Monolithic GaAs Phase Shifter Circuit with Low Insertion Loss and Continuous 0–360° Phase Shift at 20 GHz

Amit S. Nagra, *Student Member, IEEE,* Jian Xu, *Student Member, IEEE,* Erich Erker, *Student Member, IEEE,* and Robert A. York, *Member, IEEE*

***Abstract*— We present here a circuit capable of continuous 0–360° phase shift at 20 GHz with only 4.2 dB of insertion loss. The phase shifter employs a variable velocity transmission line obtained by periodically loading a coplanar waveguide (CPW) line with GaAs Schottky diodes. The circuit is fabricated on GaAs using monolithic fabrication techniques that are compatible with commercial GaAs foundry processes. To the best of our knowledge, this circuit has the lowest reported insertion loss for a monolithic solid state phase shifter operating at 20 GHz.**

***Index Terms*—MMIC phase shifters, phase shifters.**

I. Introduction

DIODE-LOADED transmission lines have been used for a variety of applications both nonlinear [1]–[4] as well as linear [5], [6]. In the linear (small signal) regime, the diode-loaded line behaves a like variable velocity transmission line and can therefore be used as a time delay/phase shift element. In recent demonstrations [5], [6], varactor diode-loaded lines have been used as true time delay elements in prototype phased arrays. However, these time delay elements were useful at relatively low frequencies (<5 GHz) due to limitations imposed by the hybrid implementations adopted there. In this letter we present a monolithic implementation of a loaded-line phase shifter that is capable of operation at 20 GHz. The phase shifter circuit consists of a CPW line periodically loaded with varactor diodes (planar GaAs Schottky diodes, small signal cutoff frequency ~700 GHz). The circuit is capable of producing a continuously variable phase shift from 0 to 360° at 20 GHz with a maximum insertion loss of 4.2 dB. The return loss is better than −12 dB over all phase states.

The phase shifter circuit reported here has several desirable features. As opposed to digital phase shifters, it can produce continuous phase shift between 0 and 360°, resulting in accurate beam control when used in phased arrays. This circuit requires just one control line as opposed to switched line or switched network phase shifters where the number of control lines required is equal to the number of bits. The Schottky varactor diodes employed in the circuit are always reverse biased and hence the circuit dissipates extremely low power in all states. Also, the diodes have fast response times, enabling rapid phase control and beam scanning. The circuit is suitable for low-cost monolithic production and since the fabrication process is compatible with standard GaAs monolithic microwave integrated circuit (MMIC) technology, it can be easily integrated with other MMIC's. Also the distributed nature of the circuit makes it less sensitive to small variations in the varactor diode properties, thereby making the design robust.

II. Basic Principle and Circuit Design

When a uniform transmission line is periodically loaded, the structure exhibits Bragg frequencies at which the reflections add in phase and transmission through the structure is suppressed. For frequencies well below the lowest Bragg frequency, the periodic load elements can be absorbed into the line and the entire structure can be treated as an artificial transmission line with modified impedance and propagation characteristics. In the case of a CPW line loaded with varactor diodes, the capacitance per unit length of the artificial transmission line has contributions from the unloaded line capacitance (C_t) and the varactor capacitance (C_{var}). The inductance per unit length (L_t) of the artificial line is unchanged from that of the unloaded line. The characteristic impedance and phase velocity for the varactor diode-loaded line are given by (1). Note that all terms involving the varactor capacitance are divided by the spacing between the diodes (L_{sect}) to obtain an equivalent varactor capacitance per unit length. It is evident from (1) that by varying the bias across the varactor diodes, it is possible to change the varactor capacitance and hence the phase velocity. However changing the capacitance per unit length also changes the characteristic impedance of the artificial transmission line. By reducing the variation in the total capacitance, the change in the characteristic impedance can be made small, at the cost of reducing the maximum change in propagation constant $(\Delta\beta^{\max})$. However, it is still possible to design the circuit for any desired maximum phase shift $(\Delta\phi^{\max})$ by ensuring that the line is of suitable length (L_{total}) as given by (2)

$$Z_o(V) = \sqrt{\frac{L_t}{(C_l + C_{\mathrm{var}}(V)/L_{\mathrm{sect}})}} \tag{1a}$$

$$v_{\mathrm{phase}}(V) = \sqrt{\frac{1}{(L_t(C_t + C_{\mathrm{var}}(V)/L_{\mathrm{sect}}))}} \tag{1b}$$

Manuscript received July 27, 1998. This work was supported by the Office of Naval Research under ONR Young Investigator Award N00014-96-1-0799 and HRL Laboratories (formerly Hughes Research Laboratories), Malibu, CA.

The authors are with the Electrical and Computer Engineering Department, University of California, Santa Barbara, CA 93106 USA.

Publisher Item Identifier S 1051-8207(99)02003-6.

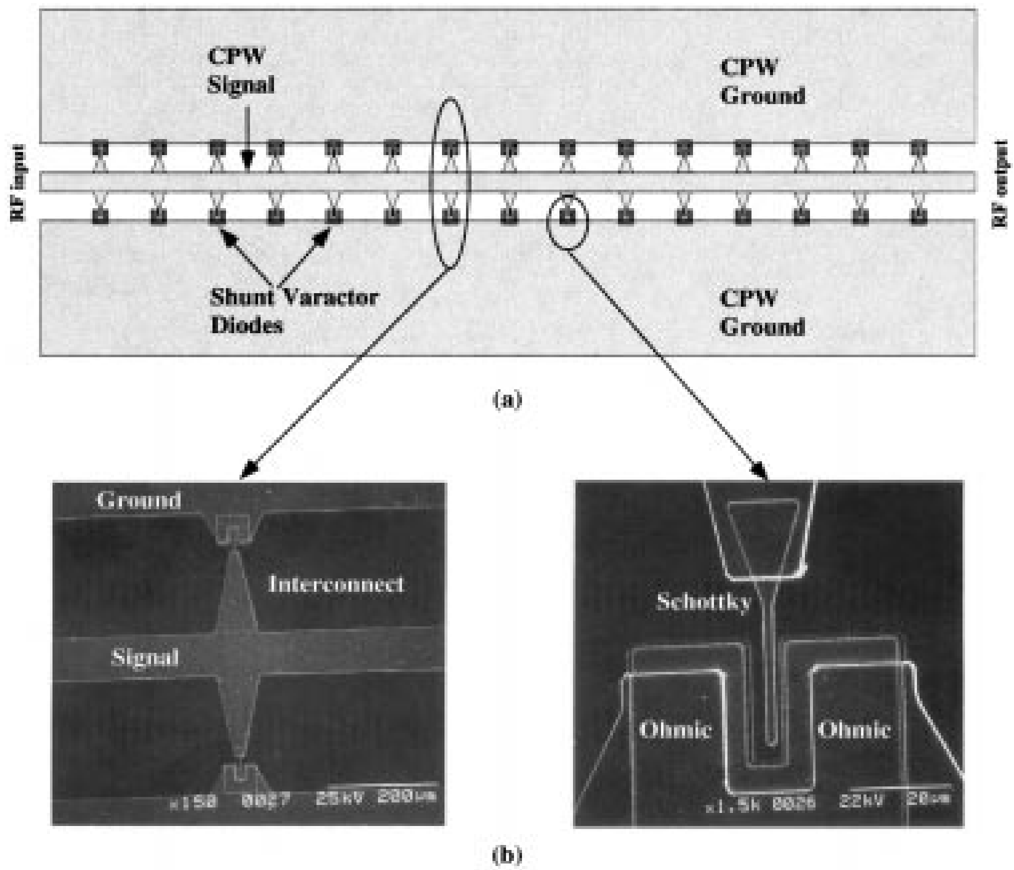

Fig. 1. (a) Schematic showing layout of the varactor loaded CPW line. (b) SEM photographs of the fabricated phase shifter circuit illustrating the details.

$$\Delta\beta^{\max} = 2\pi f \sqrt{L_t}\left(\sqrt{C_t + C_{\text{var}}^{\max}/L_{\text{sect}}} - \sqrt{C_t + C_{\text{var}}^{\min}/L_{\text{sect}}}\right) \quad \text{(2a)}$$

$$\Delta\phi^{\max} = \Delta\beta^{\max} L_{\text{total}}. \quad \text{(2b)}$$

The design used here consists of a CPW transmission line of characteristic impedance 74 Ω, periodically loaded with varactor diodes whose zero bias capacitance is 130 fF. The unloaded line is of high impedance so that after capacitive loading the characteristic impedance reduces to 50 Ω. The length of the unit cell (spacing between diodes) is chosen to be 810 μm, resulting in a Bragg frequency of 30 GHz. In order to obtain a phase shift of 360° at 20 GHz, 24 identical cells are connected in series resulting in a total length of 19.44 mm. CPW center conductor and gap dimensions of 60 and 170 μm, respectively, are used here. In order to preserve the symmetry of the structure, the periodic loading capacitors are implemented using two varactors (zero bias capacitance 65 fF) connected in parallel from the CPW center conductor to either ground plane (depicted in Fig. 1).

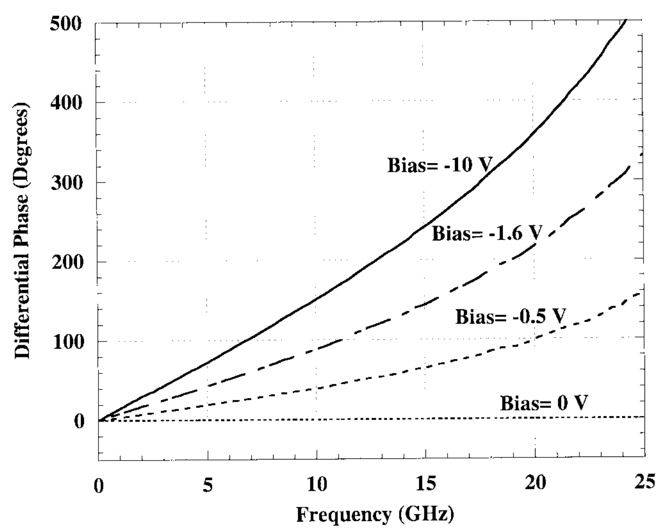

Fig. 2. Differential phase shift versus frequency for selected values of varactor reverse bias. The phase shift is with respect to the transmitted phase at 0 V bias.

III. Fabrication and Testing

The phase shifter circuits were fabricated using standard GaAs processing techniques, similar to those used in [7]. The epitaxial layers for the diodes were grown by MBE on a semi-insulating GaAs substrate of 600-μm thickness. In order to reduce the series resistance, a heavily doped layer of thickness 9000 Å and doping $8 \times 10^{17}/\text{cm}^3$ was included below the active layer of doping $5 \times 10^{16}/\text{cm}^3$ and thickness 5000 Å. Alloyed AuGe–Ni–Au ohmic contacts were made after etching down to the heavily doped layer. The Schottky contacts were made by depositing Ti–Pt–Au metal directly on the lightly doped active layer. The diodes were isolated using proton (H^+) implants and two implants of energies 120 and 175 KeV were used to ensure adequate isolation over the entire epitaxial layer

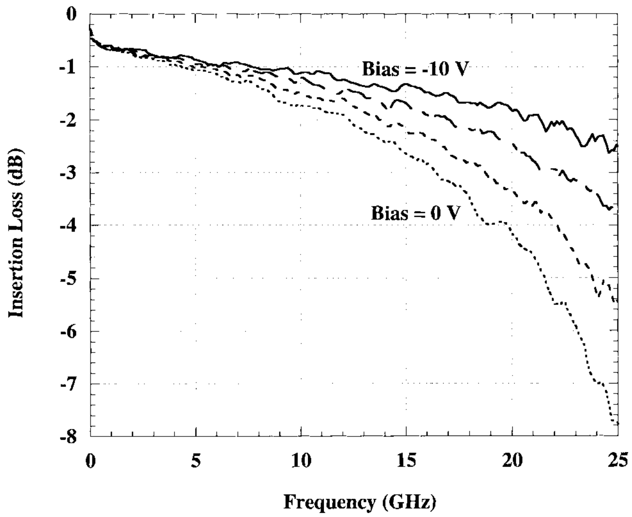

Fig. 3. Insertion loss versus frequency for selected values of varactor reverse bias.

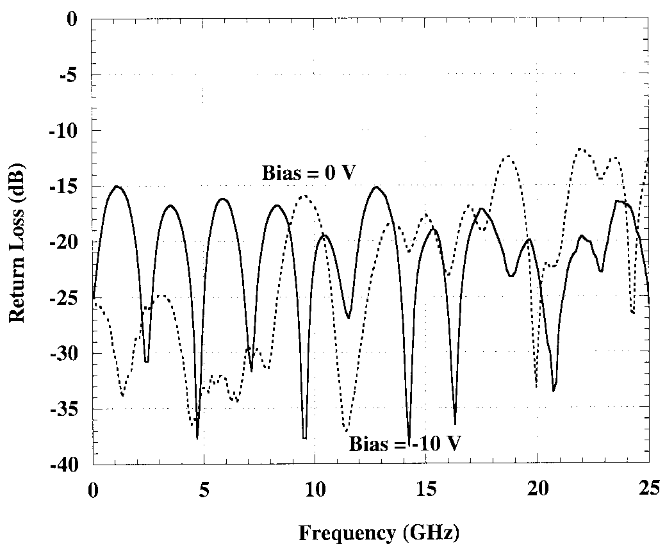

Fig. 4. Return loss versus frequency for bias voltages of 0 and −10 V. The curves for intermediate bias values lie between the two curves depicted here and have been suppressed for clarity.

thickness. The CPW and interconnect metal (1.8-μm-thick gold) was patterned using the lift-off technique. The wafer included several test structures to study the dc performance and the low-frequency (1 MHz) capacitance versus voltage characteristics of the Schottky diodes. It was determined that the Schottky diodes had an ideality factor of 1.05, reverse breakdown voltage of 15 V, series resistance of 4 Ω, and zero bias capacitance of 65 fF. The capacitance decreased by a factor of 2.4 (compared to the zero bias value) at a reverse bias of 10 V. Based on the diode parameters, the small-signal cutoff frequency was estimated to be ~700 GHz.

Microwave measurements were made on a HP 8510B network analyzer that was calibrated using on-wafer standards. Two-port s-parameters of the phase shifter circuit were recorded up to 20 GHz. Fig. 2. shows the differential phase shift as a function of frequency for several reverse bias values. As is expected for a variable velocity transmission line, the circuit produces a phase shift that varies linearly with frequency. The circuit is capable of continuous 0–360° phase shift at 20 GHz with any desired resolution. The maximum insertion loss at 20 GHz occurs at zero bias and is only 4.2 dB (see Fig. 3). Also, the circuit is well matched to 50 Ω and the return loss is less than −12 dB over all phase states, as shown in Fig. 4. The measured characteristics of the phase shifter compare well with the design specifications of 360° of phase shift with 4 dB of insertion loss at 20 GHz. This design can be adapted to any other frequency (below the Bragg frequency) by simple scaling laws. By going to a circuit with 50 sections it will be possible to obtain 0–360° phase shift at 10 GHz with only ~4-dB loss (extrapolated from data in Figs. 2 and 3).

IV. Conclusion

We have designed, fabricated, and tested a monolithic GaAs phase shifter based on varactor diode-loaded CPW lines. The phase shifter demonstrated continuous phase shift from 0 to 360° at 20 GHz with a maximum insertion loss of 4.2 dB, in good agreement with design specifications. To the best of our knowledge this is the lowest reported insertion loss for a continuously variable phase shifter at 20 GHz. The monolithic fabrication technique adopted here is compatible with commercial GaAs MMIC foundry processes leading to ease of manufacture and integration with existing GaAs products.

Acknowledgment

The authors would like to acknowledge Prof. M. J. W. Rodwell and his research group at the University of California at Santa Barbara for valuable discussions regarding the design and fabrication of GaAs varactor loaded transmission lines.

References

[1] M. J. W. Rodwell, S. T. Allen, R. Y. Yu, M. G. Case, U. Bhattacharya, M. Reddy, E. Carman, M. Kamegawa, Y. Konishi, J. Pusl, R. Pullela, and J. Esch, "Active and nonlinear wave propagation devices in ultrafast electronics and optoelectronics," *Proc. IEEE*, vol. 82, pp. 1035–1059, 1994.

[2] M. J. W. Rodwell, M. Kamegawa, R. Yu, M. Case, E. Carman, and K. S. Giboney, "GaAs nonlinear transmission lines for picosecond pulse generation and millimeter-wave sampling," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 1194–204, 1991.

[3] R. Y. Yu, M. Reddy, J. Pusl, S. T. Allen, M. Case, and M. J. W. Rodwell, "Millimeter-wave on-wafer waveform and network measurements using active probes," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 721–729, 1995.

[4] U. Bhattacharya, S. T. Allen, and M. J. W. Rodwell, "DC-725 GHz sampling circuits and subpicosecond nonlinear transmission lines using elevated coplanar waveguide," *IEEE Microwave Guided Wave Lett.*, vol. 5, pp. 50–52, 1995.

[5] R. P. Hsia, W. M. Zhang, C. W. Domier, and N. C. Luhmann, Jr., "A hybrid nonlinear delay line-based broad-band phased antenna array system," *IEEE Microwave Guided Wave Lett.*, vol. 8, pp. 182–184, 1998.

[6] W. M. Zhang, R. P. Hsia, C. Liang, G. Song, C. W. Domier, and N. C. Luhmann, Jr., "Novel low-loss delay line for broadband phased antenna array applications," *IEEE Microwave Guided Wave Lett.*, vol. 6, pp. 395–397, 1996.

[7] M. G. Case, "Nonlinear transmission lines for picosecond pulse, impulse and millimeter-wave harmonic generation," Ph.D. dissertation, Univ. California, Santa Barbara, 1993.