PHASE-SHIFTERLESS BEAM-SCANNING USING COUPLED-OSCILLATORS: THEORY AND EXPERIMENT

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Abstract — The unusual nonlinear dynamics of systems of mutually synchronized, loosely coupled oscillators have been exploited for electronic beam-scanning. Using a simple theory based on coupled Van der Pol equations, it is shown that a constant phase progression, $\Delta\phi$, can be established over the range $-90° < \Delta\phi < 90°$ by slightly detuning the peripheral elements in the array. A four element linear patch array using MESFET oscillators was designed and constructed to verify the proposed concept.

I. Introduction

Beam-steering has traditionally been accomplished in phased-array systems by using a set of electronically controlled phase-shifters in the feed network of the array. This paper describes a new method for beam steering in a spatial power-combining array which does not require any phase-shifter circuitry or RF distribution network. This approach utilizes an array of individual solid-state oscillators which are integrated with planar antennas. Mutual coupling between the antennas allows the oscillators to interact and synchronize to a common frequency via injection locking [1]. Using a previously developed theory of coupled-oscillators [1,2], it will be shown that a constant phase progression is created when the free-running frequencies of the end-elements of the array are slightly detuned with respect to the inner array elements. The concept is verified using a four-element active patch array with MESFET oscillators.

II. Beam Scanning in Oscillator Arrays

For an array of N instantaneously coupled ($\Phi = 0°$) oscillators with identical amplitudes, it has been shown theoretically [2] that a constant phase progression could be achieved if the free-running frequencies, ω_i, were distributed in the following manner:

$$\omega_i = \begin{cases} \omega_f[1 - \lambda' \sin\Delta\theta]^{-1} & \text{if } i = 1 \\ \omega_f & \text{if } 1 < i < N \\ \omega_f[1 + \lambda' \sin\Delta\theta]^{-1} & \text{if } i = N \end{cases} \quad (1)$$

where $i = 1, 2, \ldots, N$, ω_f is the desired phase-locked frequency of the coupled oscillators, λ' is related to the coupling strength (and should not be confused with the wavelength), Φ is the coupling phase [1], and $\Delta\theta$ is the desired phase shift.

From this result, we see that the phase shift between successive elements, $\Delta\theta$, is controlled by the free-running frequency of the *end elements alone*. Furthermore, the synchronized frequency is equal to the free-running frequency of the innermost oscillators. Thus by slightly adjusting the free-running frequencies of the end elements, the radiation pattern can be electronically scanned. Note that the output frequency of the array does not change as the beam is scanned. The relationship between the successive phase shifts, $\Delta\theta$, and the scan angle is given as $\Delta\theta = k_0 d \sin\Psi$, where Ψ is the scan angle (measured from broadside), d is the physical separation between adjacent elements, and k_0 is the free-space propagation constant.

III. Experimental Results

The theoretical predictions were tested with a four element 10 GHz active patch array, using the oscillator design described in [3]. The array is illustrated in figure 1. Using the methods for characterizing radiative coupling outlined in [4], it was determined that a coupling phase of zero degrees required an inter-element separation of $0.7\lambda_0$ in the array, (where λ_0 is the free space wavelength at 10 GHz). As discussed in [2], the theoretical maximum achievable phase shift between elements is $\pm 90°$. Consequently, an oscillator spacing of $0.7\lambda_0$ yields a theoretical maximum scan angle of $\pm 16.7°$ for this array. Figure 2 indicates excellent agreement between the theory and measured results for a scan angle of $-10°$. Figure 3 illustrates that it was possible to continuously scan the radiation pattern from $-15°$ to $+12.5°$ by bias-tuning the peripheral elements. Note that the measured scan angle of $-15°$ approaches the theoretical maximum for this particular array. When the pattern was scanned to $-15°$, the frequencies of the end elements were 10.0075 GHz and 9.9925 GHz, while the free-running frequencies of the innermost active antennas were set to 10.00 GHz. In the case of 12.5° beam steering, the frequencies of the outermost elements in the array were 10.015 GHz and 9.985 GHz.

IV. Conclusions

A new technique for electronic beam steering was presented, which eliminates the need for phase shifters. This new technique and its limitations can be explained using a nonlinear theory of coupled oscillators. The theory was tested in simple fashion using a 4×1 linear array of active patch antennas. By adjusting the frequencies of the end oscillators in the chain, the radiation pattern could be continously steered over a range of angles from $-15°$ to $+12.5°$. This scan range is actually very close to the theoretical limit, due to the abnormally large antenna spacing that was used; a larger scan range can be obtained for smaller inter-element spacings. If a specific element spacing is required, the full beam scanning range may still be achieved if the coupling phase is switched from 0° to 180°. This suggests the possiblity of achieving full hemispherical scan coverage by electronically switching the coupling phase between 0° and 180°, in addition to controlling the end-element frequencies. Some small discrepancies were observed between the theory and experiment as a result of nonuniform oscillator amplitudes and incorrect coupling angles, but overall the results are encouraging. Indeed, the fact that our crude array worked at all suggests that the concept is fairly robust, and that extremely tight tolerances would not be required in a practical array.

V. References

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[3] R.A. York, R.M. Martinez and R.C. Compton, "Hybrid Transistor and Patch Antenna Element fo Array Applications", *Electron. Lett.*, vol. 26, pp. 494-495, March 1990.

[4] R.A. York and R.C. Compton, "Measurement and Modelling of Radiative Coupling in Oscillator Arrays", to appear in *IEEE Trans. Microwave Theory Tech.*.

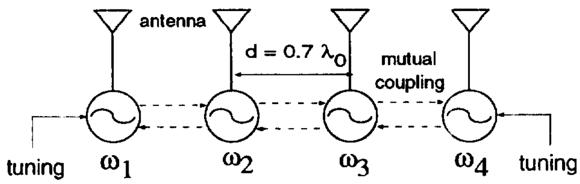

Figure 1 —Schematic of the 4×1 active patch antenna array for demonstrating the proposed beam-scanning concept. The dotted lines represent radiative coupling between oscillators.

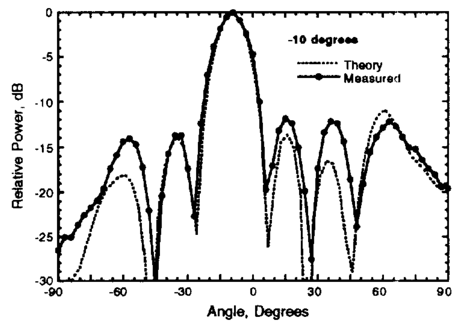

Figure 2 —Theoretical and measured radiation patterns at -10 degree beam scanning obtained from the 4×1 array constructed.

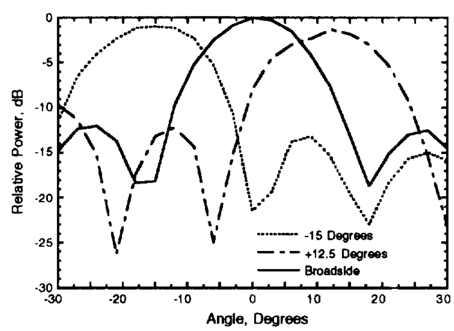

Figure 3 —Measured radiation patterns from the 4×1 array constructed which illustrate -15, 0, and 12.5 degree beam scanning.