Simultaneous, Multi-Frequency, Multi-Beam Antennas Employing Synchronous Oscillator Arrays


The theoretical foundations of coupled, nonlinear oscillator arrays as applied to beam forming have, almost exclusively, presumed the unit cells are well described by a Van der Pol oscillator model. In the past, a “weak” association was made between the spectral output of the differential-pair oscillator and that of an ideal Van der Pol oscillator. By applying the Method of Multiple Scales to the Van der Pol dynamical equations, one finds that only odd order harmonics are present. Moreover, one can determine the key Van der Pol parameters (i.e., the amplitude parameter, $p$, and nonlinearity parameter, $\mu$) through the power contained in the first and third harmonics. Forgoing the details of the derivation, this relationship is given by:

$$p = \frac{1}{4} \times 10^{H_1/10} \text{ and } \mu = \frac{4}{p^{3/2}} \times 10^{H_3/20}$$

where $H_1$ and $H_3$ are the powers contained in the first and third harmonics, respectively. The spectral content of an ideal differential-pair oscillator also only possesses odd harmonics of the fundamental frequency. By measuring the power contained in the first and third harmonics, the above relationships can be applied; the resulting parameter values can be used describe the differential-pair oscillator with an “associated” Van der Pol oscillator. Obviously, this approach cannot rigorously prove that the underlying dynamics of the differential-pair oscillator is given by the Van der Pol equations. However, it does provide us with a motivation to use cross-coupled differential oscillators for this purpose. To this end we are developing, in tandem, two oscillator and circuit designs: a discrete board based oscillator and an ASIC design. For the discrete design we have largely used ADS and its’ Harmonic Balance tool to simulate the basic oscillator unit and the coupled oscillator array. The discrete design leverages off of earlier non-published work that was somewhat successful in achieving the desired beam-forming results. For the ASIC design we have largely
used CADENCE and its time-based transient analysis tool to simulate the basic oscillator unit and its’ arrays. The designs are somewhat independent of each other though the two design teams are coordinated. If successful, the ASIC design could reduce the electronics for a phased array antenna into a single small IC (improved cost, reliability, power optimization) design with multiple Defense and commercial applications. It remains to be seen if either design is Van der Pol-like enough to match to the existing beam-forming model. Fundamental mathematical analysis of the circuits has proved non-trivial and we have yet to range test either current design.

The discrete oscillator design uses a cross-coupled differential pair of matched transistors. The differential structure inherently suppresses even-order harmonics of the fundamental oscillation frequency when the output signal is taken differentially across symmetrically located points in the circuit. Due to the resonant length of the inter-oscillator coupling transmission lines, coupling energy spectral components at the fundamental frequency and its odd-order harmonics controls the array inter-oscillator phase-shift stability for a given resonator tuning arrangement, while coupling energy at even-order harmonics tends to decrease phase-shift stability.

Differential symmetry is maintained in the inter-oscillator coupling transmission lines, such that each oscillator is connected to each of its nearest neighbors by a pair of differential transmission lines. (Fig. 1) shows a circuit model, executed in Agilent Advanced Design System (ADS) software, of a single differential oscillator. The model uses microstrip elements to form the inductive part of the oscillator’s resonator and for the transmission line elements for inter-oscillator coupling. The coupling lines are connected via DC blocking capacitors to opposite ends of the parallel LC resonator and to the collectors of the two transistors. This oscillator is the central element in an array of three oscillators, and has differential coupling lines connected to its neighbors on either side.

Use of closed commercial software such as ADS for analysis of coupled oscillator arrays is problematic in that oscillator analysis tools provided by the software vendor do not easily find simultaneous solutions for multiple coupled oscillators. Typically the software measures the loop gain and phase of a single oscillator vs. frequency, and uses this information to set up initial circuit conditions for the harmonic balance oscillator plus analysis. These initial conditions are generally not sufficiently accurate for convergence of the harmonic balance analysis of a multiple oscillator array.

Suarez and Quere [1] have shown methods for establishing initial conditions in commercial harmonic balance analysis software through use of auxiliary signal generators. This technique was employed for the present array by installing auxiliary generators in the end oscillator array elements. The initial auxiliary generator voltages and phases are controlled by the initial conditions found by the ADS analyzer for corresponding points in the central oscillator circuit. After an initial harmonic balance solution for the entire array is found with the auxiliary generators in place, a series of optimizations are executed such that at final convergence, the auxiliary signal generators are effectively removed from the circuit because their amplitudes and phases exactly match those of their connection points in the oscillators’ circuits at steady state. Figure 1 shows the auxiliary generator connection points in ADS.