

## MEASUREMENT OF THE PHASE AND AMPLITUDE DISTRIBUTIONS OF COUPLED OSCILLATOR ARRAYS

Paolo F. Maccarini, Thai-Phuong Dao, Amit S. Nagra, Andrea Borgioli, and Robert A. York  
Electrical and Computer Engineering Department

\*University of California in Santa Barbara

### ABSTRACT

This paper describes the analysis, design, implementation and characterization of a computer-controlled system that accurately measures the phase and amplitude distributions of a phased antenna array.

The proposed setup allows 'on board' measurements and far field radiation pattern collection at the same time.

We have measured the phase and amplitude distributions of a coupled oscillator array at 2.4-2.6 GHz. The results are coherent with the theoretical expectations. The amplitude error is less than 5% and the phase error is less than 5°. This simple and inexpensive measurement system can be used for automated diagnostics of linear and nonlinear antenna arrays.

### INTRODUCTION

Phased array systems, once realm of military and university research, are now receiving increasing interest. Coherent power combining, beam scanning and signal tracking at microwave frequencies are typical applications of array of radiating structures, where linear or nonlinear devices control the amplitude and phase distributions.

Structures in which the antenna is fed by non-linear elements, such as coupled oscillators, are very interesting because there is no need of expensive phase shifters (and eventually variable gain amplifiers) to change the phase (and the possibly amplitudes) along the array. In the most common configuration, the mutual injection between oscillators is obtained by using high

impedance transmission lines and the power flowing from one oscillator to the other drive the oscillators to lock themselves at a common frequency. In the steady state, the phase distribution is determined by the free running oscillation frequencies, tunable with low cost varactors [1].

Another advantage of couple oscillator systems is that the phase noise is reduced by a factor of  $\sqrt{N}$  ( $N$  is the number of oscillators), and it tends to follow the phase noise characteristic of the oscillator with the lowest noise [2-3].

The locking of the oscillators is a nonlinear phenomenon and many of its theoretical aspects are difficult to master: a reduced locking range and parasitic effects are often limiting factors in the design of such systems.

However recent studies show the possibility of drastically improving the operating frequency, the locking range, and the phase noise by using subharmonic injection locking phase locked loops [4]. Several configurations for the coupling network have also being proposed [5].

Since the phase and the amplitude of the radiating element can only be determined when the antenna system is complete, most of the theoretical results have been proved by using a far field radiation pattern measurement to deduce the signal distributions along the array. These measurements sometimes are not easy to understand because of the presence of unexpected sides lobes. Moreover, inaccurate designs of the antennas and their mutual coupling network quickly compromise the performance of the system. It is also worth noticing that finding the causes of possible

malfunctions can be very difficult in the presence of a large number of oscillators.

All these reasons justify the need of an alternative, low cost technique to characterize the performance of coupled oscillator systems.

With this paper we present a 5-element array that allows accurate measurement of the phase and the amplitude of the signal at the oscillating element output, without affecting the radiation pattern. The antenna design, in this fashion, becomes a separate issue from the array characterization. The frequency has been chosen to be between 2-3 GHz in order to use standard low cost components, but the idea can be implemented at higher frequencies by using MMIC technology. To verify the accuracy of the measurement system, we have compared our results with the radiation pattern for a passive power divider and for an active coupled oscillator array. The array factor calculated from the 'on board' measured distributions is in close agreement with the radiation pattern.

### THEORY AND IMPLEMENTATION

The center element is used as the phase reference. We used isolator to offer to the active elements a constant load.

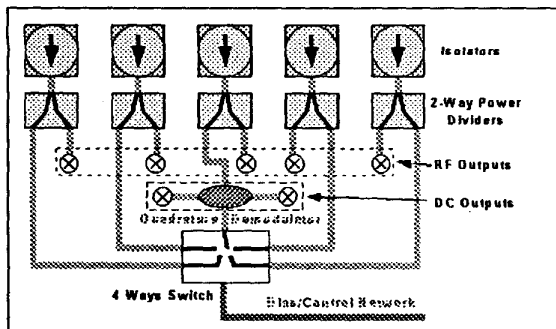


Fig. 1: Block diagram of the phase and amplitude measurement module.

As shown in Figures 1 and 2, the signal of all the oscillators is split in two directions. Half of the signal goes to the radiating element (or to a

power meter or to a spectrum analyzer), while the other half is used for the 'on board' detection.

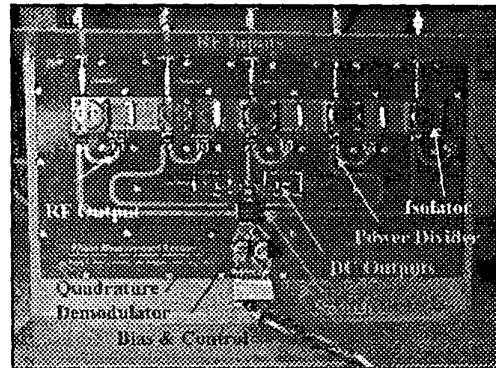


Fig. 2: Picture of the phase and amplitude measurement module.

The center signal is connect to a hybrid coupler that splits the signal in two and delays one side of 90° with respect of the other. The  $N-1$  oscillators are connected to a common switch, so that we can choose which one is 'ON' and we can leave the others terminated on a 50-Ω load. The output of the switch is then divided in two parts. The two halves of the signal are then mixed with the 0° and 90° phased outputs of the hybrid coupler. Since the two incoming signal are at the same frequency, the mixer outputs will have an RF and a DC component. The RF component is then filtered out (or absorbed in a 50-Ω load) while the DC component is measured. The DC component is linearly related to the cosines and sinus of the phase difference between the incoming signals. It also contains the information on the amplitude product. That is,

$$V_{Out,0^\circ} = \frac{V_3 V_j}{2} \sin(\Delta\phi_j) + RF$$

$$V_{Out,90^\circ} = \frac{V_3 V_j}{2} \cos(\Delta\phi_j) + RF$$

where  $V_{Out,0^\circ,90^\circ}$  are the outputs of the two mixers,  $V_{3,j}$  the mixer inputs from the center and the  $j$  side element and their phase difference  $\Delta\phi_j$ .

We chose to work with the signal amplitude values (not the rms and not the peak-to-peak values) to simplify the math.

The hybrid coupler and the two mixers could be also integrated in a quadrature modulator. We actually used both architectures and verified similar results.

The system needs a calibration, for two main reasons. First, an ideal mixer has an offset and a phase coefficient (slope of the input-output phase relation) and a non-flat amplitude-phase response (that also depends on frequency). Second the phases and attenuations along the channels are frequency dependent. Nevertheless, since most commercially available mixers are relatively stable and linear (in phase), the calibration process avoids systematic errors.

### CALIBRATION PROCEDURE

To calibrate the system, we designed a calibration board with a 5-way power divider. The centerline is used as input of a 4-way switch that allows us to choose between 4 paths of different length (each with a  $90^\circ$  electrical length increase). The 4 center paths are then combined in a single output. The design of the divider/combiner was kept simple, according to the design rules described in [6]. The measured isolation was  $\sim 20$  dB and the input and output reflections less than  $-12$  dB. The operating frequency band is 2-3 GHz.

It is possible to determine phase and amplitude distributions at the output ports of such a structure by using the measured S parameters.

This board allows us to calculate, at each frequency, the slope and the offset of the phase measured with respect to the actual phase. For

each frequency and each of the four delays we also stored the amplitude correction factor, which takes into account the different path losses and the nonlinear amplitude and phase response of the mixers.

We implemented a Windows®-based computer program with a user-friendly interface in order to perform the automatic calibration and the actual measurement with a HP GPIB and PCI 1200 (analog-digital) network. Sample & hold devices on a printed circuit board are used to control the voltage on the varactors and thus the free running frequencies of the oscillators. Figure 3 shows a picture of the complete measurement setup.

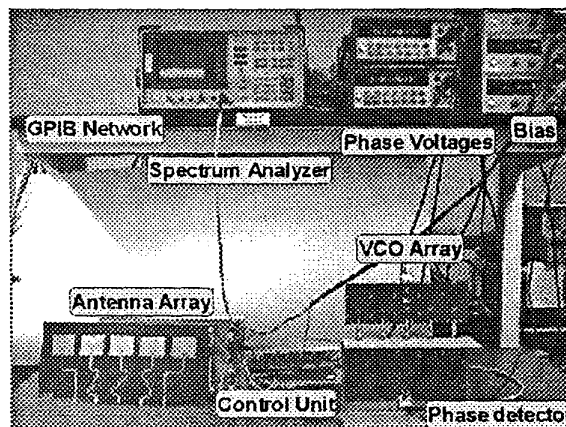


Fig. 3: Picture of the complete phase and amplitude measurement setup.

### MEASUREMENTS

To verify the performance of the proposed calibration procedure, we measured a passive structure, such as a power divider with known delay lines. Remarkably, the phase error was less than  $5^\circ$  and the amplitude one less than 5%.

The real challenge is however the measurement of nonlinear active antennas for which the system has being designed. To verify the ability to perform accurate measurements, we designed and built a 5-element coupled oscillators array. We used standard surface

mounted oscillators with external resonant circuitry. The output power is  $\sim 13$  dBm and the tuning range is determined by the tuning external varactor. In our design, the oscillation frequency could be tuned from 2 to 3 GHz. The locking range is measured to be 80 MHz. In the near future we are also planning to implement the ILPLL scheme design.

The coupling network is made of  $100\text{-}\Omega$  transmission lines with  $100\ \Omega$  isolation resistors.

We designed and built an array of radiating element. For the sake of simplicity, we used patch antennas with recessed feeds to improve the input matching. The bandwidth is somewhat limited compared to the tuning range, but as stated previously, the isolators separate the antenna behavior from the measurement procedure. Finally, Figure 4 shows the excellent agreement between the measured and the 'estimated' radiation patterns of the array. The 'estimated' pattern is obtained as the product of the single antenna radiation pattern and the array factor for a linear array, using the measured phase and amplitude distributions.

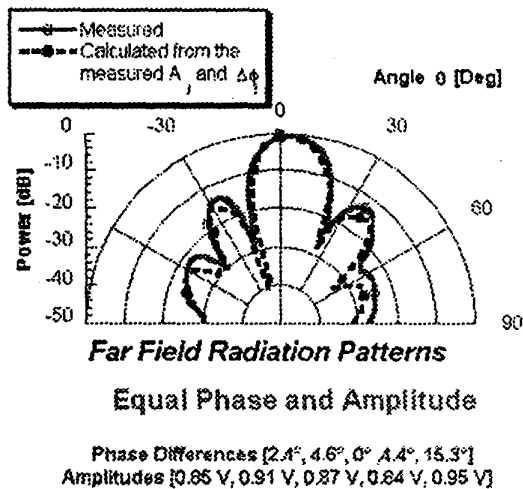


Fig. 4: Measured radiation pattern of the array for almost equal phases and amplitudes. The measured and calculated patterns are in very good agreement.

## CONCLUSIONS

We presented a low cost measurement technique capable of accurate detection of the phase and amplitude distributions of a coupled oscillator array system. The measurements obtained are in good agreement with the results from standard measurement techniques (far field radiation pattern) and the 'on-board' distribution measurement. The measured amplitude and phase errors are within 5% and  $5^\circ$ , respectively. Future developments of this work include the design and implementation of different coupled oscillator architectures (by changing both the oscillating elements and the coupling network designs) to further investigate the performance of these systems.

## REFERENCES

- [1] R. A. York, "Nonlinear Analysis of Phase Relationships in Quasi-Optical Oscillator Arrays", IEEE Trans. Microwave Theory and Tech., Vol. MTT-XLI, No. 10, pp. 1799-1809, October 1993.
- [2] H.-C. Chang, X. Cao, M. J. Vaughan, U. K. Mishra, R. A. York, "Phase Noise in Externally Injection-Locked Oscillator Arrays", IEEE Trans. Microwave Theory and Tech., Vol. MTT-XLV, No. 11, pp. 2035-2042, November 1997.
- [3] H.-C. Chang, X. Cao, U. K. Mishra, R. A. York, "Phase Noise in Coupled Oscillators: Theory and Experiment", IEEE Trans. Microwave Theory and Tech., Vol. MTT-XLV, No. 5, pt 1, pp. 604-615, May 1997.
- [4] S. Kudszus, M. Neumann, T. Berceli, W. H. Haydl, "Fully Integrated 94 GHz Subharmonic Injection-Locked PLL Circuit", to be published on IEEE Trans. Microwave Theory and Tech., 2000.
- [5] R. A. York, P. Liao, J. J. Lynch, "Oscillator Array Dynamics with Broadband N-Port Coupling Networks", IEEE Trans. Microwave Theory and Tech., Vol. MTT-XLII, No. 11, pp. 2040-2045, November 1994.
- [6] A. A. M. Saleh, "Planar Electrically Symmetric N-Way Hybrid Power Dividers/Combines," IEEE Trans. Microwave Theory and Tech., Vol. MTT-XLII, No. 6, pp. 553-563, June 1980.