# A Ka-band PA Module using Low-Cost SMT Packaged GaN PAs

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## Introduction

This paper describes the development of a Ka-band PA module that combines four SMT packaged GaN PA MMICs to produce an RF output power of 17W at 28GHz. The module covers 28 to 31GHz with a gain of around 26dB and includes printed gain compensation circuitry to flatten the gain versus frequency response.

The PA MMIC component is a low-cost composite GaN die plus IPD (Integrated Passive Device) housed in a common 4mm x 4mm SMT package. The design, implementation and measured performance of the SMT component will be described. It is a commercially available PA designed by PRFI (the CMX90A705A6 from CML Micro [1] ), which benefits from a low unit cost made possible by the use of the IPD output die allowing a much smaller GaN die compared to a single chip GaN solution.

## Realisation of the SMT GaN PA

One of the key design tasks for the PA MMIC was to minimize GaN die area. This was achieved by using physically large transistors so the combining/splitting networks could be simpler and more compact and by realising the majority of the passive output network, including the drain bias tees for DC bias injection, on a separate IPD (Integrated Passive Device). The two die were sufficiently compact that they could be housed in a 4mm x 4mm SMT package. Figure 1 depicts the implementation detail of the packaged PA.

The GaN PA die is realised on a commercially available 0.15µm gate length GaN on SiC process. The use of physically large devices was one of the first design challenges. The transistor models in the PDK (Process Design Kit) have a range of size validity over which they have been verified. The required transistor size to achieve the target output power from just a pair of transistors was significantly above the range of validity. Using the PDK models outside the range of validity can lead to inaccuracies, which tend to increase with increasing operating frequency. To mitigate this issue samples of larger transistors were obtained and measured, both small-signal and load-pull, and the results compared to the PDK model. This allowed adjustments to be made to the design to compensate for the use of the larger transistors.

Another key design challenge was the need for accurate simulation of the bonding parasitics, in particular the transition between the GaN die and IPD where the impedance is lower and the impact of inaccuracies more significant. The approach of implementing a packaged component incorporating a GaN active device and a passive partner die is commonly used at lower frequencies [2] but is not routinely adopted at mmWave. Careful simulation of the die-to-die bonding was required followed by optimisation of the IPD design. This approach allowed first pass design success with the challenging architecture adopted to reduce unit cost.

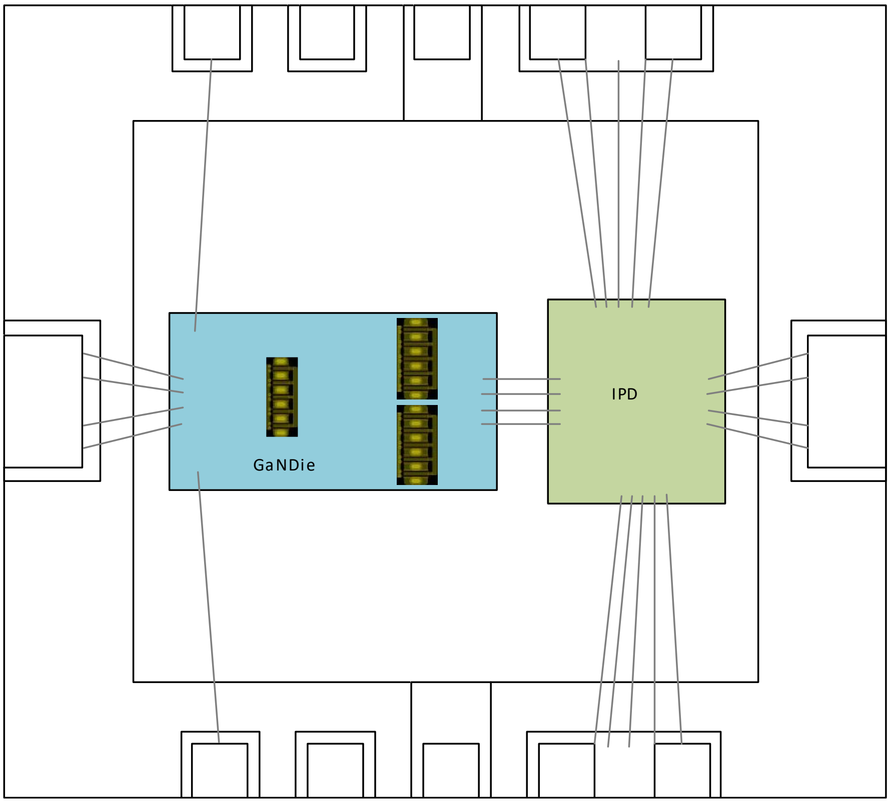


**Figure 1: Implementation approach used for the PA IC**

A photograph of one of the SMT packaged PA MMIC components mounted on an evaluation PCB is shown in Figure 2. The PCB material has a thin substrate thickness for good performance to mmWave (low dispersion), low grounding inductance for the QFN paddle and low thermal impedance. It is attached to a copper carrier for robustness and heat-sinking.

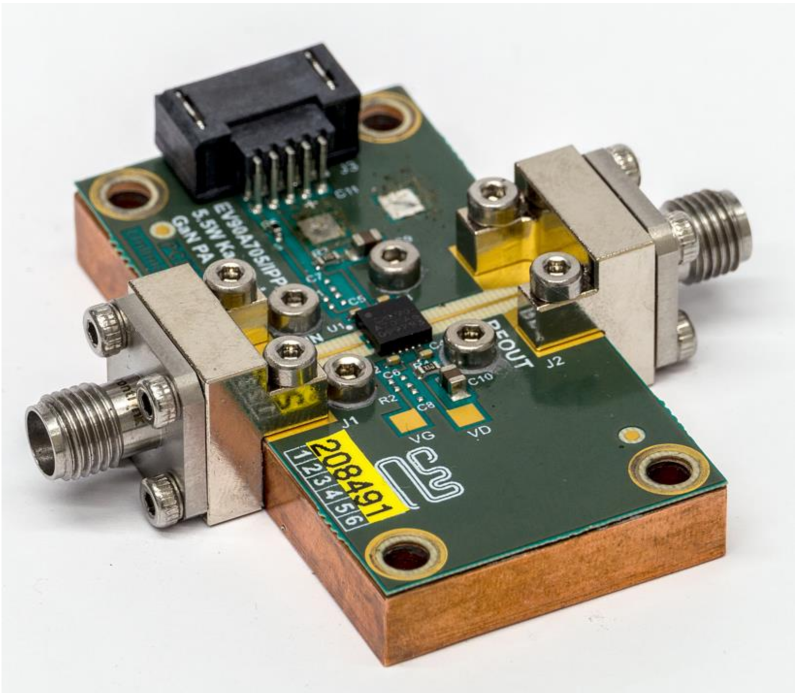

**Figure 2: Photograph of the PA MMIC mounted on an evaluation PCB**

## Measured Performance of the GaN PA MMIC

The packaged GaN PA MMIC has been measured on the evaluation PCB using a TRL calibration to reference the measurement data to the package ports. A plot of the measured s-parameters for two quiescent bias conditions (27.5V, 80mA and 27.5V, 100mA) is shown in Figure 3.

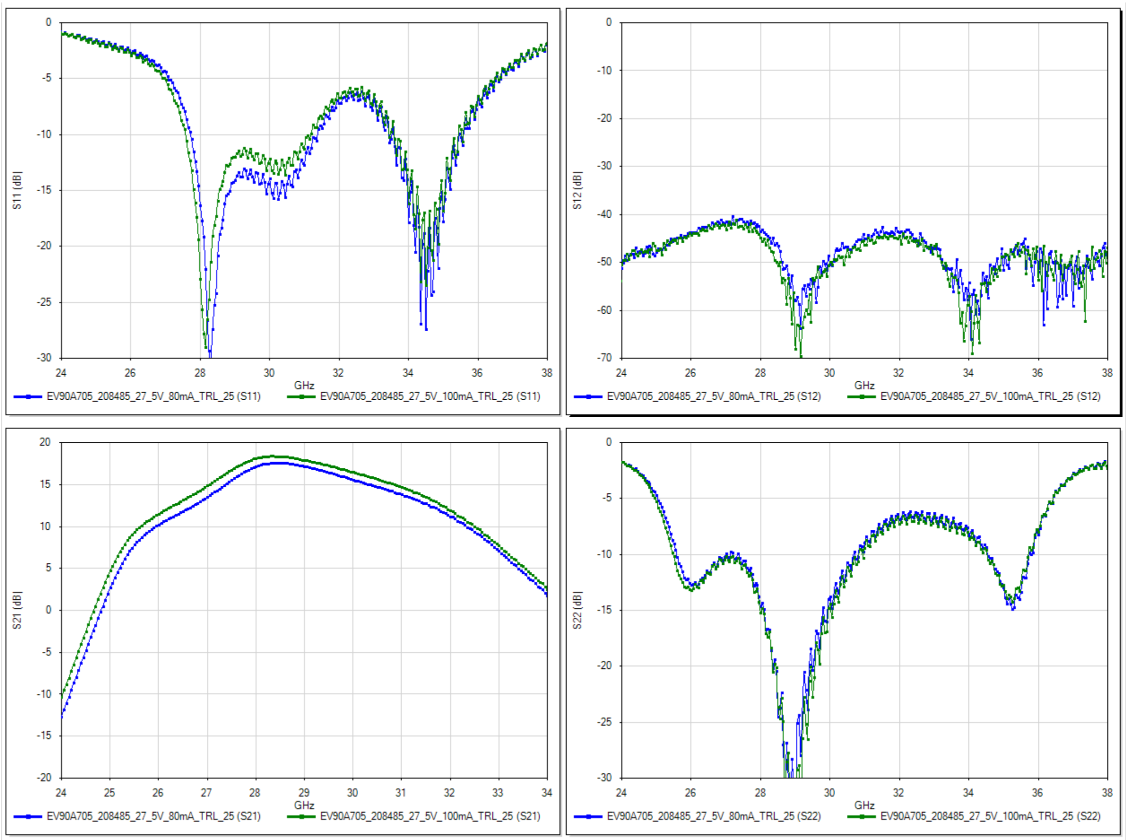


**Figure 3: Measured s-parameters of the packaged PA MMIC**

Power compression measurements in pulsed mode with a 10% duty cycle and 100µs pulse width are shown in Figure 4 to Figure 6 for frequencies of 27.5GHz, 29GHz and 31GHz.

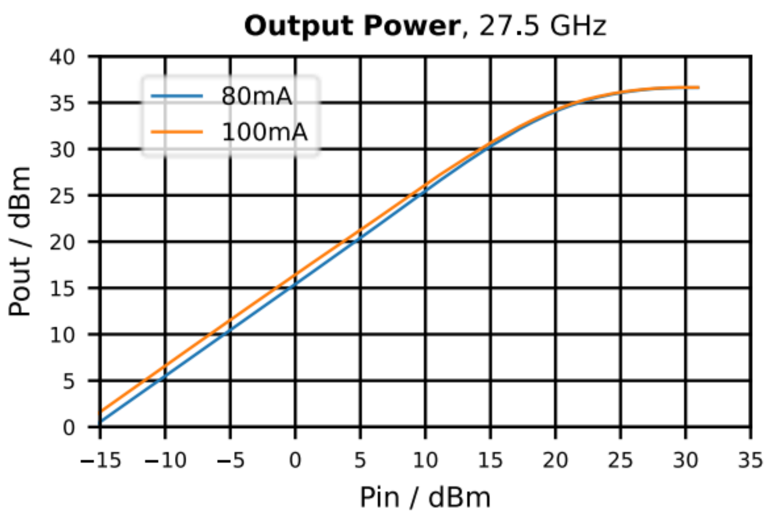


**Figure 4: Measured power transfer of PA MMIC at 27.5GHz; 10% duty cycle and 100µs pulse width**

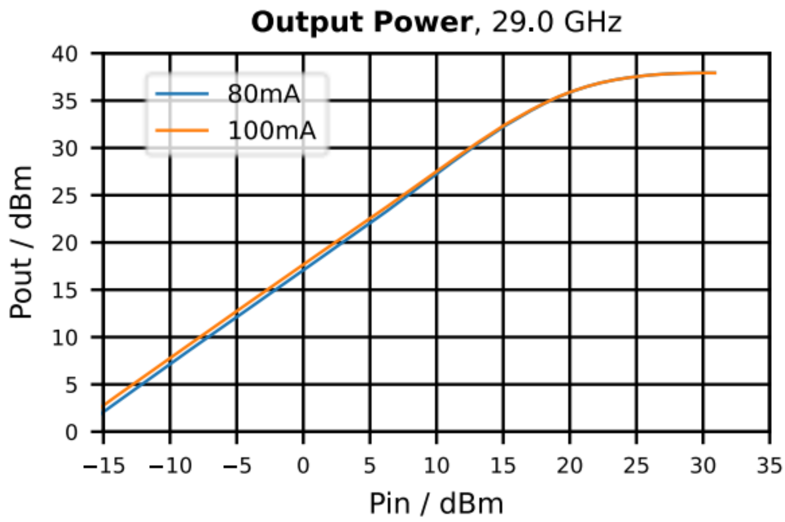


**Figure 5: Measured power transfer of PA MMIC at 29GHz; 10% duty cycle and 100µs pulse width**

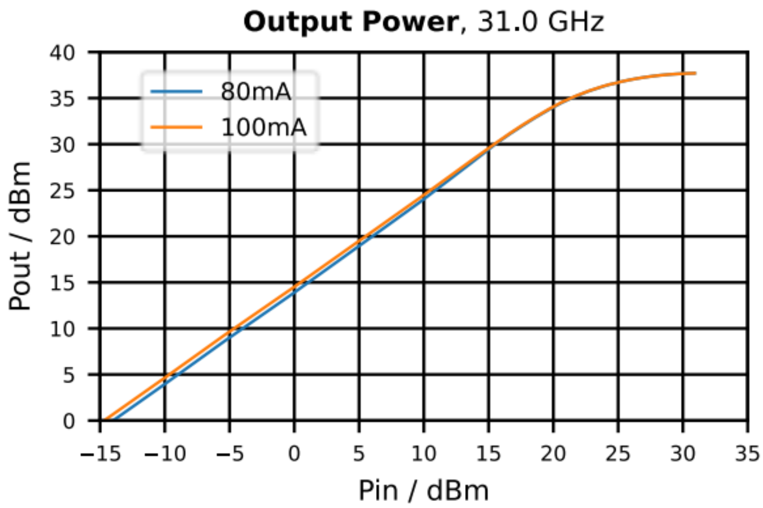


**Figure 6: Measured power transfer of PA MMIC at 31GHz; 10% duty cycle and 100µs pulse width**

The PAE versus output power is plotted for the same 3 cases in Figure 7.

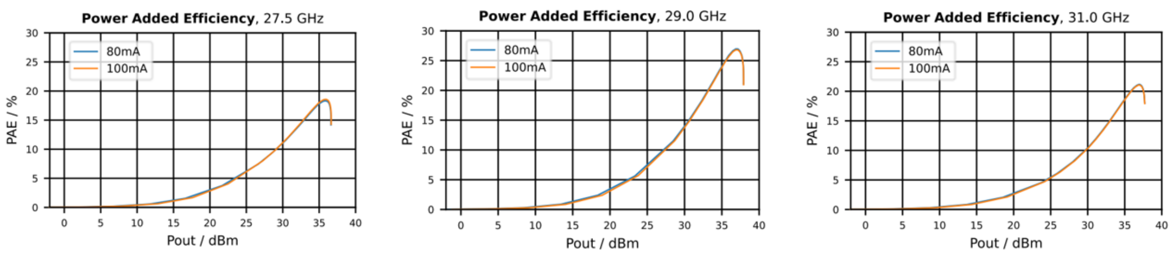


**Figure 7: Measured PAE of PA MMIC at 27.5GHz, 29GHz and 31GHz; 10% duty cycle and 100µs pulse width**

Figure 8 shows the measured output referred third order intercept point (OIP3) versus frequency for 3 different tone spacings. Quiescent bias was 27.5V and 100mA.

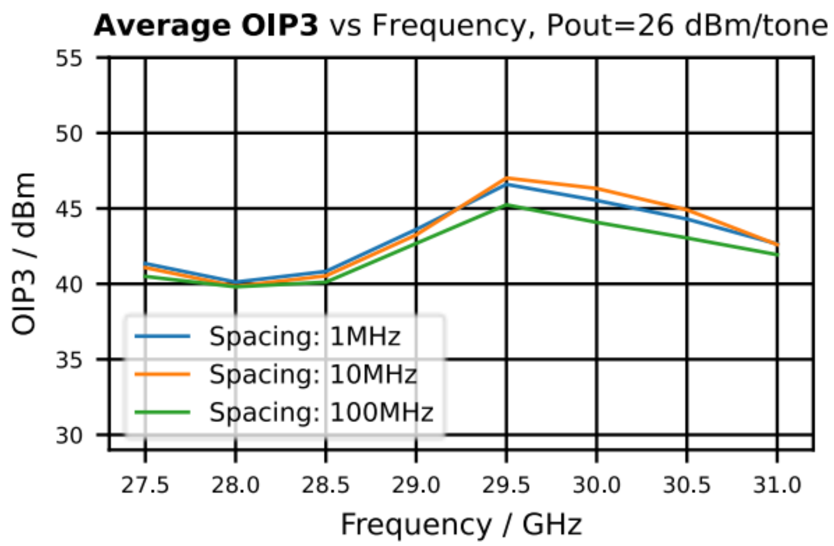


**Figure 8: Measured OIP3 of the PA MMIC versus Frequency for Different Tone Spacings**

## Realisation and Simulated Performance of the PA Module

The PA module was realized on a laminate substrate and used 4 of the SMT PA component power combined to generate an output power of 17W at 28GHz. A block diagram of the PA module is shown in Figure 9. The input stage uses a pair of the MMIC devices. The power combiner/splitter networks are resistor-less Wilkinson splitters. The balancing resistor used in a conventional Wilkinson splitter provides isolation between the two output ports of the splitter but the equal amplitude split does not require the balancing resistor when driving identical loads or combing coherent signals. Gain slope equalization networks were realised as printed structures on the PCB. These were tailored to flatten the gain versus frequency response.

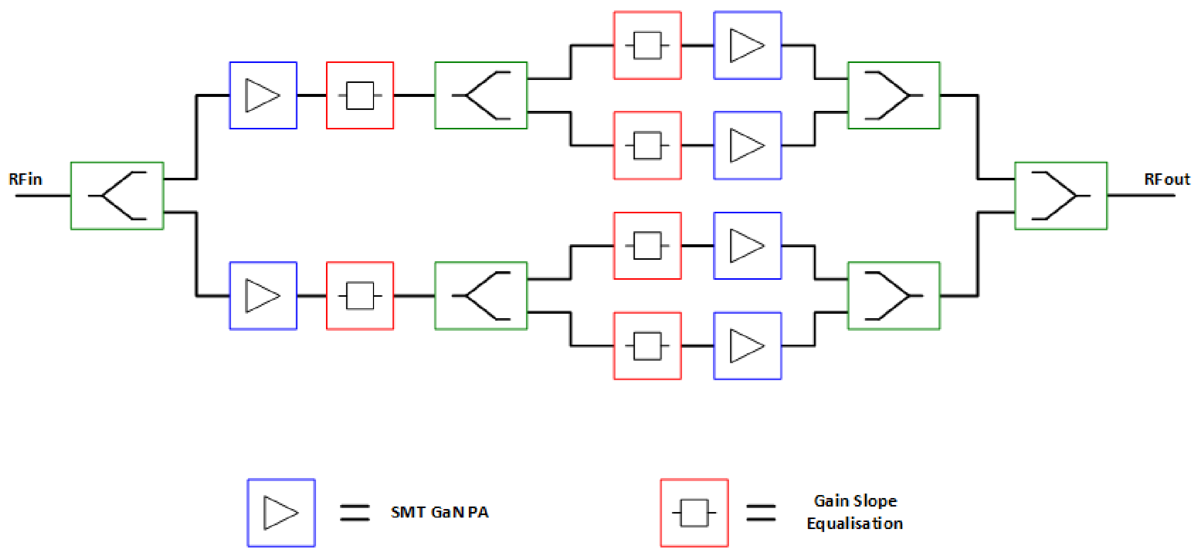


**Figure 9: Block Diagram of the PA Module**

The selected PCB material was Rogers' RT6035 HTC, which offers a high thermal conductivity. A substrate thickness of 0.01" (~0.25mm) was used, a thin substrate is required for low grounding inductance of the SMT packaged GaN devices. It also offers lower dispersion at mmWave frequencies and reduces the thermal impedance through the PCB substrate. Solid copper filled vias were used for good thermal heat-sinking. An Immersion Silver finish was adopted to provide a solderable finish without the higher RF losses associated with a conventional ENIG (Electroless Nickel Immersion Gold) finish. A useful guide to the design of laminate PCBs at microwave and mmWave frequencies can be found in [3].

The simulated small signal performance of the PA module is plotted in Figure 10. The gain slope equaliser blocks and splitter/combiner networks are all EM simulated. The simulated gain is 26.6dB ± 0.6dB from 28 to 30.5GHz dropping to just below 25dB at 31GHz.

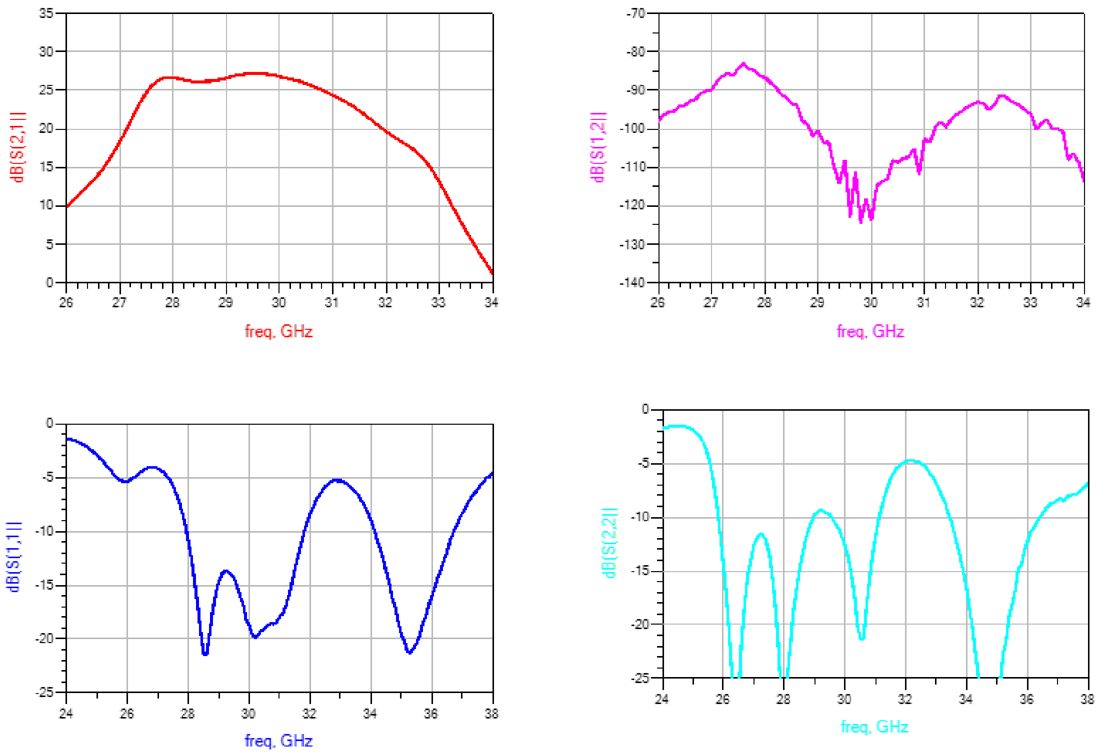


**Figure 10: Simulated s-parameters of the PA module**

A photograph of the assembled PA module is shown in Figure 11. A short through line can be seen at the top of the photograph. This allows calibration of the RF connector and the short 50Ω output trace to reference the measured power performance to the output of the 4-way printed combiner. This allows better comparison to the performance offered by single device packaged PA components.


**Figure 11: Photograph of the assembled PA module**

## Measured Performance of the PA Module

A thermal photograph of the PA module operating at quiescent bias, each amplifier set to +27.5V and 100mA, is shown in Figure 12. The peak device temperature is a modest 34.2°C and the absence of hot-spots suggest good void free solder attach of all of the SMT PA components.

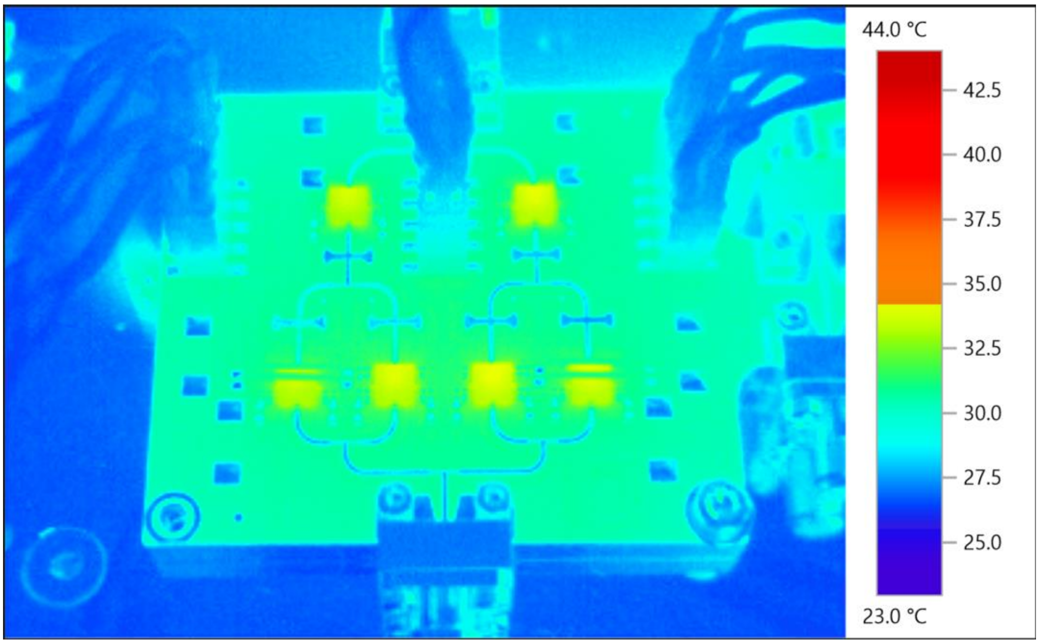


**Figure 12: Thermal image of PA module at quiescent bias**

A plot of the measured s-parameters compared to simulated is shown in Figure 13. Quiescent bias of each individual PA component was 27.5V, 100mA. The measured gain has a little more slope than simulated varying from 30dB at 28GHz dropping to just below 25dB at 31GHz.

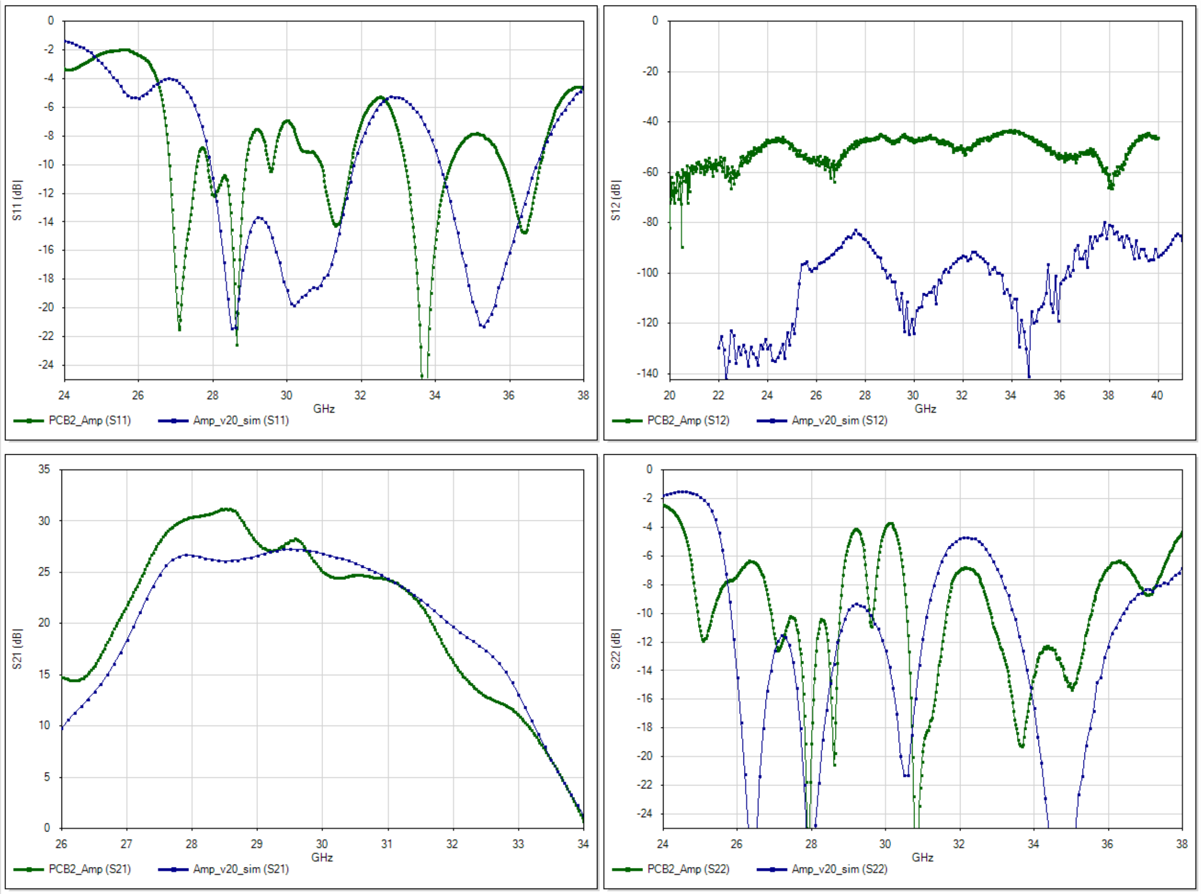


**Figure 13: Measured s-parameters compared to simulated**

The power transfer characteristics of the PA module are plotted in Figure 14. The four traces represent frequencies of 28GHz, 29GHz, 30GHz and 31GHz. RF was pulsed with 100µs pulse width and 10% duty cycle. These measurements are referenced to the output of the printed 4-way power combiner. The losses of the RF connector and the short 50Ω connecting trace have been calibrated out. A summary of the Psat at each measurement frequency is provided in Table 1. Psat is 17.4W at 28GHz and varies from 14.9W to 18.4W across the measurement range.

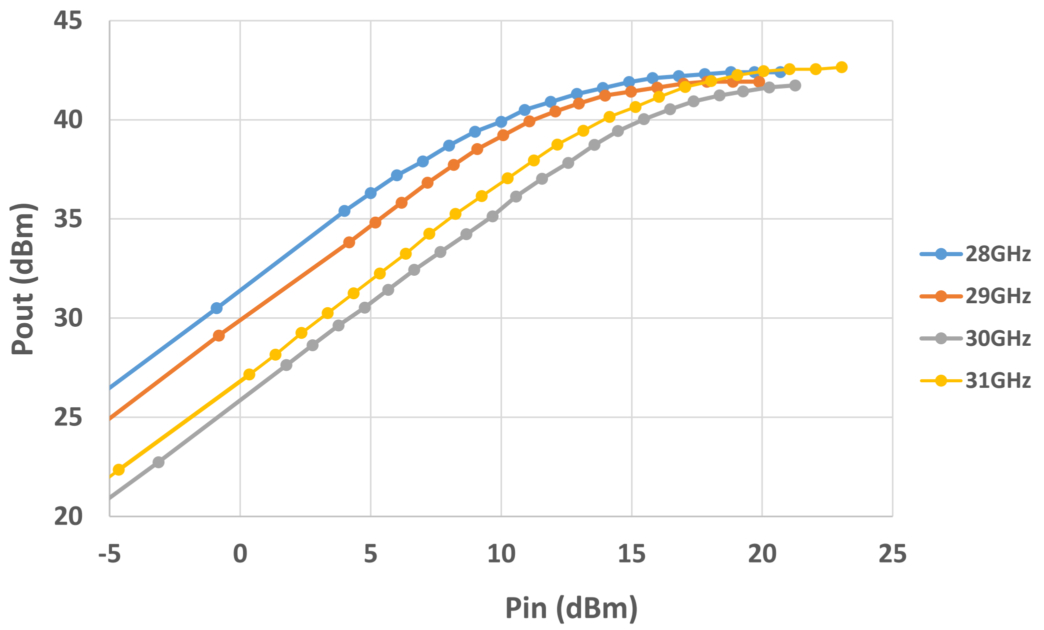


**Figure 14: Measured power transfer characteristics of the PA module at 28, 29, 30 and 31GHz (100µs pulse width, 10% duty cycle)**

| Freq (GHz) | Psat (W) |
|---|---|
| 28 | 17.4 |
| 29 | 15.6 |
| 30 | 14.9 |
| 31 | 18.4 |

**Table 1: Tabulated Psat versus frequency (100µs pulse width, 10% duty cycle)**

A plot of the measured RF power pulse is shown in Figure 15. The measured power in the plot includes the losses of the RF connector and the short 50Ω connecting trace (0.6dB). Allowing for these losses gives an RF output power of 42.3dBm (17W) at the output of the printed 4-way power combiner.

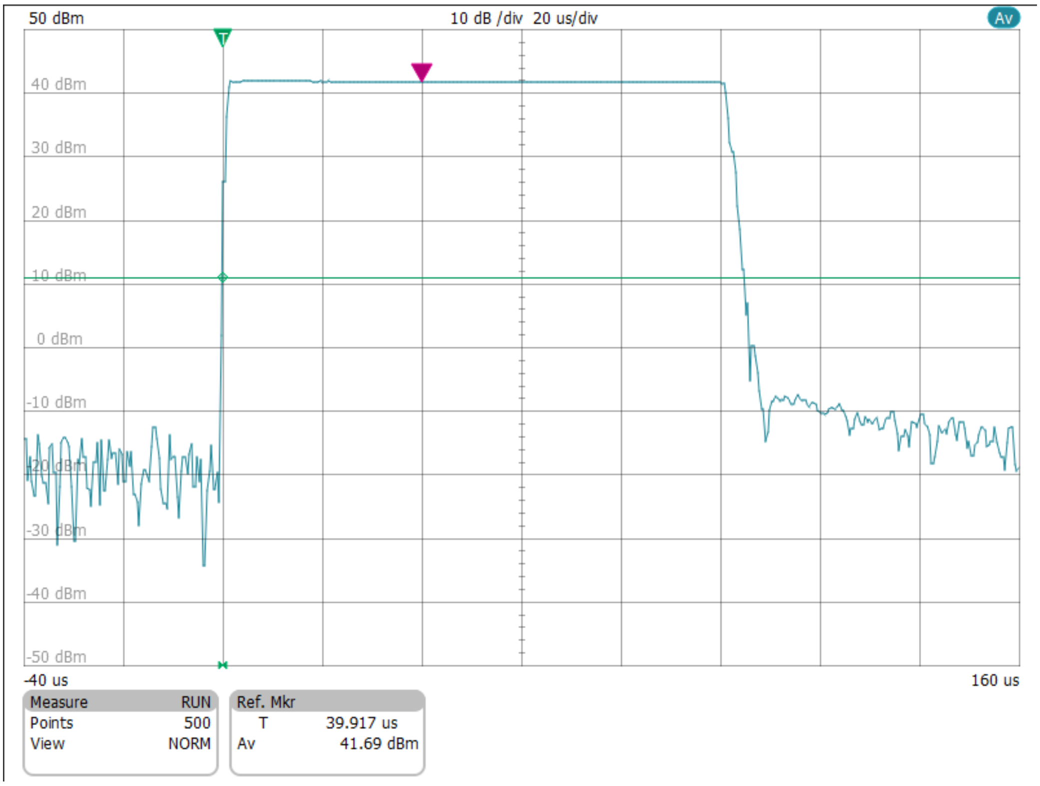


**Figure 15: Measured pulsed RF power waveform at 28GHz (at RF connector)**

Figure 14 shows a thermal photograph of the PA module operating at Psat (17W RF out at 28GHz, pulsed operation, 10% duty cycle). The peak device temperature is a modest 36.4°C and the absence of hot-spots suggest good void free solder attach of all of the SMT PA components.

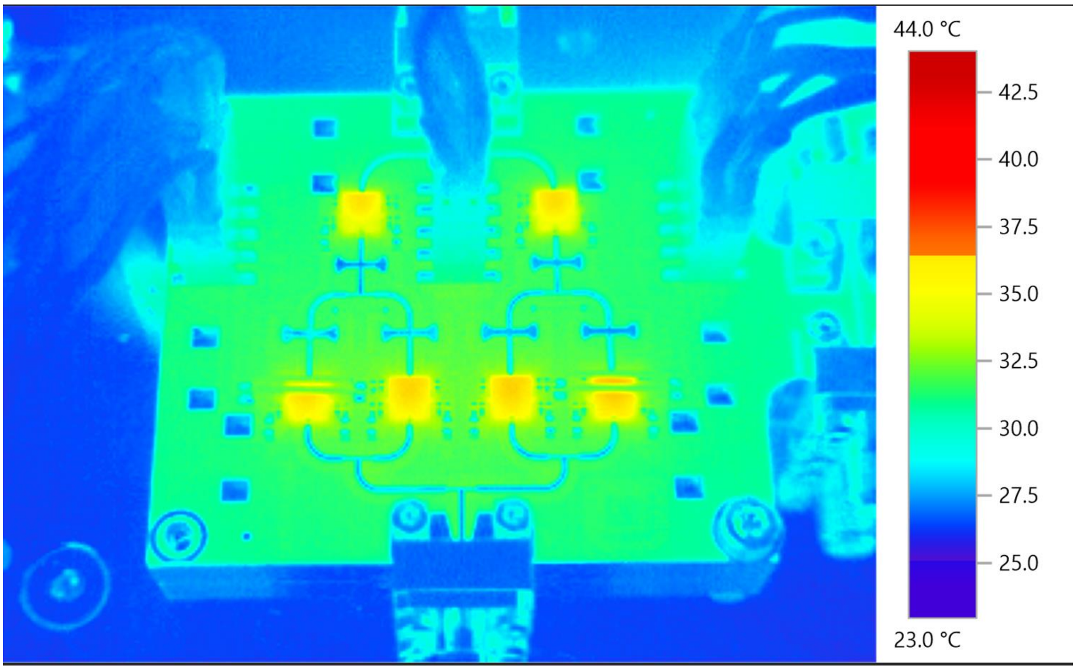


**Figure 16: Thermal image of PA module at Psat; 28GHz, 17W RF out (100µs pulse width, 10% duty cycle)**

The module was also measured in CW and a comparison of the pulsed to CW power transfer characteristics at 28GHz are plotted in Figure 17. The saturated RF output power at the output of the combiner in CW operation is 13.8W – a drop of 1dB.

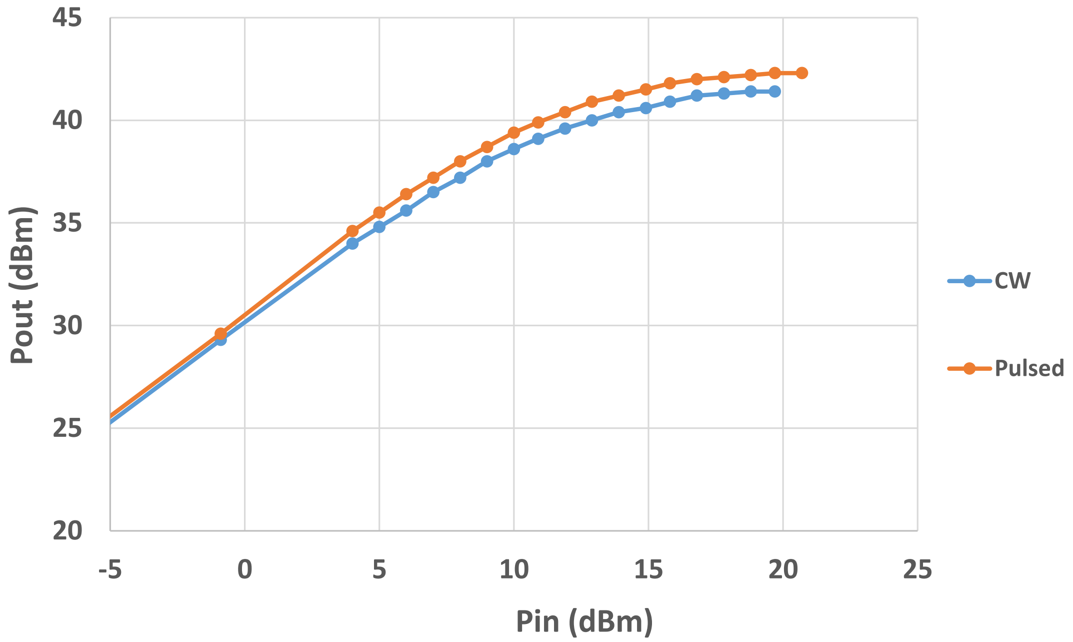


**Figure 17: Comparison of CW to pulsed power transfer at 28GHz**

Figure 18 shows a thermal photograph of the PA module operating at Psat, CW operation at 28GHz with an RF output power of 13.8W. The peak device temperature is a comfortable 80°C. This is measured at the top the package, the actual junction temperature will obviously be higher. All devices are operating at a similar temperature indicating a balanced drive and good void-free solder attach.

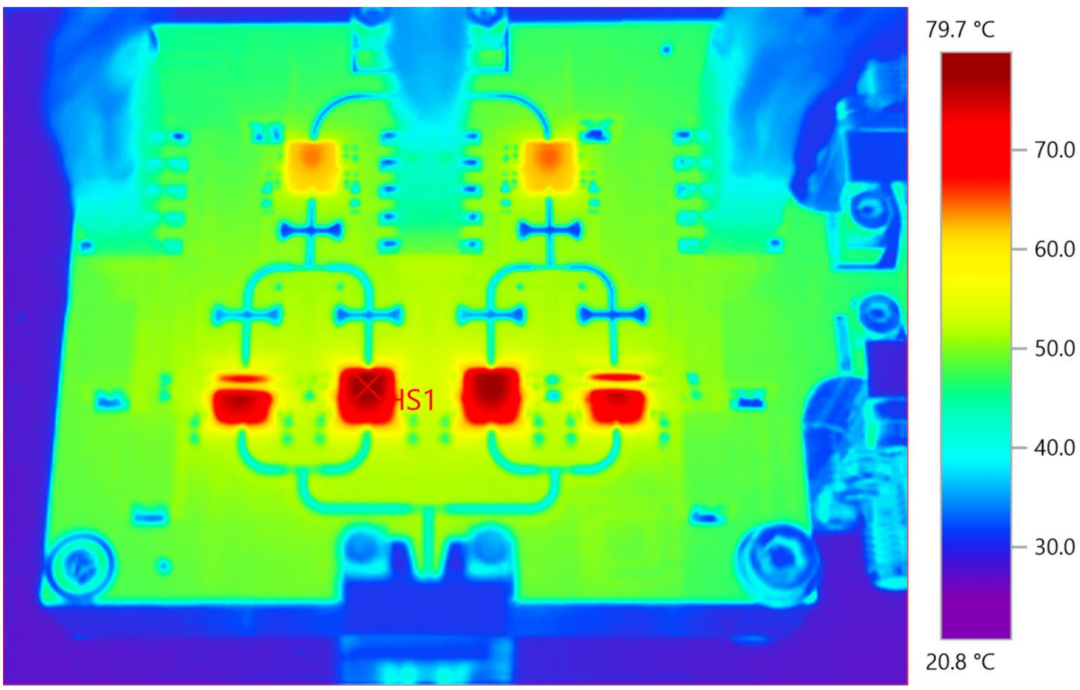


**Figure 18: Thermal image of PA module at Psat, CW operation; 28GHz, 13.8W RF out**

## Summary and Conclusions

A K-band PA module based on commercially available plastic packaged GaN PA components (the CMX90A705A6 from CML Micro) has been described. The GaN PA component is housed in a 4mm x 4mm QFN package and benefits from a low unit cost made possible by the use of an IPD output die allowing a much smaller GaN die compared to a single chip solution.

The PA module is realised on a laminate substrate incorporating printed gain slope compensation networks to flatten the gain versus frequency response and resistorless Wilkinson combiners for low-loss RF power combining.

The module has a measured gain of 30dB at 28GHz dropping to just below 25dB at 31GHz. Measured Psat in pulsed operation (100µs pulse width and 10% duty cycle) is 17.4W at 28GHz and varies from 14.9W to 18.4W across the 28 to 31GHz measurement range. The module is also suitable for CW operation with the Psat reducing by ~1dB to 13.8W at 28GHz. Thermal images in CW operation at 28GHz indicate a temperature at the top of the SMT packaged PAs of 80°C. The junction temperature will be higher than this but comfortably below the peak recommended temperature of the GaN process. All devices are operating at a similar temperature indicating a balanced drive and good void-free solder attach.

## References


[1] https://cmlmicro.com/products/surf-rfics-and-mmics/product/cmx90a705

[2] Robert Smith, Liam Devlin, Raj Santhakumar, Richard Martin, “Cost-Effective Hybrid Input-Matched GaN Transistor for S-band Radar Applications”, proceedings of the RF and Microwave Society (ARMMS) Conference, November 2013

[3] Liam Devlin and Graham Pearson, “A Guide to the Design of Laminate PCBs at Microwave Frequencies”, proceedings of the RF and Microwave Society (ARMMS) Conference, November 19th and 20th, 2012