An E-band Voltage Variable Attenuator Realised on a Low Cost 0.13μm PHEMT Process

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Abstract

E-band spectrum at 71 to 76GHz and 81 to 86GHz offers worldwide availability and wide bandwidths under a light license system [1]. This makes it very attractive for very high data rate applications such as cellular back-haul. Component availability is currently relatively limited and cost relatively high [2] but this is starting to change. This paper describes the development of an E-band Voltage Variable Attenuator (VVA) realised on a low cost 0.13μm gate length PHEMT process. The core VVA is a single-ended design that operates from a control voltage of between -2V and +0.6V. Simulated insertion loss is <1dB at 50GHz rising to 2.8dB at 90GHz. The E-band design uses two of the core circuit in a balanced configuration for improved return loss and increased linearity. It has an insertion loss of <4dB over 71 to 86GHz and a dynamic range of >30dB. Good performance is exhibited over an extended band of 50 to 90GHz. Devices are currently in fabrication and it is anticipated that measured results will be available in time for the presentation.

Introduction

When biased at 0V Vds ("zero-biased"), PHEMT transistors essentially behave as voltage variable resistors [3]. The resistance varies from a low value, when Vgs is biased to turn the transistor "on" (0V for a depletion mode process) to a high value when Vgs is set to below pinch-off. For lower frequency applications a simple compact VVA can be implemented by arranging three zero-biased transistors in a Tee or Pi configuration, as depicted in Figure 1. Two control voltages are required and these are simultaneously adjusted to give the desired attenuation and high input return loss.

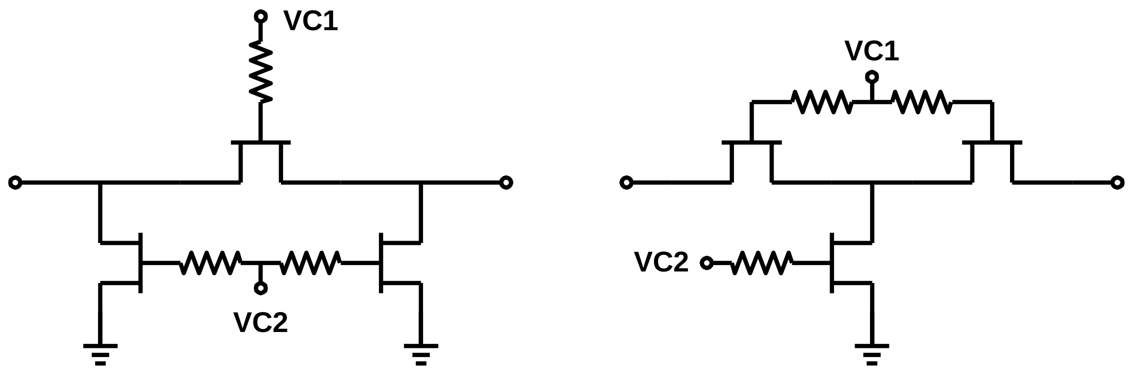

Figure 1: Simple, compact, low frequency PHEMT VVAs

As operating frequencies increase simple topologies, such as those in Figure 1, no longer work. The reason for this is that the zero-biased PHEMT is not a pure resistor, it has significant parasitic capacitance. A simplified equivalent model for a PHEMT, which includes this parallel capacitance, is shown in Figure 2.

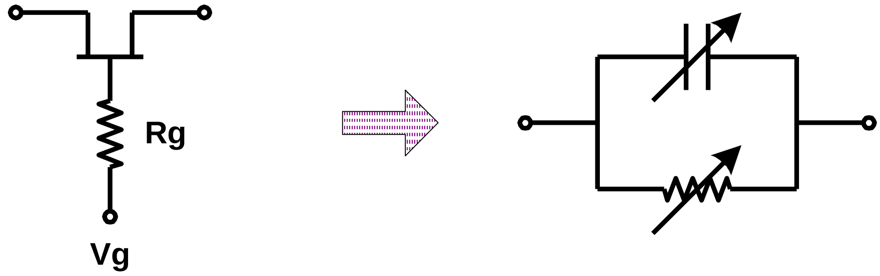

Figure 2: Simplified equivalent circuit model for a zero-biased PHEMT

The value of the parasitic capacitance reduces as the transistor size (total gate periphery) reduces. At low frequencies the transistor size can be adjusted to give a parasitic capacitance that is high reactance. This approach is, however, not practical at mm-wave frequencies. If it were attempted the transistor would be so small that its on-case resistance would be impractically high.

Approaches for extending the operating frequency of PHEMT and FET based switches are discussed in [3]. Highest frequency performance is achieved with a distributed approach, where the off-state capacitance of shunt monuted transistors is absorbed into a low pass filter. This approach is suitable for both PHEMT based [4] and PIN diode based [5] switch ICs and is the approach used for the design of the VVA described here.

In order to meet its high volume potential, E-band radio links require the availability of low-cost high performance ICs. The VVA described here was designed on a low cost GaAs PHEMT process available on a commercial foundry basis through TriQuint Semiconductor. The process (TQP13) features optically defined 0.13μm gates and is fabricated on 6” diameter wafers.

Design and Simulated Performance

The design flow for the core, single-ended VVA is depicted in Figure 3. It commences with the design of an ideal Low Pass Filter (LPF) with a cut-off frequency beyond the desired upper operating frequency. The dynamic range of attenuation of the VVA is a function of the number of shunt elements in the LPF. The higher the required dynamic range, the higher the number of shunt elements that must be included.

The next step is to replace the shunt capacitive elements with shunt-mounted, zero biased off-state transistors. Three shunt mounted devices connected in series were used as this improves the linearity of the VVA compared to using a single device [3]. The geometry of the shunt transistors is selected so that the equivalent shunt capacitance, with the transistors pinched-off, is equal to the shunt capacitance of the LPF. The series inductor values can then be re-optimised to improve the return loss of the filter.

The gate control voltages are applied through high value (several kΩ) resistors to provide isolation between the RF path and the control port. The TQP13 process is a semi-enhancement process and the control voltage (Vgs) needs to be set to +0.6V to turn the transistors “on”. In the on-state the drain-source resistance of the transistors is at its lowest and the VVA is in its high loss state. With the transistors “off” the drain-source resistance is high and the VVA is in its low loss state. For the TQP13 process the transistors are pinched-off with a control voltage of around -0.2V but improved performance (slightly lower insertion loss) is observed for the VVA if a more negative control voltage is used to fully deplete the transistors; -2V was used in the simulations presented here.

The final step of the basic design process is to replace the series inductors with transmission lines and to re-optimise again for low insertion loss in the low-loss state. DC blocks were also added to the RF ports which limit the low frequency use to around 18GHz. This could have been extended to lower frequencies but as the aim was to develop an E-band component a smaller value (and smaller area) capacitor was selected. EM simulation of key parts of the metalwork was also undertaken following layout.

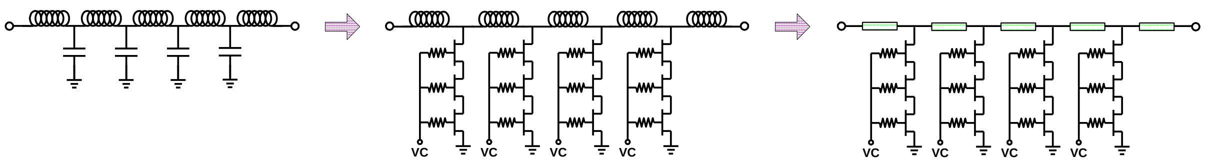

Figure 3: Design flow for the core VVA

The simulated insertion loss and return loss of the core VVA in three control states (low-loss, mid-range and high-loss) are plotted against frequency (from 1 to 120GHz) in Figure 4. The control voltages were -2V (low-loss), +0.1V (mid-range loss) and +0.6V (high-loss). A gentle increase in insertion loss with frequency can be seen in the low loss state. At 18GHz the insertion loss is < 0.2dB rising to 2.9dB at 90GHz. This gradual increase with frequency is because of losses in the LPF. Both the series inductive transmission lines and the shunt capacitors (off-state transistors) have resistive losses.

In order to allow operation at E-band the shunt transistors must be small enough to ensure that the effective capacitance is adequately low. This means that the on-state drain-source resistance is not very low, which limits the dynamic range of attenuation particularly at low frequencies where the dynamic range falls to 16dB. At frequencies below the cut-off of the LPF the on-state drain-source resistance dominates the parasitic drain-source capacitance. At low frequencies the maximum attenuation is due to the combined effect of the on-state resistances of the multiple shunt transistors. As the operating frequency increases the series inductance of the transmission lines between the shunt devices start to contribute to the loss. The single-ended VVA essentially becomes a lossy inductor and the dynamic range increases to 31dB at 70GHz and 33dB at 90GHz.

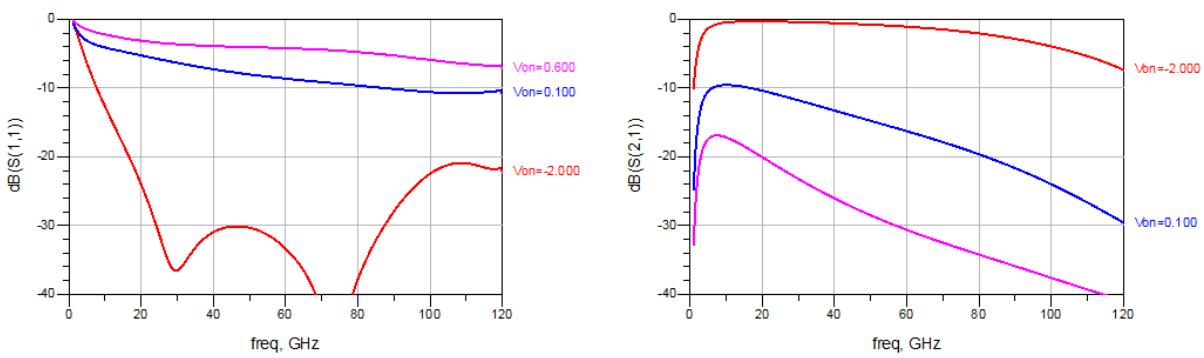

Figure 4: Simulated small-signal performance of the core VVA

The simulated input return loss of the single-ended VVA is better than 20dB in the low loss state, however, in the attenuating states the return loss degrades. This can be addressed by incorporating two of the core-VVA circuits in a balanced structure between a pair of Lange couplers, as shown in the schematic of Figure 5. This approach has the advantage of ensuring high input and output return losses and also increases the linearity by 3dB. The Lange couplers were designed for optimum performance from 60 to 90GHz. The downside to the balanced topology is increased insertion loss and die size.

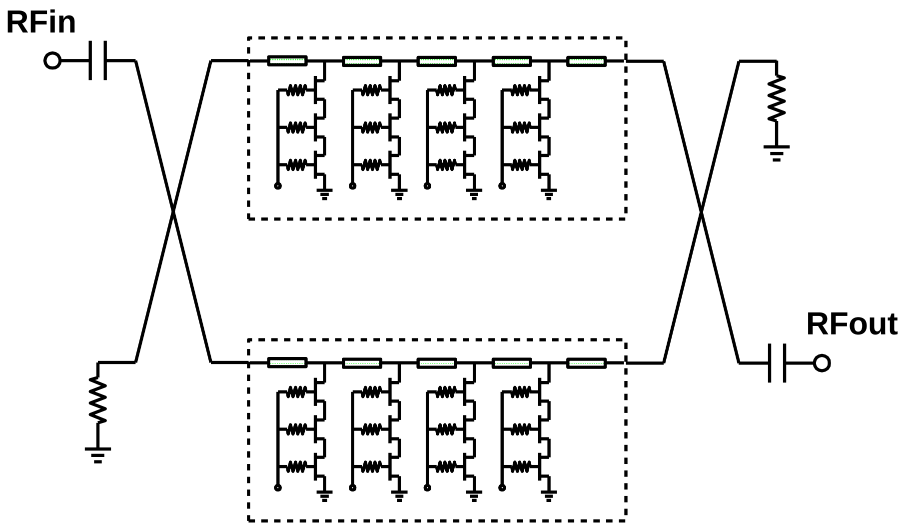

Figure 5: Schematic of the balanced E-band VVA

The simulated insertion loss and return loss of the balanced VVA are plotted against frequency for 5 attenuation states in Figure 6. This includes EM simulation of the Lange couplers. As with the single-ended VVA the control voltage is -2V for the low loss state and +0.6V for the high loss (maximum attenuation) state. Adjusting the control voltage between these two values controls the attenuation. Traces are plotted for control voltages -2V, 0V, +0.1V, +0.2V and +0.6V.

The insertion loss of the balanced VVA is less than 4dB across the 71 to 86GHz band with a dynamic range of attenuation in excess of 30dB. Although optimised for 60 to 90GHz operation the Lange couplers work well down to 50GHz. Below this frequency the amplitude imbalance starts to become excessive. The balanced VVA thus functions well across an extended band of 50 to 90GHz.

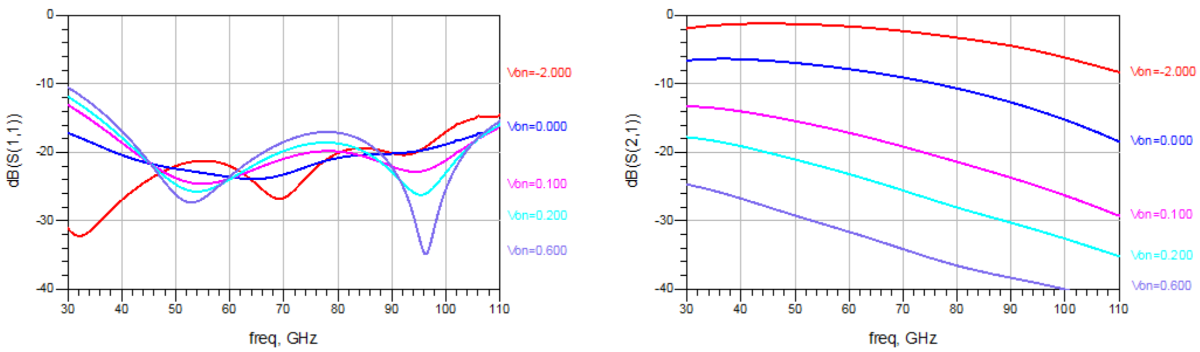

Figure 6: Simulated small-signal performance of the balanced VVA

A plot of the simulated control characteristics of the balanced VVA is shown in Figure 7. It shows the attenuation, relative to the low loss state at -2V control, at 80GHz.

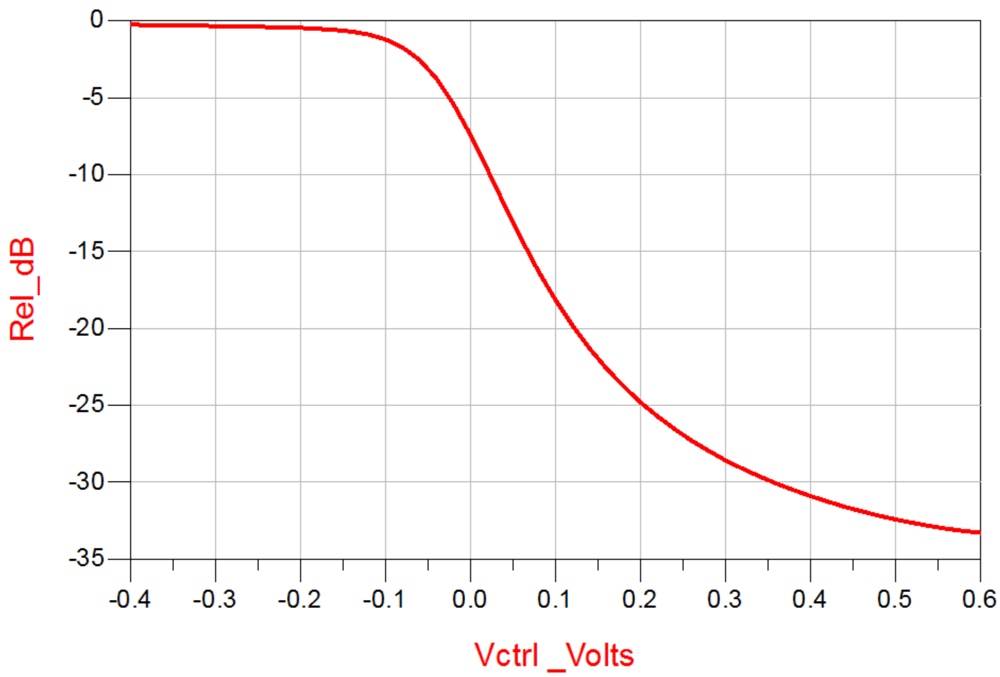

Figure 7: Control voltage versus relative attenuation at 80GHz for the balanced VVA

The layout plot of the balanced VVA is shown in Figure 8.

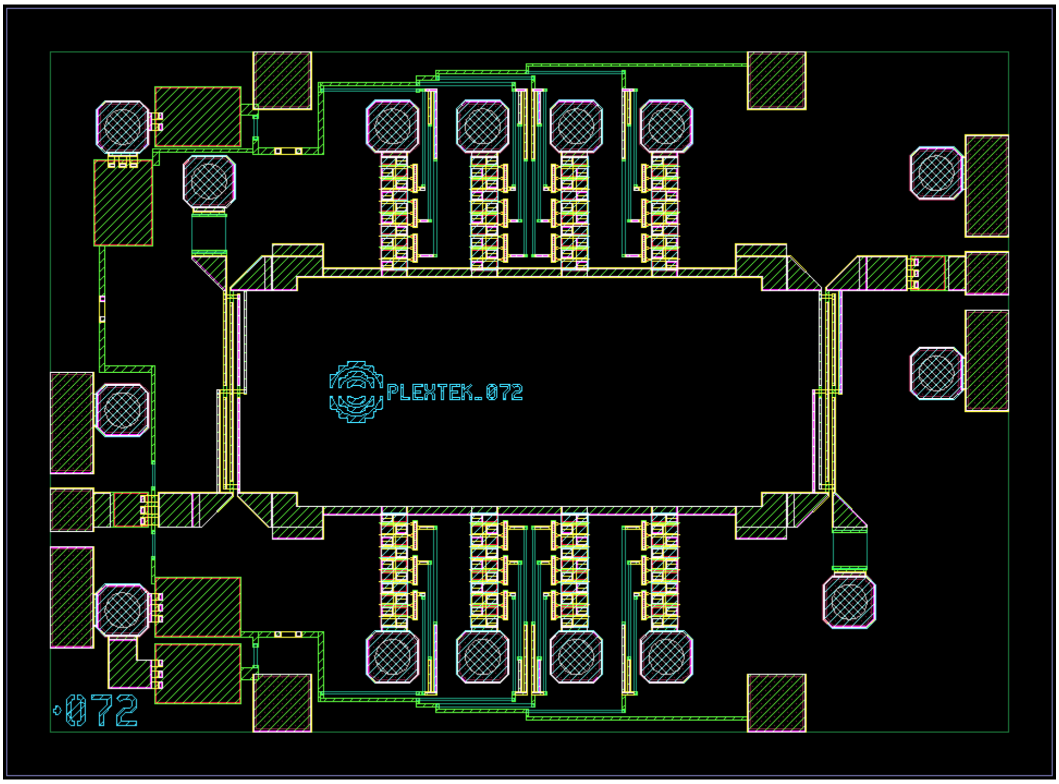

Figure 8: Layout of the balanced E-band VVA

Fabrication and Measured Performance

At the time of writing the IC has just completed fabrication; a photograph of one of the die is shown in Figure 9. RFOW measurement is scheduled but has not yet taken place.

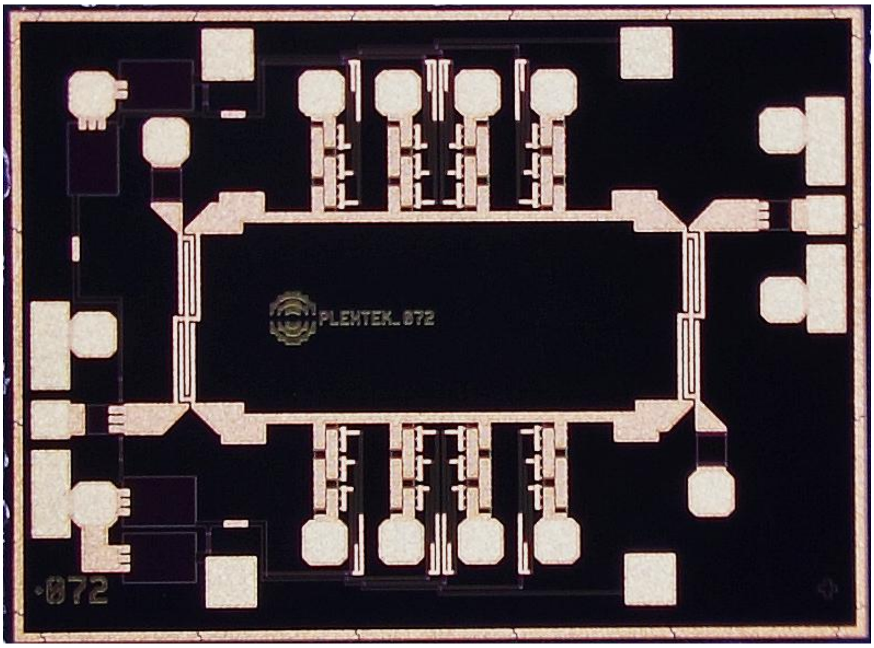

Figure 9: Photograph of the balanced E-band VVA

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