The Design of a Dual-Band PA for mm-Wave 5G Applications

Stuart Glynn and Liam Devlin

Plextek RFI, The Plextek Building, London Road, Great Chesterford, Saffron Walden, CB10 1NY, UK; (liam.devlin@plextekRFI.com)

Abstract

Considerable time and money are currently being invested in developing millimeter-wave technology for 5G, and there is much debate and lobbying around the most suitable frequency bands for this application. Development work is currently underway in many candidate bands and it is looking increasingly unlikely that a single band will be designated on a worldwide basis for millimeter-wave 5G in the immediate future. This means that the availability of dual-band or multi-band millimeter-wave components will become increasingly attractive. This paper describes the design, layout, and performance of a dual-band power amplifier (PA) monolithic microwave integrated circuit (MMIC), capable of electronically switching its operating band between the 26GHz pioneer band identified by the EU's RSPG (24.25 to 27.5 GHz) and the 32GHz band (31.8 to 33.4 GHz). The design was implemented on a commercially available 0.15μm gate length PHEMT process and has an output power capability of 1 W at 1dB gain compression (P-1dB) with a small signal gain of 20dB.

Introduction

5G is intended to offer a step change in data rates with seemingly infinite capacity. In order to meet this challenging requirement a move to mm-wave frequency operation is planned where large contiguous bands of spectrum can be made available. Although the final agreement of the mm-wave bands for 5G will not take place until the World Radio Conference in 2019 (WRC-19) much development work is already underway and numerous demonstrator systems are being designed, assembled and trialled.

The candidate bands for mm-wave 5G include the FCC licensed spectrum at 28GHz, 37GHz and 39GHz. In Europe the Radio Spectrum Policy Group (RSPG) has recommended the 26GHz band (24.25 to 27.5GHz) as the pioneer band for 5G, and development work is now underway targeting this band. The RSPG also recognized that the 32GHz band (31.8 to 33.4GHz) could be made available by many European administrations and identified 40.5 to 42.5GHz as a potential longer term option. All of this parallel development activity in differing mm-wave bands suggests that the availability of a single operating band for 5G across the globe is unlikely in the immediate future. This means that the availability of dual-band or multi-band mm-wave components, such as the dual band PA described here, will become increasingly attractive.

Design Approach

The design commenced by selection of the transistor sizes for each stage of the PA. This started with the selection of the output transistor size and bias, a common size would be required for each band and so the selection process focused on the higher frequency band with the knowledge that this selection would also be adequate for the lower frequency band.

Selection of the transistor size for a mm-wave PA is a trade-off between output power capability and available gain: A physically larger transistor (more gate fingers and/or wider unit finger width) will have a higher available RF output power. However, the higher parasitics of the physically larger transistor result in a reduction in available gain. The best way to address this issue is to select a transistor with the largest gate periphery that can provide a practical level of available gain and to combine multiple transistors in a low-loss on-chip combining and matching structure. For the dual-band amplifier described here, an output stage of four power-combined 8-finger transistors was selected to achieve the target output power of 1W.

Similar trade-offs were then undertaken to select the size and number of transistors in the preceding stages. The overall impact on compression and linearity of the complete cascaded arrangement must also be considered in making this selection. This process resulted in selecting a pair of power combined transistors to drive the output stage and a single transistor to drive this. The topology adopted is evident from the layout plot of the dual-band PA shown in Figure 1.

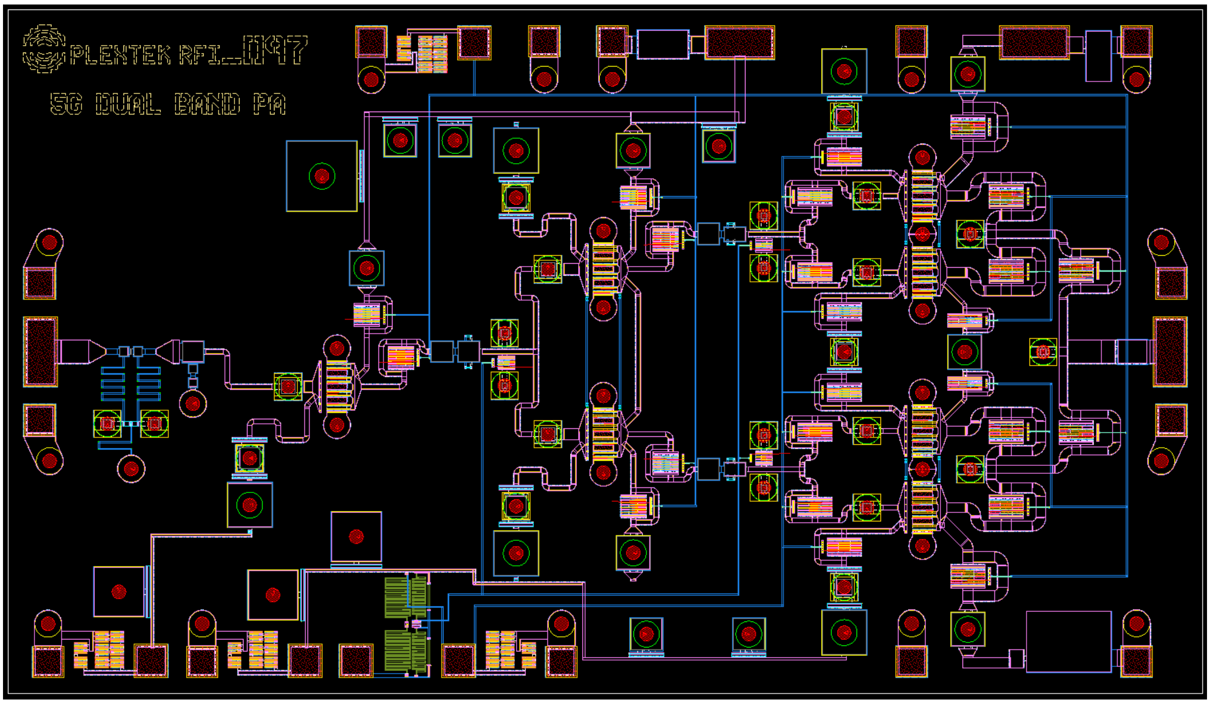

Figure 1: Layout plot of one channel of the dual-band PA IC

The design progressed by considering the optimum architecture for each of the two bands. In order to implement a band switchable PA it was necessary to have a degree of commonality in the matching structures used in the two PAs. The component values could be different but the use of the same topology was adopted wherever feasible as it simplified the complexity of the dual band PA.

Converting the two individual PA designs into a single switched design commenced at a relatively early stage in the design process. The basic approach was to switch certain RF elements in and out of the circuit. PHEMT transistors can be used to realise good RF switches by biasing the drain-source voltage (Vds) at 0V and controlling the gate bias voltage [1]. A simple equivalent circuit for a PHEMT operating as a switch is depicted in Figure 2. The resistance varies from a low value with the gate at

0V to a high value when the transistor is pinched off. This provides a simple but effective switching function, which is the basic means of realizing RF switches.

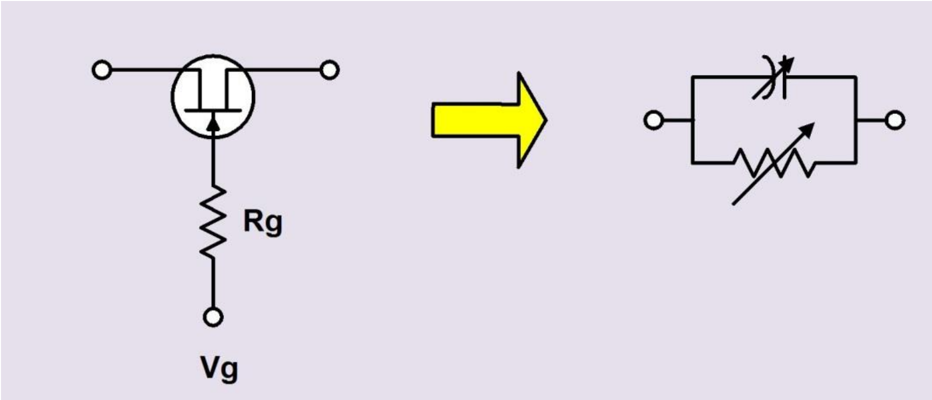

Figure 2: Simple equivalent circuit of a PHEMT as an RF switch

The problem with using PHEMTs as mm-wave switches is the parasitic capacitance. This capacitance can be lowered by reducing the total gate width of the switching transistor, but that in turn increases the insertion loss. The basic structure of the PHEMT—with its parallel drain and source fingers—means that pushing the parasitic capacitance to very low levels results in small transistors that have high insertion loss and poor linearity.

Figure 3 shows the simulated insertion loss of a 4x50µm transistor operating as an RF switch (as depicted in Figure 2) in both its on-state (red trace) and its off-state (blue trace). Although the on-state insertion loss is relatively low across the full 40GHz band shown, the off-state loss (isolation) is high at low frequencies but degrades to just 3.3dB at 30GHz. In essence the transistor is not operating as an effective RF switch across the frequency ranges over which the dual band amplifier operates.

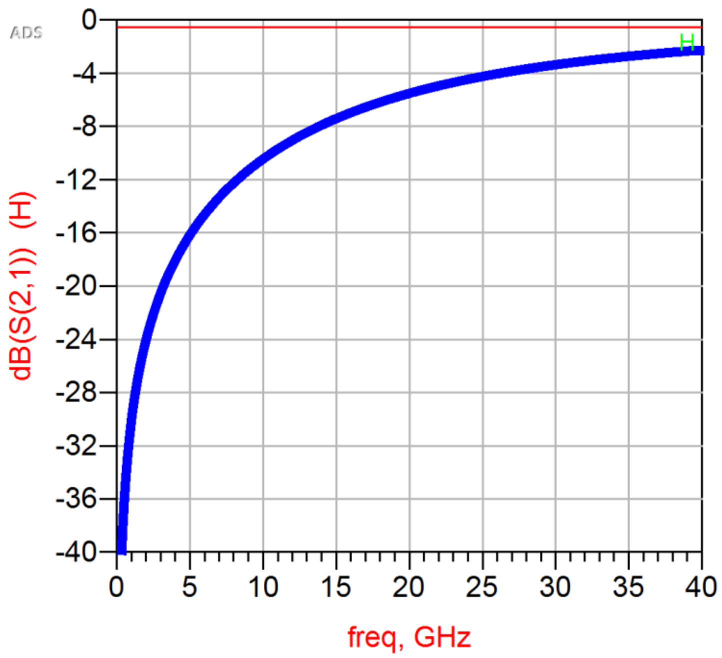

Figure 3: On-state and off-state insertion loss of a 4x50µm PHEMT

If the drain-source impedance of the 4x50µm transistor is considered (plotted in Figure 4) it can be seen that in the on-state (red trace) the impedance approximates a low value resistor in series with a small inductance and in the off-state (blue trace) it approximates a capacitor with a small series resistance. At mm-wave frequencies the switch does not move between a low and high insertion loss state but between a resistive state and a capacitive state. It is this change in electrical equivalence that must be used to electrically switch the components of the dual-band PA.

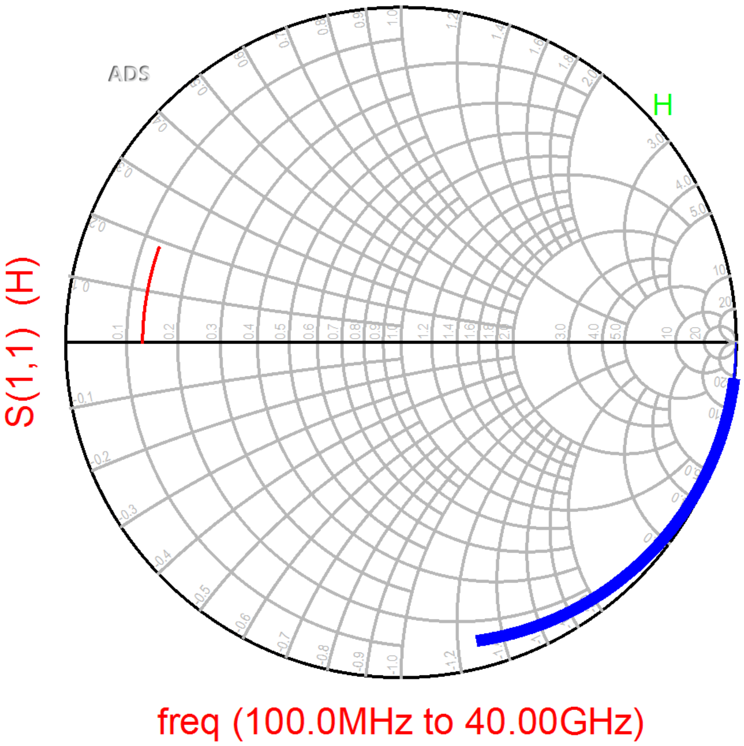

Figure 4: Drain-source impedance of a 4x50µm PHEMT in the on-state and off-state

Thus the key to implementing the RF switches in the dual-band PA was to consider them not as ideal switching elements but as varying reactance elements, and to absorb the reactance into the PA matching structures such that the switch parasitics became an integral and required part of the matching networks. The matching networks of the two PAs were reviewed individually from output to input. It was necessary to adopt common positions for certain key matching elements such as the drain bias feeds, which were configured with switching elements to shorten the effective electrical length in the higher band implementation. It was even possible to retain some matching elements as common for both bands, but others were switched in or out as appropriate. The key in all cases was to adopt a topology that could accommodate the switch parasitics in both bands.

The process of implementing switchable matching structures throughout the entire amplifier required great care and attention to detail. Much effort was expended on keeping the number of switching elements down to an acceptable level. If the number of required switching elements becomes excessive, the size and cost benefits of having a dual-band PA start to diminish. The resulting design was ultimately of comparable size to a single band PA, as can be observed from the layout of Figure 1. The band switching elements are integral to the matching networks, as can be seen by inspection of the layout.

The PA is switched from low-band to high-band operation using two control inputs that bias the on-chip switching transistors appropriately and re-configure the PA. One input controls the switching transistors in the drain-side networks and the other the switching transistors in the gate-side matching networks. On-chip inverter circuits have been included where required, to generate complementary switching signals from each single-ended control input.

Simulated Performance

The simulated s-parameters of the dual-band PA are plotted for both bands in Figure 5. The dual-band responses are clearly evident (26GHz band in red and 32GHz band in blue). The amplifier shows good input and output return loss in each band and has a small signal gain of around 20dB.

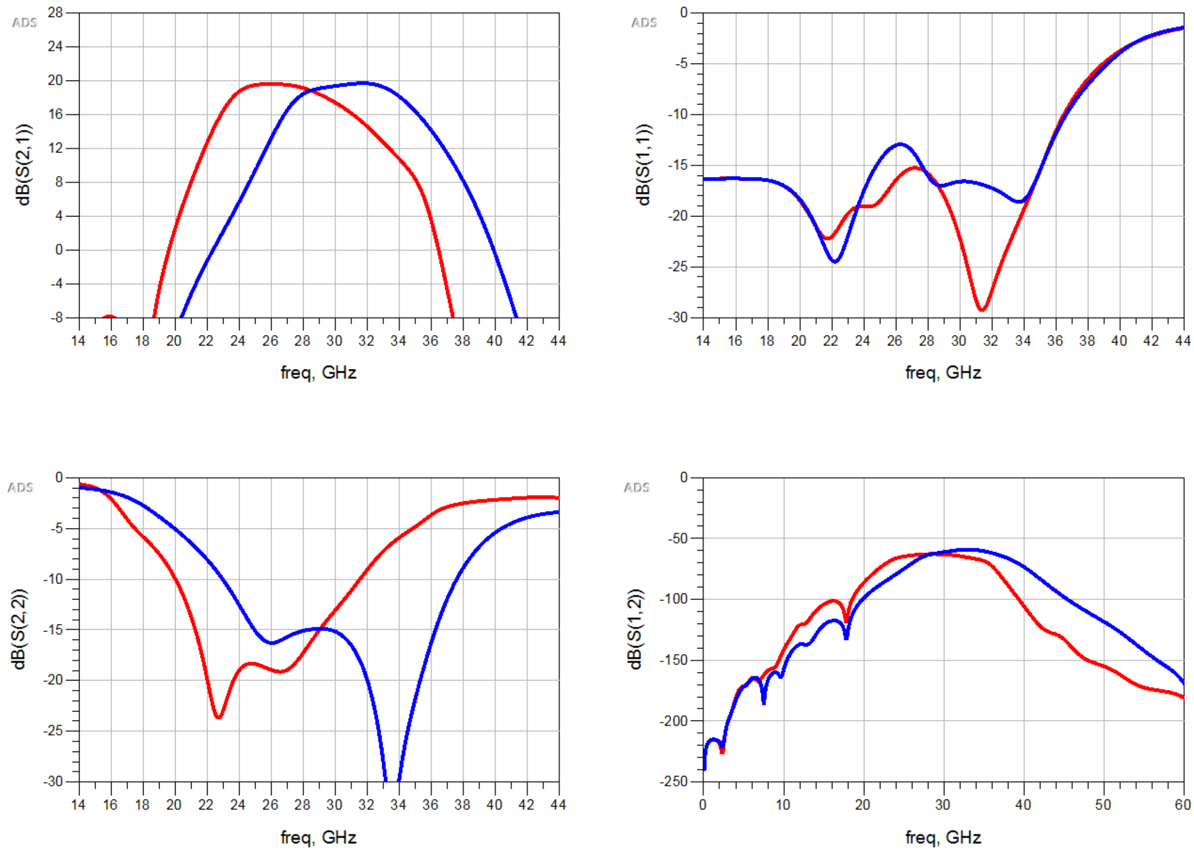

Figure 5: Simulated s-parameters of the dual-band PA

The simulated large-signal performance is plotted in Figure 6. As with the small-signal case the performance of the amplifier operating in the 26GHz band is plotted in blue and that for the 32GHz band is in red. The output power at P-1dB is around 1W (+30dBm) for both bands, being slightly higher in the 26GHz band and slightly lower in the 32GHz band. The efficiency at P-1dB is just over 30% in the 26GHz band, dropping to around 26% at 32GHz.

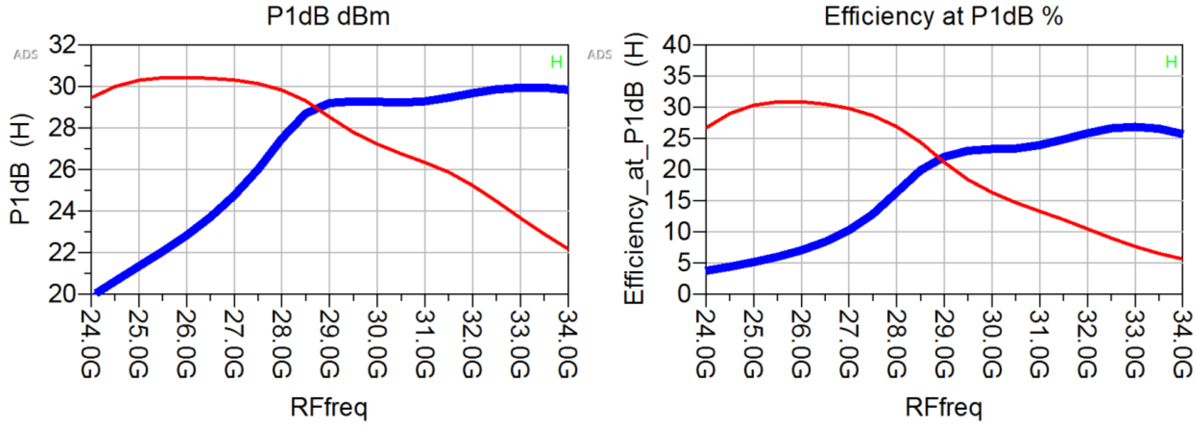

Figure 6: Simulated large signal performance of the dual-band PA

An alternative to the dual-band approach would be to design a broadband amplifier capable of covering both bands. However, it is likely that the gain, output power, and efficiency would all be lower with a broadband design. The compact layout and excellent dual-band performance demonstrated here shows the potential benefits that this approach can bring to dual-band mm-wave PAs. It is likely that dual-band operation will be highly desirable for 5G Ka-band systems, and this approach could bring huge benefits it terms of size and cost.

Conclusions

This paper describes the design of a dual-band power amplifier (PA) MMIC optimised for operation in both the 26GHz (24.25 to 27.5 GHz) 5G pioneer band and the 32GHz band (31.8 to 33.4 GHz) identified by the RSPG as a potential future mmwave 5G band in Europe. The desired operating band is selected by control inputs that electronically reconfigure the PA accordingly. It uses a 0.15µm gate length PHEMT process and has an output power capability of 1 W at 1dB gain compression (P-1dB) and a small signal gain of 20dB. RF performance is similar in both bands.

References

[1] [Liam Devlin, "The Design of Integrated Switches and Phase Shifters", Proceedings of the IEE Tutorial Colloquium on "Design of RFICs and MMICs", Wednesday 24th November 1999, pp 2/1-14