Millimeter Wave Monolithic Solid State Device Arrays

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ABSTRACT

Current research efforts involve the design and fabrication of two-dimensional grids loaded with oscillators, frequency multipliers and electronic beam steerers which employ quasi-optical coherent spatial combining of the outputs of a large number of solid state devices. This paper is specifically connected with our work on diode frequency multipliers, resonant tunneling oscillators, and Schottky diode beam steerers and focussers.

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INTRODUCTION

Major advances in materials technology, solid state electronics, integrated circuit technology, quasi-optics and quantum theory promise a new generation of high frequency devices and systems to solve critical problems in radar, electronic warfare and countermeasures, remote sensing, communications, and imaging. Such systems require power sources up to the THz region for transmitters ($\simeq$1 W to 100 W) and low noise local oscillators for receivers. Those needs have been traditionally satisfied by electron tube oscillators and amplifiers. However, the size, cost, and lifetime of the tube sources have severely limited their usage. This dictates the use of solid state sources. However, it is well known that the power handling capability of solid state devices is relatively low, especially at higher frequencies. Therefore, we have employed quasi-optical spatial power combining of the outputs of large planar arrays of devices to provide the required power levels, as well as to avoid the Ohmic losses and limitations associated with conventional power combining techniques. Monolithic integration is essential so that the required output power can be obtained without excessive cost and the performance can be more easily optimized. Current development efforts involve frequency multiplier arrays, Schottky diode beam steering arrays, and resonant tunneling oscillator arrays. This work is discussed in the following sections.

QUANTUM WELL ARRAYS

a) Quantum Barrier Varactor (QBV)

The concept of a single quantum barrier varactor (QBV) for frequency multiplification has been impressively demonstrated by Rydberg et al [1] with output at frequencies up to 280 GHz with 5% efficiency. However, it has also been observed that the large thermionic current as well as large Ohmic contact resistance of the GaAs/AlGaAs QBV limited its performance. Our approach is to utilize the InGaAs/InAlAs system with the InGaAs lattice matched to the InP substrate. with $In_{0.32}Al_{0.68}As$ serving as the barrier. A composition of 68% of AlAs has been chosen in order to obtain a high barrier ($\simeq$800 mV) with an acceptable lattice mismatch (1%). Also, InGaAs is a narrow band gap material, so that the Ohmic contact resistance is significantly smaller than GaAs. In addition, InGaAs has superior electronic transport properties. However, this system has its high power limitations. The main limitation to our device is due to avalanche breakdown because of the narrow band gap of InGaAs. Space charge effects and thermal heating will also degrade the device performance at high power. However, these effects can be greatly ameliorated by employing the new concept of stacking many barriers in the epitaxial structure. Since each QBV only shares part of the pumping power, very high power generation is feasible. Besides improving high power generation, the use of many QBVs in series also increases the cutoff frequency, since C_{min} can be dramatically reduced. Alternatively, the series resistance can be reduced by increasing the active area while the C_{min} is still sufficiently low. The other important advantage of many QBVs in series is in improving the yield of the array. The so called "back-to-back" fabrication method can be employed [2]. Using this method, only one metalization is required. On the other hand, since a larger area can be employed, higher lift-off yield can be obtained. Figure 1 shows the profile of four QBVs in series. The epitaxial structure provides two QBVs while the "back-to-back" process doubles the numbers of QBVs in series.

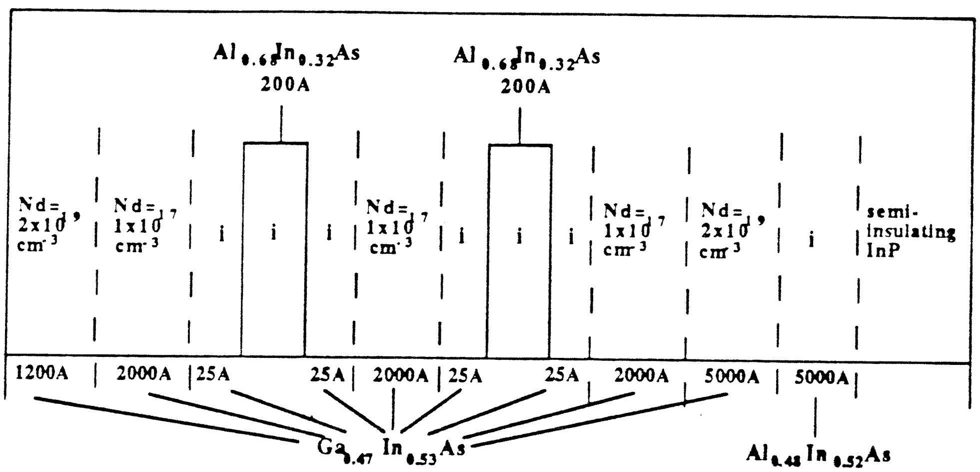


Figure 1. The profile of four QBVs in series.

The output power versus pumping power at 1.5 THz has been simulated as shown in Fig.2.

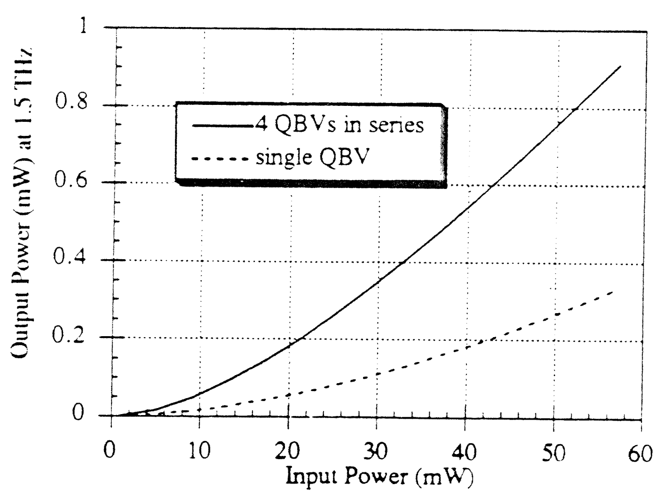


Figure 2. Comparison of the output power of four QBVs with single QBV.

The efficiency of four QBVs in series is almost four times larger than the single QBV at a pumping power level of 30 mW. This indicates that many QBVs in series provide a promising approach for THz multiplification. The setup for testing a proof-of-principle tripler array is demonstrated in Fig.3.

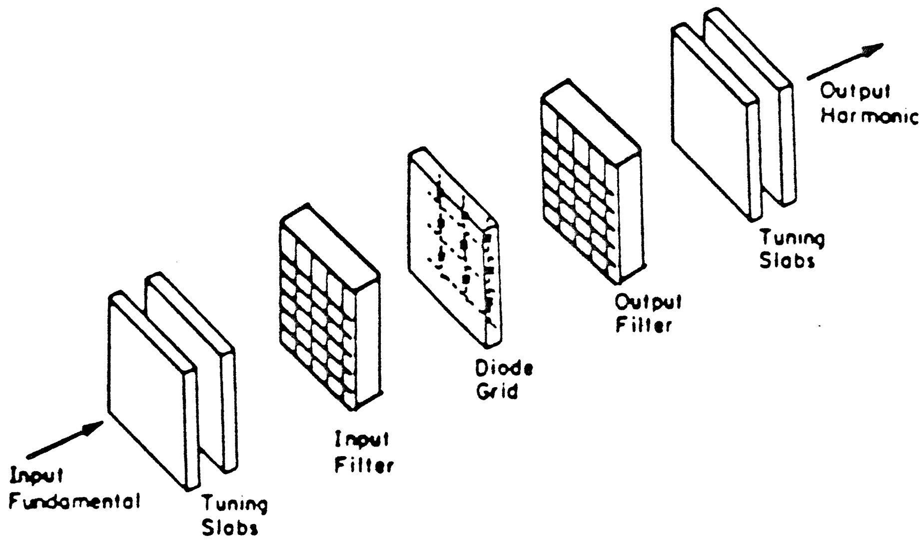


Figure 3. Quasi-optical tripler configuration.

The quasi-optical input filter consists of inductive strip arrays on both sides of a quarter wavelength quartz slab, while the output filter consists of two capacitive slot arrays on a like slab. The dual quartz tuning slabs are used for impedance matching.

b) Resonant Tunneling Diode (RTD) Arrays

In addition to the development efforts on QBV arrays, a study of resonant tunneling device (RTD) [3] [4] for multiplier as well as oscillator applications is being conducted. Test devices have been fabricated using an MOCVD wafer provided by Bellcore. Figure 4 shows that a current peak-to-valley ratio of 19:1 with peak current density of 1.6×10^5 A/cm^2 has been achieved at room temperature, which is the highest current peak-to-valley ratio achieved for MOCVD wafers at such a high current density.

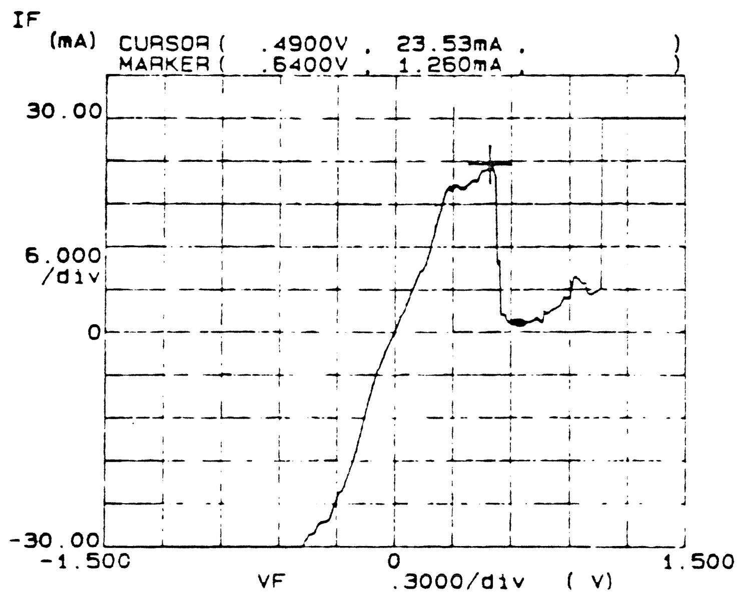


Figure 4. Measured I-V characteristics of RTD.

The RTD oscillator array presents a significant challenge due to the difficulty in stabilizing the low frequency oscillations resulting from the large negative differential resistance. Based on the equivalent circuit analysis of the grid array, work has been initiated on simulating the frequency dependent characteristics of the RTD array.

LINEAR SCHOTTKY VARACTOR ARRAY

The linear Schottky varactor array is being developed because it has the potential for a number of quasi-optical circuit functions. When the array is operated with a uniform DC bias to all the diode rows, the array can function as a reflection phase shifter, transmission amplitude modulator, or reflection polarizer as shown in Fig.5.

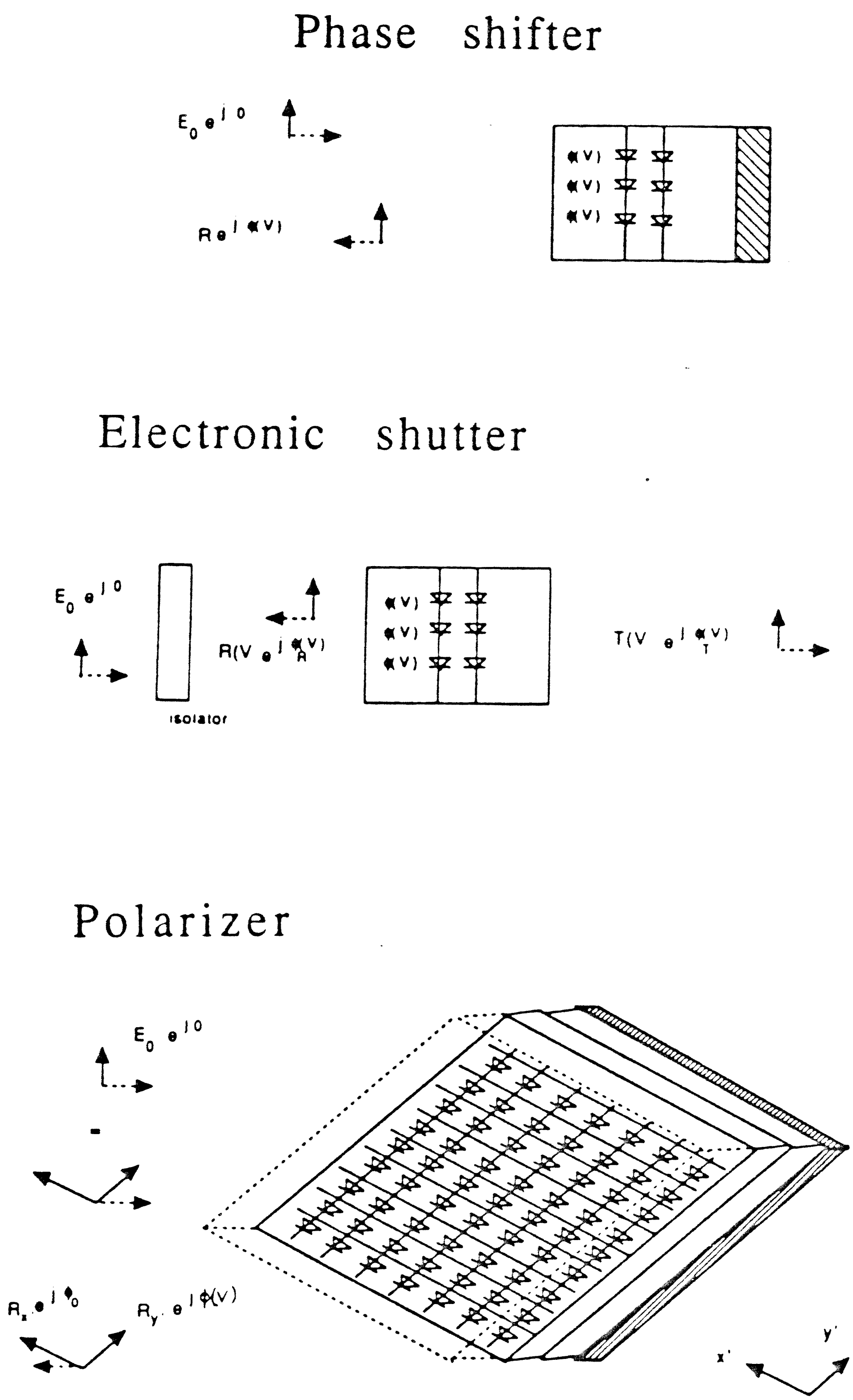


Figure 5. Capabilities of stacked varactor array under uniform bias.

When different bias is applied to the rows of the array, the grid can be operated as a phased array beam steerer, electronically focusable mirror, or phase conjugation surface (Fig.6).

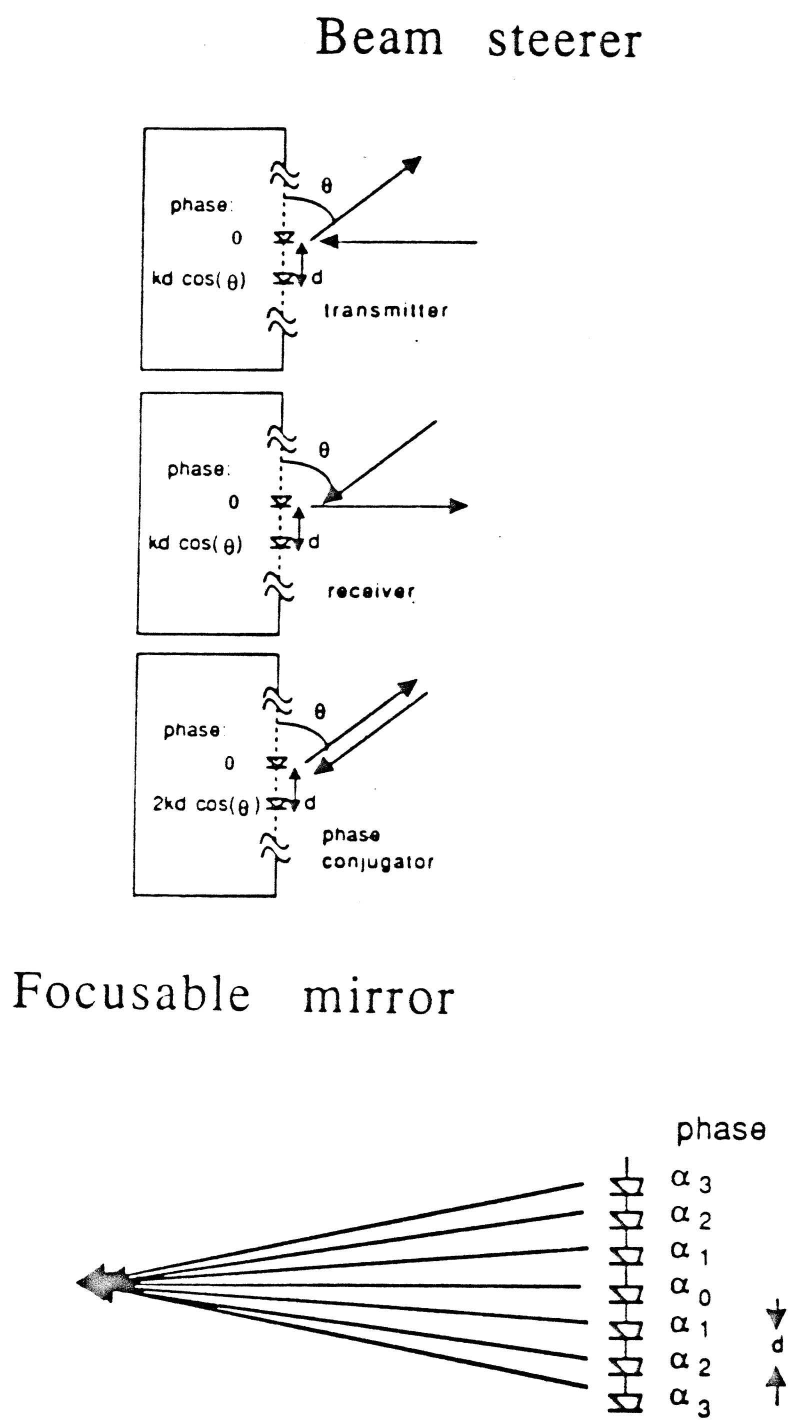
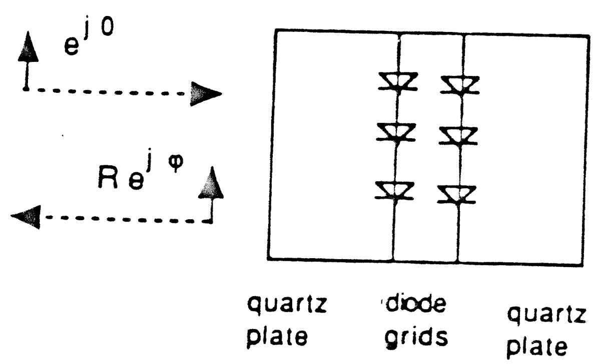


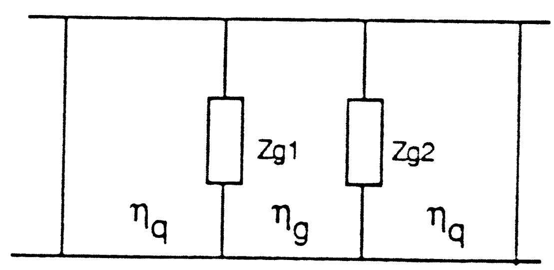
Figure 6. Capabilities of stacked varactor array under nonuniform bias.

The concept was pioneered by W. Lam, who successfully demonstrated the use of such an array as a phase shifter, with 70 degrees of phase and 6.5dB loss [5]. Lam also proposed an extension of the phase shifter array concept to achieve a full 360 degrees of phase. The design involves stacking two phase shifter arrays with a quarter wavelength separation (Fig.7).

Schematic view



Quasi-optical circuit



Layers are odd multiple quarter wavelength thick

Figure 7. Two layer stacked linear varactor array

This is the concept we are pursuing. Using the full phase range with different phasing of the rows allows beam steering operation as well. The model used for a diode array is that of a lumped impedance in a transmission line system. Lam obtained good agreement between theory and experiment using an impedance consisting of an inductance in series with the diode impedance. His array had a rather large diode C_{min}, however, which hid the effect of the "gap capacitance" associated with the non-uniformity of the strip current at the gap as shown in Fig.8.

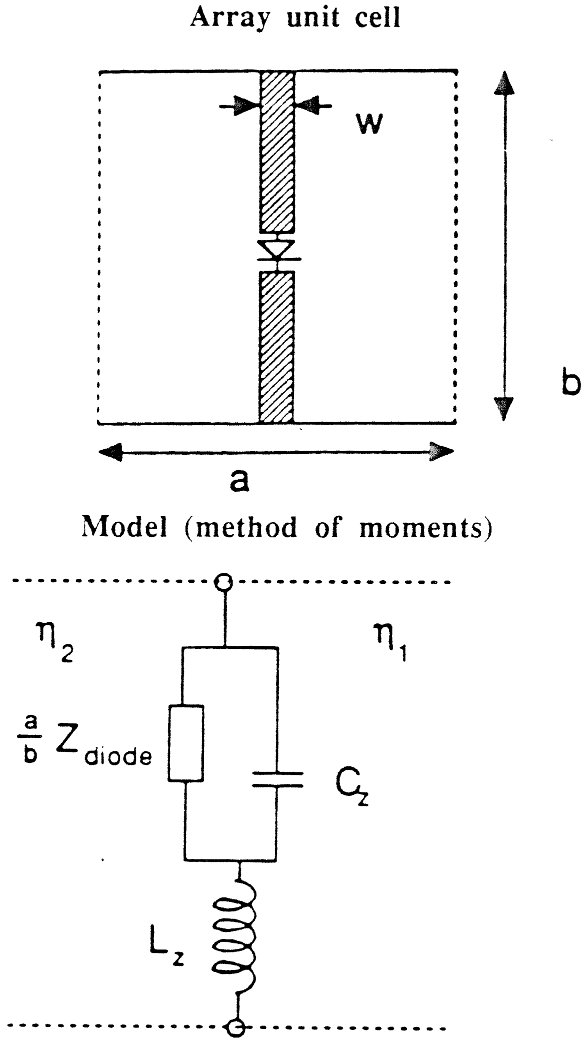


Figure 8. Quasi-optical impedance model of the diode array.

A method of moments simulation developed for the current work has shown that at small diode capacitance the gap capacitance will severely degrade the grid performance. However, a small C_{min} is essential to achieve the 360 degree phase shifting. Fortunitely, the gap capacitance effect can be reduced to an acceptable level by use of a rectangular array unit cell (Fig.9).

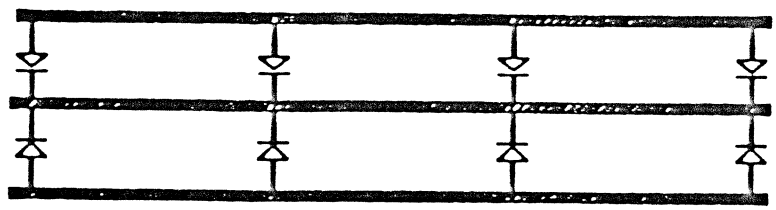
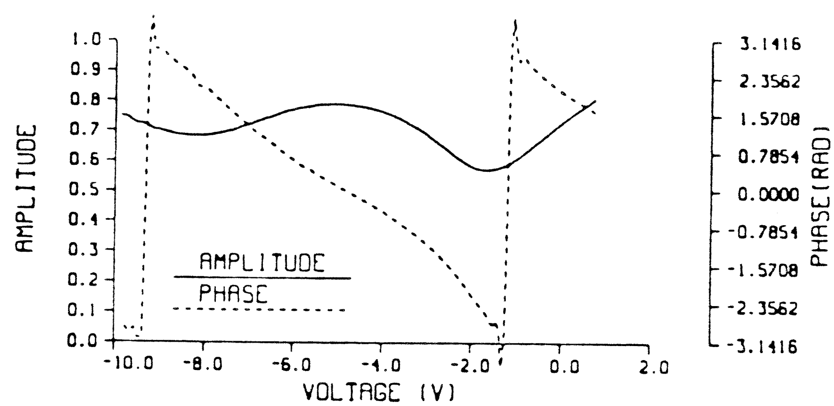


Figure 9. Rectangular unit cell array design.

A rectangular array requires a larger diode, which, fortunitely, is easier to fabricate with high yield and improves power handling capability. Based on the electromagnetic model of the diode array, C-V characteristics of the diode, and transmission line circuit model, simulations of the reflection phase shifting and transmission amplitude modulation as functions of DC bias have been carried out as displayed in Fig.10.

Reflection phase shifter



Transmission amplitude modulator

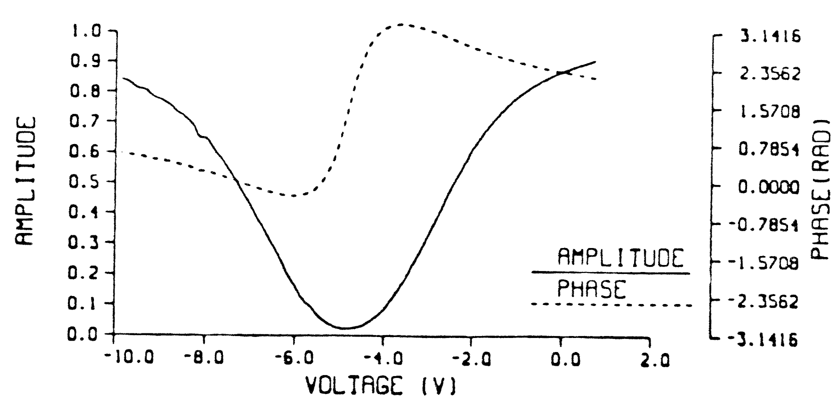


Figure 10. Simulated performance of the stacked linear varactor arrays

It is observed that 360 degrees of phase shifting and an amplitude modulation of 3% to more than 90% are both achievable. A high breakdown voltage is essential to achieve a small diode capacitance. An AlGaAs barrier layer with 50% of AlAs has therefore been used to improve the breakdown voltage. The testing of the array will be performed using a reflectometer based on Lam's design [6].

BNN VARACTOR ARRAY

This work, is an extension of the work of Jou [7] and of Hwu [8]. By using a hyperabrupt Schottky diode array, Jou successfully demonstrated a frequency multiplification from 33 GHz to 66 GHz. The small breakdown voltage of the Schottky diode motivated the follow-in work on the BIN diode array by Hwu. However, the intrinsic region of the BIN causes a large space charge resistance. As a result, the efficiency and the cutoff frequency are severely degraded. The space charge effect can be suppressed by adding doping in the previous intrinsic region while still preserving a reasonably high C-V nonlinearity. A comparison of the C-V characteristics of the hyperabrupt Schottky, BIN and BNN diodes is shown in Fig.11.

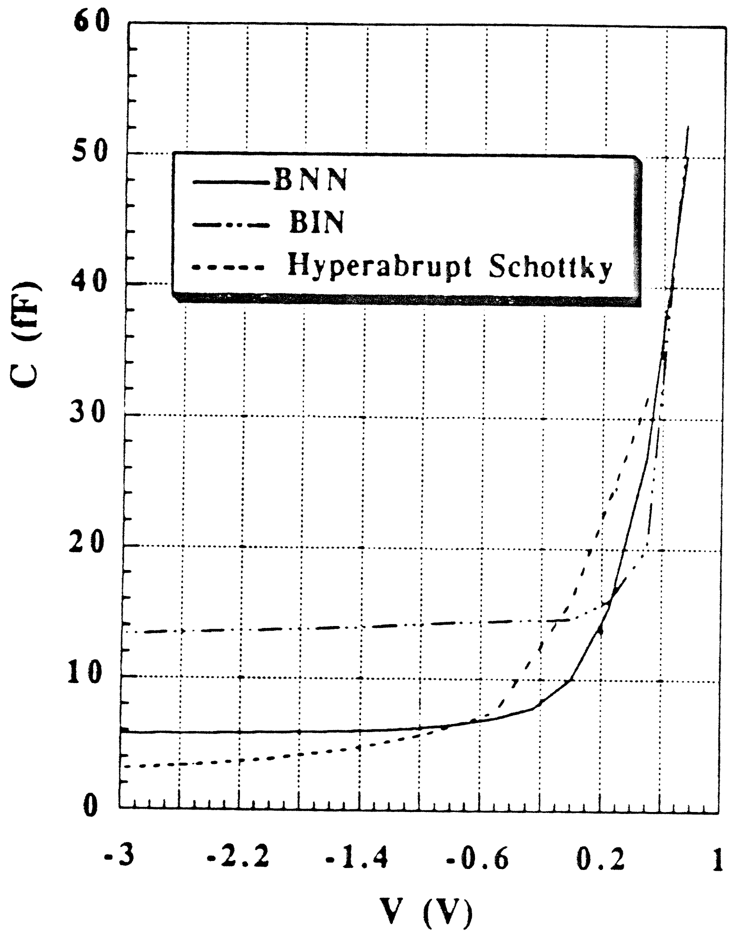


Figure 11. Comparison of the C-V characteristics of hyperabrupt Schottky, BIN, BNN diodes.

Both BNN doubler and tripler array work is underway. Figure 12 shows the measured C-V characteristics of the BNN back-to-back tripler and its profile.

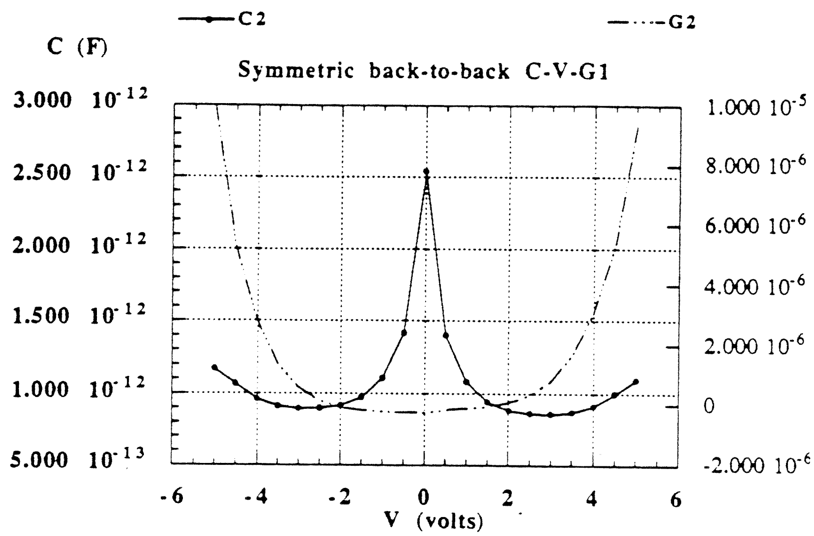


Figure 12. Measured C-V characteristics of back-to-back BNN.

The testing of the BNN doubler array will be demonstrated using the configuration of Jou [7], while the BNN tripler array will be tested using the setup arranged for the QBV tripler array.

CONCLUSION

We are actively working on the development of millimeter wave monolithic solid state device arrays. The new concept of many QBVs in series and BNN monolithic quasi-optical arrays offer great promise for THz frequency multiplification. The linear Schottky varactor array has numerous useful quasi-optical functions. In the design of this array, a more accurate electromagnetic model has been developed.

ACKNOWLEDGEMENTS

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