A THREE-BIT MONOLITHIC PHASE SHIFTER AT V-BAND

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Abstract

This paper describes the design and performance of a three-bit monolithic phase shifter at V-band. The selected circuit approach was a reflection phase shifter with switched delay lines. Schottky diodes were used as the switching elements. Tested at 62.5 GHz, the RMS phase error was 2.7°, the insertion loss 10.8 $\pm$ 1.8 dB (including fixture loss), and the VSWR was better than 2.1:1. The maximum DC power requirement was 40 mW.

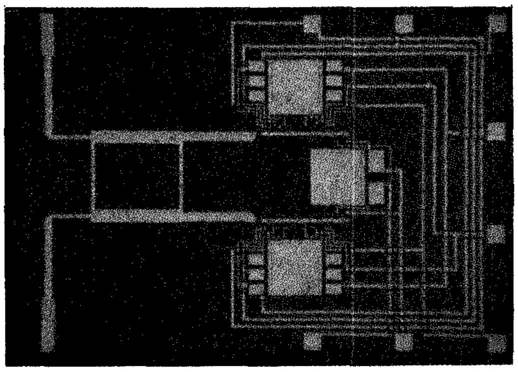

Figure 1. V-Band Phase Shifter

Introduction

Recent advances in transistor technology are paving the way for active phased array radars at millimeter-wave frequencies. In these radar systems, one essential element will be the phase shifter. This paper describes the design and performance of a three-bit phase shifter covering the 60-65 GHz frequency band. The circuit is a reflection phase shifter with switched delay lines [1] and it was selected because it conveniently absorbs the capacitative parasitic associated with the switching element and because of its small size.

Phase Shifter Design

The fabricated phase shifter MMIC is shown in Figure 1, with the chip size being 3.16 x 1.91 mm. As can be seen in Figure 2, the circuit uses a branch line coupler to combine two identical reflection phase shifters thus forming a transmission phase shifter. Each reflection phase shifter consists of eight Schottky barrier diodes linked by short sections of high impedance line. When the diodes are reverse biased, their capacitance loads the real transmission line to form an artificial transmission line. By forward biasing one diode, it is possible to short circuit the artificial transmission line, reflecting the power back into the coupler. The relative phase of the reflected signal depends on which diode is forward biased. In effect the circuit forms an adjustable length of line, and hence a switchable time delay. Over a narrow bandwidth this circuit can be used as a phase shifter. The diode capacitance and the transmission line parameters were selected so that the electrical length of each section of the artificial transmission line is 22.5° at the design frequency. This leads to phase increments of 45° and a total of eight sections of artificial transmission line were used to form a three-bit phase shifter.

The design of the artificial transmission line involves finding the best tradeoff between the

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diode capacitance, the length of the physical transmission line and the impedance of the physical transmission line. In conducting this tradeoff it was necessary to compromise the phase shifter insertion loss in order to obtain a realizable diode to diode seperation. For a lower insertion loss, it would be necessary to use larger diodes. Such diodes have a lower resistance, but they also have a larger capacitance. To absorb this increased diode capacitance, it would be necessary to use a lower artificial transmission line impedance. Reducing the artificial transmission line impedance, however, reduces the length of the transmission lines linking adjacent diodes, which is not physically practical.

The dimensions of the Schottky contacts in the diodes used for this phase shifter were 4 x 1 μm. Based on these dimensions, the reverse bias capacitance of these devices was predicted to be 16 fF, and the differential resistance in forward bias was predicted to be 10 Ω. Because of this high resistance, some of the incident power leaks past the forward biased diode. This power reflects off the short circuit at the end of the artificial transmission line, introducing phase errors. A second problem caused by the high diode resistance is high insertion loss. Both of these problems can be minimized by turning on two adjacent diodes. Further details concerning these diodes are given in a previously published paper [2]. The physical transmission lines have an impedance of 80 Ω, which leads to a 43 Ω impedance level for the artificial transmission line.

In this design a branch line coupler was used, because its line widths were more convenient to realize than those required for a Lange coupler. The branch line coupler was designed using analysis routines based on the planar waveguide model [3], to operate in a 75 Ω system in order to minimize the junction effects. Quarter wavelength transformers were included on-chip to match the artificial transmission lines to the coupler and the coupler to the I/O impedance of 50 Ω.

Measured Results

Test diodes were measured over the 2-18 GHz frequency range. Equivalent circuit models, which were fitted to this data, indicated that the total (junction and fringing) reverse bias capacitance of the diodes was 25 fF and that the differential resistance in forward bias was 8 Ω. This capacitance was significantly higher than the value used in the design. This reduced the effective impedance of the artificial transmission line and increased the electrical length of each section of the artificial line. It was found, however, that by selecting the bias conditions for each phase state good performance could still be obtained.

These circuits were tested in the demountable microstrip fixture shown in Figure 3. This fixture consists of two stepped ridge waveguide to microstrip transitions and a removable center piece. The DUT is mounted on a center piece between two short sections of 50 Ω line. Both 10 mil quartz and 5 mil quartz have been used as substrates on the center piece. 5 mil quartz was used to test the phase shifter, because the discontinuity between a 50 Ω line on 10 mil quartz and a 50 Ω line on 4 mil GaAs is very severe. The insertion loss of the fixture with a 5 mil quartz through line was just over 2 dB at 60 GHz. Further details concerning this fixture are given in a previous paper [2].

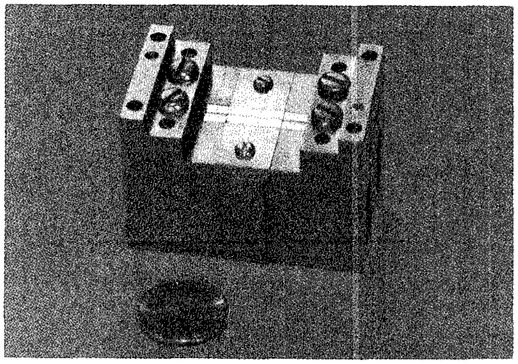

Figure 3. V-Band Demountable Fixture

These circuits were measured in an Automatic Network Analyzer based on the HP8510A system. All of the experimental data shown in this paper is referenced to the waveguide ports of the fixture.

Figure 4 shows the measured phase shift of the phase shifter with the bias conditions in each state optimized to minimize phase errors. These bias conditions are summarized in Table 1. Approximately 1 V was required to drive 40 mA through the diodes, so the maximum DC bias required to power this circuit was 40 mW. At 62.5 GHz, the maximum phase error in any state was 5° and it can be seen from Figure 5 that the RMS phase error at 62.5 GHz was 2.7°. The RMS phase error was less than 5.2° over a 1.5 GHz bandwidth. From Figure 6 it can be seen that the measured insertion loss across this 1.5 GHz band was 10.8 ± 1.8 dB, with approximately 2 dB of this insertion loss due to the fixture loss. Across the same 1.5 GHz bandwidth the VSWR was better than 2.1:1 for all eight phase states (see Figure 7). It is believed that a dominant contribution to this VSWR is the effect of the discontinuity between the 50 Ω lines on the GaAs and the quartz substrates.

Table 1 Optimum Bias Conditions

State	Diodes "On"	Total Current/mA
1	1&2	40
2	1	3
3	8	7
4	7&8	10
5	6&7	40
6[1]	5&6	40
7	2&5	40
8	1&5	40

1. In this state +0.5 V was applied to all the "Off" diodes. In all other states -2.0 V was applied to all of the "Off" diodes.

Another chip was measured using the design bias condition of adjacent pairs of diodes forward biased to a total current of 20 mA. Over the frequency range 59-64 GHz the insertion losses were between 6.5 and 11 dB. The tightest grouping of insertion losses was at 63.5 GHz where the loss was 8.5 ± 1 dB for all phase states. The VSWR was better than 2.3:1 and the RMS phase error rose from a minimum of 8.5° at 58 GHz to 22° at 64 GHz.

Conclusions

A three-bit phase shifter has been demonstrated at V-band with 2.7° RMS phase error, 10.8 ± 1.8 dB insertion loss and a VSWR of better than 2.1:1. These results demonstrate the feasibility of monolithic phase shifters at V-band.

References

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3. R.Mehran, "A method of analysis and design of microstrip directional couplers considering dispersion and discontinuity effects," Proc. of the 1979 International Symposium on Computer Aided Design of the Electronics for Space Application, (Bologna, Italy).

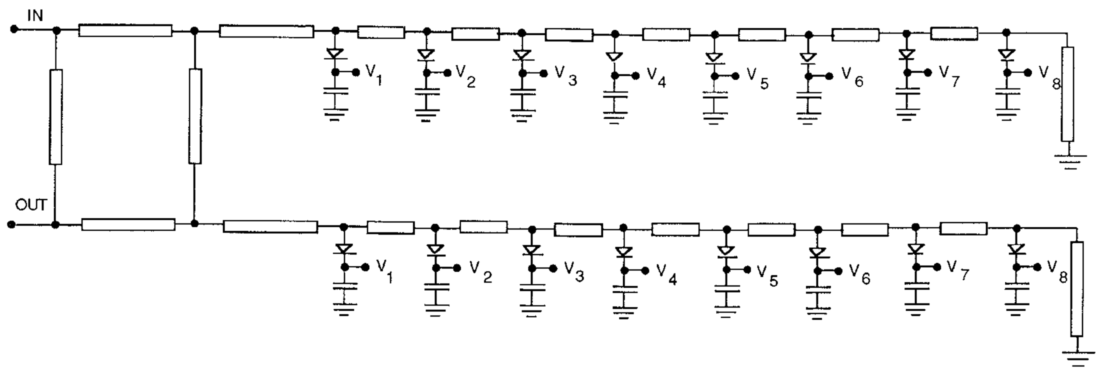

Figure 2. V-Band Phase Shifter Schematic

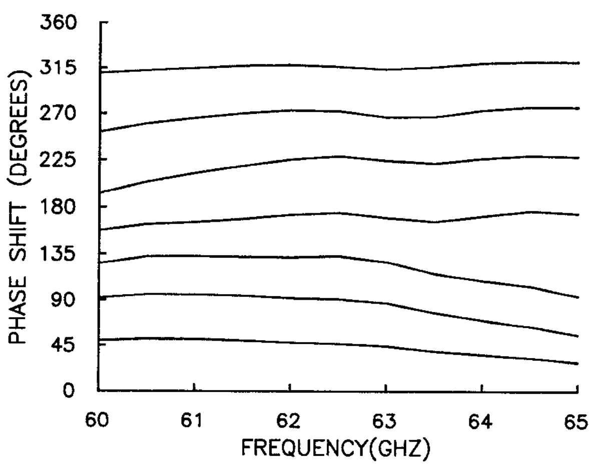

Figure 4. Measured Phase Shift of V-Band Phase Shifter

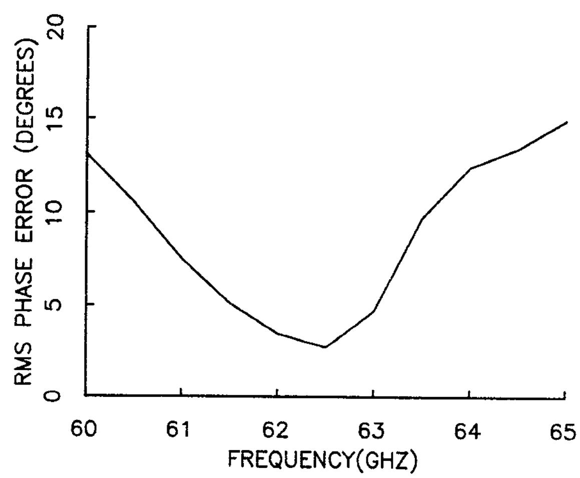

Figure 5. RMS Phase Error of V-Band Phase Shifter

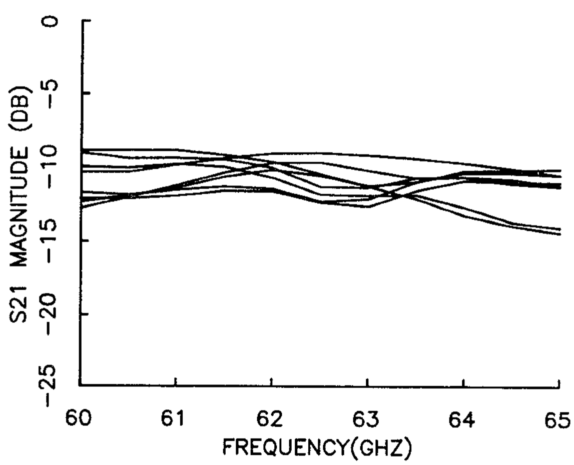

Figure 6. Measured Insertion Loss of V-Band Phase Shifter

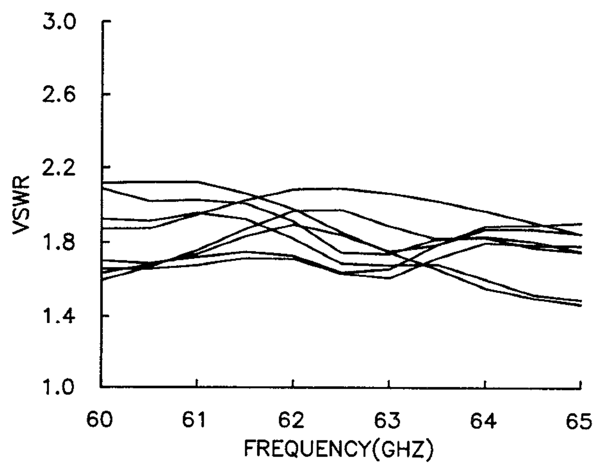

Figure 7. Measured Input VSWR of V-Band Phase Shifter