Broadband Push-Pull Power Amplifier Design at Microwave Frequencies

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A broadband, high efficiency push-pull power amplifier is presented between 0.5GHz and 1.5GHz. Coaxial cable transmission line baluns are utilised to transform the impedance environment of the transistors down to 25Ω, greatly simplifying the matching, whilst still providing a 50Ω environment to interface with other components. Using packaged GaN HEMT transistors, typical output powers of 45dBm and efficiencies of 44% to 75% have been measured across a 3:1 bandwidth. The small signal input match is less than -10dB and small signal gain is greater than 10dB across the entire band.

1 Introduction

Achieving broadband operation at microwave frequencies is a challenge which has confronted power amplifier designers for many years. If high-power operation and reasonable power efficiency is also required, the challenge is significantly increased. High-efficiency operation using continuous modes such as Continuous Class F can be shown to extend to a bandwidth of an octave [1], however for larger bandwidths a different approach is required. The push-pull configuration has demonstrated excellent performance at frequencies below 1GHz [2] but is rarely found at higher frequencies. In this paper two prototype push-pull power amplifiers are presented, demonstrating encouraging performance across significant bandwidths.

2 The Microwave Push-Pull Approach

Previous work [3] has demonstrated the advantages of the push-pull configuration at microwave frequencies, where it is not traditionally used. The transmission line baluns that convert an unbalanced signal to a balanced signal, and vice versa, also transform the system reference impedance down by a factor of two. For an amplifier designed to interface with a 50Ω system, the individual transistors are presented with a 25Ω system impedance. This is an advantage when matching high-power transistors, which typically have an optimum output impedance much lower than 50Ω. The output balun also serves as a power combiner, so that double the output power is produced by the overall amplifier. Therefore, for a particular transistor it can be stated that the push-pull configuration offers a 4:1 advantage compared to a conventional, single-ended amplifier.

The other advantage of the push-pull amplifier is that its operation can be maintained across a very wide bandwidth. Baluns present odd- or even-mode impedances, depending on how they are excited, and these impedances can be maintained over very wide bandwidths. The operational bandwidth of the amplifier is highly dependent on the balun components. The insertion loss of the baluns should be kept to a minimum, as loss in the output balun will decrease output power and efficiency, and loss in the input balun will reduce gain and power-added efficiency (PAE). The baluns used in this work are simple coaxial cable transmission line baluns, such as the one shown in Fig. 1.

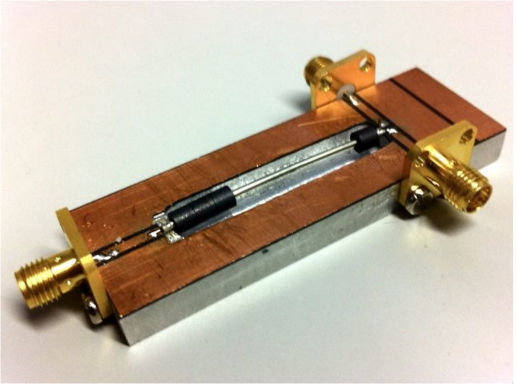

Figure 1: Coaxial cable transmission line balun

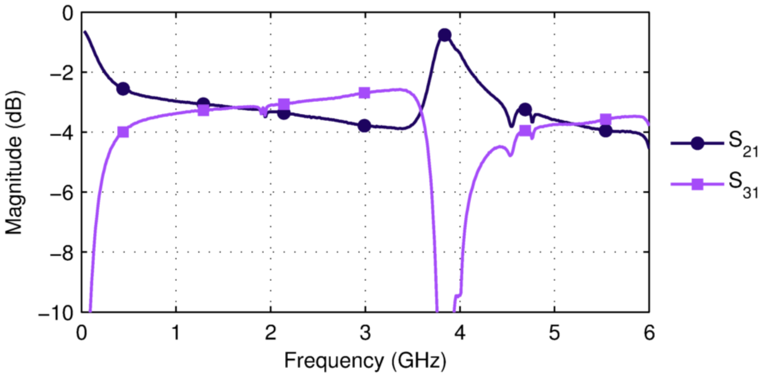

Figure 2: S_{21} and S_{31} of coaxial cable balun without ferrite

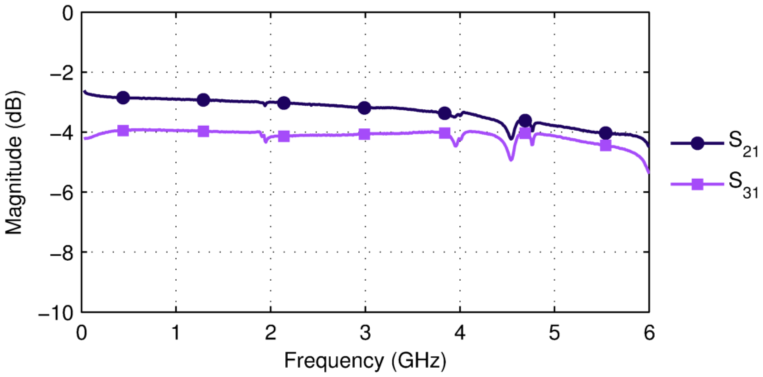

Figure 3: S_{21} and S_{31} of coaxial cable balun with ferrite

It has been shown in [4] that for coaxial cable baluns, ferrite beads can be used to suppress the balun's half-wavelength resonance. This increases the upper cut-off frequency of the balun and hence increases its bandwidth. The effect of adding ferrite beads to the coaxial cable can be seen by comparing Fig. 2 to Fig. 3. The low frequency performance has been improved, and the resonance is no longer present. The performance of the balun extends from 30MHz to 6GHz. The insertion loss of the balun is shown in Fig. 4. It can be seen that insertion loss is increased when ferrite is added, but that the bandwidth of the balun is also increased.

There are many methods of implementing baluns, including in planar form. An excellent source of information on the various types of baluns at RF and microwave frequencies can be found in [5].

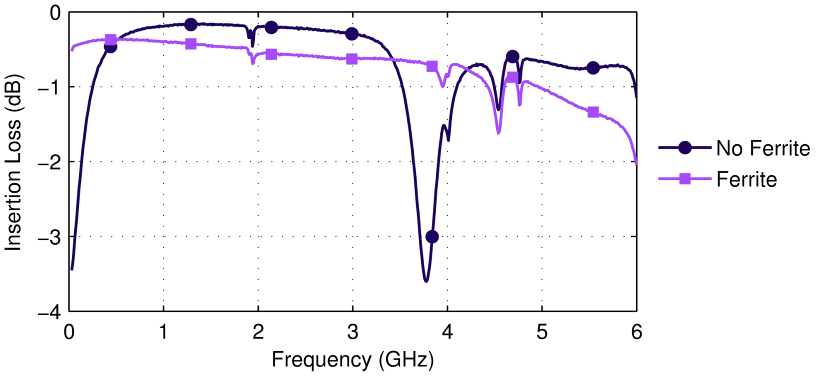

Figure 4: Insertion loss of coaxial cable balun with and without ferrite

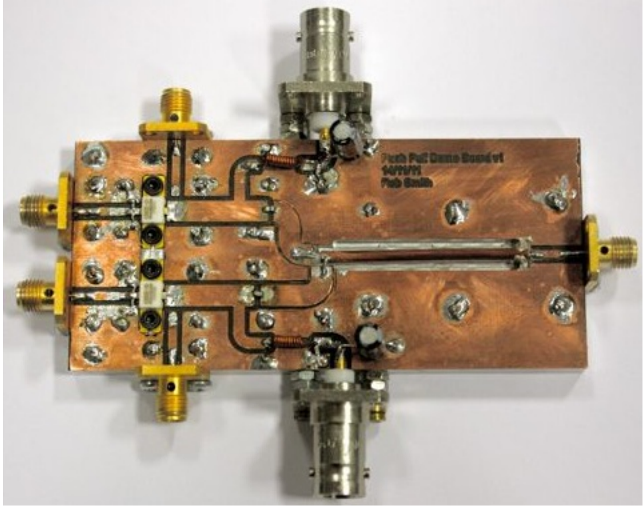

Figure 5: Prototype amplifier v1

3 Prototype Amplifier v1

A prototype power amplifier was presented in [6] in order to demonstrate the performance that could be achieved by the push-pull configuration in practice. The PA, shown in Fig. 5, consists of a single output stage, and is driven by differential inputs.

The output balun provided a 2:1 impedance transformation ratio at the fundamental frequency, which greatly reduces the matching requirement. Two Cree CGH400025F packaged GaN HEMTs were used, and load-pull measurements indicated that their optimum output impedances were close to 25Ω. GaN transistors are well suited to broadband applications, due to their low drain-source capacitance (C_{DS}) and high output impedances compared to LDMOS or GaAs. This reduces the need for conventional matching networks. Gate bias tees were omitted to simplify the design.

Fig. 6 shows the amplifier's performance across frequency, where the phase between the inputs has been varied to obtain optimum performance. The input power is also varied with frequency in order to compensate for the amplifier's gain variation with frequency and hence keep the output power constant.

The prototype power amplifier exhibited 46dBm (40W) output power and greater than 45% drain efficiency between 700MHz and 2GHz. Between 250MHz and 3.1GHz, a minimum of 43dBm (20W) output power is achieved. High drain efficiencies of at least 60% were measured between 350MHz and 1GHz.

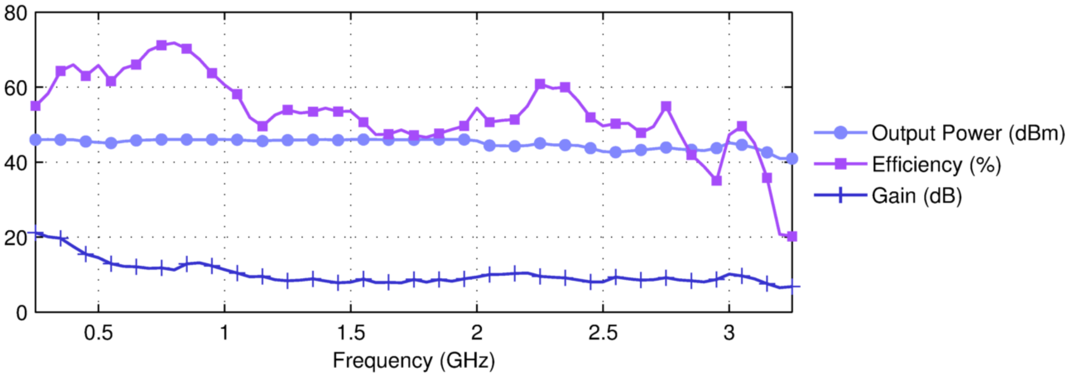

Figure 6: Large signal measurements of PA v1

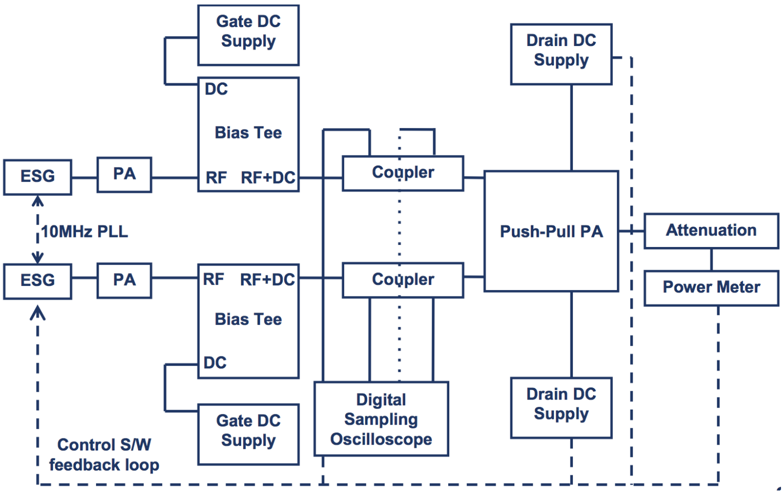

Figure 7: Push-pull power amplifier measurement setup with differential input

3.1 Differential Measurement Setup

The differential input provides an opportunity to investigate the push-pull power amplifier in greater depth. In order to measure the effect of amplitude and phase balance, a measurement setup had to be developed that was capable of providing the necessary phase difference between the inputs. The setup is shown in Fig. 7.

Two Electronic Signal Generators (ESGs) are phase locked together to provide a differential input. When the phase lock between the ESGs is established, there is an arbitrary phase difference. This phase difference is measured using a digital sampling oscilloscope, and the measurement software changes the phase of one of the ESGs to achieve the desired phase difference. Similarly, the amplitude of each ESG can be varied in order to set the amplitude balance of the differential input.

3.2 Amplitude and Phase Balance

Fig. 8 shows the variation in output power of the PA with amplitude balance. The total power driving the PA is the same for all cases, as shown in Table 1.

It can be seen that the PA is relatively tolerant to a change in amplitude balance. There is clearly an advantage to trying to set the amplitude balance correctly, but the amplifier's operation is not dependent on achieving a particular balance. The variation in output power is only 0.4dBm for a wide range of amplitude balance conditions. It is speculated that the transistors influence each other through the coupling between the two halves of the balanced port of the output balun. The output

Amplitude Balance	Input A (dBm)	Input B (dBm)	Input A (W)	Input B (W)	Total Power (W)	P (dBm)
- 3.0 dB	25.236	28.236	0.334	0.666	1	30
- 2.5 dB	25.562	28.062	0.360	0.640	1	30
- 2.0 dB	25.876	27.876	0.387	0.613	1	30
- 1.5 dB	26.175	27.675	0.415	0.585	1	30
- 1.0 dB	26.461	27.460	0.443	0.557	1	30
- 0.5 dB	26.733	27.233	0.471	0.529	1	30
0.0 dB	26.990	26.990	0.500	0.500	1	30
0.5 dB	27.233	26.733	0.529	0.471	1	30
1.0 dB	27.461	26.461	0.557	0.443	1	30
1.5 dB	27.675	26.175	0.585	0.415	1	30
2.0 dB	27.876	25.876	0.613	0.387	1	30
2.5 dB	28.062	25.562	0.640	0.360	1	30
3.0 dB	28.236	25.236	0.666	0.334	1	30

Table 1: Amplitude balance and corresponding input powers for a total input power of 1W

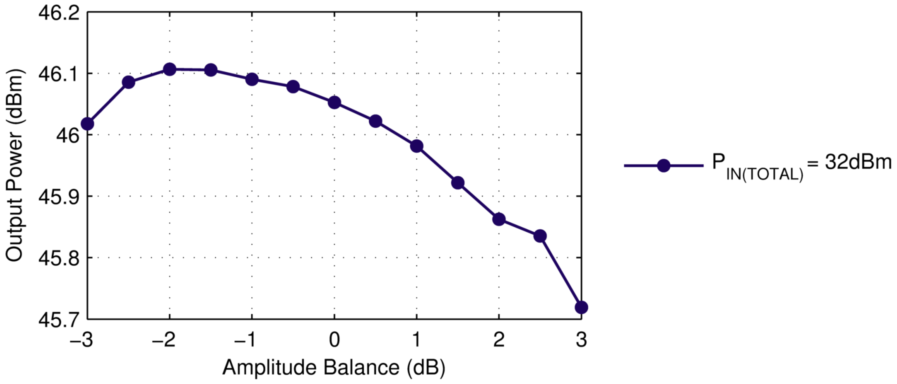

Figure 8: Output power variation with amplitude balance

power from one transistor is fed back through the balun to effectively 'load-pull' the other transistor. Further work will be done to investigate this effect.

4 Prototype Amplifier v2

The first prototype provided promising results, but is not suited to practical implementation. Several factors make it difficult to use in practical applications, the primary one being its differential inputs. For this reason, the second prototype included an input balun, so that the amplifier could be driven by a single-ended input. A target input return loss of -10dB was set. This was only achievable by including a resistive element in the input matching network, which reduced the gain of the amplifier. As with the first prototype, the output match consisted of minimal components, as the 25Ω impedance environment provides a reasonable match for this particular device. Gate bias networks were integrated into the amplifier, obviating the need for external bias tees.

The second prototype used the same GaN transistors as the first. For larger devices with lower impedances, the 25Ω environment reduces the matching ratio and increases bandwidth compared to

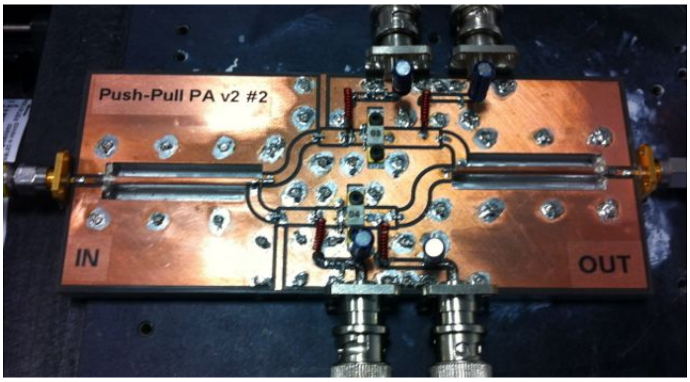

Figure 9: Prototype amplifier v2

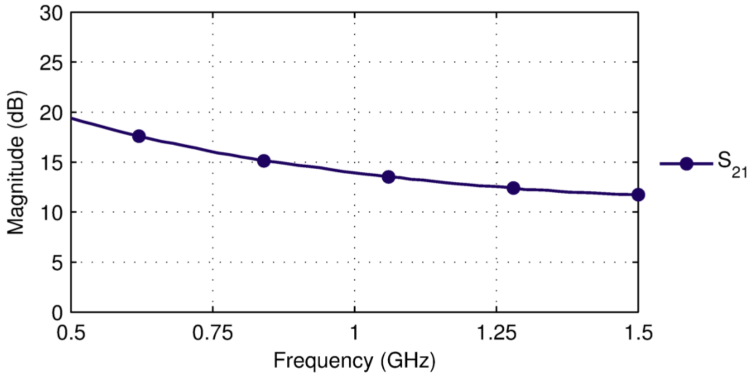

Figure 10: S_{21} of PA v2

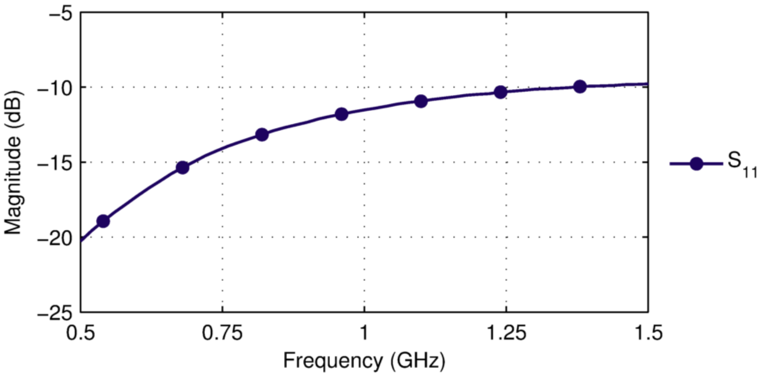

Figure 11: S_{11} of PA v2

a single-ended design into 50Ω. The disadvantage of the input balun is that the loss in the input side of the PA is increased and so the overall gain of the amplifier is reduced.

4.1 Small-Signal Measurements

Between 500MHz and 1.5GHz, a small signal gain greater than 12dB was measured, as shown in Fig. 10. The input match, shown in Fig. 11, was better than -10dB across most of the band, but degrades with frequency.

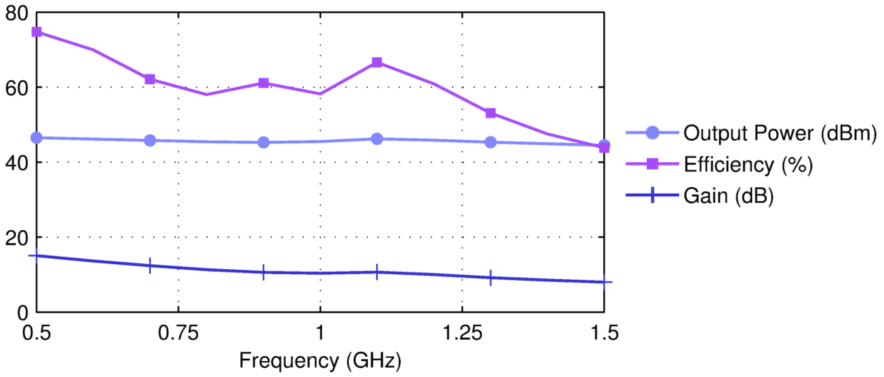

Figure 12: Large signal measurements of PA v2

4.2 Large-Signal Measurements

Preliminary large signal measurements for the second prototype amplifier are shown in Fig. 12. Measurements were made at 100MHz intervals from 0.5GHz to 1.5GHz. Over a 3:1 bandwidth, the efficiency is around 60% for much of the band, falling to 44% at 1.5GHz. Unlike the first prototype, it was not possible to vary the amplitude and phase balance to optimise performance. The output power varies between 44.5dBm and 46.5dBm. Input power is varied with frequency in order to compensate for the gain variation of the PA.

One problem with using coaxial cable baluns is the difficulty in assembling the baluns reliably. As each balun is assembled by hand, the quality of the assembly is variable and it is difficult to find faults in the balun once the whole PA has been assembled. Planar baluns can be manufactured more reliably, but in general these do not perform as well as coaxial cable baluns.

Further measurements are to be carried out on the amplifier to establish its performance under different conditions, included modulated signals.

5 Conclusions

The advantages of the push-pull configuration for microwave power amplifiers have been outlined. Two prototype amplifiers have been shown to exhibit good performance across wide bandwidths. This shows that the push-pull configuration has potential for use in the realisation of very broadband amplifiers at microwave frequencies, an area where it has rarely been used. It is probable that further improvement can be achieved by adopting a chip-and-wire approach, and by further investigation into the balun structures. The push-pull configuration was used to investigate broadband applications, but its 4:1 impedance advantage can also be utilised for narrow-band applications, especially where high-power transistors are to be used.

Acknowledgement

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