WIDEBAND S-C BAND MONOLITHIC PHASE SHIFTER

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ABSTRACT

A wideband monolithic phase shifter operating in the 2-8 GHz frequency range is reported. Six GaAs FETs per bit are used as switch elements in a bridge configuration which alternatively becomes a highpass or a low-pass section. Their low impedance state is modeled as a resistor, the high impedance state as a combination of capacitors and resistors. In the design approach, the high impedance state equivalent shunt capacitor is not resonated. Instead, these capacitors become part of the resulting high-pass, low-pass sections. In this way the maximum theoretical bandwidth that a high-pass, low-pass section can provide is achieved despite the nonideal switching elements.

INTRODUCTION

A low-pass filter made up of series inductors and shunt capacitors provides phase delay to signals passing through it. A high-pass filter composed of series capacitors and shunt inductors provides phase advance. By arranging switch elements as shown in Fig. 1, to permit switching between low-pass and high-pass sections, it is possible to realize a compact phase shifter with wideband performance [1]. The actual size and bandwidth of the phase shifter will also depend on the size and the low insertion, high-isolation bandwidth of the two 1 × 2 switches required for each phase bit.

For monolithic circuit applications, the available switch elements are FETs. Unlike the PIN diode, the total capacitor shunting the high impedance switch state is large; to realize the switching action, this capacitance must either be resonated or its effect must somehow be included in the design of the impedance-matching sections. In both cases the bandwidth is limited.

A better approach would be to eliminate the input and output 1 × 2 switches completely; if this can be done, then one may expect to achieve the intrinsic bandwidth of the high-pass, low-pass sections alone. In addition, the savings in chip area will be quite significant, as the switches usually take more space than the phase-shifting sections.

This paper describes one such approach to achieving wideband phase shifter function in monolithic form.

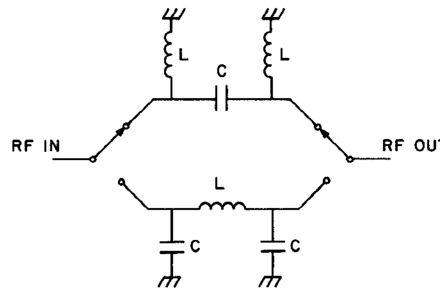

Fig. 1. A typical low-pass high-pass phase shifter schematic circuit diagram.

WIDEBAND HIGH-PASS/LOW-PASS PHASE SHIFTER DESIGN CONSIDERATIONS

Consider the circuit shown in Fig. 2. In this circuit there are six discrete FETs, connected in two sets of T-configurations. The series elements of one T and the shunt element of the other T are switched from a single gate control voltage.

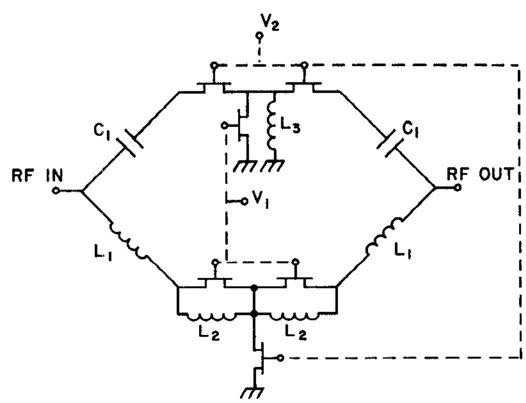

Fig. 2. Schematic circuit diagram for a single bit phase shifter illustrating the present approach.

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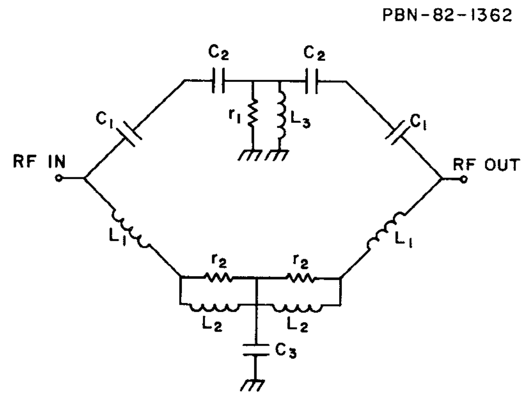

Fig. 3. The circuit shown in Fig. 2 when V_1=0 and $|V_2| > |V_1|$

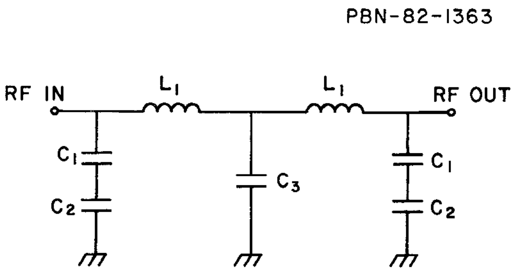

Fig. 4. The circuit shown in Fig. 3 reduces to this form if the resistive components r_1 and r_2 are small compared with the resistive impedances in series or parallel with them.

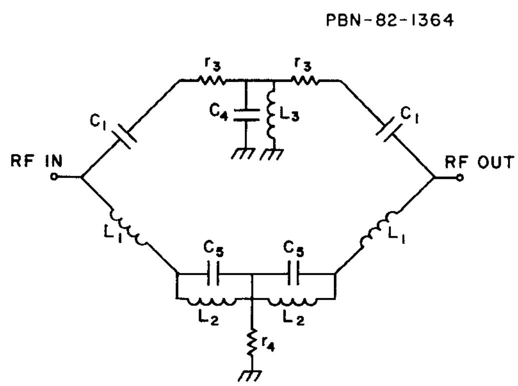

Fig. 5. The circuit shown in Fig. 2 when $|V_1| > |V_r|$ and V_2=0.

When control voltage V_1 is zero and V_2 is beyond the pinch-off voltage of the switch FETs, the circuit of Fig. 2 can be reduced to the form shown in Fig. 3 if we represent for the sake of simplicity the OFF state FET impedance as a capacitor and the ON state impedance as a resistor. If, by suitable design, the resistive components r_1 and r_2 are negligibly small compared with the resistive impedance in series or parallel with them, the circuit can be further simplified to the form shown in Fig. 4, which is a five-section low-pass filter.

On the opposite switch state, that is, when V_2 is equal to zero and V_1 is more negative than the device pinch-off voltage, the circuit of Fig. 2 reduces to the form shown in Fig. 5. If again by suitable design the resistive components r_3 and r_4 are small compared with the reactive impedances in series or parallel with them, the circuit can be further simplified to the form shown in Fig. 6. If the capacitors C_4 and C_5 are small enough that they do not shunt L_2 and L_3, this circuit has the basic form of a five-section high-pass filter.

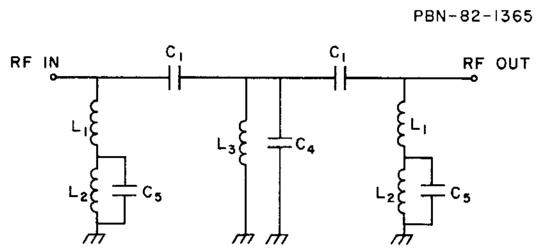

Fig. 6. The circuit shown in Fig. 5 reduces to this form if the resistive components r_3 and r_4 are small compared with L the reactive impedances in series or parallel with them.

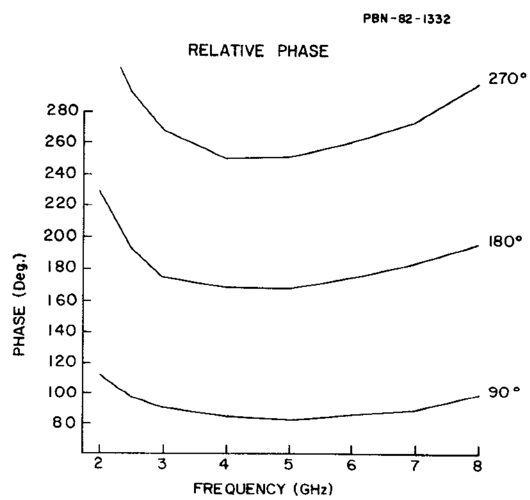

Fig. 7. Predicted performance of the phase shifter.

In summary, the bridge circuit shown schematically in Fig. 2 does allow us to realize a high-pass, low-pass phase shifter without external switch circuitry. Hence operating bandwidth can be maximized with a compact circuit lay-out.

This phase shifter concept has been applied to a 2-8 GHz two-bit phase shifter design. For monolithic implementation, high impedance transmission lines are used instead of lumped inductors. Switching FETs are represented by their full model, including the effect of the gate control terminal [2]. During the design, both the periphery of the individual FETs and the input/output impedance levels were treated as parameters to be optimized. As the result of this optimization process, the periphery of the FETs in the circuit varies from as small as 83 μm to as large as 1333 μm. The 180° phase bit is designed for a 50 Ω system, whereas the 90° bit is designed for a 26 Ω system. All the calculated and measured data presented in this paper include the effect of the impedance transformers required to bring the circuit to a 50 Ω system. The transformers are part of the monolithic circuit design.

Fig. 7 shows the predicted phase response of the two-bit phase shifter. Fig. 8 shows the predicted insertion loss for the four phase states.

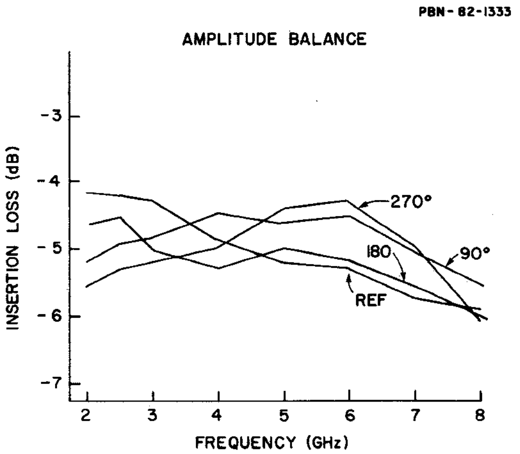

Fig. 8. Predicted insertion loss performance of the phase shifter for each of the four phase states.

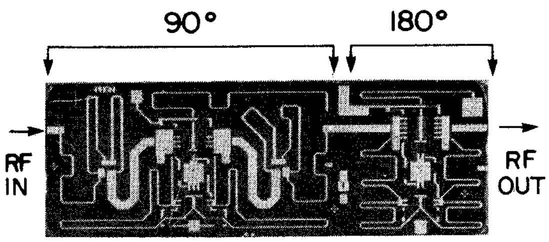

Fig. 9. Photograph of the finished chip.

EXPERIMENTAL RESULTS

The two-bit phase shifter is designed and fabricated on 0.1 mm GaAs substrate in monolithic form. A photograph of the finished chip appears in Fig. 9. The chip dimensions are 4.8 × 1.7 mm (186 × 67 mils) with 7457 μm of total 0.9 μm gate per-periphery. Moving left to right on the chip, we see the 2:1 impedance transformer, the 90° bit, the 2:1 impedance transformer, and the 180° bit.

Fig. 10 shows the measured performance of the phase shifter. For comparison, computer predictions are also presented in the same figure. The measured insertion loss performance for each phase state is shown in Fig. 11; loss is 2-3 dB higher than predicted. The input/output return loss is better than 10 dB across the full frequency band.

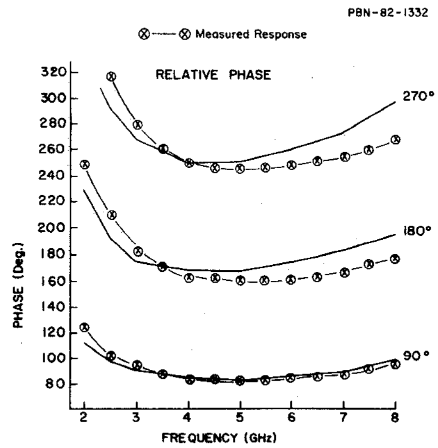

Fig. 10. Predicted and measured performance of the two-bit phase shifter.

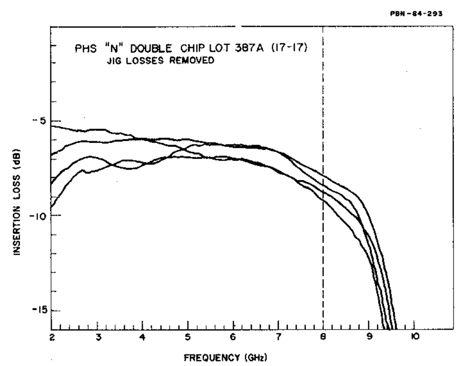

Fig. 11. Measured insertion loss performance of the two-bit phase shifter for each phase state.

CONCLUSION

A novel approach, using nonideal switch elements as part of the phase-shifting low-pass or high-pass section, has been demonstrated in monolithic form using GaAs FETs as switch elements. The concept has been applied to a two-bit phase shifter covering a 4:1 frequency bandwidth.

REFERENCES

[1] R.V. Garver, "Broad-Band Diode Phase Shifter," IEEE Transactions on Microwave Theory and Tech., Vol. MTT-20, No. 5, pp. 314-323, May 1972.

[2] Y. Ayasli, "Microwave Switching with GaAs FETs," Microwave Journal, pp. 61-74, November 1982.