A Seven-Element S-Band Coupled-Oscillator Controlled Agile-Beam Phased Array

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***Abstract*—This paper describes the design, fabrication, and testing of a seven-element S-band phased array, in which the beam is steered by means of a coupled-oscillator technique. Seven monolithic-microwave integrated-circuit-based voltage-controlled oscillators were coupled via microstrip transmission lines in such a manner that they mutually injection locked and, thus, oscillated as an ensemble. The output of each oscillator was connected to a microstrip patch array element and the seven elements were disposed in a line on a Duroid substrate. The resulting antenna was characterized in benchtop tests, revealing the relative phase behavior of the oscillators, and in range tests, producing far-field pattern cuts. Patterns showing beams steered to several angles were obtained by applying appropriate tuning voltages to the end oscillators of the array.**

***Index Terms*—Coupled oscillators, injection locking, phased arrays.**

I. BACKGROUND

SOME YEARS ago, it was suggested that an array of coupled oscillators can be used to control the phase distribution across the aperture of an array antenna in such a manner as to effect steering of the beam without the use of phase shifters [1]. One merely detunes the end oscillators of the array antisymmetrically to effect the steering. The behavior of such arrays of oscillators has been described in detail using a coupled set of nonlinear differential equations [2], [3]. These equations are derived by first describing the behavior of an individual oscillator with injection locking in the manner of Adler [4] and then allowing the injection signals to be provided by the neighboring oscillators in the array. More recently, an alternative description was developed by Pogorzelski *et al.* [5] in which the phase distribution across the array is represented by a continuous function governed by a partial differential equation of diffusion type. This formalism provides considerable insight concerning the relationship between the phase distribution and the tuning of the oscillators.

One result of the above theoretical treatments is a detailed understanding of the beam-steering scheme proposed by York and demonstrated in four-element X-band arrays by Liao and York [1], [2]. Their approach made use of the mutual coupling between the radiating elements of the array to achieve mutual locking of the oscillators. Thus, the element spacing was constrained by the necessary coupling strength. In another experiment, the coupling was accomplished by connecting the radiating elements by microstrip lines [6]. This also rendered the coupling dependent on the element disposition. In the approach described here, the coupling is achieved through microstrip transmission lines between the oscillator resonators. The RF outputs connected to the radiating elements are isolated from the oscillators (and their resonators) by buffer amplifiers intrinsic to the monolithic microwave integrated circuits (MMIC's) that were used. Thus, the element spacing is independent of the coupling and can be chosen for optimum performance of the radiating aperture. This is the primary difference between our work and that of our predecessors. The theory provides the relationship between coupling phase (the phase shift through the coupling network between nearest neighbors) and the ensemble frequency and locking range, relationships which were observed experimentally during the development of the present seven-element array. Moreover, the theoretical results were shown to accurately predict the beam-steering behavior of this array.

It is important to distinguish from the outset between arrays of oscillators with *strong* coupling to nearest neighbors such as those considered by Nogi *et al.* [7] and the present array of oscillators with *weak* coupling to nearest neighbors. In the strong-coupling regime, the neighboring oscillators influence both the phase and amplitude of the oscillation, leading to ensemble modes with both phase and amplitude variations across the array. The stability of these modes has been investigated in detail theoretically and verified experimentally [7]. The lowest order mode is the one desired for spatial power combining in that it has uniform amplitude and linear phase, and Nogi *et al.* [7] suggest a clever method of assuring dominance of this mode by inserting resistors in the coupling lines. In the weakly coupling regime, this lowest order mode dominates because the dynamic behavior of the amplitude is dominated by the saturation of the oscillator and is not significantly influenced by the signals coupled from the neighboring oscillators. Thus, in the present weak-coupled case, as indicated by York [2], "the amplitudes of the oscillators will remain close to their free running values. . ." and the phase can be controlled via tuning of the end oscillators.

In this paper, we describe the fabrication of the array of voltage-controlled oscillators (VCO's), the experimental determination of the behavior of this array, and comparison of the experimentally observed behavior with theoretical predictions. We further discuss the design of the microstrip patch radiating

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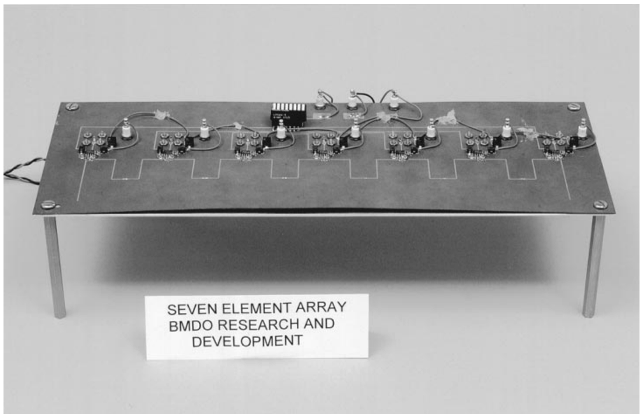


Fig. 1. Seven-element oscillator array.

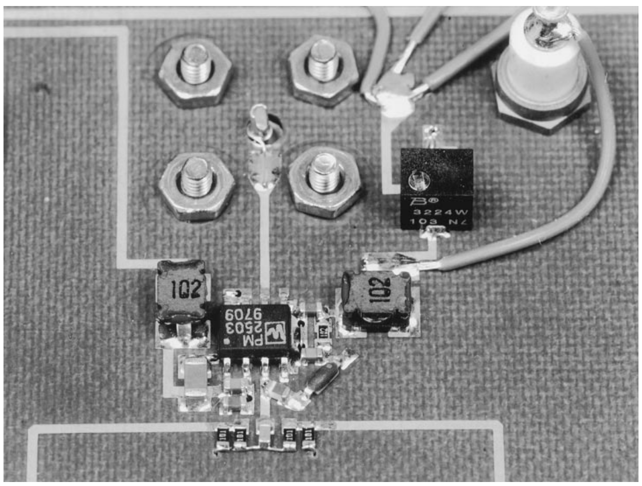


Fig. 2. Close up of one oscillator of the seven-element oscillator array.

aperture and the characterization of the resonant S-band elements. Finally, we describe the experimental measurement of the antenna patterns under various scan conditions.

II. Fabrication and Bench Testing of the Array

A commercial MMIC VCO suitable for operation at a nominal 2.5 GHz was selected[1] and a number of preliminary characterizations were performed to ascertain its suitability for the present application. Using the selected VCO, a seven-oscillator linear array was fabricated. This seven-element array is shown in Fig. 1 with an enlargement of the center oscillator shown in Fig. 2. A partial schematic is illustrated in Fig. 3, which includes an end oscillator and the oscillator adjacent to it. The rest of the circuit continues in a like manner to the far end.

The theoretical treatment is based on the assumption that the Q of the coupling circuit is much lower than that of the oscillators. To achieve this in our implementation, we terminated the 100-Ω coupling lines using 100-Ω chip resistors, as shown in Fig. 3. This was intended to reduce reflections from the ends of the line so that energy storage on the line in the form of standing wave was minimized. Minimum energy storage implies minimal Q (for a fixed loss). However, the actual termination of the line is modified by the value of the series coupling resistor, which is, in turn, set by the desired coupling strength. Moreover, Q is a function of the resistive loss as well as stored energy in the line. Thus, a matched termination does not necessarily correspond to minimal Q. Nevertheless, the present arrangement lowers the Q of the coupling line by roughly two orders of magnitude, which is considered sufficient for applicability of the theory.

It has been established that, for the parallel resonance of the present MMIC, the appropriate coupling line length is one wavelength [3]. However, because of the unknown phase shift inherent in connecting the lines to the MMIC, it was found useful to arrange for variable line length. Therefore, the inter-connecting (coupling) lines were meandered in a U shape such that they could easily be made to be full wavelength or half-wavelength or anything in between by moving the shorting bar along the U-shaped portion. With detailed measurements and modeling it should be possible to ascertain the proper line length and fabricate it without adjustment, and this may ultimately be the preferred method of manufacture. However, this was beyond the scope of the present effort. The U-shaped lines were a simpler solution for the present experimental array. (One might be concerned about the presence of two parallel lines over a portion of the path, but, at a single frequency, this is equivalent to a single line cut and terminated so as to have the same scattering parameters.) Once the optimal positions for the shorting bars were determined, the original lines were cut at each end of the bars to remove the excess line. Technically, this cutting operation changed the coupling phase to a slightly nonoptimal value, but the array locking range remained quite acceptable. Two discontinuities are introduced in each line by the difference in impedance between the lines and shorting bar, and this affects the impedance match at the oscillators. However, as discussed earlier, this match was not optimal in the present array regardless.

Fig. 4 illustrates a representative portion of the seven-element array. The layout includes a printed common-ground interconnect trace beneath the MMIC with several through connections to the underside ground plane. The board also features coaxial connectors so that each of the oscillators could either be monitored or influenced by external injection and a common tuning voltage bus so that only a single precision tuning supply was needed for test. Tuning of the individual oscillators was accomplished via ten-turn potentiometers connecting each oscillator to the bus. Note that the coupling lines have a gap halfway between the oscillators. This was to provide for a blocking capacitor, which, in fact, was not used. The blocking was actually accomplished via capacitors at the ends of the lines because the portion of the lines containing the gap were ultimately removed from the circuits by cutting the line as described above.

The oscillators, tested one at a time with no coupling, have the tuning curves illustrated in Fig. 5. The frequency spread from maximum to minimum for all seven oscillators is a nominal 4.5%. The entire group of seven curves are plotted so that the spread may easily be observed. Coupling the oscillators and tuning one at a time yields a 2.6-GHz breakpoint in the shape of the curves. The tuning curves for the seven coupled oscillators

[1]The authors gratefully acknowledge the assistance of Prof. R. A. York, University of California at Santa Barbara, and P. F. Maccarini, University of California at Santa Barbara, in selecting the Pacific Monolithics [PM2503] MMIC for the experiment and designing a preliminary board layout.

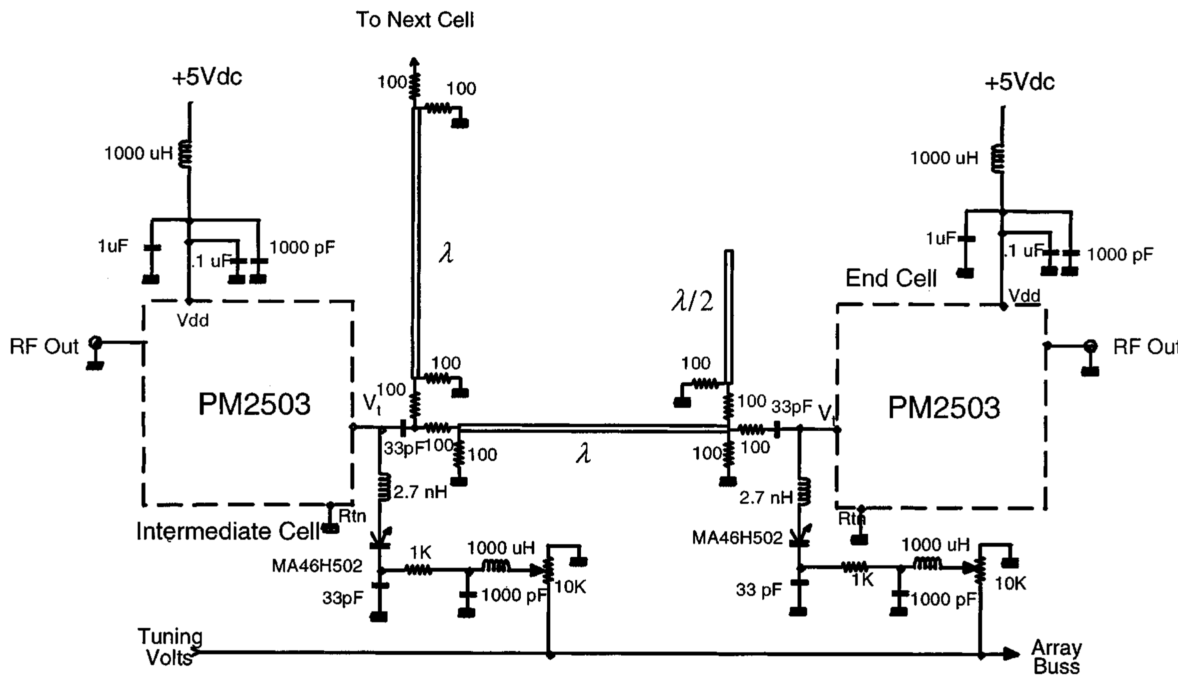


Fig. 3. Partial schematic of the seven-element oscillator array.

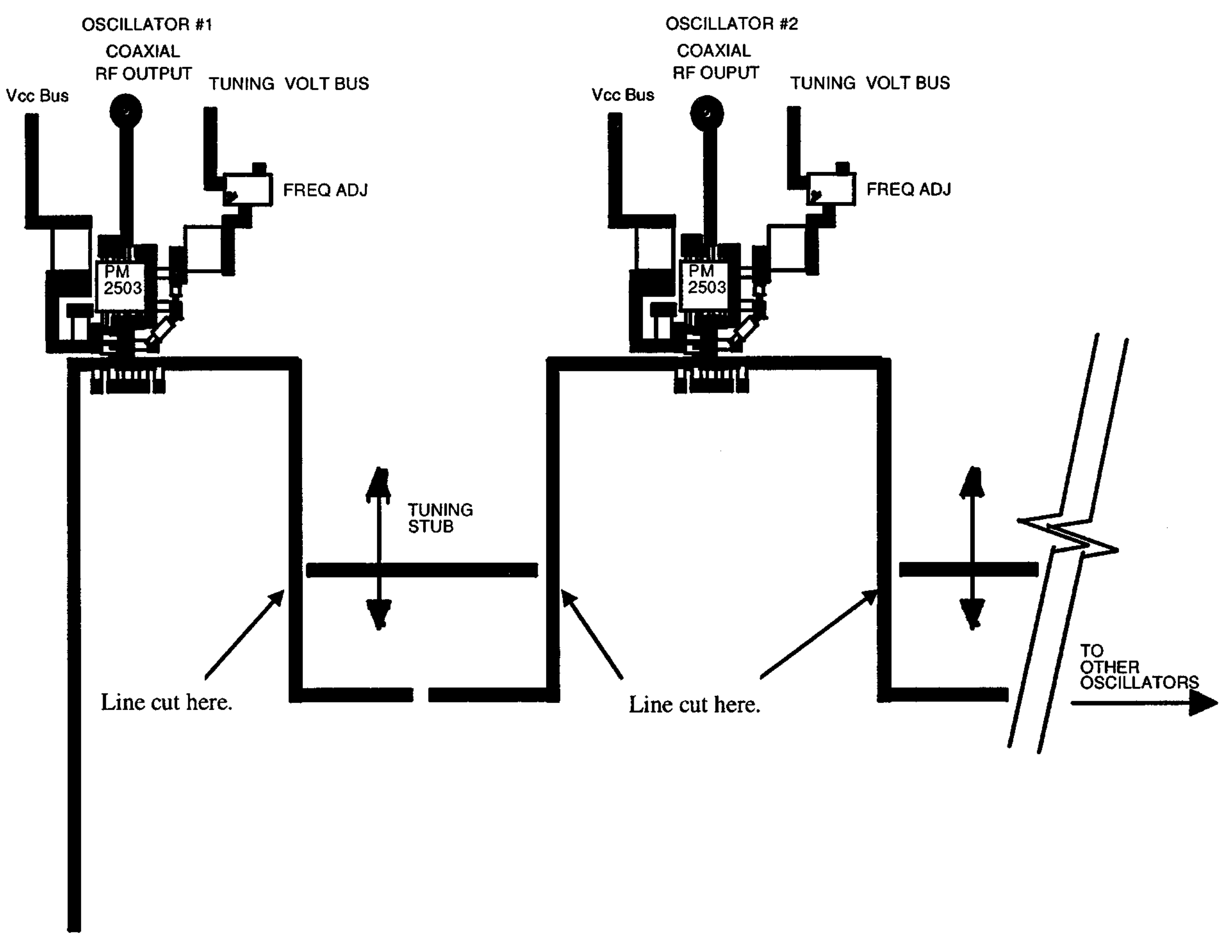


Fig. 4. Partial layout of the seven-element oscillator array.

are illustrated in Fig. 6. The tuning curves are nearly straight lines below 2.6 GHz, and discontinue below approximately 2.45 GHz. (The curves end because the oscillators ceased to function below this lower frequency.)

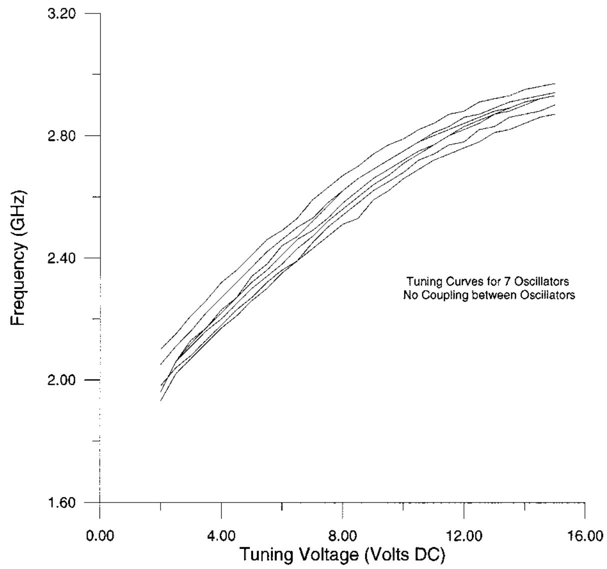


Fig. 5. Tuning curves of the uncoupled oscillators.

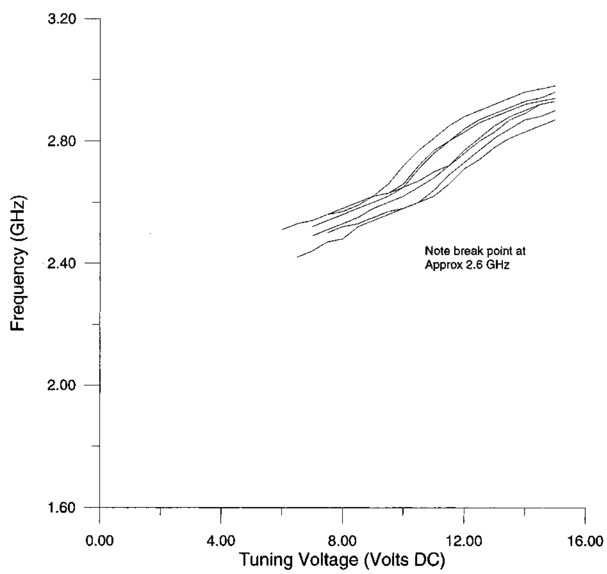


Fig. 6. Tuning curves of the coupled oscillators.

The locking range exists in the straight (linear) portion of the tuning curve below 2.6 GHz. Locking was not achieved above the 2.6-GHz breakpoint. Line-length adjustment via shorting bars permitted two theoretically predicted behaviors to be observed and, thus, confirmed during this investigation. First, when the coupling lines are an odd multiple of a quarter-wavelength in effective length, the locking range of the array is reduced to zero and no locking is possible. Second, when the coupling lines are an even multiple of a quarter-wavelength in effective length, the ensemble frequency is equal to the tuning frequency of the individual oscillators, whereas it differs from this value for other line lengths. This difference is maximized at odd multiples of a quarter-wavelength. These phenomena can be understood theoretically as follows.

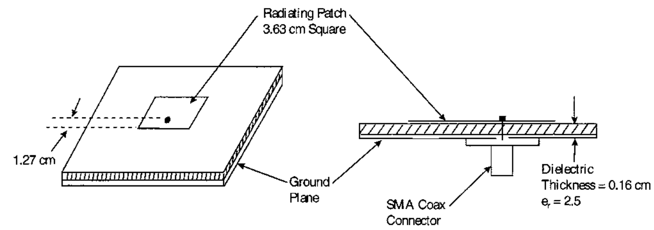


Fig. 7. Configuration of a single S-band microstrip patch radiator.

Beginning with [5, eq. (1)] for the present case of nearest neighbor coupling

$$\frac{d\theta_i}{dt} = \omega_{\text{tune},\,i} - \sum_{\substack{j=i-1\\ j\neq i}}^{i+1} \Delta\omega_{\text{lock},\,ij} \sin(\Phi_{ij} + \theta_i - \theta_j) \quad (1)$$

in which $\omega_{\text{tune},\,i}$ is the free-running frequency of oscillator i, $\Delta\omega_{\text{lock},\,ij}$ is the inter-oscillator locking range, Φ_{ij} is the coupling phase, and θ_i is the phase of oscillator i, we expand the sine function to yield

$$\frac{d\theta_i}{dt} = \omega_{\text{tune},\,i} - \sum_{\substack{j=i-1\\ j\neq i}}^{i+1} \Delta\omega_{\text{lock},\,ij} \Big[\sin(\Phi_{ij})\cos(\theta_i - \theta_j) + \cos(\Phi_{ij})\sin(\theta_i - \theta_j)\Big]. \quad (2)$$

Now, assuming that the phase differences are small as was done in deriving the linearized continuum model [5], this equation becomes

$$\frac{d\theta_i}{dt} = \omega_{\text{tune},\,i} - \sum_{\substack{j=i-1\\ j\neq i}}^{i+1} \Delta\omega_{\text{lock},\,ij} \Big[\sin(\Phi_{ij}) + \cos(\Phi_{ij})(\theta_i - \theta_j)\Big]. \quad (3)$$

For a uniform array, this becomes

$$\frac{d\theta_i}{dt} = \omega_{\text{tune},\,i} - \sum_{\substack{j=i-1\\ j\neq i}}^{i+1} \Delta\omega_{\text{lock}} \Big[\sin(\Phi) + \cos(\Phi)(\theta_i - \theta_j)\Big] \quad (4)$$

for all i. Defining the relative phase ϕ_i by

$$\theta_i = \omega_{\text{ref}} t + \phi_i \quad (5)$$

and selecting $\omega_{\text{ref}} = \langle\omega_{\text{tune},\,i}\rangle$; i.e., the average of the tuning frequencies over the array, we have

$$\frac{d\phi_i}{dt} = \omega_{\text{tune},\,i} - \langle\omega_{\text{tune},\,i}\rangle - \sum_{\substack{j=i-1\\ j\neq i}}^{i+1} \Delta\omega_{\text{lock}} \Big[\sin(\Phi) + \cos(\Phi)(\phi_i - \phi_j)\Big]. \quad (6)$$

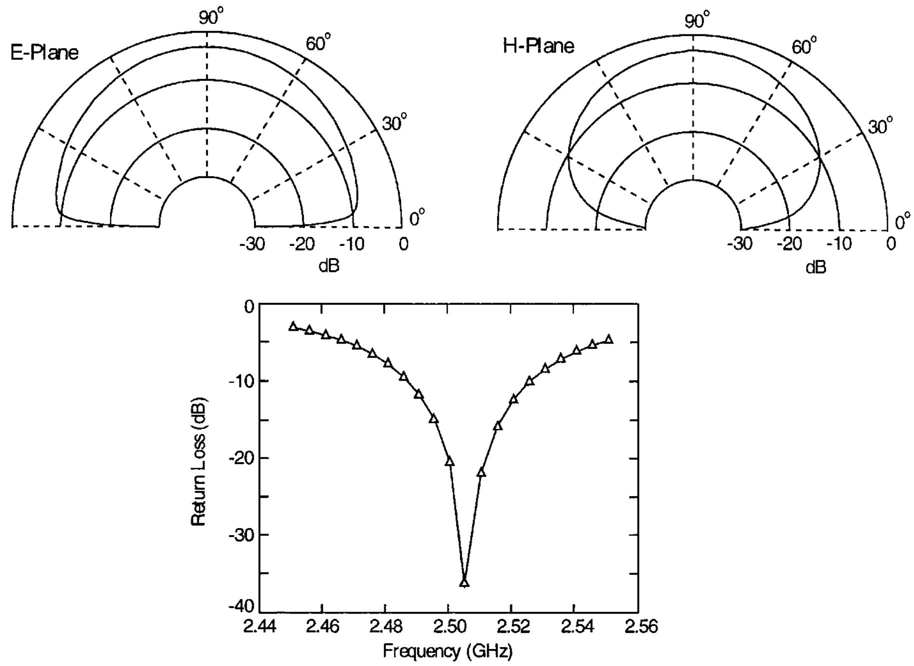


Fig. 8. Calculated performance of the single S-band patch radiator.

This equation can now be expressed in the form

$$\frac{d\phi_i}{dt} = \left(\omega_{\text{tune},\,i} - \langle\tilde{\omega}_{\text{tune},\,i}\rangle\right) - \sum_{\substack{j=i-1 \\ j\neq i}}^{i+1} \Delta\tilde{\omega}_{\text{lock}}(\phi_i - \phi_j) \quad (7)$$

where

$$\langle\tilde{\omega}_{\text{tune},\,i}\rangle = \langle\omega_{\text{tune},\,i}\rangle + \Delta\omega_{\text{lock}}\sin(\Phi) \quad (8)$$

and

$$\Delta\tilde{\omega}_{\text{lock}} = \Delta\omega_{\text{lock}}\cos(\Phi). \quad (9)$$

In [5], it was shown that the steady-state ensemble frequency of the array is equal to the average of the free-running frequencies $\omega_{\text{tune},\,i}$ of the oscillators. From (8), it is clear that when the coupling phase is an odd multiple of $\pi/2$, this ensemble frequency is shifted by one locking range. Similarly, from (9), we see that under these conditions the effective array locking range is reduced to zero. Ideally then, the coupling phase should be an even multiple of π, resulting in maximal locking range and no shift in the ensemble frequency. This was the goal in adjusting the coupling phase in the experimental array. Note that if the coupling phase is an odd multiple of π, the oscillators lock with an additional phase difference of π; i.e., their phases will alternate along the array. This behavior has been explained in detail by Chang *et al.* [3].

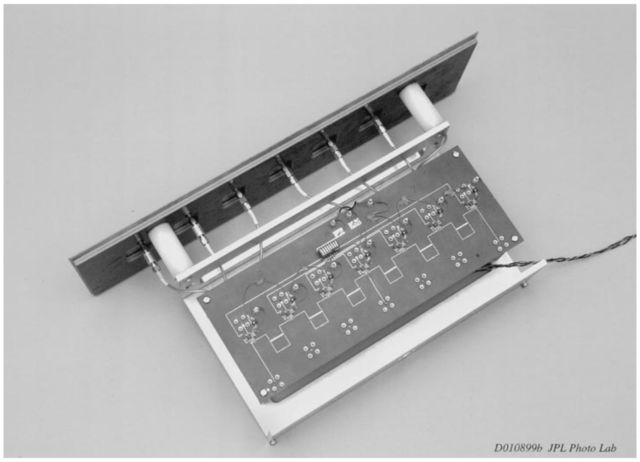
Although the theory predicts a maximum differential of ±90° between adjacent oscillators only about ±60° was actually observed. This was accomplished by adjusting the tuning bias upward in voltage (and frequency) on one end oscillator and downward in voltage (and frequency) on the other end oscillator, thus maintaining a constant average tuning frequency. The oscillators, being locked to their neighbors, do not actually change oscillation frequency. The result is that the array oscillator output signals remain at the same frequency, but their differential phase is controlled by the tuning. It is believed that the inability to achieve the full 90° phase difference between adjacent oscillators was due to the limited tuning range available. That is, before 90° was reached, one or more oscillator outputs decreased in amplitude to a level at which they no longer participated in the interaction.

III. Design and Fabrication of the Radiating Aperture

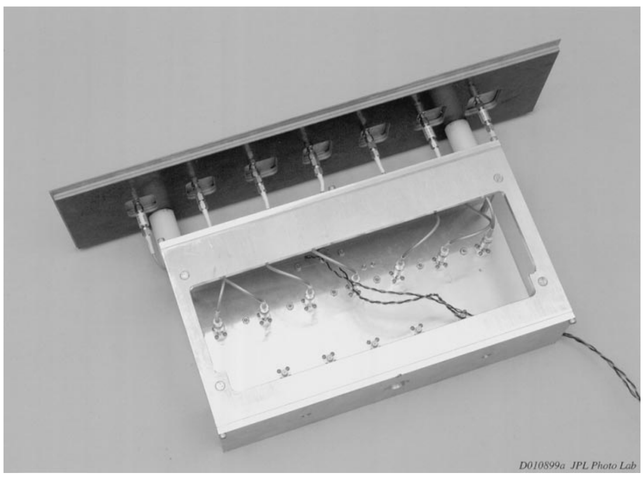
Each oscillator in the array provides an output RF signal properly phased with respect to the others. To radiate this signal, one must provide each oscillator with a properly designed radiating antenna element. Each element must be properly impedance matched to the oscillator and must radiate the RF energy with a wide enough beamwidth to achieve wide-angle beam-scanning capability. The overall array antenna beam will then be a result of the spatial power combining that takes place in the radiating aperture. A microstrip patch was selected as the radiator because of its low profile and small weight, as well as its capacity to be conformally mounted onto a curved surface. This choice also provides negligible mutual coupling between the elements, a property that was confirmed by the agreement between the measured array pattern and that predicted theoretically neglecting mutual coupling. A practical advantage of the microstrip patch is that all array elements can be fabricated on a single slab of substrate material with a single chemical etching process, which can significantly lower the production time and cost.

A. Microstrip Patch Element

The configuration of a single microstrip patch element is shown in Fig. 7, where a square metallic patch is constructed, by a conventional chemical etching process, on a thin dielectric substrate with a conducting ground plane situated beneath it. The square patch, which was designed to resonate



(a)



(b)

Fig. 9. (a) Seven-element phased-array antenna (top view). (b) Seven-element phased-array antenna (bottom view).

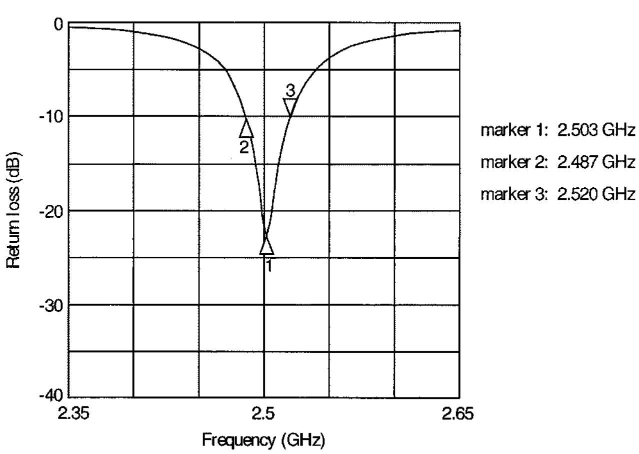


Fig. 10. Measured return loss of one patch element of the seven-element array.

at 2.50 GHz, has a dimension of 3.63 cm. It is designed by using the Ensemble computer software, which employs an integral-equation technique (method of moments). To have a comfortable bandwidth for the radiator, the dielectric substrate was designed to have a thickness of 0.16 cm with a relative dielectric constant of 2.5. This dielectric substrate is made of the Rogers Duroid Teflon impregnated fiber-glass material,

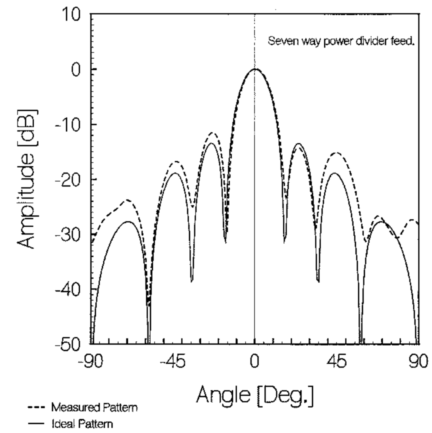


Fig. 11. Measured array pattern of the seven-element array with the oscillator circuit replaced with a master oscillator and a seven-way power divider.

which can survive extreme temperature variations of more than 100 °C. The square patch is excited at its 50-Ω input-impedance location, which is 1.27 cm from the patch's edge, by an SMA coaxial probe.

The calculated radiation patterns of the single-patch element in the two principal planes (E- and H-planes) are given in Fig. 8, where relatively wide beamwidths are demonstrated. In the same figure, the calculated input impedance match, in terms of return loss, is also given. It shows that the antenna resonates at 2.505 GHz and has a 2 : 1 VSWR (−10-dB return loss) bandwidth of about 35 MHz (1.4%).

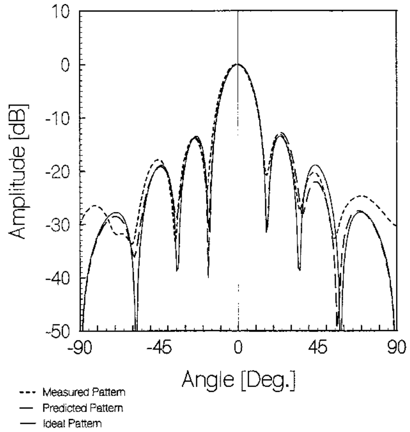
B. Seven-Element Microstrip Patch Array

A seven-element array achieves sufficiently narrow beamwidth to demonstrate the beam scanning with adequate beam resolution. Photographs of the actual fabricated array (top and bottom views) are shown in Fig. 9. The seven identical elements are spaced uniformly with half free-space wavelength spacing of 6.0 cm at 2.50 GHz. They are fabricated by etching on a rectangular substrate panel of 51 $\times$ 15 cm. The elements are arrayed in the H-plane.

The measured input return losses of all seven patch elements are very much the same, and a typical measured return-loss-versus-frequency plot is given in Fig. 10. A resonant frequency of 2.503 GHz and a bandwidth of 33 MHz were measured and found to be very close to the calculated values in Fig. 8. The radiation pattern of the seven element array, measured with a conventional seven-way power divider, is shown in Fig. 11. By using the conventional power divider, the radiation performance of the array can be independently assessed without including the effect of the oscillator circuits. These results indicate that the seven-element microstrip array developed here is adequate for the oscillator array demonstration.

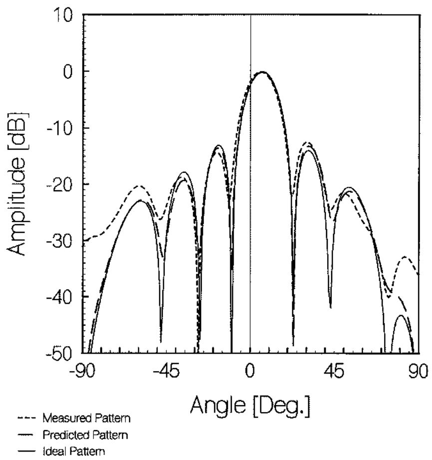
IV. Range Testing of the Array Antenna

Having established that the seven-element oscillator array could be mutually injection locked and could provide linear phase distributions suitable for beam steering and controllable by detuning the end oscillators, a matched set of seven cables was fabricated with which to connect the outputs of each of the



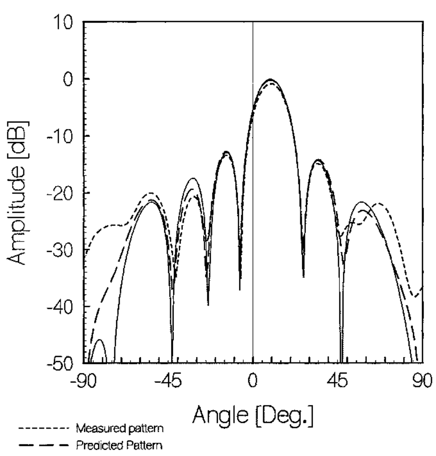
Osc.	Freq. (GHz)	Pwr (dBm)	Tuning Voltage	Phase (Deg.)
1	2.530	- 9.67	7.39	0.0
2	2.530	- 9.50	8.40	-4.9
3	2.530	- 9.17	9.65	-6.7
4	2.546	-10.00	6.99	6.8
5	2.530	- 9.17	8.01	0.0
6	2.530	- 8.83	8.29	-5.6
7	2.530	-10.83	8.72	2.3

Fig. 12. Experimental array pattern for 0° scan.



Osc.	Freq. (GHz)	Pwr (dBm)	Tuning Voltage	Phase (Deg.)
1	2.547	- 9.00	7.89	0.0
2	2.530	- 9.67	8.40	- 32.2
3	2.530	- 9.50	9.65	- 45.5
4	2.546	-10.00	6.99	- 59.6
5	2.530	- 9.17	8.01	- 83.6
6	2.530	- 9.00	8.29	-106.5
7	2.519	- 10.83	8.50	-121.7

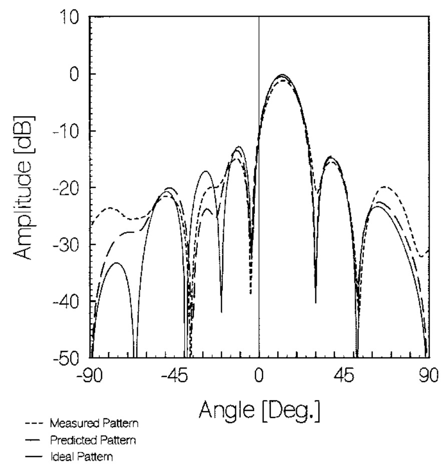
Fig. 13. Experimental array pattern for 6.38° scan.



Osc.	Freq. (GHz)	Pwr (dBm)	Tuning Voltage	Phase (Deg.)
1	2.553	- 8.83	8.03	0.0
2	2.530	- 9.67	8.40	- 37.0
3	2.530	- 9.50	9.65	- 63.4
4	2.546	-10.17	6.99	- 99.7
5	2.530	- 9.17	8.01	-123.5
6	2.530	- 9.17	8.29	-155.0
7	2.514	-11.17	8.37	-179.5

Fig. 14. Experimental array pattern for 9.59° scan.

seven oscillators to a corresponding microstrip patch element in the radiating aperture. In preparation for the measurement, each of the oscillators was tuned to 2.522 GHz measured with a spectrum analyzer (HP-8562A) and the voltage necessary to do this was recorded. However, it was found that the amplitudes of the oscillator outputs were not equal. In fact, they varied over a range of approximately plus or minus 3.5 dB. Therefore, attenuators (pads) were inserted in each of the lines to equalize the amplitudes while maintaining equal phase change in each line. (Of course, a production array would be designed so as to obviate the need for these attenuators and their inherent loss.) Having done this, the end oscillators were detuned by an amount necessary to create phase progressions corresponding to steering angles of 6.38°, 9.59°, and 12.84° (phase differences



Osc.	Freq. (GHz)	Pwr (dBm)	Tuning Voltage	Phase (Deg.)
1	2.554	-8.83	8.07	0.0
2	2.530	-9.67	8.40	- 49.4
3	2.530	-9.50	9.65	- 71.6
4	2.546	-10.33	6.99	-128.0
5	2.530	-9.17	8.01	-156.0
6	2.530	-9.50	8.29	-192.0
7	2.496	-12.50	7.95	-242.0

Fig. 15. Experimental array pattern for 12.84° scan.

between the end oscillators of 120°, 180°, and 240°) and the necessary tuning voltages recorded. The array was then placed on the measurement range and patterns were measured using each of the above four tuning voltage configurations.

In anticipation of the need for a reference signal to which to lock the range receiver, provision was made to injection lock the center oscillator of the array to a master oscillator (HP-8648C), which would provide the necessary locking signal to the receiver. Thus, the oscillator array and receiver were locked to the same signal during the measurement. However, it was found that the injection line to the center oscillator tank circuit loaded the circuit, thus changing its free-running frequency to approximately 2.55 GHz. Nevertheless, when the injection signal was applied, the oscillator of course oscillated at the desired 2.523 GHz. According to the theory, the effect of this is a phase shift between the external injection signal and the output of the center oscillator, but no effect is anticipated regarding the relative phase of the center oscillator and the others in the array. The anticipated phase shift with respect to the injection signal is of no consequence in the measurement because the system only depends on the coherence of the reference signal and not on its absolute phase.

A uniform set of 10-dB pads was installed, one at the back of each of the patch elements in the radiating aperture to eliminate the effects of the mismatch due to operation slightly off the patch resonance, and a set of measurements was taken. This mismatch is evident in the return loss of approximately −7 dB at 2.53 GHz shown in Fig. 10. Here, again a production array would be designed for a good match at the operating frequency and no attenuators would be used.

The corresponding results are shown in Figs. 12–15 in which the ensemble frequency and injection frequencies were 2.522 GHz. The chart associated with each graph shows the free-running frequency to which each oscillator was tuned and the voltage required to tune it. Also shown is the relative output power level and relative phase of each oscillator under locked conditions. These levels, read from the spectrum analyzer, and phases, measured with a network analyzer (HP-8410A), were used to computationally predict the pattern shown in long dashes for each scan angle.

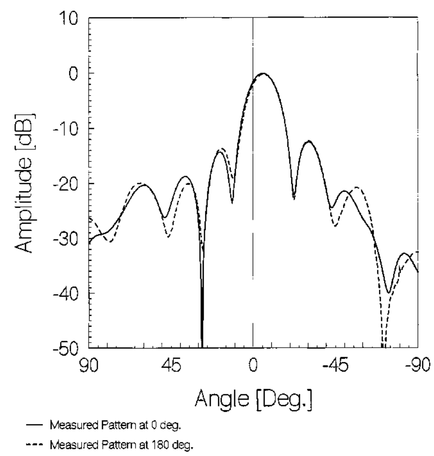


Fig. 16. Comparison of patterns at 0° and 180° of roll and 6.38° scan.

As a final check, the array was tuned for 6.38° of scan and the pattern was measured at roll angles of 0° and 180°. Then the 180° pattern was reversed and plotted over the 0° pattern. This effectively compares measurements with the anechoic chamber rotated 180° about the boresight. The comparison is a measure of the degree to which chamber artifacts have affected the measurement accuracy. In the absence of chamber asymmetries, the two patterns would overlay perfectly. The results of this test are shown in Fig. 16. It is noted that chamber asymmetries are below 2 dB above the −20-dB level.

These results show very satisfactory agreement between the measured and predicted patterns and close alignment with the desired beam scanning. Based on these results, it is believed that the array is performing in a manner consistent with utility in a communications application.

V. Concluding Remarks

A seven-element S-band phased array based on the coupled oscillator beam-steering concept has been fabricated. We have described an experimental investigation of the behavior of this array in which several theoretically predicted characteristics of such an array have been verified experimentally. The array provided an agile beam, which could be steered from boresight to nearly 13° by merely adjusting the voltages applied to the tuning ports of the end VCO's in the array. High efficiency, however, will require additional attention to uniformity in the oscillator output levels and to the impedance match between the oscillator outputs and the radiating elements; a match which was not optimal in the present experiment due to the difference between the design frequency of the patch elements and the ultimate ensemble frequency of the array.

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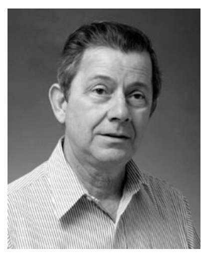

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