International Journal of Infrared and Millimeter Waves, Vol. 18, No. 10, 1997

VARACTOR-TUNED GUNN DIODE VOLTAGE CONTROLLED OSCILLATOR ANTENNA ARRAY

Shing Horng Lee,[1] Christina F. Jou,[2] Chien Ping Lee,[1] and Cheng Chi Hu[2]

[1]*Institute of Electronic Engineering*
National Chiao Tung University
Hsinchu, Taiwan, Republic of China
[2]*Institute of Communication Engineering*
National Chiao Tung University
Hsinchu, Taiwan, Republic of China

Received July 1, 1997

Abstract

A simple varactor tuned X-band Gunn diode VCO antenna array which is strongly coupled has been demonstrated. These arrays have the advantages of simple biasing circuit, no resistors required to eliminate multimode problem and suitable for monolithic integration circuit. Preliminary results show a maximum tuning range of 47MHz for 1×1 array and 170MHz for 2×2 array. In order to solve power combining heating problem, we move the backside metal forward and it becomes a microstrip form. The measured frequency and radiation patterns of these grid arrays agree very well with theoretical calculations.

Key Words:

Varactor tuned, X-band, Voltage Controlled oscillator (VCO)

0195-9271/97/1000-2001$12.50/0

I. Introduction

In the recent years, power-combining schemes in using antenna array involving solid-state devices quasi-optically coupled in free space have been employed to develop high-power microwave oscillators[1]-[4], mixer[5], doubler[6], phase shifter[7] and so on. However, oscillators are one of many electronic components that are amenable to packaging in the grid configuration. Thus a way is proposed to use a antenna array loaded with solid state devices to generate high power combined in the free space. Recent efforts in using MESFET devices [1] gives 21W of CW effective radiated power with a 20% dc to RF conversion efficiency at 5GHz. To obtain higher frequency source, Robert M. Weikle [2] proposed a method for quasi-optical power combining the output power of MESFET's in which drain and source leads couple directly to the radiated field. Generally speaking, two terminal devices will generate even higher frequency source. Therefor, Zoya B. Popovic and David B. Rutledge [3] first demonstrated an X-band Gunn Diode grid oscillators. Their approach is attractive because the active devices do not need external locking signal, and the power combining is done in free space. The horizontal metal lines do not perturb the RF field, and they are also used for DC bias lines. Here, in our design, we use these horizontal bias line not only for biasing but also for matching and coupling lines. In 1995, a 16-element Tunnel diode grid array quasi-optical oscillator prototype was demonstrated by D. B. Rutledge [4]. In their antenna array design, each unit cell antenna size is much less than $\lambda/(n+1)$, where λ is the operating wavelength, n is the index of the substrate. They analyze the array by considering a unit cell antenna of this array in an infinite periodic array of identical devices. In general, as the designed frequency increasing, the array condition $\lambda/(n+1)$ is not easily satisfied and we must consider the array as a two-dimensional array not only as a single unit cell when predicting the frequency of this array. In their experimental setup, a mirror behind the antenna array is used to tune the operating frequency.

In 1993, Mader, Bundy and Popovic proposed a quasi-optical VCOs [8], the frequency tuning active antenna array. These VCOs consisted of an array of oscillators, a dielectric spacer, a variable capacitance array, and a mirror. Two types of arrays are compared, one consisting of short dipoles, and the other of bow-tie elements.

They show a frequency tuning range 154MHz by changing the bias voltage of capacitance array at the 6.0GHz operating frequency for a 7×7 bow-tie oscillator array. In their experiment, a 10% tuning bandwidth with less than 2 dB power change was measured in the case of a bow-tie VCO. In our study, because we know in the quasi optical grid oscillators' design, one of the main problems is heating because heat sink can not be put in. In order to be more efficiently removing the heat from backside, we put the metal right behind the thin substrate, and let it becomes a microstrip form. It serves as a ground plane and a heat sink at the same time. Therefore, a microstrip line antenna array is formed, which can distribute heat more efficiently and the analysis of this structure becomes very easy. Because these spatial power combiners are using microstrip lines as radiation elements, mcirostrip antenna RF characteristics is important.

In order to tune the combiners' frequency, varactor diodes are added along the bias line during those microstrip lines. Therefore, the bias lines serve not only for bias but also for matching and tuning. Therefore, we can tune a spatial antenna array electrically, not by moving the mirror behind backward and forward. In this paper we also develop a simple model to accurately predict the frequency of this strongly coupled microstrip line antenna array and the radiation patterns. At last, we show the theoretical and experimental results from a single element , a four-element to a 16-element X-band VCO antenna array, and also the maximum frequency tuning range of the varactor added array.

II. Two-dimensional Oscillator Array Design

An equivalent circuit of this two-dimensional spatial power combining oscillator employing Gunn diodes is shown in Fig. 1. The admittance of each diode is -Gr+ jB. Each interior diode is connected to four similar diodes via sections of transmission lines with length L. Gr represents the radiation conductance of antennas connected to each port, and it must be equal to -Gr under steady state oscillation. When we analyze the antenna array, because the wavelength is longer than the unit cell size, the antenna array must be treated as a whole system. To analysis the antenna array, the first important thing is to determine the exact Gunn diode admittance and then the admittance of the unit

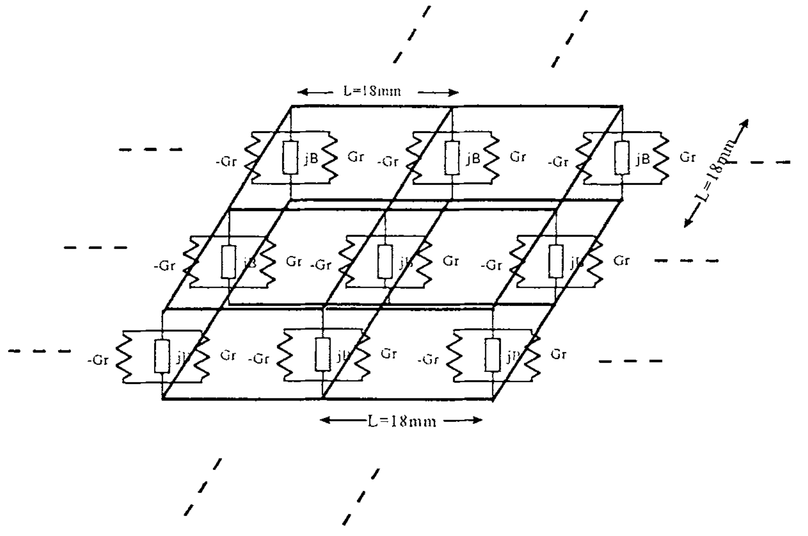

Fig. 1 Equivalent circuit for a two-dimensional quasi-optical power combining oscillator employing two-terminal devices.

cell antenna. In order to obtain the Gunn diode admittance, the method we used is to design a planar Gunn diode oscillator using microstrip line. The exactly equivalent circuit model of the Gunn diode is obtained by using the HP8563E spectrum analyzer to measure the exact oscillating frequency. The radiation frequency of a single unit cell antenna is designed by equal the imaginary part of diode admittance to the imaginary part of the half unit cell antenna admittance in parallel. The method is the same in a larger antenna array. Fig. 2 shows the realization of a 4×4 spatial varactor tuned VCO's antenna array. Here 4×4 spatial varactor tuned VCO's antenna array is represented for repeating a unit antenna cell four times both in the x and y direction. The unit cell antenna configuration is also shown. It has the horizontal line d=18mm length, 1mm width and a vertical line L=18mm, 1mm width. In Fig. 2, the varactors are adding to the edge of bias line every two lines. More varactors could be put in the configuration, not only the end of the bias line but also the middle places between every two unit cell antennas. Here the substrate used is PTFT Duroid 5880, its dielectric constant is 2.2 and the thickness is 0.5 mm. The Gunn diodes used are C&K w2420 X-band Gunn diodes. The varactor diodes used here are ALPHA DKV 3803.

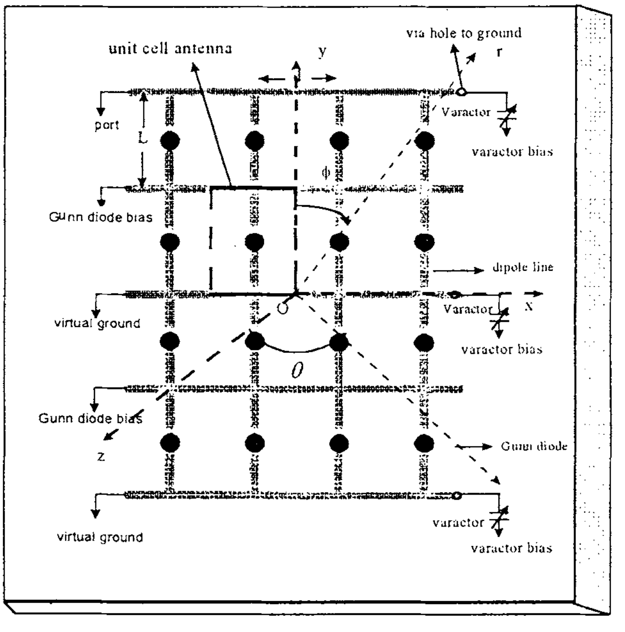

Fig. 2. The realization of 4x4 spatial microstrip dipole power combiner

III. Grid Performance

The far field experimental setup is shown in Fig 3. The basic characteristics of 1×1, 2×2, and 4×4 spatial antenna arrays were measured. Table I shows their measured and predicted frequency, effective radiation power(ERP), and power/device. Here n×n array is represented for repeating the unit antenna cell n times both in the x and y direction. The oscillation frequency of the 2×2 array is about 1.05% lower than the designed frequency. The oscillation frequency of the 4×4 array is about 1.77% higher than the designed frequency. And the power per diode increases for the 2×2 array but decreases for the 4×4 array. The reason is mainly due to heat. The maximum efficiency shows the same situation. The grid-to-horn distance (75 centimeters) is considered according to the far field condition $L \geq 2D^2/\lambda$. The ERP is calculated by $P_r(4\pi L/\lambda)^2/G_r$, where L is the distance between the oscillator array and the horn, D is the maximum length of the line source, P_r is the received power and G_r is the gain of the horn.

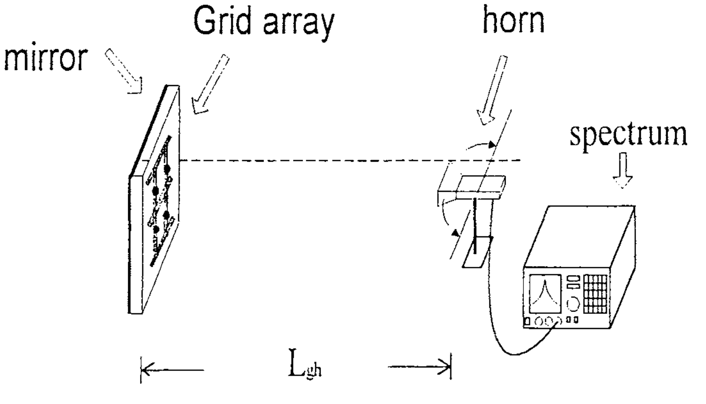

Fig. 3. General quasi-optical far field experimental setup
Lgh is represented the distance between grid power combiner to standard horn.

In calculating the radiation patterns of these arrays, considering a simple short dipole at first, .if the current distribution along the antenna of the vertical bias line (see Fig. 2.) is given

$$I(z) = I_m \sin[\beta(\frac{L}{2} - |z|)] \qquad |z| \le \frac{L}{2}$$

(1)

where $I(z)$ is represented for assumed RF current at z position, I_m is the maximum RF current in the dipole, and β is propagation constant, L is the length of dipole antenna of the vertical microstrip line in these array.

The radiation pattern of a simple short dipole of finite length is given by a dipole radiation integral as following

$$f_{un} \equiv \int_{-\frac{L}{2}}^{\frac{L}{2}} I(z') e^{j\beta z' \cos\theta \sin\phi} dz'$$

(2)

where f_{un} is the unnormalized pattern factor. When $\phi=\pi/2$, f_{un} can be represented E-plane pattern, and $\phi=0$, f_{un} is H-plane pattern.

Thus we can get far field zone pattern of a single dipole with finite length. About the strongly coupling spatial power dipole array, we may not multiple a array factor to do this work, because the combining effect is different in x direction and y direction. We must consider them separately. In y direction, the RF current flows through each dipole antenna from a top bias line to a bottom bias line. Therefore the array was considered as a group of columns, and the single column could be calculated by integrating the entire RF current path from top bias line, passing through middle vertical lines of several unit cell antennas and finally to bottom line. So equation (2) becomes to (3).

$$f_{un} \equiv \int_{-N\times\frac{L}{2}}^{N\times\frac{L}{2}} I(z)e^{j\beta z\cos\theta}dz$$
(3)

where N is represented for the combining unit cell antenna number in the array in the y direction. And f_{un} is integrating by taking O point as a original point, such as Fig. 2.

In x direction, there are strongly coupling lines between these columns in these arrays. the bias line added a phase difference between different columns in the array is given by

$$\varphi \equiv \frac{2\times\pi\times d}{\lambda}$$
(4)

where d is represented for the spacing between columns in the array in the x direction.

Thus we calculate these arrays by integrating one column dipole antenna and then multiplying it with exp(-jβφ) by every adjacent column. So when we treat the n×n dipole array, we can simply consider it as a 1×n linear array. The array factor could be used in only x direction. We replace the array factor in y direction by integrating the full RF current path by equation (3). The radiation pattern of the entire array can be easily obtained in superposition by adding the n columns together with consideration of the phase differences between the columns.

These arrays were measured at 6.5V DC and 0.1 Amperes bias current per diode for a long duration time. In far field condition, the theoretical and measured E and H field plane pattern of a single unit cell antenna are shown in Fig 4(a) and 4(b).The theoretical and measured data agree well without heat dissipating problem. The theoretical and measured E and H field plane pattern of a 2×2 array are shown in Fig 5(a) and 5(b). The four peaks of the 2×2 array measured pattern in the E plane are slightly shifted compared to the theoretical peak position. This is the result of the heating effect.

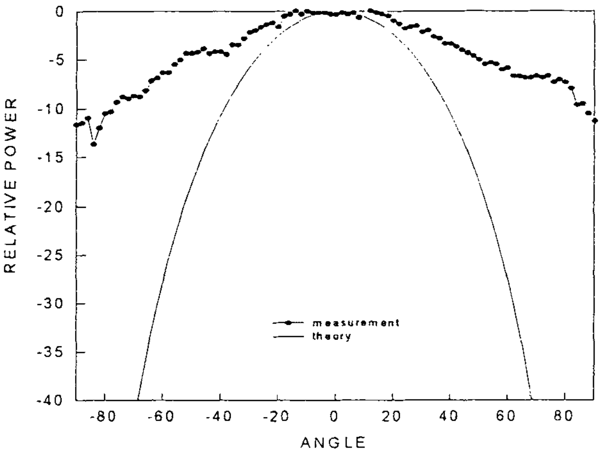

Fig. 4(a) Measured and calculated H-plane radiation pattern for a single unit cell antenna

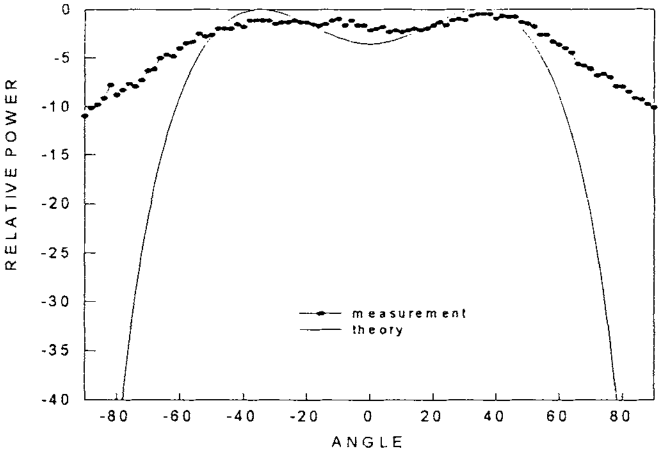

Fig. 4(b) Measured and calculated E-plane radiation pattern for a single unit cell antenna

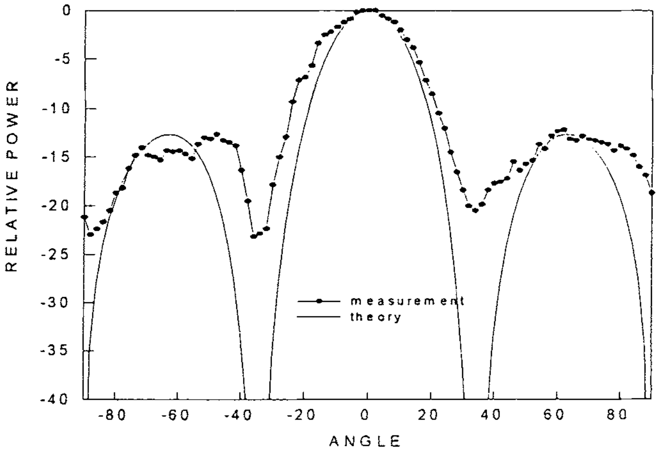

Fig. 5(a) Measured and calculated H-plane radiation pattern for 2x2 Gunn Grid dipole array

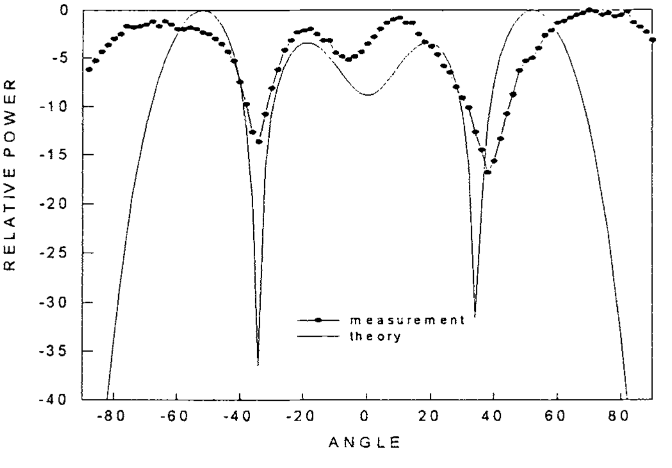

Fig. 5(b) Measured and calculated E-plane radiation pattern for 2x2 Gunn Grid dipole array

Although the back side metal ground plane can distribute heat, we still observe that there are heat localized around the center of the diode. The local heat around the diode in the substrate seriously concave or convex the surface so the individual diodes are not on the same plane. This problem influenced the electric and magnetic field in outer space of the dipole array. Fig 6(a) and 6(b) show the theoretical and measured E and H field plane patterns of the 4×4 diode dipole array. The measured pattern is distorted even more significantly than the 2×2 grid array. However, the heat didn't influent the predicted frequency.

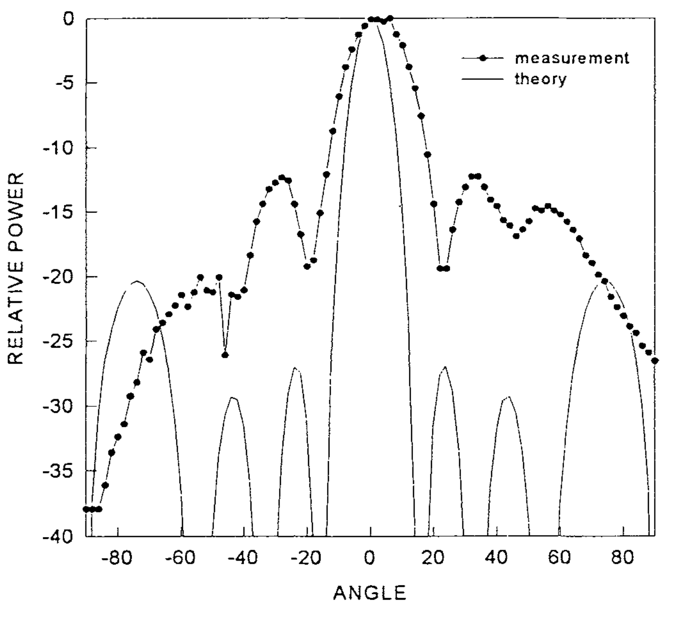

Fig. 6(a) Measured and calculated H-plane radiation pattern for 4x4 Gunn Grid dipole array

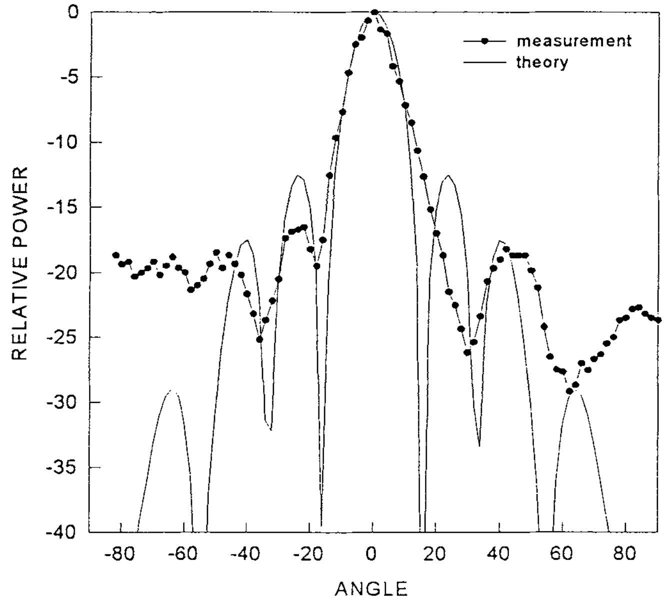

Fig. 6(b) Measured and calculated E-plane radiation pattern for 4x4 Gunn Grid dipole array

Three varactors could be added at the ends or middle of the bias microstrip lines, shown as Fig. 7. When the varactor is tuned by the negative bias voltage, the frequency of the grid oscillator array will change. Fig. 8 shows the oscillating and the simulated frequency of a 1×1 array from EEsof Libra^{TM} as a function of capacitance of a single varactor diode. According to the data sheet of the varactor diode, the capacitance change of the varactor in our bias range is above 2pF. So our experimental results agree approximately the calculated result. A tuning bandwidth of 47MHz is obtained and a smaller tuning bandwidth appears in the 2×2 Grid array with only one varactor (c1) is added. This is because the tuning capacitance of varactor cannot change the large impedance of the outer environment very much. The simulated and measured frequency agree well in Fig. 8, and Fig. 9 shows the 2×2 Grid array tuning range with three varactor diodes c1, c2, and c3 involved. Thus, more varactors becomes necessary to get a wider tuning range, as shown in Fig. 9, with comparison of the measured result with the simulation prediction of 1×1 and 2×2 grid array. The frequency tunable spatial antenna array is also designed using a simple microstrip line model. We have also calculated the tuning range based on this model. Table II shows the predicted tuning range of a 1×1 and 2×2 array as only one varactor is added in the end of one bias line and 4×4 as three varactors are added in the end of every two bias lines. For a capacitance changes from 1pF to 5pF, a tuning bandwidth of 0.97% was obtained in 1×1 array, and the maximum tuning bandwidth is 1.83% for a 2×2 array. For the 2×2 array, we have tried several ways to connect the varactors (see Fig. 7). The tuning characteristics are shown in Fig. 9. It shows that a smaller tuning range with only a single varactor added, and if two varactors are used, a larger tuning range could obtain. It is clear, a wider tuning range is obtainable when more varactors, or larger capacitance change, are used. When c2 and c3 were used together, a frequency change of 170MHz was achieved.

Table I
Summary of results obtained from a single, four and sixteen Gunn diode spatial power combiners, for L=18cm d=18mm in Fig. 1.

Spatial Combiner	Measured Frequency (GHz)	Predicted Frequency (GHz)	Measured ERP (mW)	Average Power per Diode	Maximum Efficiency (ERP/DC power) (%)
1×1 array	11.13	11.12	19.1695	19.1695	2.658
2×2 array	11.40	11.28	79.1010	19.7752	3.247
4×4 array	11.27	11.47	217.597	13.5998	2.188

Table II
The frequency tuning characteristics of a single, four and sixteen Gunn diode spatial power combiner, for L=18cm d=18mm in Fig. 1.

Combined Circuits	Oscillation Frequency (GHz)		Bandwidth (%)
	Capacitance =1PF	Capacitance =5PF	
1×1 array	11.34	11.45	0.97
2×2 array	11.37	11.58	1.83
4×4 array	11.46	11.66	1.73

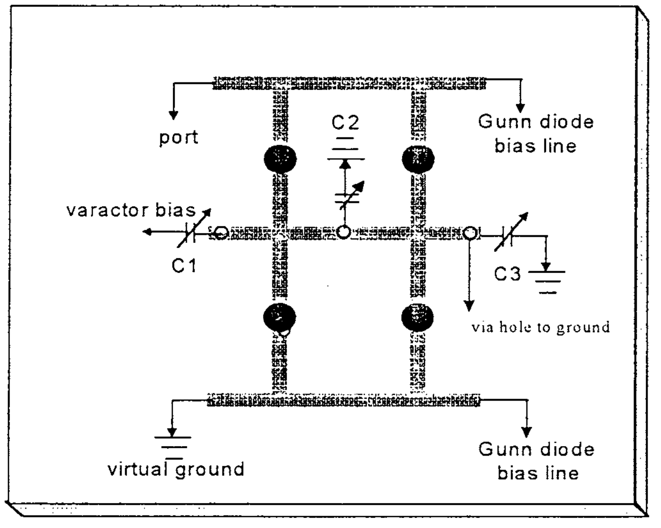

Fig. 7. The realization of frequency tunable quasi-optical microstrip dipole array

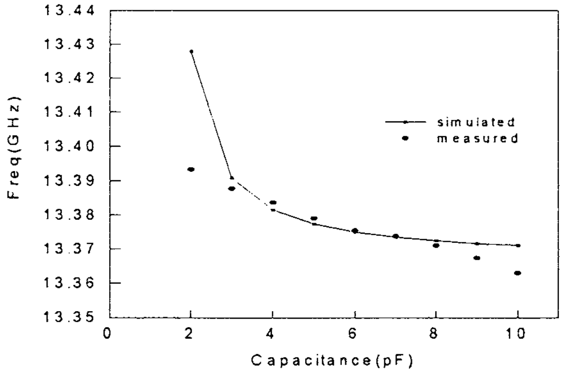

Fig. 8 The measured and simulated frequency tuning characteristic of 1×1 Grid VCO array by changing the varactor capacitance from 2pF(18V) to 10pF(0V)

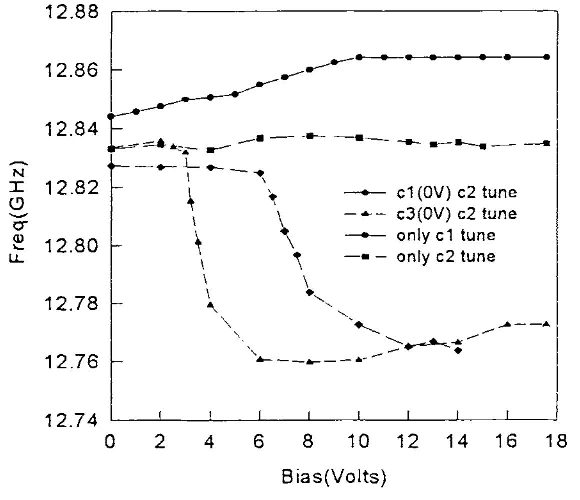

Fig. 9 The measured frequency tuning characteristic of 2×2 Grid VCO array by changing the varactor bias voltage from 0V(10pF) to 18V(2pF)

IV. Conclusions

A simple varactor tuned Gunn diode VCO antenna array is demonstrated. The frequency tunable oscillator array is demonstrated by adding several varactors on the ends or middle of the biasing line. The frequency of the oscillator array becomes tunable electrically, not by moving a mirror in the back side than ever. More varactors can be added between each diode along the bias line in order to improve the bandwidth. This tunable oscillator array structure can also be easily implemented by 3-terminal devices.

We have also developed a numerical method to actually predict the antenna characteristics from the basic short dipole formula. The advantages of the dipole array is its simple bias structure, and no need for resistors to eliminate multimode problem like in the patch array. Therefore, we can easily integrate many diodes on the same plane with using planar microstrip lines. And it can easily combine a large number of devices. Its backside ground plane helps to dissipate the heat of power combining. The E and H plane patterns of 1×1, 2×2 and 4×4 array still show that there are a serious heat problem. The most serious heat problem can be solved by using the pulse dc input power or the substrate with high thermal dissipation capability.

The dipole array concept can be suitable for much higher frequencies. Monolithic dipole array should be possible.

Acknowledge:

The authors wish to thank the financial support from the National Science Council under contract NSC86-2215-E009-032.

References:

[1] Zoya B. Popovic, Robert M. Weikle II, Moonil Kim, and David B. Rutledge, "A 100-MESFET Planar Grid Oscillator." *IEEE Trans. Microwave Theory Tech., vol. 39, pp. 193-200, Feb. 1993.*

[2] Robert M. Weikle, Moonil Kim, Jonathan B. Hacker, Michael P. De Lisio and David B. Rutledge, "Planar MESFET Grid Oscillators Using Gate Feedback," *IEEE Trans. Microwave Theory Tech., vol. 40, pp. 1997-2003, Feb. 1992.*

[3] Zoya B. Popovic and David B. Rutledge, "Diode-Grid Oscillators," *IEEE AP-S International Symposium, pp442-445, 1988.*

[4] Michael P. De Lisio, John F. Davis, Shi-Jie Li and David B. Rutledge, "A 16-Element Tunnel Diode Grid Oscillator," *IEEE AP-S International Symposium, pp1284-7, 1995.*

[5] Jonathan B. Hacker, Robert M. Weikle, II, Moonil Kim, Michael P. De Lisio, and David B. Rutledge, "A 100-Element Planar Schottky Diode Grid Mixer," *IEEE Trans. Microwave Theory Tech., vol. 40, No3, pp. 557-562, March, 1992.*

[6] Christina F. Jou, Wayne W. Lam, Howard Z. Chen, Kjell S. Stolt, Neville C. Lumann, Jr. And David B. Rutledge, "Millimeter-Wave Diode-Grid Frequency Doubler," *IEEE Trans. Microwave Theory Tech., vol. 36, No11, pp. 1507-1515, Nov, 1988.*

[7] Wayne W. Lam, Christina F. Jou, Howard Z. Chen, Kjell S. Stolt, Neville C. Lumann, Jr. And David B. Rutledge, "Millimeter-Wave Diode-Grid phase Shifter," *IEEE Trans. Microwave Theory Tech., vol. 36, No5, pp. 902-906, May, 1988.*

[8] Thomas Mader, Scott Bundy, and Zoya Basta Popovic, "Quasi-Optical VCOs.", *IEEE Trans. Microwave Theory Tech., vol. 41, pp. 1775-1781, Oct, 1993.*