A DUAL-VARACTOR, ANALOG PHASE SHIFTER OPERATING 6 TO 18 GHz

D. M. Krafcsik, S. A. Imhoff, D. E. Dawson, and A. L. Conti

Westinghouse Electric Corp., Advanced Technology Division
P. O. Box 1521, MS 3FT2, Baltimore, MD 21203

ABSTRACT

An MMIC analog reflection phase shifter achieves 120 degrees of phase shift from 6 to 18 GHz using a dual-varactor reflection circuit which allows varactors with 3:1 capacitance ratio to achieve the performance that normally requires 10:1 diodes. The varactor diode is a surface-oriented structure with a hyperabrupt doping profile selectively ion implanted to a depth of 0.70 μm.

INTRODUCTION

A dual-varactor, reflection phase shifter has been fabricated and tested. The use of a dual-varactor reflection circuit on each of the direct and coupled ports of a quadrature coupler gave an equal-ripple phase shift versus frequency response over 6 to 18 GHz that would otherwise not be obtained by a single-varactor circuit. Typical single varactor circuits are based on a diode structure of a thick n layer on top of an n^+ layer. The thick n layer allows a high capacitance ratio and the buried n^+ layer lowers series resistance. Monolithic processing of this structure is complicated because the n and n^+ layers must be mesa etched leaving a high mesa. Also, an airbridge over the mesa edge must be used and has only a small anode dot or finger to which to make contact. The circuit design of this paper is based on a surface oriented, selectively ion implanted, hyperabrupt (within the limitations of a Gaussian) varactor with a deep implant rather than a buried n^+ layer. The varactors made by this process had a 3:1 capacitance ratio compared to commercially available diodes with VPE grown layers on n^+ substrates that have greater than 10:1 capacitance ratios. The dual-varactor circuit allows 3:1 diodes to get the performance of 10:1 diodes and maintain a monolithic process.

Measured phase shift was typically 0 to 150 ±20 degrees with 2.7 dB typical insertion loss (4.0 dB worst case) for one coupler section over 6 to 18 GHz.

CIRCUIT DESCRIPTION

The circuit of figure 1 shows the dual-varactor reflection circuit. The circuit is patterned after a dual-varactor circuit proposed in [1] for the UHF band and adapted here for the 6 to 18 GHz band. Reverse bias is applied simultaneously to both varactors on each port of the coupler. The circuit resonant at f_1 (zero-bias resonance at 5.4 GHz) results in phase shift over 6-9 GHz; however, the f_1 circuit is inductive and insensitive to varactor tuning from 9-18 GHz. The circuit resonant at f_2 (zero-bias resonance at 25 GHz) is capacitive from 9-18 GHz and over 9-18 GHz tunes the inductive f_1 circuit so that phase shift occurs over the 9-18 GHz part of the band. Adding two additional elements (shown in figure 2) during optimization gave the best phase flatness. The final circuit element values are given in figure 2. The inductors when replaced with the equivalent length of 100 ohm microstrip give the modeled response described below. The coupler of figure 2 is slightly over-coupled (K = 2.25 dB) to minimize the VSWR by spreading the VSWR ripple equally over the 3:1 band [2]. The corresponding even- and odd-mode impedances are 142 and 18 ohms, respectively, and the modeled VSWR is a maximum of 1.5:1 over the 6 to 18 GHz band.

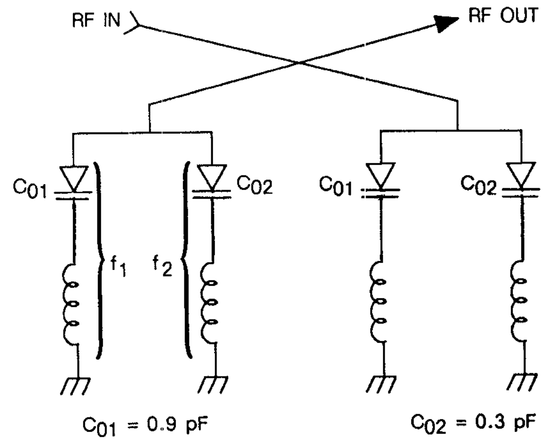

Figure 1. The Combination of the f_1 Circuit and the f_2 Circuit Gives Flat Phase Shift Response From 6 to 18 GHz. The varactor-inductor zero-bias resonances, f_1 and f_2, are 5.4 GHz and 25 GHz respectively.

PERFORMANCE RESULTS

Modeled and measured phase shift is shown in figure 3. An equal-ripple response is observed in both the modeled and measured curves. The phase flatness of the measured device is ±20 degrees, and the minimum amount of phase shift is

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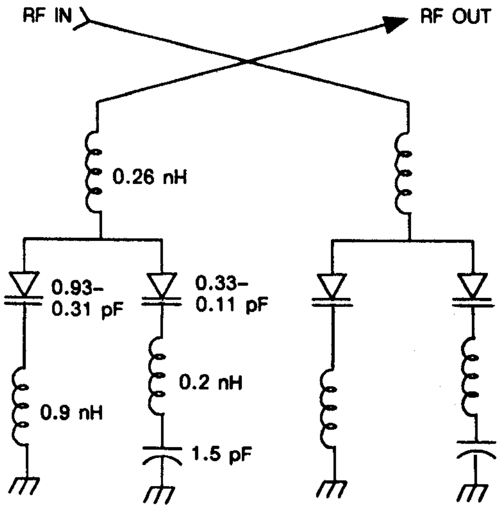

Figure 2. Elements Were Added to the Circuit of Figure 1 to Help Flatten Phase Shift.

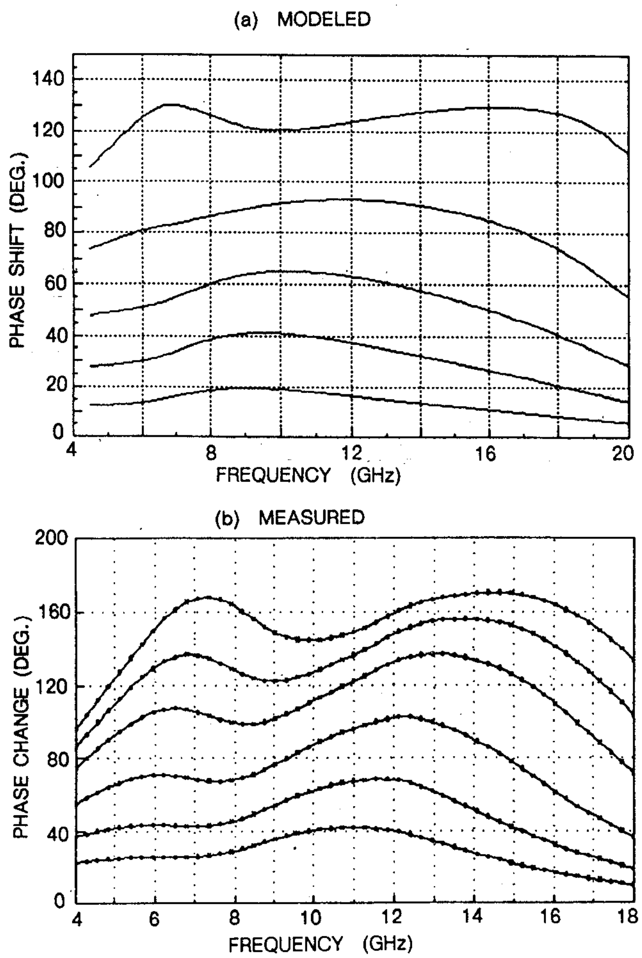

Figure 3. The Modeled (a) and Measured (b) Phase Shift Both Show the Same Trends. The measured ripple is greater due to differences in the characteristics of the varactor as modeled vs. measured.

130 degrees at all points across the band. The corresponding measured insertion loss (figure 4) is 2.7 dB ±1.3 dB over the frequency and bias control voltage range. Both the modeled and measured curves show the same trend of the zero-bias curve having more insertion loss below 12 GHz and less insertion loss above 15 GHz relative to the 8 volt curve. The modeled insertion loss curves are different in absolute value by 0.5 dB than the measured curves because a 100 GHz f_{co} ($f_{co} = 1/\{2\pi R_s C_o\}$, R_s and C_o measured at zero bias) was assumed in the modeled calculations and the varactor as fabricated had 75 GHz f_{co}. Input/output VSWR was measured to have a maximum over frequency and bias control voltage of 2.0:1 compared to the expected VSWR of 1.5:1. The coupler as fabricated had 2.0 dB rather than the modeled

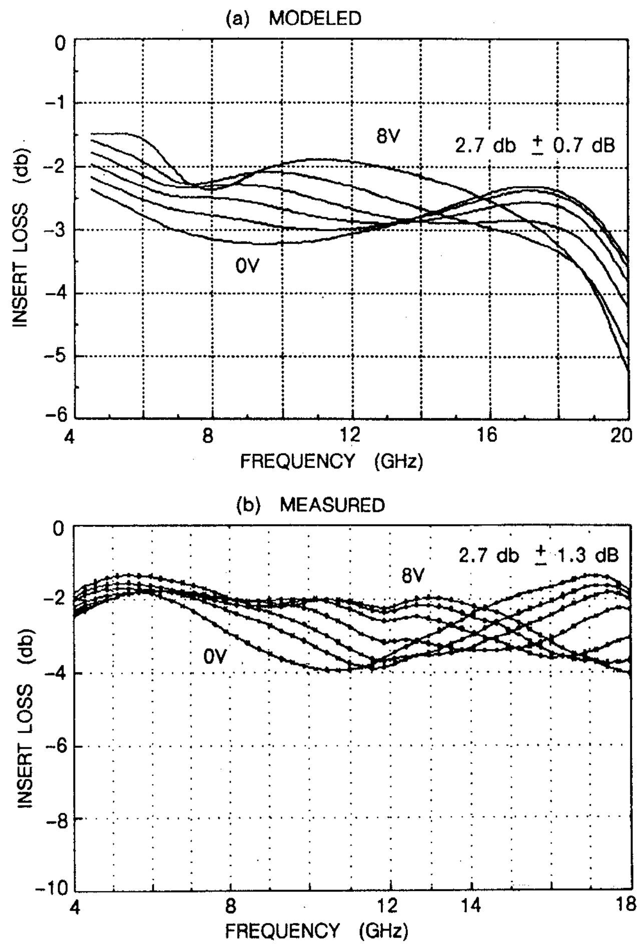

Figure 4. The Modeled (a) and Measured (b) Insertion Loss Show the Same Trends. The measured loss is 0.5 dB higher because measured f_{co} was 75 GHz vs. a modeled value of 100 GHz.

value of 2.25 dB for the coupling coefficient which caused greater VSWR at band center than necessary. The modeled curves agreed with the measured curves when the coupling coefficient was increased to 2.0 dB.

VARACTOR MODELING AND CIRCUIT OPTIMIZATION

A process for the varactor had already been established, and the varactor capacitance and series resistance variations with bias were known. The f_c as a function of bias was therefore known. During circuit optimization C_{01} and C_{02}, or the area of each varactor, were varied to optimize circuit performance. The R_s parasitic for each varactor was computed from f_c and the area (C_0) for a given bias by computing f_c as a dependent variable with bias as the independent variable. In other words, C_0 was the variable of optimization and $f_c(V)$, $C(V)$, and R_s were computed as dependent variables as C_0 was changed during optimization. The modeled curves of figures 3 and 4 include these interdependencies and optimization for minimum insertion loss and insertion loss modulation was done simultaneously as phase shift and phase shift flatness were optimized.

FABRICATION

The varactor is an anode finger along each side of which there is ohmic metal area. The anode finger is 0.75 µm x 140 µm and the ohmic area on each side of the anode is 10 µm x 140 µm. The ohmic-anode spacing is 1.0 µm. The doping profile under the anode is hyperabrupt obtained by selective ion implantation (figure 5). The depth of the doping profile is 0.70 µm in order to insure a conducting layer underneath the depletion region over the range of control voltage. A single $^{28}Si^{++}$ and three $^{29}Si^{+}$ implants were chosen to produce a profile which is doped at 2 X 10^{17} cm^{-3} near the surface, dropping off to a deep, low-doped tail. The f_{co} of the varactor was measured to be 75 GHz, and the capacitance ratio was 3:1. Without fringing, the capacitance ratio would be approximately 6:1.

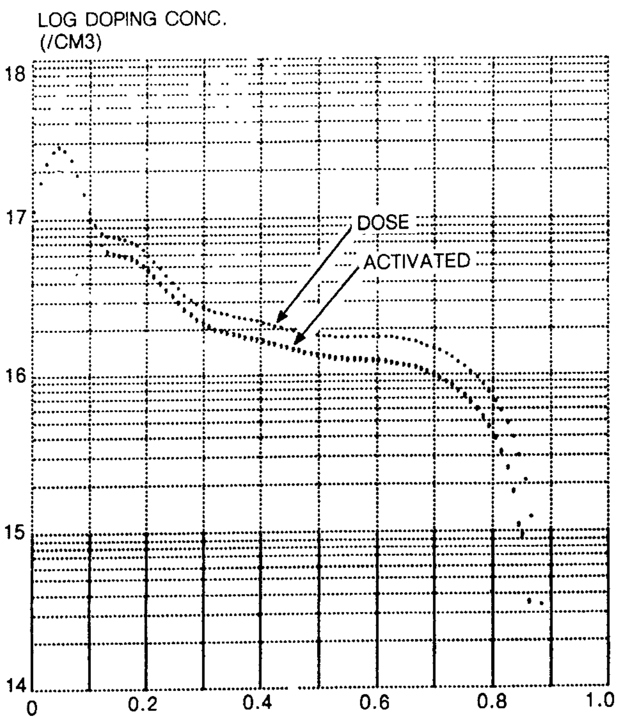

Figure 5. The Doping Profile Was Obtained by Ion Implantation at a Depth of Up to 0.70 µm.

The chip of figure 6 is 0.148" x 0.068" x 0.015". The substrate thickness was chosen to be 0.015" rather than 0.004" to make the interdigitated Lange coupler lower loss. A resist thickness and profile appropriate to lift off 4 µm of metal was chosen so that a thicker than usual overlay metal could be used to lower the loss of the coupler while maintaining better dimensional control than that offered by a plating process. The coupler loss was measured to be 0.25 dB (for single pass) above the coupling losses.

COMPARISON WITH PRESENT AND PRIOR ART

It is interesting to note how different approaches to improving varactors for MMIC applications have evolved over the last seven years. Surface oriented varactors with capacitance ratios greater than 10:1 were reported in [3], but as pointed out in [3] the high capacitance ratio was obtained under the condition of punch-through with the result that the varactor Q degraded just before punch-through. Based on avoiding varactor punch-through, a flat-profile, ion implanted thick layer was reported in [4]; a flat profile ramping up to an ion implanted thick n^+ layer was reported in [5]; an MBE hyperabrupt profile on n^+ (planar structure) was reported in [6]; and in this work a hyperabrupt ion implanted thick layer (figure 5) is reported.

With respect to the circuit design, single-varactor reflection circuits implemented monolithically were reported at X-band in [4] and at Ku-band in [6]. Each of these two designs were of less than 40 % bandwidth. In the hybrid circuit area, 150+ degrees of phase shift 6 to 18 GHz was reported in [7] using a single-varactor design with 15:1 planar varactors. Also, binary phase modulators using two PIN diodes in a dual-diode reflection circuit configuration were reported in [1] with measured results over several octaves in the UHF band. A dual-varactor analog circuit was proposed in [1] where computer simulation of the circuit was done at UHF over octave-plus bandwidths, but measured results were not presented.

The diode design discussed above and the dual-diode reflection circuit discussed above have been combined to achieve broader band monolithic analog phase shifter performance than reported to date.

CONCLUSION

An analog, 6 to 18 GHz, 120-degree phase shifter has been fabricated and measured. A dual-varactor reflection circuit obtained 3:1

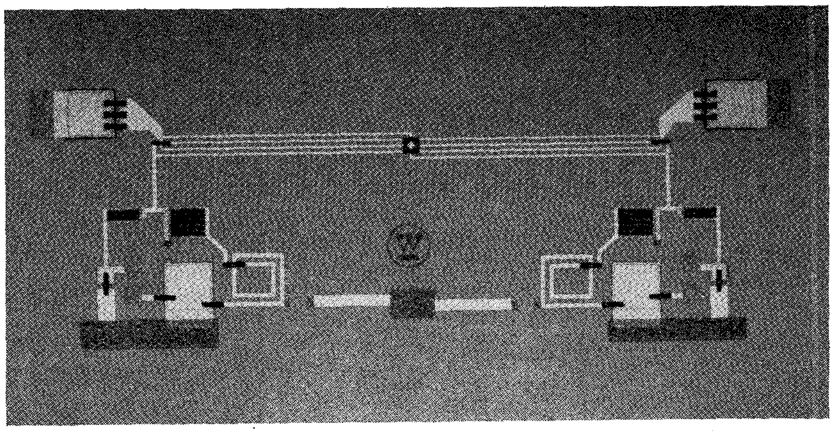

Figure 6. The Phase Shifter Chip Size Is 0.148" x 0.068" x 0.015".

bandwidth using varactors with 3:1 capacitance ratio, a result that has not been achieved by single-varactor circuits. Planar, discrete chip varactors with 15:1 capacitance ratio and 0-30 V bias control voltage were used in a single-varactor hybrid circuit with 150-plus degrees of phase shift over 6 to 18 GHz [7], but the dual-varactor circuit allows a low-cost, ion implanted, monolithically compatible process to achieve performance suitable for wideband applications.

ACKNOWLEDGEMENT

This work was supported by NRL contract N00014-85-C-2583. The contract monitors were Barry Spielman and Max Reuss.

REFERENCES

[1] T. Morawski, J. Zborowska, and P. Miazga, "Multi-octave phase modulators," 1984 IEEE Int. Microwave Symp. Dig., pp. 378-380.

[2] J.F. White, Semiconductor Control. Dedham, MA: Artech House, 1977, P.203.

[3] G.E. Brehm, B.N. Scott, D.J. Seymour, W.R. Frensely, W.N. Duncan, and F.H. Doerbeck, "High capacitance ratio monolithic varactor diode," 1981 Eighth Biennial Cornell Elec. Conf. Dig., vol. 8, pp. 53-63.

[4] D.E. Dawson, A.L. Conti, S.H. Lee, G.E. Shade, and L.E. Dickens, "An analog X-band phase shifter," 1984 IEEE Microwave and Millimeter-Wave Monolithic Circuits Symp. Dig., pp. 6-10.

[5] L.C.T. Liu, C.S. Liu, J.R. Kessler, S.K. Wang and C.D. Chang, "A 30-GHz Monolithic Receiver," IEEE Trans. Microwave Theory Tech., vol. MTT-34, no. 12, pp. 1548-1552, Dec. 1986.

[6] C.L. Chen, W.E. Courtney, L.J. Mahoney, M.J. Manfra, A. Chu, and H.A. Atwater, "A low-loss Ku-band monolithic analog phase shifter," IEEE Trans. Microwave Theory Tech., vol. MTT-35, no. 3, pp. 315-320, Mar. 1987.

[7] D.C. Boire, J.E. Degenford, and M. Cohn, "A 4.5 to 18 GHz phase shifter," 1985 IEEE Int. Microwave Symp. Dig., pp. 601-604.