COMPARISON OF A 4-ELEMENT LINEAR ARRAY AND A 2x2 PLANAR ARRAY

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ABSTRACT

Spatial power-combining arrays integrating single oscillator units are designed in two types of configurations. The first type is a 4-element linear array which connects single oscillator units in a straight line. The other type is a 2x2 planar array which connects single oscillator units in a loop. The oscillation modes of these two types of arrays are analyzed. The measurement results are compared. In each type of array, the oscillator units can be connected by metal strips or chip resistors. In the 4-element linear array, connecting with chip resistors can achieve the stable in-phase mode oscillation while connecting with metal strips cannot. In the 2x2 planar array, both types of connection are able to achieve the in-phase mode oscillation. The result shows that, for the power combining of 4 oscillator units, connecting them in loop does not require using resistors to stabilize the in-phase mode. The measured radiation patterns of both types of arrays are compared to the theoretical patterns.

INTRODUCTION

Power combining of solid state sources is of growing interest since the available power from a single device decreases as the frequency increases[1]. The quasi-optical power-combining technique has been proven to be a very efficient method to achieve high power from solid-state oscillators in millimeter wave region[2][3]. Several types of quasi-optical power-combining techniques have been reported. To combine the power spatially, individual oscillators can be synchronized by the Fabry-Perot resonator[4], an external injected signal[5], or through the mutual coupling[6][7]. The stability of oscillation modes in a spatial power-combining array with strongly coupled oscillators has been analyzed and an effective method of stabilizing the in-phase mode was proposed[8]. The use of resistors in the coupling line suppresses the undesired modes and stabilizes the in-phase mode.

However, the analysis in [8] discussed the case of linear arrays only. In the application of two-dimensional arrays, other types of connections are of interest, e.g., connecting the oscillators in a loop. In this paper, the oscillation modes of a 2x2 array in which oscillators are connected in a loop-structure are analyzed. The result is compared to the mode analysis of a 4-element linear array. Both types of the circuits are fabricated using Gunn diodes and microstrip patch antennas. The radiation patterns are measured and compared to the theoretical patterns. The arrays containing up to eight elements are analyzed and discussed.

CIRCUIT STRUCTURE

(i) 4-element linear array

The structure of the 4-element linear array is shown in Fig. 1. The circuit integrates four identical oscillators. Each oscillator unit consists of a Gunn diode as the source and a microstrip patch antenna as the radiator. The oscillators are connected by a microstrip coupling line for strong coupling. The length of the coupling line between oscillators is $1\lambda_g$, where λ_g is the guided wavelength of the in-phase mode frequency. The junctions at the mid-points of the coupling lines are designed for connecting oscillators with metal strips or chip resistors. The circuit is designed to have the in-phase mode oscillation at 12.45 GHz.

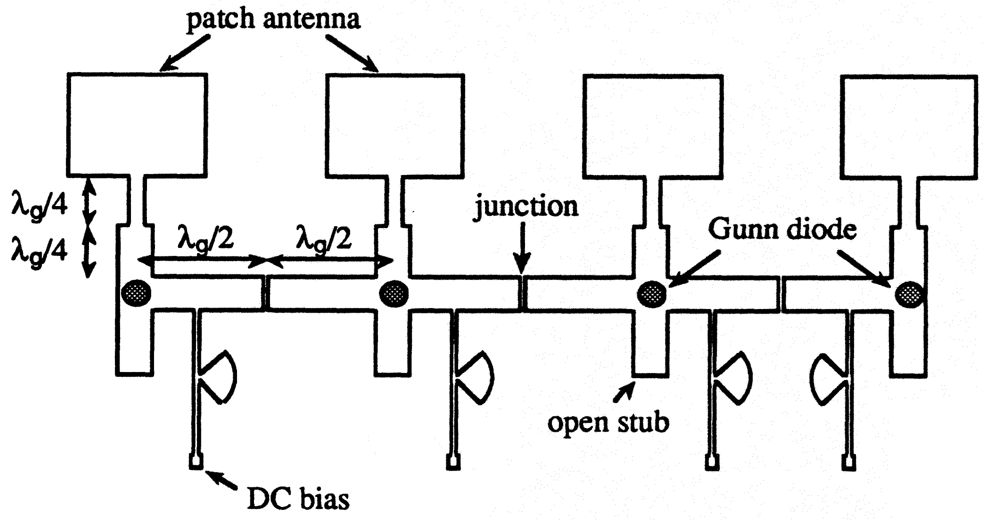


Fig. 1 Circuit structure of the 4-element linear array

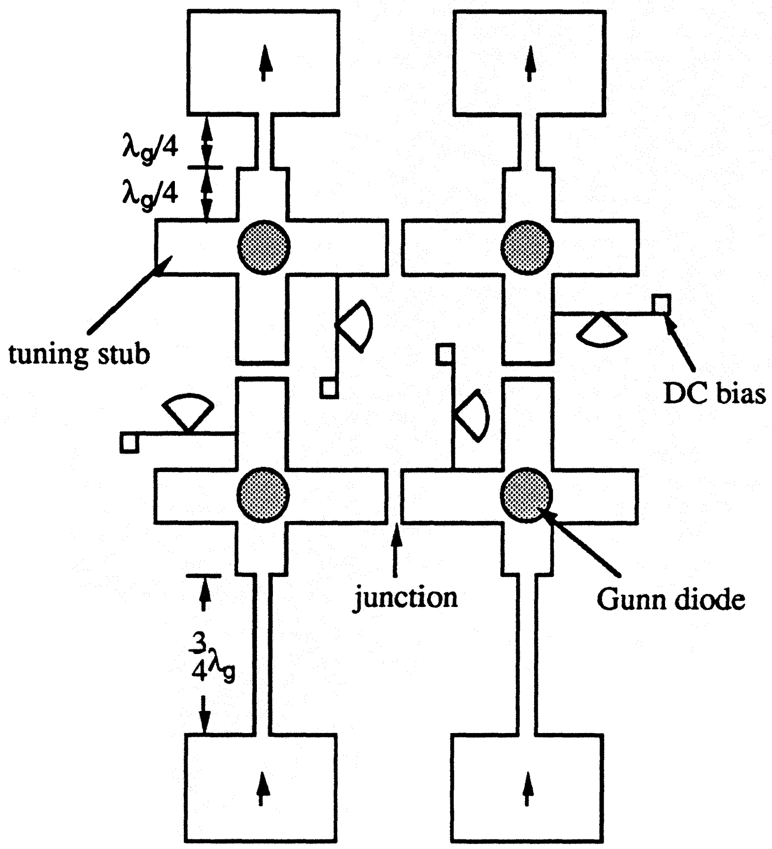


Fig. 2 Circuit structure of the 2x2 planar array

(ii) 2x2 planar array

The structure of the 2x2 planar array is shown in Fig. 2. Unlike the linear array, this 2x2 array is connected by a microstrip coupling line in the loop-structure. Each oscillator unit in this array is the same as in the 4-element linear array except that two of the feed lines are extended by $\lambda_g/2$ to compensate the phase shift of 180 degrees when two of the patch antennas are reversed. If these two feed lines are not extended, a difference pattern in E-plane will be obtained. The junctions are designed for connecting oscillators with metal strips or chip resistors. The operating frequency is also designed at 12.45 GHz.

MODE ANALYSIS

(i) 4-element linear array

The frequencies and the voltage distributions of normal modes in the linear array can be determined by the reactive system of the circuit(Fig. 3). The circuit equations are

$$j(b+b_d)V_1 + jb_tV_2 = 0 \qquad (1.a)$$

$$jb_tV_{k-1} + j(b+2b_d)V_k + jb_tV_{k+1} = 0 \qquad k=2,3,\ldots,N-1 \qquad (1.b)$$

$$jb_tV_{N-1} + j(b+b_d)V_N = 0 \qquad (1.c)$$

where

$$b = (\omega C - 1/\omega L)/Y_0 = Q_{ex}(\Omega - 1/\Omega) \qquad (2.a)$$

$$b_d = -\cot(\phi) = -\cot(\phi_0\Omega) \qquad (2.b)$$

$$b_t = \operatorname{cosec}(\phi) = \operatorname{cosec}(\phi_0\Omega) \qquad (2.c)$$

$$\omega_0 = 1/\sqrt{LC} \qquad (2.d)$$

$$\Omega = \omega/\omega_0 \qquad (2.e)$$

$$\phi_0 = \beta(\omega_0)d \qquad (2.f)$$

$$Q_{ex} = \omega_0 C/Y_0 \qquad (2.g)$$

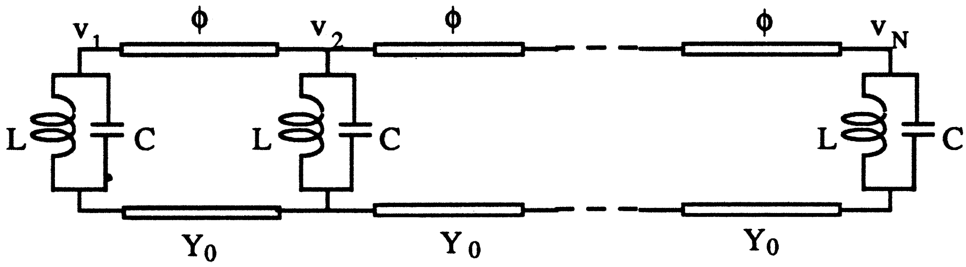


Fig. 3 Reactive system of the linear array

Eq.(1) can be written in a matrix form as

$$jb\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} + jb_t\mathbf{B}\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} = 0 \qquad (3)$$

where

$$\mathbf{B} = \begin{bmatrix} \gamma & 1 & & & & & \\ 1 & 2\gamma & 1 & & & \mathbf{0} & \\ & 1 & 2\gamma & 1 & & & \\ & & \ddots & \ddots & \ddots & & \\ & & & 1 & 2\gamma & 1 & \\ & \mathbf{0} & & & 1 & 2\gamma & 1 \\ & & & & & 1 & \gamma \end{bmatrix} \qquad (4.a)$$

with

$$\gamma = b_d/b_t = -\cos(\phi_0\Omega) \qquad (4.b)$$

The frequencies and the voltage distributions of the normal modes can be obtained from the eigenvalues and eigenvectors of matrix **B**, respectively. The value of Q_{ex}=5.5 is used, which is calculated from the simulation result of EEsof® EMSim. For the 4-element linear array in Fig. 1, N=4 so that four modes exist. By using the averaged potential theory and nonlinear device model, the stability of each mode is analyzed[8][9]. Here the van der Pol type of oscillator model is used. Two modes are stable single modes and the other two are stable double modes. The spectrum of the possible stable oscillation modes is shown in Fig. 4. For the purpose of power combining, the mode i=1 is required. This mode is called the desired mode or the in-phase mode, since the oscillator units oscillate in the same phase and with the same amplitude. Other modes are called undesired modes. Each undesired mode can oscillate at two frequencies of which one is higher than ω_0 and the other is lower than ω_0. They are then denoted by 2^H, 2^L, 3^H, 3^L, 4^H, and 4^L, respectively. The voltage distributions and the stabilities of all the modes are listed in Table 1.

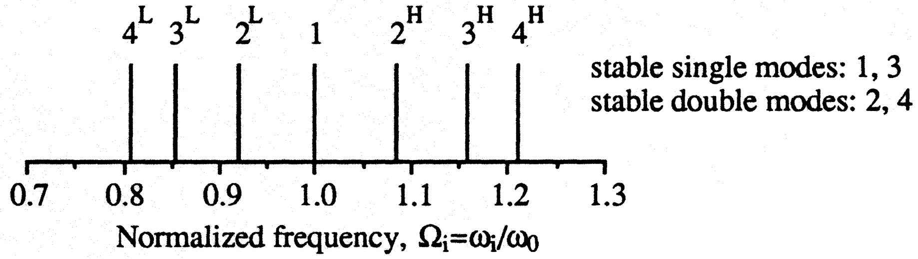


Fig. 4 Spectrum of the stable oscillation modes in the 4-element linear array

mode	voltage distribution	stability
1	1 1 1 1	stable, single
2^H	-.6487 -.2814 .2814 .6487	stable, double, with 4^H or 4^L
2^L	-.6489 -.2810 .2810 .6489	stable, double, with 4^H or 4^L
3^H	-.5519 .4421 .4421 -.5519	stable, single
3^L	-.5465 .4487 .4487 -.5465	stable, single
4^H	.3424 -.6187 .6187 -.3424	stable, double, with 2^H or 2^L
4^L	.3270 -.6269 .6269 -.3270	stable, double, with 2^H or 2^L

Table 1 Oscillation modes in the 4-element linear array

(ii) 2x2 planar array

The frequencies and the voltage distributions of normal modes in the planar array with loop-structure are determined by the reactive system of the circuit, which is similar to Fig. 3 but with a coupling line connecting the two ends to form a loop. The circuit equations then become

$$jb_tV_N + j(b+2b_d)V_1 + jb_tV_2 = 0 \tag{5.a}$$

$$jb_tV_{k-1} + j(b+2b_d)V_k + jb_tV_{k+1} = 0 \qquad k=2,3,...,N-1 \tag{5.b}$$

$$jb_tV_{N-1} + j(b+2b_d)V_N + jb_tV_1 = 0 \tag{5.c}$$

The corresponding matrix equation is similar to Eq. (3) but with

$$\mathbf{B} = \begin{bmatrix} 2\gamma & 1 & & 0 & & & 1 \\ 1 & 2\gamma & 1 & & & & \\ & 1 & 2\gamma & 1 & & 0 & \\ 0 & & \ddots & \ddots & \ddots & & 0 \\ & 0 & & 1 & 2\gamma & 1 & \\ & & 0 & & 1 & 2\gamma & 1 \\ 1 & & & & & 1 & 2\gamma \end{bmatrix} \tag{6}$$

Usually there are N modes in a system of N elements. However, in the loop-structure degeneracy occurs and the number of modes is reduced. For N=4, three modes exist. The stability of each mode is analyzed by using the averaged potential theory. Of these three modes, two are stable single modes and one is unstable. The spectrum of the possible stable oscillation modes is shown in Fig. 5. The mode i=1 is the desired power-combining mode and has the in-phase oscillation condition. Compared to the spectrum of linear array(Fig. 4), the separation between modes is larger and the number of possible oscillation modes is reduced. The voltage distributions and the stabilities of all the modes are listed in Table 2.

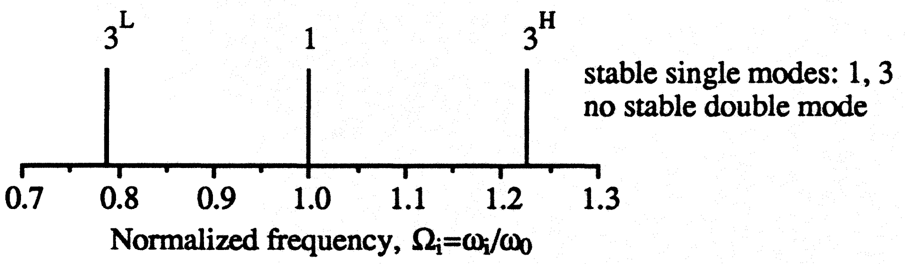


Fig. 5 Spectrum of the stable oscillation modes in the 2x2 planar array

mode	voltage distribution				stability
1	1	1	1	1	stable, single
2^H	.7071	0	-.7071	0	not stable
2^L	.7071	0	-.7071	0	not stable
3^H	.5	-.5	.5	-.5	stable, single
3^L	.5	-.5	.5	-.5	stable, single

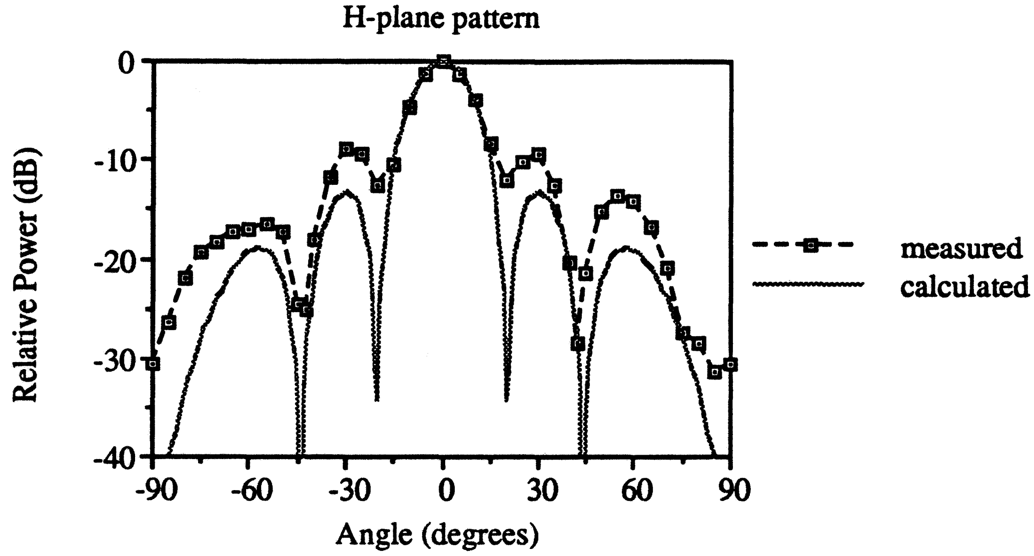
Table 2 Oscillation modes in the 2x2 planar array

EXPERIMENT

The oscillator units in the circuits were connected by metal strips or chip resistors at the junctions. The oscillation frequencies and the far-field radiation patterns were measured. The purpose of using resistors is to suppress the undesired modes, since the current distributions at the junctions are zero for the in-phase mode but are not zero for all the undesired modes. Resistors of 4.7Ω were chosen based on the theory of [8] for the coupling line with Z_0=50Ω. The insertion of metal strips at the junctions has no effect on the suppression of undesired modes since the resistance of metal is nearly zero. The measured radiation patterns are compared to the theoretical patterns to confirm the in-phase mode oscillation.

(i) 4-element linear array

The use of chip resistors was able to achieve the stable in-phase mode oscillation while the use of metal strips was not. When the chip resistors were used, the stable in-phase mode oscillation at 12.423 GHz was observed, which was only 0.2% deviated from the designed frequency 12.45 GHz. When the metal strips were used, the array could not oscillate at the in-phase mode and a spectrum of multi-frequencies was observed. The measured radiation patterns of the array with resistors are compared to the theoretical patterns(Fig. 6). The agreement between the measured patterns and the theoretical patterns confirms the in-phase mode oscillation. The Effective Radiated Power(ERP) was 25.1 dBm.



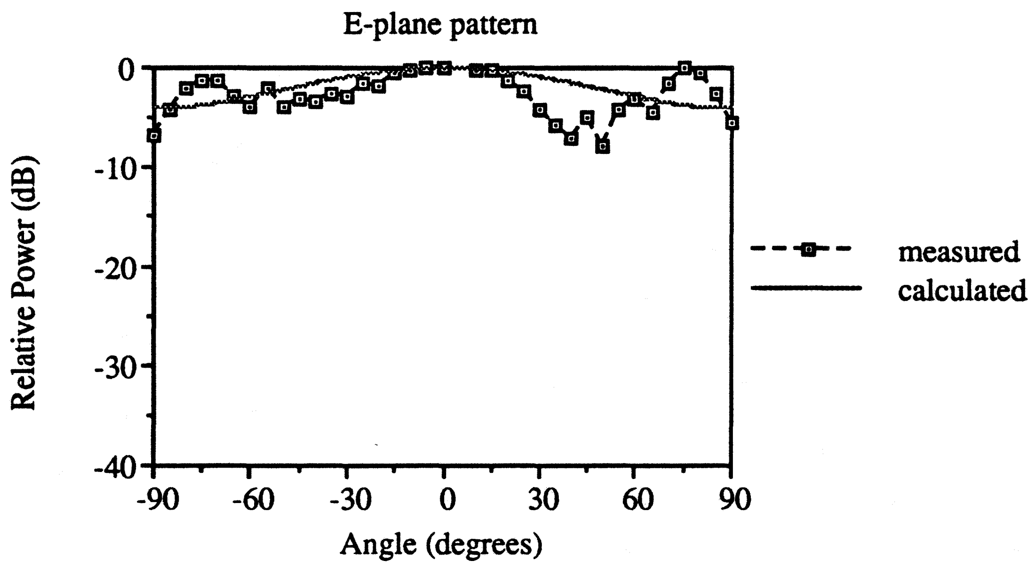


Fig. 6 Radiation patterns of the 4-element linear array

(ii) 2x2 planar array

The stable in-phase mode oscillation was obtained by using the chip resistors or the metal strips. Since the use of metal strips was not able to suppress the undesired modes, the success of stable in-phase mode means that there was only one stable mode in the circuit. This can be explained by the spectrum in Fig. 5. In Fig. 5, there are three possible oscillation frequencies. However, the difference between frequencies of the undesired mode and the in-phase mode is over 20% of the in-phase mode oscillation frequency ω_0. Due to the limited bandwidths of the Gunn diode and the patch antenna, the undesired mode 3^H and 3^L become unstable and the only stable oscillation mode is the in-phase mode. The oscillation frequency of the array was 12.395 GHz, which was 0.4% deviated from the designed frequency 12.45 GHz. The radiation patterns were measured and compared to the theoretical patterns(Fig. 7). The agreement between the measured patterns and the theoretical patterns confirms the in-phase mode oscillation. The ERP was 25.1 dBm, which was the same as in the linear array. The grating lobes in the E-plane can be eliminated by modifying the circuit design, e.g., separating the antenna elements from the feed network in multi-layer structure[10].

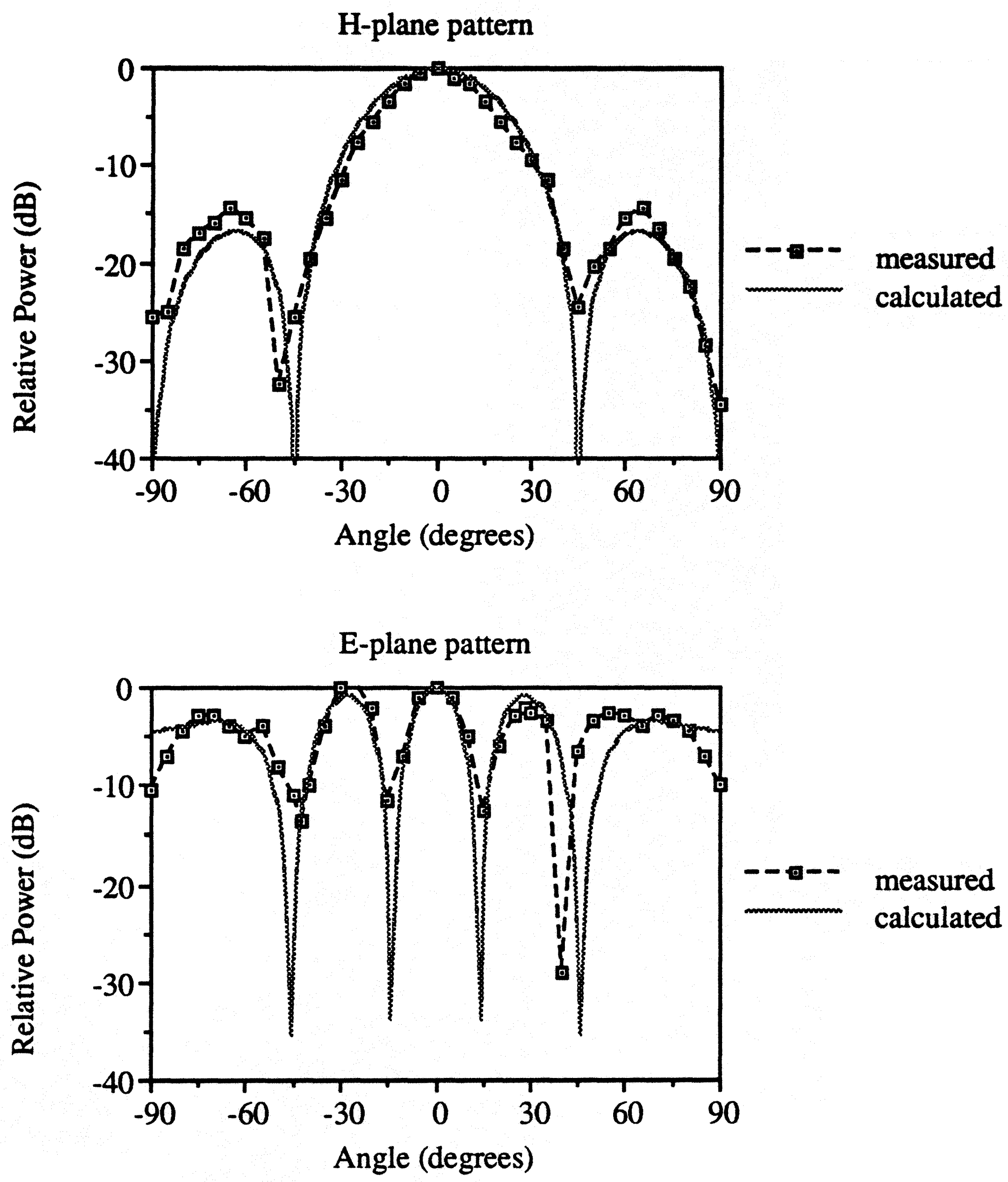


Fig. 7 Radiation patterns of the 2x2 planar array

DISCUSSION

The experimental result of achieving the in-phase mode oscillation in the 2x2 planar array without the use of chip resistors does not imply that such loop-structure power-combining arrays are free from the multi-moding problem. In fact, the number of modes increases and the frequencies of modes get closer when the number of oscillators increases. The comparison of modes in two different structures for the case of N=4, 5, 6, 8 is listed in Table 3. With the same number of devices, the loop-structure has fewer modes than the line-structure due to the degeneracy of modes. However, the total number of stable modes in loop-structure still increases and the use of chip resistors is needed for the effective suppression of undesired modes.

number of elements N	Total number of modes		stable modes of LINE-structure		stable modes of LOOP-structure	
	LINE	LOOP	single	double	single	double
4	4	3	2	2	2	0
5	5	3	1	4	3	0
6	6	4	2	4	4	0
8	8	5	2	6	4	0

Table 3 Comparison of modes in line-structure and loop-structure

CONCLUSION

Two types of configurations of the power-combining arrays with strongly coupled oscillator units are discussed. The theoretical analysis and the experimental investigation have been done. Oscillation modes in both types of arrays are analyzed and compared. The experimental results of the 4-element linear array and the 2x2 planar array are compared. Both types of structures can be applied to the circuit layout of the 2-dimensional arrays with strongly coupled elements.

ACKNOWLEDGMENT

This work was supported by the US Army Research Office under contract DAAH04-93-6-0068 and in part by the Joint Services Electronics Program F49620-92-C-0055.

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