X-Band and K-Band Balanced Power Amplifiers for Small Satellite Applications

by

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ABSTRACT

This work presents two balanced power amplifier (PA) architectures, one at X-band and the other at K-band. The presented balanced PAs are designed for use in small satellite and cube satellite applications.

The presented X-band PA employs wideband hybrid couplers to split input power to two commercial off-the-shelf (COTS) Gallium Nitride (GaN) monolithic microwave integrated circuit (MMIC) PAs and combine their output powers. The presented X-band balanced PA manufactured on a Rogers 4003C substrate yields increased small signal gain and saturated output power under continuous wave (CW) operation compared to the single MMIC PA used in the design under pulsed operation. The presented PA operates from 7.5 GHz to 11.5 GHz, has a maximum small signal gain of 36.3 dB, a maximum saturated power out of 40.0 dBm, and a maximum power added efficiency (PAE) of 38%.

Both a Wilkinson and a Gysel splitter and combiner are designed for use at K-band and their performance is compared. The presented K-band balanced PA uses Gysel power dividers and combiners with a GaN MMIC PA that is soon to be released in production.

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CHAPTER 1

INTRODUCTION

In the field of satellite communication (SATCOM) technologies, there is an ever growing need to increase transmitted radio frequency (RF) power, decrease physical size, and maintain high power added efficiency (PAE). Fig. 1 illustrates the trend of increasing solid-state PA (SSPA) output power over time for various frequency bands. These trends hold for X-band and K-Band PAs, as well as for smaller SATCOM satellites. In addition to increasing output power, small form factor PAs are increasingly important for the growing market of small satellites. Because of these considerations, a PA for small satellite communication applications is evaluated based on its saturated output power, PAE, gain, and physical size.

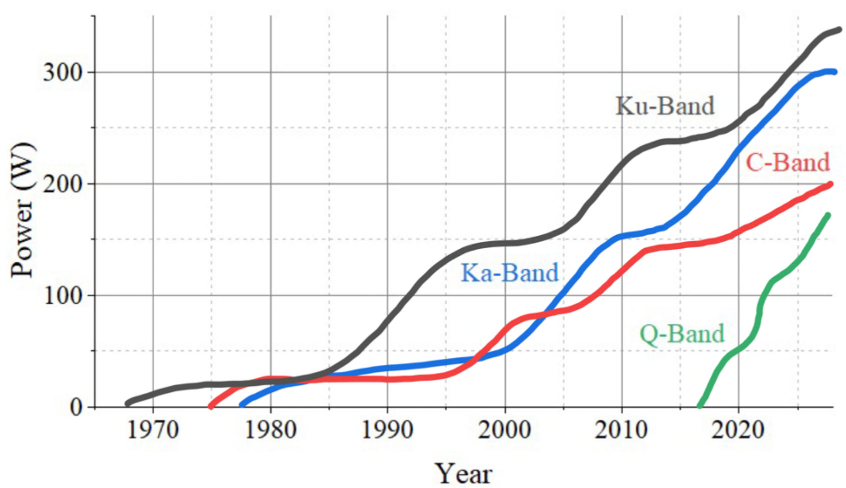


Figure 1. General Output Power Trends of Solid-State PAs Over Time

The X-band, ranging from 8 GHz to 12 GHz, is frequently used for SATCOM uplink, military SATCOM, and radar applications [1]. There are many existing COTS

MMIC X-band PAs available from various manufacturers, but many of them have not evolved to meet the power requirements while maintaining small formfactors required for future small satellite (e.g. CubeSat) applications. Similarly, there are many existing K-band COTS MMIC PAs that encounter the same issues for implementation into small satellites and CubeSats. To solve the issues with the COTS parts available at both frequency bands, balanced PAs are a viable solution by enabling an increase in output power by combining the RF output power of two PAs. A generic block diagram of a balanced amplifier is shown in Fig. 2.

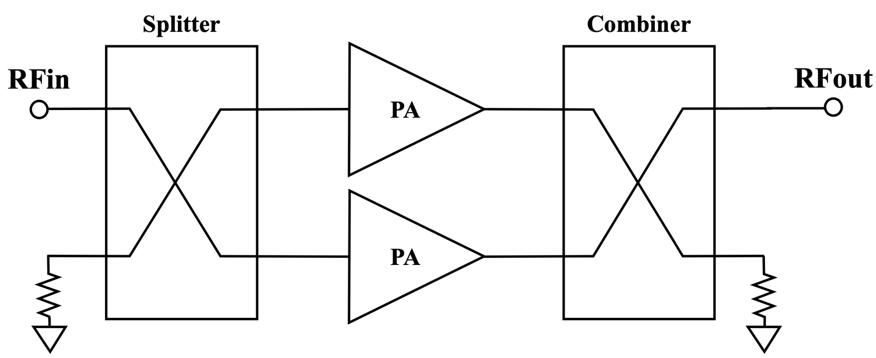


Figure 2. Conceptual Diagram of a Balanced Power Amplifier

Ideally, a balanced design increases the output power by 3dB. In real implemented designs, there are losses in both the splitter and the combiner. There are also design challenges introduced by using a splitter and a combiner, including a need for equal power split, low insertion loss, and minimal reflections (Pozar).

This work presents two balanced PA architectures. Each balanced PA uses two COTS PA MMICs to increase the output power in CW operation compared to that of the single PA MMIC, while maintaining adequate PAE. The block diagram of the X-band balanced PA is shown in Fig. 3 using the Qorvo QPA2611. The block diagram of the presented K-band balanced PA is shown in Fig. 4.

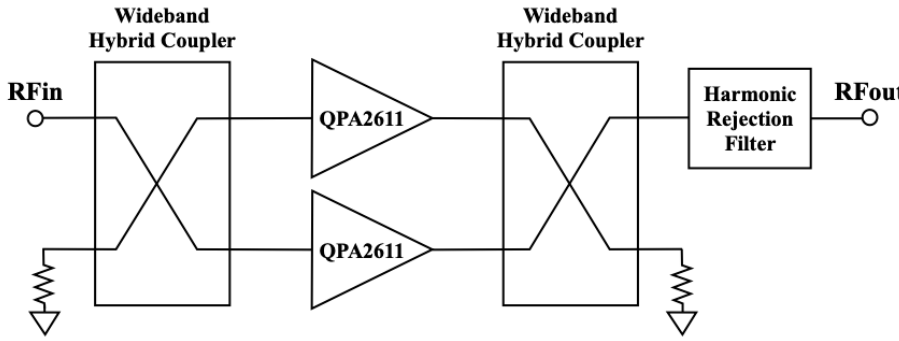


Figure 3. Block Diagram of Presented X-Band Balanced PA

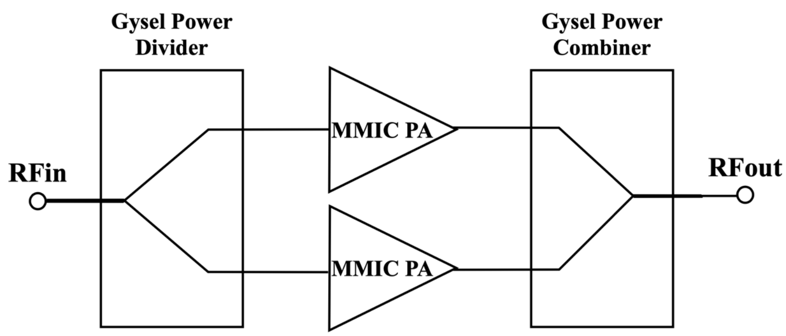


Figure 4. Block Diagram of Presented K-Band Balanced PA

CHAPTER 2

X-BAND BALANCED POWER AMPLIFIER

2.1 Design

The designed X-band PA is a balanced PA operating from 7.5 to 11.5 GHz employing two Qorvo GaN-on-SiC QPA2611 MMICs, a wideband hybrid coupler, and a harmonic rejection low pass filter designed on the Rogers 4003C substrate with 20 mils thick with 1 ounce copper weight.

The X-band QPA2611 has been characterized under pulsed operation but approved for CW operation. It was characterized as providing a saturated output power of 38.2 dBm up to 42% PAE with 12 dBm input RF power and 35 dB of small signal gain [3]. However, the maximum saturated output power listed in the datasheet for pulsed operation is difficult, if not impossible, to achieve under CW operation. Thus, it was not unexpected that lower output power, efficiency, and gain were observed when operating the PA under CW operation, instead of pulsed operation. The presented balanced PA provides an increase of 1.8 dB saturated output power under CW operation over its single GaN MMIC counterpart operating under pulsed operation. The presented design has a small formfactor with an active RF area of 28 cm^2.

2.1.1 Wideband Hybrid Coupler Design

The hybrid coupler is used as both a power splitter in the input path feeding the QPA2611 MMICs and a power combiner in the output path of the QPA2611 MMICs. The RF input power is evenly split with the wideband hybrid coupler. The output power from each MMIC is combined using the same wideband hybrid coupler architecture. The wideband hybrid coupler, shown in Fig. 5, is a two-section wideband 90-degree hybrid coupler designed for frequencies between 7.5 and 11.5 GHz.

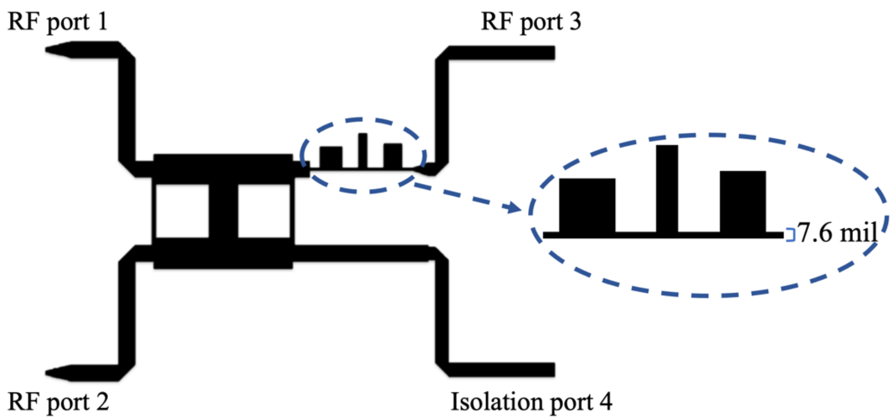
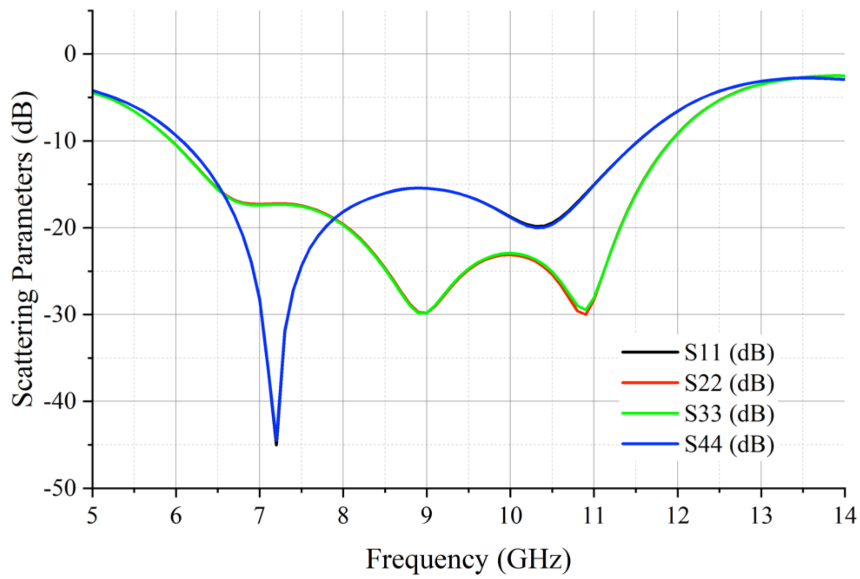
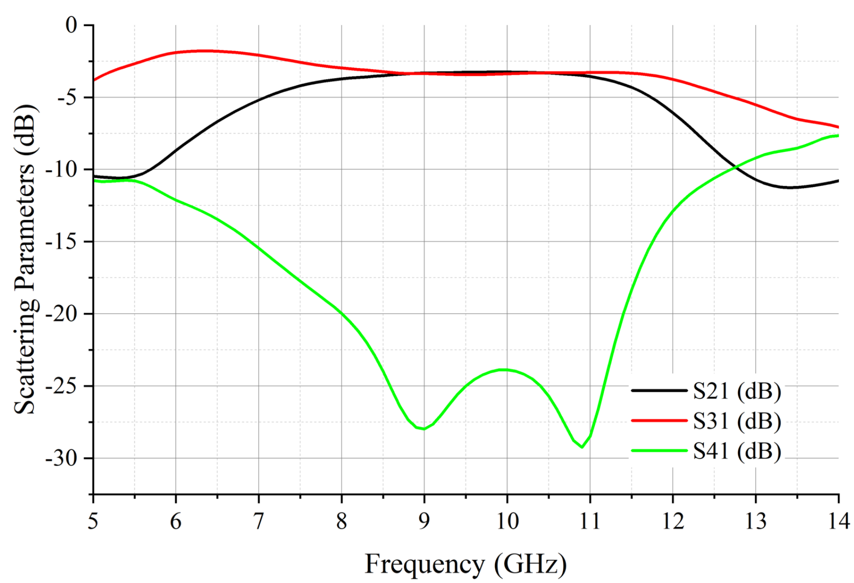


Figure 5. Layout of Wideband Coupler with Harmonic Rejection Filter Design

The coupler was designed to have low insertion loss, with an average loss of 0.52 dB from one input port and 0.23 dB from the other input port across the 7.5 - 11.5 GHz band. The coupler was also designed for low transmission through the terminated (isolated) port with S41 less than -17.3 dB across the same frequency range. These EM simulated transmission scattering parameters (s-parameters) are shown in Fig. 6a. The hybrid coupler was also designed to have low reflection s-parameters, with S11, S22, S33, and S44 all less than -15 dB across the 7 to 11 GHz range, as displayed in Fig. 6b.



(a)



(b)

Figure 6. Wideband Hybrid Coupler: (a) Transmission and (b) Reflection S-Parameters

2.1.2 Harmonic Rejection Low Pass Filter Design

The output of the power combiner passes to a harmonic rejection low pass filter. A harmonic rejection low pass filter was designed at the output of the balanced PA to filter out signals from 16 GHz to 22 GHz, which encompasses all second harmonics from the operating frequency range of 8 to 11 GHz. The harmonic rejection filter is implemented as a 7th order elliptic low pass filter, with the layout shown integrated with the hybrid coupler in Fig. 5. The EM simulated insertion and return loss results for that layout are shown in Fig. 7.

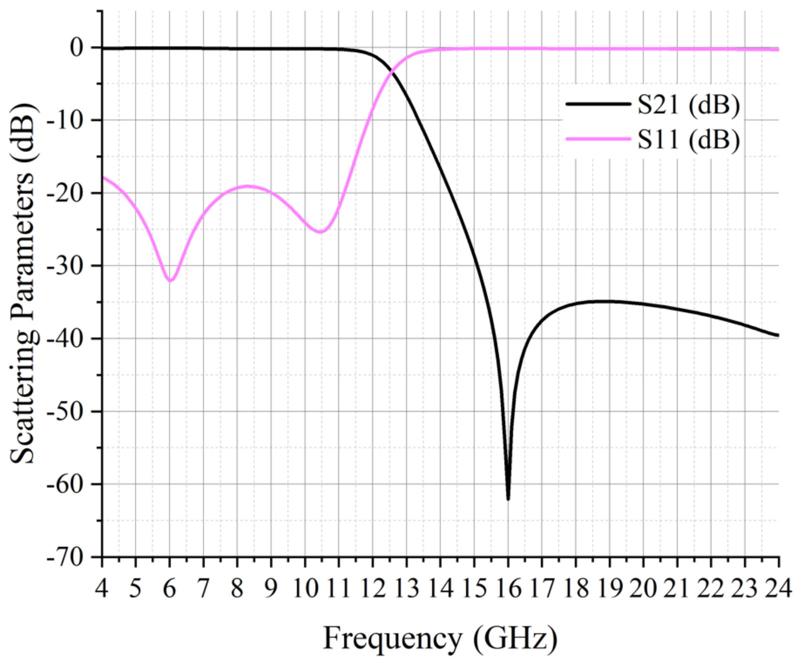


Figure 7. Simulated S-Parameters of Harmonic Rejection Filter

The harmonic rejection low pass filter has a line width on the output of 7.6 mils. This line carries a maximum of 0.45 A of RF current at the maximum saturated output power of 10 W, as calculated via P=R∗I2 in a 50 Ω system. A line width of this thickness is able to support approximately 1 A current, so the line width is adequate for the designed output power.

2.1.3 Balanced PA Design

The fully balanced PA design, including the two hybrid couplers, output filter, and two QPA2611 MMICs, was simulated using electromagnetic (EM) simulations and a foundry-provided model for the MMIC. The EM simulations were performed using Cadence AWR AXIEM and the simulated results are given in Fig. 8 showing a wide band small signal gain that peaks at 37.3 dB at 7.6 GHz.

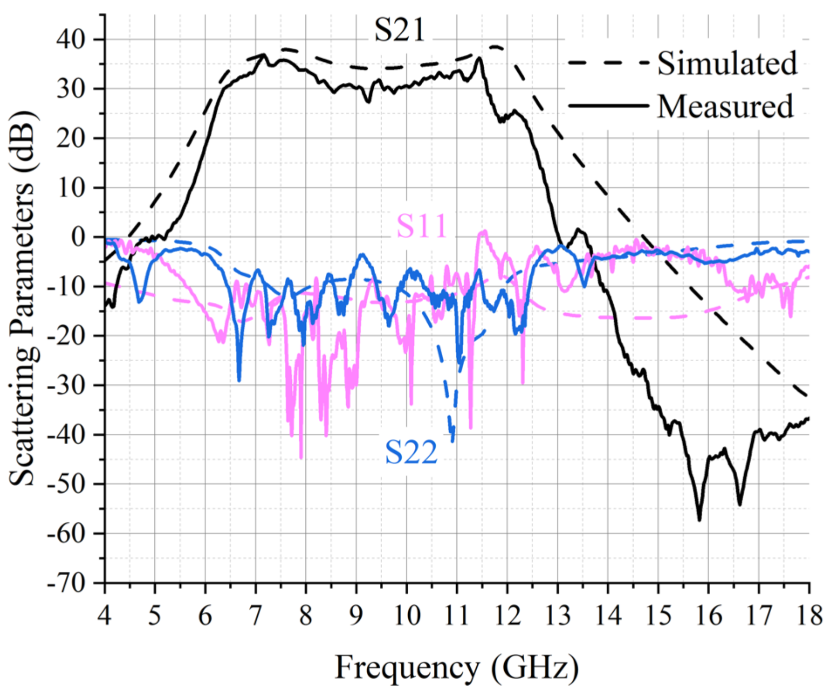


Figure 8. Simulated and Measured S-Parameters of the Presented Balanced X-Band PA

2.2 Implementation

The presented balanced PA is integrated onto a printed circuit board (PCB) on Rogers 4003C material that is 20 mils thick with 1 ounce copper conductor. The board has a width of 7.4 cm and a height of 6.8 cm, with an active RF area of dimensions 7.4 cm by 4.0 cm, making this a compact design. The board is attached to a brass block approximately 1.3 cm thick to act as a heat sink. The individual MMIC PAs are biased with separate pads and voltage sources to allow for flexible control of the DC bias drain current. An image of the manufactured board is given in Fig. 9.

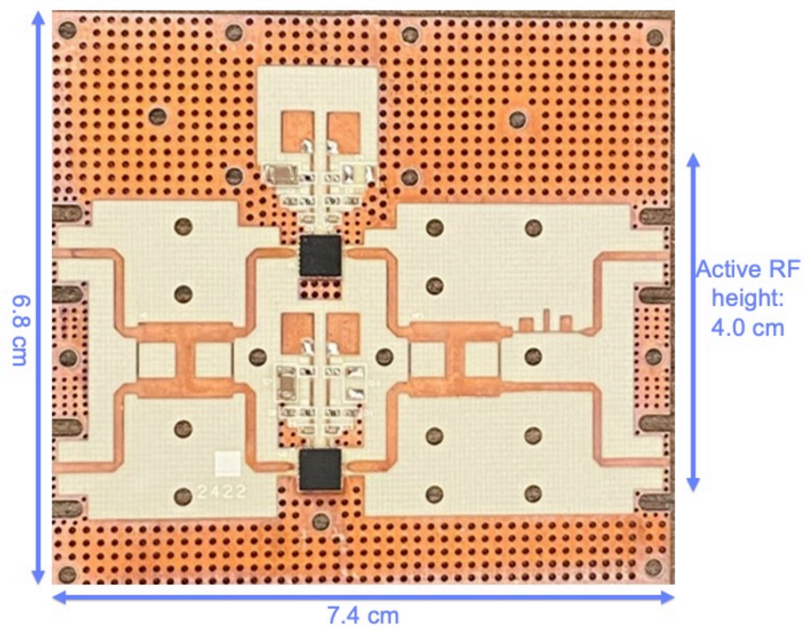


Figure 9. Photograph of the Full X-Band Design Implementation

Because the GaN-on-SiC process technology can have die-to-die variations, separate bias and supply voltage sources were provided to each MMIC to account for process variations between the two MMICs. The terminations for the isolation ports on the input and output were also provided off-chip to ensure reliable 50 ohm terminations.

The MMICs are both biased with a drain voltage of 24 V, and gate voltages of about -2.32 V and -2.28 V. A total of four balanced PAs were measured and the presented measurement results are representative of all four PAs.

2.3 X-Band PA Results

The presented balanced PA was measured to have a maximum small signal gain of 36.3 dB, as shown in Fig. 8. These small signal measurements are somewhat noisy measurements in S11 across the entire bandwidth. Stability was verified with large signal measurements and with spectral analysis over the entire range of input power. No oscillations were observed. Fig. 10 shows the spectrum with an RF input signal at 7.5GHz at 14.3 dBm and its second harmonic at 15 GHz with only -27 dBm power. The spectral measurements verify the effectiveness of the output harmonic rejection filter.

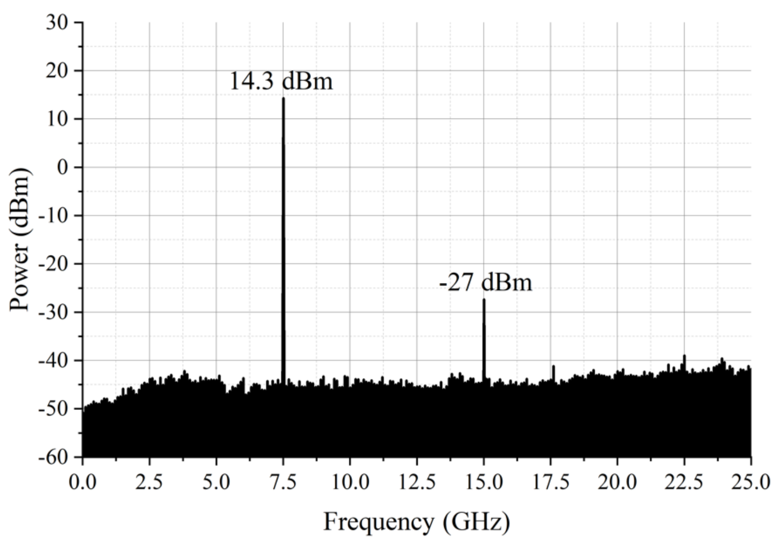


Figure 10. Spectrum of the X-Band Balanced PA’s Output with RF Input at 7.5 GHz

The design exhibited high output power across the full bandwidth, with a maximum saturated output power of 40 dBm with 14.5 dBm input power at 10.5 GHz, as shown in Fig. 11. The measured PA gain versus input power at different PA operating frequencies is plotted in Fig. 12 and confirms that the PA achieves 36 dB linear gain and between 24 dB to 25 dB gain at saturated output power. The maximum PAE of the PA is 38% at the same maximum saturated output power, as shown in Fig. 13.

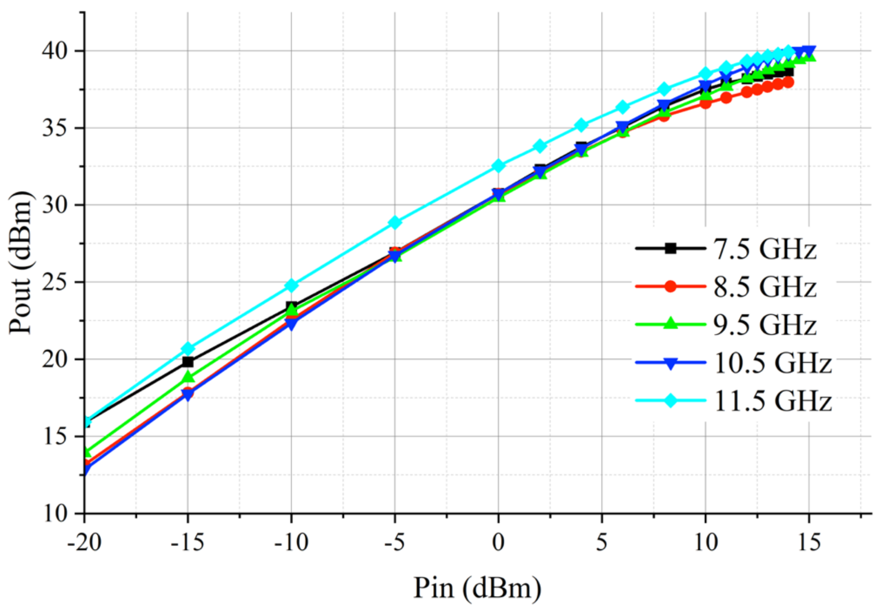


Figure 11. Measured Output Power (Pout) Versus Input Power (Pin)

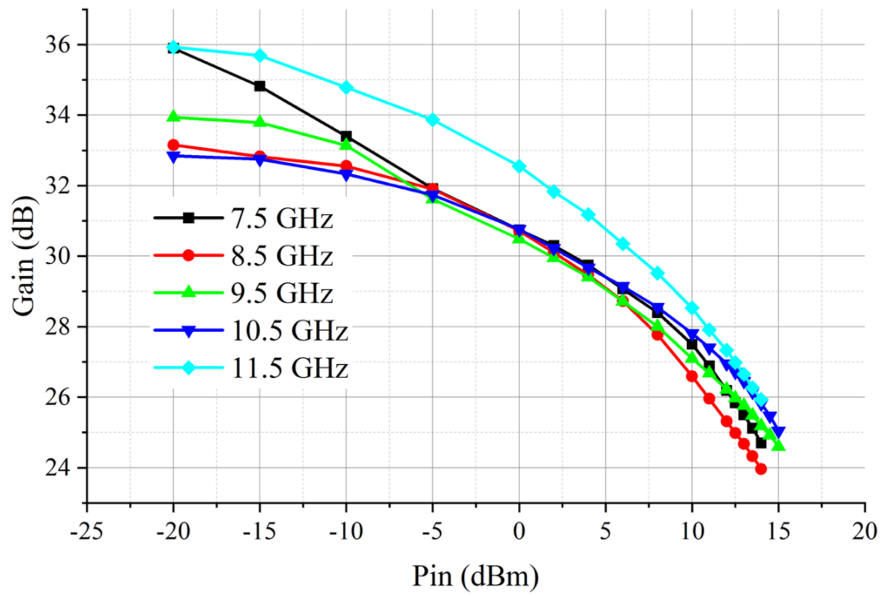


Figure 12. Measured Power Gain Versus Input Power (Pin)

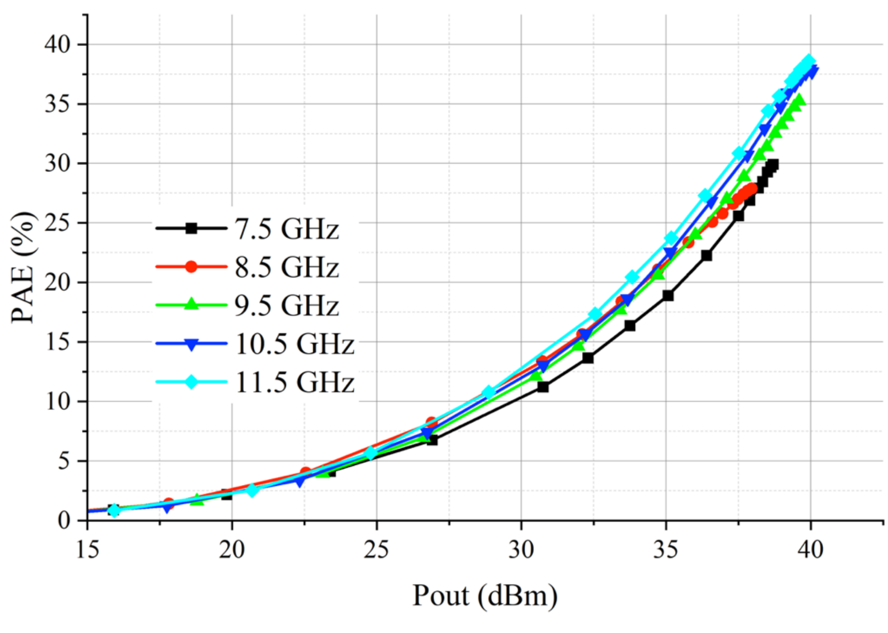


Figure 13. Measured PAE Versus Output Power (Pout)

These measured results are summarized in Table 1, where they are also compared to the single-MMIC used in this design as well as other state-of-the-art X-Band PAs.

Table 1

Comparison Between this Work, the Singular PA MMIC, and Other X-Band PAs.

Reference (Year)	Process	Frequency (GHz)	$S21_{max}$ (dB)	P_{SAT} (dBm)	PAE_{max} (%)	Pulsed or CW
This Work	0.15 µm GaN	7.5 – 11.5	36.3	40	38	CW
Qorvo QPA2611 (2020)	0.15 µm GaN	8 – 12	35	38.2	42	Pulsed
(2018)	0.25 µm GaN	8 – 12	36	43 *	37	CW
(2020)	0.25 µm GaN	9 – 10	19	41.7	37	Pulsed
(2017)	0.25 µm GaAs	8 – 13	22	31	35	--
(2020)	0.25 µm GaN	9.2 – 9.7	13	36.7	43.9	Pulsed

* This work reports very high saturated output power but is a highly nonlinear PA. It is thus not suitable for communications at high power levels.

Table 1 shows wide bandwidth, high small signal gain, high output power, and high PAE. While there are PAs that match or even exceed a particular performance metric, this design exhibits high performance especially after taking into consideration the CW operation and the use of cables in the measurement setup with a PCB integrated design as opposed to probed MMIC performance.

CHAPTER 3

K-BAND BALANCED POWER AMPLIFIER

Like in the X-band, there is a need for a small-formfactor, high power PAs at K-band for small satellite applications. For a particular K-band cube satellite, over 50 COTS PAs were evaluated against design constraints, but all PAs fell short of the requirements. The PA must have a small form factor suitable for the cube satellite, it must provide a saturated output power of 10 watts at 25-27 GHz, and as high efficiency as possible. Heat dissipation is also of key importance for space applications. A balanced architecture is explored using a COTS PA to increase the maximum output power, maintain a small formfactor, and improve thermal dissipation properties.

For the balanced design, a COTS PA that is soon to be released to production was selected that is designed to operate at the desired frequency range. It has a saturated output power of 38 dBm and is packaged in a 5 mm by 5 mm package. To achieve the targeted 40 dBm output power, it is implemented in a balanced PA design. A balanced PA is a good solution for the problems presented above. A balanced PA can provide better thermal management by spreading out the source of heat to two areas. It can also provide higher output power by up to 3 dB with ideal power splitters and combiners. So, we can use a PA that does not hit our power requirements due to thermal constraints at CW operation in a balanced PA to have fewer thermal runaway issues, higher saturated output power, similar small signal gain, and similar PAE.

The splitter and combiner are reciprocal transmission-line networks, typically designed so that the splitter can be mirrored and used as the combiner as well. The goals of the splitter and combiner are to provide low loss across the 25-27 GHz bandwidth.

Since the same design is used as both a power splitter and a power combiner to form a balanced amplifier, all ports must have low return loss. Minimizing reflections is also important to maintain PA stability and signal integrity. For this design, two types of splitter and combiner were investigated: the Wilkinson and the Gysel power splitter.

3.1 Wilkinson Power Splitter

The Wilkinson power divider was introduced by E. J. Wilkinson in 1960 (Wilkinson). Unlike the simpler resistive power divider, the Wilkinson achieves isolation between output ports when all ports are matched to the same impedance. This means that when all ports are perfectly matched, the only source of loss is from reflections from the output ports (Pozar). A basic Wilkinson schematic for equal power division is shown in Fig. 14. Modifications are possible to split the power N-ways or to split the power unevenly to the output ports. For this application, a 2-way, equal split divider is required.

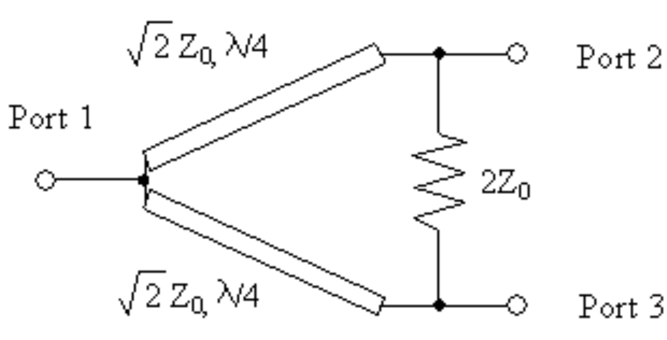


Figure 14. Wilkinson Power Divider
("Wilkinson Power Splitters")

A disadvantage to the Wilkinson power divider is the resistor between port 2 and port 3. Because that resistor is not tied to ground, it cannot dissipate heat to ground. This becomes of key importance in high-power applications, where there is more energy being dissipated as heat.

A Wilkinson power splitter was designed for operation at 25-27 GHz using Keysight's ADS software. It designed for implementation on Rodgers TC35 material with a thickness of 10 mils. All ports are matched to 50 ohms. The schematic for the Wilkinson power splitter is shown in Fig. 15. The schematic was exported into a layout and simulated with ADS Full Electromagnetic (FEM) simulator. The layout is shown in Fig. 16 and has a small area of only 2.55 cm^2.

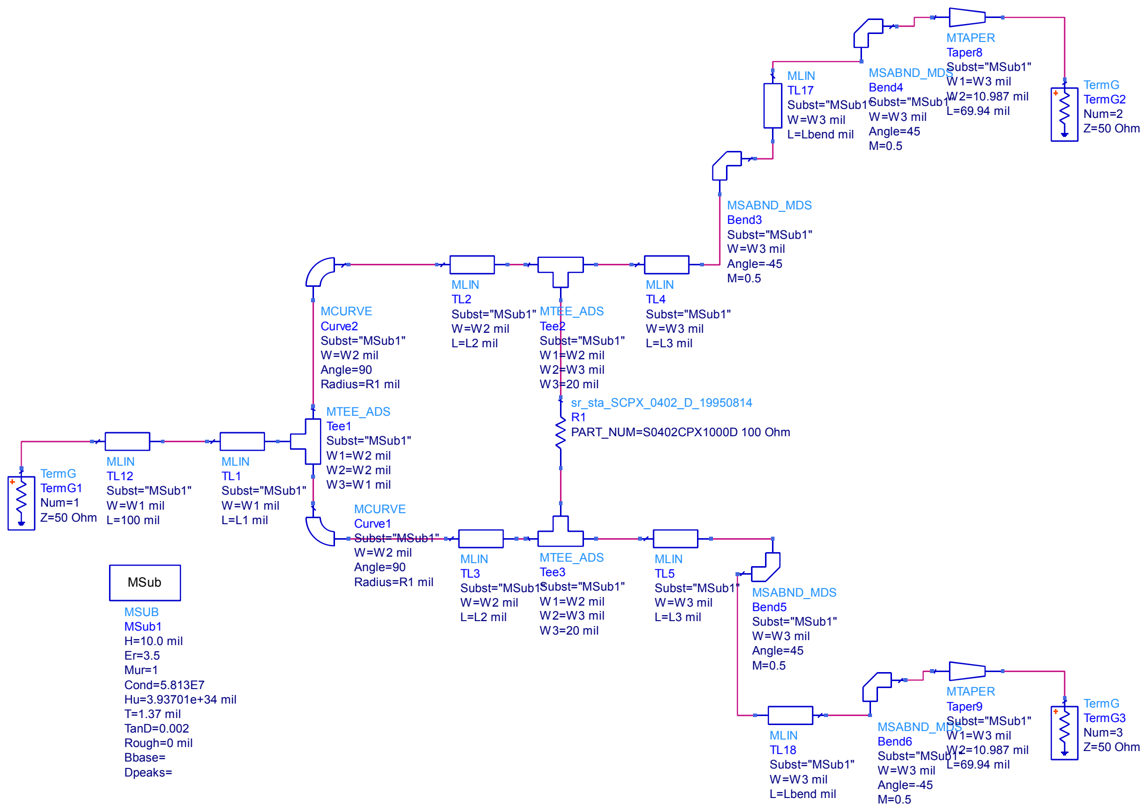


Figure 15. K-Band Wilkinson Schematic

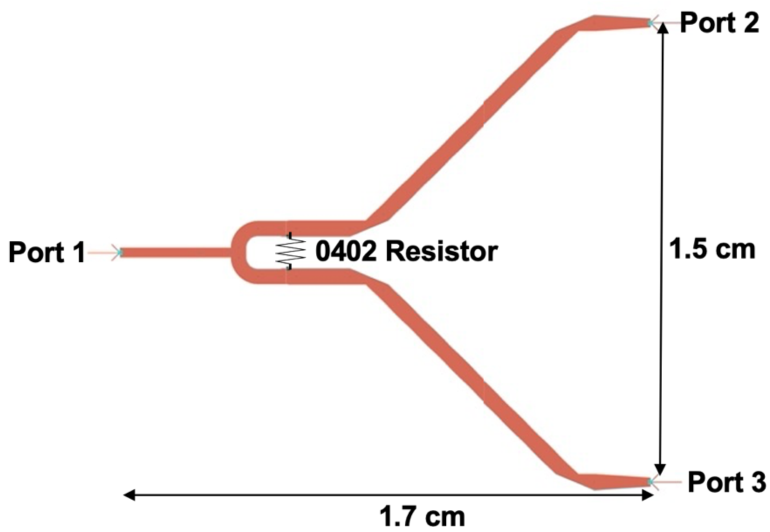
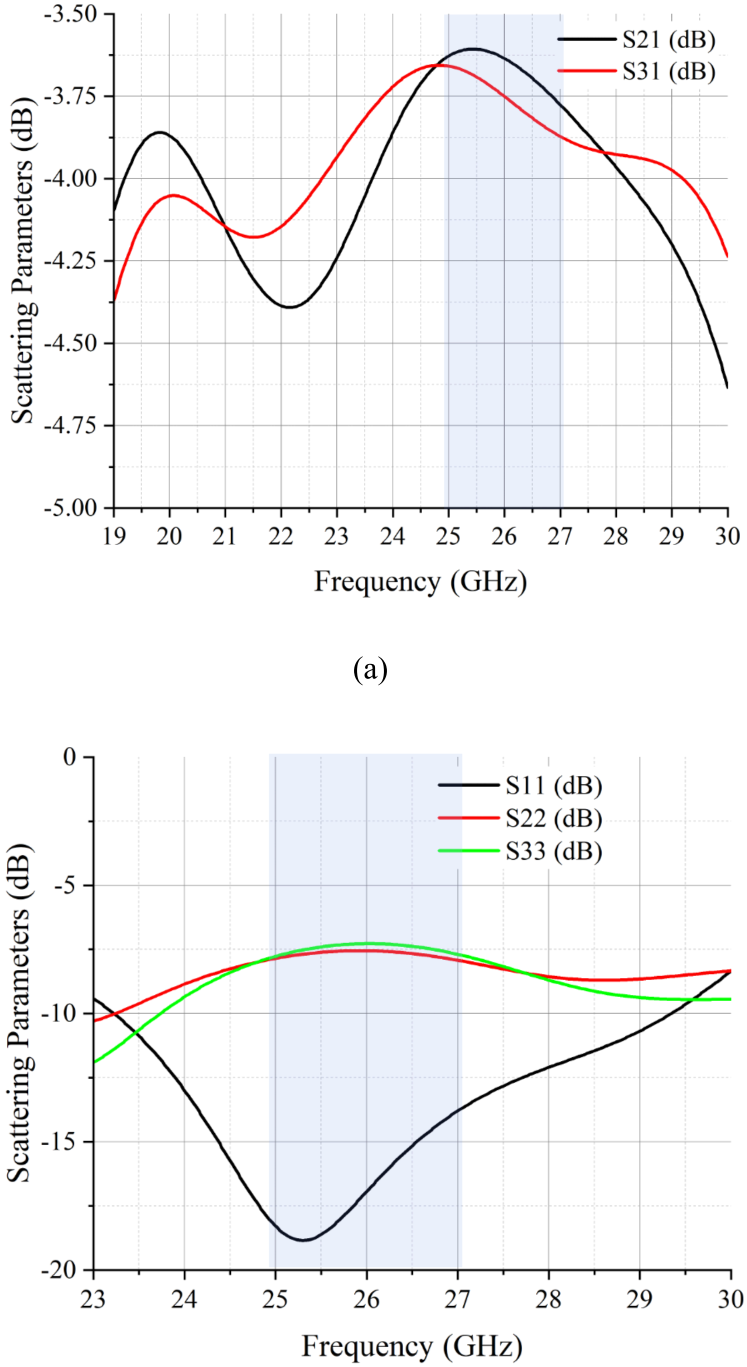


Figure 16. K-Band Wilkinson Layout

The FEM simulation transmission and reflection S-parameter results are shown in Fig. 17. The transmission S-parameters, S21 and S31, include the 3 dB power split from port 1, the input port, to port 2 and port 3. Thus, the transmission S-parameters show an insertion loss of only 0.68 – 0.88 dB across the bandwidth. The reflection S-parameter results show good input match for port 1, with a maximum S11 of -14 dB. The input match on port 2 and port 3 is fairly good, with an S22 and S33 maximum of -7.5 dB. However, because the same design is used as a splitter and a combiner, the return loss needs to be very low for port 2 and 3 so that minimal power is reflected from the combiner and into the output of the MMIC PA. This input matching can be improved with minor design optimizations, which could be implemented if the Wilkinson design proves favorable compared to the Gysel design for the K-band PA.



(a)

(b)

Figure 17. Wilkinson Power Divider: (a) Transmission and (b) Reflection S-Parameters

3.2 Gysel Power Splitter

The Gysel power divider was introduced by Ulrich Gysel in 1975 (Gysel). Similar to the Wilkinson, the Gysel achieves isolation between output ports when all ports are matched to the same impedance. This means that when all ports are perfectly matched, the only source of loss is from reflections from the output ports (Pozar). A simple Gysel schematic for equal power division is shown in Fig. 18. Unlike the Wilkinson power divider, the isolation is provided by resistors tied to ground that can be considered port 4 and 5. Because these resistors are tied to ground, the Gysel power splitter is a good choice for high-power designs.

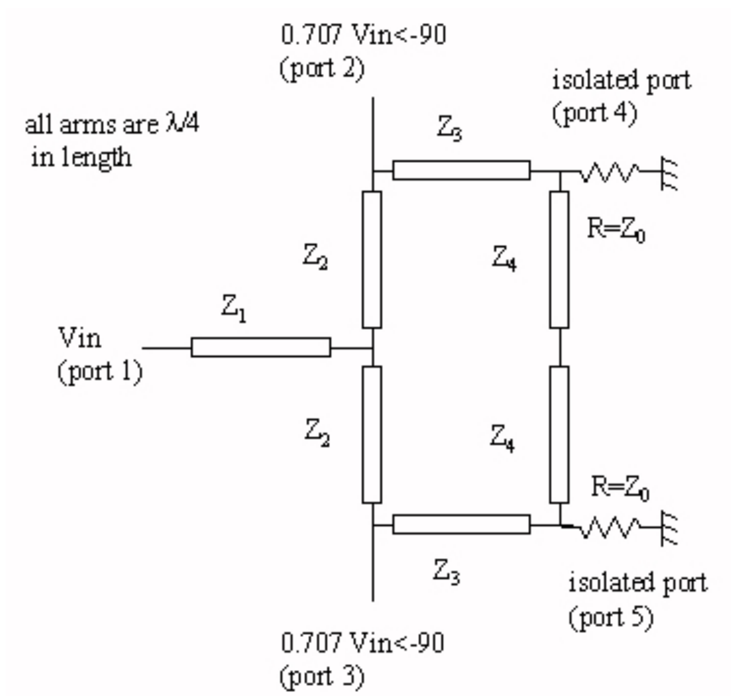


Figure 18. Gysel Power Divider
("Gysel Power Splitter")

A Gysel power splitter was designed for operation at 25-27 GHz using Keysight's ADS software. It designed for implementation on Rodgers TC35 material with a thickness of 10 mils. All ports are matched to 50 ohms. The schematic for the Gysel power splitter is shown in Fig. 19. The schematic was exported into a layout and simulated with ADS FEM simulator. The layout is shown in Fig. 20 and has an even smaller area than the Wilkinson power splitter of only 1.65 cm^2.

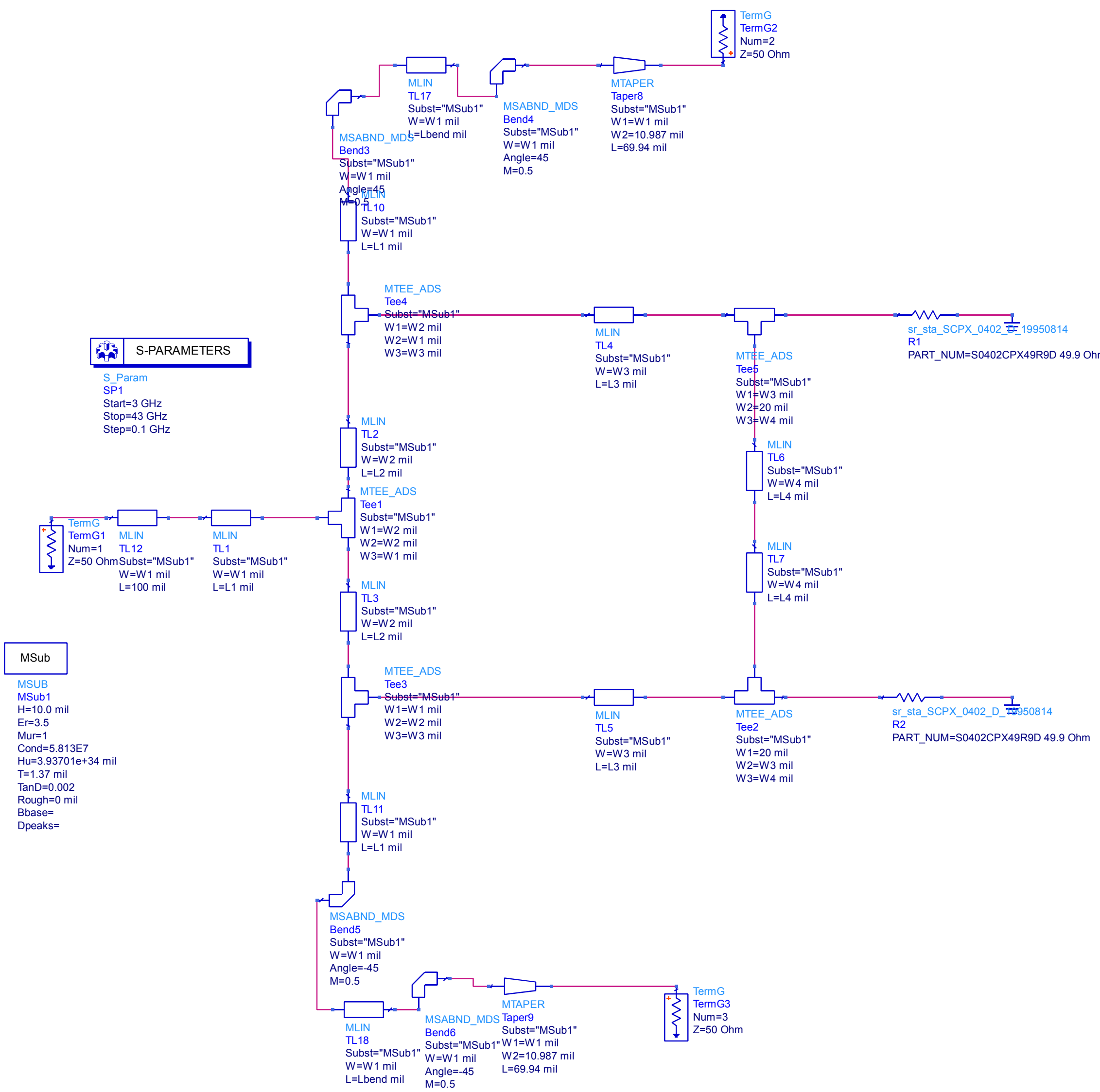


Figure 19. K-Band Gysel Schematic

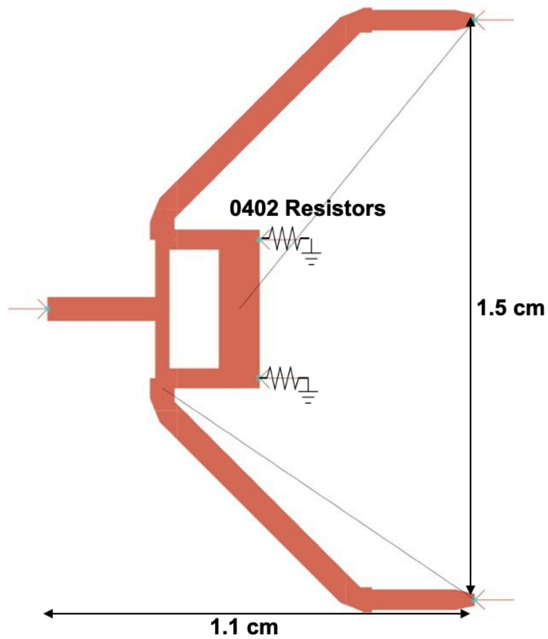
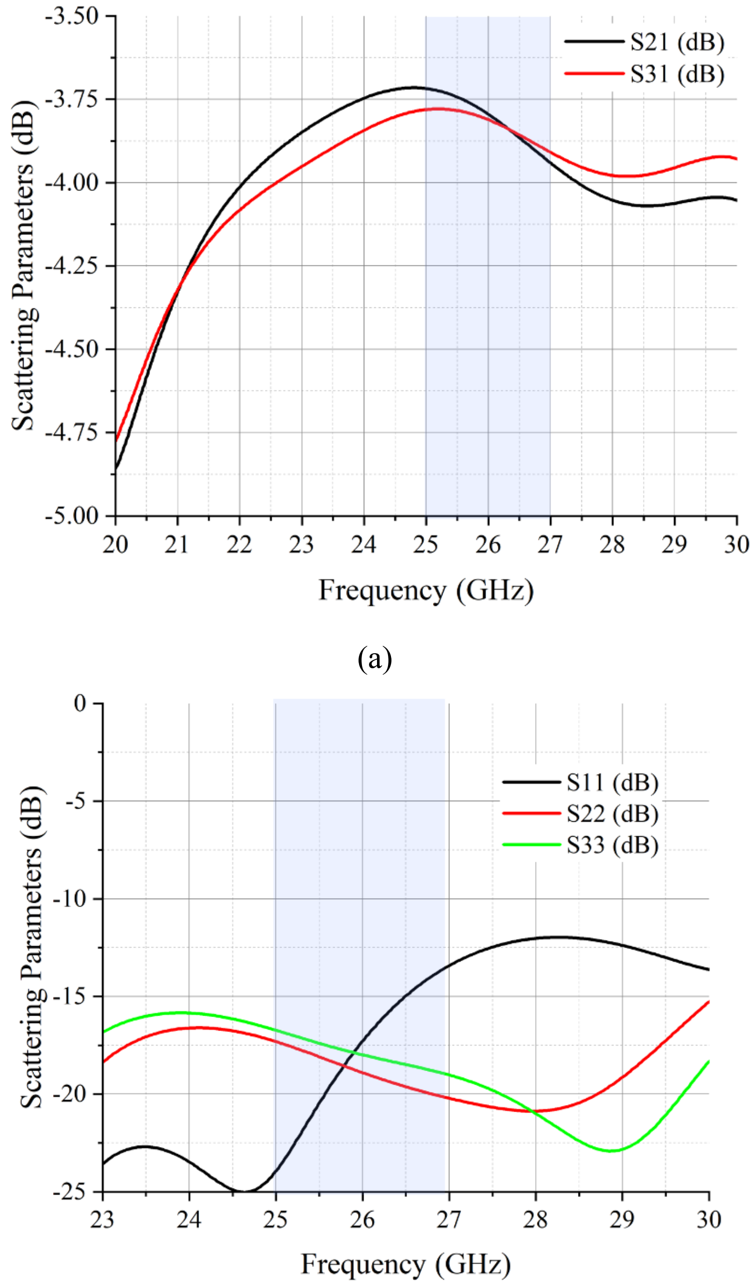


Figure 20. K-Band Gysel Layout

The FEM simulation transmission and reflection S-parameter results are shown in Fig. 21. The transmission S-parameters, S21 and S31, include the 3 dB power split from port 1, the input port, to port 2 and port 3. Thus, the transmission S-parameters show an insertion loss of only 0.7-0.9 dB across the bandwidth. The maximum difference between S21 and S31, and thus the maximum mismatch in power division, is less than 0.1 dB across the bandwidth. The reflection S-parameter results show good input match for all ports, with a maximum S11 of -14 dB, a maximum S22 of -17 dB, and a maximum S33 of -18 dB. Again, because the same design is used as a splitter and a combiner in a balanced PA, the return loss needs to be very low for port 2 and 3 so that minimal power is reflected from the combiner and into the output of the MMIC PA, which the Gysel design achieves.



(a)

(b)

Figure 21. Gysel Power Divider: (a) Transmission and (b) Reflection S-Parameters

3.3 Splitter Comparison and Balanced Integration

The two presented power splitters were compared for viability in the proposed balanced PA. The K-band Wilkinson and Gysel power splitters presented both show promising performance. They have low insertion loss and good input matching. The Gysel design has better input matching for ports 2 and 3, which is important when it is used as a combiner. The Wilkinson's S22 and S33 could likely be improved with small design modifications, so that is not a barrier to its use in the balanced PA. Additionally, the Wilkinson is a slightly wider design, but is still a very compact design and that additional width would not be an issue for the small satellite applications.

Because both designs performed similarly in FEM simulations, the deciding factor between the two is the known power handling capabilities. As discussed earlier, the Wilkinson power divider has a resistor providing isolation that is not tied to ground on either terminal, which makes heat dissipation through this resistor difficult. The resistors tied to ground in the Gysel power splitter provides a path to ground for heat dissipation. Because of this property, the Gysel power splitter was selected for implementation in the K-band balanced PA.

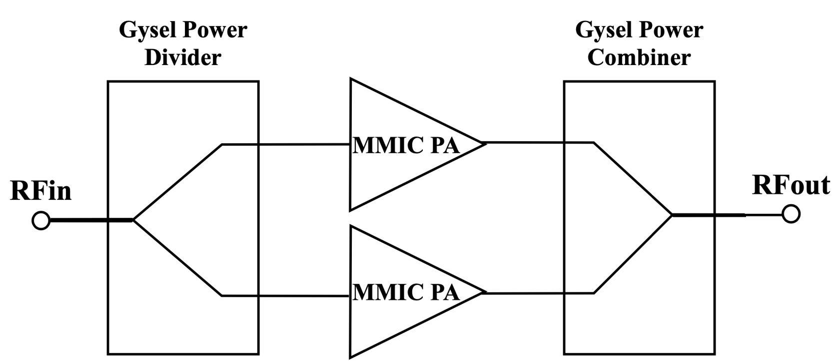


Figure 22. K-Band Balanced PA Block Diagram

The results of the Gysel integration into a balanced PA are simulated using the FEM results for the Gysel splitter and the S-parameters provided by the selected COTS MMIC PA. A simple block diagram of the setup for these simulations is shown in Fig. 22. They were simulated in ADS. The results are shown in Fig. 23.

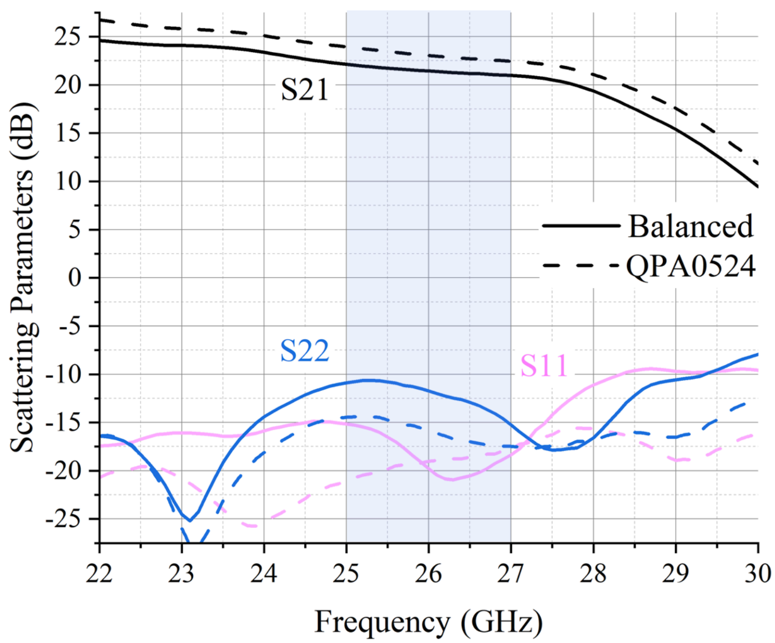


Figure 23. Simulated Balanced PA Small Signal Results with Gysel Power Splitter

These small signal results show very promising results. They show low insertion loss through the design, with a small signal gain only 1.5 dB lower than the single PA performance. The input matching is not as good as the singular PA, but still a very good match. The S22 is at least -11 dB across the bandwidth, and the S11 is at least -15 dB. Large signal performance simulations are not available for the selected PA, so large signal simulations are not possible.

The presented balanced PA will be fully implemented on a board and manufactured. Its large signal and small signal performance will then be tested and compared to the individual PA and other competitive K-Band PAs.

CHAPTER 4

CONCLUSION

This work presented a solution to a gap in the market for power amplifiers. Small satellite and CubeSat applications require a small formfactor with high output power, high PAE, and good thermal management. The COTS PAs available are either too large for the application, do not provide enough output power, or struggle to dissipate heat away from the amplifying device. This work presents two balanced PAs at different operating frequencies to address these issues in the market. The balanced PAs are designed to provide more output power and provide more area on which the active devices can dissipate heat. Balanced architectures are investigated at X-band and K-band.

The presented balanced X-band PA displays high small signal gain, output power, and PAE across a wide bandwidth of 7.5 to 11.5 GHz while maintaining a small formfactor. The presented PA improves upon the small signal gain and the output power of its single MMIC counterpart by 1.3 dB and 1.8 dB, respectively. While it shows reduced PAE of about 4%, this can be explained as a result of the CW operation of this design and the minimal insertion losses of the output combiner and filter.

Two types of splitter and combiner were investigated for a balanced PA at 25-27 GHz. A Wilkinson power divider and a Gysel power divider were designed and simulated using ADS FEM simulator. Results were compared for viability in the K-band balanced design. They achieved similar performance, and the Gysel was elected to be implemented in the balanced PA design. The small signal results of the full balanced PA were simulated and appear very promising. Future work includes the production and testing of the balanced PA.

Through these designs at X-band and K-band, amplifier solutions are introduced to the market for CubeSat applications seeking to achieve 2-5 times more power than current solutions while maintaining small formfactors and the ability to be operated under CW.

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