A 40 GHz Low Phase Noise VCO in 40 nm CMOS

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Abstract—This paper presents a 40 GHz voltage-controlled-oscillator (VCO) in 40 nm RF CMOS technology. The proposed integrated VCO is based on an LC-tank topology with n-type cross- coupled transistors as well as n-type varactors. It covers a tuning range of 5.9 GHz by altering the oscillation frequency via both an analog dominant varactor and by a 3-bit varactor structure. The VCO oscillates from 39.33 to 45.32 GHz with a simulated phase noise (PN) lower than -100.6 dBc/Hz at 1 MHz frequency offset and lower than -121 dBc/Hz at 10 MHz frequency offset in all bands, dissipating 8.97 mW from a 1.1 voltage supply.

Keywords— CMOS, cross-coupled, n-type varactors, voltage-controlled oscillator (VCO)

I. Introduction

This paper presents a voltage-controlled oscillator (VCO) covering 5.9 GHz in the 40 GHz millimeter-wave (mm-wave) frequency band. Millimeter waves (mm-waves) refer to the frequency bands between 30 and 300 GHz. Due to the rapid evolution of the fifth-generation mobile communications (5G) whose frequency bands include mm -waves, there is a growing interest in the research of wideband and low power VCOs used in mm-wave phase locked loops (PLLS). The scaling of CMOS process has improved tremendously, thus making possible the design of a CMOS transceiver in a single chip. Furthermore, due to the low cost and high reliability of CMOS process it is the preferred technology for designing VCO [1], [2], [3], [4], [5], [6].

The VCO as an integral part of a CMOS transceiver has a large and dominant effect on its performance. In mm-wave VCO design the quality factor of the varactor is poor and dominates the overall quality factor of the LC-tank [2]. The quality factor has a strong effect on the resulting phase noise as dictated by Leeson's equation [6]. Thus, it is extremely difficult to achieve both low phase noise and large tuning range as the second would require the use of a large varactor leading to severe phase noise degradation.

In order to increase the tuning range of a mm-wave VCO, tuning must be separated into coarse and fine. It is customary to use an analog varactor for the continuous fine tuning and switched capacitive elements for the coarse tuning. Moreover, the design strategy of a multiband VCO without the use of a large varactor tend to keep the KVCO almost constant which is of paramount importance for the PLL to lock [6].

Several mm-wave VCO papers have been published near the 40 GHz frequency band. In [8] a 40 GHz VCO with a 3.5 GHz tuning range has been designed, albeit the phase noise is high and in [9] satisfactory phase noise performance and large tuning range has been accomplished but at the cost of high-power consumption. Finally, in [10] the VCO performance is decent, although the phase noise varies more than 4 dB across the bandwidth.

In this paper a mm-wave VCO is presented with a considerable tuning range of nearly 6 GHz, (operating from 39.33 to 45.32 GHz), and achieving a phase noise below -100.6 dBc/Hz in all bands along with a power budget lower than 9 mW. Furthermore, the phase noise variation of 1 dBc is one of the smallest in existing literature. In contrary to existing literature, in this work three n-type varactors are used to achieve coarse tuning. The VCO is designed in Cadence software using TSMC's 40nm (1P10M) PDK, whereas the electromagnetic simulations have been carried out using Advanced System Design's (ADS) Momentum tool.

II. Design Of The Proposed VCO

In a mm-wave oscillator design, transistor's capacitive parasitics gravely lower the frequency of oscillation and the tuning range. Employing smaller transistors as the cross coupled pair results in both greater tuning range and frequency of operation as also to less phase noise degradation from the bottom current source [7]. Regarding the LC Tank, the varactor is the most critical component in the mm-wave VCO design, contrary to the inductor in lower frequencies. Its quality factor (Q) determines the overall Q of the tank and has a detrimental effect on the phase noise. It is well known that there is a tradeoff between tuning range and phase noise in a LC VCO as a larger tuning range require a larger varactor which leads to phase noise increment. Furthermore, the interface of the VCO to the rest of the system (buffer, etc.) may result to phase noise degradation and has to be taken into account.

Fig. 1 depicts the simplified schematic of the proposed VCO. The cross-coupled pair consists of two n-type transistors where in the bottom are the current source transistors. The bias voltage is applied to the gates of the transistors through resistors. The intermediate inductor between the cross-coupled pair and the current source transistors is made on metal 7 and helps to further reduce the phase noise as it resonates with transistor's parasitic capacitances to reduce the tail current noise at $2\omega_0$ [7]. It is a single loop inductor which proved to be adequate to obtain high Q required to significantly improve the phase noise performance. The inductor which is shown in Fig.2 is a single turn differential inductor designed using the two upper layers of the technology (M8 and aluminum) to enhance the quality factor of the LC-tank. It has an inner diameter of 74 μm and a width of 11 µm which enhances the quality factor of the inductor as it minimizes the ohmic losses. The inductor, which has a patterned ground shield (PGS) made off from metal 1 to further reduce substrate coupling, was simulated using ADS Momentum. This inductor structure achieves an inductance of 142 pH and a quality factor of 36 at 40 GHz. The inductance value vs. frequency is depicted in Fig.3.

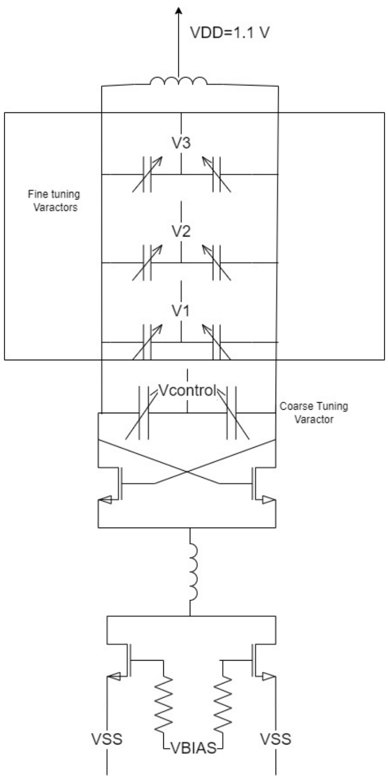

Fig. 1. Simplified schematic of the designed VCO

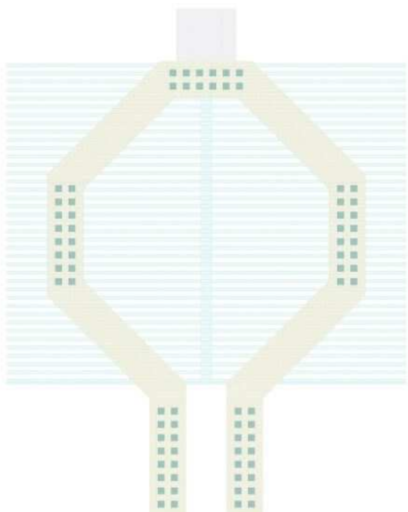
Fig. 2. Differential Inductor

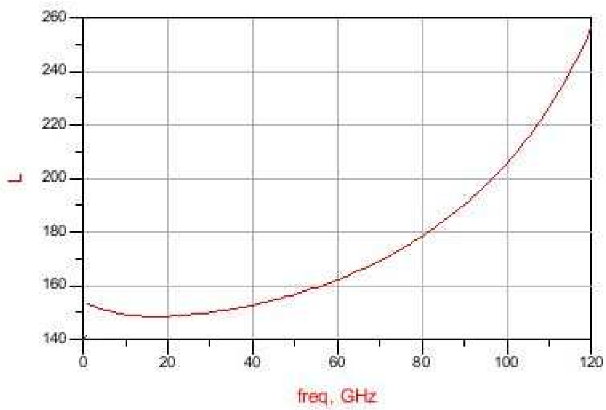

Fig. 3. Inductance of the differential inductor versus frequency

Fine tuning is accomplished by a n-type varactor where the control voltage is applied to the negative terminal of the varactor. The coarse tuning is utilized by three smaller varactors where each one's capacitance boundary is two times larger than the previous emulating a 3-bit binary switched capacitor scheme. The difference from traditional designs where binary switched capacitors are employed, is that switched capacitors present to the VCO output a stable capacitance when the switch is ON or OFF, contrary to switched varactors where the capacitance presented to the VCO is a strong function of the voltage applied to the control terminal and therefore it is dynamic in nature. In particular, utilizing a switched varactor scheme as coarse tuning presents to the VCO tank a continuous capacitance which can be altered by an analog control voltage offering more versatility to the circuit. As a result, band overlap and frequency step which is strongly affected by process and temperature variations can be controlled even after chip fabrication. In the chosen technology, the maximum voltage difference between the positive and negative terminal of the varactor must be 1.1 V. The positive terminal of the varactor is dc biased at V_{DD}=1.1 V through the symmetric differential inductor. Thus, the negative terminal can be switched ON or OFF by applying a voltage as large as 2.2 V resulting in the max step from band to band and larger tuning range. As a result, this coarse tuning structure achieves dynamic regulation of the band overlap depending on phase noise and application requirements. In the proposed design when all varactors offer their maximum capacitance to the circuit the frequency nests at its lower value which is 39.33 GHz. When each varactor is turned OFF in a binary manner, the operating frequency increases, reaching finally 45.32 GHz at its highest band.

III. Simulation Results

Fig. 4 depicts the frequency bands of operations, where the bandwidth coverage and band overlap are depicted.

Since the oscillation frequency is strongly altered by temperature and bias current variation, due to the change in MOSFETS intrinsic capacitances [6], the chosen band overlap is considerable.

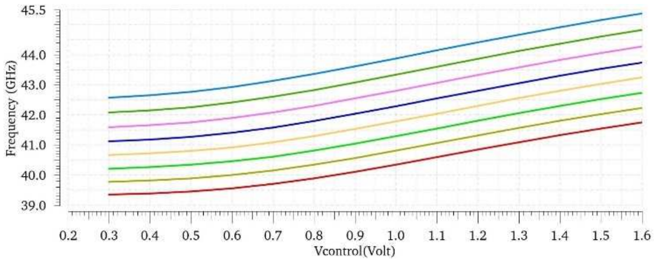

Fig. 4. VCO bands in 100 mV step of control voltage

The total Phase noise of all bands versus control voltage is demonstrated in Fig.5 The VCO shows a phase noise below -100.65 dBc/Hz at 1 MHz away from the carrier throughout the whole operation bandwidth. It must be noted that phase noise is not the least at the minimum frequency, as the switched-type varactors yield the maximum capacitance, and their quality factor is at its minimum. At the maximum frequency the switched-type varactors yield their minimum capacitance and thus their maximum quality factor, so the phase noise is not significantly deteriorated in the region where the control voltage varies between 0.3 and 1.1 V. The 1 dB phase noise variation in the upper four bands is due to the highly nonlinear behavior of the varactor after control voltage exceeds 1.1 V as the frequency rapidly increases and so the phase noise deteriorates. Fig. 6 shows the phase noise in all the eight bands versus the control voltage at 10 MHz offset from the carrier frequency. Fig.7 shows the differential outputs of the VCO at the lowest frequency whereas in Fig.8 the transient response at the maximum frequency is depicted. As it is demonstrated, the peak value of the output voltage is higher at the highest frequency end due to the increased quality factor of the switched varactor block. Furthermore, the VCO reached the steady state faster at the highest frequency, indicating a larger quality factor and hence a larger loop gain.

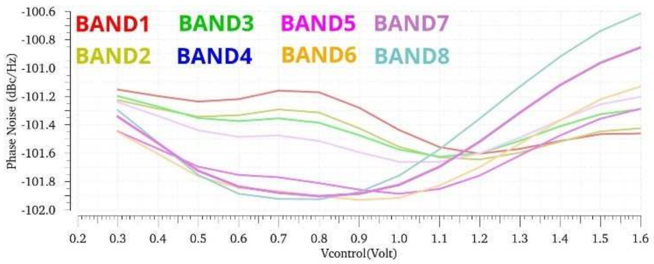

Fig. 5. Simulated Phase Noise of the VCO at 1 MHz frequency offset away from carrier

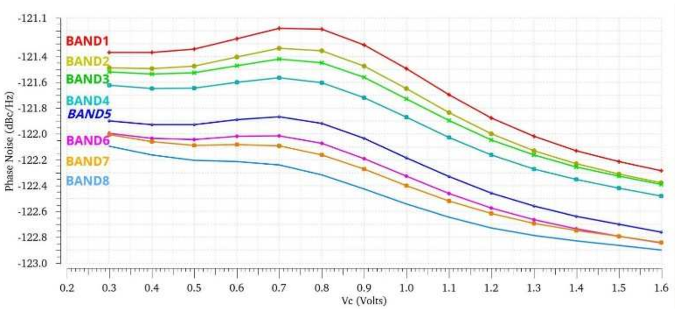

Fig. 6. Simulated Phase Noise of the VCO at 10 MHz frequency offset away from carrier

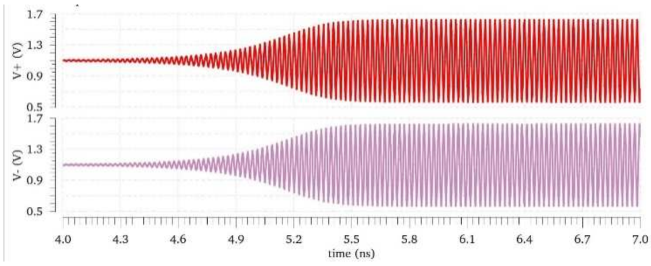

Fig. 7. Transient response of the differential outputs of the VCO at the lowest frequency

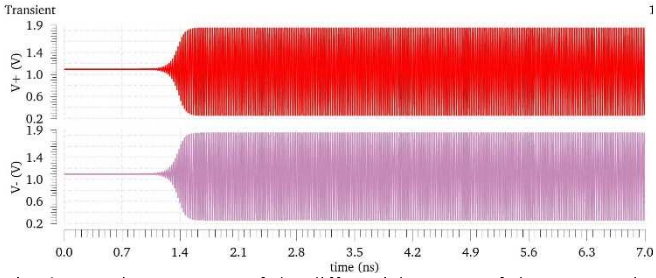

Fig. 8. Transient response of the differential outputs of the VCO at the highest frequency

Fig. 9 depicts the oscillation frequency and the phase noise of the highest and lowest band of operation in the FF (Fast-Fast) corner case while in Fig. 10 the aforementioned results are demonstrated regarding the SS(Slow-Slow) corner case.

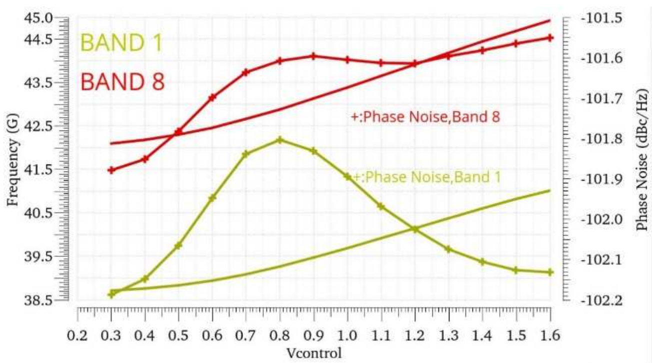

Fig. 9. Frequency and Phase Noise simulation across the upper and lower frequency bands at FF corner case.

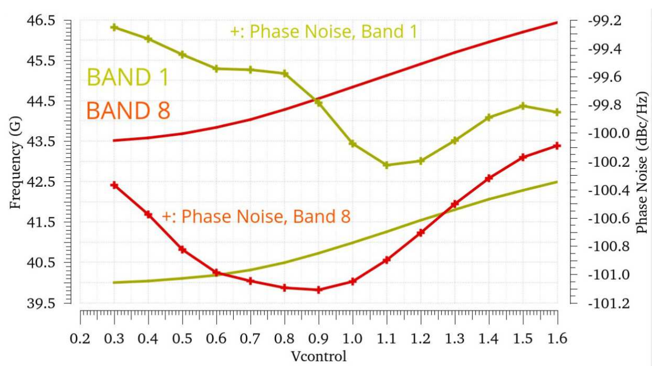

Fig. 10. Frequency and Phase Noise simulation across the upper and lower frequency bands at SS corner case

Furthemore, Fig.10 presents the simulated thermal analysis between -40 ℃ to 105 ℃ . The phase noise varies around 4 dB accors the whole temperature range.

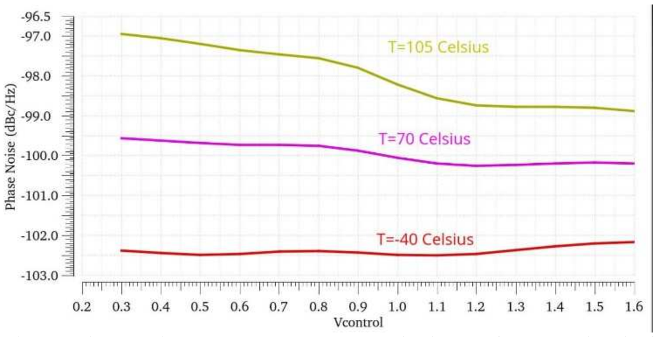

Fig. 11 Phase Noise versus Temperature at the lowest frequency band of operation

The layout of the VCO is shown in Fig.12. The dimensions are 120×315.55 μm^2. At the top of the layout the differential inductor is located with the varactors and at the bottom are the core transistors with the the current source and the intermediate inductor. In Table I, the perfomance of the proposed VCO is summarized and compared with alternative topologies in the literature at the same frequency band. The FOM of the proposed VCO is -184dBc/Hz at 1 MHz offset from f_{osc}=42.325 GHz which is the center frequency. The designed VCO achieves very low phase noise with low power consumption compared to the existing literature.

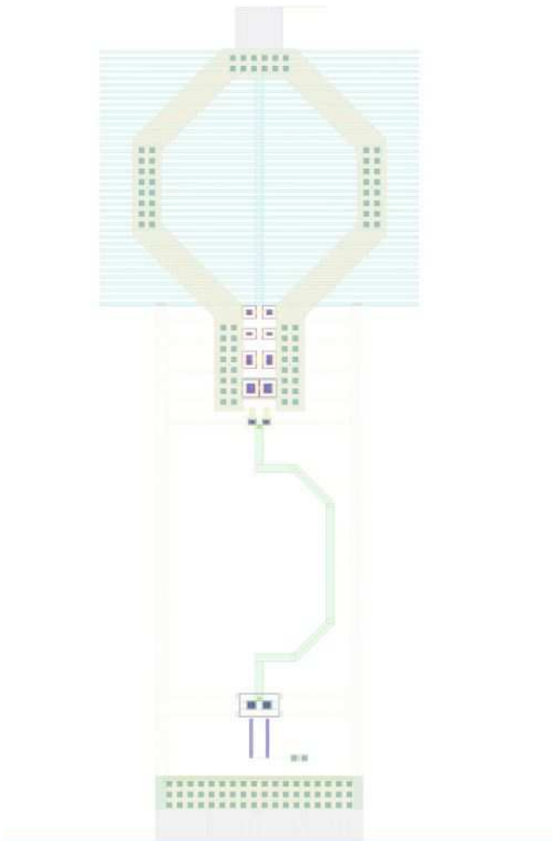

Fig. 12. Layout of the designed VCO

TABLE I
COMPARISON WITH STATE-OF-THE-ART DESIGNS

Main parameters	Reference [8]	Reference [9]	Reference [10]	This work
Frequency (GHz)	36.7-41	34.4-41.9	39.3-42.9	39.33-45.32
Phase Noise [dBc/Hz] @ 1 MHz	-94.3	-100.2	-99.5 $^{(2)}$	-101
Power Supply(V)	1.8	1.5	1	1.1
Power consumption (mW)	15.4 $^{(1)}$	27	10.5	8.97
Tuning range (GHz)	3.5	7.5	3.6	5.9
FOM	-177.5	-177.9	-176.7	-184
Technology	28 nm FDSOI	0.18 μm CMOS	28 nm BULK	40 nm CMOS

FOM= $L(\Delta_f)$ -20log $\left(\frac{f_0}{\Delta_f}\right)$ +10log $\left(\frac{P_{dc}}{1mW}\right)$), $^{(1)}$ including buffer, $^{(2)}$measured at 39.3 GHz

IV. CONCLUSION

The proposed VCO shows a phase noise better than -100.6 dBc/Hz at 1 MHz offset over a 5.9 GHz bandwidth while consuming only 8.97 mW from a 1.1 Volt supply. Additionally, dynamic frequency step and band overlap is accomplished by utilizing varactor-type switches instead of standard switched capacitors. The large tuning range combined with low phase noise and limited power budget makes the proposed VCO design promising for future integration in mm-wave transceivers.

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