MONOLITHIC MILLIMETER WAVE BEAM CONTROL GRID

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[ABSTRACT]

Monolithic integrated diode grid beam controllers can perform beam steering/focusing, switching and phase/amplitude modulation functions at relatively high power levels. Wide angle reflection beam steerer arrays have been designed for use at 60 GHz. In our design, a stacked grid pair with an optimum unit cell size is predicted to provide an ~360° phase range with a constant insertion loss of ~1.5 dB (average loss of 1.0 dB) in the reflection mode when a back reflector is employed. Such a stacked grid pair can function as a beam focuser and modulator as well as a beam switch (45 dB contrast ratio at 60 GHz and a minimum loss of 0.5 dB).

[INTRODUCTION]

Numerous application areas of current interest require electronic systems operating in the millimeter and submillimeter-wave frequency regime. Examples of such applications include fusion plasma diagnostics, radar (including automobile collision-avoidance radar), communications and imaging [1,2]. Both transmitters and receivers are required, with high speed electronic scanning capabilities highly desirable. A diode grid phase shifter has been successfully fabricated by W. Lam [3,4], with a measured 70° phase shift with 6.5 dB loss, at 93 GHz. To expand the phase range to 360°, a quasi-optical version of a method used in microwave circuits was suggested [5,6], in which two such arrays were stacked together. Electronically-controlled beam control arrays for use at D-band (110-170 GHz) have been built and have demonstrated amplitude modulation of the transmitted beam at 165 GHz. This was not designed for high switching speed but still resulted in a measured modulation response which was flat up to 50 MHz, with a 3 dB point of ≈ 150 MHz. The transmittance control is over the range of 20% to 50% at 99 GHz, and 20% to 70% at 165 GHz. A usable "flat amplitude" phase shift of 70° has been observed with a measured insertion loss of 3.5 dB of the reflected beam. Limited beam steering and beam focusing/defocusing has also been experimentally demonstrated at 120 GHz [7]. In addition, a high speed transmission beam switch array has been designed and built employing a coplanar waveguide bias arrangement, resulting in 300 MHz switching speed at V band and D band [8]. Finally, an initial demonstration of Schottky photodiode transmitted beam controller has been successfully performed albeit with furthur work required to produce the low loss, large phase range and contrast ratio necessary for practical applications. [9] The above experimental results were in good agreement with theoretical predictions, thereby motivating the current work where high performance beam control arrays have been designed, and fabricated with testing underway. These are predicted to provide the performance parameters required for actual applications.

Figure 1. illustrates a section of an array fabricated in these studies. The two dimensional periodic grids loaded with Schottky varactor diodes comprise a surface whose reactance is controlled by the bias imposed on the individual diodes. In transmission, the changing reactance with bias allows the amplitude of the transmitted wave to be electronically modulated. In reflection, the changing reactance with bias controls the phase of the reflected wave such that a uniform variation of the phase across the grid performs phase shift, a linear variation sets the direction of the reflected beam and a quadratic variation of the phase focuses the reflected beam.

[DESIGNS AND DISCUSSIONS]

A monolithic millimeter wave beam control array consists of thousands of Schottky varactor diodes (shown partly in Fig. 1). The capacitance of the varactor changes with the applied bias voltage, resulting in an associated change in the varactor grid reactance. This capacitance-voltage (C-V) variation allows the array to function as an electrically or optically controlled phase shifter, amplitude modulator, beam focuser/defocuser, and beam steerer, etc. in either the reflection or transmission mode.

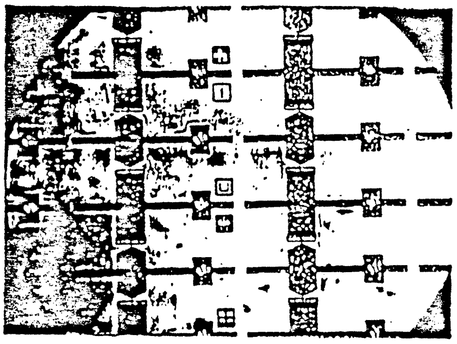


Figure 1. Photograph of a section of an array fabricated at Martin Marietta Laboratories, (Baltimore.)

Four beam control arrays have been fabricated on 3" diameter GaAs substrates. 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/Pt 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. 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. Simulations show that a low loss transmission switch and wide angle reflection beam steerer can be achieved with a stacked grid pair of such diodes in an optimum grid structure design. The grid is a two dimensional periodic grid loaded with Schottky varactor diodes. The symmetry of the grid imposes boundary conditions, which define a unit cell as shown in Fig. 2. This reduces the problem of analyzing the grid to that of analyzing an equivalent waveguide. The equivalent waveguide has electric walls on the top and bottom, and magnetic walls on the sides, which extend along the z axis. The varactor resides in the z=0 plane. An accurate solution has been obtained by L.B. Sjogren [10] by segmenting the current and applying the method of moments to construct an equivalent circuit model of the

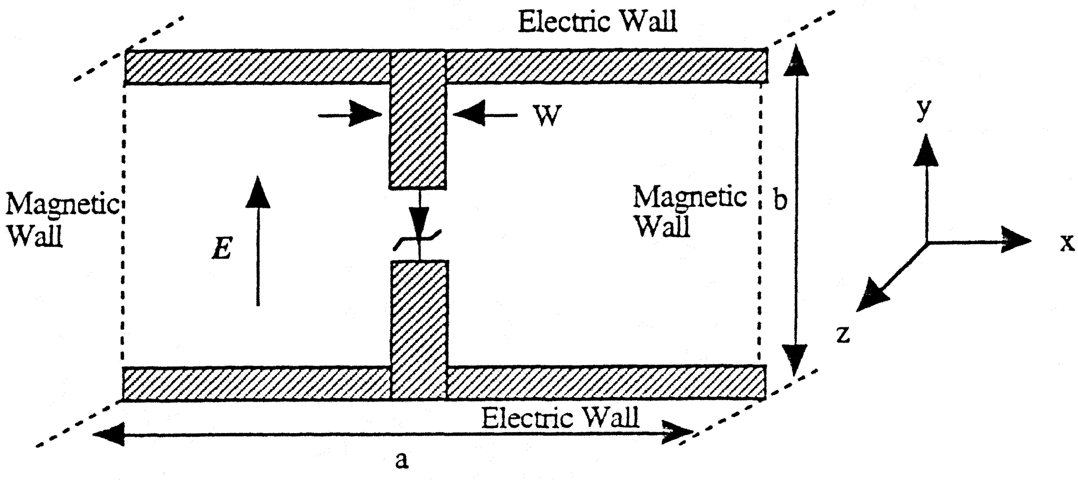


Fig. 2 Illustration of the unit cell of the beam control grid (*E* field and current are oriented parallel to the vertical diode embedding strip.

unit cell as shown in Fig. 3. The horizontal leads are bias lines, and the vertical lines serve as antennas. The equivalent impedance of the grid is represented by Z_g.

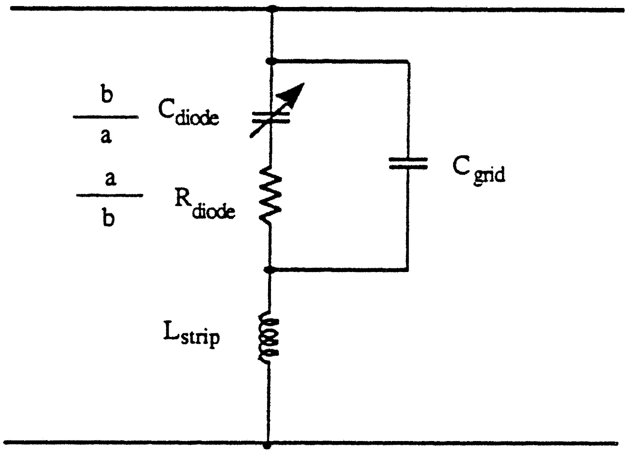


Fig. 3. An equivalent circuit model of the unit cell of beam control grid

The basic operation of the array can be explained by the quasi-optical plane wave approximation. A millimeter-wave beam incident upon the array is modeled as a TEM wave propagating on a transmission line representing the medium through which the beam is propagating. Simulations have demonstrated that for a stacked pair of varactor grids, large reflected beam phase range and transmitted beam amplitude On/Off contrast ratio can be achieved at the design frequency due to the composite effect of the two grids.[4] Figures 4 and 5 illustrate the stacked configuration for reflected and transmitted beam control. Ssimulations 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. A stacked grid pair of such structures provides a large phase range of ~320 ° at ~61 GHz with a maximum insertion loss of 3.5 dB.

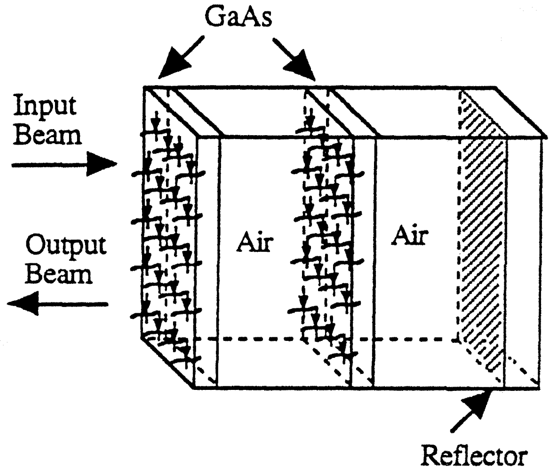


Fig. 4 Stack configuration for reflected beam control

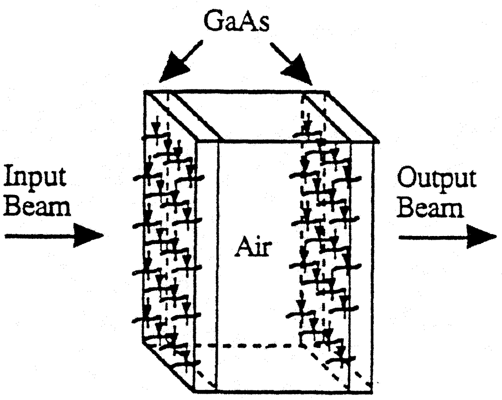


Fig. 5 Stack configuration for transmitted beam control

This grid pair configuration will also serve as a good transmission switch with a contrast ratio of ~45 dB (the contrast ratio is defined as the ratio of the transmitted power in the ON state to the transmitted power in the OFF state). The minimum insertion loss is ~3 dB at 60 GHz and ~0.5 dB at 45 GHz. The present dc bias arrangement is predicted to result in a switching speed of ~100 MHz. For fast switching application, coplanar waveguide bias lines will be employed. Here, it is projected that switching speeds as fast as several hundred picoseconds may be obtained. Automated low frequency characterization has been performed, using a computer controlled measurement system. Figure 6 illustrates the I-V mapping of the varactor diodes contained in a small section of the array. All diodes have been mapped and all detected shorted diodes have been removed from the arrays.

The typical measured diode breakdown voltage is ~ 10 V. Typical C-V characteristics are shown in Fig. 7, together with the envelope (spread) in parameters.

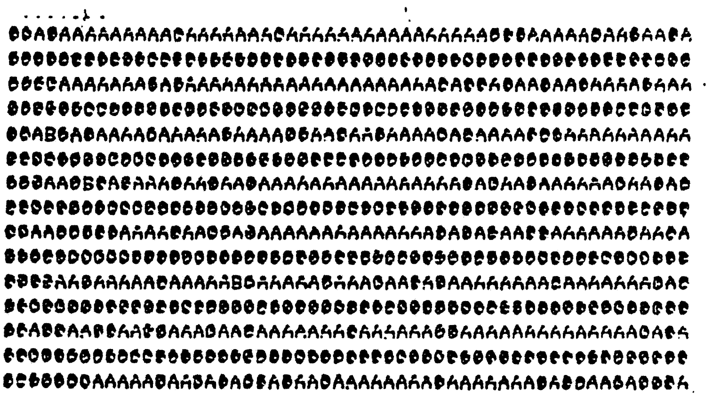


Fig. 6 I-V map of an array section 47 mm X 5.4 mm, (810 elements), where "@,A,B,C,D,*" represent different diode breakdown voltages.

Simulation results employing the measured low frequency and dc parameters of the diodes are illustrated in Figs. 8, 9(a) & 9(b). An ON/OFF contrast ratio of ~50 dB is predicted when the array serves as an transmission switch at 60 GHz. A reflection phase range of ~330° with a maximum insertion loss of ~3 dB (average loss of ~2.5 dB) is predicted at ~60 GHz.

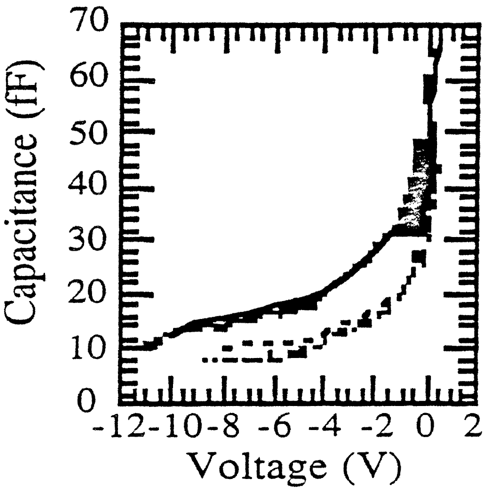


Fig. 7 Typical C-V Characteristics.

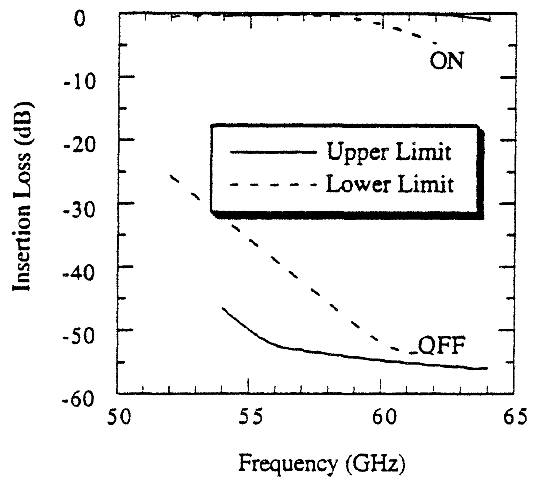
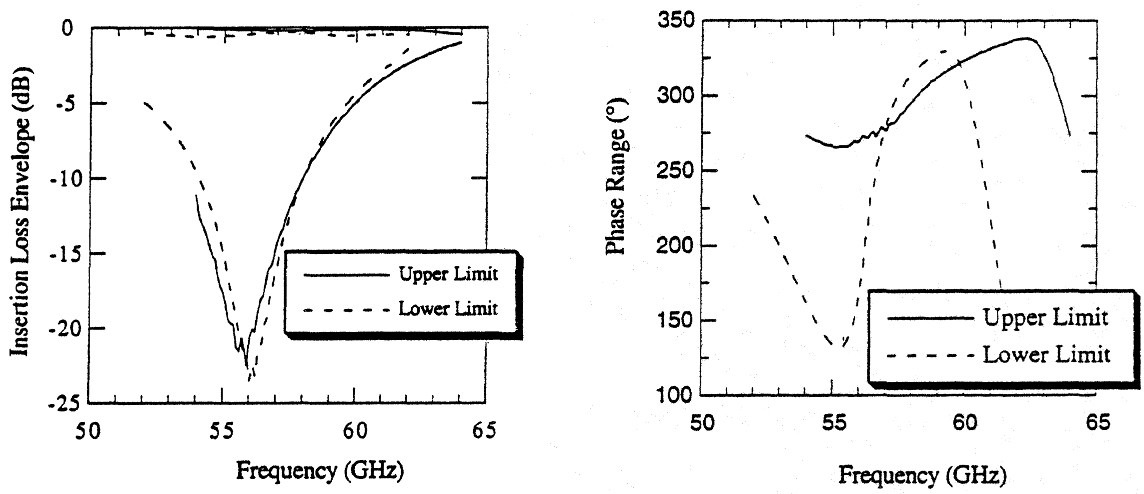


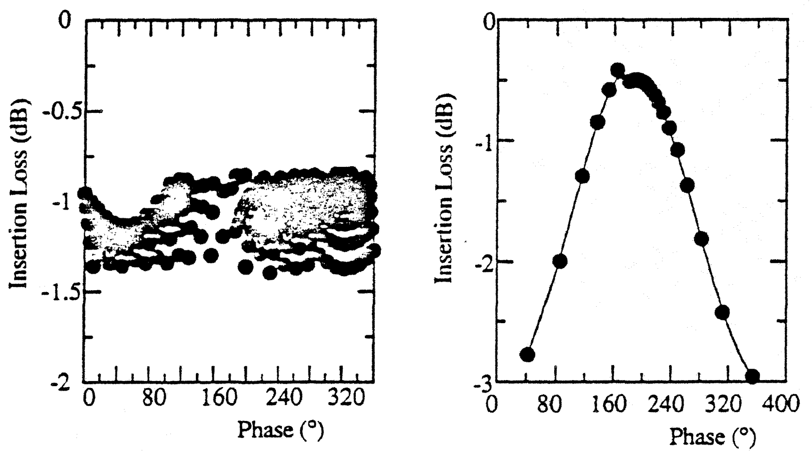
Fig. 8 Insertion Loss Envelope of Transmitted Beam.



(a) (b)

Fig. 9 (a) Insertion Loss Envelope, (b) Phase Range of Reflected Beam.

By non-identically biasing the two grids, a full 360° is predicted with a flat insertion loss of 1.5 dB. (see Figs. 10 (a) & (b))



(a) (b)

Fig. 10 Simulation results of reflected beam with non-identical (a) and identical bias (b) of the beam control grid pair

[MILLIMETER WAVE TESTING]

Reflection measurements of single grid and two grid configurations, including reflected phase shifting, beam steering, beam focusing/defocusing and frequency shifting are underway. Transmission measurements of single and two grid configurations, including transmitted beam switching and modulation are also being performed currently. All the above testing utilizes a computer controlled system. The biasing is also controlled by an IBM PC computer through 64 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. The millimeter wave steering testing will be performed with a 6-axis computer controlled arm with control over the desired beam direction obtained by varying the bias across the grids linearly. Antenna patterns for the steered beam can be measured with the arm. Overmoded waveguide may be used to test the transmitted power for amplitude modulators. [8]

High performance 60 GHz two-grid Schottky varactor beam control arrays (including reflection beam phase shifters, steerers, transmission beam modulators and switches) have been designed. 3-4 dB insertion loss, 330° phase shift, 45 dB contrast ratio have been predicted by identically biasing the two grids pair. ~1.5 dB constant insertion loss, 360° phase shift can be theoretically achieved by biasing the two grids pair nonidentically. Millimeter wave testing in reflection/transmission modes are underway.

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