was that the bandwidth could be adjusted.

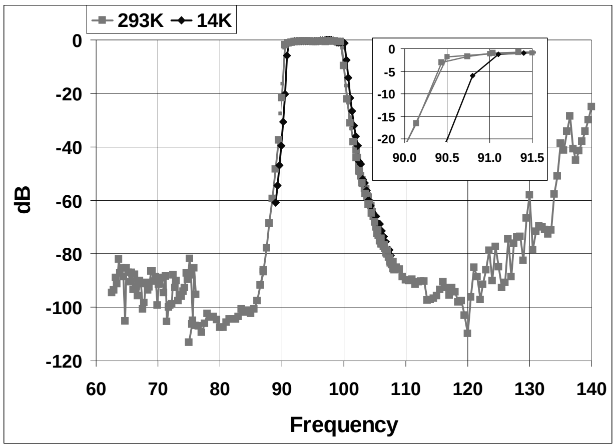

Figure 2: Measured band-pass characteristic of the prototype w/g filter at 300K and at 20K. The total power was determined with a calorimeter from Neal Erickson [3] (0.1microwatt to 200mW) and a vector network analyzer.

III. RF INPUT POWER LEVEL

A major concern in radar applications, aside from reliability [4, 5], is that high RF power may leak into the front-end of the LNA chain. Therefore the minimum RF level that would cause damage needs to be determined. An indirect method is to observe the MMIC for changes in the DC bias conditions after the RF is removed. In this study, three different LNA chips from the same wafer were exposed to excessive RF powers at 20K in order to determine the maximum safe RF input power. The RF power was increased in steps and applied for at least five minutes to allow thermal heating to stabilize. Some of the measured DC bias conditions under increasingly higher applied RF powers are presented in Figure 3. At each increment, the bias conditions were compared to the initial recorded values without applied RF in order to check for permanent damage.

The biases of the LNA were separated as follows: Each LNA MMIC contained 4 FET stages each with two 2x20 micrometer fingers. The first and second stages were biased with a single gate power supply (Gate 1) and the third and forth stages were biased with an independent supply (Gate 2). All of the drains were biased together.

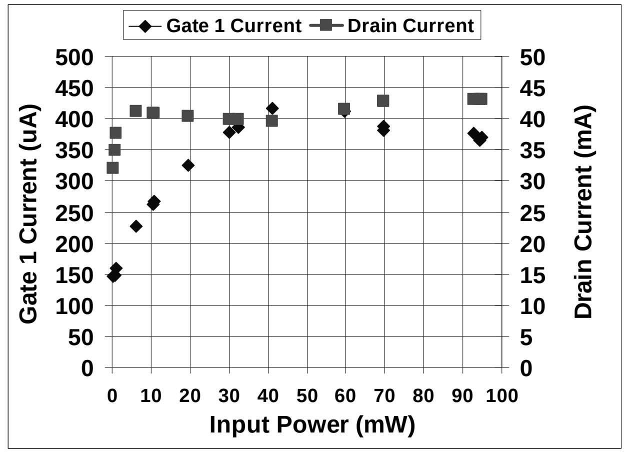

Figure 3: Measured bias conditions while RF was applied. Displayed are the changes in gate 1 bias current and drain current on one of the three LNAs when exposed to high RF input power. Permanent damage was observed above 40mW levels. No changes on gate 2 were observed.

The effect of high RF input power was detected on the drain current much earlier than at the gate 1 current. This is a result of small changes in the gate bias condition causing large changes of the drain current. The change in drain current at 0.5mA was in most cases nearly two times that of the initially measured bias conditions without RF applied. At these high RF levels the LNA did not contribute to the gain anymore because it was saturated already at a fraction of a microwatt. A maximum drain current was observed at RF levels around 10mW. When the RF power was increased above 10mW the current decreased by 10%. At RF levels above 40mW, permanent changes in the bias parameter were detected. The slope of the gate 1 current remained close to zero until the RF reached 1mW. Above this value the gate current increased nearly monotonically to more than a factor of 2 from the initial value. However, no change on gate 2 was observed down to the microampere level. This indicates that mostly the first two stages of the LNA were impacted by the applied RF.

The degradation of noise temperature was measured on one LNA only. It was confirmed that the noise temperature of the LNA degraded in concert with the changes in DC condition at levels above 40mW RF input power.

Additionally it was investigated whether RF power applied to the LNA at zero bias voltages would impose risk to the device. The induced currents for this condition were 240uA on gate 1 and 1mA on the drain at 20mW input power. The nominal bias conditions were used as the base-line to compare the actual measurements at each increment of RF power. No change was detected when a

RF level of 20mW was applied over 48 hours. In addition, the bias conditions were verified at 0.1mW, 0.2mW, and 0.3mW output power. Any change in input coupling on the first FET would have indicated a change from the initial bias values. However no changes in bias were detected.

The test confirmed that the LNA device would survive in an emergency “bias-supply-off” state, probably due to mismatching of the incident power when no bias voltage is applied. These results show that the LNA is much more robust than anticipated and that the incident RF power can be monitored even under saturation by monitoring the drain current for input power levels below 0.5mW and by the gate current for higher RF levels. These currents could be used as indicators of the applied power level even if the LNA is saturated.

In order to budget sufficient margin, it is not recommended to expose the LNA to RF levels above 10mW when biased at nominal conditions, assuming that 6dB de-rating is sufficient to maximize the LNAs life time. At this RF level the calculated power per micrometer gate length (2x20micrometer) was 250uW/um. Further investigations need to be performed to determine the effect of pulsed RF power to the LNA.

IV. STATE-OF-THE-ART PERFORMANCE

Optimal performance of the LNA chains was obtained by trading-off noise temperature, gain, 1dB compression point, and DC power consumption. A number of iterations on the combination of LNA, driver, and power amplifier were performed to satisfy most of the trade-off conditions. The performance of the final configuration of the four LNA chains was measured and the results are displayed in Figures 4-6.

The driver and power amplifier drains dominated the power consumption. Thermal dissipation was minimized at the expense of the 1dB compression and the gain. In this case the gate voltage was reduced until the amplifiers became current starved where gain and compression are a rapid function of gate voltage which is called the region of pinch-off. Above this point the gain and compression improved marginally with increasing gate. This is the most efficient operation point for these amplifiers but the 1dB compression point was reduced by about 2dB and the gain by about 1.5dB. However, the thermal dissipation was reduced by 50% which was very important to reduce the required cooling power. The maximum allotted power dissipation was 2W but the power dissipation was 1W under nominal operation.

Optimum gain (~22dB) of the LNA was observed to occur at $V_d \approx 0.9V$. The contribution to the drain current from Gate 1 was 4-7mA and for Gate 2 it was 3-5mA when optimized for noise temperature and gain. Both gates had similar voltages when optimized. The driver amplifier (~15dB) had its best gain between V_d = 2.2 and 2.6V at 20K. Increasing the drain current by applying positive gate voltage improved the gain slightly in the 92-100GHz range. While the best performance was observed at the maximum current tested, it should be noted that the gain difference between 200mA and 300mA was less than 0.5dB. The power amplifier (~22dB) had its best gain at 2.2V at 20K. Increasing the drain current by applying positive gate voltage increased the gain until about 320mA was reached. There was less than 0.5dB loss in gain when the current was reduced to 250mA.

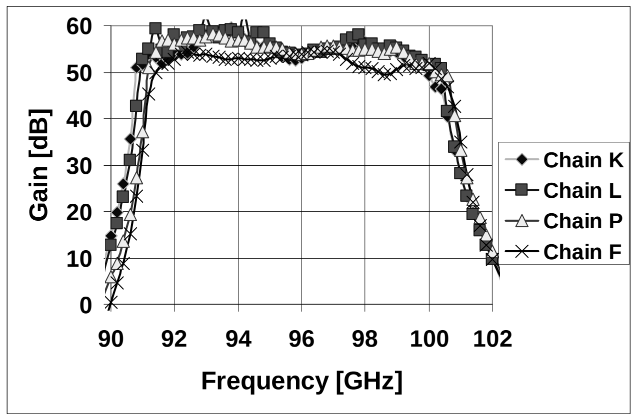

Figure 4: Measured gain of four LNA chains.

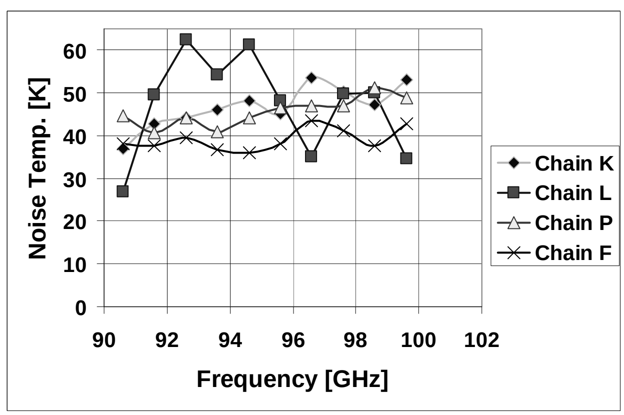

Figure 5: Measured noise temperature of four LNA chains.

In figure 5 the overall noise temperature is provided. The LNA noise dominates the noise temperature of the LNA chain. The driver and the power amplifier contributed approx. 10% to the noise temperature due to their noise figure of roughly 8dB. Excess noise had been observed in similar amplifiers when biased higher than 3V with maximum rated current on the drain.

The 1dB compression point (see Figure 6) was limited by either the driver or the power amplifier depending on their operation point. The compression point was always increased with increasing drain voltage. In this study the best compression was at 3V for the driver and 3.2V for the power amplifier. Additionally, more drain current resulted in a slow increase in compression point. Typically the improvement was 0.2dB from the nominal current to the current limit. The measured 1dB compression point was observed to be between 10 to 16dBm.

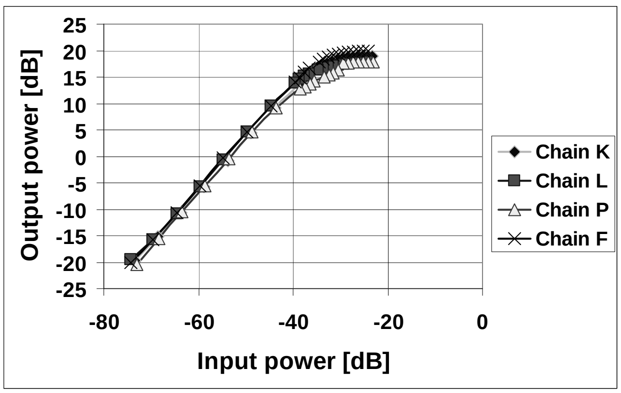

Figure 6: Measured 1dB compression point of four LNA chains at 96GHz.

V. CONCLUSION

State-of-the-art MMICs that have been primarily designed and developed for astrophysics applications have been utilized to develop a wide-band low-noise millimeter-wave detector for radar. By optimizing low-noise and high-gain a compact chain that provides more than 50dB of gain with 50K of noise temperature has been demonstrated (at 20K). The 1dB compression point of a nominal chain is measured to be between 10 to 16dBm. Safe RF and operating conditions for these chains have been investigated for their utilization in radar applications.

VI. ACKNOWLEDGEMENT

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