Very Low Phase-Noise Fully-Integrated Coupled VCOs

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Abstract — **With the aim of achieving very low phase noise, two area and power consumption efficient methods of coupling two or more identical VCOs are presented. To verify the principles, a set of fully integrated, coupled VCOs of the cross-coupled differential pair type, was manufactured in a commercial SiGe HBT technology. The measured phase noise at 100 kHz offset frequency was -106 dBc/Hz at 6 GHz using two coupled VCOs and -103 dBc/Hz at 12 GHz using four coupled VCOs. A phase noise reduction of 1-6 dB was achieved relative to a single VCO of the same topology. In one of the two methods, output signals are additionally obtained in quadrature.**

I. INTRODUCTION

Frequency generations circuits are one of the most critical parts of a high performance radio. It is often the most difficult part to put onto a fully integrated transceiver due to very stringent phase noise requirements. In addition, cost concerns require that as small area as possible is used and for portable devices low power consumption is paramount. Over the last couple of years, substantial progress has been made in achieving very low phase noise also in fully integrated VCOs [1]-[4]. However, as more advanced, spectrum efficient, modulation schemes are being employed, the requirement on VCO spectral purity increases and there is a constant drive for higher performance integrated VCOs.

One of the most efficient methods of reducing phase noise is to increase the signal amplitude in the resonator. However, the maximum resonator signal amplitude is limited by breakdown mechanisms in the devices used.

An efficient method to overcome the break down limitation, is to "parallel connect" two or more resonators, thereby effectively increasing the total resonator signal amplitude, while still keeping within the break-down limits of each separate resonator. If N identical oscillators are coupled to each other the phase noise will be reduced by a factor 1/N [5]

Several methods of coupling oscillators have been demonstrated [6]-[9]. Most of these require special, power and area consuming circuitry to achieve the coupling.

In the present paper two simple methods of coupling VCOs are presented. One of them is very area efficient, occupying almost the same area as a single VCO. The other one provides output signals in quadrature. Both of them have been experimentally characterized and demonstrate state-of-the-art phase noise performance.

II. VCO TOPOLOGIES

In the designs the VCO core is made up of a cross-coupled differential pair with a parallel resonator connected between the collector nodes. This design has been extensively used for the last couple of years and has proven to be a robust and high performance topology.

A. Quadrature coupling

In the cross-coupled differential pair, there are a number of virtual ground points, indicated by A to E in Fig. 1. At these nodes, the fundamental tone, i.e. the operating frequency of the VCO, and all odd harmonics, cancel, whereas the second harmonics, and all other even harmonics, add in phase. In the proposed topology, two identical such VCOs are connected via two identical virtual ground points. Since the two VCOs are free to move in phase relative to each other, they move phases in such a way that the first harmonic cancel at this virtual ground point, which seems to be a stable operating point of the coupled VCO system.

In doing so, two advantages are obtained. First, the two VCOs are locked together thereby the phase noise is reduced by 3 dB. Second, when the second harmonic lock 180° out of phase, the fundamental frequency of the two VCOs will have a quadrature phase relation to each other.

The suggested coupling, is very simple and requires no extra area or power consuming circuitry. Either point A to E in of the first VCO (Fig. 1) can be DC connected to its counterpart in the second VCO. To achieve stable oscillations though, it was found that points B are best connected by a capacitor, as shown in Fig. 1. If points C, D, or E are used for quadrature locking, an ac-blocking element, such as an inductor, must be placed between the

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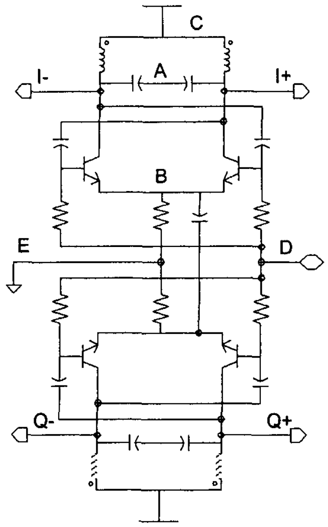


Fig. 1 Two standard type cross-coupled differential pair VCOs coupled in quadrature. Points A-E denote possible virtual ground points. I and Q are the quadrature outputs.

point and the bias supply to ensure proper DC biasing. This inductor could be the bond wire used for the bias supply.

B. Inductive Coupling

A disadvantage of the locking method described above is that it occupies twice the area of a single VCO. Since the largest area occupied by the VCO is made up of the inductor, it would be strongly desired to integrate the inductors together. In Fig. 2, an intertwined, coupled inductor structure serving this purpose is suggested. It is basically a 1:1 transformer made up of two single turn differential inductors. Similar structures for two or more turns can also be made if larger inductance values are desired.

By connecting Port 1 of the inductor in Fig. 2, to one differential VCO and Port 2 to another, identical VCO, the two VCOs will strongly lock to each other (Fig. 3). They will lock in phase with each other, so that a positive mutual inductance is obtained. In this way the size of the inductors can be decreased, while keeping the effective inductance equal to the inductance of the original, separate inductor. The stronger the coupling, the smaller the inductors can be made.

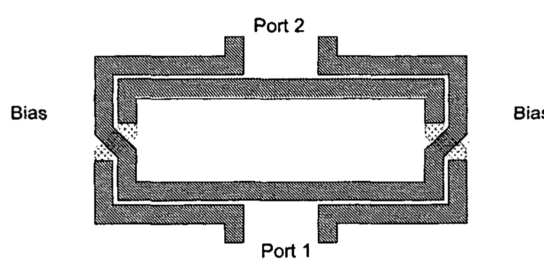


Fig. 2 Two strongly coupled, one turn, differential inductors.

In addition to locking the VCOs to each other, the coupled inductors form a second order filter together with the resonator capacitors. This acts to further reduce noise.

For the test VCOs presented here, the size of a coupled oscillator made this way, has an active die area which is 500x650 μm^2, compared to 500x500 μm^2 for a single VCO using identical circuitry. The expected improvement in phase noise thus comes with only a small penalty in occupied area.

III. FINAL DESIGNS

For verification of the suggested principles, three different VCOs were designed.

VCO1 A single differential VCO of conventional type.
VCO2 Two inductively coupled VCOs
VCO3 Four coupled VCOs made up of two pairs of VCO2-type coupled in quadrature to each other.

All three VCOs had a combination of pn-junction varactor diodes for continuous fine tuning and PMOS varactors for coarse band switching.

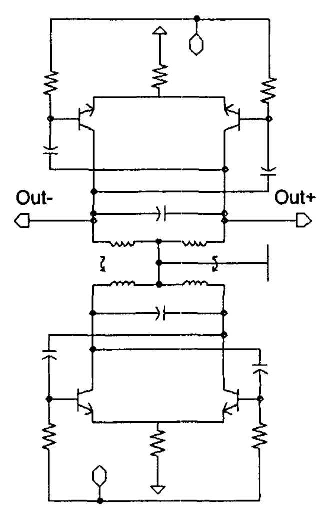


Fig. 3. Simplified schematic of two VCOs coupled via coupling of the resonator inductors. VCO2 is designed this way.

Inductors were simulated and optimized using a 2.5 dimensional electro-magnetic simulator. A lumped model was fitted to the obtained s-parameters and used in circuit simulations. Because of the higher complexity of the coupled inductor structure, uncertainties in simulation results and modeling, are expected to be larger for this structure than for the separate inductor.

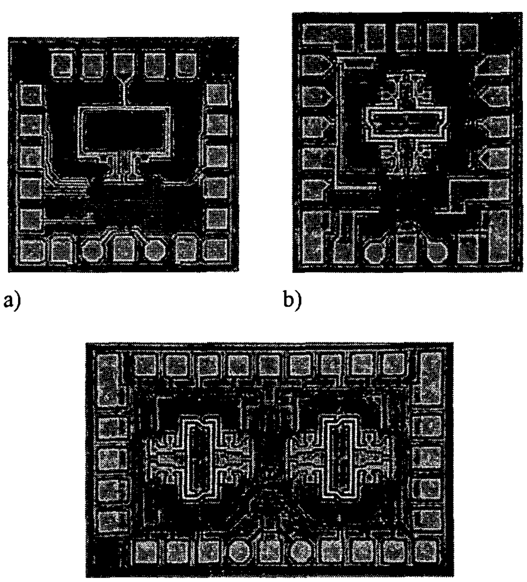
In VCO3 the output signal is taken from the emitters so that twice the fundamental, operating, frequency of the VCO is obtained. By taking signals from one of each double pair, a differential signal is obtained.

Chip photographs of the VCOs are shown in Fig. 4.

The circuits were realized in IBM's BiCMOS 5AM, a silicon germanium process technology featuring f_T=47 GHz and f_{max}>60 GHz. It provides a 4 μm thick top Al metalization layer for making high Q-factor inductors and low loss interconnects. Additionally, 0.5 μm CMOS transistors are available.

IV. EXPERIMENTAL RESULTS

The VCO dies were wire bonded onto a dedicated test substrate. The substrate was put into a fixture and placed in a shielded box. All measurements presented here were made in a dedicated phase noise measurement system based on the delay line discriminator technique.



a) b) c)

Fig. 4 Chip photograph of a) VCO1: 1.1x1.1 mm^2 b) VCO2: 1.1x1.2 mm^2 c) VCO3: 1.8x1.1 mm^2. All three VCOs are on the same relative scale and include a buffer amplifier and a 50 Ω driver circuit.

TABLE I

SUMMARY OF MEASURED VCO PERFORMANCE

	VCO1	VCO2	VCO3
No. of coupled VCOs	1	2	4
Vcc (V)	3.3	3.3	3.3
Core current bias (mA)	9	16	32
Frequency (GHz)	6.3	5.9	11.8
Tuning range (%)	17	17	17
Phase noise @ 100 kHz (dBc/Hz)	-104	-106	-103

A summary of the performance of the three VCOs are given in Table I. Due to non-optimum design of the MOS varactor geometry, the phase noise degrades substantially for the lower frequencies. However, within the 4% continuous tuning range of the pn-junction varactor, the phase noise is stable to within 2 dB.

In Fig. 5, the measured phase noise for the three test VCOs is given. Operating frequencies for the measurements are as given in Table I. Phase noise performance of all VCOs is excellent and it is quite clear that the phase noise is reduced when two or four VCOs are coupled. To illustrate this more clearly, the difference in phase noise between a double VCO and a single VCO is plotted in Fig. 6 for two bias conditions.

Relative to the single VCO the phase noise of the double VCO is reduced by 1-3 dB and the quadruple VCO by 3-6 dB, for the same bias current per VCO. On the other hand, when the bias condition of each VCO is optimized for best phase noise (by externally varying the bias point), the double VCO has 3-5 dB better phase noise than that of the single VCO (Fig. 6).

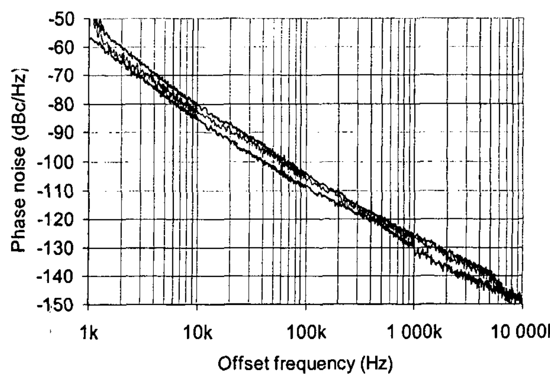


Fig. 5 Phase noise measurement results. The top curve is for VCO1, the middle curve for VCO2 and the bottom curve for VCO3. Since VCO3 is measured at twice the frequency the bottom curve has been scaled by –6 dB to be comparable to the others. All VCOs are biased at the same bias current per VCO.

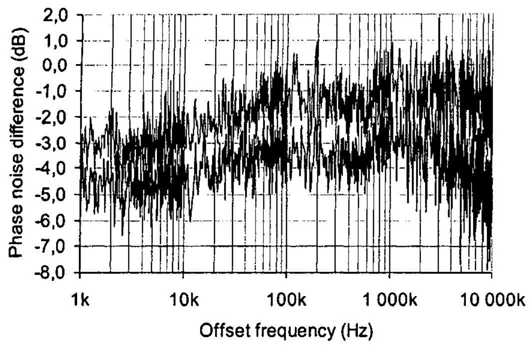


Fig. 6. The difference in phase noise between a double VCO and a single VCO. In the upper curve the VCOs operate at the same bias current per VCO, in the lower curve the VCOs are optimized for best phase noise.

The more than 3 dB reduction in phase noise achieved for a double VCO compared to a single VCO, is likely caused by the combined effect of VCO coupling and second order filtering. The same effect has been observed in simulations.

By further improving the coupled inductor layout for better Q and optimized coupling, even better phase noise and/or lower current consumption should be achievable.

The fact that VCO3 gives an output power in reasonable agreement with simulation suggests that the two VCO2 blocks lock to each other in quadrature, just as expected. Otherwise the output at the emitters at twice the frequency would not be differential and the subsequent differential amplifiers would not provide an appreciable output signal.

In Table II, published state-of-the-art, fully integrated VCOs are compared to the results obtained in this work. To be able to compare VCOs operating at different frequencies and measured at different frequency offsets, the results have been scaled to an operating frequency of 1 GHz and an offset frequency of 100 kHz, assuming a 20 dB phase noise degradation per decade of operating frequency and a 20 dB phase noise reduction per decade of offset frequency. Our VCOs clearly out-perform all published VCOs in terms of phase noise.

In principle it should be possible to extend the proposed concept to a larger array of VCOs and reduce the phase noise even further.

V. Conclusion

Two efficient methods of coupling VCOs to reduce phase noise have been proposed. The methods have been experimentally verified and excellent phase noise performance in reasonable agreement with predictions has been obtained.

TABLE II
COMPARISION OF PUBLISHED STATE-OF-THE-ART VCOS

Ref., Year	f_0(GHz)	Δf (kHz)	Phase Noise (dBc/Hz)	Phase noise normalized to f_0=1 GHz Δf=100kHz (dBc/Hz)
[1], 00	1.5	100	-111	-115
[2], 00	4.8	100	-100	-114
[3], 00	5.0	100	-98	-112
[4], 00	2.0	600	-125	-115
[6], 01	1.9	100	-106	-112
[7], 00	0.9	100	-112	-111
[9], 98	1.9	600	-123	-113
This work				
VCO1	6.3	100	-104	-120
VCO2	5.9	100	-106	-121
VCO3	11.8	100	-103	-124

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