MONOLITHIC MILLIMETER-WAVE BEAM CONTROL ARRAY

Xiaohui Qin, W-M. Zhang, C.W. Domier, and N.C. Luhmann, Jr.
Dept. of Applied Science, University of California, Davis, California

W. Berk, S. Duncan and D.W. Tu
Martin Marietta Laboratories, Baltimore, Maryland

ABSTRACT

A high performance V-band beam control array has been designed, developed and demonstrated. A transmission switch with 24 dB ON/OFF ratio for a single grid and 42 dB ON/OFF ratio (4 dB minimum loss) at ~62 GHz for a grid pair has been experimentally demonstrated. A 130° reflection phase shift with ~2.7 dB loss at 60 GHz for a single grid has been successfully obtained.

INTRODUCTION

Construction of complete millimeter-wave systems requires not only sources, but also control components for such functions as amplitude modulation, phase modulation, and beam steering or scanning. Beam scanners have use in millimeter-wave imaging applications, while beam amplitude controllers can be employed as light weight, high-speed (≈100 ps switching times) modulators for use in radiometers or in pulsed radar systems. The power combination of thousands of individual Schottky varactor diodes greatly increases the power handling capability.

Electronically-controlled beam phase shift arrays were first fabricated and demonstrated by W. Lam with 70° phase shift with 6.5 dB loss in reflection,[1] and later by L.B. Sjogren with a usable "flat amplitude" phase shift of 70° with a measured insertion loss of 3.5 dB of the reflected beam. Electronically controlled beam control arrays for use at D-band (110-170 GHz) have demonstrated amplitude modulation of the transmitted beam at 165 GHz by L.B. Sjogren.[2] It is required to have low loss, large phase range and contrast ratio for practical applications. To expand the phase range to 360°, a quasi-optical version of a method used in microwave circuits was suggested [3, 4], in which two such arrays were stacked together.

DESIGN, DEVELOPMENT AND RESULTS

A low loss transmission switch and large reflection phase shifter array, consisting of thousands of Schottky varactor diodes, has been designed at 60 GHz. The capacitance-voltage (C-V) variation of varactor diodes allows the array to function as an electrically controlled phase shifter, amplitude modulator, beam focusser / defocusser, and beam steerer, etc. in either the reflection or transmission mode. The primary goal for the device profile is to provide a suitable C-V characteristic with a minimum of conduction current and a large capacitance variation range over the useful bias voltage range. The varactor diode consists of Au/Ti as the Schottky contact, a 0.7 μm thick, 6.0×10^{16} cm^{-3} doped n type epi-layer and a 2.5 μm thick, 6×10^{18} cm^{-3} heavily doped n^+ type epi-layer. Four beam control arrays have been fabricated at Martin Marietta Laboratories on 3" GaAs substrates. The measured C_{max} value is ~80 fF, C_{min} is ~10 fF, and $C_{parasitic}$ is ~8 fF for the 8 μm diameter diodes. The typical breakdown voltage is ~12 V. Figure 1 illustrates the typical parameter spread of the C-V characteristics for Schottky varactor diodes over an entire beam control array.

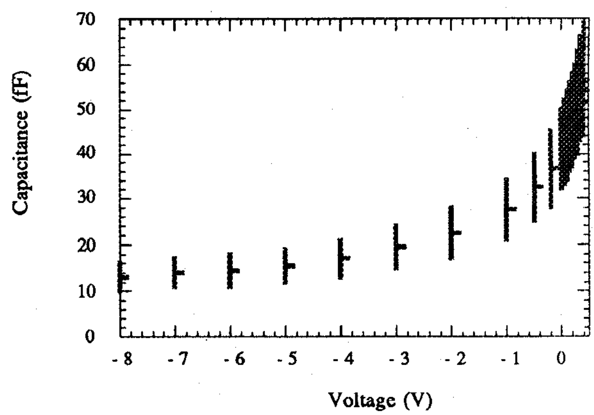

Fig. 1 Typical C-V characteristic spread of Schottky varactor diodes over an entire beam control array.

Simulations have demonstrated that for a stacked pair of varactor grids, large reflected beam phase range and transmitted beam amplitude ON/OFF contrast ratio

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can be achieved at the design frequency due to the composite effect of the two grids. Numerous simulations have been performed to optimize the grid structure for high performance of the reflection phase shifter, beam steerer and transmission amplitude switch at the design frequency of 60 GHz. A unit cell size of 900x360 μm^2 with a vertical strip width of 150 μm is found to represent the optimum grid design.

Simulations employing the measured low frequency characterizations of the diodes demonstrate an ON/OFF contrast ratio of ~48 dB (2.4 dB minimum insertion loss), and a reflection phase range of 360° phase range may be achieved with an insertion loss of 5 dB over the entire phase range at 60 GHz. Experimental results agree well with the predictions.

Millimeter wave beam amplitude switching in both the transmission and reflection mode has been demonstrated with the overmoded waveguide measurement system shown in Fig. 2. The beam is launched onto the array with dual waveguide transitions from V-Ka and Ka-X bands, the transmitted beam is received by another dual waveguide transition set and detected by a calibrated V-band diode detector. A single array has been tested in the system, demonstrating an ON/OFF ratio of 24 dB for single grid at 62 GHz, (minimum insertion loss: 2 dB). (see Fig. 3)

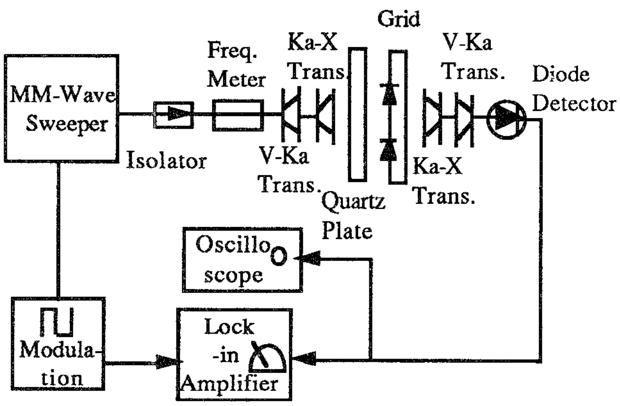

Fig. 2 Transmitted beam amplitude modulation system using overmoded waveguide approach.

To further increase the measurement dynamic range of the system, a heterodyne detection system is utilized, (see Fig. 4), where two sources with a slight difference in frequency are employed as LO source and RF source to generate a reference IF and a transmitted IF signal. A measured ON/OFF ratio of 42 dB is obtained, (minimum loss: 4 dB) for a stacked grid pair, and a bandwidth of ~6 GHz, with an average contrast ratio of 30 dB. (see Fig. 5)

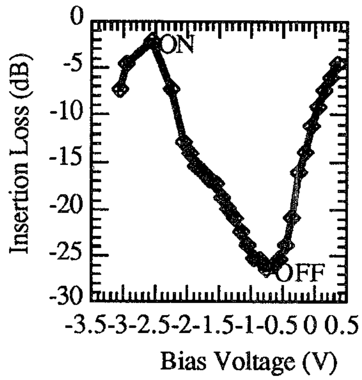

Fig. 3 Transmission switch for single grid at 62 GHz, ON/OFF ratio of 24 dB, and a minimum insertion loss of 2 dB.

A reflected beam phase shift of ~130 ° has been experimentally obtained by using the heterodyne detection system shown in Fig. 4 (where the receiving dual transitions are replaced with a mirror and the directional coupler for transmitted signal is inserted in front of the input dual transitions for reflected signal from the grids), with an average reflection loss of 2.7 dB for a single grid. (as shown in Fig. 6) The predicted reflected beam phase shift is ~180° with an insertion loss of 1.5 dB. (as shown in Fig. 6. Reflected beam amplitude switching with a ON/OFF ratio of 22 dB has been demonstrated.(see Fig. 7))

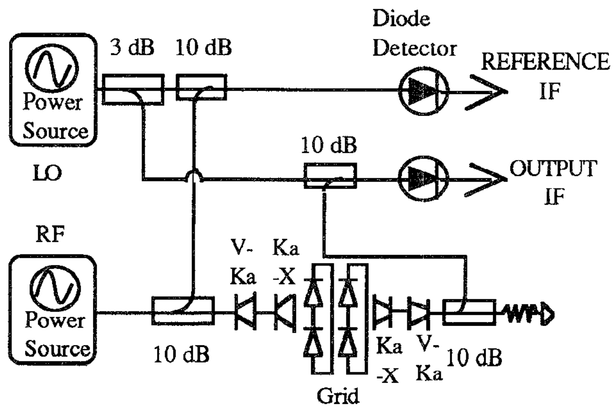

Fig. 4 Heterodyne detection system for large dynamic range amplitude modulation in the transmission mode.

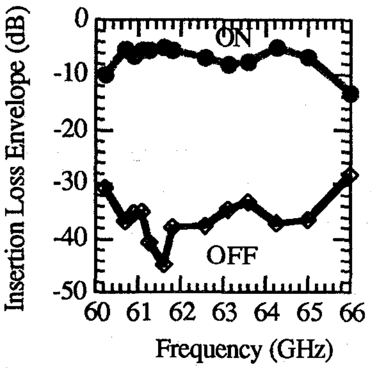

Fig. 5 Transmission switch for stacked grid pair, ON/OFF ratio of 42 dB, with a minimum loss of 4 dB.

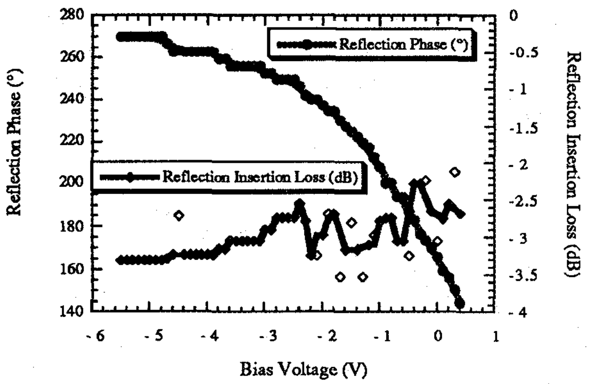

Fig. 6 Measured reflected phase shift and insertion loss as functions of bias voltage across each row of beam control array at V-Band.

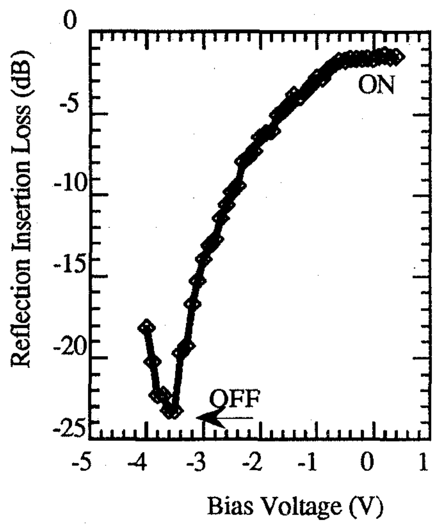

Fig. 7 Measured reflected beam amplitude switch with ON/OFF ratio of 22 dB (minimum loss: 1.8 dB).

Reflection measurements of single grid and two grid configurations, including reflected phase shifting, beam amplitude modulation as well as transmission measurements using both single and two grid pair configuration, including transmitted beam switching and modulation have been demonstrated successfully. All the above testing utilizes a computer controlled system with biasing controlled by an IBM PC computer through 128 channels of D/A converters for optimization of the bias voltage across the grids to maximize the On/Off contrast ratio for the switching and the phase range of the reflected phase shifter with minimum insertion loss envelope. Dual transitions from V-Band to X-Band overmoded waveguides have been used to test the transmission switch array, 1.5 dB waveguide losses have been detected. The signal transmitted through the system including the 5.8 mm airgap between X-band flanges is employed as the reference (down 0.8 dB from no gap). A quasi-optical measurement system has been used for the transmission switch.

Recently, a more accurate diode grid circuit model utilizing the HP HFSS simulation tool has been developed, which includes parasitic effects from the specific varactor diode layout structure and the shape of the beam control grid. Simulations predict that a stacked grid pair can provide a reflection phase shift of 360° with a constant insertion loss of ~5 dB when the grid pair is non-identically biased. Figure 8 shows the comparison of the predicted reflection phase shift as a function of insertion loss when a grid pair is non-identically biased, using the HFSS model and using the Method of Moment (MOM) model.

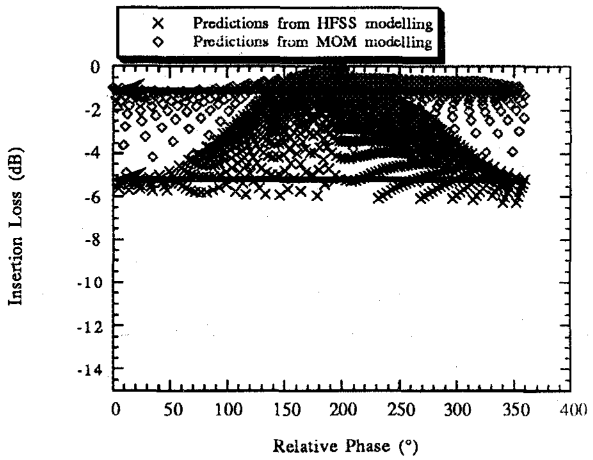

Fig. 8 Simulation results of reflected beam with non-identical of the beam control grid pair.

CONCLUSION

High performance 60 GHz two-grid Schottky varactor beam control arrays (including transmission beam modulators and switches, and reflection beam phase shifters) have been designed, fabricated and successfully demonstrated. A V-band transmission switch of 24 dB ON/OFF contrast ratio has been achieved with a single grid, and 42 dB contrast ratio with a grid pair in transmission. ~2.7 dB constant insertion loss, and 130 ° reflection phase shift has been demonstrated with a single grid. Table 1 illustrates the significant improvement on beam control performance over the previous experimental results. 360° phase shift can be theoretically achieved by biasing the two grids non identically.

	Transmission Switch	Reflection Phase Shifter
Monolithic Beam Control (W. Lam)	N/A	70° phase shift, 6.5 dB reflection loss
Monolithic Beam Control (L.B. Sjogren)	7 dB ON/OFF ratio, 1.5 dB minimum loss	70° phase shift, 3.5 dB reflection loss
Monolithic Beam Control (X. Qin)	24 dB ON/OFF ratio, 2 dB minimum loss (single grid) 42 dB ON/OFF ratio, 4 dB minimum loss (grid pair)	130° phase shift, 2.7 dB reflection loss

Table 1. Comparison of beam control performance from the experimental results on monolithic Schottky varactor diode arrays.

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