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Injection-Locked Fully-Monolithic Bilaterally-Coupled RF 1-Dimensional Voltage-Controlled-Oscillators Arrays in 0.18μm SiGe BiCMOS

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Invited Talk

***Abstract* — A fully-monolithic 3-element 1-Dimensional (1-D) array of bilaterally coupled voltage-controlled-oscillator (VCO) network was designed and fabricated in a 0.18μm SiGe BiCMOS process. Each VCO unit cell consists of a cross-coupled differential pair with on-chip inductors and varactors and oscillates at around 1.5GHz. A digitally controlled on-chip resistors network was designed and used for controlling the bilateral coupling strength across the array VCO units. The integrated coupled VCO array can be injection-locked via an external RF source to achieve excellent phase noise performance. These characteristics make this coupled-VCO network an attractive choice for possible use in phased-array applications.**

***Index Terms* — SiGe/BiCMOS LC VCO, phased array, coupled VCO, phase-shifterless phased array, injection locking, non-linear dynamics**

I. INTRODUCTION

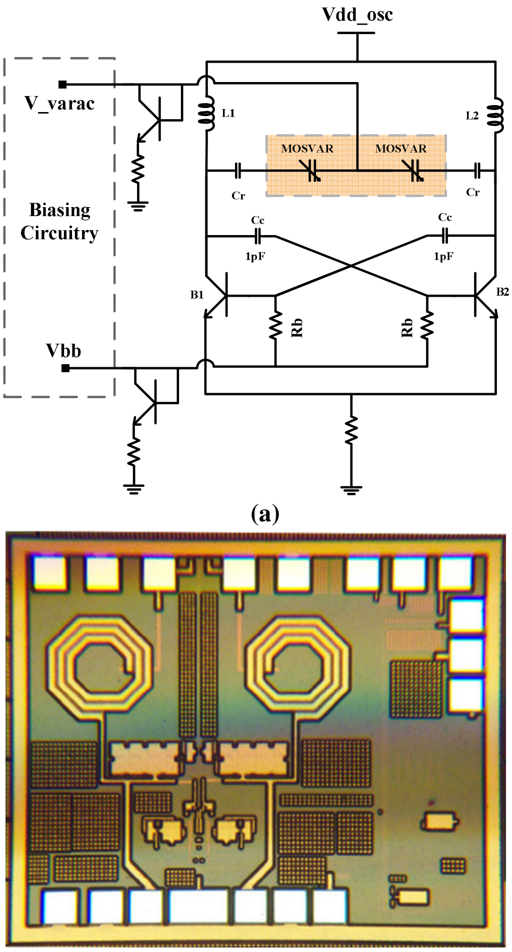
Recently, the interests for RF phased array systems have grown significantly for both Department of Defense (DoD) and commercial applications. Examples of such applications include ground, sea air, and space-based phased array radar, sonar scanning system, cellular base station, automobile driver assistance system, etc. . The concept of phased arrays has existed for several decades and most systems today are assembled with discrete components and particularly with bulky phase-shifters, increasing their form factors, weight and cost considerably. However, new advancements in semiconductor technologies, and DSP algorithms are making the full integration of phased-array system a reality A sample of reported integrated active array systems can be found in [1,2], designed to operate at Ka and Ku-bands, making use of locally interpolated oscillators to achieve several discrete phases. An attractive approach based on [3] proposed the used of nonlinear dynamics inherited to coupled VCO networks to generate continuous, gradient phase shift across VCO arrays. Advances have been made in this nonlinear dynamics approach in which λ/4 structures and coupling circuits are used to control coupling strength across the coupled network elements. Even though some of these approaches have proven to be highly effective for frequencies at X-band and above, their ability to generate phase locking at S-Band has been a challenge. Furthermore, each of these approaches can either work for an Rx chain or a Tx chain but not both. In this paper we focus on achieving a proof of concept prototype of a fully monolithic coupled VCO array having the characteristics previously seen at X-Band and proposed by [3,4,5] that takes full advantage of the nonlinear dynamics of self-locked and injection-locking techniques. To our approach, a module chip was designed and tested, giving fruitful preliminary results and showing that the most behaviors seen at a X-band discrete system can be translated at S-band on a fully monolithic implementation.

II. COUPLED OSCILLATOR ARRAY DESIGN

The design and integration of our proof-of-concept system consists of the design and integration of an LC-based coupled VCOs network. A single LC VCO unit cell was designed, and each VCO is coupled to its nearest neighbors with a passive variable resistive network. The design and implementation of each is presented next.

A. Unit Cell VCO Design and Implementation

The design and integration of the VCOs was done on IBM 0.18μm BiCMOS 7HP Technology. A schematic of the VCO is shown in Fig.1. Each VCO consists of a differential pair formed by devices B1 and B2 with dimensions of 2x10x.280μm resistively biased at base. The DC biasing current was carefully chosen at 1.5mA to avoid any startup issues due to the low Q of the tank (Q_L~6)[6]. The LC tank is composed of a hex-spiral integrated inductor with value of 2.68nH with total dimension of 350μx350μm. The capacitance is composed of parallel MIMCAP structures in series with a MOS Accumulation-Mode Varactor (MOSVAR). The total area for the MOSVAR and MIMCAP are 2x20x14μm and 230x130μm, respectively. A die picture of our integrated VCO is shown in Fig. 1(b) with a total area of 1300x1600μm (including the biasing circuitry for V_{bb} and V_{V_varac} and the pads). The tuning port for the MOSVAR can be externally adjusted. The VCO was simulated in SPICE using Cadence Spectre and designed to have a total consumption of 3.6mA from a 2.5V supply for a unit cell K_{VCO} of 394 MHz/V (Fig. 2). This K_{VCO} was intentionally made large to increase the tuning range. Also, simulations showed no



(b)

Fig. 1 – A LC-based VCO as the unit cell for the coupled 1-D VCO Array: (a) schematics; (b) die picture

performance differences between external biasing and on-chip bandgap biasing.

B. Array design and Implementation

Based on the single VCO design, monolithic integration of a coupled 1-Dimensional (1-D) VCOx3 network configuration was designed and fabricated to proof the concept of injection locking and phase noise improvement in a monolithic coupled VCO array for S-band applications. A simplified schematic of the digitally controlled coupling network and the coupling scheme is shown in Fig.3. The VCO array network coupling design is based on bilateral resistive variable network as seen in Fig.3(b). The array is AC coupled and allows for large ranges of coupling strengths. Therefore, our system is able to provide weakly coupled cases in which the equation described in [3,4] can be emulated in our integrated array. Additionally, strong AC-coupling can also be induced such that cases where numerical analysis and simulation results can be verified on hardware. The work presented in this paper is concerned with the weakly coupled case where the coupling achieved from network to network

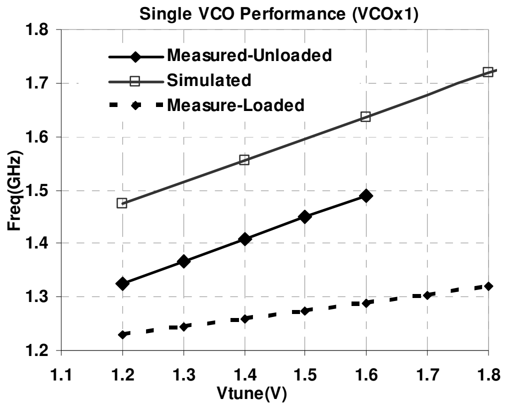


Fig. 2 Simulated (unloaded from coupling networks and other VCOs) and measured frequency responses for a unit cell VCO design

is ~30dB in attenuation from a VCO port to the next VCO port.

III. MEASUREMENTS

The measurement of our design was carried out in three steps. First, a single unloaded VCO was tested in a chip-on-boar fashion to verity its performance with simulation. The second set of measurements was realized with on a VCO loaded with the variable coupling network at each side. The third set of measurements consisted in the verification of a 1-D three unit cell VCO coupled array (VCOx3) with integrated coupling network as shown in Fig.3. When plotting the output frequency responses of the single VCO cell, a well-behaving linear frequency vs. V_{tune} curve emerged shown in Fig.2. This behavior yields a K_{VCO} of 412.5 MHz/V. This performance is consistent with the designed and simulated values of 394MHz/V. Since K_{VCO} is highly dependent on the biasing point, the frequency tuning range was measured and simulated using the same biasing values for V_{V_varac} and V_{bb}. The tuning range of our single VCO can be over 300-500MHz in measurement as one should be able to tune the on-chip varactor from 1.2V to 2.5V. Power consumption for our die was of 3.7mA (including the biasing) from a 2.5V supply, which is in close agreement to simulated values. In the case of the loaded VCO, power consumption also remained in close agreement with the simulated value. However, as the single VCO was loaded with the coupling network, the tuning range was reduced as shown in Fig.2. This decrease in tuning range was expected as the loading at the output ports will increase the capacitance at that node, thus reducing the tuning ability of the MOSVAR. Nonetheless, the ability of injection locking in addition to the phase noise enhancement is not expected to be altered by the lessening in tuning range. The loaded case exhibited a K_{VCO} of 148MHz/V due to the reduction in frequency tuning. On the other hand, the phase noise performance of the loaded VCO was of 86.6@100KHz, 115.5@1MHz when tuned to 1.232GHz under loaded conditions. The Phase noise performance of the loaded VCO had a variation of less than 1dB over it tuning range shown in Fig.2. Despite of the loading, the Figure of Merit (FOM) of the two-side-loaded unit cell VCO based on Equation (1) is around 170:

$$FOM = L(f_c) - 20\log(\frac{f_o}{f_c}) + 10\log(\frac{P_{dc}}{1mW}) \qquad (1)$$

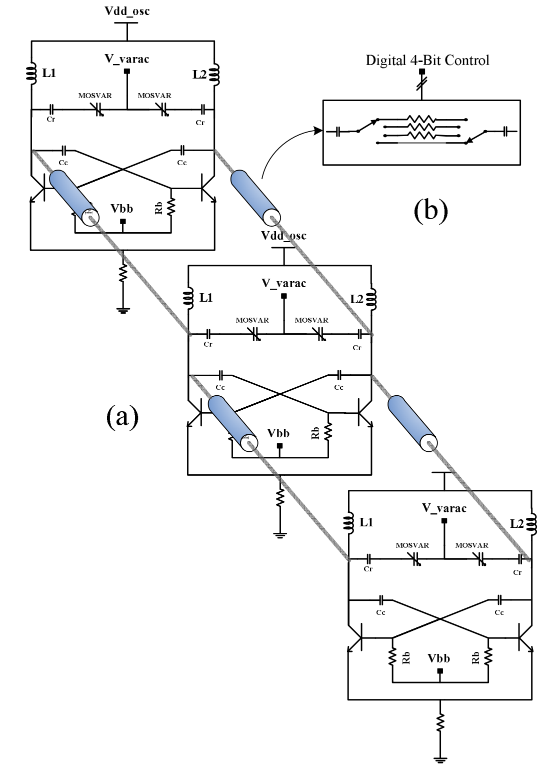


Fig.3 – Simplified system schematic of the integrated coupled-VCOx3 array: (a) digital coupling scheme; (b) simplified coupling network

A 1-D coupled VCO network was subsequently designed and integrated on chip. The network consists of five single VCOs coupled via a variable resistor network. In this measurement, only three VCOs were used in the network, leaving the edge 2 VCOs turned off to create a VCOx3 network as shown in Fig.3(a). The power consumption of the network was measured at <12mA from a 2.5V supply. For the work presented in this paper, voltage supply to the VCOx3 network was provided by external LDOs mounted on the same board to avoid phase noise degradation. As previously addressed, weakly coupling is the case of interest in this work such that Adler's equation can be reduced to its simplest form given in [4], where mutual amplitude interactions of the VCOs are highly attenuated. This amplitude independence will allow for the phase dynamics to be described by [5]:

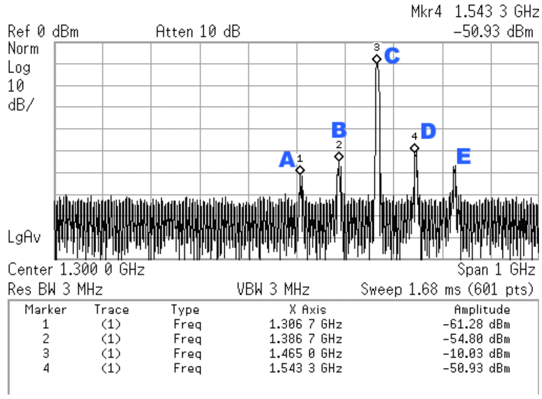


Fig.4 – Measured spectrum of the coupled 1–D VCOx3 array. Tone C= 1.465GHz (array loaded VCO free running frequency); Vtune= 1.8V, Vdd=2.5V

$$\frac{d\theta_i}{dt} = \omega_i - \frac{\omega_i}{2Q}\sum_{j=1}^{N}\varepsilon_{ij}\frac{\alpha_j}{\alpha_i}\sin(\Phi_{ij} + \phi_i - \phi_j) \qquad (2)$$

Additionally, if we can assure that we have set our array to a weakly coupled condition we can therefore laterally injection lock the on-chip integrated array. The injection locking ability has been previously described by [3] and presented in [4] where $d\theta/dt=\omega_{inj}$ reducing (2) to:

$$\Delta\omega_{lock} = -\frac{\omega_i}{2Q}\varepsilon_{ij}\frac{\alpha_j}{\alpha_i} \qquad (3)$$

This locking bandwidth is highly depending on the Q of the network and it is band limited as the mutual coupling coefficient ε_{ij} is decreased (i.e. weakly coupled array)

The VCOx3 network was tested with the weakest coupling setting, achieving ~35dB coupling from network to network and allowing the network to run with loads of 50Ω at each port to mimic the loading of driving a mixer, antenna or power amplifier. The network port V_{tune} of each VCO was set to 1.8V, with a V_{dd}=2.5V. A strong oscillation was observed at the output of each VCO in the phase array network. A sample output from VCO2 is shown in Fig.4. This output exemplifies all the VCO outputs in the phase array (i.e. VCO3, VCO2, VCO1). The fundamental frequency in Fig. 4 is 1.465GHz with a clearly overmoded response, where close-in tones are evenly spaced at ~80MHz away. The fundamental tone has a power of -10dBm with side tones at levels of -41dBc (Fig.4 point B,D) and -50dBc (Fig.4 point A,E) from the fundamental. In short, the network was loosely locked when powered up, exhibiting strong sidelobes. While keeping the same settings (i.e. V_{dd}=2.5V, V_{tune}=1.8V), a lateral RF injection signal was applied in the network as shown in Fig.5. The signal of injection was -25dBm at a frequency of 1.470GHz

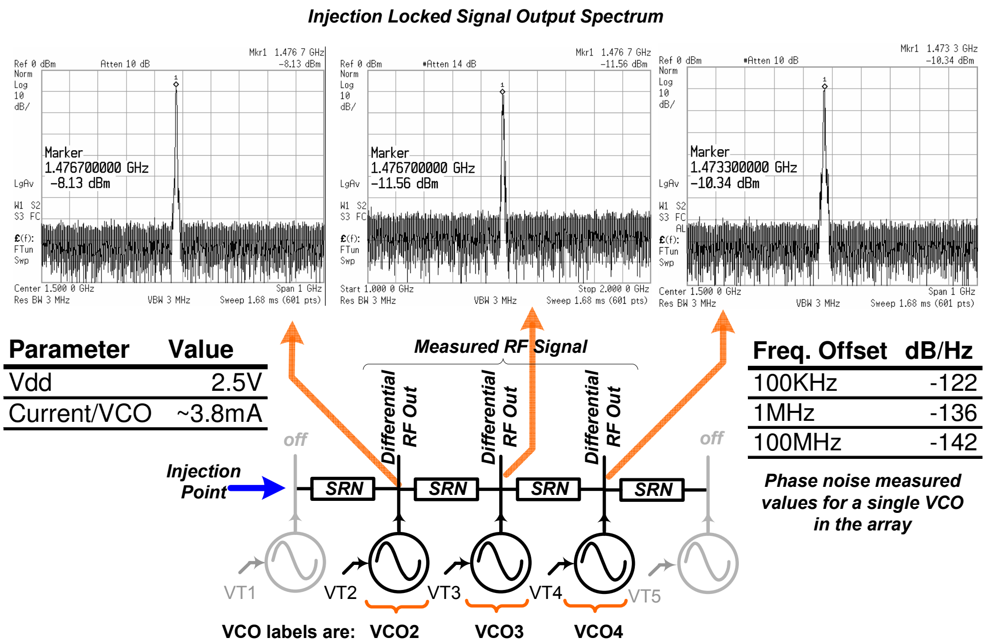


Fig. 5- Simplified 1-D coupled VCOx3 array network schematic, showing its measured output spectra, DC conditions and phase noise performance for VCO2 under an injection-locked condition

and generated by an Agilent E4432B the injection signal was applied to our network while the coupled array was actively running with output shown as in Fig. 4. As the injection signal was applied, the network was instantly locked and its outputs are shown in Fig.5. The phase noise performance is also shown in Fig.5. The FOM of an array VCO under locked conditions improves greatly, reaching 190 based on Eq. (1) as the excellent phase noise of the injection signal is transferred to the VCO array. The chip's total power consumption is 30mW (12mA at 2.5V).The expected phase-shifting properties of the coupled-VCO array will be experimentally verified next, as we anticipate this coupled-VCO array may open up new avenues for designing future phase-shifterless phased-array systems as monolithic SoCs.

VII. CONCLUSION

A fully integrated proof-of-concept 1-D coupled-VCO network was implemented in a 0.18µm SiGe BiCMOS process. The design and analysis of each of its components was presented. The simulated single unit agreed largely with the testing results. It was demonstrated that the unit cell VCO could drive the coupling network and therefore function in coupled array. A coupling variable network was introduced to control the coupling coefficient between the network unit VCOs. A VCO coupled array was designed under weakly coupled conditions to proof that injection locking techniques predicted by [3,4,7] could be implemented in and fully monolithic VCO coupled array operating at S-band. Moreover, the network was able to be laterally injection locked, opening the possibilities of a S-band fully monolithic SoC array using coupled VCO network for phased array applications with excellent phase noise.

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