TRANSMISSION LINE COUPLED ACTIVE MICROSTRIP ANTENNAS FOR PHASED ARRAYS

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ABSTRACT

An effective transmission line coupling network for spatial power combining and beam scanning purposes is reported. The harmful effect of radiative coupling is eliminated using a modified version of this network for peripheral elements. A technique to control the inter-element phase differences of planar arrays was also developed. Experiments on 1×4 and 2×2 oscillator arrays using the proposed coupling network agrees well with the theory.

INTRODUCTION

In active phased antenna arrays precise adjustment of magnitude and phase of coupling between array elements is necessary. The transmission line coupling has been found fairly suitable for this purpose [1], [2], since the coupling between the array elements can be adjusted at even small antenna separations to overcome undesired radiative interactions. On the other hand, special care must be taken to maintain the mode stability [1] and a required amplitude-phase distribution of strongly coupled oscillator arrays [2] in the desired power combining mode. Also the problem of nonuniform signal injection, especially to the peripheral elements, becomes more serious when the radiative coupling between the array elements is strong. This causes nonuniform amplitude distribution in the array and consequently side-lobe level of the radiation pattern increases.

In this paper we propose a transmission line coupling network whose characteristics has small variation with frequency and with which it is also easy to obtain real coupling coefficients. A uniform net signal injection is achieved by using a modified version of this network for the peripheral oscillators. The technique described in [3] to control the inter-element phase differences in a linear array is extended for a general planar array. The effect of progressive phase shifts on the oscillator amplitudes is also explored. 1×4 and 2×2 beam scanning arrays were constructed and good agreement was observed with the theory.

COUPLED OSCILLATOR ARRAY

An active antenna is an antenna associated with an active device. It can be represented by an equivalent RLC circuit including a nonlinear impedance for active device. The nonlinear conductance of the active device is approximated by $g(V) = -g_1 + g_3|V|^2$. The free-running frequency, ω_i, can be slightly detuned by varying the capacitance of the active element via bias voltage. (Throughout this paper the variables belonging to the ith oscillator will be denoted by a subscript i.) In an array of mutually coupled N oscillators the injection current due to the couplings between the oscillators can be expressed as

$$I_{inj,i} = \sum_{j=1}^{N} Y_{ij} V_j \tag{1}$$

where $V_i = A_i e^{j(\omega_0 t + \phi_i)}$, ω_0 is the synchronization frequency and $Y_{ij} = |Y_{ij}| e^{-j\psi_{ij}}$ is the N-port Y-matrix element describing the coupling between the ith and jth elements.

Consider a linear array of identical oscillators in which nearest neighbor coupling is dominant. A practical in-phase operation can be obtained with equal free-running frequencies and $\psi_{ij} = \pi$ where i and j are the nearest neighbor elements. To obtain equal oscillator amplitudes $I_{inj,i}$ should be the same for any element in the array, which requires

$$\sum_{j=1}^{N} Y_{ij} = c \tag{2}$$

where c is an arbitrary constant.

COUPLING NETWORK

Consider the transmission line coupling network in Fig. 1 which is adopted from [1]. A chip resistor of conductance Y_c is assembled on the midpoint of a transmission line each ends of which are connected to the edges of nearest neighbor antennas where the polarity of instantaneous voltages are the same.

In Fig. 2 the variation of Y-matrix elements as a function of L/λ_g is shown. Keeping the difference between ψ_{11} and ψ_{12} close to 180° has two advantageous. First; imaginary part of (2) is kept small even when L is not exactly equal to λ_g, which is commonplace due to the manufacturing difficulties. Second; total variation of Y-matrix elements with frequency also decreases, which is necessary for broadband operation [2]. For $L = \lambda_g$ Y-matrix elements are purely real and can be represented as

$$Y_{ij} = \begin{cases} -Y_c & \text{if } j \text{ is a nearest neighbor to } i. \\ kY_c & \text{if } j = i, \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

where k is the number of the transmission line connected to the ith antenna. It is obvious that (3) satisfies (2) with $c = 0$.

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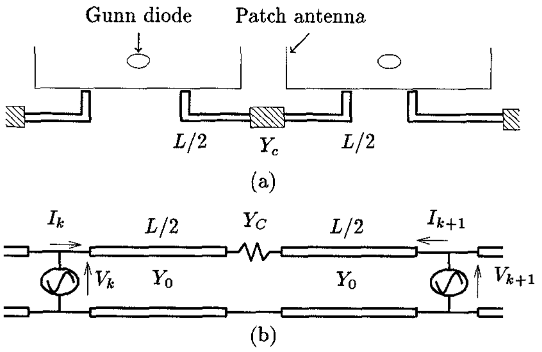

Fig.1 (a) The transmission line with a chip resistor on the midpoint to be used for the coupling of nearest neighbor oscillators. (b) Equivalent representation.

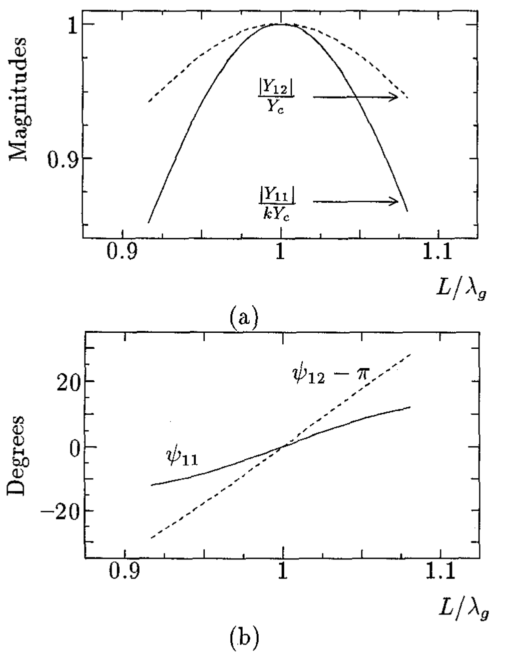

Fig.2 Y-matrix elements as functions of length of the transmission line ($Y_c = Y_0$). (a) Magnitudes, (b) phases.

In beam scanning arrays radiating elements are placed closely to increase the scanning ability of the array. Our experiments showed that the mutual radiative coupling between closely separated oscillators results anti-phase operation. Let us represent this coupling by an equivalent Y-matrix coefficient Y^R. In a linear array signal injection to the end elements is from one side while it is from both sides to inner elements. To satisfy (2) for the end elements as well, their self Y-matrix elements should be increased by Y^R. Provided that Y^R is purely real and positive, this can be achieved by using an extra transmission line network of which the open end part is $\lambda_g/4$ shorter, with a chip resistance of Y^R (see Fig. 5).

Phased Array Operation

A beam scanning technique for linear oscillator arrays where the nearest neighbor coupling is dominant and purely real was reported in [3]. It can be explained by mutual injection-locking theory [5] shortly as follows: Assume that initially all oscillators are operating at the same free running frequency which certainly results an in-phase operation. When free-running frequency of the first oscillator is increased slightly, a phase difference is established between the first and the second oscillators. While they are locking to a new frequency that is between their free-running frequencies, another injection locking takes place between the second and the third oscillators simultaneously. Since the injection signal to the third oscillator has a lower frequency than that of the second oscillator, third oscillator lags the second less than the second does the first. This process goes on till the last element of the array. To obtain a uniform phase shift along the array free-running frequency of the last element should also be detuned but in the opposite direction of which first oscillator was done.

If the oscillators are positioned along a rectangular grid to form a planar array, the free-running frequency distribution to establish progressive phase shifts, ϕ_x and ϕ_y along x- and y-axes respectively, can be obtained by superposing the free-running frequencies of each linear array; i.e.,

$$\Delta\omega_{i,j} \equiv \omega_{ij} - \omega_0 = \Delta\omega_{mx}\delta_i \sin\phi_x + \Delta\omega_{my}\delta_j \sin\phi_y \qquad (4)$$

where $\Delta\omega_{mx}$, $\Delta\omega_{my}$ are the locking bandwidths of the oscillators, and δ_p is defined as

$$\delta_p = \begin{cases} 1 & \text{if } p = 1 \\ -1 & \text{if } p \text{ is the last element along the row or column} \\ 0 & \text{otherwise} \end{cases}$$

The theoretical limit for ϕ_x, ϕ_y is $\pm 90°$. The angular synchronization frequency, ω_0, is obtained as the average of free-running frequencies of all oscillators in the array. A free-running frequency distribution for a planar array is illustrated in Fig. 3.

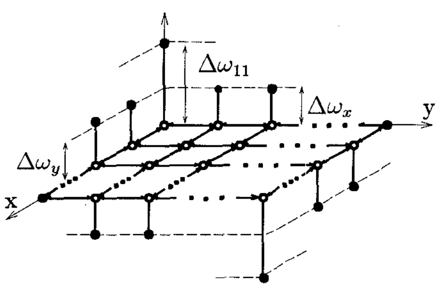

Fig.3 The free-running frequency distribution to obtain 45° successive phase shifts along both axes of a two-dimensional oscillator array.

Steady-state amplitude and phase solutions of a 4 × 4 oscillator array are shown in Fig. 4 as functions of free-running frequency of the first oscillator. Phase shifts along both axes are varied together according to (4). Particularly the effect of the progressive phase shifts on the oscillator amplitudes is explored. It is clear that as the progressive phase differences increase, the injection signal to each oscillator given by (1) becomes different. Consequently oscillator amplitudes deviate gradually from the uniformity. This non-uniformity causes desynchronization before reaching the theoretical limit of ±90°.

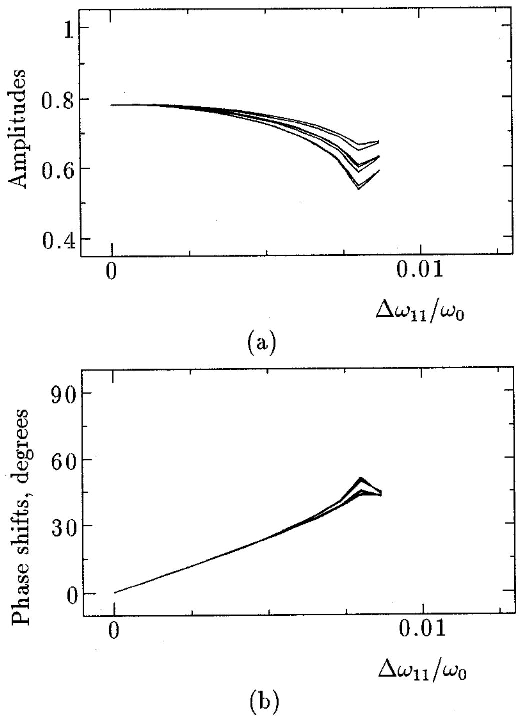

Fig.4 Steady-state solution of a 4 × 4 array. Parameters are $G_L = 0.005\mho$, $g_1 = 0.036\mho$ (seen from the coupling network), $Y_{cx} = Y_{cy} = 0.01\mho$, $Y_x^R = Y_y^R = 0.005\mho$. (a) Oscillator amplitudes normalized by $|V_{opt}|$ at which maximum power is obtained from the active device, (b) phase shifts between successive elements along both direction.

Experimental Results

A patch antenna with dimensions 12×9.5 mm^2 was constructed on a 0.508mm thick substrate with $\epsilon_r = 2.33$. An X- band Gunn diode was mounted at a location where the input admittance of the patch is calculated to be equal to the negative conductance of the diode to give maximum output power. The oscillator could be detuned by approximately 140 MHz at a centered frequency of 9.1GHz, within ±1.5dB power variation by changing the bias voltage from 8V to 12V.

1 × 2 **Array :** After a few trials the antenna separation, at which a two-element array operates anti-phase under the radiative coupling only, was determined to be 3.5mm edge to edge. When a λ_g length transmission line of characteristic impedance 100Ω with a 100Ω chip resistor on its midpoint

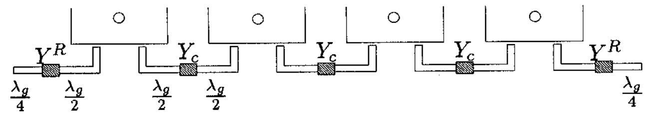

Fig.5 The 1 × 4 oscillator array. Small gaps were left between transmission lines and antennas for accurate free-running measurements.

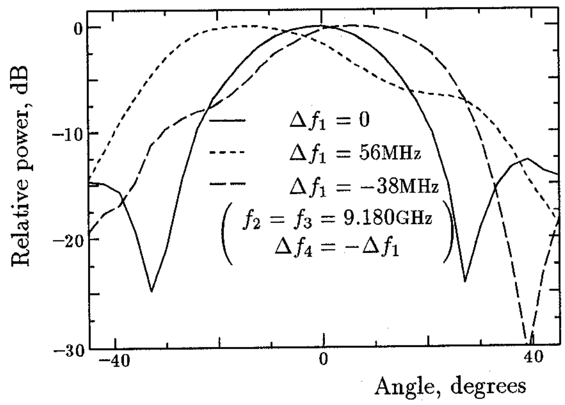

Fig.6 Radiation patterns of the 1 × 4 array.

was connected to antennas, oscillation turned out to be in-phase. The main beam could be steered from -10° to 15° off broadside where the theoretical limit is ±18° assuming a simple radiation pattern for the patch antenna. The radiative coupling was almost as half strong as the transmission line coupling.

1 × 4 **Array :** This time 4 oscillators were coupled with the same transmission line network. Keeping all oscillators synchronized to a single frequency the main beam could be steered only from 7° to -4°, where the theoretical limit is 27°. This obviously shows that the sum of radiative and transmission line coupling parameters does not satisfy (2). When the modified coupling network shown in Fig. 5 for end oscillators were connected with 200Ω chip resistors, scanning range increased to -17° to 10° (Fig.) Considerable decrease in the side-lobe power level was also observed.

2 × 2 **Array :** Next, a 2 × 2 array was constructed as shown in Fig. 7. Since each oscillator is a peripheral element, modified coupling network is not necessary for this array. Several radiation patterns of this array are shown in Fig. 8. The maximum scanning ranges were 25° in H-plane (the same as that of 1 × 2), 15° in E-plane and 20° for an elevation angle of $\phi = 45°$.

During the experiments synchronization frequency of the arrays were ±100MHz within the vicinity of average frequency. In our simulation results we found that if the mutual coupling coefficients are not purely real, scanning range is shortened in one side depending on the sign of the coupling phase angle. This must be the main reason for unequal scanning range limits towards the left and the right of the broadside.

CONCLUSION

A transmission line coupling network whose characteristics have small variation with frequency and with which it is easy to obtain in-phase operation was proposed. The harmful effect of radiative coupling on the transmission line network parameters can be eliminated using a modified version of this network for the peripheral oscillators. This was experimentally verified by a 1×4 array.

A free-running frequency distribution equation to establish progressive phase shifts along both axes of a planar array was derived. A 2×2 oscillator array was constructed and its maximum radiation beam was steered by 25° in H-plane and 15° in E-plane totally. These figures are almost half of the theoretical limits.

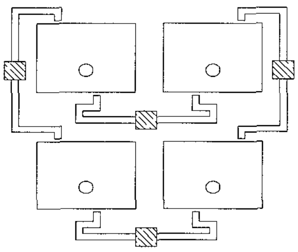

Fig.7 The 2×2 oscillator array.

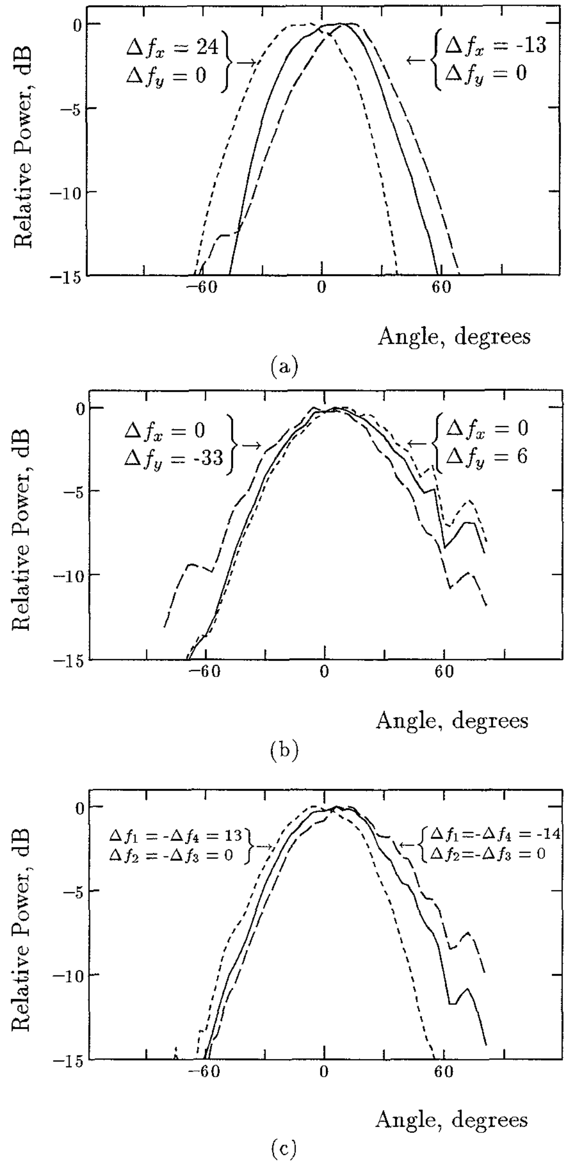

Fig.8 Radiation patterns of 2×2 oscillator array. Δf_x and Δf_y are in in MHz. (a) H-plane, (b) E-plane, (c) An elevation angle of $\phi = 45°$ plane. Solid lines are the radiation patterns in which free-running frequencies of all oscillators are the same.

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