Low Loss mm-Wave Monolithic SP4Ts

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Abstract

Many of the emerging broadband wireless access systems operate at mm-wave frequencies where large allocations of spectrum are available. GaAs Monolithic Microwave Integrated Circuits (MMICs) offer a means of realising low cost, high performance, high volume, reproducible mm-wave components. This paper details two Single Pole 4 Throw (SP4T) switch MMICs covering 24 to 34GHz and 34 to 45GHz. The measured insertion loss of the switches is 1.1dB ± 0.3dB and 1dB ± 0.3dB respectively. The two die were fabricated on Triquint Semiconductor Texas' (TQT) commercially available GaAs Vertical PIN diode (VPIN) process. Good agreement between measured and modelled performance was achieved.

Introduction

High order multi-way mm-wave switches will allow a single mm-wave transceiver to be routed to one of a number of independent antennas. This will allow the development of low cost nodes for "mesh-network" [1] broadband, wireless access systems. This paper details two SP4Ts fabricated on a commercially available GaAs PIN diode process. They cover the frequency range 24 to 45GHz in two bands.

The VPIN process

A PIN diode takes its name from its structure; it comprises a region of high resistivity Intrinsic material sandwiched between a region of P-type semiconductor and N-type semiconductor. When the PIN diode is forward biased, charge carriers are injected into the I region lowering its resistance. Thus at RF and microwave frequencies a PIN diode behaves as a current controlled resistor. They are optimised to achieve wide resistance range, good linearity, low distortion, low drive current and high power handling capability. These properties mean that PIN diodes can be configured to make excellent RF/microwave switches and also find applications in variable attenuators and phase shifters.

Figure 1 shows an equivalent electrical circuit model for a PIN diode at RF/microwave frequencies. A model for a discrete, packaged diode would also need to incorporate appropriate packaging parasitics. In the case of the monolithic PIN diodes used here, the feed structure was also modelled to ensure accurate simulated performance to mm-wave frequencies.

The forward current through the diode controls its resistance Rj. For zero or reverse bias, with no current flowing, the resistance Rj is high, in the region of several kΩ. As the forward bias current through the diode is increased, the charge carriers injected into the I region reduce the value of Rj to values as low as one or two ohms, depending on the diode structure.

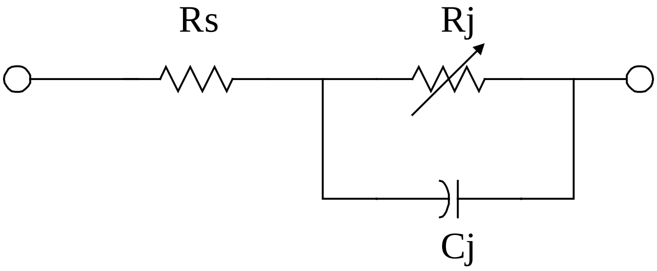

Figure 1: Electrical equivalent model of a pin diode

The TQT process offers diodes with low on-state resistance, low off-state capacitance and a reverse breakdown voltage in excess of 35V. Diodes are fabricated from a Metal-Organic Chemical Vapour Deposition (MOCVD) grown expitaxial layer. The diode is defined photo-lithographically and does not require any sub-micron feature definition, which is undoubtedly a contributing factor to the high circuit yields achieved using this process. Passive structures such as transmission lines, Metal-Insulator-Metal (MIM) capacitors, resistors and low-inductance through substrate via connections can also be monolithically fabricated with the PIN diodes.

Circuit Design

The fact that a PIN diode is essentially a voltage variable (current controlled) resistor means it is extremely well suited to switch realisation. A simple series mounted diode can be used in each arm of a multi-pole switch. With the diode forward biased and conducting a DC current, the switch arm is on. With the diode reverse biased the switch arm is off. This arrangement is shown in Figure 2 for a Single Pole Double Throw (SPDT) switch and can be easily extended to multi-throw implementations.

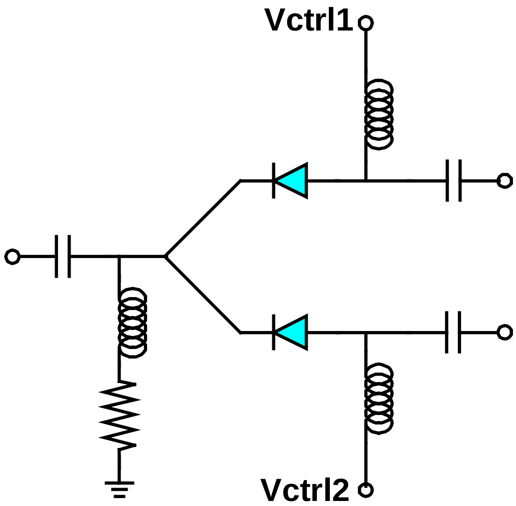

Figure 2: Typical simple PIN diode SPDT

The off-state capacitance of the diodes tends to limit the isolation that can be achieved at RF and microwave frequencies. Decreasing the size of the diode (which involves selecting a different diode in the case of discrete designs) will reduce the off-state capacitance (so increasing the isolation) but will also increase the on-state resistance (so increasing the on-state insertion loss). Switch implementations using combinations of series and shunt diodes, switching complementarily, can be used to provide additional isolation [2]. This also increases the complexity of the biasing arrangement.

Although the PIN diodes fabricated on TQT's process have very low off-state capacitance, the problem is that at mm-wave frequencies this still represents a significant reactance. Thus an off-state capacitance of only 0.1pF would reduce the isolation of an SPST to just 1.22dB. Achieving adequate isolation from a series mounted diode would require so small a diode that the design rules of the process would be infringed. Additionally the on-state resistance would result in unacceptably high insertion loss. The technique adopted to resolve this dilemma was to use a switch design that only requires shunt mounted diodes.

A reverse biased shunt mounted PIN diode presents a low capacitance to ground. This capacitance can be absorbed into a low pass filter structure to give a low loss, well-matched two port. When a forward bias current is allowed to flow in the diode, it presents a low resistance path to ground. Thus the same structure can provide a high insertion loss (or high isolation) two port.

The design route is illustrated in Figure 2. The starting point is to design a conventional low pass filter with acceptable upper operating frequency [3]. The diode size(s), which has(have) the equivalent or slightly lower capacitance(s), is(are) then selected. All of the shunt capacitors are replaced with the diodes and the filters performance is re-optimised. Choosing the number of shunt capacitors in the filter (and so the number of shunt diodes in the switch) is a compromise between high isolation and lower die area/current consumption. In the designs reported here, two shunt diodes were selected. In the case of mm-wave switches, the series inductors are very low in value and are replaced by short lengths of high impedance, microstrip transmission line. Again the filters performance is re-optimised is give acceptable insertion loss and match.

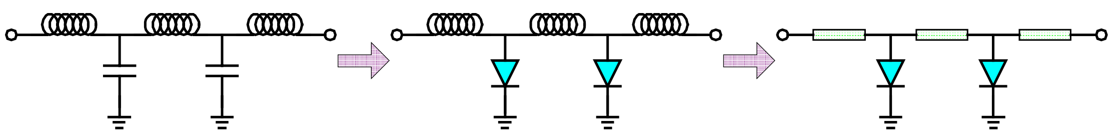

Figure 3: The design path

In order to realise multi-throw switches the input impedance of the filter structure with the diodes in the on-state (low-impedance), must approximate an open-circuit. If this is the case, a number of switch branches can be connected to a common input (or output) port to realise a single pole multi-throw switch. The series transmission line at the input of the filter is used to transform the low impedance of the on-state diode to a high impedance, thus ensuring this is the case.

In summary, the filter structure that has been designed is well matched with a low insertion loss when the diodes are "off" (reverse biased) and has a high insertion loss with a near open-circuit input impedance when the diodes are "on" (forward biased). Biasing elements must also be added to the switch. Series capacitors (DC blocks) are added to the input and output of the filter structure and a shunt stub, approximately a quarter wavelength long at the centre of the desired operating band, is used to inject the forward bias current. The far end of the stub is RF-grounded with an integrated capacitor so the stub's input impedance is open circuit at band centre. The final circuit topology for the complete SP4T is shown in Figure 4.

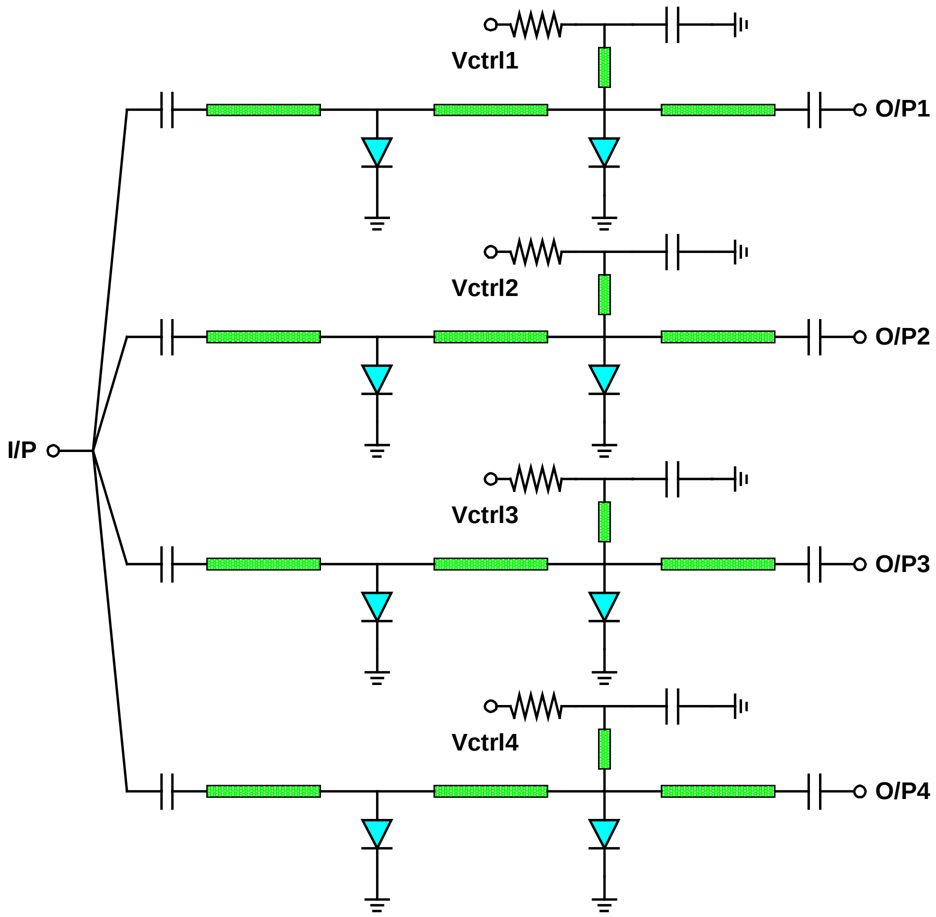

Figure 4: Final circuit topology for the SP4T

The series resistors in each control line are set to provide the required forward biased diode current from the available operating voltage. Choosing the forward bias current at which the diodes are operated is a compromise between improved isolation (for higher bias currents where the on-state diode impedance is lower) and lower current consumption but reduced isolation (with the on-state diode impedance of the diode being higher).

Two versions of the SP4T were designed, each having the same circuit topology, shown in Figure 4, but covering different operating bands:

- Low band SP4T: 24 to 34GHz
- High band SP4T: 34 to 45GHz

Together this pair of switches cover 24GHz to 45GHz, a frequency range which encompasses the vast majority of the broadband wireless access systems currently under development. A photograph of the two different MMICs is shown in Figure 5.

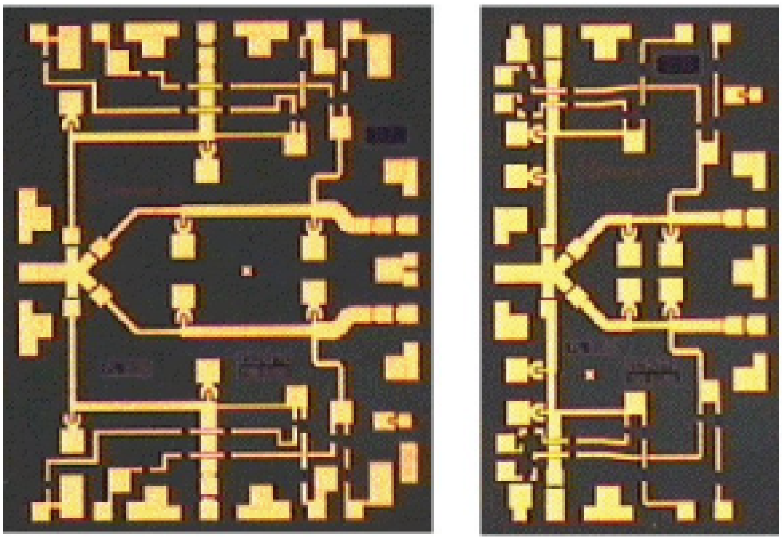

Figure 5: Photograph of the SP4T MMICs (24 to 34GHz design on the left, 34 to 45GHz on the right)

Measured Performance

The small-signal s-parameters of all switches, from two wafers have been measured, RF yield was high at 95%. Figure 6 compares the typical RF On Wafer (RFOW) measured performance against simulated for the low-band (24-34GHz) design in the on-state. Agreement between measured and simulated performance is very good. Although, from a practical layout implementation, the different branches of the switch are not identical, the measured on-state performance through each different branch is virtually the same. The insertion loss is just 1.1dB ± 0.3dB and return losses are better than 17dB across the entire 24 – 34GHz band. A plot showing the measured versus modelled output return loss is given in Figure 7. The off-state isolation is better than 19dB across the band.

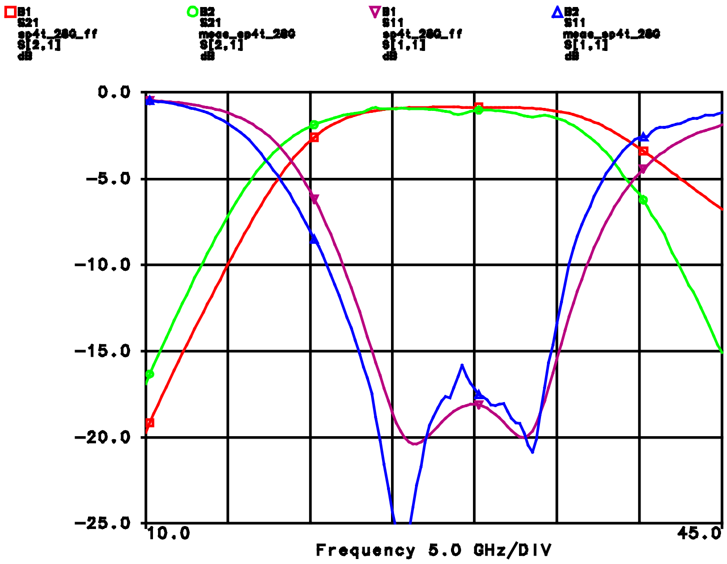

Figure 6: Measured versus simulated small-signal performance of one branch of the low-band SP4T MMIC in the on state

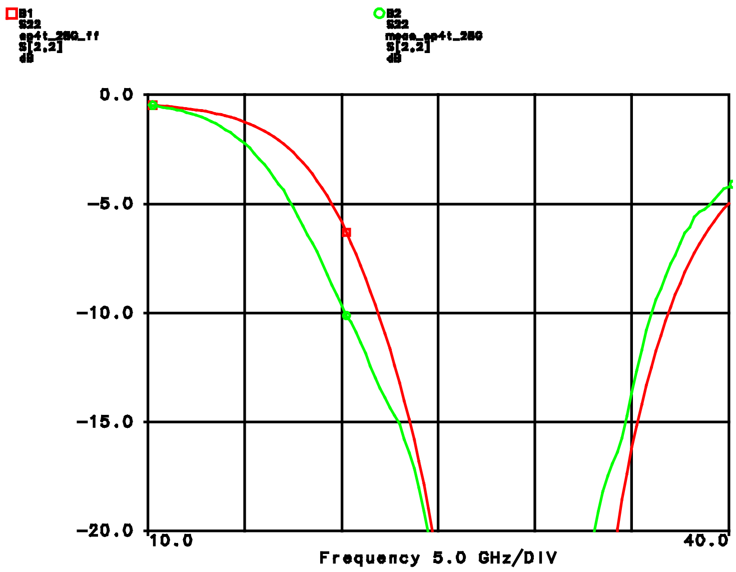

Figure 7: Measured versus simulated S22 of one branch of the low-band SP4T MMIC in the on state

Figure 8 is a plot of the typical RF On Wafer (RFOW) measured performance against simulated for the high-band (34-45GHz) design. The measured insertion loss is 1dB ± 0.3dB and return losses are better than 14dB across the entire 34-45GHz band. A plot showing the measured versus modelled output return loss is given in Figure 9. The off-state isolation is better than 20dB across the band.

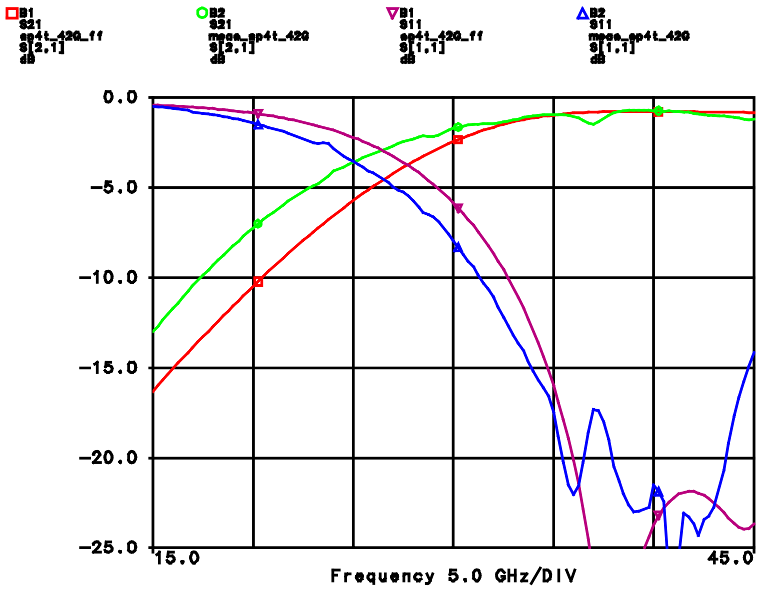

Figure 8: Measured versus simulated small-signal performance of one branch of the high-band SP4T MMIC in the on state

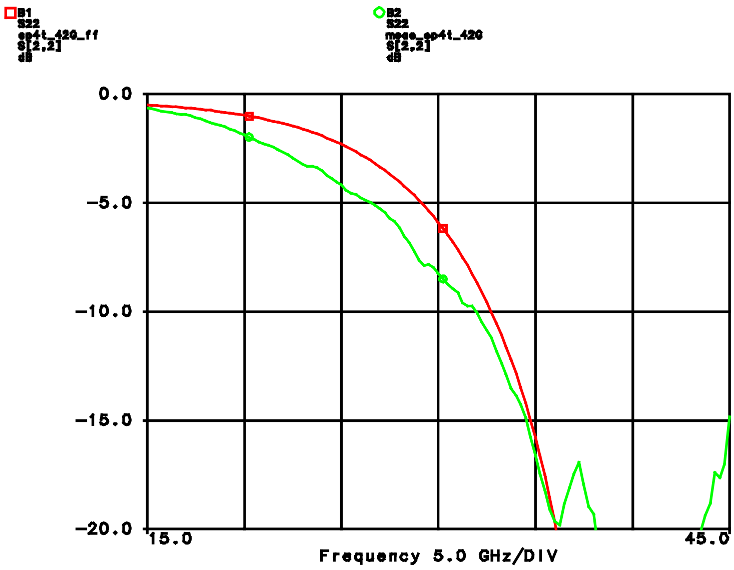

Figure 9: Measured versus simulated S22 of one branch of the high-band SP4T MMIC in the on state

Conclusions

Two monolithic mm-wave SP4Ts, covering 24-34GHz and 34-45GHz, have been designed fabricated and measured. The typical measured performance of the two designs is summarised in Table 1 and Table 2. Performance across potential application sub-bands of the full operating band of the parts has also been included. The switches were produced on a commercially available GaAs PIN diode process and had an RF yield of 95%.

Band →	**24.25 – 26.5GHz**	**27.5 - 29.5GHz**	**24 – 34GHz**
On-case loss	0.92 ± 0.02dB	1.15 ± 0.12dB	1.14 ± 0.27dB
Off-case isolation	> 19.5dB	> 20dB	> 19dB
Input return loss	> 20dB	> 15dB	> 15dB
Output return loss	> 19dB	> 27dB	> 19dB

Table 1: Summary of the low-band SP4T performance

Band →	**40.5 – 43.5GHz**	**34 - 45GHz**
On-case loss	0.8 ± 0.1dB	0.75 ± 0.19dB
Off-case isolation	> 24dB	> 24dB
Input return loss	> 21dB	> 14dB
Output return loss	> 20dB	> 17dB

Table 2: Summary of the high-band SP4T performance

Acknowledgement

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[3] Matthaei, Young and Jones, "Microwave Filters, Impedance-Matching Networks and Coupling Structures", Artech House 1980, ISBN 0-89006-099-1