A LOW LOSS MONOLITHIC FIVE-BIT PIN DIODE PHASE SHIFTER

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ABSTRACT

A new monolithic five-bit phase shifter topology made realizable by the use of PIN diode switching elements has demonstrated lower insertion loss than that available from more conventional configurations. The novel phase shifter features predicted insertion loss <3.0 dB and VSWR <1.6 :1 over the 20 percent frequency band in the X-band region. Monolithic chips have been fabricated and evaluated. The experimental results presented indicate that these performance goals are achievable.

INTRODUCTION

Both switched-path and loaded-line forms of digital phase shift bits have been successfully realized in monolithic form using field effect transistors (FETs) for the control elements. Many narrow-band (10-20 percent bandwidth) phased array systems requiring greater than three-bit phase resolution have utilized phase shifters which employ these bit forms. The five-bit X-band phase shifter described in this paper is a monolithic realization of these two forms that utilizes PIN diodes for the control elements. The use of GaAs vertical PIN diodes as switching elements in monolithic microwave circuits has been successfully demonstrated [1]. The reduced size and higher cut-off frequency offered by these elements over ion-implanted FETs are important advantages available to the monolithic circuit designer. The X-band five-bit phase shifter described herein has a predicted insertion loss of less than 3 dB. Low loss is a result of the use of high quality PIN diodes and a novel switched-path topology (patent pending) which minimizes the total number of cascaded switch elements in the transmission path. The predicted loss of the phase shifter is 3 dB less than a comparable design employing FETs as switching elements.

DESCRIPTION

The five-bit phase shifter, shown in Figure 1, consists of three cascadable phase shift elements. Elimination of two cascadable elements which would normally be employed in a more conventional configuration utilizing PIN diodes results in a loss reduction of approximately 1.0 dB. Elimination of two cascadable phase bits is accomplished by employing SP4T switches in each of the two switched-path phase shift elements. The first of these elements provides two bits of constant differential phase shift by employing hi-pass/lo-pass filters in the transmission paths to divide the 360 degree phase space into 90 degree segments. The second of the switched-path phase shift elements provides two additional phase bits by dividing the 90 degree segments provided by the first switched-path circuit into 22.5 degree segments. Phase shift is achieved by selecting the transmission-line path which provides the desired differential phase shift (relative to the reference state) at the low end of the desired frequency band. The phase error resulting from the use of true time delay phase in the second switched-path phase shift element is acceptable for the application under consideration. The fifth phase bit is provided by a conventional shunt loaded-line topology. Realization of the two switched path phase shift elements was made possible because of the availability of vertical PIN diodes for control elements. The equivalent circuit of the diodes employed is shown in Figure 2. Predicted loss goals were set by use of circuit analysis employing diode models which resulted from the application of 4 mA of forward current for series mounted diodes and 1 mA of forward current for shunt mounted diodes.

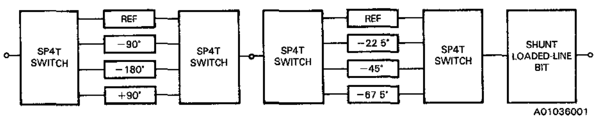


Figure 1. Form of the Low-loss Pin Diode Phase Shifter

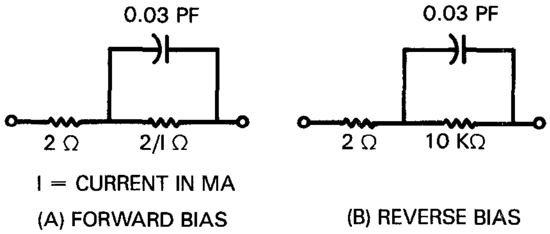


Figure 2. GaAs Vertical PIN Diode Equivalent Circuit

The constant phase shift two-bit phase shifter was realized using filters designed by the image method [2]. The image admittance and image propogation function for the symmetrical pi section network of Figure 3 are

$$Y_{I1} = Y_{I2} = \sqrt{Y_1(Y_1 + 2Y_3)} \qquad (1)$$

and

$$\gamma = 2\sinh^{-1}\sqrt{\frac{Y_1}{2Y_3}} \qquad (2)$$

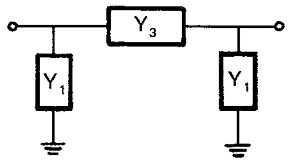


Figure 3. Prototype PI Section Filter Form

Prototype low and high pass filters providing 45 degrees of phase shift in a 50 ohm impedance environment at 9.5 GHZ are shown in Figure 4. The form of the two-bit phase shifter employing these filters is shown in Figure 5. The predicted performance of the distributed forms of filters in each path are shown in Figure 6. Switching between the paths is accomplished by use of series PIN diodes wherever possible. Two of the circuit paths are sufficiently long for the reactive isolation provided by the series diodes to be inadequate over the frequency band of interest. These paths (the reference and 180 degree paths) require the additional isolation provided by shunt diodes [3].

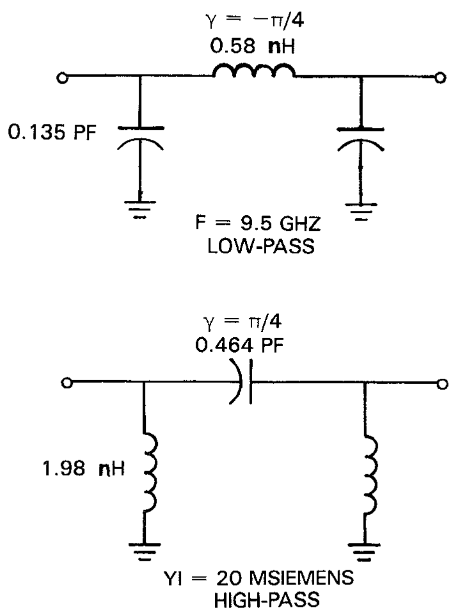


Figure 4. Prototype Filters Designed Using Image Method

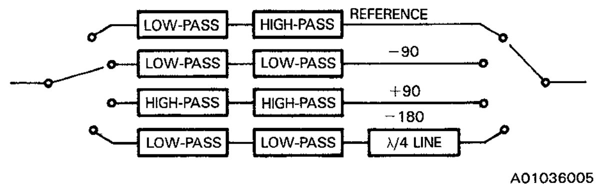


Figure 5. Two-bit Constant-Phase Phase Shifter

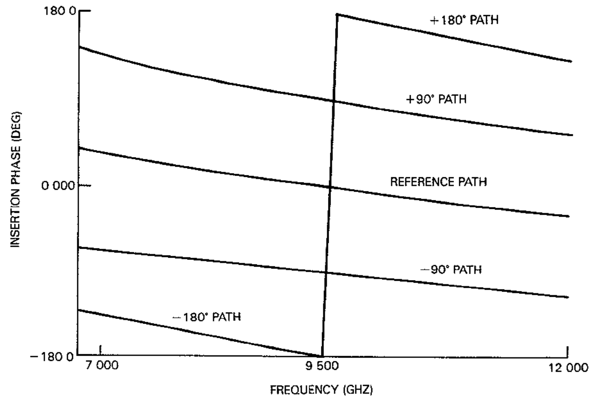


Figure 6. Predicted Performance of Filter Forms Employed in the Two-bit Constant-phase Element

A schematic diagram of the complete five-bit phase shifter is shown in Figure 7. Additional PIN diodes are used as reference diodes to permit reverse bias of the shunt PIN diode switches. The monolithic circuit form is shown in Figure 8. The bar size is 0.260x0.150x0.004 inches with all bias input pads located on the upper edge. Reference diodes located at the lower bar edge provide for biasing of both series and shunt diodes from transistor-transistor logic (TTL) voltage levels.

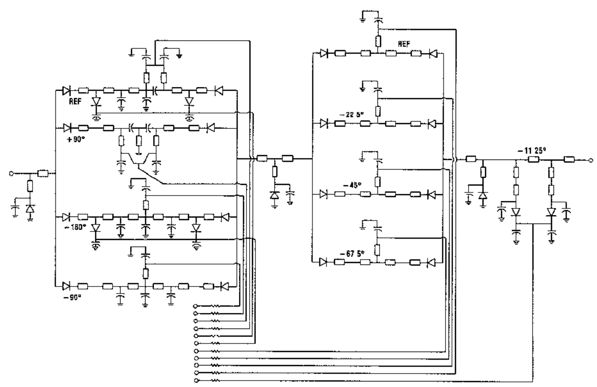


Figure 7. Schematic Diagram of the Five-Bit Pin Diode Phase Shifter

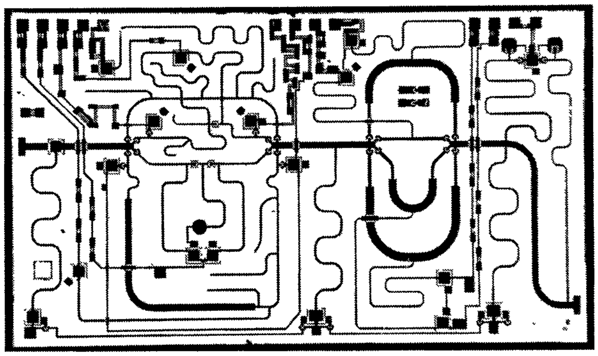
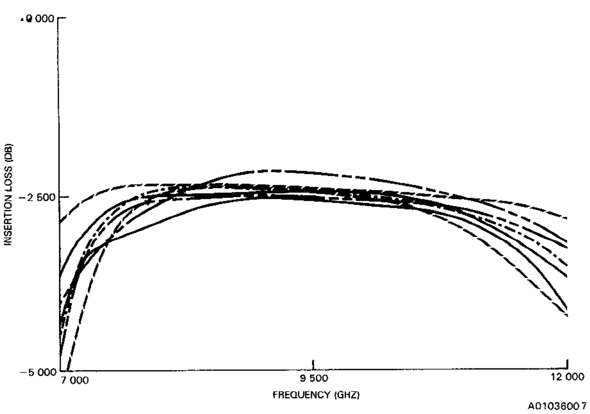


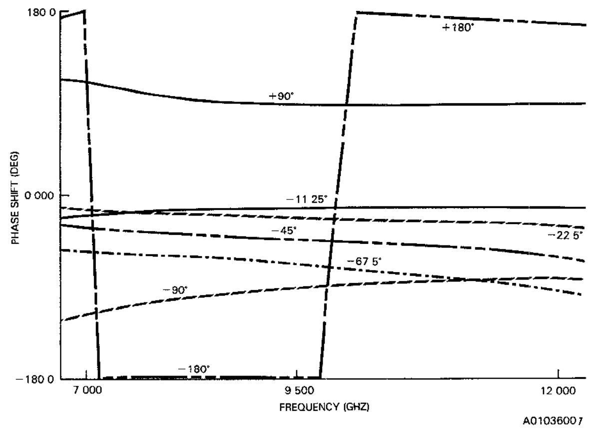
Figure 8. The Five-bit Phase Shifter Monolithic Chip

PERFORMANCE

Design and analysis of the phase shifter was carried out using the EESOF CAD software LIBRA 2.0. Predicted performance of the complete five-bit phase shifter is shown in Figures 9a and 9b. In the 20 percent frequency band centered at 9.5 GHz the insertion loss is less than 3.0 dB and the VSWR is less than 1.6:1. A total of twelve monolithic phase shifter chips have been assembled in fixtures and evaluated. The de-embedded performance of a typical unit is shown in Figures 10a and 10b. The measured insertion loss is approximately 2 dB greater than the predicted value. Use of the CAD model revealed that an increase in diode series on- resistance from 2.5 ohms to 9.0 ohms could cause such a degradation. A re-evaluation of the phase shifter with series diodes in one path shorted verified this supposition.

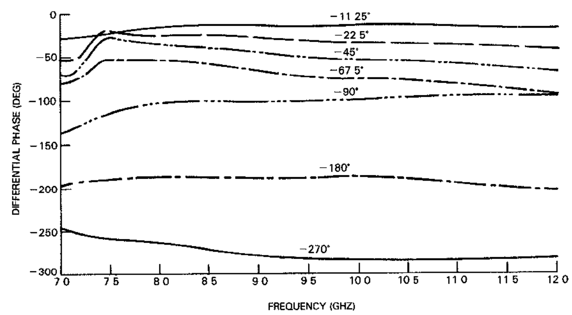


(a)



(b)

Figure 9. Predicted Performance of the Complete Five-bit Phase Shifter



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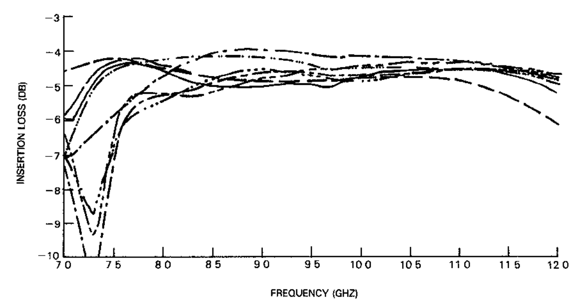

(b)

Figure 10. Measured Performance of the Five-bit Phase Shifter

CONCLUSIONS

The availability of PIN diodes for use as switching elements in monolithic microwave circuits has made it possible to employ a novel circuit form which will enable the circuit designer to realize predicted loss savings of approximately 3.0 dB for five- bit phase shifters operating in the X-band region. The results presented in this paper show the lowest loss yet demonstrated for an X-band five-bit monolithic phase shifter. The diode quality required to realize the desired predicted loss characteristics has been realized in other monolithic circuit forms. [4]

REFERENCES

[1] Sam D. Pritchett and David Seymour, "A Monolithic 2-20 GHz PIN Diode SP16T Switch", 1989 IEEE MTT-S Digest, pp. 1109-1112.

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[3] Robert P. Coats, "An Octave-Band Switched-Line Microstrip 3-b Diode Phase Shifter", IEEE Trans. MTT-21, July 1973, pp. 444-449.

[4] David J. Seymour, David D. Heston, Randall E. Lehmann and Donna Zych, "X-Band Monolithic GaAs Pin Diode Variable Attenuation Limiter", 1990 IEEE MTT-S Digest.