A Two-Dimensional Coupled Oscillator Array

Ronald J. Pogorzelski

***Abstract*—Design, fabrication, and test of a two-dimensional (2-D)coupled oscillator array is described. The array consists of nine voltage-controlled oscillators in a 3 $\times$ 3 configuration and operates at S-band. It is demonstrated experimentally that the array can generate planar phase distributions suitable for producing a radiated beam which is agile in two dimensions via tuning of the perimeter oscillators only. This is believed to be the first implementation of such an array.**

***Index Terms*—Injection locking, phased arrays, voltage controlled oscillators.**

I. Introduction

ONE-DIMENSIONAL (1-D) arrays of mutually injection locked voltage controlled oscillators with bi-directional nearest neighbor coupling topology have been shown to generate linear phase distributions suitable for producing agile radiated fan beams.[1], [2] The beam steering is accomplished by antisymmetric detuning of the free running frequencies of only the end oscillators of the array. It has been conjectured that a similar two-dimensional (2-D) array could generate, via detuning of the perimeter oscillators, planar phase distributions suitable for producing radiated beams which are agile in two dimensions. In fact, analysis has shown that the necessary detuning of the perimeter oscillators is constant along each edge of the array thus reducing 2-D beam steering to the control of four applied tuning voltages in equal and opposite pairs.[3] To test this conjecture, a 2-D array of oscillators was built and characterized. The results of this are reported here.

II. Array Design

The voltage controlled oscillators which were selected for the array are model PM-2503 by Pacific Monolithics. These are the same oscillators as were used in the seven element 1-D array reported previously [2]. The primary advantage of this particular MMIC for the present application is the fact that the tuning varactor is external to the package. This provides appropriate access to the oscillator for coupling purposes. A second advantage is the presence of a buffer amplifier between the oscillator FET and the output of the MMIC. This isolates the output from the oscillator circuit so that the design of the antenna to which the outputs are to be connected is separated from the design of the oscillator coupling network.

Manuscript July 27, 2000; revised September 15, 2000. This work was performed by the Telecommunications Science and Engineering Division, Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

The author is with Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA.

Publisher Item Identifier S 1051-8207(00)10940-7.

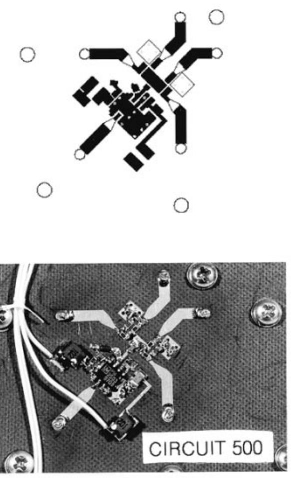


Fig. 1. Board layout for one unit cell and the assembled oscillator circuit.

The primary difference in design between the previously reported 1-D array and that of the present 2-D one lies in the design of the coupling network which connects the nearest neighboring oscillators. In the case of nonedge oscillators there are four such nearest neighbors in 2-D whereas in 1-D there are only two. Another difference, abeit a nonessential one, is that the coupling transmission lines for the 2-D array have a characteristic impedance of 50 Ω while those of the 1-D array were 100 Ω lines.

As in the 1-D case, the coupling between neighboring oscillators is accomplished via a transmission line with a resistor network at each end. The resistor network consists of a parallel resistor to lower the Q of the coupling network and a series resistor to control the strength of the coupling. A low Q coupling network is required for consistency with the theoretical analysis which assumes that the coupling is independent of frequency over the operating band. The strength of the coupling must be sufficient to provide adequate locking range for operational convenience. A further consideration is that a wide locking range implies a rapid response time for the array as a whole. On the other hand, the coupling must be sufficiently weak that the oscillator amplitudes remain nearly equal to each other and that network does not load the oscillators too heavily thus squelching the oscillation. In the two dimensional case, this loading effect is typically twice that encountered in the one-dimensional case. With these considerations in mind, the parallel resistance was chosen to be 220 Ω and the series resistance was chosen to be 120 Ω replacing the 100 Ω resistors used in the 1-D array.

The board layout of one oscillator is shown in Fig. 1 together with a photograph of the physical circuit. Note the four coupling lines and the provisions for the associated resistors. The ground pads are connected through the board to the ground plane with a number of wires passing through the holes in each pad. The microstrip lines end in SMA jack connectors to which

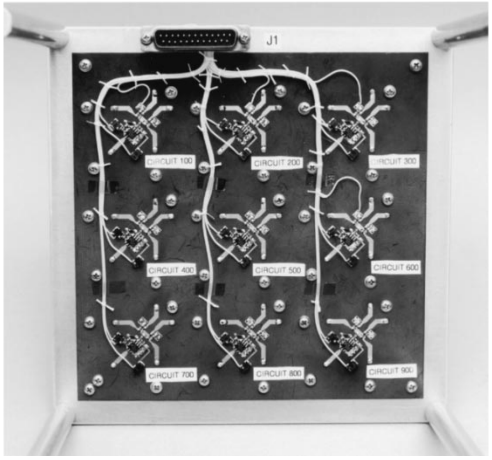


Fig. 2. Assembled nine-element board.

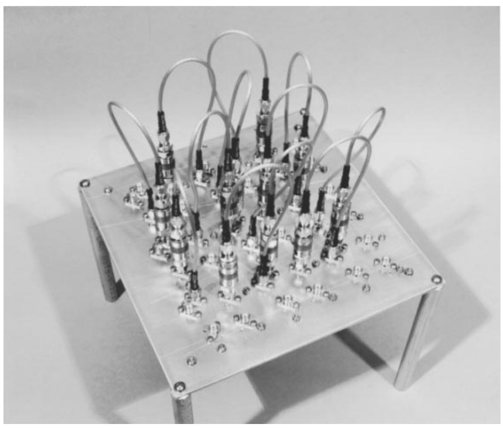


Fig. 3. Interoscillator coupling lines.

coaxial lines are connected between the oscillators. The assembled nine element array on Rogers 5880 Duroid™ (0.031-in dielectric thickness with 0.005-in rolled copper on both sides) is shown in Fig. 2. The connector at the top of the photograph is used to supply power and individual tuning voltages to the oscillator MMIC's. According to previously published analysis and corroborating experiment, the parallel resonant behavior of the MMIC dictates the use of coupling lines of a length that will yield a coupling phase of an integral multiple of 2π [4]. Due to the presence of an unknown phase shift from the ends of the coupling line into each MMIC, a line which is an integral number of wavelengths long will not necessarily yield a coupling phase which is an integral multiple of 2π. Therefore, coaxial "line stretchers" were inserted in the lines between the oscillators to provide for fine adjustment of the coupling phase. (The approximate line length was chosen on the basis of experience with the one-dimensional array.) For mechanical convenience, a coupling phase of 6π was actually implemented. This coupling arrangement is shown in Fig. 3.

III. Array Diagnostics

In order to demonstrate the generation of planar phase distributions over the array, a method of real-time phase measurement was required. Connection of the MMIC outputs to radiating elements arranged in a 3×3 radiating aperture would produce an agile beam but would not provide direct access to the aperture phase except perhaps via near field scanning. In the present case, direct phase measurement was preferred so a diagnostic system based on the scheme shown in Fig. 4 was implemented. As shown, each oscillator is connected through a 3 dB hybrid coupler to a double balanced mixer. The mixer output is then a function of the phase difference between the adjacent oscillators. The hybrid coupler introduces a 90° phase shift in one input to the mixer so that the dc mixer output is proportional to the sine of the phase difference. The dc outputs of the mixers are converted to digital form and transmitted to a computer running a virtual instrument programmed in LabView™. Because the packaged mixers are not designed for the present application, the radio frequency (RF) and local oscillator (LO) inputs have differing effective line lengths resulting in a phase offset of the ideal sine function characteristic. Moreover, the output d.c. voltage is not exactly zero when the input phases are equal due to slight imbalance in the mixers and this produces a voltage offset. These offsets are compensated for in the computer thus producing a direct indication of the phase difference between adjacent oscillators.

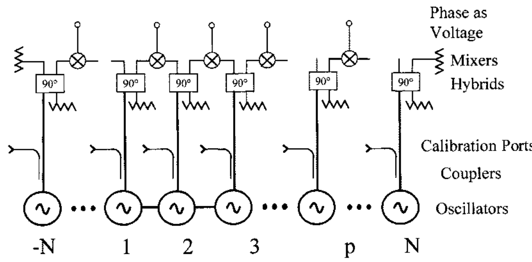


Fig. 4. Diagnostic circuit for phase measurement.

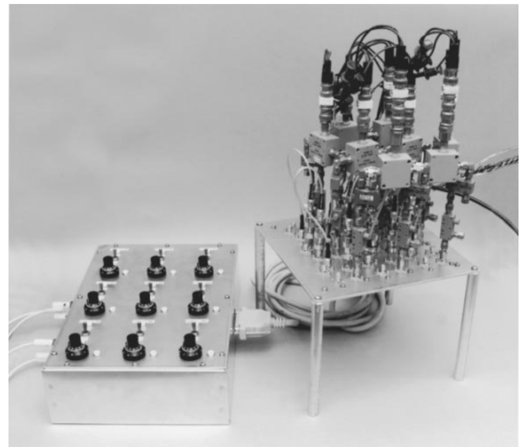
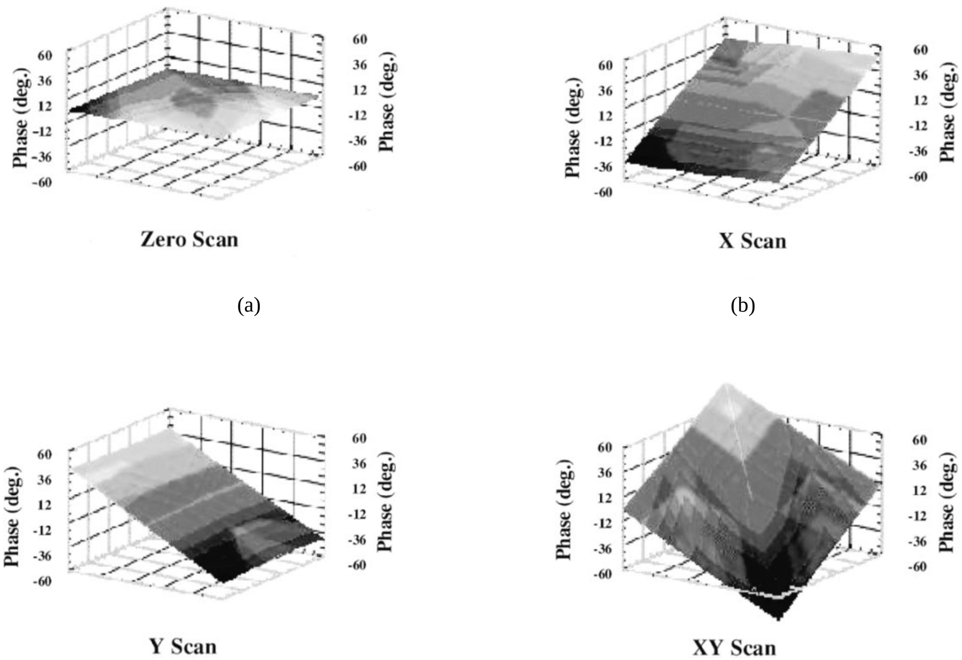


Fig. 5. Implementation of the phase diagnostic system.

In the present implementation, eight mixers and nine hybrid couplers are used. This linear array of mixers is connected to the 3×3 array of MMIC outputs in an "S" shaped configuration. That is, couplers 1 through 9 are connected in sequence to MMIC's 1, 2, 3, 6, 5, 4, 7, 8, and 9, numbered as a telephone keypad. Thus, the diagnostic system yields the phase differences between these MMIC outputs. Then, the center MMIC, number 5, is taken to be a reference and the differences are integrated to produce the phase of each MMIC output relative to



(a) (b) (c) (d)

Fig. 6. Computer display of the measured phase distribution for four example scan conditions.

that of MMIC 5. Finally, these phases are rearranged into the corresponding 3×3 array and displayed as a phase surface in three dimensions.

The physical implementation of this diagnostic system is shown in Fig. 5. In the present implementation, 10 dB directional couplers were inserted between the MMIC outputs and the hybrid couplers to provide samples of the MMIC output signals for use in calibrating the mixer array. Also shown in Fig. 5 is the remote control box used to apply power to each oscillator independently and to adjust the tuning bias voltages on each oscillator.

Fig. 6(a) shows the computer display of the phase when the tuning voltages are set to produce a uniform phase distribution over the array. The nominal tuning voltage is about 12 V and the nominal ensemble frequency is 2.75 GHz. Fig. 6(b) shows the phase distribution which results when oscillators 1, 2, and 3 are tuned upward by changing the tuning voltage by 0.1 V and oscillators 7, 8, and 9 are correspondingly tuned downward by changing their tuning voltage by –0.1 V. The result is a tilted phase distribution planar to within about 3°. If applied to a 3×3 array of radiating elements with half wavelength spacing, this would produce a beam scanned to about 13.5° from normal. Similarly, Fig. 6(b) shows the phase distribution which results when oscillators 1, 4, and 7 are tuned upward by changing the tuning voltage by 0.1 V and oscillators 3, 6, and 9 are correspondingly tuned downward by changing their tuning voltage by -0.1 volt. Fig. 6(d) shows the effect of application of the sum of the tuning voltages for Fig. 6(b) and (c), a phase distribution corresponding to a beam scanned about 19.3° from normal at a 45° azimuth angle.

Finally, it is noted that, while the tuning voltages used in Fig. 6(b) were to produce a 13° scan in the x direction only, they in fact produced an additional 1.6° scan in the y direction as an artifact. It is believed that this is primarily due to variations in the tuning characteristics of the oscillators in which case it can be largely corrected by simultaneous application of a compensating y scanning voltage. However, it is also possible that some of this effect is an artifact of the phase measurement system.

IV. Concluding Remarks

Based on a concept due to Liao and York [1], a 2-D array of voltage-controlled oscillators coupled to nearest neighbors has been implemented and shown to produce planar phase distributions suitable for phased array excitation. The beam control simply consists of varying two antisymmetric pairs of bias voltages, one for "x scanning" and the other for "y scanning." This represents a remarkable simplification over conventional schemes involving control of every element of the array.

Acknowledgment

The author gratefully acknowledges the services of the Electronic Packaging and Fabrication Section of JPL and the design contributions of S. M. Petree of ACRO Service Corporation.

References

[1] P. Liao and R. A. York, "A new phase shifterless beam-scanning technique using arrays of coupled oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-41, pp. 1810–1815, Oct. 1993.

[2] R. J. Pogorzelski, R. P. Scaramastra, J. Huang, R. J. Beckon, S. M. Petree, and C. Chavez, "A seven element S-band coupled oscillator controlled agile beam phased array," *IEEE Trans. Microwave Theory Tech.*, vol. 48, pp. 1375–1384, Aug. 2000.

[3] R. J. Pogorzelski, "On the dynamics of two-dimensional array beam steering via coupled oscillators," *IEEE Trans. Antennas Propagat.*, to be published.

[4] H.-C. Chang, E. S. Shapiro, and R. A. York, "Influence of the oscillator equivalent circuit on the stable modes of parallel-coupled oscillators," *IEEE Trans. Microwave Theory and Tech.*, vol. 45, pp. 1232–1239, Aug. 1997.