Coupled-Oscillator Phased Array Systems for Millimeter Wave Applications*

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ABSTRACT

An array of oscillators coupled through mutual injection locking on a nearest neighbor basis has the property of automatically adjusting itself to linear phase progression across the array in response to appropriate adjustment of the elements at the edge of the array. This mechanism is well-suited to phase generation for phased array antennas at millimeter wavelengths because it obviates the topological complexity associated with feed and control manifolds found in conventional phased arrays. This paper discusses recent understanding gained in the operation of coupled-oscillator arrays and their exploitation for phased array antennas.

COUPLED OSCILLATOR PRINCIPLES

The use of phase-locked oscillators for beamsteering was proposed in 1974 by Al-Ani, *et. al.* [1]. The exploitation of the phase dynamics of coupled-oscillator systems to generate phase gradation across an array was first proposed by Stephan [2] and have been substantially elaborated upon by York and his colleagues [3]. A key result of [3] is a set of coupled non-linear differential equations that describe the phase dynamics of a coupled oscillator array:

$$\begin{aligned}
\frac{d\theta_1}{dt} &= \omega_1 - \frac{\omega_1\kappa}{2Q}\cdot\sin(\Phi+\theta_1-\theta_2)\\
\frac{d\theta_i}{dt} &= \omega_i - \frac{\omega_i\kappa}{2Q}\cdot[\sin(\Phi+\theta_i-\theta_{i-1})+\sin(\Phi+\theta_i-\theta_{i+1})], \qquad 1<i<N,\\
\frac{d\theta_N}{dt} &= \omega_N - \frac{\omega_N\kappa}{2Q}\cdot\sin(\Phi+\theta_N-\theta_{N-1})
\end{aligned} \tag{1}$$

where θ_i is the instantaneous phase of each oscillator, ω_i is the free-running frequency of the ith oscillator, and Q is the quality factor of the oscillator elements, and $\kappa e^{j\Phi}$ is the coupling factor between adjacent oscillators. The oscillator configuration is shown schematically in Fig. 1. The notation can be trivially extended to address two-dimensional arrays. The system of equations (1) is actually coupled to a system of equations in which the oscillator amplitudes are the unknowns (see [3]), but the amplitude variations are quite weak, and (1) is sufficient to the design of a coupled oscillator system.

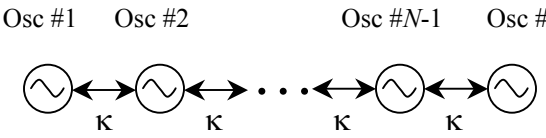

Fig. 1. A Linear Coupled-Oscillator Array

In sinusoidal steady state, the interior element (middle) alternative in (1) becomes

$$\omega_0 = \frac{d\theta_i}{dt} = \omega_i - \frac{\omega_i\kappa}{2Q}\cdot[\sin(\Phi+\theta_i-\theta_{i-1})+\sin(\Phi+\theta_i-\theta_{i+1})],$$

or

$$\frac{\omega_0-\omega_i}{\omega_i} = \frac{\kappa}{2Q}\cdot[\sin(\Phi+\theta_i-\theta_{i-1})+\sin(\Phi+\theta_i-\theta_{i+1})], \qquad i=2,3,\ldots,N-1. \tag{2}$$

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Here, ω_0 is the ensemble average of the free running frequencies of all of the oscillators in the array. Beamsteering can be achieved with the array in Fig. 1 by detuning the free-running frequencies of the end elements away from ω_0 by equal and opposite amounts. This does not change the ensemble average frequency of the array, but one can observe in (2) that a phase difference is imposed between θ_1 and θ_2. This phase difference is established progressively across the row of oscillators, so that a linear phase progression ensues. This is the noteworthy useful feature of coupled-oscillator arrays: *A linear phase progression can be produced across a row of oscillators by way of control applied at the perimeter alone.*

PHASED-ARRAY BASED ON COUPLED OSCILLATORS

The coupled oscillator array mechanism may be employed to produce a phased array antenna as shown in Fig. 2. A modulated carrier is mixed with the output of individual oscillators in a coupled oscillator array. By following the mixer with an image rejection filter, the output signals are block converted upward by a frequency increment corresponding to the oscillator array ensemble average frequency, and the phase of the respective oscillators are imposed on the corresponding output signals. These signals can be amplified and transmitted. A similar process can be employed in reception [4]. This topology is significantly simpler than that of a traditional phased array because of the elimination of phase shifters and the associated control manifold. This is particularly valuable in the confined dimensions of millimeter wave arrays, where suitably miniaturized long life-cycle phase shifters are not available. (Certainly, MEMS phase shifters show promise, though life cycle is a persistent shortcoming of these devices.)

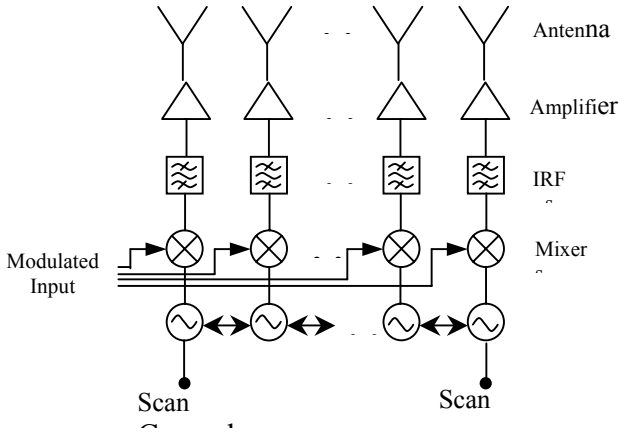


Fig. 2. Phased-Array Based on Coupled-Oscillator Array

The key difficulties that one encounters in realizing good performance from a coupled oscillator array are that of fabricating a number of oscillators with free-running frequencies that are closely matched and of maximizing the locking bandwidth

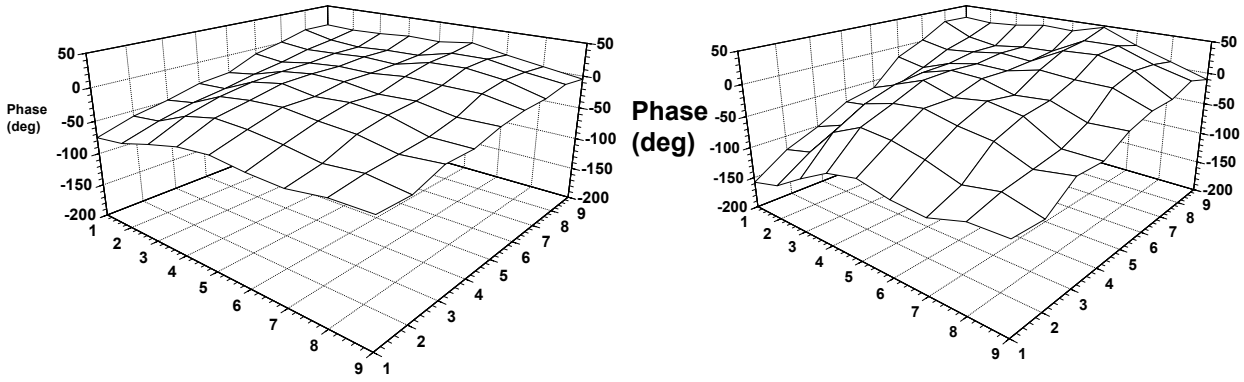
$$\Delta\omega_{\max} = \frac{\omega_0 \kappa}{2Q} = \frac{1}{\Lambda} \cdot \frac{E_1}{E}, \tag{3}$$

where $\Lambda = d\varphi / d\omega$. In (2), the random frequency variation can be observed to create phase error between adjacent cells in the array, while, at the same time, a large locking bandwidth κ/Q ratio reduces sensitivity of this effect. Fig. 3 demonstrates this feature of the oscillator array. Wide locking range makes an oscillator a poor signal source because the frequency, and hence the phase noise of the oscillator is not tightly controlled. This is easily remedied, however, by injection locking the array at one or more points to a high-purity signal at the ensemble average frequency ω_0 [5].

It is evident from (2) that one is limited to a cell-to-cell phase change significantly smaller than 90° because of the sine term. This limits the scan range of the array in Fig. 2 to something less than 20° or so. Frequency multiplication of the outputs. Fig. 4 shows a planar realization of the architecture of Fig. 2. One observes the relatively limited (-8°,+7°) phase shift range. Two methods for improving this range are discussed below.

IMPROVING SCANNING RANGE

Frequency multiplication of the oscillator outputs multiplies the phase of the output by the same factor. Fig. 5 shows a two- dimensional 4x4 array that employs frequency multiplication. The oscillator array, shown in the left photograph,



(a) (b)

Fig. 3. Random phase front for a 9x9 oscillator array with locking ranges of (a) .056 GHz and (b) of .112 GHz. The ensemble average frequency is 10 GHz. The widened locking range reduceds the phase error in the (a) array. The free running frequencies of individual oscillators were chosen randomly in an interval ±.050 GHz about the 10 GHz ensemble average frequency.

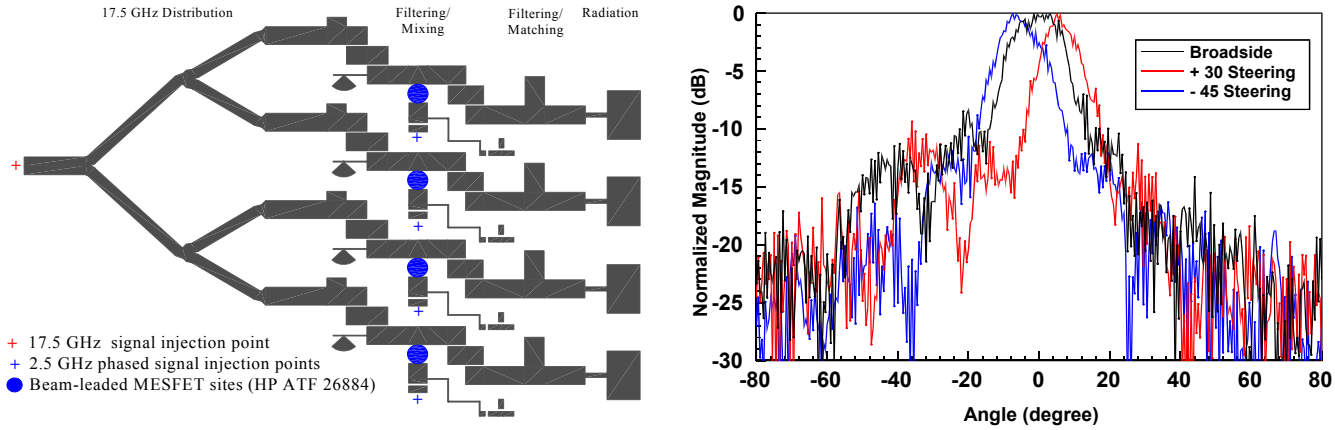


Fig. 4. A planar realization of the architecture in Fig. 2 (left), and the associated patterns for three different element-to-element phase shifts: broadside-black; +30°-red, -45°-blue. The scillators would not maintain lock for greater phase progression. (The lack of final amplifiers is responsible for the relatively noisy patterns.)

operates at 10 GHz. These outputs are doubled to produce radiation at 20 GHz. This array yields beam steering with nominal limits of ±25° in each principal plane.

It is evident that the locking bandwidth, defined in (3), poses a fundamental limitation on scanning range as well as having the direct influence on random phase error discussed above. The scanning process produces transient changes in an the instantaneous frequencies of oscillator cells. Too great a phase change can pull the instantaneous frequency of one cell outside the locking bandwidth of its neighbor so that lock between the two cells is lost. This provides incentive to design oscillator cells with center frequencies that agree closely and with wide locking ranges. Wang, *et. al.* have demonstrated a design methodology that allows one to optimize the design of an oscillator cell to meet both of these goals simultaneously [6]. Fig. 6 shows results from [6] illustrating such optimization results. The schematic of the oscillator circuit in Fig. 6 indicates the optimization parameters used. Table 1 shows the results of harmonic balance simulation of the three designs. The improvement in locking range with lower phase slope is evident. Experimental validations consistent with these simulation results have been achieved and improved scanning ranges accordingly demonstrated. These results will be discussed as a part of the oral presentation.

Table 1. The simulation results for the 10GHz oscillators

P_{inj} (dBm)	Locking Range (MHz)		
	Case1	Case2	Case3
-35	26	34	88
-30	45	61	155

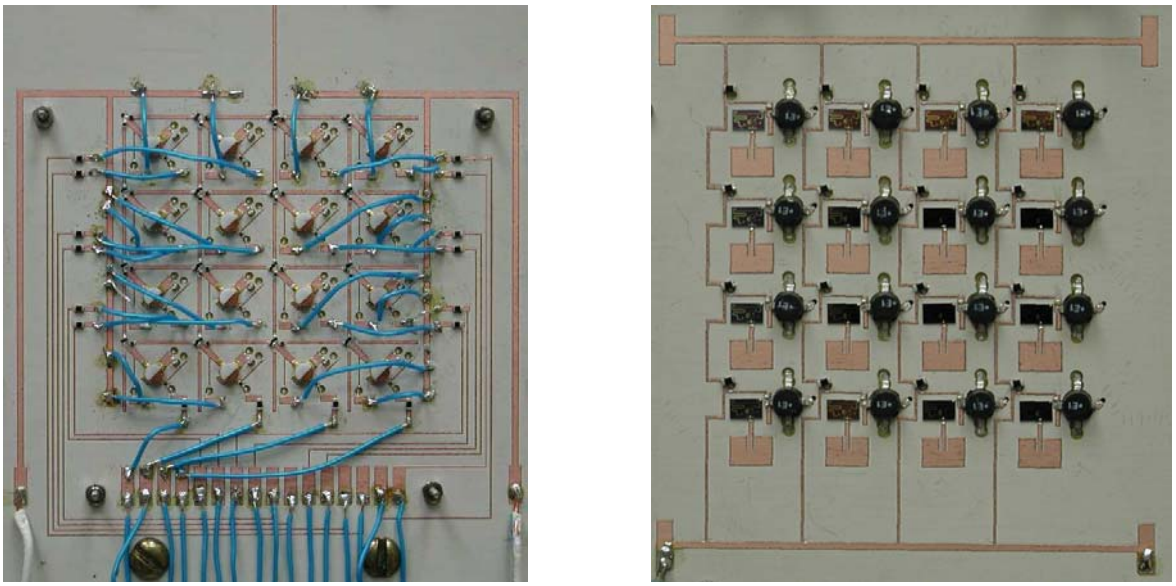


Fig. 5. Oscillator side (left) and radiator side (right) of two-dimensional frequency-multiplying array. Oscillator signals feed through common ground plane into MMIC amplifier (round packages) and 10-20 GHz 2X frequency multiplier (rectangular dice) into patch radiators.

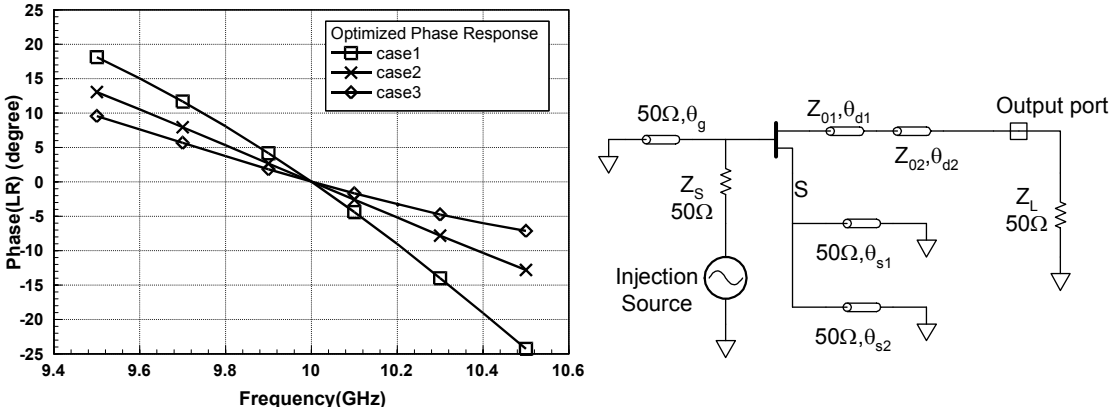


Fig. 6. Three design results where specified phase slope in (3) is achieved. The parameters indicated symbolically in the schematic are the optimization parameters.

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