Electronics Division Internal Report No. 333

GaN Power Amplifier Development Study for ALMA Band 10 Local Oscillator

P. Mondal, D. Vaselaar, K. Saini, B. Hawkins

Abstract

The suitability of Gallium Nitride (GaN) power amplifier (PA) for use in the ALMA Band 10 local oscillator (LO) is explored. PAs have been developed using the GaN high electron mobility transistor (HEMT) MMICs from Hughes Research Laboratories. Necessary experimental studies are performed with view of requirements for its use in ALMA Band 10 LO.

1. Introduction

Gallium Nitride (GaN) high electron mobility transistor (HEMT) MMICs [1], [2] have the capability to provide high output power density. Availability of W-band off-the-shelf GaN power amplifier (PA) MMICs made it possible to explore the possibility of using it for ALMA Band 10 local oscillator (LO). PAs have been developed using a PA MMIC with the balanced amplifier configuration from Hughes Research Laboratory (HRL) mounted in a split block amplifier housing.

2. ALMA Band 10 LO System and the existing PA

The ALMA band 10 receiver operates over the RF frequency band 787 – 950 GHz and employs an LO with the minimum and maximum frequencies of 795 GHz and 942 GHz, respectively. A Block diagram of the LO system [3] is shown in Figure 1. which illustrates four basic modules: (i) YIG tuned oscillator covering 14.7 – 17.4 GHz, (ii) active multiplier chain (AMC), (iii) the power amplifier (PA10), and (iv) cryogenic frequency

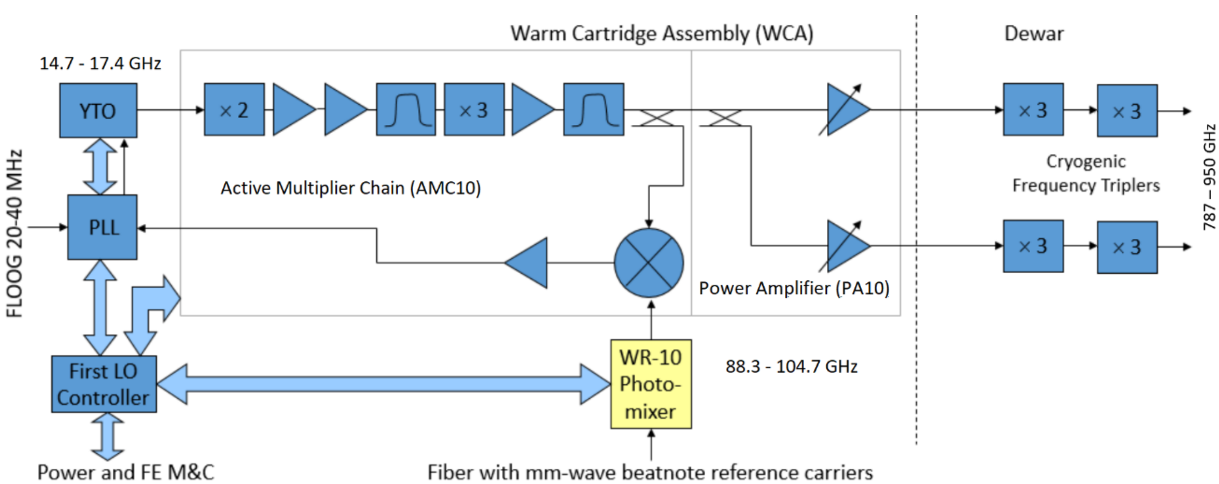
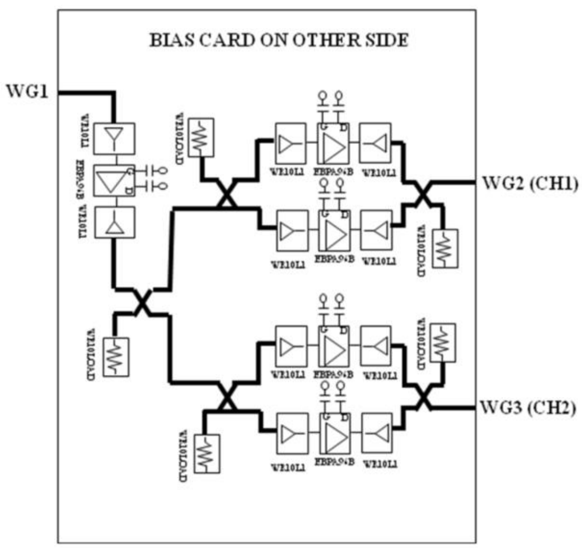


Figure 1 Block diagram of ALMA Band 10 LO system.

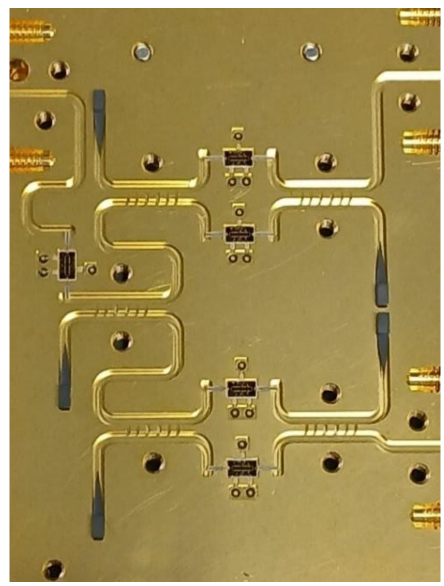
triplers. Varistor triplers are used to satisfy wide bandwidth requirements and placed inside cryostat to minimize the LO signal attenuation after this stage of frequency multiplication. Drive power in excess of 100 mW is required at the input of the cryogenic tripler stage in order to drive the SIS mixers adequately. DC

Table 1 DC and RF Specifications of PA10

DC Specifications			**RF Specifications**		
Voltage (V)	Tolerance (V)	Max. Current Draw (mA)	Frequency (GHz)	Input Power (mW)	Output Power (mW)
+ 15	+/- 0.5	20	88.333-104.667	5-20	> 100
- 15	+/- 0.5	20			
+ 6	+/- 0.5	2500			



(a)



(b)

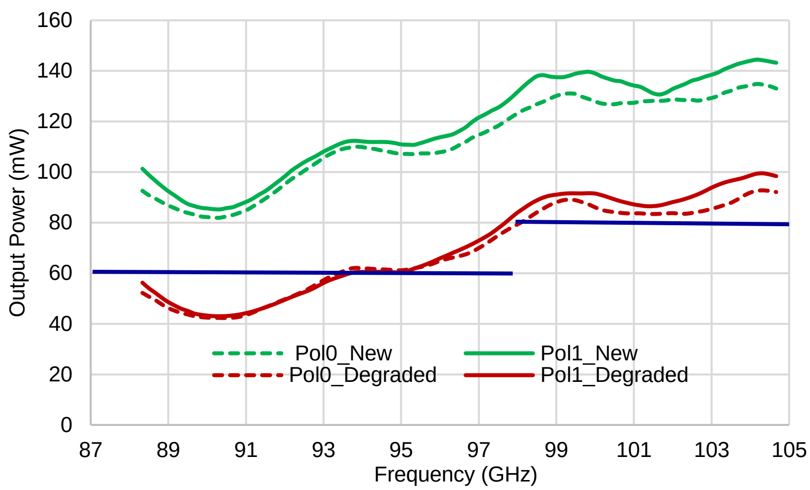
(c)

Figure 2 (a) Block diagram of the existing two channel PA10, showing two PA MMICs in each channel, power combined using 3-dB hybrid couplers, (b) photograph of one half of the split block assembly, showing the physical implementation and (c) the fully packaged amplifier.

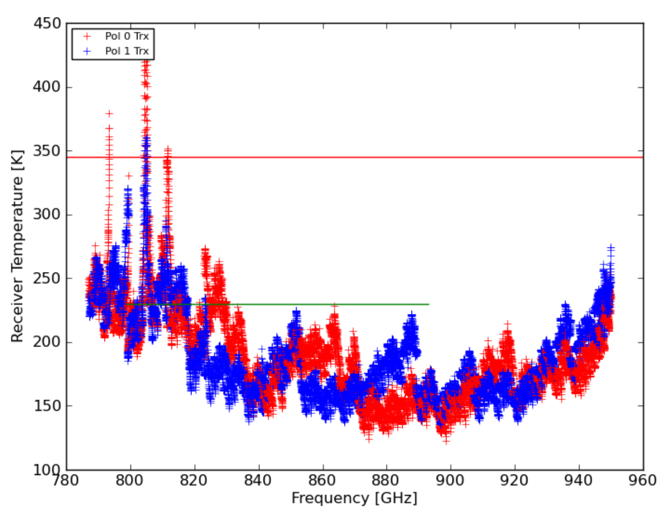
and RF specifications of the PA are listed in Table 1. The existing PA is based on power combined GaAs pHEMT MMIC, EBPA96B, as shown in Figure 2.

3. Motivation for an alternative PA

Measured performances (green lines) of a two channel warm cartridge assembly (WCA) (AMC+PA10) [4] with EBPA96B GaAs pHEMT PA MMICs are shown in Figure 3(a). It produces < 100 mW power at the lower frequency end. Thus, a compromised specification has been used and the blue lines in the figure indicate the minimum power requirements at the lower and higher frequency bands. Thus, the ALMA Band 10 receiver is LO starved at the lower frequency band and the non-compliant receiver noise temperature is illustrated in Figure 3(b), the green line being the acceptable receiver noise temperature. Moreover, there is degradation of its output power over time (red lines in Figure 3(a)). There are 80 Band 10 WCAs in total.



(a)



(b)

Figure 3 (a) Output power of the installed WCAs and after failure, (b) receiver noise temperature with LO frequency.

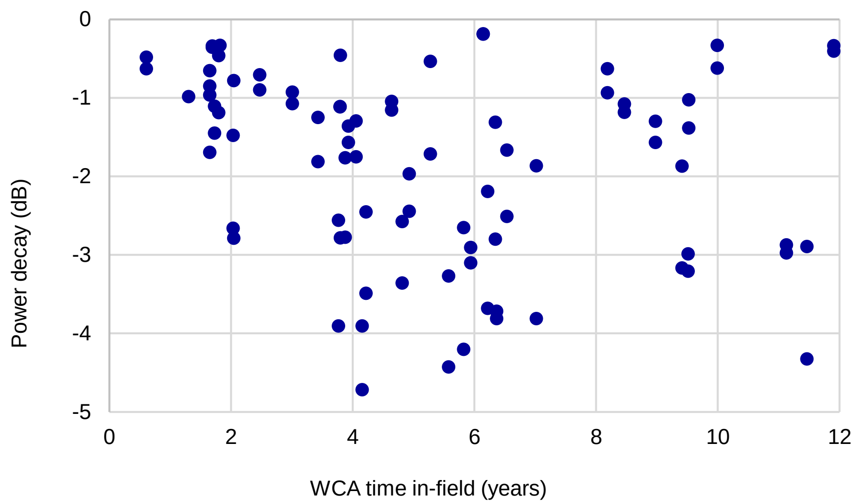


Figure 4 Measured output power of the Band 10 WCAs returned from the ALMA telescope presented as a scatter plot versus years that the WCA was deployed in the field. Note: the number of years of deployment is not a true representation of the actual duration the WCA was turned on and used.

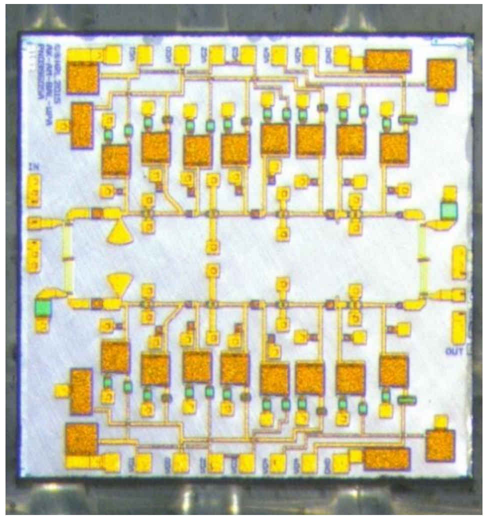
From 2014 to 2024 there have been 73 Band 10 WCA repairs completed at NRAO. Of the 73 repairs, 63 have had output power problems [5] and needed to have their power amplifiers refurbished to replace the PA MMICs with new devices. Figure 4 is the scatter plot of the output power decay of the Band 10 WCAs returned from the ALMA telescope as a function of the number of years the WCAs were in the field. Note that the calculated number of years of each WCA has been in-the-field is determined by the time difference of the respective WCA last measured at CDL, it is not the actual ON duration of each WCA. To find a solution of the LO starvation and long-term output power degradation, alternative PAs with similar form factor and power dissipation to the existing amplifier are required. Commercially available solutions are Indium Phosphide (InP) Heterojunction Bipolar Transistor (HBT) from Teledyne and GaN HEMT from HRL. InP HBTs have been previously studied for a different ALMA band and are being used. So, this study is focused on characterizing the performance of GaN MMIC based PAs.

4. Development of GaN MMIC Based PA

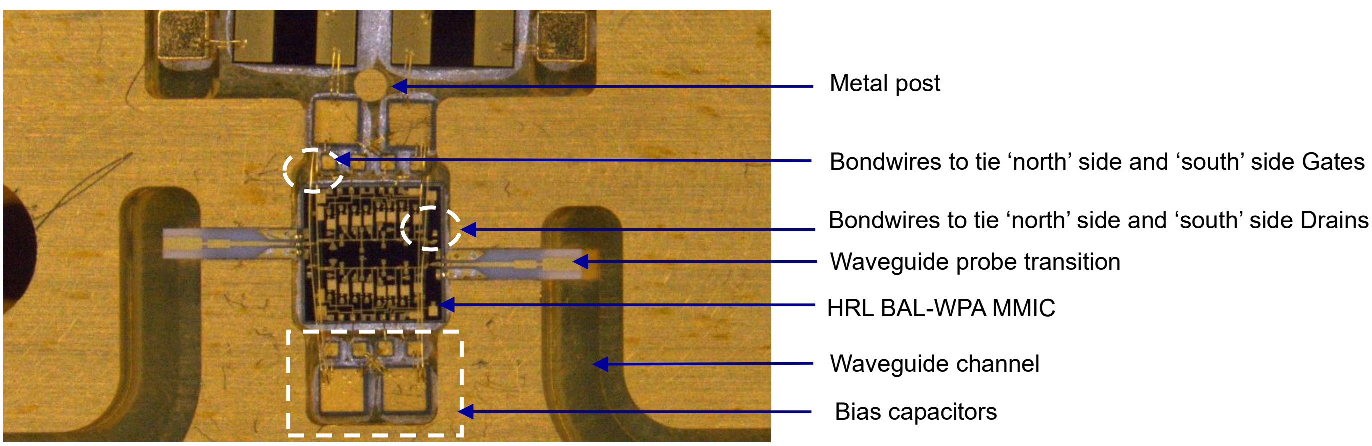
A balanced W-band MMIC [6] from HRL, operating over 70 – 105 GHz was used to develop the PAs with an output power of 100 mW over the desired frequency band 88.333 – 104.667 GHz. Following are the device characteristics of the candidate MMICs:

- Pout: 20 dBm
- Gain: 15 dB
- Bias: V_d = 12V, I_d = 90 mA
- Chip dimensions: 2.23 x 2.18 x 0.05 mm.

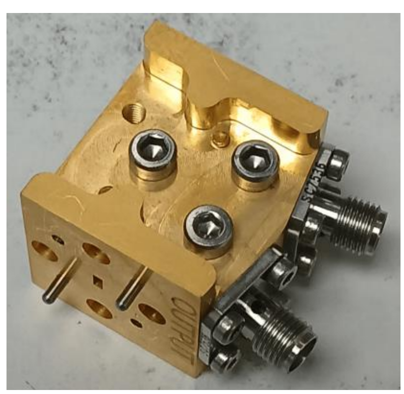
A photograph of the MMIC is shown in Figure 5(a). It is a balanced four stage power amplifier fabricated using HRL's T-gate GaN HEMT process (GaN-on-SiC). PA housing especially designed for the candidate MMIC and incorporating the biasing arrangement recommended by HRL was fabricated as a brass split-block at the CDL machine shop and gold plated. 0.7 mil diameter bondwires were used for wiring the bias chip capacitors and resistors and configuring to the MMIC (Figure 5(b)). A cylindrical metal post was used to prevent any unwanted cavity mode oscillation. An oscillation was observed at 67 GHz, and it was removed by placing foam absorber around the PA MMIC in the cavity of PA housing. “North side” and “south



(a)



(b)



(c)

Figure 5 Photograph of the (a) MMIC, (b) detail of the region showing the micro assembly of the PA in the split block and (c) packaged PA.

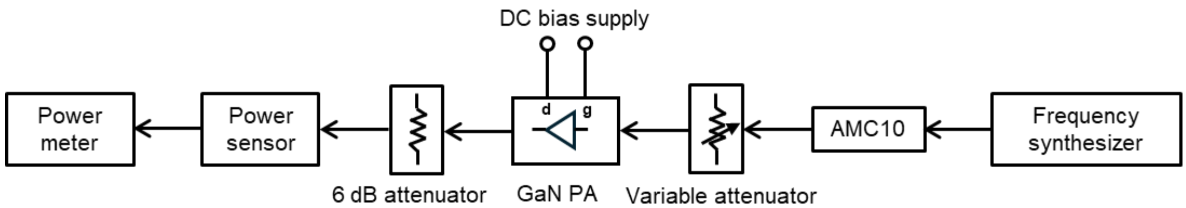
side" Gates were bonded together through bias capacitors by using bondwires across the MMIC as shown in the figure. It is followed for the Drains also. This arrangement allowed us to use only two bias points instead of four: one for the Gate and the other for the Drain. SMA connectors were used for the Gate and Drain biasing. The waveguide to microstrip transition was used to couple the signal from the input WR-10 rectangular waveguide on to the MMIC input and off the MMIC output back into the output waveguide. An existing design on 89 μm thick Alumina substrate: WR10L1; being used for the GaAs MMIC PA10 has been used for this.

5. Experimental Studies

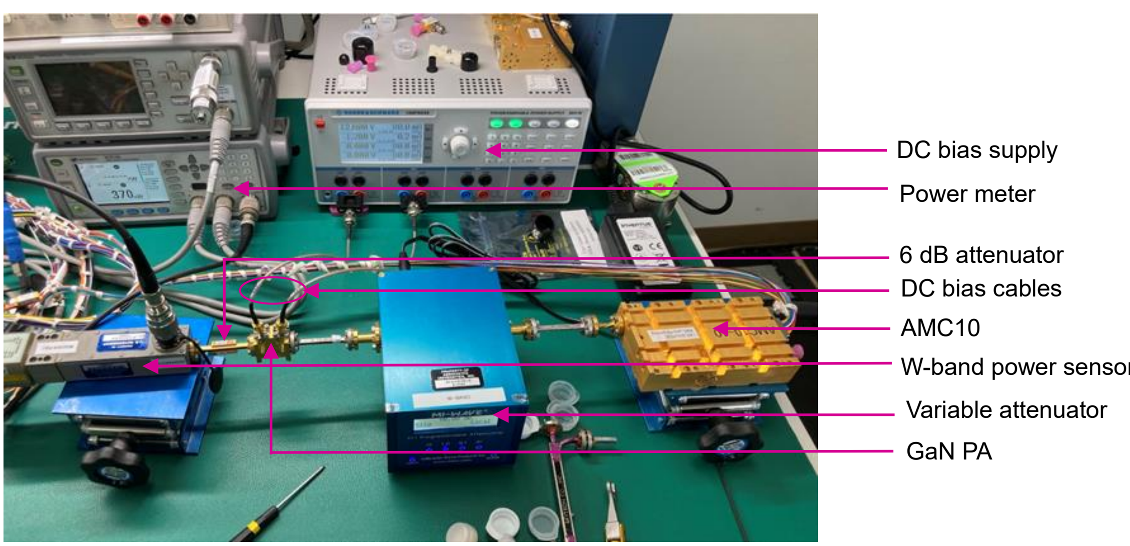
The selected GaN HEMT is a depletion mode device. For this device, the channel is active and large current flows from Drain to Source even if at 0V Gate bias. Thus, to initially set up the DC bias of the amplifier, the Gate voltage is set to the value recommended in the datasheet which is -6 V, then the Drain voltage is adjusted to +12 V. Subsequently, the Gate voltage is adjusted to obtain the nominal Drain current I_d = 90 mA. The same biasing sequence is maintained throughout the experiments to avoid permanently damaging the amplifier by accident.

5. 1 Output Power

The block diagram and photograph of the output power measurement setup is shown in Figure 6. A Frequency synthesizer and a Band 10 AMC were used to drive the PA. Figure 7(a) shows the output power



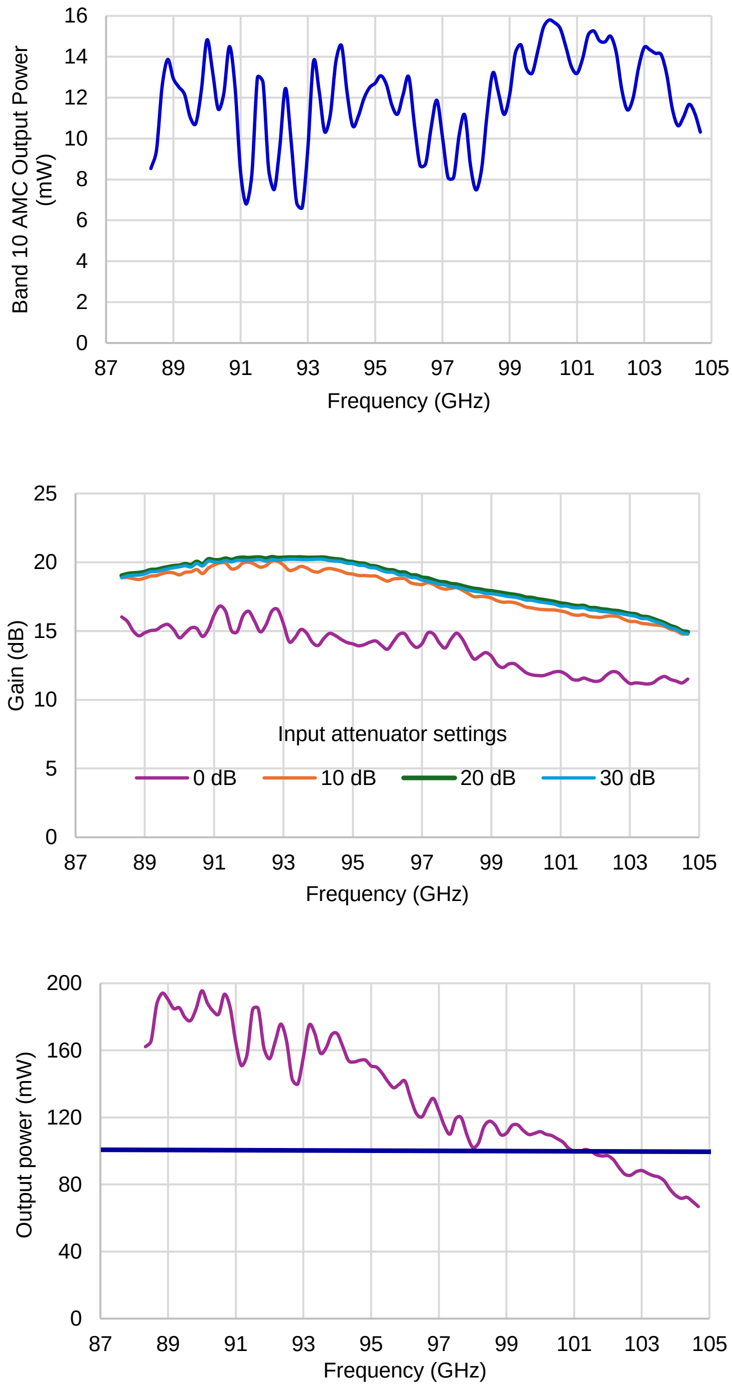
(a)



(b)

Figure 6 (a) Block diagram and (b) experimental setup used for making the output power measurements.

of the AMC10 (representing the input to the PA) at its nominal bias condition. A variable attenuator was used to vary the input power of the amplifier to evaluate the saturation performance of the amplifier. The input power range of the Keysight waveguide power sensor W8486A is -30 to + 20 dBm and it stops reporting data for a power above 100 mW. So, a W-Band 6 dB attenuator is used after the PA under test as



(a)

(b)

(c)

Figure 7 (a) Band 10 AMC output power, (b) gain variation vs frequency of the GaN PA as a function of input power, (c) Saturated output power from the PA DUT.

the expected output power from HRL datasheet is 20 dBm. Bias point was set at Vd = 12 V and Vg = -1.2 V. Reduction of the gain was observed as the attenuation was reduced from 10 dB to 0 dB (Figure 7(b)). So, the amplifier is in saturation at the attenuator setting of 0 dB and the corresponding output power from the PA is shown in Figure 7(c). This amplifier produces 100 mW of output power up to 101 GHz. High gain slope is observed at the higher frequency end, which strangely, contrasts with the S-parameter data in the HRL datasheet.

5. 2 AM Sideband Noise

The amplitude and phase flucttutation of the sine-wave generated by an oscillator system can give rise to amplitude modulation (AM) noise or phase noise modulation (PM) noise, respectively. AM noise sidebands are in-phase with each other and PM noise sidebands are 180^{o} out-of-phase [7], [8]. So, when it is downconverted to the same intermediate frequency (IF) AM sideband components add coherently and PM sideband components cancel each other. As a result, single ended mixers are only sensitive to the LO's AM noise sideband components. ALMA SIS mixers are single-ended. However, there could be conversion between these two forms of noise modulation. AM noise in the LO sidebands is indistinguishable from other receiver noise and degrades the receiver sensitivity. AM noise of an amplifier can be reduced by driving it into saturation such that the output voltage saturates and no longer varies with small changes in input voltage. Block diagram of the AM sideband noise measurement setup used to characterize the sideband AM noise of the LO signal is shown in Figure 8.

The AM noise measurement was performed at 50 mW of constant LO power. The bias was adjusted to keep the output power level fixed at this value. AM noise performance of the WCA at this input power level with the existing GaAs PA10 [4] as well as the prototype GaN PA are shown in Figure 9. The requirement for the maximum AM noise averaged over 4-12 GHz IF bandwidth for ALMA Band 10 is 20 K/μW and Figure 9(a) shows that it is within the limit.

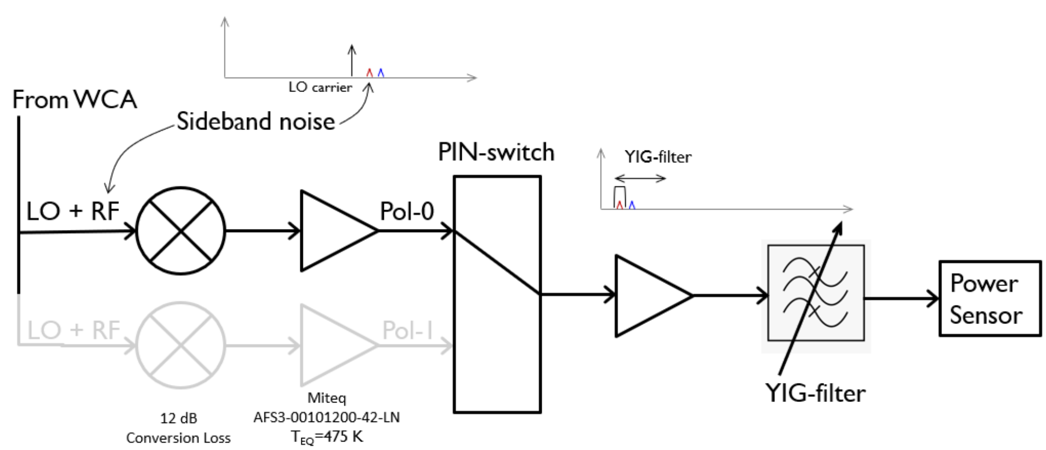
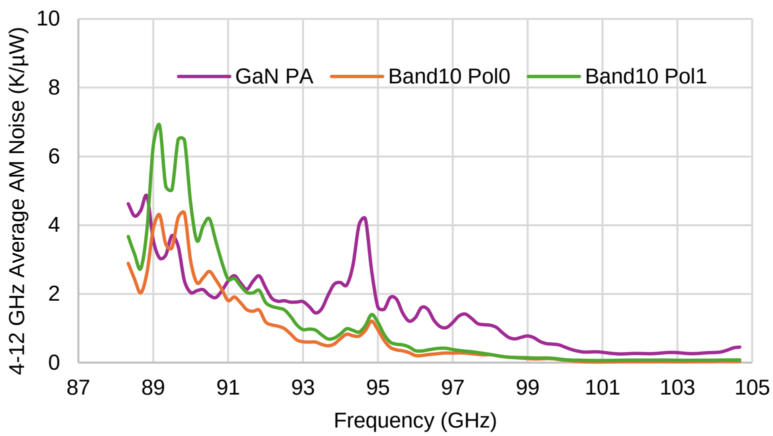
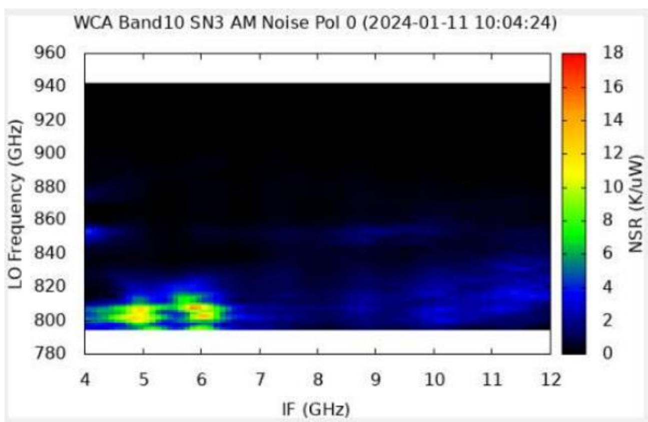


Figure 8 Block diagram of the AM sideband noise measurement setup.

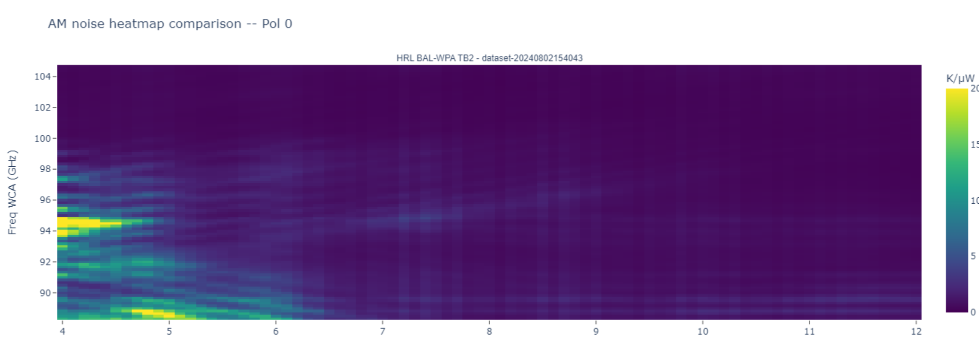
The phase noise measurement is performed with a spectrum analyzer by using direct spectrum analyzer technique. A 30 MHz signal is generated beating the amplifier output signal with a harmonic mixer with another signal generated by the signal generator and multiplier. This measurement setup can not differentiate between AM and PM noise since the spectrum analyzer does not look into the phase relationship between the sidebands. Additionally, instrument phase noise, AMC, and mixer phase noise



(a)



(b)



(c)

Figure 9 (a) Average AM noise of the WCA over the IF bandwidth with GaN PA compared to the existing PA10.The requirement of 20K/μW (average) is met. (b) AM noise at each IF over LO frequency band of the WCA with the present PA10, and (c) corresponding plot for the GaN PA.

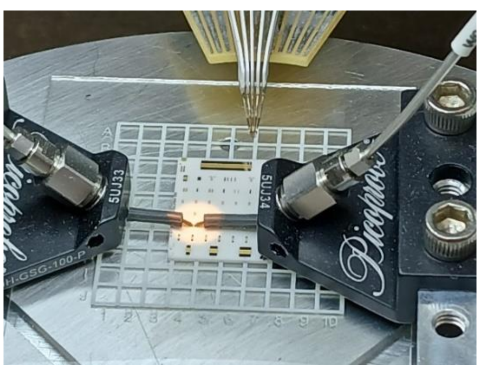
also contribute to the overall “measured” phase noise. These extra contributions make the test data appear worse than actually it is. In our case it still meets the specifications. The calculated jitter obtained by integrating the phase noise over 10 Hz to 10 MHz offset from the carrier at 104 GHz is ~ 22 femtosecond which meets the jitter requirement of 38 femtosecond for ALMA.

5. 3 RF Probing

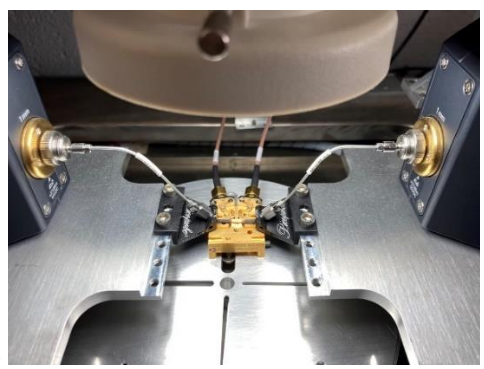
Probe station measurements were carried out to better understand the effect of amplifier housing (RF) and bondwires (DC biasing) on the packaged amplifier performance and to determine the reason behind the measured gain roll off described earlier. Figure 10(a) shows the probe station meaurement setup. The PNA Network Analyzer N5222B is connected to the probe station through the PNA Millimeter Test Set N5292A. The VNA is calibrated at the probe tip reference plane by using short, open, load, thru (SOLT) standards. Input power at the VNA port was set at -10 dBm. The measured gain of the amplifier is shown in Figure 11

(a)

(b)



(c)



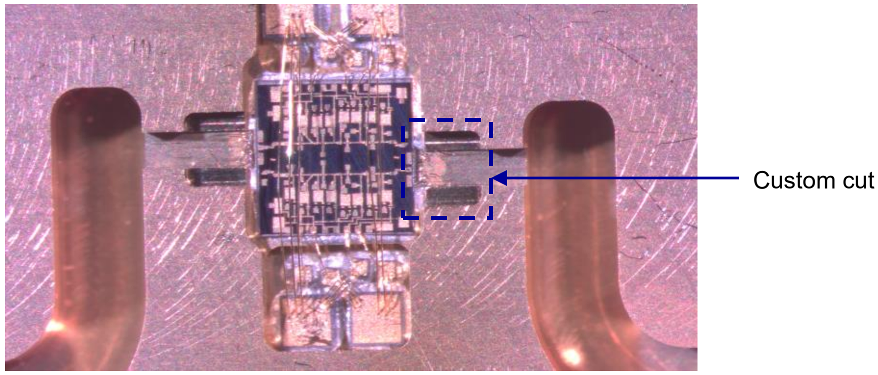
(d) 

Figure 10 (a) Probe station measurement setup, (b) SOLT calibration, (c) amplifier under test, (d) close-in view of the packaged MMIC prepared for probe tests. The input and output waveguide transitions were removed, and the block modified to incorporate a custom cut out to make it wide enough to contact the MMIC G-S-G pads for RF probing.

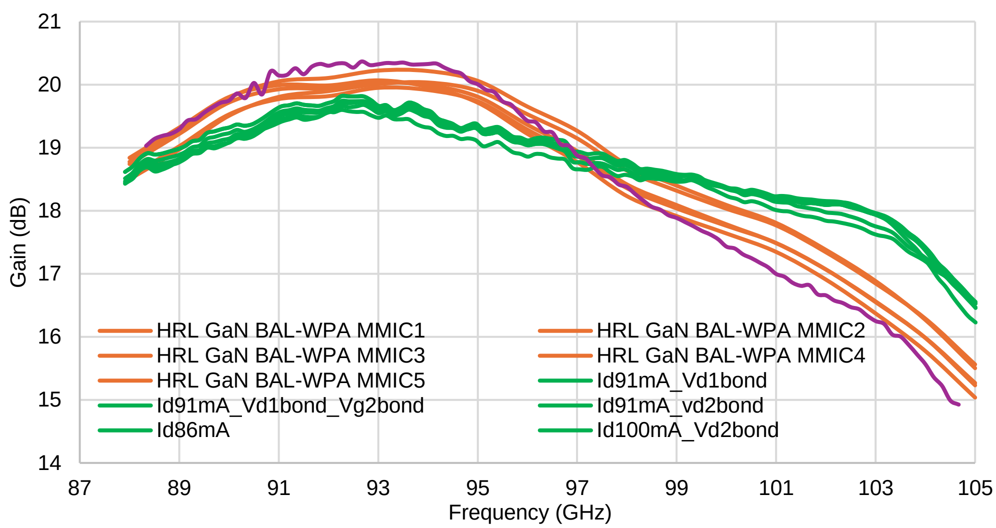
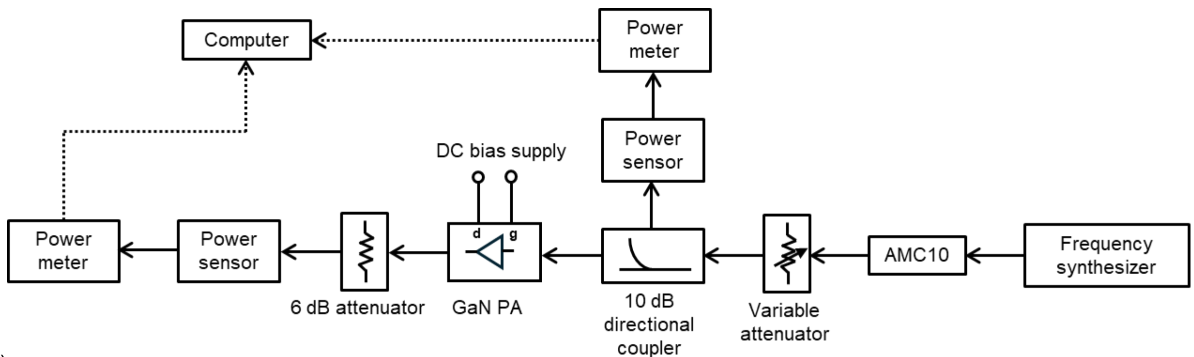


Figure 11 Comparison of small signal gain measurements data from HRL (orange-traces), RF probing at NRAO (green-traces) and packaged PA measurements (purple-trace).

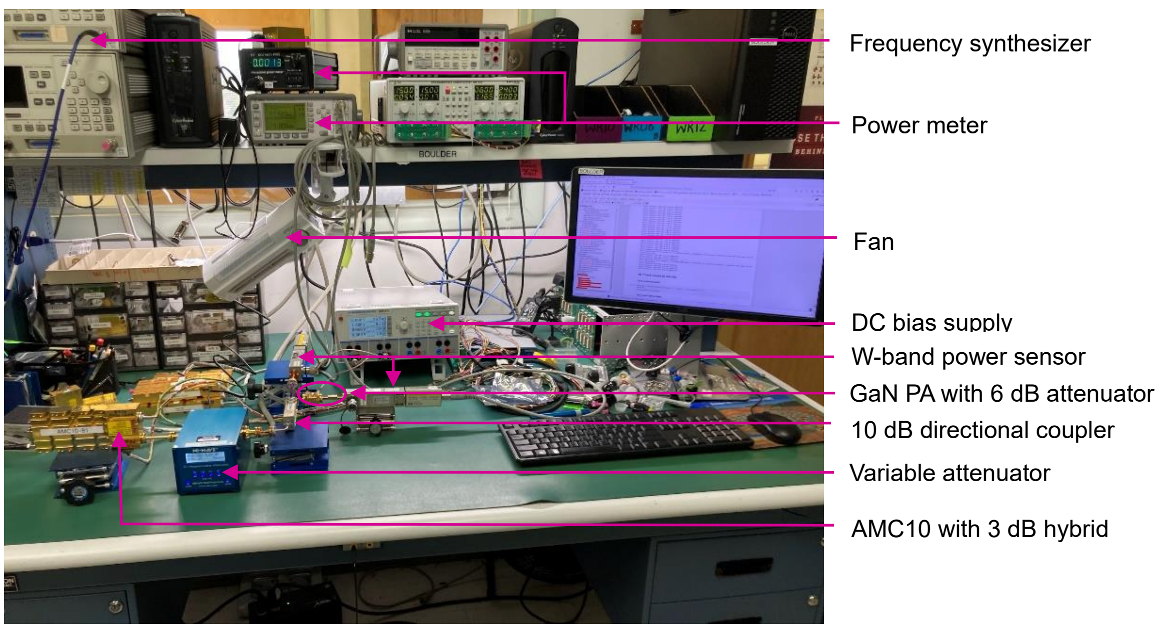
along with the data received from HRL corresponding to five MMICs. Data for different bondwire schemes is provided for comparison (to determine if there are inductive effect from the long bondwires on the DC biasing scheme used across the MMIC). No significant differences were observed on removing some of the parallel bondwires used to bias the North side and South side Drains and Gate connections through the capacitors. Thus the conclusion after direct RF probing is that the gain roll off behavior is primarily due to the PA MMIC, not due to stray inductance of the bond wires. The difference in gain between the direct RF probe measurements and the packaged PA over the frequency band 101-104.667 GHz (where the power failure is observed with respect to the 100 mW specification, Figure 7(c)) is 1 to 1.4 dB. So, there is a possibility to improve the RF housing of the PA MMIC by about 1 dB over this frequency range.

5. 4 Output Power Decay

To characterize the GaN PA output power over time, it was kept biased for 14 days continuously for two different bias conditions.The measurement setup with its block diagram is shown in Figure 12. A PA10 was used on the output of the AMC10 to boost the input power to the device under test (GaN PA).The operating frequency was set at 104 GHz. Data have been collected for two different bias conditions and the experimental results are shown in Figure 13. It included one programable variable attenuator. Input power to the test device was servoed hourly to +9 ± 0.005 dBm by adjusting the attenuation factor of the attenuator to compensate for the power decay of the AMC 10 (due to the decay of the present GaAs PA). Python code is written for that purpose and the computer controlled data collection is done at every hour of a day.Temperature was maintained at 21°C for the entire duration of the experiment throughout the measurement setup by using one fan. For bias 1: V_d = 12 V, V_g = -1.24 V the output power decay is 0.004 dB/day and corresponding decay in drain current is 0.082 mA/day. For bias 2: V_d = 10 V, V_g = -1.4 V these

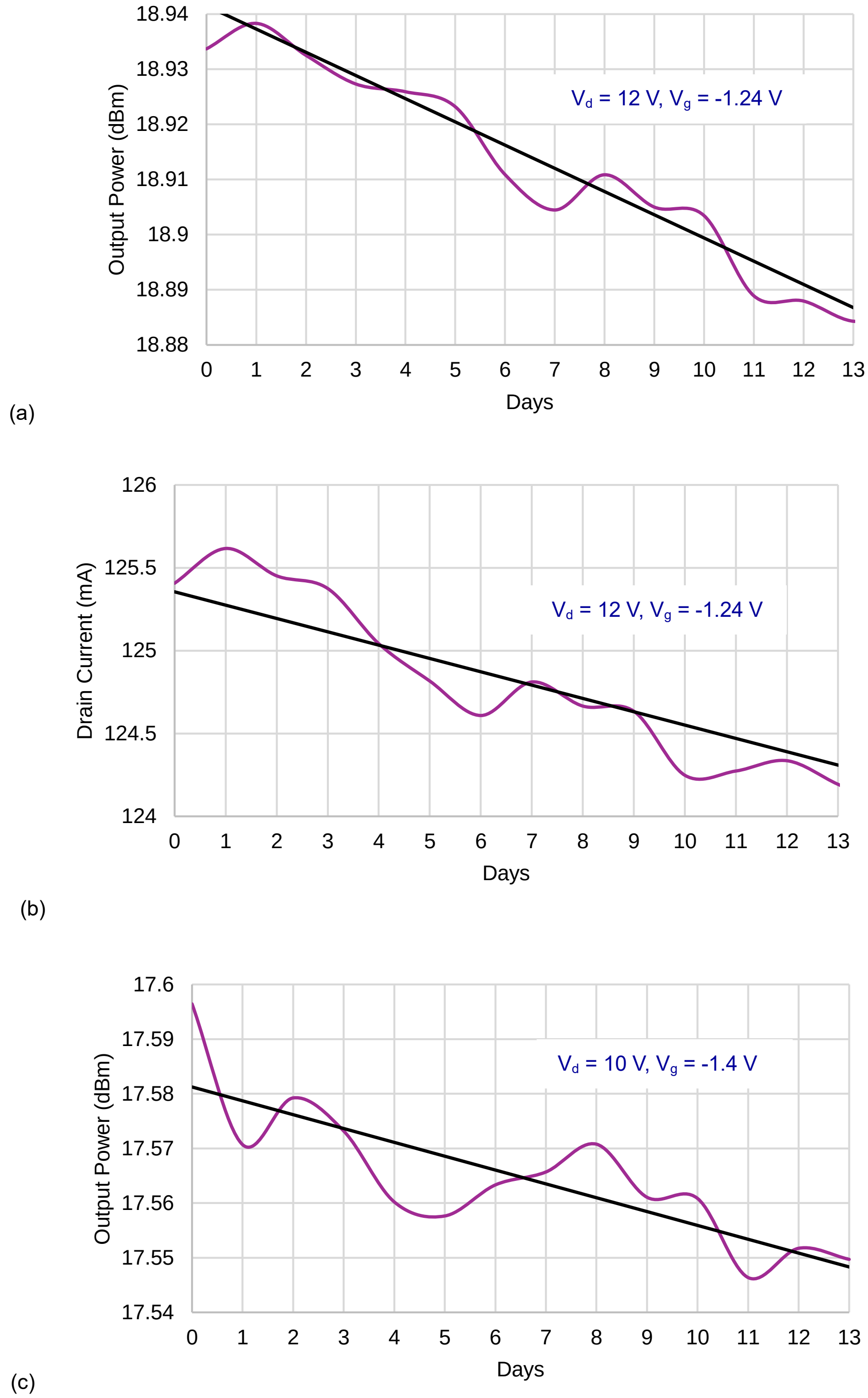


(a)

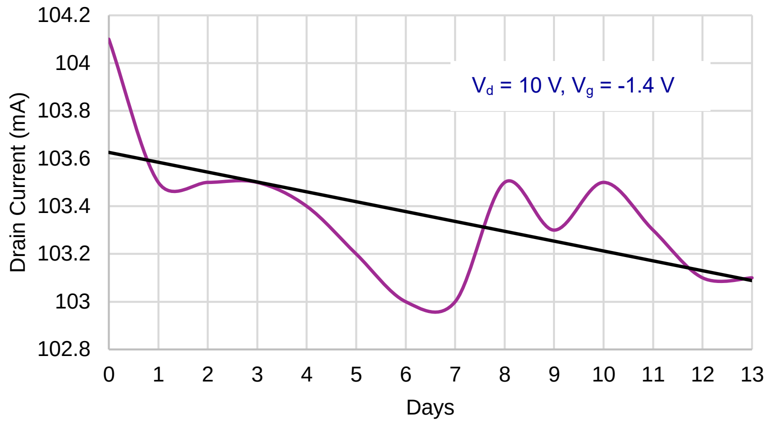


(b)

Figure 12 (a) Block diagram and (b) measurement setup for long term output power decay.



Output Power (dBm)
18.94
18.93
18.92
18.91
18.9
18.89
18.88
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Days
Vd = 12 V, Vg = -1.24 V
(a)
Drain Current (mA)
126
125.5
125
124.5
124
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Days
Vd = 12 V, Vg = -1.24 V
(b)
Output Power (dBm)
17.6
17.59
17.58
17.57
17.56
17.55
17.54
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Days
Vd = 10 V, Vg = -1.4 V
(c)

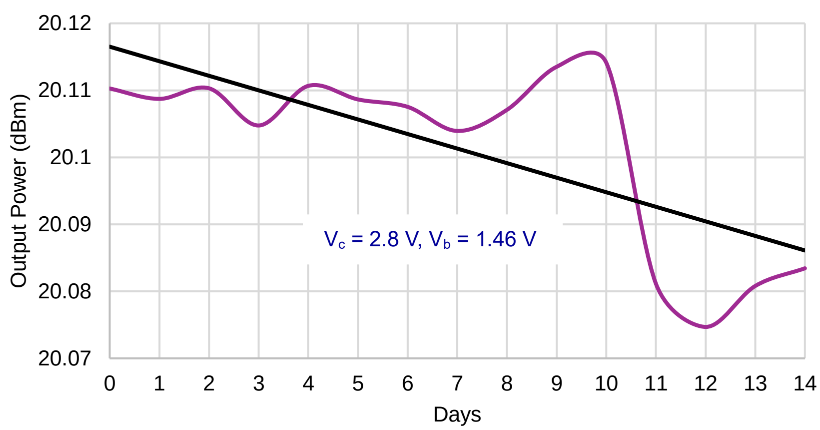


(d)

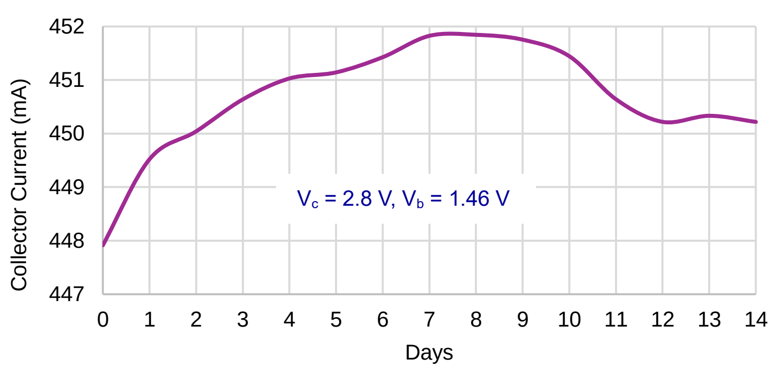
Figure 13 Decay of the GaN PA over 14 days (a) output power for bias 1, (b) Drain current for bias 1, (c) output power for bias 2, (d) Drain current for bias 2. Bias 1: V_d = 12 V, V_g = -1.24 V, Bias 2: V_d = 10 V, V_g = -1.4 V.

values are 0.0036 dB/day and 0.071 mA/day respectively.The output power and current decay profile over 14 days indicates that it follows a linear trend, i.e. the decay rate is a constant.

In this context, the output power and collector current of the power amplifier with a Teledyne InP TSC 70-130G-4S2C MMIC over time has also been studied and are shown in Figure 14. The nominal bias condition



(a)



(b)

Figure 14 (a) Output power and (b) collector current wit time of Teledyne InP TSC 70-130G-4S2C.

is Vc = 2.8V, Vb = 1.46V at 104 GHz and the input power is maintained at +9.99 dBm over the time period. It shows that the collector current is leveling off and there is a sudden change in the output power after an initial flat output power response. Further investigation is necessary to identify the reasons behind these behaviors.

5. 5 A Survey of the Output Power Decay Mechanisms

A schematic cross-section of an AlGaN/GaN HEMT, annotated with the output power degradation mechanisms is shown in Figure 15. The three primary degradation mechanisms [9], [10] are:

- Electron Trapping: because of the crystal imperfections that arise in the deposition of GaN and AlGaN layers on the substrate and the associated lattice mismatch.
- Surface Pitting: lattice defects, even cracks, in the Gate and Drain side due to high Gate-Drain potential, Piezoelectric effect nature of GaN.
- Hot Electrons: electrons which acquire kinetic energy values enough to overcome the potential energy barrier into the buffer, barrier, insulating layer and being trapped there.

The degradation rates are expected to be bias voltage dependent, as also can be observed from the collected data. However, an optimal DC biasing is required to obtain the desired output power with sufficient headroom for the ALMA Band 10 LO to operate over a stipulated time period before power failure. So, this is not a free parameter to alleviate output power degradation issue.

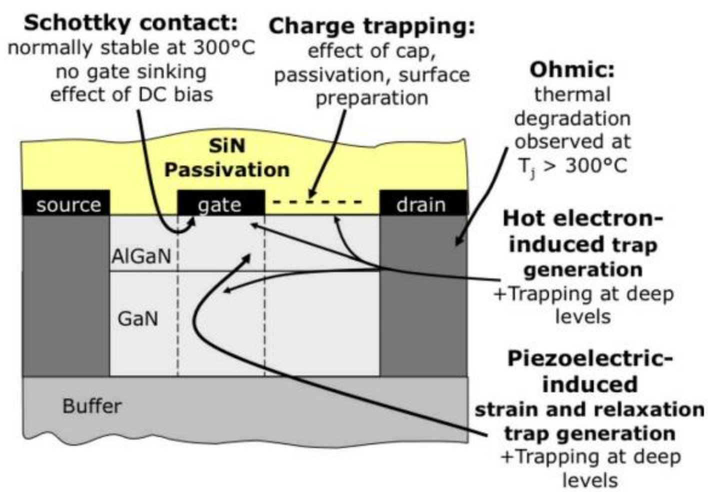


Figure 15 Schematic cross-section of AlGaN/GaN HEMT with different degradation mechanisms.

5. 6 Power Combination

After reviewing the above measured experimental data, HRL provided replacement MMICs with higher gain values to attempt to increase output power at the higher frequency end. Comparative small signal gain data are shown in Figure 16. The replacement MMIC was mounted in the block and measurements were performed with the measurement setup of Figure 6. Figure 17 shows the PA output powers with the original and replacement MMICs. No improvement in output power has been observed. Consequently, it was decided to resort to power combine two PAs.

The power combination measurement setup is shown in Figure 18. Two external waveguide 3 dB hybrid couplers have been used for this purpose. Isolated port of these couplers are terminated internally. To measure input power level to each of the PAs, one hybrid coupler is connected to the output of the AMC10 and the unused port is terminated by W-band waveguide load as shown in Figure 18(a) and Figure 18(b). Figure 19 shows the experimental results. To measure the output power from each of the PAs, the PAs are connected to the coupled ports of the hybrid coupler and each PA output power is measured by terminating the other one as shown in Figure 18(c) and Figure 18(d). Then the input and output power combination is applied. Figure 18(e) and (f) show, respectively, the measurement setup and the block diagram of this

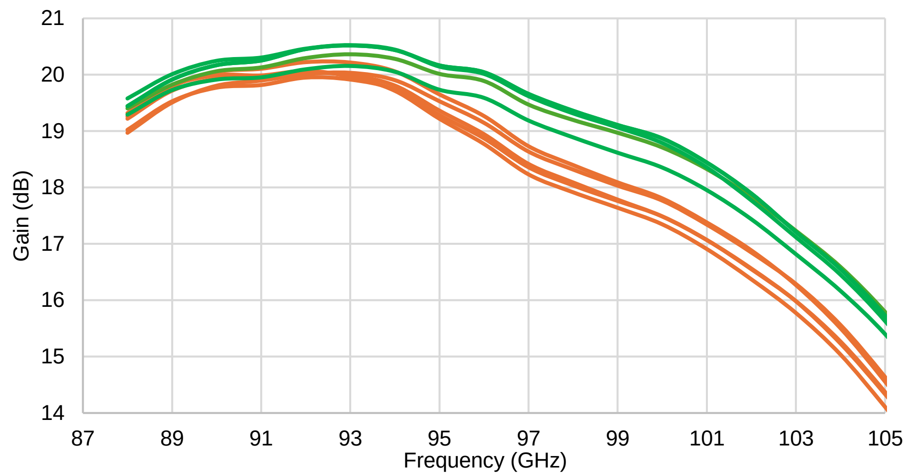


Figure 16 Small signal gain comparison of original (orange-traces) and replacement (green-traces) GaN MMICs based on the S-parameters data from HRL.

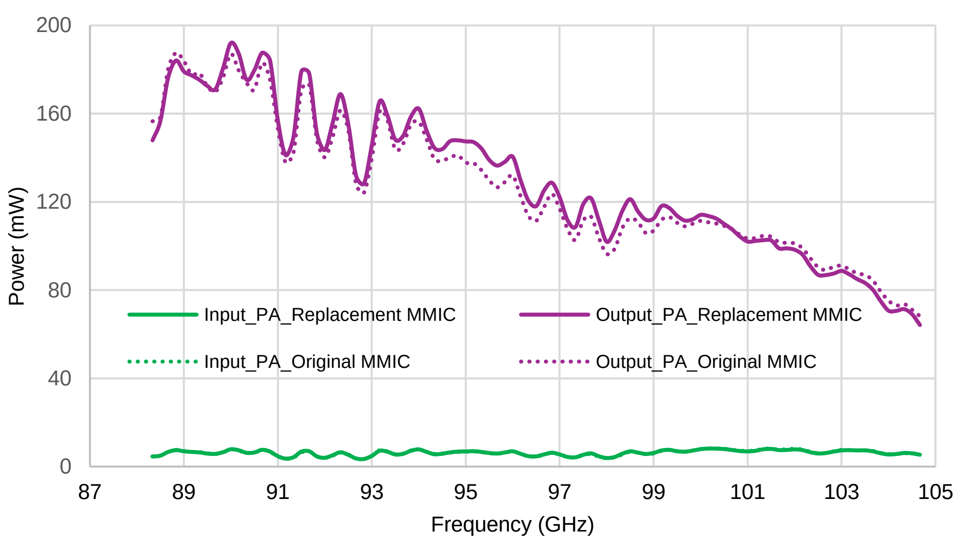
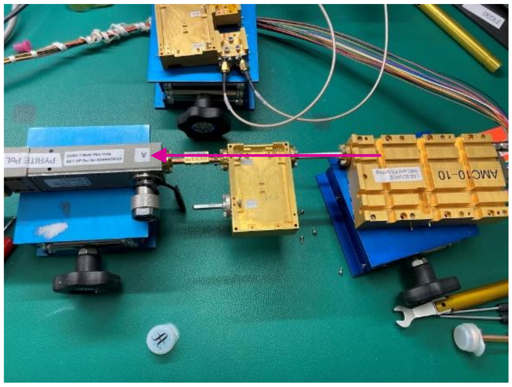
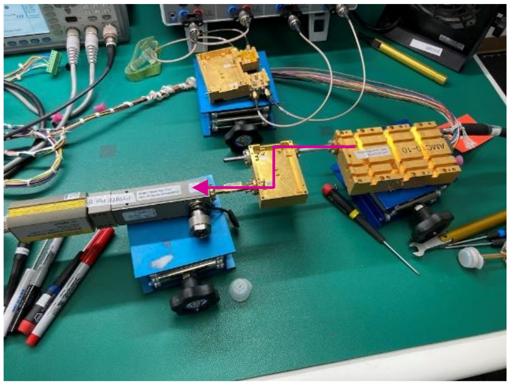
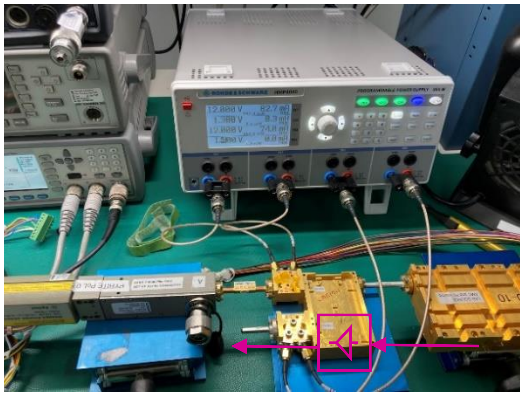
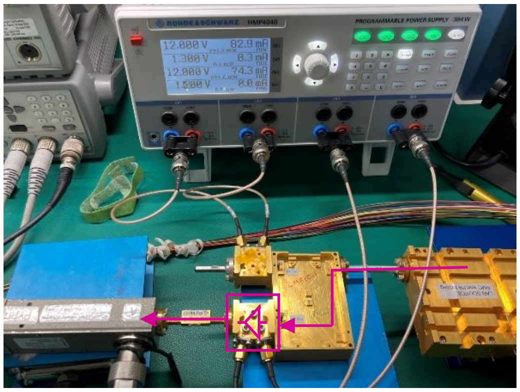


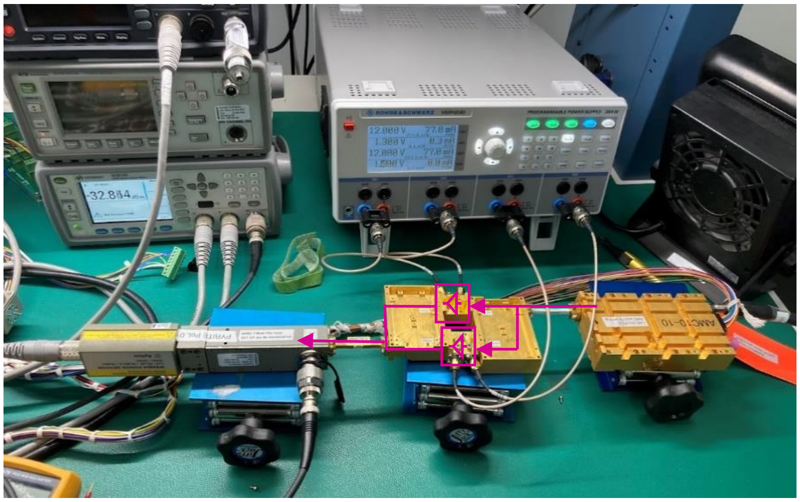
Figure 17 Comparison of output power of the Packaged GaN MMIC-based PA for the original and replacement HRL GaN MMICs.

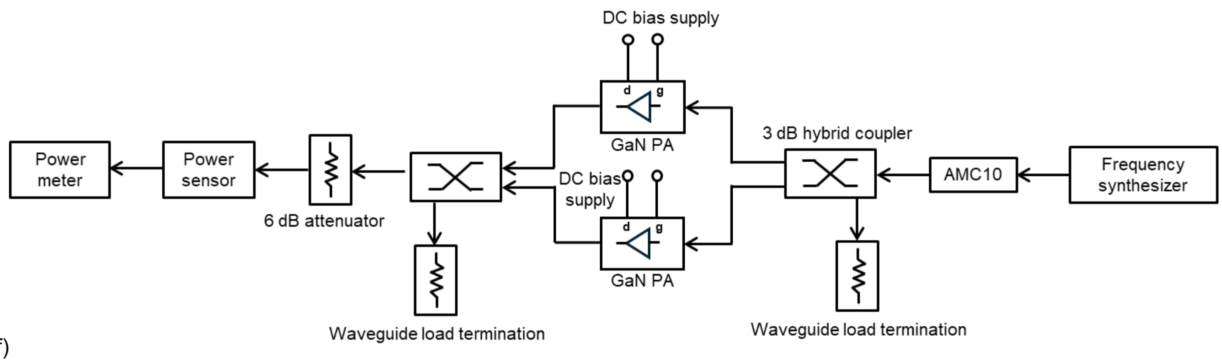

(a)


(b)


(c)


(d)


(e)



(f)

Figure 18 Measurement setups for (a) input power at channel 1: input of amplifier 1, (b) input power at channel 2: input of amplifier 2, (c) output power at channel 1: output of amplifier 1, (d) output power at channel 2: output of amplifier 2, (e) input and output power combination, (f) block diagram of the input and output measurement setup. The arrows in (a) – (e) indicate signal flow directions.

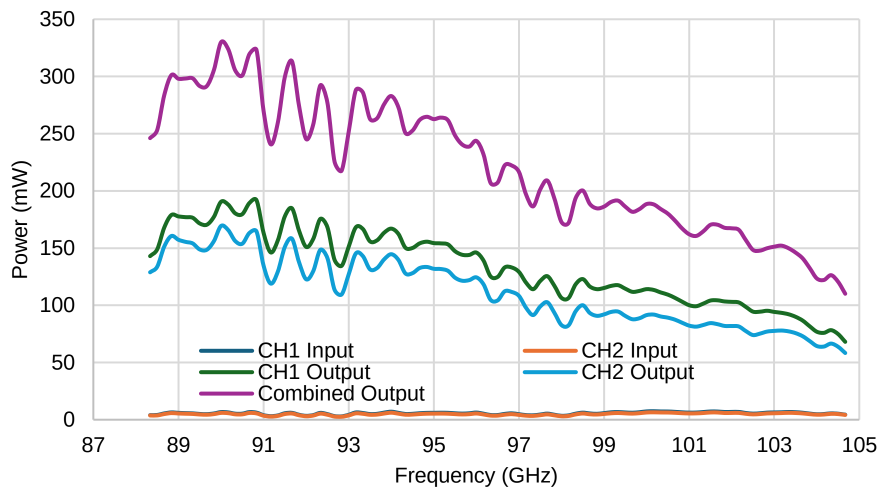


Figure 19 Power at the input and output of the two amplifiers that were power combined and combined output power over the frequency band of interest.

scheme. It yields 110.1 mW of output power at the highest frequency of operation thus meeting the stated requirement of output power > 100 mW over the entire band.

6. Conclusions

ALMA has 66 antennas with 10 receivers placed in a large cryostat at each antenna. At a time, only three receivers are powered up due to electrical and thermal limitations. So, most of the receivers are powered off including the LO PAs. The actual "on" time for the Band 10 LO in each of the 66 antennas is plotted in Figure 20 (data for 2024). ALMA Band 10 being a higher frequency band is only turned on at very specific atmospheric conditions for astronomical observations. For Band 10, the longest on time in 2024 was 24.3 days while most of the LOs were on for a period of under 20 days. With the measured decay rates of Figure 13(a), the power combined PA can run 104.5 days if it is kept ON continuously until the output power degrades to the required 100 mW specification over the entire band. With operational duty cycles commensurate with the data of Figure 20, the candidate GaN PA in power combination scheme has the potential to resolve the LO starvation problem of ALMA Band 10 receivers and can run for 4-5 years before the output power falls below the 100 mW limit (not the compromised specification limit as is currently being adopted due to lack of output power from the EBPA96B GaAs pHEMT PA even after the use of pre-amplifier over the frequency range 88.333–92 GHz). Moreover, it needs refurbishments of the amplifiers due to degradation of output power of the present GaAs PAs. HRL GaN PA MMICs are easy to bond on the RF and DC pads unlike InP HBT MMICs and offers 100% repeatability as observed from our block mountings experimental results.

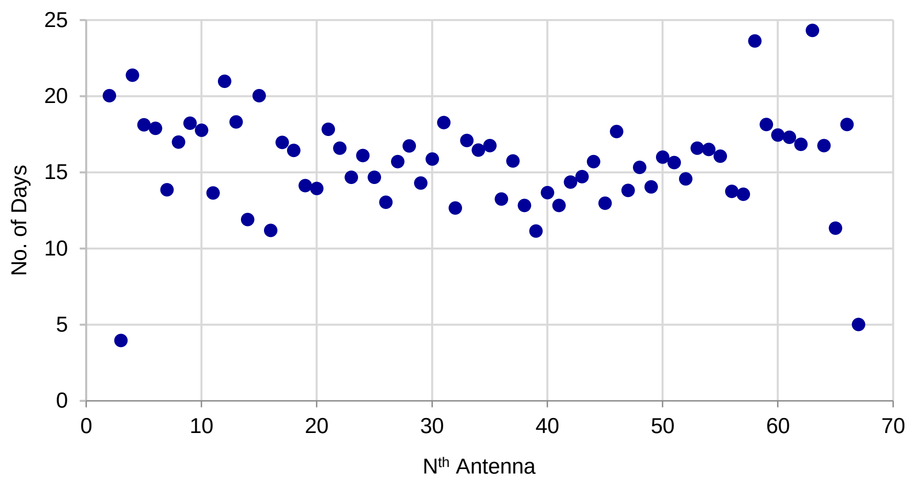


Figure 20 Band 10 LO on period of each of the 66 antennas in the year of 2024.

7. Acknowledgements

Sincere gratitude to:

- B. Casto, D. Tilley and G. Morris of Machine Shop, CDL – For the split block model generation, fabrications of the blocks, custom cut outs.
- D. Forsberg of FE LO lab, CDL – For the micro assemblies of the MMIC and its biasing on the block.
- E. Lilly of FE LO lab, CDL – For his assistance on jitter measurements.
- T. Boyd of Integrated Receiver Downconverter lab, CDL – For his assistance on the probe station measurements.
- S. Dadafshar and A. Arias-Purdue of HRL – For their kind consideration of providing replacement MMICs.
- G. Siringo of European Southern Observatory – For his sincere efforts on extracting the data and providing the database of active periods of the ALMA Band 10 receivers.

9. References

[1] J. M. Schellenberg, “A 2-W W-Band GaN Travelling-Wave Amplifier With 25-GHz Bandwidth”, IEEE Transactions on Microwave Theory and Techniques, September 2015.

[2] F. Medjdoub, K. Shinohara, F. Thome, J, Moon, E. Chumbes, M. T. Guidry, U. Mishra, E. Zanoni, M. Meneghini, G. Meneghesso, J. W. Pomeroy, T. Thingujam, M. Kuball, “Emerging GaN Technologies for Next-Generation Millimeter-Wave Applications” IEEE Microwave Magazine, October 2024.

[3] E. Bryerton, L. Muehlberg, and K. Saini, “Front-End Local Oscillator Design Report”, FEND-40.10.00.00-064-F-REP, August 2013.

[4] D. Vaselaar, “Band 10 Warm Cartridge Assembly Acceptance Report WCA10-3”, FEND-40.10.10.00-0103-B-REP, January 2024.

[5] P. Mondal, D. Vaselaar, K. Saini, B. Hawkins, “GaN Power Amplifier Development Study for ALMA Band 10 Local Oscillator”, NRAO Scientific Staff Retreat, November 2024.

[6] https://mmics.hrl.com/_assets/datasheet/BAL-WPA_Datasheet_190508.pdf

[7] E. Bryerton, “AM Noise in Front End Local Oscillators”, FEND-40.10.00.00-093-F-REP, August 2013.

[8] N. Erickson, “AM Noise in Drivers for Frequency Multiplied Local Oscillators” 15th International Symposium on Space Terahertz Technology, April 2004.

[9] B. M. Paine, S. R. Polmanter, V. T. Ng, N. T. Kubota, C. R. Ignacio, “Lifetesting GaN HEMTs With Multiple Degradation Mechanisms” IEEE Transactions on Device and Materials Reliability, December 2015.

[10] E. Zanoni, F. Rampazzo, C. D. Santi, Z. Gao, C. Sharma, N. Modolo, G. Verzellesi, A. Chini, G. Meneghesso, M. Meneghini, “Failure Physics and Reliability of GaN-Based HEMTs for Microwave and Millimeter-Wave Applications: A Review of Consolidated Data and Recent Results”, Physica Status Solidi (a) Applications and Materials Science published by Wiley-VCH GmbH, January 2022.