The Design of High Performance L-band GaN PAs Using Commercially Available Discrete Transistors

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Abstract

This paper describes the design and evaluation of four different single stage L-Band GaN Power Amplifiers (PAs) using commercially available, low-cost packaged transistors. Two of the transistors are housed in SMT plastic packages and two in metal-based ceramic packages. The transistors are commercially available parts from Qorvo realised on a high voltage 0.25 µm GaN process. All four amplifiers have been optimised for the 0.96 to 1.215 GHz band and are designed to operate in CW or pulsed mode. The plastic packaged parts offer output powers of 11 W and 14 W with corresponding PAEs of 65% and 55%. The ceramic packaged parts offer higher output power levels of 59 W and 125 W with PAEs of 60% and 70% respectively. This paper describes the design, realisation and measurement of the four PAs, which demonstrate high performance using cost-effective commercially available transistors.

Introduction

Gallium Nitride (GaN) is increasing in popularity for high power RF applications such as radar. Qorvo has recently released four new GaN transistors based on its QGaN25HV process. This is a 0.25 µm gate length process with advanced field plates to enable operation at high drain supply voltages. High drain supply voltages reduce current and thus resistive losses and improve PA efficiency, simplifying thermal management.

The QPD1008 and QPD1015 are high-power transistors packaged in metal-based ceramic air-cavity packages and the QPD1009 and QPD1010 are medium-power transistors packaged in low-cost 3x3 mm plastic Quad-Flat No Leads (QFN) packages. Surface-mount plastic packages allow simpler PCB assembly, but the superior thermal performance of metal-ceramic packages is required at higher power levels.

Figure 1: Metal-based ceramic package (left) and plastic overmould QFN package (right)

The performance offered by the four transistors is summarised in Table 1. This is based on measured load-pull data of the transistors mounted on a representative evaluation PCB; the performance is referenced to the terminals of the transistor package and has been tuned for optimum output power.

Transistor	Quiescent Bias (V, mA)	Package	P-3dB @ 1.0 GHz (dBm)	PAE @ 1.0 GHz (%)	MAG / MSG @ 1.0 GHz (dB)
QPD1008	50V, 260 mA	NI360 ceramic	52.1	62.7	26.6
QPD1009	50V, 26 mA	3x3mm plastic QFN	41.9	64.1	27.2
QPD1010	50V, 18 mA	3x3mm plastic QFN	40.9	69.4	26.5
QPD1015	50V, 65 mA	NI360 ceramic	48.4	67.3	28.2

Table 1: Summary of the performance capabilities of the four transistors

Four evaluation power amplifier boards were designed by Plextek RFI using these newly released transistors. The evaluation boards operate at high efficiency at L-band frequencies between 960 MHz and 1215 MHz and demonstrate the transistors' suitability for a variety of applications including military and civilian radar systems. A summary of the performance offered by the four PA designs is presented in Table 2.

Transistor	EVB Quiescent Bias (V, mA)	Package Mount	P-3dB (dBm)	Efficiency (%)	Small-signal Gain (dB)
QPD1008	50V, 260 mA	Flange	51.0	70	20.0
QPD1009	50V, 26 mA	SMT	41.5	55	19.7
QPD1010	50V, 18 mA	SMT	40.4	65	19.5
QPD1015	50V, 130 mA	Flange	47.7	60	19.7

Table 2: Performance summary of the four Plextek RFI designed EVBs

All four PA evaluation boards (EVBs) share some common design elements and these are explained first. The evaluation boards for the QFN-packaged QPD1009 and QPD1010 are then discussed simultaneously as their designs share a number of similarities. The design of the QPD1008 evaluation board has been described in detail in a previous white paper [1] (available on the Plextek RFI website) and is discussed alongside the design of the EVB for the ceramic-packaged QPD1015.

Design Approach

Common Design Features to all Four PAs

The QPD1008 and QPD1015 evaluation boards use 32 mil (0.81 mm) thick Rogers 4360G2 material. The QPD1009 and QPD1010 EVBs use 20 mil (0.51 mm) Rogers 4360G2 material. The relatively thick PCB materials allow wide transmission lines to be used, improving power handling capabilities. Copper-filled through-via holes provide a low thermal impedance and low electrical inductance path to the metal carrier. A metallisation weight of 1 oz. copper, equivalent to a thickness of 35µm, is necessary to handle the high DC current at the drain of the transistors when under high RF drive.

The PCBs are bonded to bespoke aluminium carriers featuring metal end plates with banana plug connectors allowing convenient DC connections for testing. Low-cost SMA connectors are edge-mounted to the metal carriers. The metal carriers for the QPD1008 and QPD1015 are gold plated to allow the package base to be soldered to the carrier, improving the thermal conductivity and reducing the transistor die temperature. The temperature under the package can be measured through a hole drilled in the side of each aluminium carrier.

QPD1009 & QPD1010 EVB Design

Figure 2 shows that both of the QFN-packaged transistors require stabilising at L-band and only become unconditionally stable above 3 GHz. High levels of gain are present at low frequencies and care must be taken to stabilise the transistors at these frequencies. Unconditional stability is required at all frequencies down to a temperature of -40°C. As measured data was only taken at room temperature, extra margin was included in the stability factor to ensure unconditional stability at low temperatures.

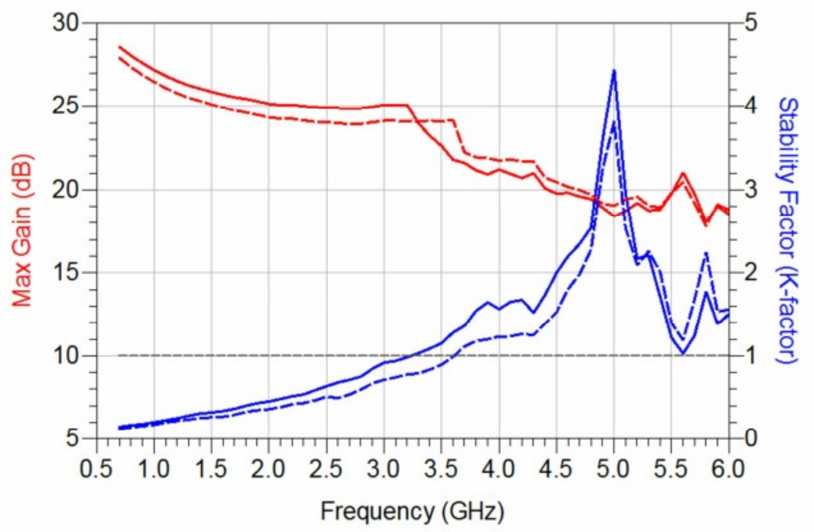


Figure 2: G_{MAX} and stability factor of QPD1009 (solid lines) and QPD1010 (dashed lines) transistors

As these transistors are new products, a large-signal non-linear simulation model was not available when designing the EVBs. Instead load-pull data was used in conjunction with measured S-parameters. Load-pull data for the two QFN-packaged transistors at 1 GHz is shown in Figure 3. A compromise match between optimum efficiency and optimum output power was chosen.

Second harmonic load pull data (not shown) was used to optimise the efficiency of the PA.

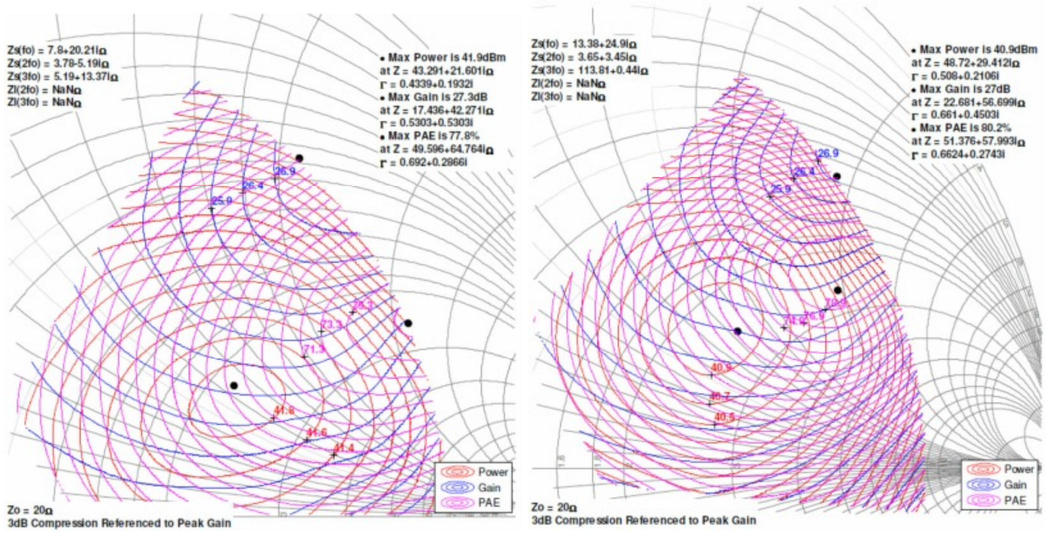


Figure 3: Optimum load impedances for the QPD1009 (left) and QPD1010 (right) at P-3dB compression (Z_0 = 20 Ω) at 1 GHz

Two-pole low-pass filter networks are used for matching both input and output, with in-band series stabilising resistors at the input. This enables operation over a sufficiently wide bandwidth whilst minimising insertion loss. A small capacitor close to the drain tab of the package positions the second harmonic impedance towards a region of higher efficiency.

The matching networks are implemented as a mixture of lumped-element and distributed components, with SMT capacitors and resistors used in conjunction with microstrip transmission lines. Physically small capacitors were chosen to minimise parasitic effects from the packages.

QPD1008 & QPD1015 Design

Figure 4 shows that QPD1008 is only unconditionally stable in a narrow frequency range just above the frequency design band, and the QPD1015 is unconditionally stable across an even smaller frequency range. Great care must be taken to ensure stability across the band. The low-pass response of the matching networks helps with stability above the target frequency band.

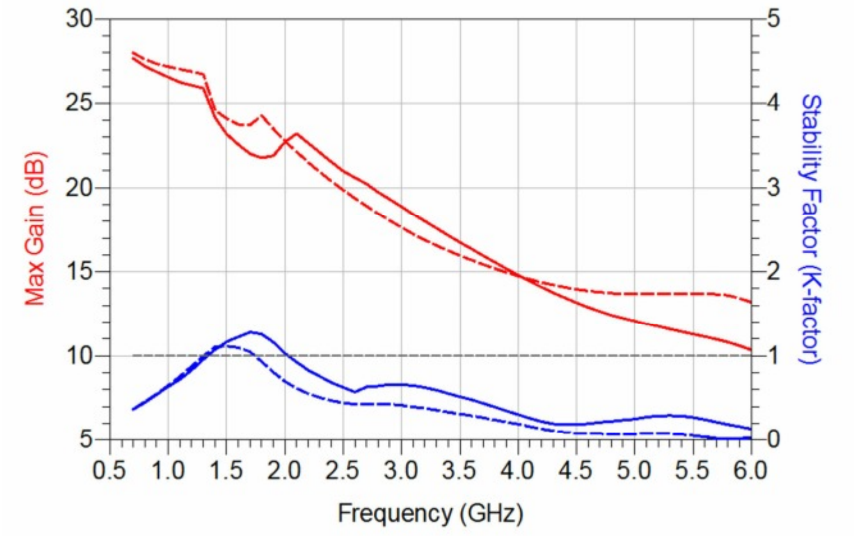


Figure 4: G_{MAX} and stability factor of QPD1008 (solid lines) and QPD1015 (dashed lines) transistors

As with the QFN-packaged transistors, the design of the PAs using the ceramic-packaged components also made use of measured load-pull data and S-parameters. The available load-pull data is shown in Figure 5.

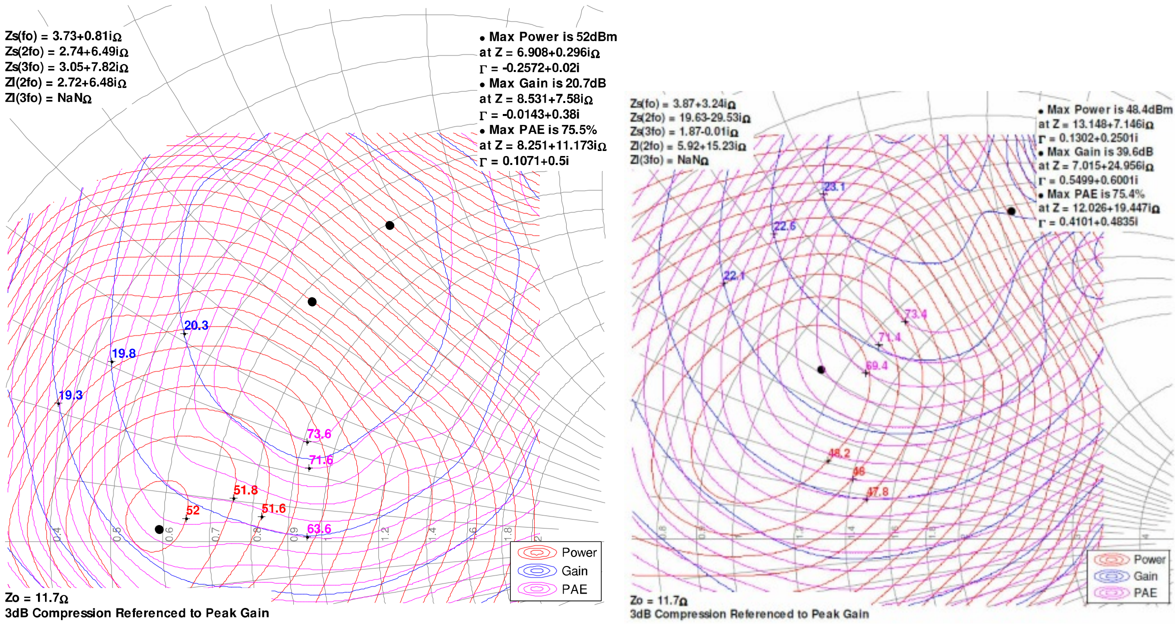


Figure 5: Optimum load impedances for the QPD1008 (left) and QPD1015 (right) at P-3dB compression (Z_0 = 11.7 Ω) at 1 GHz

Because the EVBs are designed for CW operation, the SMD components need to handle high power levels. The stabilising resistors on the QPD1008 EVB in particular have to be able to handle up to 1.5 W (31.8 dBm). Standard 0805 resistors are typically only able to handle up to 125 mW, so specialist high-power resistors that can handle up to 25 W of CW power are used.

Measured Performance

Measurement Setup

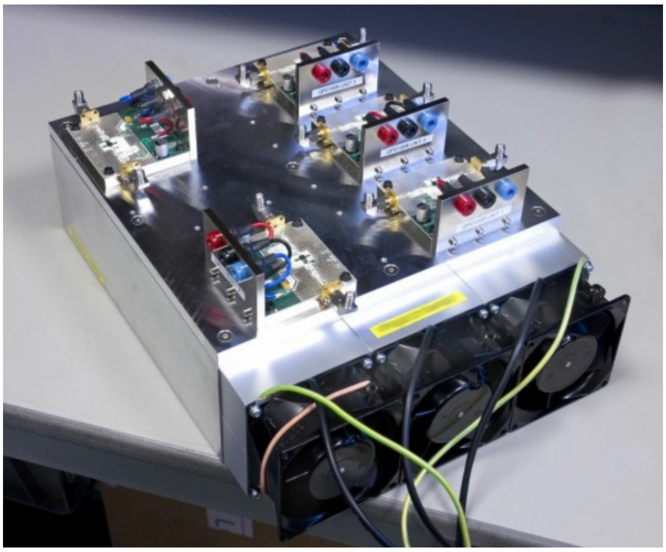


Figure 6: Heatsink with five EVBs attached for testing in temperature chamber

Measurements were taken inside a temperature chamber that could test the EVBs up to +85°C and down to -40°C. A bespoke heatsink and carrier plate (shown in Figure 6) was designed so that five evaluation PCBs could be tested consecutively without having to open the temperature chamber between measuring each Device Under Test (DUT). This greatly helped speed up testing times by eliminating the time needed for the temperature to re-stabilise. Measurements were also accelerated using automated test software.

All measurements are calibrated to the SMA connectors and include matching network and connector losses. Care is taken when measuring these high power devices to ensure that the VNA, power meters and other test equipment would not be damaged by any DUT malfunction.

QPD1009 Measurement

The QPD1009 is the 15 W transistor packaged in a 3x3 mm QFN. A photograph of the QPD1009 EVB is shown in Figure 7.

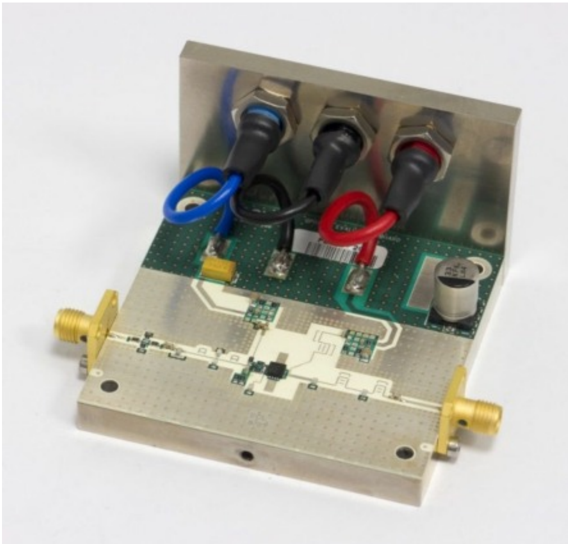


Figure 7: Photograph of the QPD1009 EVB

The QPD1009 EVB S-parameters are shown in Figure 8. The power amplifier exhibits flat small-signal gain across the frequency band, good input return loss and stability at all frequencies. The output return loss is comparatively poor compared to the input return loss as the output was matched for good large-signal performance. Small signal gain of 19 dB is achieved between 0.95 GHz and 1.21 GHz and this performance was replicated across a number of units.

Large signal measurements are shown in Figure 9. The QPD1009 EVB produces a minimum of 14 W of output power across the band, including matching network and connector losses. The gain is relatively flat across the band with a slight positive gain slope. The drain efficiency is greater than 53%, exceeding 60% at the high end of the frequency band.

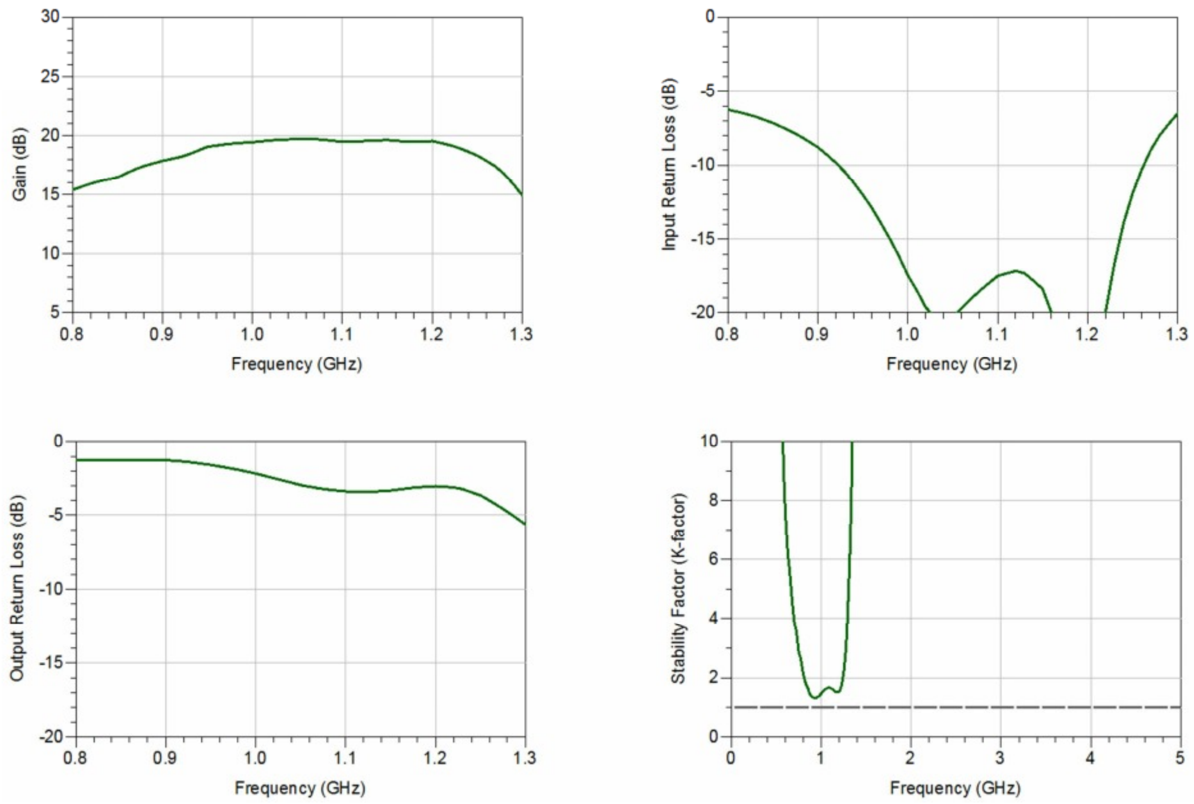


Figure 8: Gain, input and output return loss and stability factor for QPD1009 EVB at 25°C

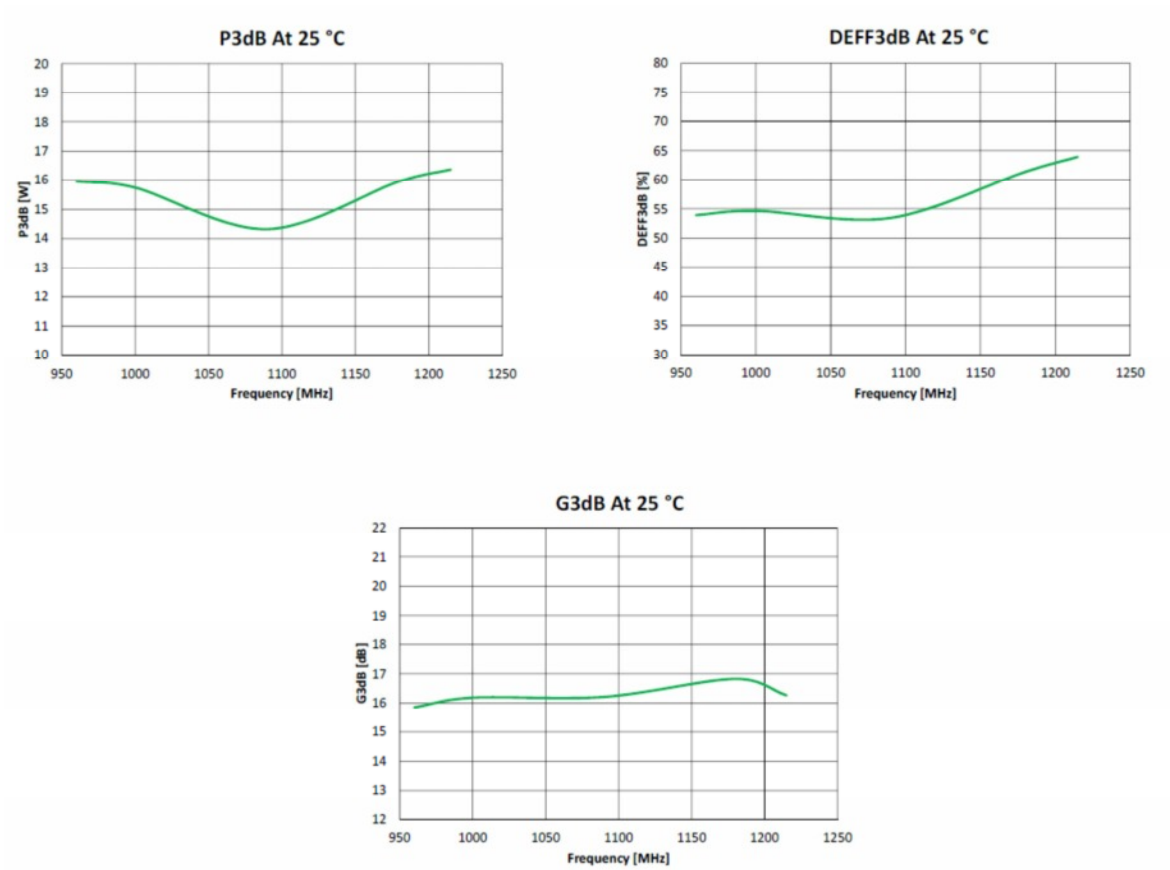
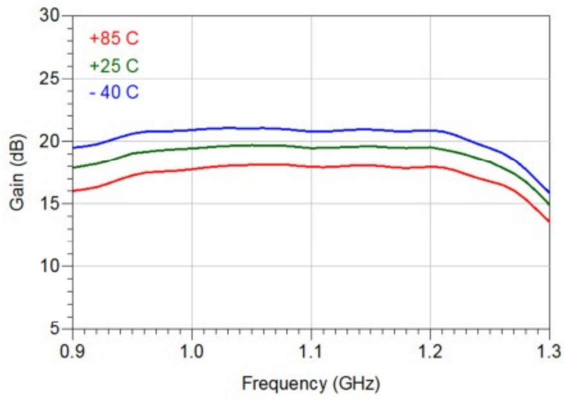


Figure 9: Output power, drain efficiency and gain for QPD1009 EVB at P-3dB compression (25°C)

The measured small signal gain and stability factor are plotted against frequency at baseplate temperatures of -40°C, 25°C and 85°C in Figure 10. As would be expected, gain is higher at lower temperatures and the stability factor decreases slightly.



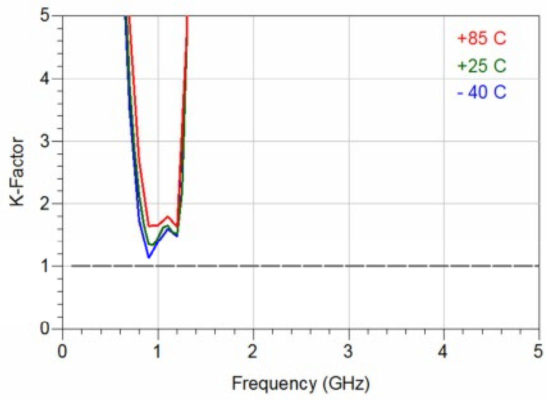


Figure 10: Small-signal gain and stability factor for QPD1009 EVB at -40°C, +25°C and +85°C

QPD1010 Measurement

A photograph of the QPD1010 EVB is shown in Figure 11.

Figure 11: Photograph of the QPD1010 EVB

The small-signal measurements for the 10 W QPD1010 evaluation board are shown in Figure 12. Flat gain is achieved with a minimum stability factor of 1.4. As with the 15 W QPD1009, good input return loss with a two-pole response can be observed.

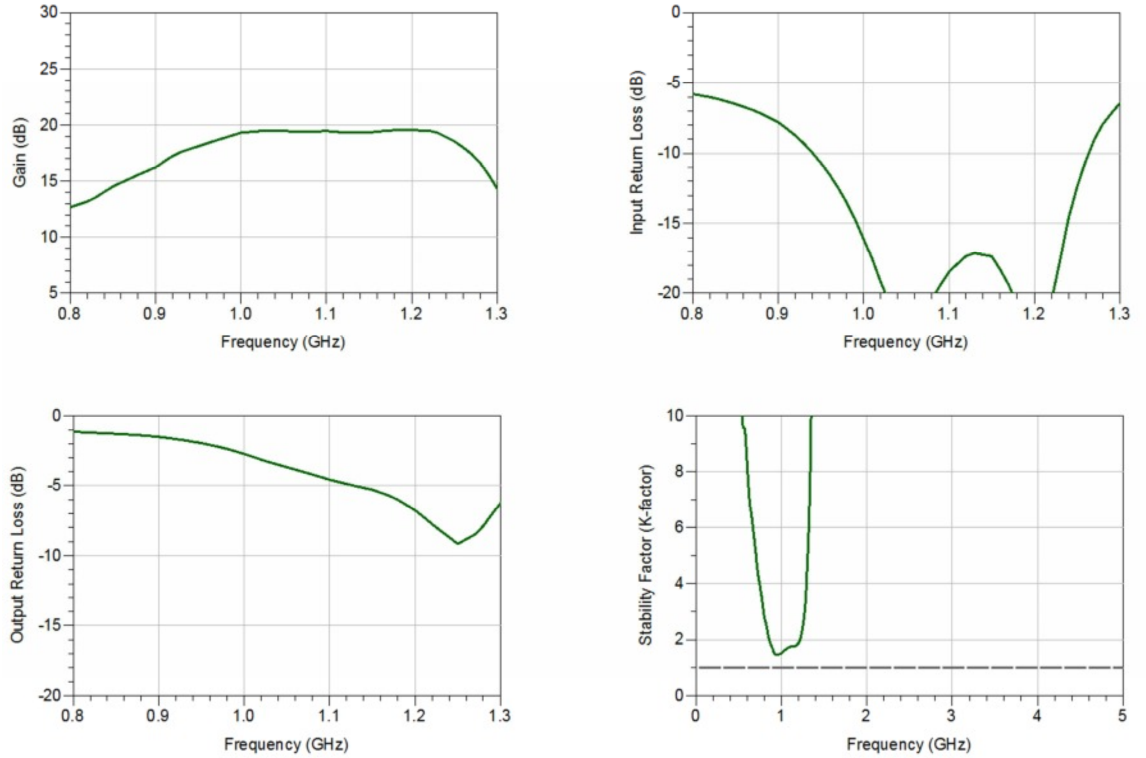


Figure 12: Gain, input and output return loss and stability factor for QPD1010 EVB at 25°C

The large signal performance of the QPD1010 evaluation board is shown in Figure 13. Good power and efficiency are achieved simultaneously across the band. The small signal gain and K-factor versus temperature is shown in Figure 14. The gain decreases as temperature increases, but the gain shape remains flat across all temperatures. It can be seen that the stability factor is greater than 1.2 even at -40°C.

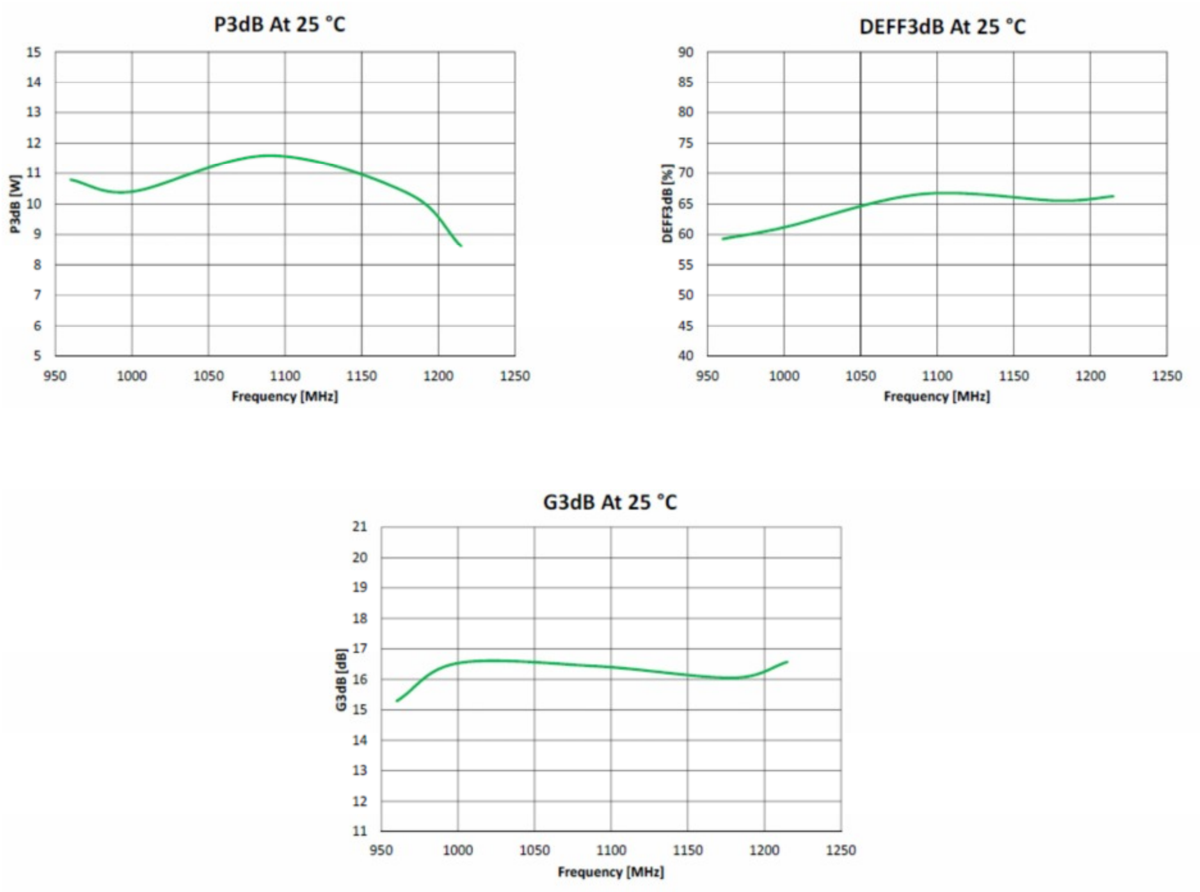


Figure 13: Output power, drain efficiency and gain for QPD1010 EVB at P-3dB compression (25°C)

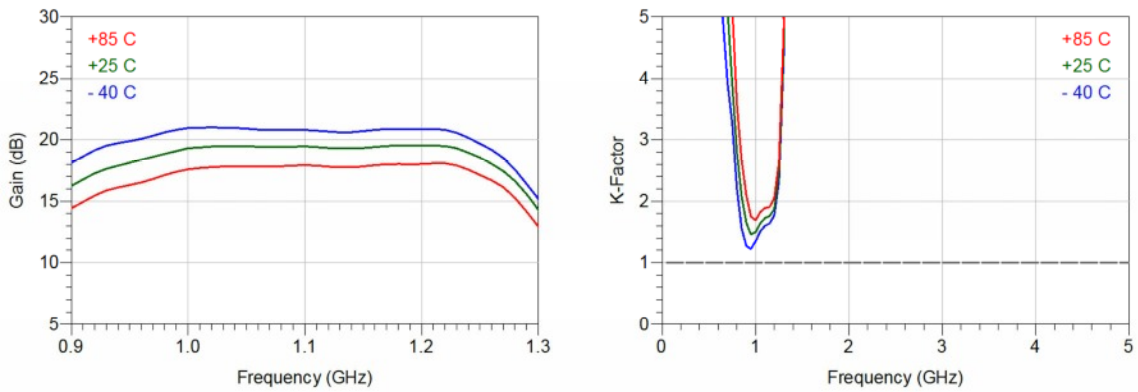


Figure 14: Small-signal gain and stability factor for QPD1010 EVB at -40°C, +25°C and +85°C

QPD1008 Measurement

A photograph of the QPD1008 EVB is shown in Figure 15.

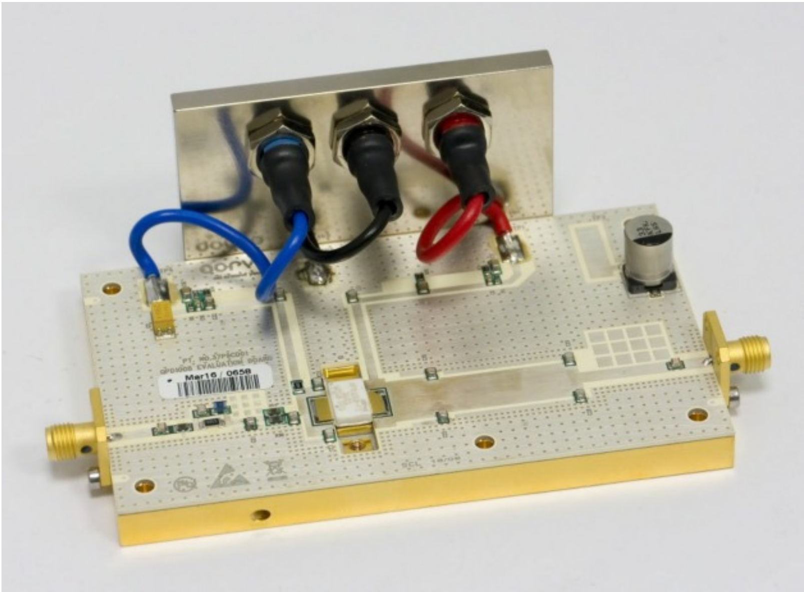


Figure 15: Photograph of the QPD1008 EVB

The QPD1008 is the metal-ceramic packaged transistor rated at 125 W. Figure 16 shows the S-parameters for the QPD1008 EVB at room temperature. The small-signal gain is 20 dB at the centre of the band and the input return loss shows a two-pole response. The output return loss is relatively poor due to the transistor being matched for large-signal output power and efficiency rather than a conjugate match. The stability factor is greater than unity across the measured frequency range.

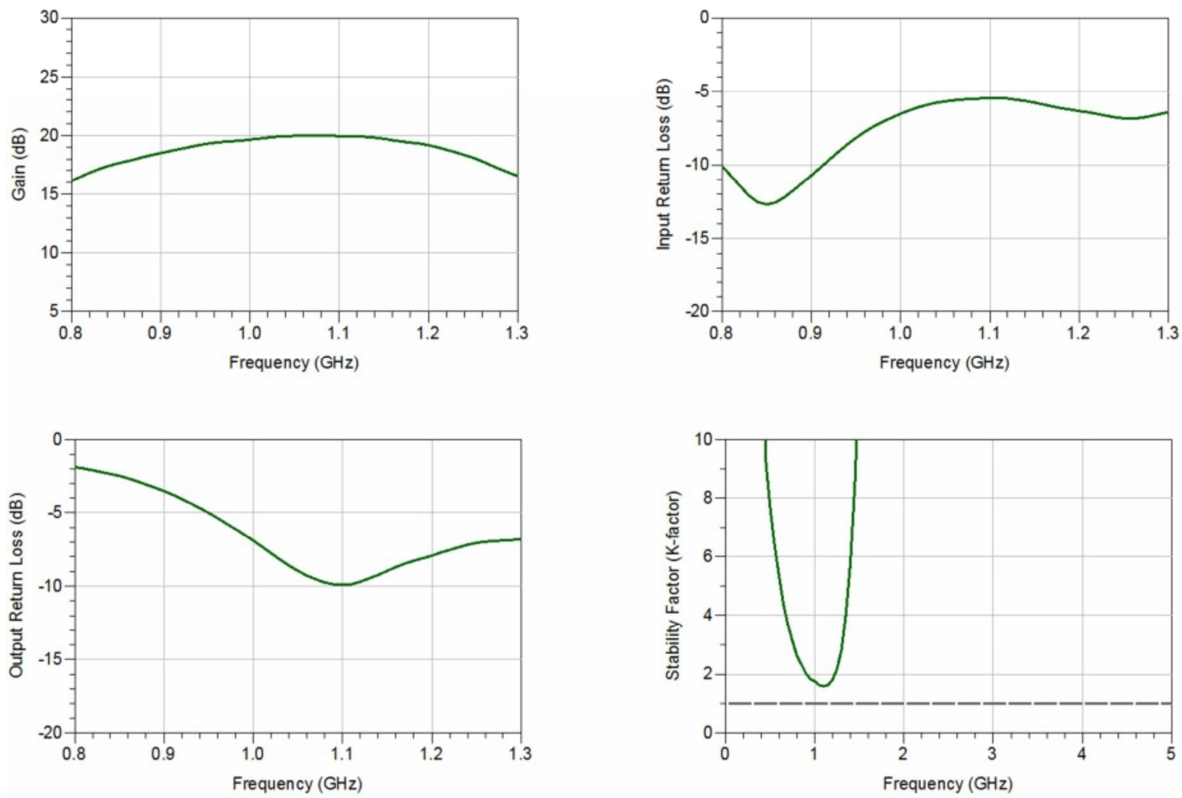


Figure 16: Gain, input and output return loss and stability factor for QPD1008 EVB at 25°C

Across the measured band the QPD1008 produces a minimum 110 W of power and 58% drain efficiency, with at least 16.5 dB of large signal gain. The peak efficiency is 73% and peak output power is 135 W, which is particularly notable given that matching network and connector losses are included. The high dissipated power, whilst modest considering the RF output power, shows the need for a packaging and assembly solution which minimises the thermal impedance to the carrier.

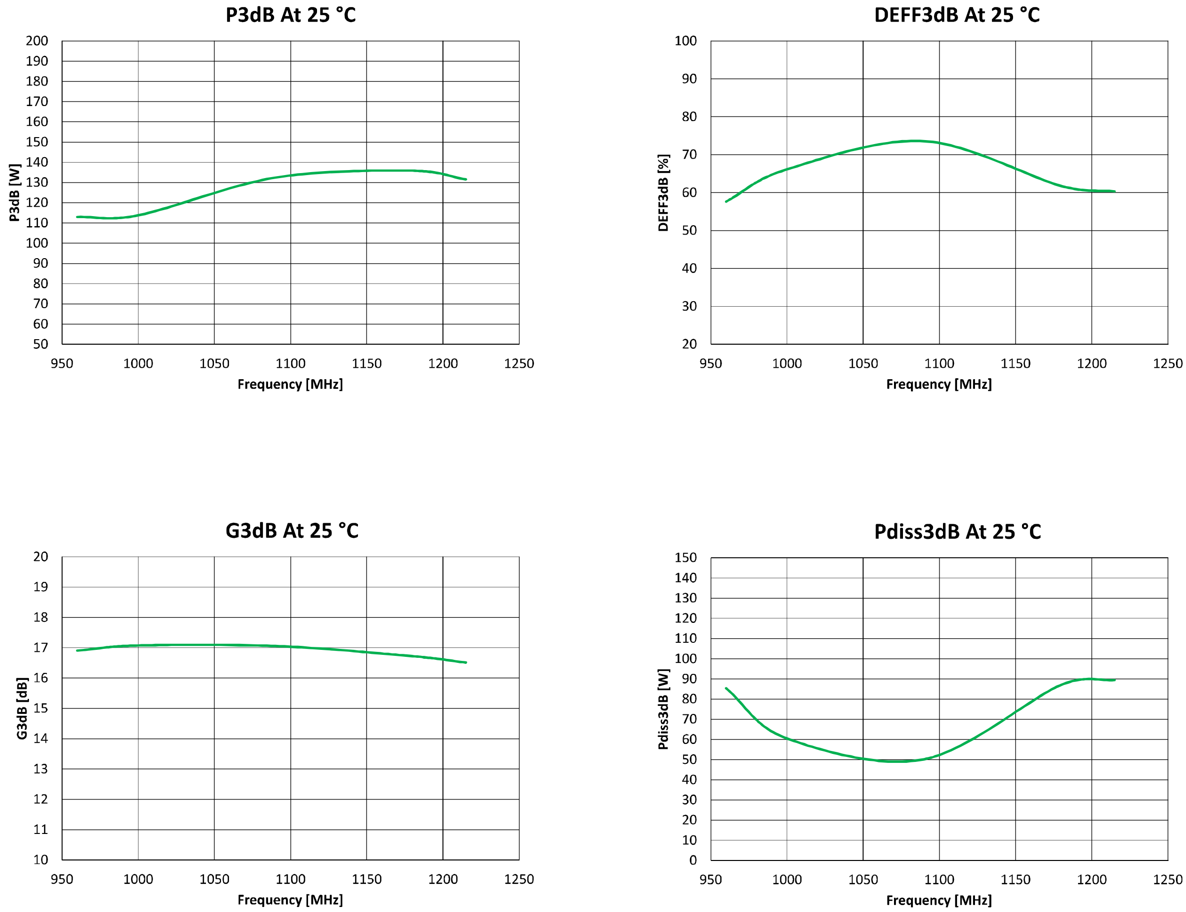


Figure 17: Output power, drain efficiency, gain and dissipated power for QPD1008 EVB at P-3dB compression (25°C)

The measured small signal gain and stability factor are plotted against frequency at baseplate temperatures of -40°C, 25°C and 85°C in Figure 18.

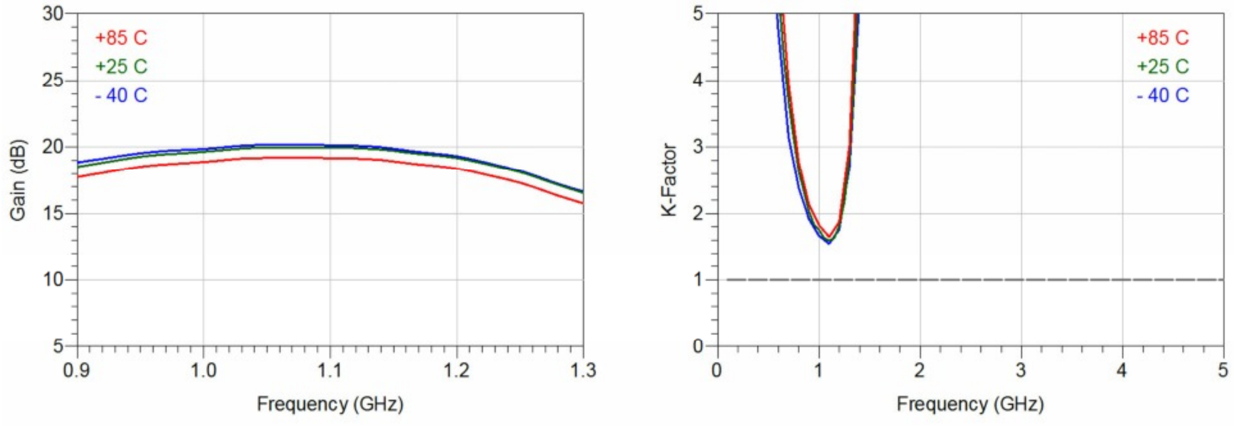


Figure 18: Small-signal gain and stability factor for QPD1008 EVB at -40°C, +25°C and +85°C

QPD1015 Measurement

A photograph of the QPD1015 EVB is shown in Figure 19.

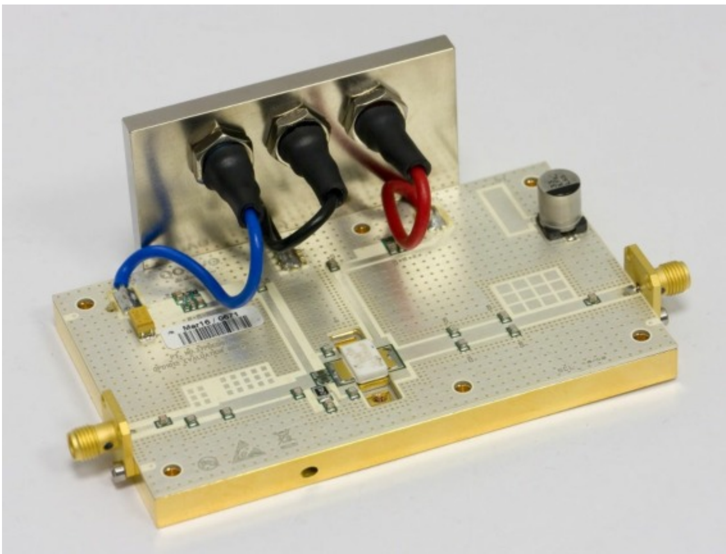


Figure 19: Photograph of the QPD1015 EVB

Figure 20 shows the measured S-parameters for the QPD1015 (the 65 W transistor). The small-signal gain is 19 dB at the low-frequency end of the band, reducing to 17.5 dB at the high-frequency end of the band. The input return loss is 12 dB across the band with plenty of margin either side of the operating band. The EVB is unconditionally stable at all frequencies and the output return loss is reasonable considering the requirements for large-signal performance.

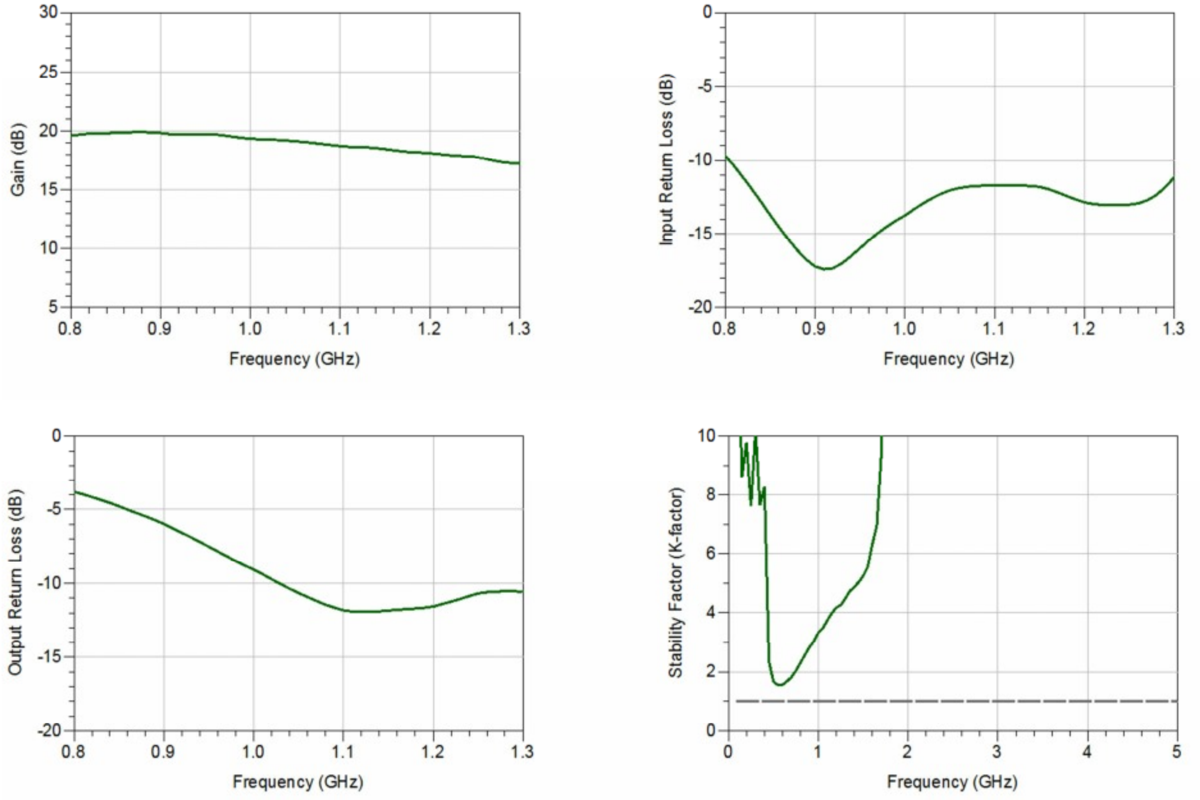


Figure 20: Gain, input and output return loss and stability factor for QPD1015 EVB at 25°C

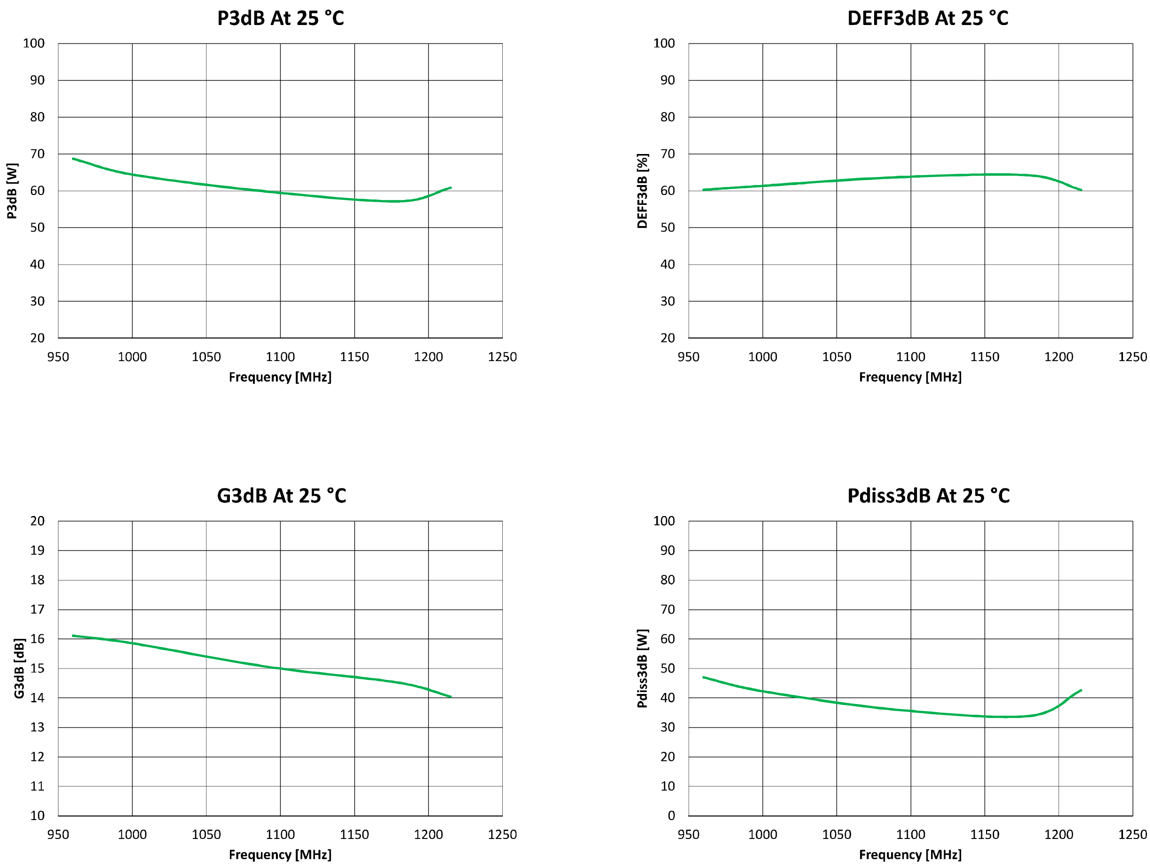


Figure 21: Output power, drain efficiency, power dissipation and gain for QPD1015 EVB at P-3dB compression (25°C)

The QPD1015 EVB has a drain efficiency of greater than 60% across the measured bandwidth, including matching network and connector losses. The measured small signal gain and stability factor are plotted against frequency at baseplate temperatures of -40°C, 25°C and 85°C in Figure 22.

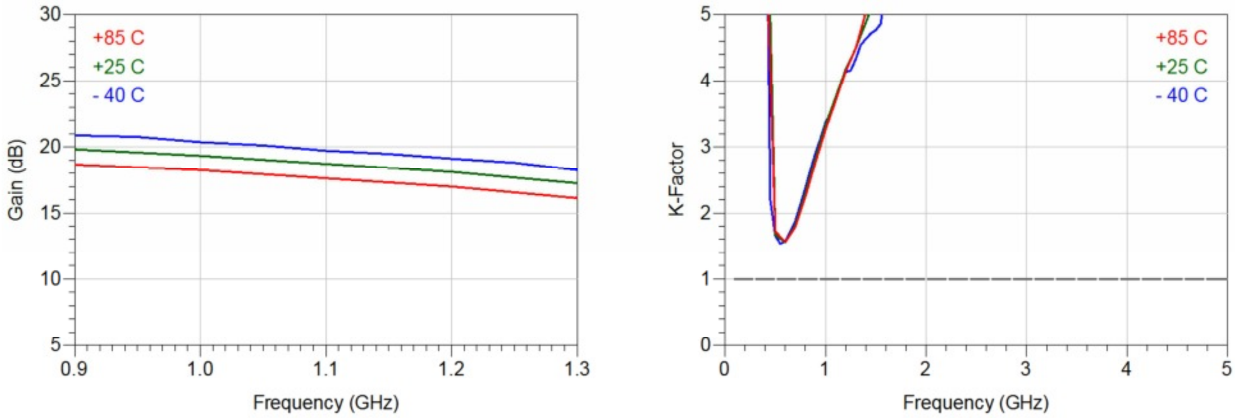


Figure 22: Small-signal gain and stability factor for QPD1015 EVB at -40°C, +25°C and +85°C

Summary

Four evaluation boards were designed and measured by Plextek RFI to demonstrate the high performance possible using the Qorvo 0.25 µm high voltage GaN process. Industry standard QFN packages reduce cost for the lower power QPD1009 and QPD1010 transistors whilst thermally optimised packages are used for high power QPD1008 and QPD1015 parts. Efficiencies up to 70% and power levels up to 135 W are demonstrated at L-band between 0.96 GHz and 1.215 GHz. The transistors and evaluation boards can be operated in either pulsed or CW mode, making them suitable for a wide range of applications.

References

[1] A. Dearn and R. Smith, *The Design of a 125W L-Band GaN Power Amplifier,* Plextek RFI.