Millimeter-Wave Phase Shifters Utilizing Planar Integrated Schottky Barrier Diodes

Zhiyang Liu [1], Jason C. Midkiff [2] and Robert M. Weikle II [1]

[1]Department of Electrical and Computer Engineering, University of Virginia, Thornton Hall, 351 McCormick Road, PO Box 400743, Charlottesville, VA 22904-4743, U.S.A.
[2]Engineering Physics, School of Engineering and Applied Science, University of Virginia, Thornton Hall, 351 McCormick Road, PO Box 400238, Charlottesville, VA 22904-4238, U.S.A.

Abstract — **Two prototype phase shifters operating at 220 GHz and based on planar integrated Schottky barrier diodes have been designed, fabricated, and tested. A 180° reflection-coefficient phase shifter has demonstrated a measured phase shift of 184°±22° over the 216—221 GHz band with return loss no greater than 6 dB. A quadrature (90°) branchline-coupler phase shifter has given a measured phase shift of 85°±10° over the 219—225 GHz band with insertion loss no greater than 8.5 dB. The phase shifters presented in this work can be used as modulators for RF front-ends as well as for sideband generation.**

I. INTRODUCTION

Phase shifters are important components used as modulators in the RF front-ends of wireless communication systems based upon phase-shift-keying techniques. Quadrature (90°) shifters are especially useful for communication systems that utilize QPSK modulation schemes. 180° phase shifters are used for BPSK systems as well as sideband generation [1]. Phase shifters operating at millimeter and submillimeter wavelengths require switching devices capable of broadband performance and low insertion loss. GaAs Schottky barrier diodes are well-suited to these applications and have demonstrated state-of-the-art performance in phase-modulated sideband generators operating to 1.6 THz [1]. In this paper, two new prototype phase shifters are presented. These proof-of-concept circuits, which are designed to operate at 220 GHz, utilize planar GaAs Schottky barrier diodes as impedance switches. A 180° reflection-coefficient phase shifter for sideband generation and BPSK modulation is presented as well as a 90° (quadrature) branchline-coupler phase shifter.

II. BACKGROUND

A large variety of RF and microwave phase-shifters are based on semiconductor switching devices. Among the more common types are reflection-coefficient phase shifters (often used as sideband generators) [1, 2], switched-line phase-shifters, 3dB-hybrid phase shifters [2, 3, 4], loaded-line phase-shifters [5, 6] and switched-filter phase shifters [7]. The design of loaded-line or switched-filter phase shifters at millimeter-wave frequencies can be very challenging because their performance is strongly influenced by the parastics of the switching devices, which are notoriously difficult to model [5, 7]. For switched-line phase shifters, shunt capacitances associated with the switching devices degrade the isolation of the two paths — a problem that becomes more acute as the operating frequency approaches the millimeter-wave band. Barker has proposed and demonstrated a class of distributed phase shifters capable of operating up to 110 GHz with low loss (insertion loss estimated less than 2.6 dB) based on capacitive MEMS bridges [6]. However, the modulation speed of MEMS phase shifters is limited to approximately 10 kHz due to the mechanical parameters of the bridges [8].

Reflection-coefficient and 3dB-hybrid phase shifters are both based upon using diode switches to modulate the reflection or transmission coefficient presented to a carrier signal [2]. They have been studied for years and, because of the potentially fast switching speeds, offer a sound and attractive approach for frequencies approaching the submillimeter region. They are also attractive because they can be designed to operate over a relatively large bandwidth [4]. Their primary drawback, is the ohmic loss arising from diode series resistance. However, with proper attention to design, these losses can be mitigated to some extent or compensated for through the use of amplifiers (which are becoming more common in the 200—300 GHz range). This paper explores the design and performance of these types of phase shifters for the millimeter-wave band and focuses on two basic

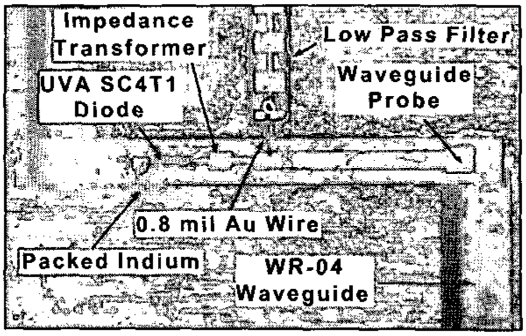

Fig. 1 Photograph of the reflection-coefficient phase shifter.

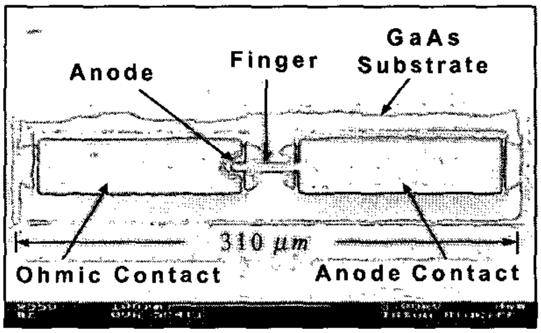

Fig. 2 Scanning electron micrograph of a UVA SC4T1 diode.

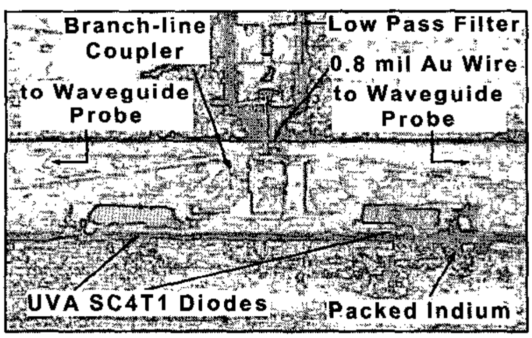

Fig. 3 Photograph of the branchline-coupler phase shifter.

approaches: (1) a reflection-coefficient phase shifter and (2) a branchline-coupler phase shifter.

III. DESIGN

A. Reflection-Coefficient Phase Shifter

Fig. 1 shows a photograph of the reflection-coefficient phase shifter investigated in this work. A WR-04 waveguide (dimensions of 21.5mil × 43mil and single-mode propagation over the 170—260 GHz band) is used as the transmission medium. The phase shifter consists of two microstrip circuits fabricated on quartz substrates. The primary circuit is composed of a waveguide probe, an impedance transformer, and a SC4T1 planar Schottky barrier diode fabricated at the University of Virginia (UVA). This circuit lies in a waveguide channel that is 19-mils wide and 110-mils long and is fabricated on a 5-mil-thick, 18-mil-wide quartz substrate. Electrically, the diode lies between ground (the waveguide block) and the impedance transformer. The transformer is designed to maximize the diode's impedance swing and achieve a phase shift of 180° in the reflection coefficient presented to the millimeter-wave carrier. The impedance transformer consists of two cascaded 90° microstrip lines of high impedance (Z_h=111 Ω) and low impedance (Z_l=65.7 Ω). The impedance seen looking into the transformer is given by:

$$Z_{in} = \left[\frac{Z_h}{Z_l}\right]^2 \cdot Z_d \qquad (1)$$

where Z_d is the impedance that the diode presents to the transformer. Equation (1) shows that the impedance transformer can significantly increase the impedance swing the diode presents to an incident millimeter-wave carrier.

The second microstrip circuit is a low pass filter that accommodates the diode's DC bias. A 10-mil-long 0.8-mil-diameter bonding wire is used to feed the DC bias to the diode. The microstrip circuits lie in waveguide channels perpendicular to one another as seen in Fig 1. The impedance that the diode presents to the incident 220 GHz carrier is varied with the applied DC bias. The channel for the low pass filter is 12-mils wide and 70-mils long. The UVA SC4T1 diode used as the switching element has an anode diameter of 5 μm, a series resistance of approximately 3 Ω, a zero-bias junction capacitance of 33 fF, and a junction capacitance of 17 fF when reversed bias to 10 V. Fig. 2 shows an SEM picture of the diode.

B. Branchline-Coupler Phase Shifter

Fig. 3 shows a photograph of the branchline-coupler phase shifter. Its circuit architecture is based on the well-known 3dB-hybrid phase-shifter described by White [2]. The same waveguide block is used as that shown in Fig. 1. This phase shifter also consists of two microstrip circuits lying in perpendicular channels and connected by a bonding wire. The primary microstrip circuit is composed of two (input and output) waveguide probes, a quadrature (branch-line) coupler and two UVA SC4T1 Schottky diodes. The diodes lie at the coupler's two output ports, as shown in Fig. 3. The second microstrip circuit, as with the reflection-coefficient phase shifter, is a low pass filter that accommodates the DC bias of the diodes.

Ansoft's HFSS[1] and Agilent's ADS[2] are used to model the passive part of the phase-shifter circuits. The diode junctions are modeled as two-port passive elements within HFSS. By adjusting the material parameters beneath the finger contacts from a conducting material (to represent the diode's "on"-state) to a lossless dielectric (to represent the diode's "off"-state) the two impedance states of the diode can be simulated. The s-parameter models generated by HFSS are imported into Agilent's ADS and the circuit parameters are optimized to minimize loss and maximize the operating bandwidth.

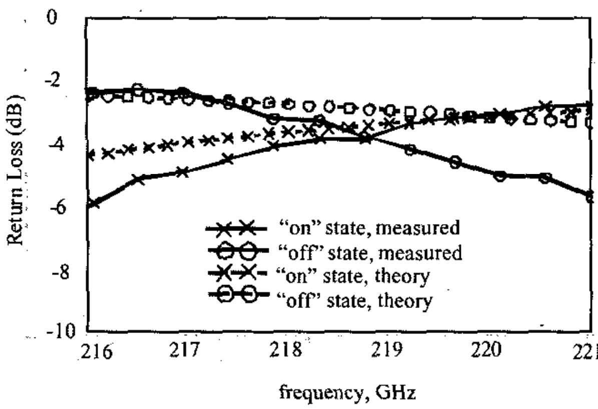

Fig. 4 Return loss vs. frequency for the reflection-coefficient phase shifter.

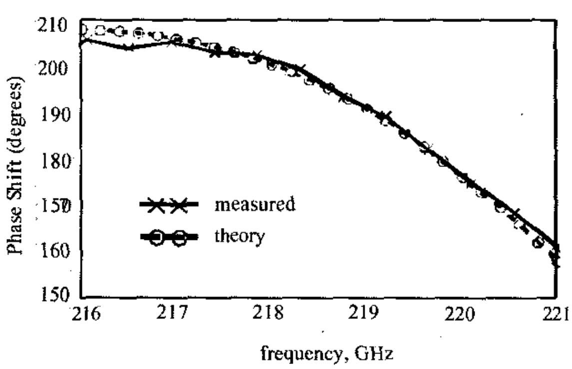

Fig. 5 Phase shift vs. frequency for the reflection-coefficient phase shifter.

IV. FABRICATION AND ASSEMBLY

The waveguide block was fabricated by Custom Microwave Inc.[3] as a split-block assembly. The microstrip circuits were fabricated in the Semiconductor Device Laboratory at the University of Virginia using a standard plating process that begins with the deposition of a gold seed layer by electron beam evaporation. The microstrip circuits are patterned with photoresist and gold is electrochemically plated to a thickness of 3μm through the patterned resist. The resist is stripped away and the excess seed layer is removed by a wet chemical etch. Finally, the circuits are diced to the desired dimensions.

The diodes are mounted onto the quartz circuits using indium solder. The final circuits are then bonded to the waveguide block using a UV-cured optical adhesive.

V. MEASUREMENTS

The phase shifters are characterized using an HP8510C vector network analyzer with millimeter wave VNA extensions manufactured by Oleson Microwave Labs[4].

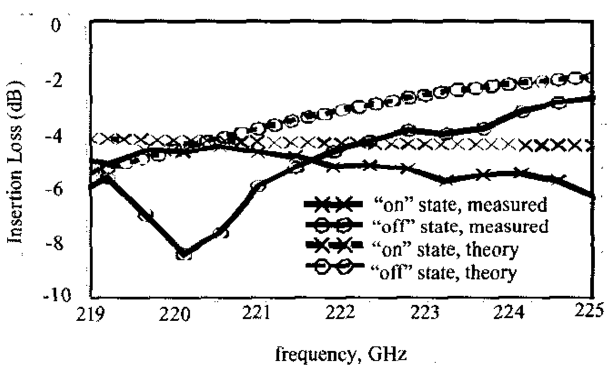

Fig. 6 Insertion loss vs. frequency for the branchline-coupler phase shifter.

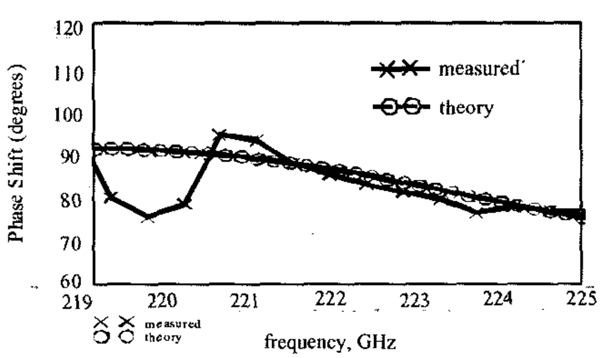

Fig. 7 Phase shift vs. frequency for the branchline-coupler phase shifter.

Figures 4 and 5 show the return loss and phase shift of the 180° reflection-coefficient phase shifter. The measured return loss does not exceed 6 dB over the frequency range 216—221 GHz. Over this range, the phase shift is 184°±22°. Two of the major factors contributing to loss are the diode junction resistance (which is responsible for approximately 2.5 dB of loss) and ohmic loss of the microstrip transmission lines (which contributes approximately 1.9 dB of loss). Another factor that contributes to the return loss is the conductivity associated with the indium solder. This quantity, however, is difficult to quantify.

Figures 6 and 7 show the insertion loss and phase shift performance of the branchline-coupler phase shifter. The measured insertion loss is less than 8.5 dB and the phase shift is 85°±10° over the frequency range 218—226 GHz. In this case, the phase shifter operates near resonance to yield the desired phase shift. However, the resonance also gives rise to significant loss as power is dissipated in the diodes series resistance (estimated to be approximately 2.5—4.5 dB from circuit simulations). Port mismatches and microstrip losses also contribute to the insertion loss.

The bandwidth for both phase-shifters is limited primarily by the diodes' relatively small capacitance swing, which necessitates the use of narrow-banded tuning circuitry for the diodes. The discrepancies between measurement and theory can be attributed primarily to uncertainties associated with manual assembly of the circuit, including the bonding wire length and diode alignment.

VI. SUMMARY

Two prototype millimeter-wave phase shifters operating at 220 GHz and utilizing Schottky barrier diodes as switching devices have been presented in this paper. The measured performance of these circuits is in good agreement with that predicted from theory. The major contributor to circuit loss is the diodes' series resistances. In addition, the operating bandwidth of the phase-shifters is limited by the diodes' relatively small capacitance swing. Improved performance in terms of loss and bandwidth can be achieved by designing devices that have a larger capacitance modulation ratio and reduced parasitics. This can be achieved, to a large extent, by fully integrating the devices with the microstrip circuits during the device fabrication process. Furthermore, such an approach will eliminate variations due to alignment and mounting, thereby improving the performance of these circuits.

ACKNOWLEDGEMENT

The authors would like to thank T.W. Crowe and W.L. Bishop for providing Schottky barrier planar diodes. This work was supported by the National Science Foundation through grant ECS 9979357 and the Virginia Center for Innovative Technology through grant INF-01-016.

REFERENCES

[1] D.S. Kurtz, J.L. Hesler, T.W. Crowe, R.M. Weikle, II "Submillimeter-wave sideband generation using varactor Schottky diodes," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-50, no. 11, pp. 2610—2617, Nov. 2002.

[2] J.F. White, "Diode phase shifters for array antennas," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, no. 6, pp. 658—674, June 1974.

[3] J.P. Starski, "Optimization of the matching network for a hybrid coupler phase shifter," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, no. 8, pp. 662—666, Aug. 1977.

[4] K. Miyaguchi, *et al.*, "An ultra-broadband reflection-type phase-shifter MMIC with series and parallel LC circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-49, no. 12, pp. 2446—2452, Dec. 2001.

[5] I.J. Bahl and K.C. Gupta, "Design of loaded-line p-i-n diode phase shifter circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, no. 3, pp. 219—224, March 1990.

[6] N.S. Barker and G.M. Rebeiz, "Optimization of distributed MEMS transmission-line phase shifters---U-band and W-band designs," *IEEE Trans. Microwave Theory Tech.*, vol. 48, no. 11, Nov. 2000

[7] H. Takasu, S. Kamihashi, H. Tokuda, M. Tanaka, and Y. Hase "K-Band GaAs MMIC phase shifter using self-switched filter circuits," *IEEE International Symposium on Phased Array Systems and Technology*, 1996.

[8] N.S. Barker and G.M. Rebeiz, "Distributed MEMS transmission-line BPSK modulator," *IEEE Microwave Guided Wave Lett.*, vol. 10, no. 5, pp. 198—200, May 2000.

[1]Ansoft Corporation, Inc., Pittsburgh, PA. [Online] Available: http://www.ansoft.com

[2]Agilent Corporation, Inc., Palo Alto, CA. [Online] Available: http://www.agilent.com

[3]Custom Microwave, Inc., Longmont, CO. [Online] Available: http://www.custommicrowave.com

[4]Oleson Microwave Labs, Morgan Hill, CA. [Online] Available: http://www.olesonmicrowave.com