MONOLITHIC MILLIMETER-WAVE DIODE ARRAY BEAM CONTROLLERS: THEORY AND EXPERIMENT

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I. Introduction

Power-combining arrays of semiconductor devices offer a promising approach to the realization of compact, reliable, economical systems for watt-level operation at millimeter-wave and submillimeter-wave frequencies. Such ("grid") arrays have demonstrated numerous functions at microwave and millimeter-wave frequencies in recent experimental efforts. Monolithic diode arrays have demonstrated phase shifting at 93 GHz [1], frequency doubling from 33 to 66 GHz [2] and frequency tripling from 33 to 99 GHz [3]. One dimensional monolithic imaging arrays have been demonstrated at 94 GHz [4]. Additional quasi-optical functions have been demonstrated at microwave frequencies by arrays employing hybrid technology. These include the oscillator grid [5-6], mixer grid [7], and amplifier grid [8]. The hybrid grids operate on the same basic quasi-optical principle as the monolithic arrays, so the functions demonstrated to-date in hybrid form should be feasible also in a monolithically integrated form at millimeter-wave frequencies. Additional array design approaches have been suggested for further development of millimeter-wave components [9].

Construction of complete systems based on the millimeter-wave array technology requires not only source and detector arrays, but control components for such functions as amplitude modulation, phase modulation, and beam steering. The first effort at addressing this need by a semiconductor device array was an experimental demonstration of a phase shifter at 93 GHz [1]. In this work, phase control of a reflected beam over a range of 70 degrees with 6.5 dB loss was achieved by a monolithic array of Schottky diodes. The stacking of more than one array [1] should allow a phase range of greater than 360 degrees to be achieved. Operated in a nonuniform phase (bias) mode, such an array should be capable of (phased array) beam steering and beam focusing.

In the current work, multi-function beam control arrays have been fabricated, and have successfully demonstrated amplitude control of transmitted beams in the W and D bands (75-170 GHz). While these arrays are designed to provide beam control under DC bias operation, new designs for high-speed electronic and optical control are under development. These arrays will fill a need for high-speed watt-level beam switches in pulsed reflectometer systems under development for magnetic fusion plasma diagnostics.

A second experimental accomplishment of the current work is the demonstration in the 110-170 GHz (D band) frequency range of a new technique for the measurement of the transmission phase as well as amplitude [11]. Transmission data can serve as a means to extract ("de-embed") the grid parameters; phase information provides more complete data to assist in this process.

Additional functions of the array beam controller yet to be tested include electronically controlled steering and focusing of a reflected beam. These have application in the areas of millimeter-wave electronic scanning radar and reflectometry, respectively.

II. Theory and Design

The beam control device consists of a monolithic two-dimensional array of varactor diodes embedded in metal strips. Its quasi-optical behavior is represented by a shunt impedance across a transmission-line representation of the beam. The impedance is that of a series RLC circuit. The inductance, some fixed (undesired bias-independent) capacitance, and a small resistance are due to the metalization grid structure; the bulk of the capacitance is due to the diode; the bulk of the (undesired) resistance is a parasitic effect of the diode and its Ohmic contact.

The initial objective of the current effort was the design of the proposed stacked 360 degree reflection phase shifter array [1]. In this approach, an effective load reactance of arbitrary value is obtained by the use of two diode grids, each of which possesses a reactance range of at least $-Z_{GaAs}$ to Z_{GaAs}, where Z_{GaAs} is the plane wave impedance of Gallium Arsenide (approximately 105 Ω), and the grids are separated by an odd multiple of $\lambda/4$.

The capability of the array to control beam transmittance is based on its ability to be switched, under bias control, between a low and high impedance state. When the array is biased at resonance, it appears to the beam as nearly a short circuit, and reflects most of the beam back. When the array is biased far from resonance (i.e. at high impedance), the beam is affected very little by it. In this case, the beam transmittance is large.

The dimensions and doping profile for the monolithic Gallium Arsenide Schottky varactor diode were determined with the assistance of a finite difference solution program for Poisson's equation in one dimension. This provided an estimate of the diode C-V characteristics. Additional routines were employed to estimate tunneling, avalanche, and thermionic emission currents. A hyperabrupt doping profile, similar to that employed by W. Lam [1], was chosen to provide linearity of reflection phase versus DC bias. Different doping levels were simulated to optimize the capacitance range and breakdown voltage. A heterojunction barrier, pioneered at JPL for frequency multiplier diodes, has been incorporated to suppress tunneling current under reverse bias and thermionic emission under forward bias. The experimental results in this paper were obtained with arrays fabricated from MBE wafers with the profile shown in Fig. 1.

Design of the array requires the theoretical prediction of the electromagnetic (grid) behavior as well as the C-V characteristics of the embedded varactor diode. For the passive (electromagnetic) design, a simple method of moments analysis has been employed. This has provided a new model which includes the effect of the discontinuity of the current at the site of the diode ("grid capacitance")[12] (Fig. 2). This model somewhat underestimates the fixed (bias-independent) capacitance at the diode site, since it idealizes the current discontinuity as that for a "gap" at the diode site when the diode is (analytically) open circuited. Even so, the capacitive effect was found to be considerable (5-10 fF for typical array geometries at 100 GHz), and sufficient to reduce the simulated phase range of the stacked phase shifter from well above 360 degrees (with the "grid capacitance" not included) to a value considerably below 360 degrees (with it included). A rigorous simulation of the C-V characteristics of the grid would require a three dimensional simulation which includes the effect of the anode "finger", absence of dielectric beyond the etched walls of the diode, etc. A more precise determination of the grid inductance should be possible with the Hewlett Packard High Frequency Structure Simulator electromagentic analysis program. Such an analysis may provide a more precise estimate of the grid capacitance.

The grid impedance model and diode model programs were combined and incorporated into a quasi-optical (transmission line) circuit analysis program based on the application of Kirchoff's laws at the dielectric (and grid) interfaces. Simulations were performed to determine unit cell and strip dimensions which maximized the grid impedance range. The grid capacitance effect was suppressed by use of a "rectangular unit cell", in which diodes are effectively placed "in series" by spacing them closer along the axis of current flow. Such a configuration has the additional benefits of allowing use of a large (easier to reliably fabricate) diode and providing significantly higher power-handling capability. The one drawback of this design is a somewhat higher loss, since the effective diode resistance is a/b times the actual diode resistance. The increased size of the diode will partially, but not completely, offset this effect. A possible alternative for the reduction of grid capacitance is to employ a narrower metal strip in the vicinity of the diode [13]. This was not feasible for the current design, since the strip was too narrow to taper.

The simulations provided the optimized unit cell dimensions a=300 μm, b=120 μm, and w=7 μm, with diode dimensions of 3 μm x 13 μm. The diode area assumed

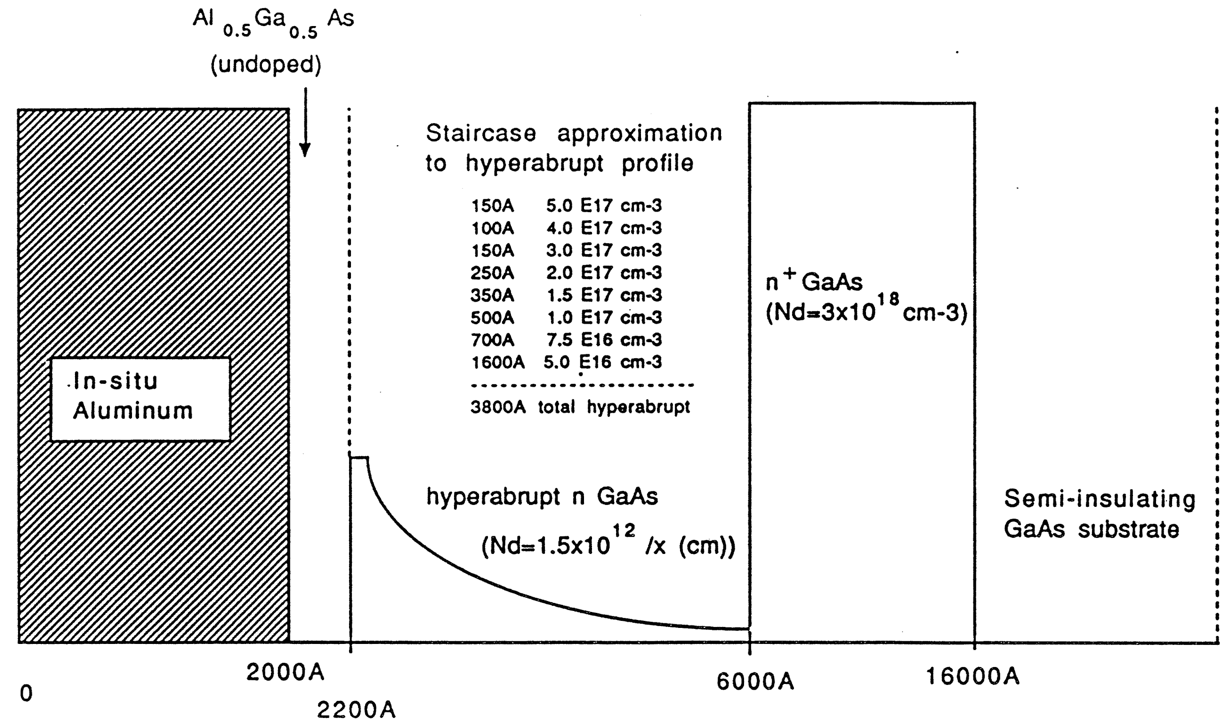


Figure 1: MBE profile of the beam control array.

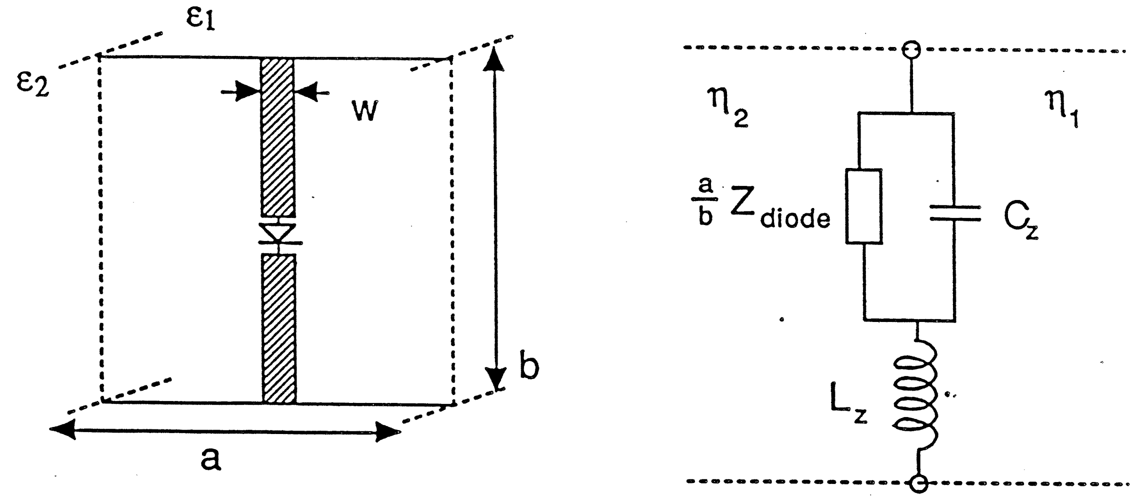


Figure 2: Electromagnetic model of the diode array.

in the simulations is 26 μm^2, since the effective diode width after fabrication should be about 1 μm less than the drawn dimension. Due to the small cell dimensions, the device count per array is very high, about 12,000 for a full sized (2.5 cm x 1.8 cm) array. To allow reasonable spacing between wirebonds, the array was layed out so that each bias line connects to eight contiguous rows of 60 diodes each. Thus, each bias line connects to 480 array diodes.

As previously stated, the array should show some capability for electronic beam steering and focusing. The array model cannot predict the extent of these capabilities, however, since it is applicable only to uniform array operation.

III. Fabrication and Testing

Array fabrication is based (with some modifications) on the self-aligned Aluminum Schottky diode process developed by C. Zah for millimeter-wave imaging diodes [4]. Most of the processing was performed at the JPL Microdevices Laboratory, a facility with state-of-the-art microfabrication capability.

Device isolation was performed, as in [4], by proton implantation, with an implant mask of thick photoresist. A two-step implant of $4x10^{14}cm^{-2}$ at 200 keV and $4x10^{14}cm^{-2}$ at 100 keV provided good isolation. However, photoresist edge bead resulted in the corners of the arrays being unisolated. Several of the arrays were therefore re-implanted to isolate these areas. However, the capacitance range of the diodes was greatly reduced after the second implant. It thus appears that some of the implant penetrates the photoresist mask and into the active device. The arrays which were not re-implanted had some unuseable areas due to the edge bead problem, but have proved sufficient for the experimental proof-of-principle testing.

Due to the parallel connection of array diodes, short circuited devices must be disconnected from the array. An HP4145 Semiconductor Parameter Analyzer, HP9836 controller, and Electroglas 1034 wafer prober were combined into a system which allowed automated testing and storage of I-V characteristics for every array device. Device probing was facilitated by an extra metalization step which creates probe pads connected to each device prior to grid (bias) metalization. With the short-circuited devices identified, a microprobe was used to sever their connection to the array. Following final metalization, very few of the bias lines were short-circuited. Therefore, further identification of short-circuited devices by "hotspot" detection [1] was not neccessary. Photographs of a single array device and a small region of an array are shown in Figs. 3 and 4, respectively. The final steps for completion of the array are the attachment and wirebonding of the array to a printed circuit "bias" board, and the attachment of bias wires to the board. Series resistors of 220 Ω are added to the bias wires to prevent damage if an array device becomes short-circuited.

IV. Results

Millimeter-wave transmission testing was performed with the system shown schematically in Fig. 5. A small array (1.8 cm x 1.0 cm, 4800 diodes) successfully demonstrated transmitted amplitude control throughout the W and D frequency bands

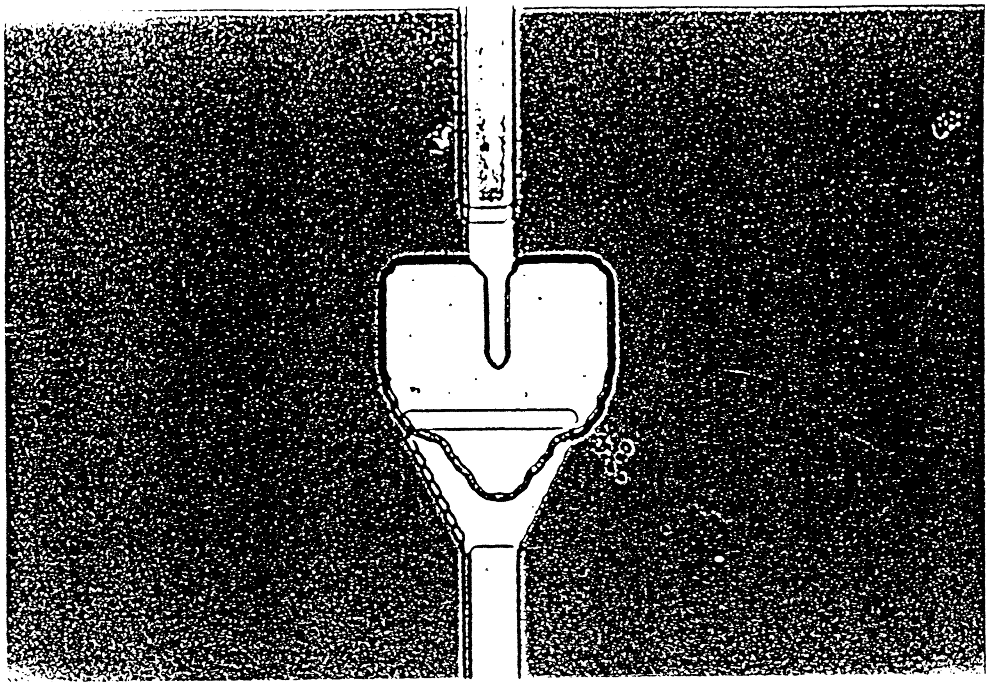


Figure 3: Photograph of a single device in a beam control array.

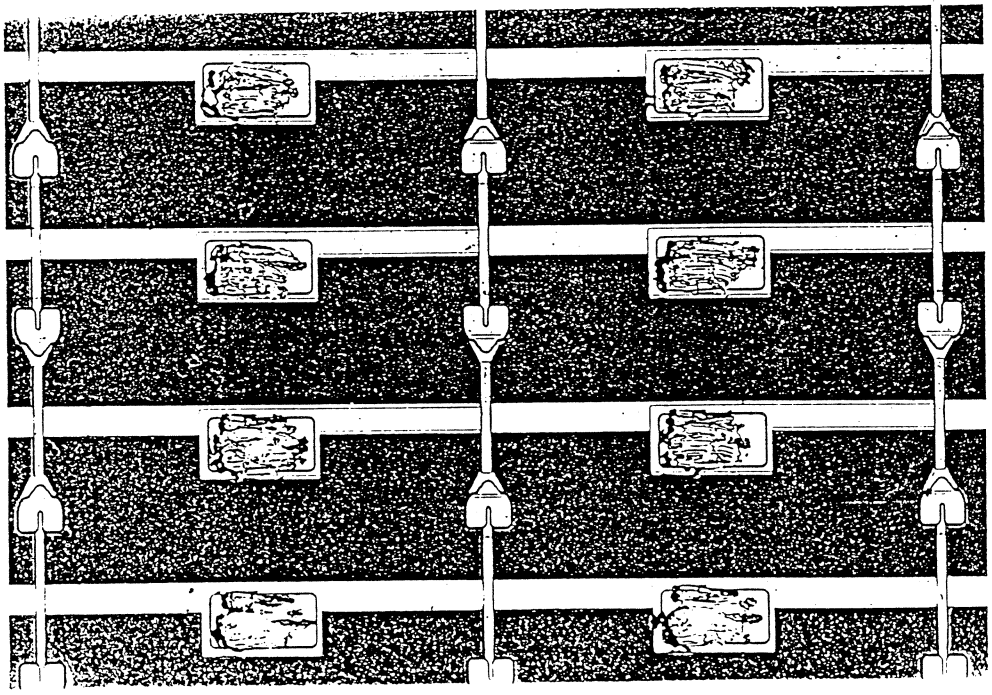


Figure 4: Photograph of a small section of the beam control array. Unit cell dimensions are 300 μm x 120 μm. The vertical strips serve as the "antenna" elements, while the horizontal strips provide bias voltage to the diodes. The marks on the large rectangular test pads are from automated device probing.

(75-170 GHz). Results at 99, 132, and 165 GHz are shown in Fig. 6. Substantial amplitude control was obtained (except near resonance), despite leakage currents on a number of the bias lines preventing most of the bias from showing up their associated sections of the array. In addition to amplitude control under DC bias, the array successfully demonstrated low frequency (200 kHz) modulation of a 165 GHz beam (Fig. 7). The modulation frequency was limited by the bandwidth of the detected beam amplifier. Further testing will be performed to determine the maximum modulation frequency of the array.

To allow further verification of the grid behavior, a technique has been developed to obtain the phase, as well as amplitude, of the transmitted beam [11]. The method involves tilting the incident beam, so that a portion of it is aligned orghogonal to the operational ("active") axis of the grid. The orthogonal beam component is employed as a reference, with the polarization of the transmitted beam providing the relative phase of the beam in the active versus orthogonal ("passive") axis. Since the phase of the passive axis is highly predictable, the absolute phase of the transmitted beam in the operating axis can be determined by this method. The method was verified by application to strip arrays, whose theoretical behavior can be well predicted and compared to the experimental results. The method was then applied to obtain the transmission coefficient of the beam control array as a function of frequency and bias. This was done for an 8600 diode beam control array. Estimates of parameters for the series RLC model of the grid were obtained by varying the parameters until a good match between the theoretical and experimental transmission curves was obtained. This provided a fairly precise estimate of grid resistance and resonant frequency $f_{res} = (2\pi\sqrt{LC})^{-1}$. For the array tested, the grid resistance is approximately 40 Ω over the entire bias range, and the resonant frequency versus bias is shown in Fig. 8. The individual value of L (or C) has some range in which the theoretical and experimental curves agree. This range is centered at an inductance value of L= 160 pH, with the capacitance ranging from 5.2 fF to 13.9 fF as a function of bias for this value of L. The results indicate a cutoff frequency for the beam control array $f_c = (C_{min}^{-1} - C_{max}^{-1})(2\pi R)^{-1}$ of about 400 GHz. It appears that both the grid inductance and capacitance are considerably lower (about 35 %) than predicted. The deviation in the inductance value is probably due to the idealization of the inductive effect as that of a uniform (and narrower than actually fabricated) vertical strip. Simulation by the High Frequency Structure Simulator will provide a more definitive verification of this. The deviation in grid capacitance is with respect to the values expected based on 1 MHz C-V measurements of sample diodes from the same wafer. This discrepancy requires further investigation.

Initial reflection tests have been performed for "calibration" devices (strip grids), with use of a focusing lens [14] and the polarization technique [11]. The phase of the reflection coefficient has been successfully obtained by this method. Since the grid parameters of the currently fabricated arrays are largely now known, the reflection phase shift for a stack of two of these grids can be well-predicted. Predicted results at 128.3 GHz (at which the thickness of the GaAs can be made the desired odd multiple of $\lambda/4$), along with the originally simulated behavior at the design frequency of 99 GHz rescaled to 128.3 GHz, are shown in Fig. 9. The lower than desired C_{max}/C_{min} ratio

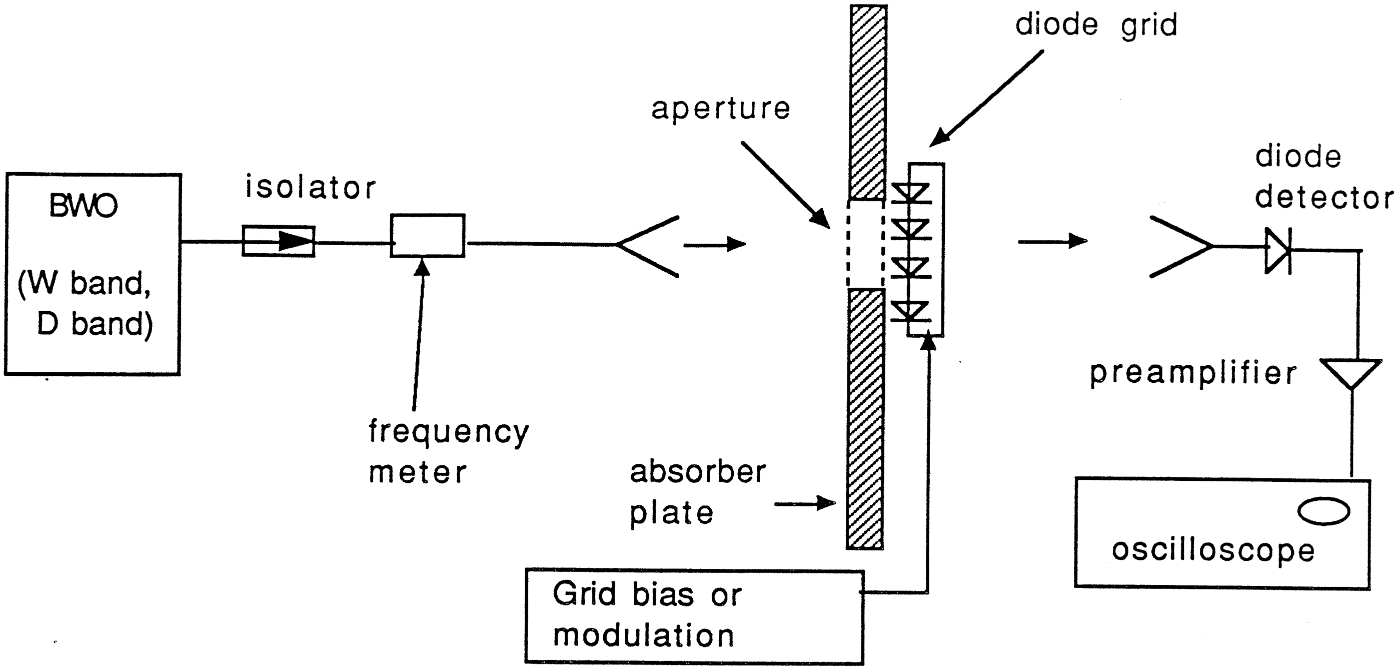


Figure 5: Schematic diagram of the test system for transmitted beam testing.

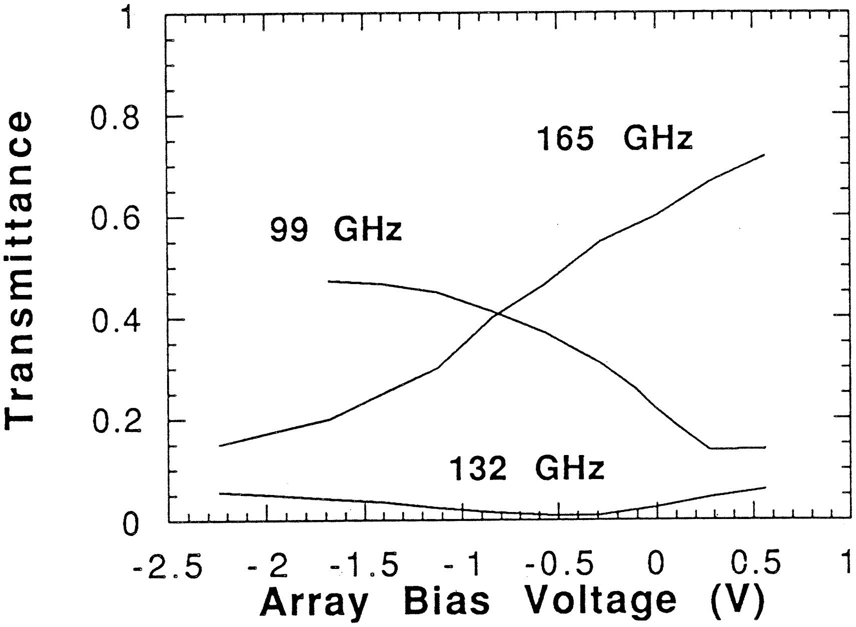


Figure 6: Experimental beam transmittance at 99 GHz, 132 GHz, and 165 GHz as a function of DC bias applied to the array. The basic form of the curves can be understood by the fact that the array is capacitive at 99 GHz, resonant at 132 GHz, and inductive at 165 GHz.

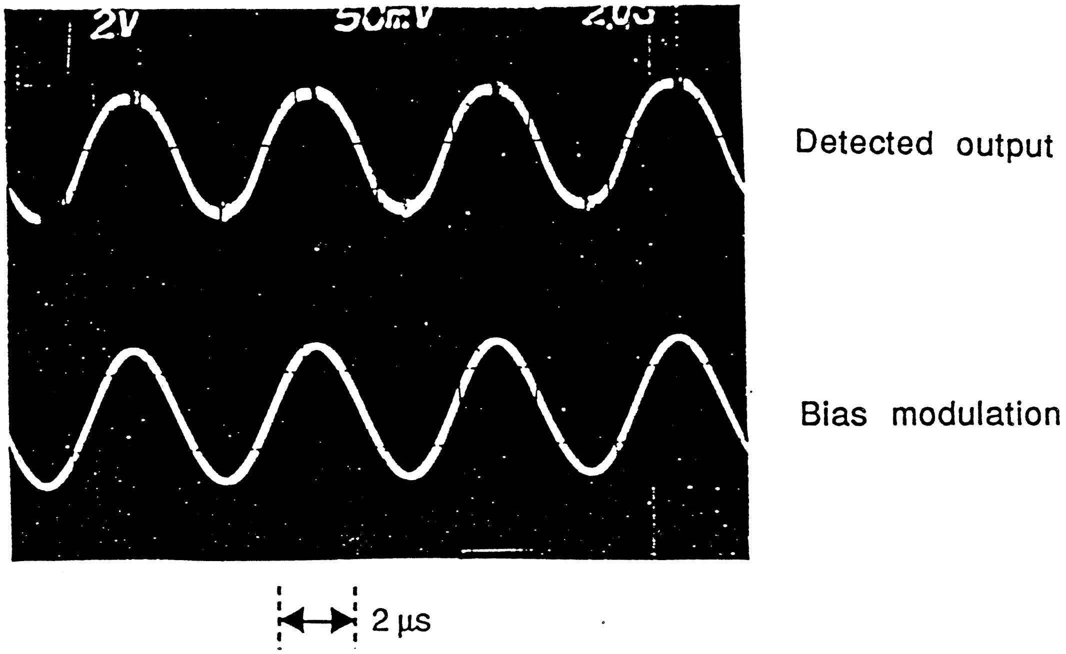


Figure 7: Detected output versus array input voltage for a sinusoidal modulation of the array at 200 kHz. The lower waveform is the array bias modulation voltage, whose range was -3V to +1V. The upper waveform is the detected output from the transmitted beam.

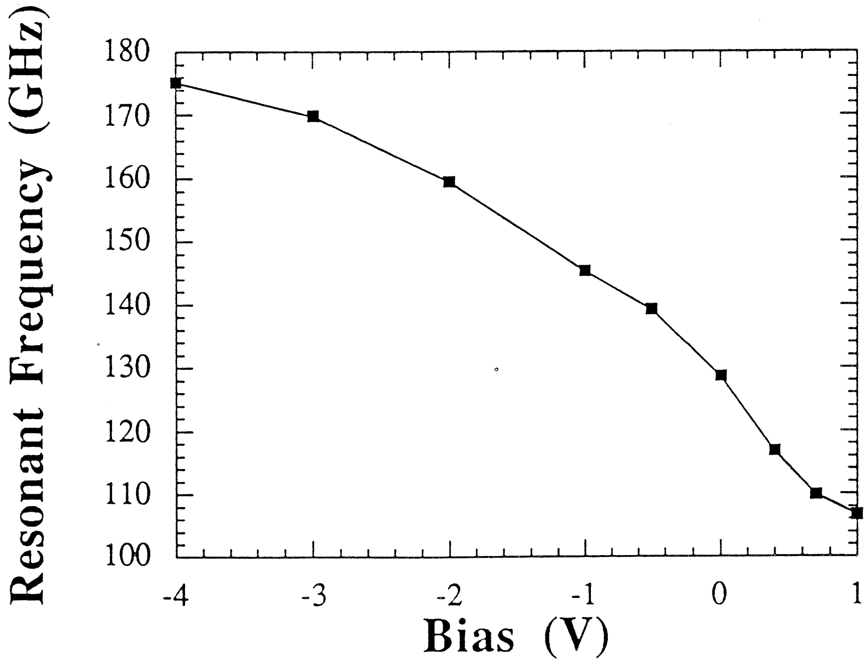
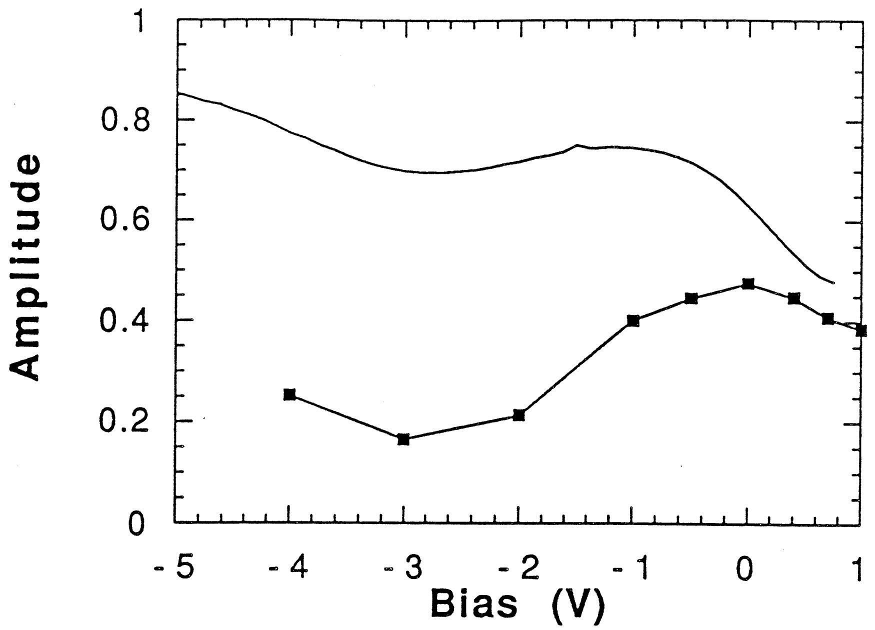


Figure 8: Resonant frequency versus DC bias for the beam control array.



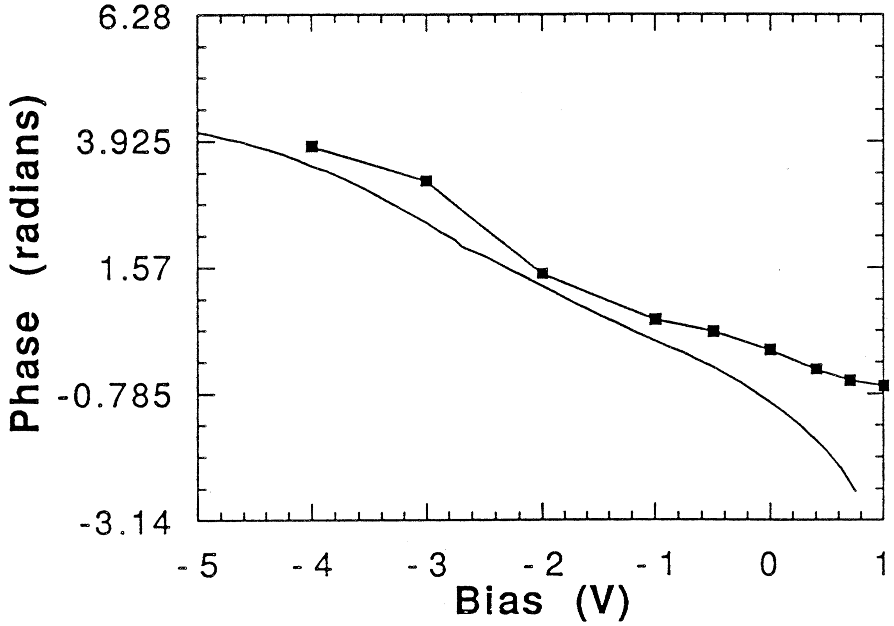


Figure 9: Predicted reflection coefficient for a two layer stacked phase shifter with fused silica "window" at 128.3 GHz. Lines with no markers represent the predictions based on originally simulated grid parameters. Lines with markers represent the predictions based on estimates of the grid parameters based on transmission measurements.

results in a phase range less than 360 degrees, contrary to the original simulation. This, however, does not preclude the possibility of beam steering to small angles. The higher than desired grid resistance results in a reflectance which is lower and is much more variable over the bias (phase) range. A preliminary attempt at steering of a transmitted beam with the current array was unsuccessful. This may be due to an inability of the grid to produce the strong amplitude variation with position associated with the desired phase distribution. Since steering to a fixed angle has been successfully demonstrated by a (low-loss) passive grid [15], the beam control array's ability to steer a reflected beam is likely to be governed largely by the grid loss as well as phase shift range. To obtain higher performance for the beam control functions, new arrays are being fabricated which should possess a larger C_{max}/C_{min} ratio and Ohmic contact resistance. In addition, we are considering the stacking of a large number of arrays of the current design and operating them in the high impedance region to accomplish transmitted beam steering.

V. Conclusions

A "second generation" millimeter-wave beam control array device has been constructed. This array has successfully demonstrated a new function by a millimeter-wave quasi-optical array, that of beam transmittance control. Phase of the transmitted beam has also been measured by a newly-developed technique. Reflection measurements, which will test the arrays as phase shifters, beam steerers, and beam focusers, will be performed soon. In addition, new arrays with a modified doping profile for higher C_{max} and lower resistance are being fabricated. These "higher performance" arrays should provide, for example, a greater "contrast ratio" (maximum to minimum transmittance) when the array is operated as a beam modulator.

New array designs have been initiated for high-speed (under 200 psec) electronic and optical beam control. For electronic control, the bias lines of the beam control array are being designed to function as high-speed guided-wave paths. For optical control, monolithic arrays of photoconductive switch devices are being fabricated. New concepts for barrier varactor photodiodes are under study for application toward optically-controlled modulator and beam steering arrays. High-speed beam switching arrays have immediate application in plasma diagnostic reflectometry, and have potential additional application for such functions as electronic input beam chopping in high-speed imaging systems. Longer term possibilities include exciting possibilities such as amplifying beam steeres with two-axis scan control.

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