DESIGN OF HIGH EFFICIENCY, MULTI-OCTAVE MICROWAVE PUSH-PULL POWER AMPLIFIERS

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Abstract - Using differential linear measurements, the harmonic impedance conditions presented by simple transmission line baluns are identified. These impedances are shown to differ significantly from the harmonic conditions usually associated with push-pull amplifiers. When taking into account these impedance conditions, a family of waveforms corresponding to the theoretical waveforms inside a push-pull amplifier can be described mathematically and measured using a harmonic load-pull system. The wideband nature of transmission line baluns can be utilised to design and build push-pull microwave power amplifiers that can operate over multiple octaves and at higher efficiencies than conventional broadband amplifiers. This concept has been demonstrated through the design and test of a push-pull PA prototype that uses packaged GaN HEMTs.

1. Introduction

The design of high-efficiency, broadband power amplifiers at microwave frequencies has always presented significant challenges to microwave engineers. A trade-off between bandwidth and efficiency is necessary, and higher power devices increase the transformation ratio required of the matching network. Two common approaches to designing power amplifiers for bandwidths greater than an octave are Class A designs, usually employing some feedback, and distributed amplifiers, commonly used at higher frequencies. Both of these approaches yield low efficiencies, however. At microwave frequencies, most amplifier designs are based around a single-ended configuration. However, at lower frequencies the push-pull configuration is used far more widely. To understand this difference in approaches, it is necessary to consider the structures that perform the balanced-to-unbalanced transformation, or 'balun' function. At lower frequencies, magnetically coupled centre-tapped transformers are used. They act as low-loss power combiners and present a short circuit to even-mode signals. Unfortunately, the properties of the ferrite materials used in these transformers prevent operation above the VHF or UHF bands. As Fig. 2 shows, the reactive permeability (also known as real permeability) decreases dramatically as frequency increases.

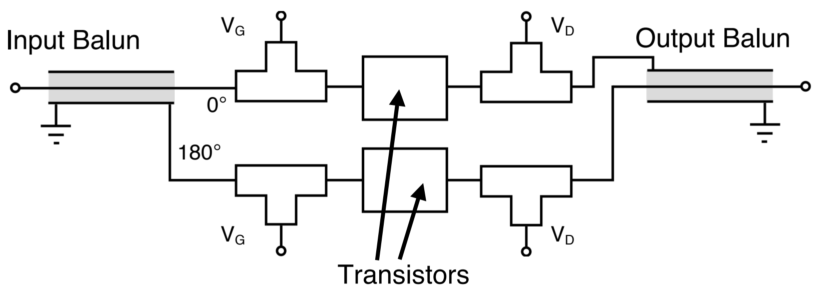

Fig. 1: Push-pull power amplifier configuration, showing back-to-back balun arrangement.

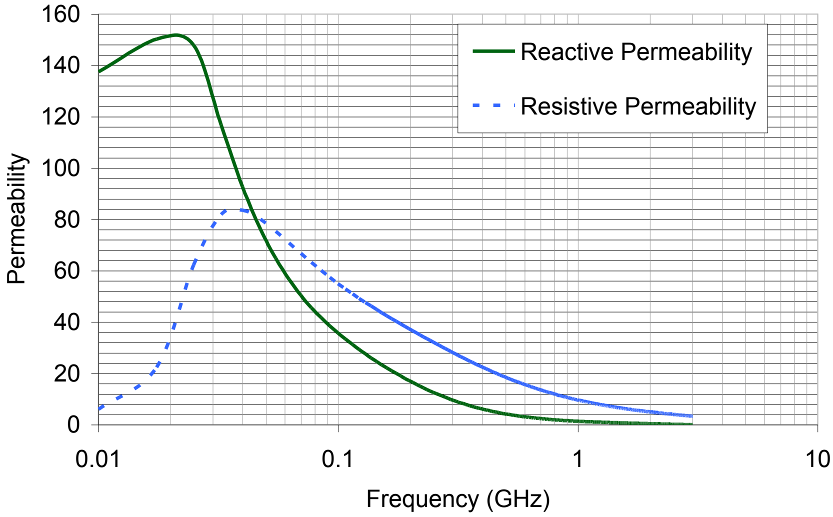

Fig. 2: Permeability versus frequency for Fair-Rite material no. 61 (measured data courtesy of Fair-Rite, www.fair-rite.com).

At microwave frequencies, the use of transmission line baluns is necessary. The limitations of these baluns, and how these can be addressed, are discussed in the next section.

2. Transmission Line Baluns

We identified early on in the project that the key component to be investigated in the design of broadband, high efficiency push-pull power amplifiers was the balun. The operational bandwidth of the balun has a large impact on the bandwidth of the amplifier as a whole, and the insertion loss of the output balun is critical in achieving high efficiency performance. The baluns we have been considering for this project are simple coaxial cable designs, such as the one shown in Fig. 3. The balun is made from low-loss RT/duroid 5880 circuit board backed with aluminium. A channel is milled in the aluminium to set the outer transmission line characteristic impedance. The cable used was 50Ω semi-rigid coaxial cable with a diameter of 1.19mm (47mil). This design was chosen to allow investigation into the effect of ferrite beads on the balun performance, as described below.

We can model the balun using the circuit schematic in Fig. 4. We use a standard floating transmission line to model the coaxial cable itself. We then model the transmission line between the outer of the coaxial cable and the ground plane using a parasitic transmission line, which we refer to as the ‘outer’ transmission line.

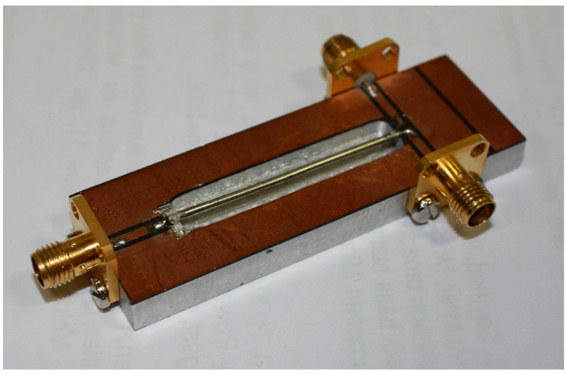

Fig. 3: Simple coaxial cable transmission line balun.

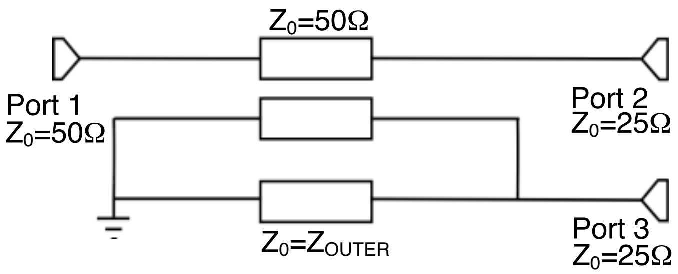

Fig. 4: Circuit model for the simple coaxial cable transmission line balun.

2.1 Bandwidth Extension

As can be seen in Fig. 5, there are two key areas where the transmission line balun is not performing the unbalanced-to-balanced transformation; at the low frequency end of the band, and at around 3.75GHz. The low frequency performance can be explained by the inability of the transmission lines to couple, as the length of the transmission lines is no longer a substantial fraction of a wavelength. The resonance at 3.75GHz occurs as the coaxial cable length is half of the wavelength of the signal, and therefore the 'outer' transmission line is a short circuit. Ferrite beads can be added to the coaxial cable in order to boost the magnetic coupling at the low frequency end of the bandwidth. This is a familiar result and is widely used.

A less familiar role that the ferrite beads can perform is the suppression of the half-wavelength resonance. This was first presented in [1]. Referring back to Fig. 2, it can be seen that although the reactive permeability has decreased to negligible values at 1GHz, there is some resistive permeability remaining. In other words, at microwave frequencies the ferrite beads can act as resistors on the outer transmission line. By adding resistance to the end of the outer transmission line, the impedance of the outer transmission line at the resonant frequency is a finite resistance rather than a short circuit. The effect of adding ferrite beads to the coaxial cable can be seen in Fig. 6. The low frequency performance has been improved, and the resonance is no longer present. It is worth noting that there is an uneven power split between the two halves of the balanced port, and that there is a 180° phase difference (not shown). The performance of the balun extends from 30MHz to 6GHz, a bandwidth greater than two decades.

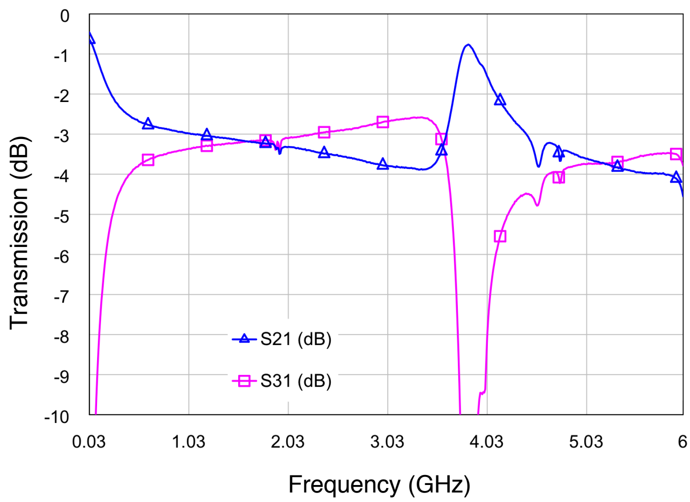

Fig. 5. Unbalanced to balanced transmission magnitude.

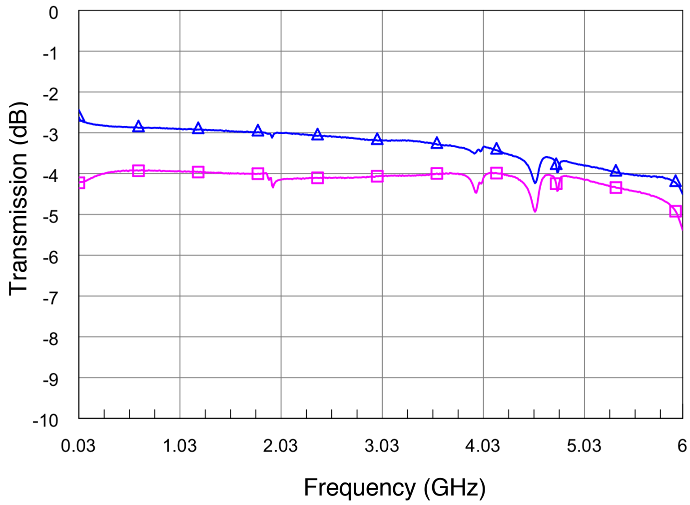

Fig. 6. Unbalanced to balanced transmission magnitude, with ferrite beads added.

2.2 Impedances Presented by a Transmission Line Balun

Both magnetically coupled transformers used at VHF frequencies and transmission line baluns present different impedances at their balanced ports depending on whether the excitation is common-mode (even-mode) or differential-mode (odd-mode). For the magnetically coupled transformer balun, the even-mode impedance is close to a short circuit, and hence any second harmonic currents are cancelled. In contrast, a simple transmission line balun presents an open-circuit to even-mode signals, i.e. even harmonics. This is a significant observation, as it affects the operation of the PA and needs to be accounted for in the design.

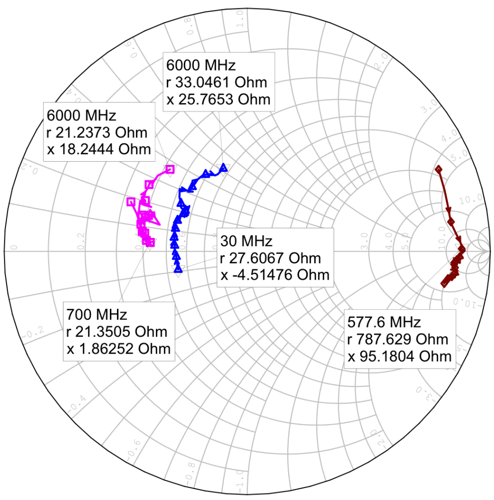

Fig. 7. Odd and even mode impedances of a transmission line balun.

The measured odd- and even-mode impedances of a transmission line balun are shown in Fig. 7. The two traces around 25Ω are the odd-mode impedances presented by each half of the balanced port. The high-impedance trace is the even-mode impedance presented by the balanced port. The balun's open circuit at the even harmonics has previously been identified in [2] for mixer applications, but seems to have received limited attention for power amplifier applications.

3. Push-Pull PA Modes of Operation

As the balun impedances differ significantly from the traditional push-pull impedance conditions, the waveforms inside a push-pull PA using microwave baluns were reconsidered. The waveform analysis will be published in a forthcoming issue of IEEE Microwave and Wireless Components Letters [3]. Using the factorised waveform approach first described by Cripps [4], analytical expressions for the voltage and current time-domain waveforms inside a push-pull PA were developed. Due to the open-circuit at the even harmonics, the waveforms bear a closer resemblance to inverted modes than conventional PA modes, as shown in Fig. 8. The maximum theoretical drain efficiency for push-pull amplifiers using ideal transmission line baluns was found to be 71.7%. This is lower than the 78.5% drain efficiency theoretically possible using magnetically coupled centre-tapped transformers, but higher than alternative broadband approaches such as single-ended Class A or distributed architectures.

The impedances of an ideal balun were emulated using the active hamonic load-pull measurement system at Cardiff University [5], and the measured waveforms were found to verify the theoretical waveforms.

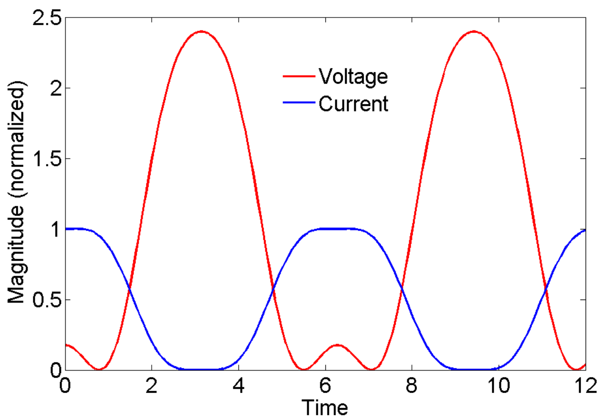

Fig. 8. Theoretical push-pull waveforms for a shallow Class AB bias.

The analysis of the waveforms shows that although the push-pull mode of operation yields lower efficiencies than harmonically tuned modes, the efficiencies are higher than those that could be achieved by the Class A or distributed amplifier approaches. Because the odd- and even-mode impedances are maintained over the operational bandwidth of the balun, this means that the push-pull mode can be maintained over multiple octaves, in contrast to harmonically tuned modes that are limited to less than an octave of bandwidth.

4. Push-Pull Power Amplifier Prototype

A prototype power amplifier was built and tested to investigate whether the theoretical performance could be realised in practise. It should be noted that the PA only consisted of an output stage, and so may not be regarded as a 'complete' PA. The full design and measurements of the PA will be published at the next International Microwave Symposium [6].

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, whose optimum output impedances are close to 25Ω. This, in theory, reduces the need for conventional matching networks.

The prototype power amplifier exhibited 46dBm output power and greater than 45% drain efficiency between 700MHz and 2GHz. Between 250MHz and 3.1GHz, a minimum of 43dBm output power is achieved. High drain efficiencies of at least 60% were measured between 350MHz and 1GHz, a greater than octave bandwidth. The PA was observed to have the soft gain compression characteristics that are typical of GaN-based amplifiers.

The half-wavelength resonance was designed to be outside the fundamental frequency band, and for the initial measurements no ferrite was added to the balun. The PA was designed with differential inputs, to allow the effects of phase and amplitude imbalance to be measured. Due to the minimal output matching on the PA, it is anticipated that these results can be improved upon, especially if a chip-and-wire approach is adopted for a future PA.

5. Conclusions

The potential for using the push-pull configuration to realise high-efficiency, broadband microwave power amplifiers was investigated. A key component in the amplifier is the balun, whose operational bandwidth can be increased with the addition of ferrite beads. The odd- and even-mode impedances presented by a transmission line balun were used to evaluate the voltage and current waveforms at the output of the transistors through the factorised waveform approach. The wideband nature of transmission line baluns can be utilised to design and build push-pull microwave power amplifiers that can operate over multiple octaves and at higher efficiencies than conventional broadband amplifiers. This concept has been demonstrated through the design and test of a push-pull PA prototype, which has produced encouraging preliminary results.

Acknowledgement

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