Experiments of Device Failures in a Spatial Power-Combining Array

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***Abstract*—The performance of a spatial power-combining array with device failure is investigated. Experimental results show that the array still combines the power in the broadside direction when the DC open-circuit failure occurs. Analysis of measured radiation patterns indicated that the power radiated from the patch antenna attached to the failed device is much smaller than the power radiated from other patch antennas. The effects of the chip resistor and the RF impedance of failed device are discussed.**

I. INTRODUCTION

QUASI-OPTICAL power-combining technology has been proven to be a very efficient method of achieving high power from solid state oscillators at high frequencies [1], [2]. As the number of devices increase, however, device failures are very likely to occur during the fabrication process or normal operation. These device failures may ruin the performance of circuit. Therefore, it is necessary to investigate the effect of device failures in power-combining arrays.

Strongly coupled power-combining arrays integrating quasi-optical oscillators were developed [3]. An advantage of this type of array is that the coupling is confined in the guided wave structure so that it can be modeled by the network theory, as in the waveguide-type power combiners [4], [5]. Since the strong coupling in the array can be analyzed by the network theory, it can be controlled by appropriate circuit design. An example is a second harmonic power combiner [3]. Recently, the strongly coupled spatial power-combining array was analyzed by a theory based on the nonlinear device model and the averaged potential theory, and a method of achieving stable in-phase oscillation mode was proposed [6]. This method employs chip resistors in the coupling lines to suppress undesirable modes and stablize the in-phase mode. It has been proven to be a very efficient method of achieving in-phase oscillation in both 1-D and 2-D oscillator arrays [7].

So far, the theories in [3]–[7] all assume identical oscillators in the array and cannot deal with device failures. In this paper, a simple theoretical analysis considering device failures in the strongly coupled power-combining array is presented first. The result shows that the in-phase oscillation mode may still be maintained when device failure occurs. Experimantal results of a four-element array indicates that the array can still combine the power from the remaining active elements in the broadside direction when a DC open-circuit failure occurs. However, the oscillation mode is not the in-phase mode of the four-element array since the radiation pattern is changed. The effects of the chip resistor and the RF impedance of failed device are discussed.

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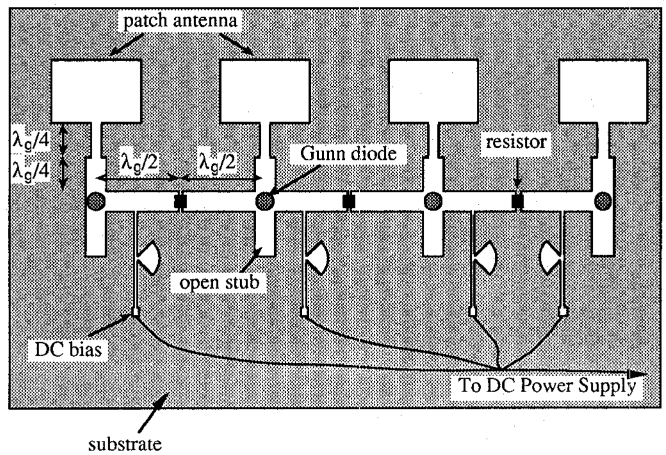

Fig. 1. Circuit structure of the spatial power-combining array.

II. CIRCUIT STRUCTURE

The structure of the spatial power-combining array to be analyzed in this paper is shown in Fig. 1. It is a microstrip circuit structure and the white portion indicates metal on the substrate. The array consists of four quasi-optical oscillators. Each oscillator integrates a Gunn diode and a patch antenna to form an active antenna unit. An inductive open stub cancels the capacitive part of Gunn diode impedance. The remained negative resistance of Gunn diode is matched to the input resistance of patch antenna at resonant frequency. To obtain maximum output power from the oscillator at the resonant frequency of patch antenna, the large-signal impedance of Gunn diode was used to design the oscillator [3]. These four oscillators are connected to a microstrip line for strong coupling. The length of the coupling line between adjacent oscillators is $1\lambda_g$, where λ_g is the guided wavelength at patch antenna resonant frequency. This array is designed to have the in-phase oscillation mode at the patch antenna resonant frequency. Chip resistors of 4.7 Ω are inserted at midpoints of the coupling lines to stabilize the in-phase oscillation mode [6]. Each oscillator has its own DC bias line, but is connected to the same DC power source. This avoids any voltage drop across the chip resistor and thus protects it from damage.

III. Theoretical Analysis

A. Power-Combining Array without Device Failure

A simple theoretical analysis based on Kurokawa's theory of multi-device oscillator circuit [8] is developed for the analysis of device failures in power-combining arrays. The in-phase oscillation condition is assumed to find out the states of the array that satisfy this condition.

From Kurokawa's theory of multi-device oscillator circuit [8], the oscillation condition is given by

$$\mathbf{ZI} = \overline{\mathbf{Z}}\mathbf{I} \tag{1}$$

where $\mathbf{Z}$ is the impedance matrix of the load circuit seen from the device ports, $\overline{\mathbf{Z}}$ is a diagonal matrix with each element equal to the negative of the device impedance $-Z_D$, and $\mathbf{I}$ is a vector containing the currents at each port. Following Mortazawi [3], assuming the insertion loss of chip resistors is neglected at in-phase mode, the impedance matrix $\mathbf{Z}$ of the array structure in Fig. 1 can be expressed as

$$\mathbf{Z} = \frac{Z_L}{4}\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix} \tag{2}$$

where Z_L is the transformed input impedance of the patch antenna after two-stage quarter-wavelength transformer.

When there is no device failure and the active devices are assumed to be identical, the impedance matrix $\overline{\mathbf{Z}}$ can be expressed as

$$\overline{\mathbf{Z}} = \begin{bmatrix} Z_D & 0 & 0 & 0 \\ 0 & Z_D & 0 & 0 \\ 0 & 0 & Z_D & 0 \\ 0 & 0 & 0 & Z_D \end{bmatrix} \tag{3}$$

When the oscillation is in-phase, voltages at device ports are the same. Currents at device ports should also be the same when device impedances are identical. The current vector $\mathbf{I}$ can be expressed as

$$\mathbf{I} = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \tag{4}$$

Multiply (2) with (4),

$$\mathbf{ZI} = \frac{Z_L}{4}\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} = Z_L\begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \tag{5}$$

Multiply (3) with (4),

$$\overline{\mathbf{Z}}\mathbf{I} = \begin{bmatrix} Z_D & 0 & 0 & 0 \\ 0 & Z_D & 0 & 0 \\ 0 & 0 & Z_D & 0 \\ 0 & 0 & 0 & Z_D \end{bmatrix}\begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} = Z_D\begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \tag{6}$$

Substituting (5) and (6) into (1), a simple relation between device impedance and load impedance is obtained:

$$Z_L = Z_D \tag{7}$$

This means that the load impedance is equal to the negative of device impedance in each oscillator, which agrees with the large-signal design of oscillator.

B. Power-Combining Array with Device Failure

When there are device failures, (2) is still valid but (3) needs to be modified. Assuming that the fourth device is failed and has a different impedance $-Z_4$, whereas all the other active devices still have the same impedance $-Z_D$.

$$\overline{\mathbf{Z}} = \begin{bmatrix} Z_D & 0 & 0 & 0 \\ 0 & Z_D & 0 & 0 \\ 0 & 0 & Z_D & 0 \\ 0 & 0 & 0 & Z_4 \end{bmatrix} \tag{8}$$

In order to have the in-phase oscillation, i.e., voltages at device ports are equal, the current at fourth port must be changed from 1 to Z_D/Z_4. Right hand side of (1) becomes

$$\overline{\mathbf{Z}}\mathbf{I} = \begin{bmatrix} Z_D & 0 & 0 & 0 \\ 0 & Z_D & 0 & 0 \\ 0 & 0 & Z_D & 0 \\ 0 & 0 & 0 & Z_4 \end{bmatrix}\begin{bmatrix} 1 \\ 1 \\ 1 \\ Z_D/Z_4 \end{bmatrix} = Z_D\begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \tag{9}$$

Left hand side of (1) then becomes

$$\mathbf{ZI} = \frac{Z_L}{4}\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} 1 \\ 1 \\ 1 \\ Z_D/Z_4 \end{bmatrix} = \frac{Z_L}{4}\begin{bmatrix} 3 + Z_D/Z_4 \\ 3 + Z_D/Z_4 \\ 3 + Z_D/Z_4 \\ 3 + Z_D/Z_4 \end{bmatrix} \tag{10}$$

Substitute (9) and (10) into (1), a relation between Z_D and Z_4 is obtained.

$$\frac{Z_D}{Z_L} = \frac{3}{4 - \frac{Z_L}{Z_4}} \tag{11}$$

Two types of device failures were observed during the operation of power-combining array. One is the DC short-circuit failure and the other is the DC open-circuit failure. If the RF impedance of a failed device is still the same as its DC impedance, the short-circuit failure is corresponding to $Z_4 = 0$ whereas the open-circuit failure is corresponding to $Z_4 = \infty$.

It can be seen from (11) that $Z_D = \frac{3}{4}Z_L$ when $Z_4 = \infty$, and $Z_D = 0$ when $Z_4 = 0$. Note that $Z_D = Z_L$ when $Z_4 = Z_L$. This means that in order to maintain the in-phase oscillation, the impedances of other active devices have to change when device failure occurs. For the short-circuit failure, the in-phase oscillation is impossible since Z_D cannot change drastically to zero. For the open-circuit failure, the in-phase oscillation can be achieved with certain amount of variations in device impedances. It is known that the device impedance will change with voltage amplitude in the large signal analysis. Therefore, the power of other active devices will change when open-circuit failure occurs.

IV. Experimental Results

A. Power-Combining Array without Device Failure

The four-element power-combining array without device failure was first investigated. This array is denoted by "1-1-1-1," of which "1" indicates the active device. The frequency, the radiation pattern, and the (ERP) of this array

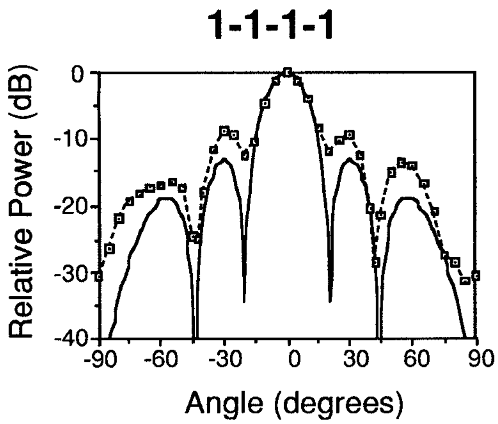

Fig. 2. H-plane radiation pattern of the four-element power-combining array without device failure.

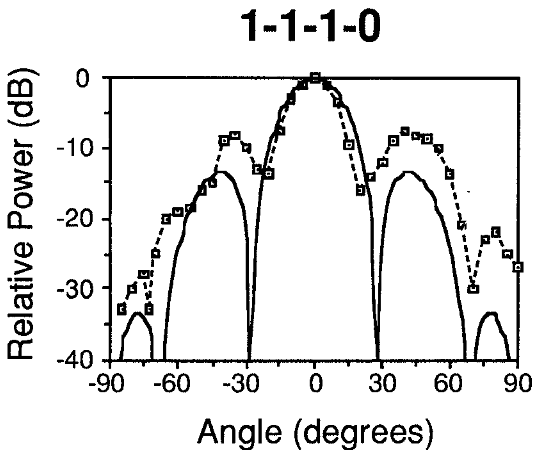

Fig. 3. H-plane radiation pattern of the four-element power-combining array with device failure "1-1-1-0."

were measured and recorded as references. Its oscillation frequency and ERP were 12.483 GHz and 25.6 dBm, respectively. The oscillation frequency is very close to the designed in-phase oscillation frequency, 12.45 GHz. The H-plane radiation pattern is shown in Fig. 2. The agreement between measured pattern and calculated pattern is quite well. The in-phase oscillation mode is thus confirmed.

B. Power-Combining Array with Device Failure

When a DC short-circuit failure occurred in the power-combining array, the DC power supply was shut off by the current limiter and the array could not work. Note that the DC bias lines are all connected together so that there is no DC voltage across chip resistors. When a DC open-circuit failure occurred, the array oscillated at a stable frequency very close to the in-phase mode, but the radiation pattern is different from the one in Fig. 2. Two examples are discussed here.

1) "1-1-1-0"

The fourth device of the array has the DC open-circuit failure, which is indicated by "0." The frequency, the radiation pattern, and the ERP of this array were measured and compared to the results without device failure. Its oscillation frequency was 12.529 GHz, which was 0.37% higher than the frequency without device failure. Its ERP was 21.6 dBm, which was 4 dB lower than the ERP without device failure. The measured H-plane radiation pattern is shown in Fig. 3. It is found that the measured pattern does not agree with the theoretical pattern of a uniformly excited four-element array, but agree more with the radiation pattern of the three-element array composed of the remaining active elements. This means that the patch antenna attached to the failed device is almost not radiating.

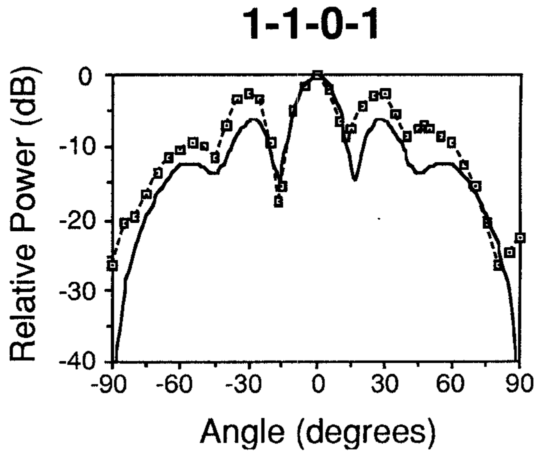

Fig. 4. H-plane radiation pattern of the four-element power-combining array with device failure "1-1-0-1."

2) "1-1-0-1"

The third device of the array, indicated by "0," has the DC open-circuit failure. The frequency, the radiation pattern, and the ERP of this array were measured and compared to the results without device failure. Its oscillation frequency was 12.432 GHz, which was 0.41% lower than the frequency without device failure. Its ERP was 22.1 dBm, which was 3.5 dB lower than the ERP without device failure. The measured H-plane radiation pattern is shown in Fig. 4. Similar to the previous case "1-1-1-0," the measured radiation pattern does not agree with the calculated pattern of a uniformly excited four-element array "1 1 1 1," but agrees more with the calculated pattern of a nonuniformly excited array "1 1 0 1." This result also shows that the patch antenna attached to the failed device is almost not radiating.

V. Discussion

The experimental result does not agree with the simple theoretical analysis. The discrepancy may come from two reasons. One reason is that the RF impedance of the failed device may not be the same as the DC impedance. The other reason is that the chip resistor will suppress the in-phase mode since its current distribution at the midpoint of the coupling line is not zero when there is a failed device in the array.

The RF impedance of the Gunn diode with DC open-circuit failure was measured. The result indicates that the RF impedance at 130 MHz is almost open, but it becomes $5.7 + j12.5\ \Omega$ at 12.45 GHz. This is a very small impedance and will affect the load condition in the array. In this case, if the in-phase mode is still maintained and all device ports have the same voltage, a very large current will flow through the failed device. This will induce a large power dissipation in the array and make this mode unstable [6].

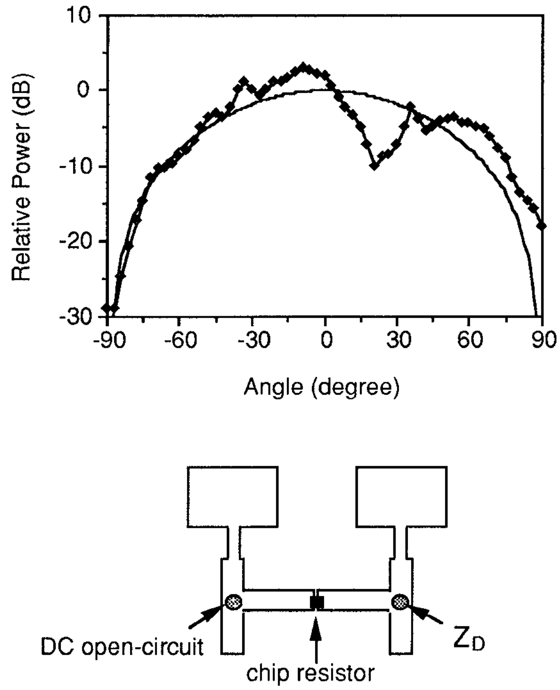

Fig. 5. Radiation pattern of the two-element array with a DC open-circuit failure and using chip resistor.

The simple theoretical analysis assumes the in-phase mode first and then gives the conditions of the array that satisfy the in-phase mode. This assumption may be invalid since this mode may not be the stable oscillation mode when device failure occurs. In the experiment, a stable oscillation was not able to be reached for the four-element array without the use of chip resistors. With chip resistors, a stable oscillation can be achieved, but the oscillation mode may not be the in-phase mode of equal excitation at each device port. The experiment of a two-element array is given as an example.

A two-element power-combining array in which one device has a DC open-circuit failure was examined. With the chip resistor placed at the midpoint of the coupling line, a radiation pattern very close to the single patch radiation pattern was observed (Fig. 5). The oscillation frequency, 12.482 GHz, is almost the same as the in-phase oscillation frequency of the two-element array without device failure. Comparing it to the radiation pattern of a single active antenna in Fig. 6, it is found that the patch antenna attached to the failed device may still radiate little power with different phase so that the radiation pattern of the other active antenna is affected. When the chip resistor in Fig. 5 is replaced by a metal strip, the oscillation frequency and the radiation pattern changed. The oscillation frequency is 13.533 GHz, which is much higher than the in-phase oscillation frequency of the two-element array without device failure. The radiation pattern is shown in Fig. 7. The radiation pattern is different from the one in Fig. 5, and it looks more like the pattern of a two-element antenna array with phase shift between two elements. This oscillation mode is different from the one observed in Fig. 5.

Therefore, the in-phase mode is not the stable mode for the two-element array with device failure and the use of chip resistor changes the oscillation mode. Because of the

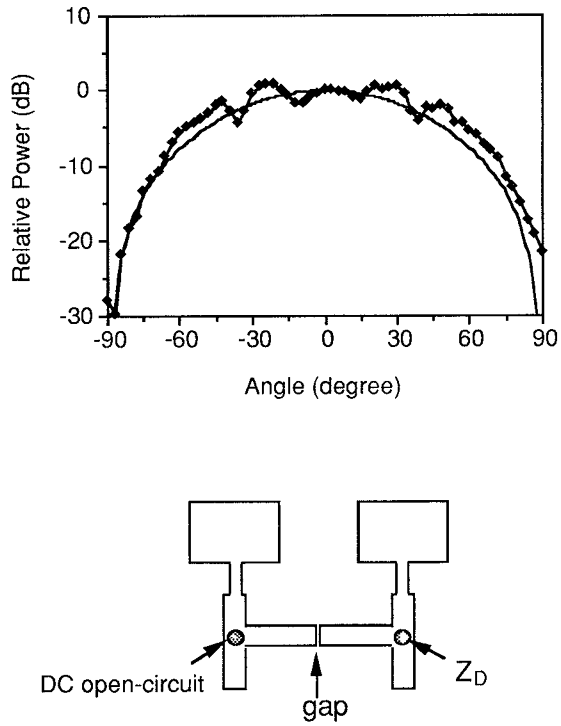

Fig. 6. Radiation pattern of the two-element array with a DC open-circuit failure and a gap on coupling line.

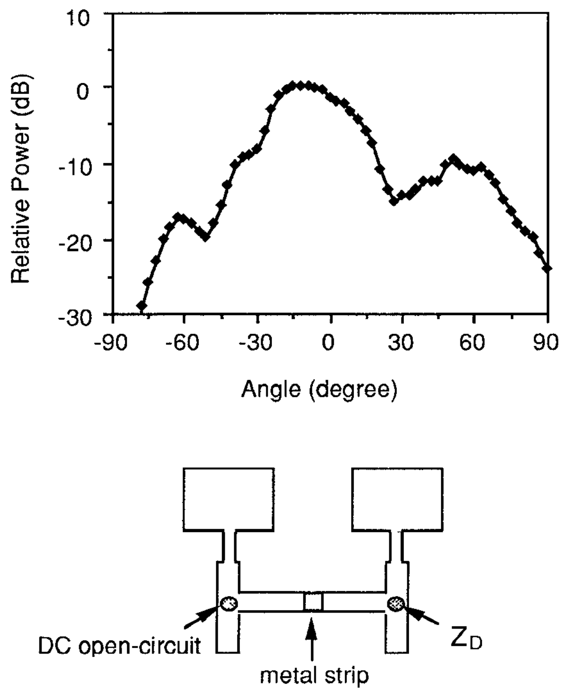

Fig. 7. Radiation pattern of the two-element array with a DC open-circuit failure and a metalstrip replacing the chip resistor.

suppression of current distribution by the chip resistor, the stable mode of the array with chip resistor should have the minimum current distribution at the midpoint of the coupling line. Since the frequency of the stable mode is almost the same as the one without device failure, the coupling line is still 1 λ_g and the current distribution at the position of failed device should also be minimum. At this position, no negative resistance of active device provides extra power.

Therefore, the power delivered to the patch antenna attached to this failed device should be very small. This explains the radiation patterns in Fig. 3 and Fig. 4. It also gives a lower averaged potential to satisfy the condition of a stable mode [9]. Instead of the simple analysis, the analytical method in [6] may be able to give an accurate solution. However, the analysis is very complex because the periodical nature is destroyed and the device impedances of the remaining active devices are unknown. The FDTD simulation [10] may be a practical method to analyze this nonlinear active circuit.

VI. Conclusion

Device failures in a spatial power-combining array are discussed in this paper. The simple theoretical analysis shows that the in-phase oscillation mode may still be maintained when device failure occurs. The analysis assumes that the array is operated at the in-phase mode and all the remaining active devices have the same impedance. The assumption may not be valid since the in-phase mode may not be the stable mode.

Experimental results of a four-element array indicates that the array can still combine the power from the remaining active elements in the broadside direction when a DC open-circuit failure occurs. Although the oscillation frequency is almost not changed, the oscillation mode is not the in-phase mode of the four-element array since the radiation pattern is changed. Analysis of the radiation patterns indicates that the patch antenna attached to the failed device radiates less power than the other patch antennas.

The RF impedance of the device with DC open-circuit failure and the experimental result of a two-element array is further examined. It is found that the RF impedance of the device with DC open-circuit failure is not an open due to the parasitic package effect. It is also found that the use of chip resistor changes the stable mode to a mode with minimum current distribution at the chip resistor site. These two factors affect the stable oscillation mode. Rigorous analysis of this complex system containing device failures may be accomplished by the FDTD simulation considering the nonlinear active device model.

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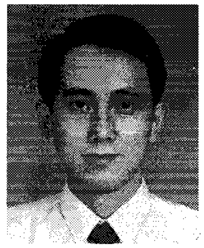

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