Coupled Phase-Locked Loop Arrays for Beam Steering

Paolo F. Maccarini, Jim Buckwalter and Robert A. York

Electrical and Computer Engineering Dept, University of California, Santa Barbara, CA, 93106, USA

***Abstract* — Some of the limitations of Coupled Oscillator Arrays, mainly intrinsic small locking bandwidth, amplitude fluctuations and limited agreement between unit cells and models, can be overcome with the use of Coupled Phase-Locked Loop Arrays, which with appropriate models are more predictable than COAs and offers larger locking range and amplitude-independent phase relationships. The two offer similar advantages, such as phase-shifterless beam scanning and modulation abilities, as well as analogous challenges, for example the modeling and consequent design of unit cell and coupling schemes at microwave frequencies. The discrete and continuum modeling of CPLLAs is presented. The phase dynamics shows a diffusion type behavior, where the locking propagates away from the detuning points. The ability of beam scanning is then showed as the steady state solution of edge detuning. Additionally, the length of the coupling line together with the sign of the IF loop gain is proved to be an important factor in the transient and the steady-state phase distribution along the array. These theoretical results are experimentally verified through the design of a 2.45 GHz CPLLA and its characterization. Being governed by strongly nonlinear behaviors, still a lot needs to be understood about these synchronized arrays: the aim of these paper is to show that, together with some limitations, they also present interesting properties that future research may exploit.**

I. INTRODUCTION

Phased array systems, once realm of military and university research, are now receiving increasing interest in commercial applications. 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 or coupled PLLs, are very interesting because together with the ability of locking to a common frequency, other interesting features arise from the equations governing their synchronization process.

Such properties include easy control of a linear phase distribution by edge detuning and overall phase noise reduction. Their characteristic equations are strongly nonlinear and thus attractive by a research viewpoint as they exhibit a full range of behaviors, from the mode locking to chaos, from quasi-periodic to synchronized state.

While Coupled Oscillator Arrays have been under intense investigation in the last decades, only recently their limitations, mainly intrinsic small locking bandwidth, amplitude fluctuations and limited agreement between unit cells and models, drove research efforts towards Coupled Phase-Locked Loop Arrays. Firstly proposed by Martinez and Compton [1], CPLLAs are, with appropriate models, more predictable than COAs and offers larger locking range and amplitude-independent phase relationships.

As it was done with COAs, a discrete and a continuum can be derived. These models predict synchronization as well as beam scanning by edge detuning. The locking process proceeds diffusively away from the detuning points.

The experimental verification of such results was done with a five element array design for at 2.45 GHz operation.

II. PHASE DYNAMICS

According to the basic laws of phase locked loops, the phase of each oscillator can be changed relative to a reference input RF signal by adjusting a DC Offset added in the feedback loop. In steady state the phase difference behaves as in the phase injection phenomenon, but shifted of 90° (Fig. 1). This occurs because the mixer DC output has the center of its stability range when the two input signals are in quadrature. The addition of a $\pi/2$ transmission line would solve this issue.

However the phase dynamics of the unit cell presents significant differences with the injection model:

$$\dot{\phi} = \omega_0 - \omega_{inj} + \alpha K_v K_p \cos(\psi - \phi) \qquad (1)$$

where $G = \alpha K_v K_p$ is the loop gain.

First even without considering filters and delays in the feedback loop, we can see from the resulting characteristic equation (1) that there is no amplitude involved in the phase dynamics. In addition the locking range is determined by the loop gain, a parameter easily controlled. Finally it is known that PLLs have lower phase noise than their open loop oscillators and the feedback loop reduces the sensibility to component tolerances.

0-7803-7695-1/03/$17.00 © 2003 IEEE

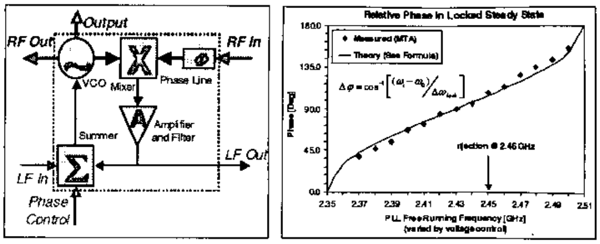

Fig. 1 Schematics of the single phase-locked loop used in CPLLAs with free-running control, IF/RF inputs and outputs for nearest-neighbors coupling. Typical relative phase vs. natural frequency measurement of a 2.45 GHz PLL.

All these observations led to consider CPLLAs better systems to implement beam scanning with large bandwidth modulation.

The coupling scheme in Fig. 2 ensures the same phase dynamics as COAs if the loops have no delay, the filters are not present and the phase detector has a sinusoidal response to phase differences. In this way a constant phase progression could be realized by adjusting the free-running frequencies of only the end elements in the array as proposed by Liao and York for COAs [2].

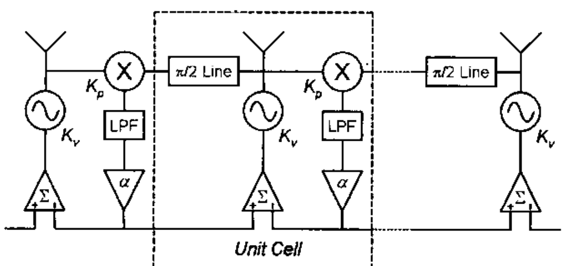

Fig. 2 Proposed schematics for coupled PLL arrays.

II. Time Delay Considerations

When a filter loop is taken into account higher order derivatives show up in the dynamic equation of the array.

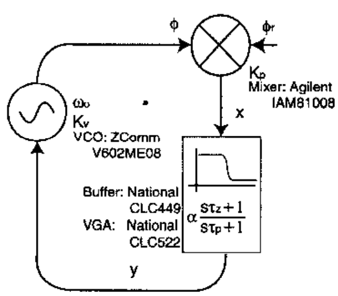

Fig. 3 PLL model modified to include a first order low pass filter. A loop delay will then be added.

Understanding the behavior of two coupled loops helps us understand how to build larger arrays. In the case of two coupled PLLs the phase equation becomes [3]:

$$\tau_p \Delta\ddot{\phi} + (1+\tau_z G \sin\Delta\phi)\Delta\dot{\phi} - G\cos\Delta\phi = \Delta\omega \quad (2)$$

where $\Delta\phi$ is the phase difference, $\Delta\omega$ is the frequency detuning, G is the loop gain and τ_p and τ_z are the filter zero and pole constants.

From (2) two quantities can be defined. Within the hold in range, Ω_h, the oscillators remain locked. In the pull-in range, Ω_p, the oscillators will come to lock. These can be evaluated as:

$$\Omega_h = 2G \quad \text{and} \quad \Omega_p \approx 2\sqrt{\frac{\sqrt{1+4\tau_p^2 G^2}-1}{2\tau_p^2}} \quad (3)$$

It can be shown [4] that from the characteristic constants in the solution of (2) as a function of G, τ_p and τ_z presents a bifurcation. The presence of a pole causes the solution to bifurcate for a particular gain, below which the acquisition time, determined by the slowest constant, diminishes. Above that value if the zero is taken into account, the gain increase improves the acquisition time.

In real systems increasing the gain brings the system to unlock. To be able to account for this phenomenon, a delay must be introduced in the feedback loop.

The solution of (2) still presents the bifurcation as before, but the gain increase after the bifurcation causes also an increase of the acquisition time (Fig. 4). Further increase of the gain lead to unstable negative solutions. Thus we can now define a range for the loop gain from the optimal gain to the critical gain. This range is strongly dependent from the delay value.

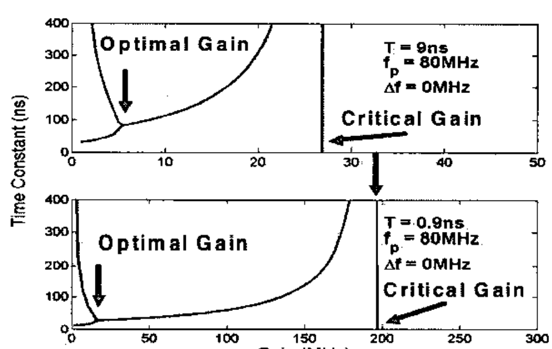

Fig. 3 Optimal gain and critical gain limit the value of the loop gain, when introducing a delay and a filter in the PLL feedback.

In integrated PLL, the effect of this delay is negligible. On the other hand, in discrete assembled PLL (as the one used in CPLLAs' prototypes) it limits the max gain loop and thus the locking range.

II. Coupling Network

Concerning the coupling network for CPLLAs, the nearest-neighbor coupling scheme proposed above present the advantage of being simple to implement and showing the promise of easy beam steering. Nevertheless, other two issues have been addressed.

First, as for COAs, the coupling phase plays an important role together with the loop gain sign in determining where the 180° phase difference range will be centered. It can be shown that to obtain a broadside beam, the PLLs must have negative loops and $\pi/2$ coupling lines or positive loops and $3\pi/2$ coupling lines. Other configurations will create endfire beams (Fig. 5).

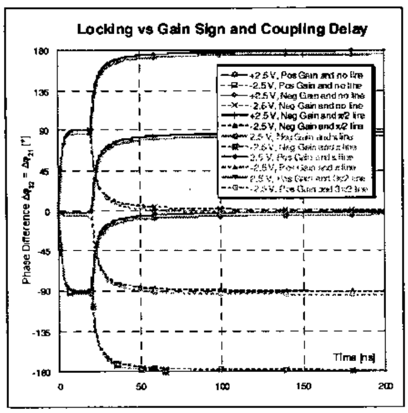

Fig. 5 Influence of loop gain sign and coupling line length on the steady state phase difference along a 3-element CPLLA.

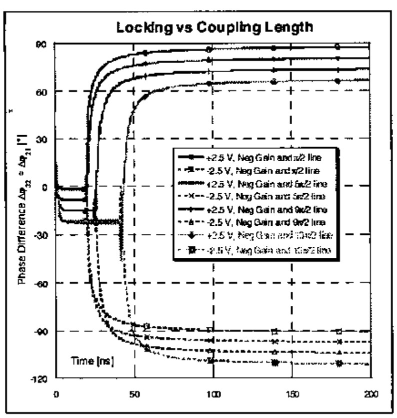

Fig. 6 Influence of the coupling line length on the locking transient time

Second, as intuition suggests longer the line, longer the delay associated with the phase information and thus slower the locking along the array. The CPLLAs with the delay line are intrinsically asymmetric, and thus the longer the coupling line, the longer and more asymmetric will be the locking phenomenon as shown in Fig. 6.

II. Experimental Results

A five-element 2.45 GHz coupled PLL array was build and tested (Fig. 7).

Based on the previous theory, we design the array for broadside radiation, thus the loop gain was negative and the coupling line phase shift was $\pi/2$. The other important parameters are:

$$G = 200\ \text{MHz} \quad \tau_p = 40\ \text{MHz} \quad T \approx 1\ \text{ns} \tag{4}$$

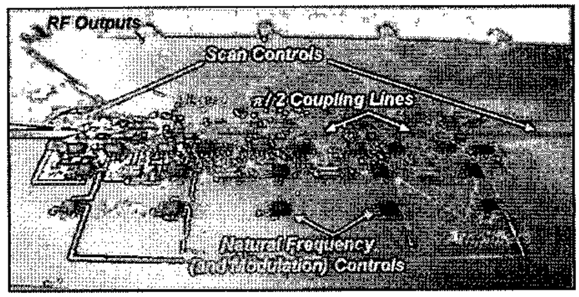

Fig. 7 A five-element 2.45 GHz coupled PLL array.

The total phase difference ranges from –315° to +300°. Digital frequency modulation by global control of the free running frequencies can be done up to 10 MHz when the beam is centered

We verified the ability to lock with a simple setup as shown in Fig. 8, where the free running frequencies are slowly changed to reach the capture range of the center element leading the array to a progressive synchronization.

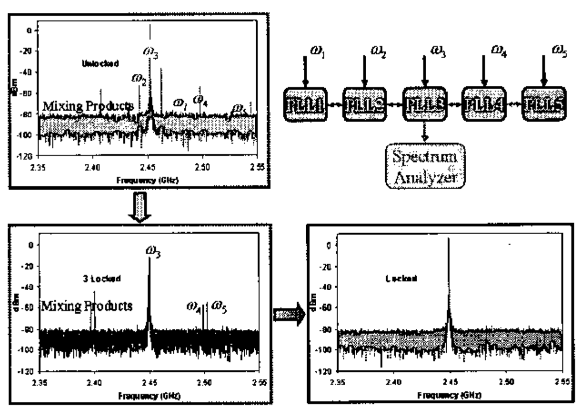

Fig. 8 Verification of the synchronization process.

The beam scanning ability by edge detuning has being experimentally verified, as shown in here the radiation beam is steered of 15°, as shown in Fig. 9.

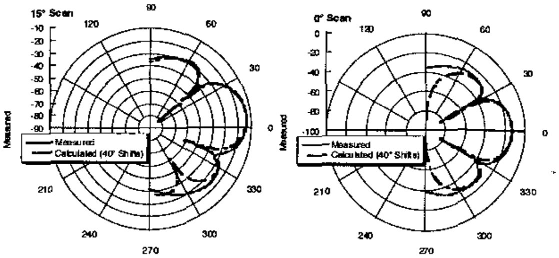

Fig. 9 Beam scanning by edge detuning of a 5-element 2.45 GHz CPLLA.

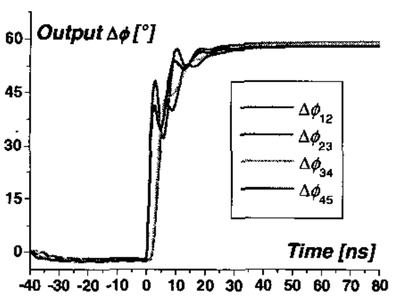

Fig. 10Transient of the beam scanning by edge detuning of the CPLLA.

Also the transient associated with the edge-detuning procedure can be measured using a fast oscilloscope with multiple input ports. The interesting feature is that the offset due to the array coupling asymmetry is present as shown in Fig. 10. Moreover the heat-type dynamics is evident as the elements at the sides reach steady state faster than the inner elements.

In conclusion the recent studies on CPLLAs have shown their interesting properties as well as the constraints associated to their design. The corrections applied to the models improved our understanding of these systems that showed to be more reliable and predictable than COAs.

We want to point out that a new idea that combines the improved locking range of PLL with the noise performances of the injection-locked oscillator was proposed in [5] and [6]. The subharmonic injection locking phase locked loops enhances drastically the operating frequency, the locking range and the phase noise. This circuit could be also embedded in a coupling network with the potential of improving the overall performance of the array.

V. Conclusion

We presented the recent findings in phase-locked loop coupled arrays. While the COAs have been extensively studied in the last two decades, the CPLLAs have been only recently proposed to overcome the limitations of COAs.

The governing equations of ideal CPLLAs are similar to the COAs ones. Thus the ability of controlling a linear phase distribution by edge detuning together with a locking range controllable and independent from the free-running frequency validate their potential for reliable low-cost beam scanning systems. The recently modified models of CPLLAs offer the tools for more predictable and performing systems.

Being governed by strongly nonlinear behaviors, still a lot needs to be understood about these synchronized arrays: the identification of other attractive features and limitations, will be particularly useful in future communications.

Acknowledgement

The authors wish to acknowledge ONR support through grant #N0014-00-1-0015. We appreciate the support and encouragement of Brian Meadows at SPAWAR, Ted Heath at Georgia Tech Research Institute and Ronald Pogorzelski at JPL.

References

[1] R. D. Martinez and R.C. Compton, "Electronic Beamsteering of Active Arrays with Phase-Locked Loops", *IEEE Microwave and Guided Letters*, vol. 4, no. 6, pp. 166-168, June 1994.

[2] R.A. York, P. Liao and J.J. Lynch, "Oscillator Array Dynamics with Broadband N-Port Coupling Network", *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-42, pp. 2040-2045, November 1994.

[3] J. Buckwalter, Ted Heath and R. A. York, "Synchronization Design of a Coupled Phase-Locked Loop", *submitted to IEEE Trans. Microwave Theory and Tech.*

[4] J. Buckwalter and R. A. York, "Time Delay Considerations in High Frequency Phase-Locked Loops", *submitted to IEEE Trans. Microwave Theory and Tech.*

[5] H.-C. Chang; A. Borgioli, P. Yeh and R. A. York, "Analysis of Oscillators with External Feedback Loop for Improved Locking Range and Noise Reduction", *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-47, pp. 1535-1543, August 1999.

[6] S. Kudszus, M. Neumann, T. Berceli and W. H. Haydl, "Fully Integrated 94 GHz Subharmonic Injection-Locked Pll Circuit", *IEEE Microwave and Guided Wave Letters*, vol. 10, no. 2, pp. 70-72, February 2000.