A 100GHz Active-Varactor VCO and a Bi-directionally Injection-Locked Loop in 65nm CMOS

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***Abstract* — A 100GHz fundamental active-varactor VCO and a bi-directionally injection-locked loop are demonstrated in 65nm CMOS. Without using a conventional passive varactor, the proposed VCO achieves a tuning range of 5.2% at 100GHz and a phase noise of -112.1dBc/Hz at 10MHz offset. By utilizing the proposed transmission-line-based capacitive coupling, four oscillators are injection-locked properly and the loop creates eight phases of the carrier and 6dB(=10log4) of phase noise improvement, realizing a measured phase noise is -118.8dBc/Hz at 10MHz offset.**

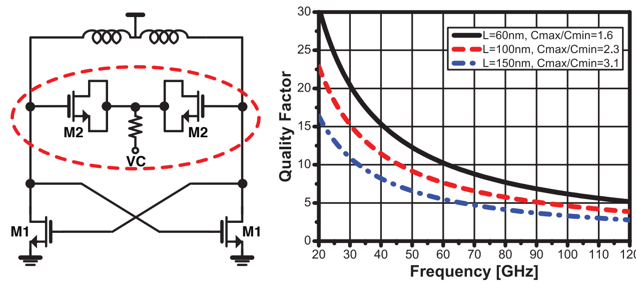
***Index Terms* — 100GHz, bi-directionally injection-locked loop, capacitive coupling, injection locking, transformer, transmission line, varactor, voltage-controlled oscillator.**

I. Introduction

The mm-Wave and THz bands have been exploited for many applications including radar, imaging, and high-speed wireless communication. In order to improve the system accuracy, spatial resolution, and data acquisition rate, a high output power and low-noise signal source is one of the important system requirements. Especially in this frequency range, it is challenging for on-chip oscillators to have high power efficiency, spectral purity, and frequency tunability. Thus, this paper proposes a 100GHz fundamental active-varactor VCO that achieves a tuning range without a conventional passive varactor in 65nm bulk CMOS. Also a transmission-line-based capacitive coupling technique is proposed as a method to achieve multiple phases and low phase noise.

II. A 100GHz VCO without a Passive Varactor

LC VCOs traditionally use passive varactors for frequency tuning as shown in Fig. 1(a). However, as the frequency increases over 100GHz, the quality factor of varactors decreases significantly. Fig. 1(b) shows the quality factors of the passive varactors of the 65nm bulk CMOS. If the parasitic resistance and inductance are taken into consideration, the quality factor can be much lower. The low Q of the passive varactor degrades the overall LC tank Q, output power, power consumption, and phase noise. As such, there have been many efforts on varactor-less VCOs but previous demonstrations are implemented at frequencies lower than 30GHz [1]. At mm-wave frequencies, the varactor Q dominates the overall tank Q



(a) (b)

Fig. 1. The varactor performance. (a) Schematic of a typical LC VCO. (Passive varactors are highlighted.) (b) The quality factors of the passive varactors (from post-layout simulations).

M1	LVT	6μm/60nm	Main Pair
M2	LVT	6μm/60nm	
M3	SVT	8μm/60nm	Auxiliary Pair
M4	SVT	12μm/60nm	
M5	LVT	4μm/60nm	Output Buffer
M6	LVT	4μm/60nm	

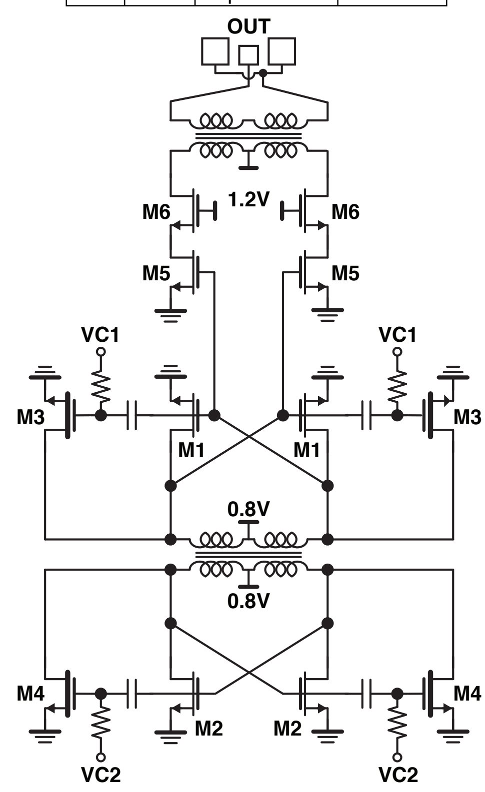


Fig. 2. Schematic of the proposed active-varactor VCO.

rather than the inductor Q, hence the advantages from removing passive varactors can be even more pronounced.

In this work, a 100GHz fundamental active-varactor VCO is proposed, schematically shown in Fig. 2. The oscillator has two cross-coupled pairs (main and auxiliary), and the control voltage changes the gate voltage of the auxiliary pair. Without using a conventional varactor, the oscillator frequency can be changed by tuning the control voltage. Increasing the control voltage increases the device capacitance, hence the frequency decreases. In addition, a transformer is employed and each side has a main pair and an auxiliary pair. Using the transformer has several advantages. First, by using two control voltages, the currents of two sides are independently controlled so inductive frequency tuning happens as well as capacitive tuning. Second, the magnetic flux of a transformer is generally lower than that of a single inductor due to two windings, thus any unwanted magnetic coupling can be reduced. Lastly, it enables bi-directional injection locking and this will be discussed in the next section.

III. Bi-directionally Injection-Locked Loop

It is well known that if multiple oscillators are coupled properly, their phase noise can be reduced [2]. Also, multiple phases can be created and used for many applications (quadrature up/down-conversion, phase rotating, and frequency multiplication). Many oscillator outputs can enable various system architectures and give higher output power if they are combined. On the other hand, the drawbacks are larger area, higher power dissipation, and more complicated routing. However, each oscillator size is relatively small at 100GHz, and DC current can be reduced by using small-size transistors and the proposed active-varactor tuning scheme. Furthermore, the proposed simple capacitive coupling solves the complex routing issues associated with locking the VCOs.

Many coupling topologies have been proposed such as cyclic or non-cyclic, uni-directional or bi-directional [2]. In this work, four oscillators in the cyclic loop are chosen for generating eight phases (45°). As shown in Fig. 3, one connection is cross-coupled for out-of-phase locking. In addition, bi-directional coupling is chosen for the following reasons. The oscillator signal and two injected signals from adjacent oscillators are vector-summed, and since the two injected signals have opposite phases (±45°), the direction of the summed signal is ideally the same as that of the oscillator signal. Thus, there is no frequency shift, and the oscillators keep operating at the LC resonance point, which is the point of the maximum swing/gain.

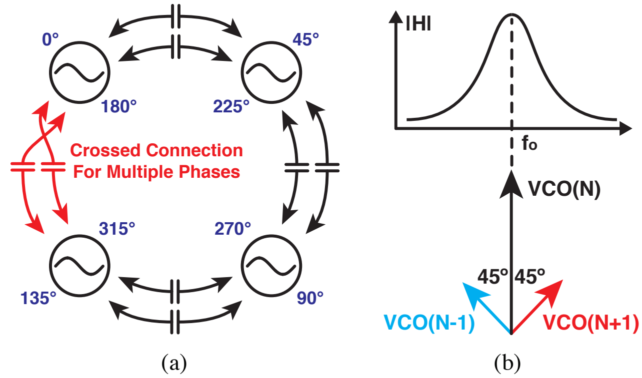


Fig. 3. (a) Bi-directional injection locking. (capacitive coupling) (b) Phase Diagram for VCO(N).

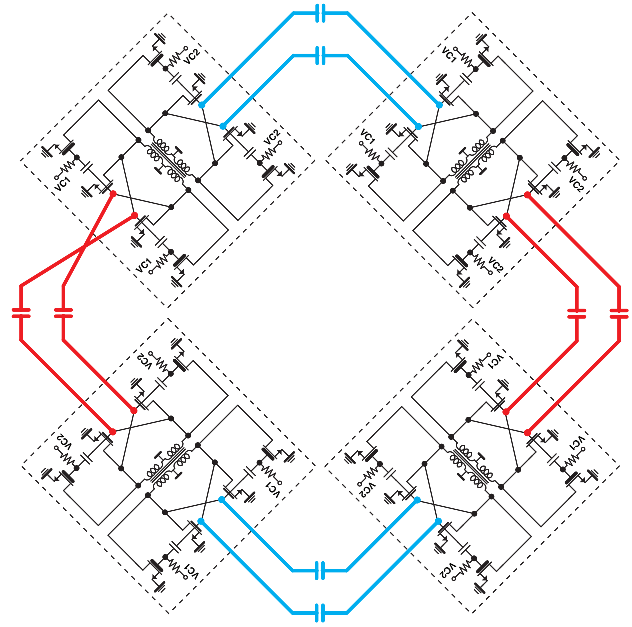


Fig. 4. Schematic of the proposed bi-directionally injection-locked loop.

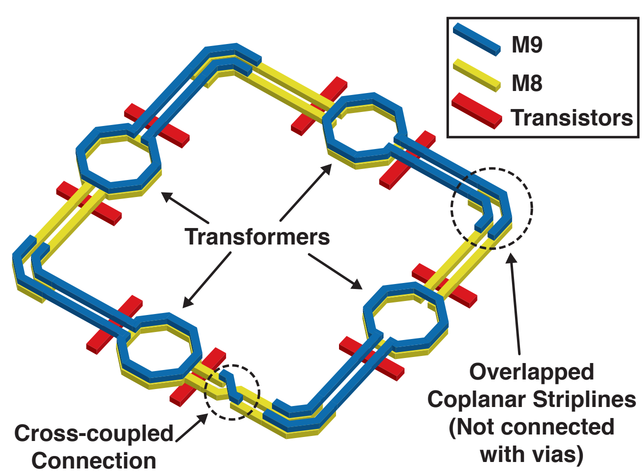


Fig. 5. Layout of the injection-locked loop. (not to scale)

But the problem is that bi-directional coupling requires more buffers and higher power consumption. To solve the problem, the transmission-line-based capacitive coupling is proposed as shown in Fig. 4 and Fig. 5. Oscillators are coupled and injection-locked simply through a capacitor. The capacitor itself is bi-directional, noise-less, and does not dissipate power. Similar techniques were reported at frequencies lower than 11GHz, but applied to only QVCO [3]. Also, a problem with reported capacitive coupling in three or more oscillators is that all the oscillators are connected through capacitors, and so an oscillator signal may affect all the other oscillators, potentially negating the effect of bi-directional coupling. Therefore, in order to enable and ensure the proper locking, the transformer of the VCO plays a role as its coupling factor (≈0.65) gives some attenuation between two sides, preventing undesired coupling. The oscillators are not in phase in this design, so the capacitor is seen by the oscillator, and as such the capacitor lowers the frequency so it should be minimized. On the other hand, if it is too small, injection locking is so weak that oscillators cannot be locked properly. In this design, 5fF is selected to balance the trade-off.

The layout of the loop is illustrated in Fig. 5. Four VCOs and four transformers are placed at corners of a square. Coplanar striplines are extended from the transformers. M8 is extended from the primary side of an oscillator and M9 is from the secondary side of the other oscillator. They are overlapped in the middle over a length of 14µm while the length of each extended line is about 70µm. Effectively the total reactance is about 5fF, and the input phase and the output phase of the coupling path (M8 lines, overlapped regions, and the M9 lines) should be the same to enable the bi-directional injection-locking.

IV. Experimental Results

The stand-alone VCO and the VCO loop were fabricated in 65nm CMOS. The die photos are shown in Fig. 6. The actual area of the VCO tank core and its output buffer is 90µm×45µm and the actual area of the injection-locked VCO loop is 320µm×320µm. A W-band probe, a DC probe, a down-converter, a spectrum analyzer and a power meter were used to perform the measurements. The measurement results are shown in Fig. 7. By sweeping two control voltages independently, the output frequency, output power, phase noise, and power dissipation are measured. The reason why VC1 and VC2 are asymmetric is that the output buffer is connected to only the primary side and the sizes of auxiliary pairs are designed to be different. Fig. 8 shows the comparison between two cases. In the case of the VCO loop, 6dB(=10log4) of phase noise improvement is clearly visible for offsets between 2MHz

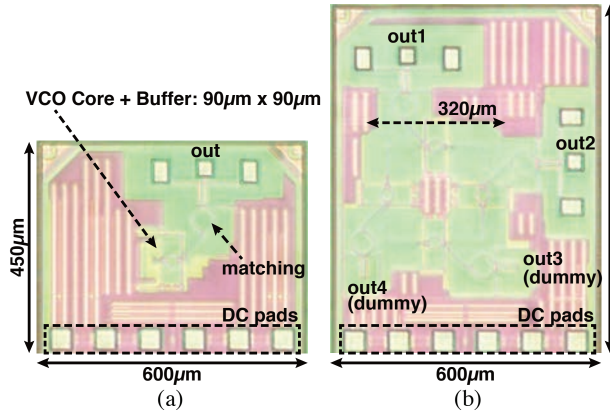


Fig. 6. Chip micrographs. (a) The single VCO. (b) The injection-locked VCO loop.

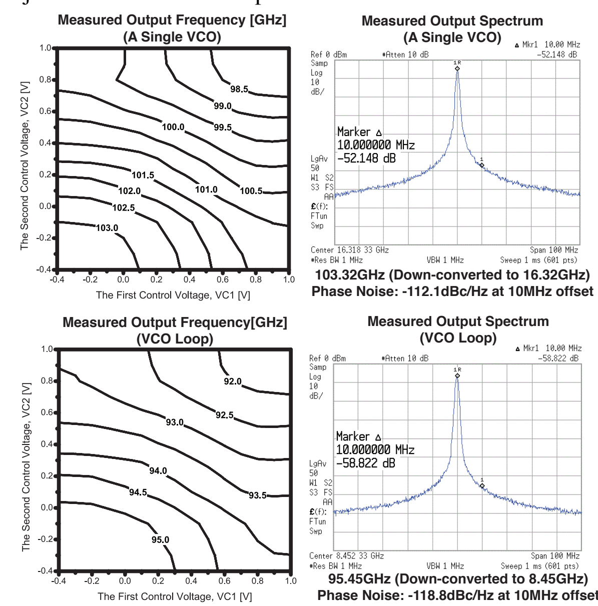


Fig. 7. Measured tuning curve and output spectrum of the single VCO and the injection-locked VCO loop.

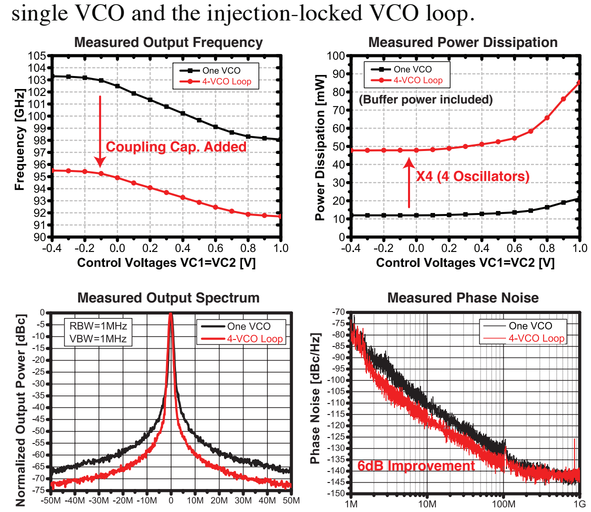


Fig. 8. Comparison between the single VCO and the injection-locked VCO loop.

TABLE I

SUMMARY OF 100GHZ CMOS VCOS

Single VCO	Tsai [4]	Laskin [5] (3)	Volkaerts [6]	This work
Technology	90nm CMOS	65nm CMOS	65nm CMOS	65nm CMOS
Frequency [GHz]	90 ~ 92.5	88.3 ~ 91.3	113.5 ~ 122.5	98 ~ 103.3
Tuning Range (TR) [%]	2.74	3.34	7.8	5.2
Phase Noise [dBc/Hz] @ 10MHz	-107.1 @ 90GHz	-115 @ 90.4GHz (4)	-104 @ 118.3GHz (4)	-112.1 @ 103.3GHz
Output Power [dBm]	-12 ~ -20	-4 ~ 3	-28 ~ -14	-5 ~ -2
Total Power Consumption [mW]	14 ~ 87.2	57.6 (5)	5.6 (5)	12 ~ 21
Control Voltage [V]	0.6 ~ 1.45	-1.2 ~ 1.8	0 ~ 2	-0.4 ~ 1.0
Supply Voltage [V]	0.6 ~ 1.45	1.2	1	0.8, 1.2
Core Area [μm^2]	620×550	150×170	105×65	90×45
FoM_{POUT} [dBc/Hz] (1)	155.8 @ 90GHz	176.5 @ 90.3GHz	156.9 @ 118.3GHz	178.6 @ 103.3GHz
$FoM_{POUT,T}$ [dBc/Hz] (2)	144.5 @ 90GHz	167.0 @ 90.3GHz	154.7 @ 118.3GHz	172.9 @ 103.3GHz

(1) $FoM_{POUT} = \left(\frac{f_{osc}}{f_{off}}\right)^2 \frac{P_{out}}{L\{f\}P_{diss}}$ (2) $FoM_{POUT,T} = \left(\frac{f_{osc}}{f_{off}}\right)^2 \frac{P_{out}}{L\{f\}P_{diss}} \left(\frac{TR}{10}\right)^2$

(3) QVCO (4) Estimated from 1MHz offset noise. (5) Buffer power is not included.

TABLE II

SUMMARY OF INJECTION-LOCKED LOOPS

Bi-directionally Injection-Locked Loop	Hekmat [2]	This work
Technology	90nm CMOS	65nm CMOS
Number of VCOs	4	4
Frequency [GHz]	19 ~ 21	91.7 ~ 95.5
Tuning Range (TR) [%]	10	4.1
Phase Noise [dBc/Hz] @ 10MHz	-121 @ 20GHz (1)	-118.8 @ 95.5GHz
Phase Error	< 1°	< 1°
Total Output Power [dBm]	-	1 ~ 4
Power Consumption [mW]	42.8	48 ~ 85
Control Voltage [V]	-	-0.4 ~ 1.0
Supply Voltage [V]	1	0.8, 1.2
Core Area [μm^2]	500×400	320×320
Coupling Method	Buffers	TL-based Capacitors

(1) Estimated from 1MHz offset noise.

and 100MHz. Also the RMS jitter integrated from 2MHz to 1GHz is reduced from 77fs to 33fs. This technique should also improve phase noise at lower offsets, but due to measurement limitations and oscillator drift, the improvement is visible above 2MHz. The results match well with theory and simulation, demonstrating that injection locking works properly.

V. CONCLUSION

A 100GHz fundamental active-varactor VCO and a bi-directionally injection-locked loop were described. Finally, the performance summary and comparison tables are in Table I and Table II.

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