A Low Phase Noise 28 GHz VCO Using Transformer-based Q-enhanced Active Impedance Converter

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***Abstract*— This paper presents a low phase noise 28 GHz voltage-controlled oscillator (VCO) using a transformer-based active impedance converter to enhance the quality factor (Q) of the capacitor in the resonator. The active impedance converter can enhance the Q of a capacitor bank and varactor by 25-40% across the VCO's tuning range. The proposed VCO is fabricated using the proposed transformer-based Q-enhancement impedance converter in a standard 65 nm CMOS process. The VCO achieves a 15.9% measured fractional frequency tuning range and phase noise of −107.6 dBc/Hz at 1 MHz offset from 28 GHz oscillation frequency while occupying only 0.05 mm² area (200 µm × 250 µm). The VCO consumes 5.1 mW power, resulting in an excellent figure-of-merit (FoM) of 189.4 dBc/Hz and a figure-of-merit-with-area (FoMA) of 202.8 dBc/Hz.**

***Keywords*—voltage-controlled oscillators, Q-boosting, compact area, 5G, low power, low phase noise.**

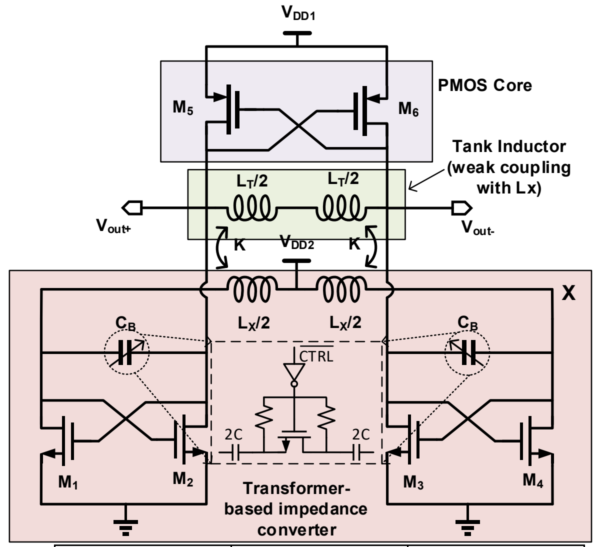
I. Introduction

The generation and conversion of signals in the mm-wave range are critical for supplying the essential local oscillation (LO) signal for 5G and future communication systems. The signal generator must deliver a high frequency with low power and narrow channel spacing, putting additional strain on phase noise performance. Typically, maintaining a wide tuning range and low phase noise performance is a design trade-off for LO generation systems.

An LC oscillator's oscillation frequency is given by $1/2\pi\sqrt{L_{tank}C_{tank}}$, where L_{tank} is the inductance, and C_{tank} is the total capacitance across the resonant tank of the oscillator. Typically for a VCO, $C_{tank} = C_B + C_{var} + C_{par}$; where C_B is the capacitance coming from a switched capacitor bank, C_{var} is the varactor, and C_P is the parasitic capacitance. At the resonant frequency, the loaded Q of the resonator directly impacts the phase noise according to Leeson's equation [1].

Typically, the loaded Q of an LC resonator depends on the quality factor of both inductor (Q_L) and capacitor (Q_C), i.e., $Q \propto (Q_L^{-1} + Q_C^{-1})^{-1}$. Several works in literature have proposed Q boosting to improve phase noise of the VCO, focusing on inductor Q enhancement [2], [3]. At 28 GHz, the quality factor of the switched capacitor bank and the varactor dominate the resonator quality factor. Hence, only inductor Q enhancement has a limited impact on the overall Q of the resonant tank at mm-wave frequencies.

To address this issue, we focus on improving the quality factor of the capacitive part of the resonator. We propose a tuned transformer-based active impedance converter that multiplies the quality factor of the total capacitance of the tank.



Transistors	M_1-M_4 (NMOS)	M_5-M_6 (PMOS)
Size (W/L)	40µm/0.06µm	22µm/0.06µm

Fig. 1. Schematic diagram of the proposed VCO with transformer-based active impedance converter. The tank inductor (Lt) and Lx forms the primary and secondary of the transformer used in the circuit. The table shows the dimensions of the transistors used.

The impedance conversion circuit is incorporated with a current-reuse core to construct a low-power, low-phase noise, compact VCO operating at 28 GHz.

II. Proposed Transformer-Based Q-enhanced VCO

A. Proposed Impedance Converter

Previously, inductor-based active-impedance converters were used to extend the tuning range in the low-frequency region [4] due to its low-pass nature. In [5], a boosted active capacitor with a band-pass response is used to extend the tuning range of the VCO in the X-band. The capacitance value and the resonator's quality factor in [5] are multiplied with a factor M_{boost}. The value of M_{boost} varies from 0.85 to 1.65 for a large capacitance tuning ratio $\left(\frac{C_{max}}{C_{min}}\right)$ of 7.8, where C_{max} is the maximum capacitance, and C_{min} is the minimum capacitance of the capacitor bank and varactor in the resonator. As a result, the effective quality factor is reduced for part of the tuning range (when $M_{boost} < 1$), which compromises the phase noise.

In this work, we propose a transformer-based band-pass impedance converter to maintain the multiplication factor $M_{boost} > 1$ around 28 GHz, resulting in enhanced quality factor across the tuning range. The schematic of the proposed VCO based on the transformer-based impedance converter is shown in Fig. 1.

The impedance converter consists of an inductor L_x, the capacitor bank (with varactor) C_B, and a pair of NMOS cores. The multiplication factor of the quality factor and total capacitance of the capacitor bank with varactor can be derived from Fig. 1 as follows:

$$M_{boost} = 1 + \frac{L_X(1-k^2)G_m^2\left(\frac{\omega^2}{\omega_m^2}-1\right)}{C_B\left(1-\frac{\omega^2}{\omega_X^2}\right)} \tag{1}$$

where $\omega_m = \frac{G_m}{C_B+C_P}$, $G_m = g_m - g_B$, $\omega_X = \frac{1}{\sqrt{L_X(1-k^2)C_X}}$, $C_X = C_B + C_{PX}$. C_{PX} is the parasitic capacitance at node X (shown in Fig. 1), g_m is the transconductance of the NMOS devices, k is the coupling factor of the transformer, and g_B is the loss of the capacitor C_B. Here, ω_X is the resonance frequency at node X, which is designed such that $\omega_X > \omega_o$, where ω_o is the oscillation frequency of the VCO output. The impedance looking into the node X behaves inductively at the desired output frequency (ω_o). The cross-coupled MOSFET pair transform the inductive load to a positive capacitance and a negative-gm in the frequency of operation. The component values L_X, L_T, k, C_B are chosen such that the multiplication factor M_{boost} is > 1 around 28 GHz.

Since the impedance converted circuit provides a positive capacitance and negative transconductance, a resonator can be formed by placing an inductor (L_T) in parallel to the output node of the impedance converter circuit. In this implementation, the tank inductor is placed closed to the other inductor (L_X) to save area. The simulated coupling coefficient of the two inductors is 0.2, which does not hamper the operation of the impedance converter significantly. The final oscillation frequency of the VCO can be derived as

$$\omega_o = \frac{1}{\sqrt{L_T C_B'\left(\frac{L_X}{L_T}+1-\frac{\omega_m^2}{\omega_X^2}\right)}} \tag{2}$$

Here, C_B' is the boosted capacitor that is seen from the output of the impedance converter circuit, given by $C_B M_{boost}$. The component values L_X, L_T, k, C_B are chosen such that the multiplication factor M_{boost} is > 1 around the desired oscillation frequency of 28 GHz.

B. Proposed VCO implementation

To implement the VCO with the transformer-based impedance converter, the secondary inductor of the transformer is used as the tank of the resonator. The L_X and L_T inductors are chosen to be 315 pH and 160 pH, respectively. The coupling factor between the two inductors is $k = 0.2$. To achieve this coupling factor, L_X and L_T are placed in two different metal layers (AP and M9) in the design. The individual quality factors of L_X and L_T are $Q_X = 25$ and $Q_T = 28$, respectively.

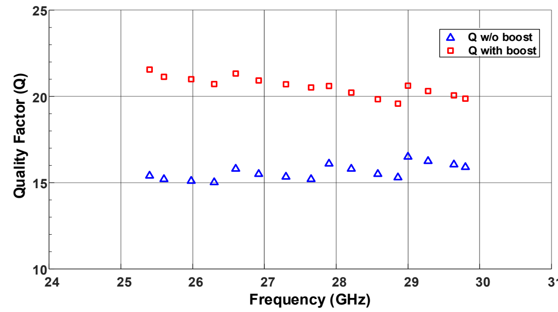


Fig. 2. Simulated Q of C_B with and without the Q-enhancement.

A two-bit binary weighted switched capacitor bank is designed in parallel with a varactor for continuous tuning for the capacitor implementation. The capacitance value (with varactor) ranges from 70 fF to 140 fF without the impedance converter. After the impedance converter, the capacitance varies from 90 fF to 195 fF. The impedance converter provides a multiplication factor M_{boost} of 1.25 to 1.40 across the tuning range for both the capacitance and the quality factor. A simulated plot for the quality factor with and without the Q-enhancement is shown in Fig. 2.

A current reuse PMOS core is incorporated with the resonator tank for complimentary VCO operation. Fig. 3 shows the layout of the designed VCO in 65 nm CMOS process. Our proposed design uses a single transformer, occupying small chip area. A noise summary of different components of the VCO is listed in Table I. We can see that the noise contribution from the capacitor is much less compared to the active devices, attributed to the enhanced quality factor of the capacitor and varactor. Fig. 4 shows the chip micrograph of the implemented prototype in a standard 65 nm CMOS process. The core active area occupies only 0.05 mm^2 (200 μm × 250 μm).

Table I. Simulated Noise Summary of the VCO

Component(s)	**Noise Contribution at 1 MHz (V^2/Hz)**	**(percentage)**
M1, M2	2.64 p	26.16
M3, M4	2.59 p	26.33
M5, M6	1.56 p	14.48
Transformer	0.83 p	9.08
Cap bank	0.97 p	10.58
Varactor	0.37 p	4.05

III. Experimental Results

The proposed VCO is tested by on-wafer probing. An open drain buffer is designed at one of the outputs of the oscillator to measure the output of the VCO (using a Keysight N9030A spectrum analyzer), while the other output is terminated to a similar buffer with a 50 Ω load on-chip. The 2-bit capacitor bank is controlled by external voltages (shown as Vsw1 and

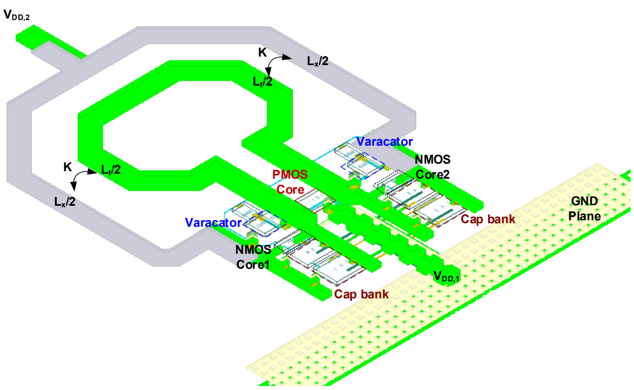


Fig. 3. Layout of the proposed VCO showing primary (Lt) and secondary (Lx) inductors of the transformer, along with the PMOS and NMOS cores, varactors, and cap banks.

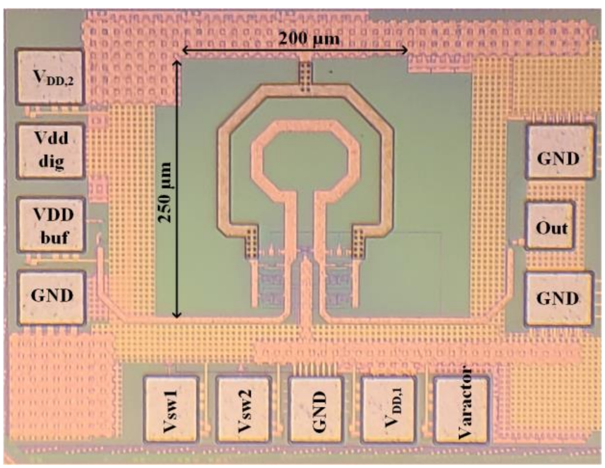


Fig. 4. Chip micrograph of the fabricated prototype in standard 65 nm CMOS process. The core area is 0.05 mm2 (200 µm × 250 µm).

Vsw2 in Fig. 4). The measured tuning range is reported in Fig. 5. The varactor is used for continuous voltage tuning. The VCO oscillates from 25.4 GHz to 29.8 GHz with 10-15% overlap between each capacitor bank setting. The fractional tuning range (FTR) is 15.9%.

Two separate supply voltages were used for the two core voltages of the VCO, which are 1 V (V_{DD1}) and 0.5 V (V_{DD2}). The lower supply voltage of 0.5 V is chosen at the halfway of the other supply and the PMOS and NMOS devices are sized accordingly. The total power consumption varies from 4−5.1 mW across the tuning range. The measured phase noise at 1 MHz offset is −108.78 and −104.1 dBc/Hz for 25.4 GHz and 29.8 GHz outputs, respectively. At 10 MHz offset, the phase noise varies from −127.23 to −122.7 dBc/Hz across the tuning range, as shown in Fig. 6. A measured phase noise curve is shown in Fig. 7 at the middle of the tuning range.

The VCO performance is compared with the prior 28 GHz LC-VCOs using conventional CMOS processes in Table . The proposed topology achieves a good phase noise compared to other works while consuming much lower power and area. As a result, the proposed VCO achieves better FoM compared to the prior work in similar conventional CMOS technology nodes operating at comparable oscillation frequencies.

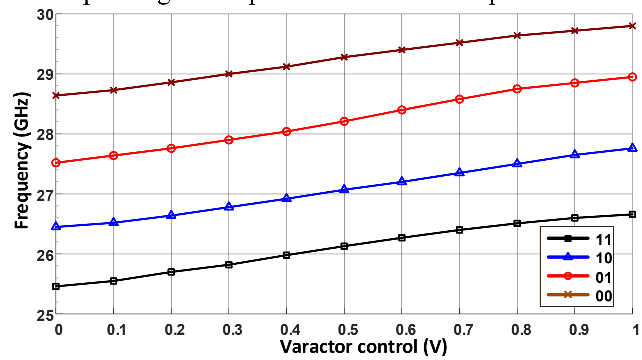


Fig. 5. The measured frequency tuning range of the VCO. Variation of oscillation frequency with respect to varactor tuning voltage is shown for each cap bank setting.

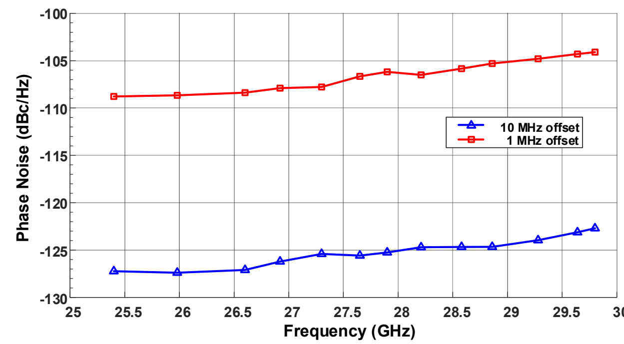


Fig. 6. Measured phase noise from 1 MHz and 10 MHz offset from the carrier frequency of the VCO.

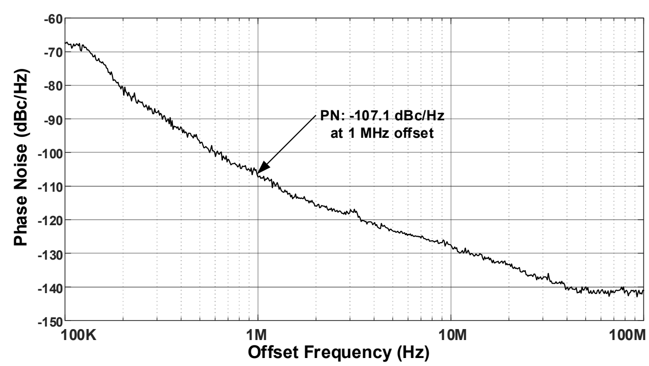


Fig. 7. Measured phase noise from the spectrum analyzer (Keysight PXA N9030A).

IV. Conclusion

This paper presents a low phase noise 28 GHz VCO using a transformer-based Q-enhanced active impedance converter. The proposed impedance converter increases the quality factor of the capacitor bank with varactor in the resonator by 25-40% across the desired frequency band. The VCO achieves a good phase noise at 28 GHz oscillation frequency while consuming low power and occupying a small area, resulting in excellent FoM and FoM_A.

Table II. VCO performance summary and comparison with using 28 GHz VCOs using conventional CMOS processes.

Reference	**This work**	[6] TVLSI'19	[7] Acess'20	[8] JSSC'18	[9] CICC'20
Tech.	**65 nm CMOS**	65 nm CMOS	65 nm CMOS	40 nm CMOS	65 nm CMOS
Topology	**Transformer-based Active Impedance Converter**	Transformer feedback	Transformer feedback with dual-core	Quad-core circular oscillator	Dual-core with common mode resonance
Freq.	**25.4-29.8**	25.7-29.7	22.5-31.2	23-29.9	27.45
FTR%	**15.9**	14	23.5	26	13.4
P_{DC} (mW)	**5.1**	10.8	4.6	16.05	3.4
PN @ 1 MHz (dBc/Hz)	**-107.6**	-105.8	-103	-110	-105.7
Core area (mm^2)	**0.05**	0.022	0.12	0.102	0.04
Control bit and K_{vco}	**2 bit, 1.275 GHz/V**	4 bit, 0.32 GHz/V	2 varactors, 0.6-2.5 GHz/V	5 bit, 300 MHz/V	3 bit, 345 MHz/V
FoM (dBc/Hz)	**189.4**	184	186.2	186.5	189
FoM_A (dBc/Hz)	202.8	200.5	195.4	196.4	202.9

$\mathrm{FoM} = |\mathrm{PN}| + 20\log_{10}(\mathrm{f_0}/\Delta\mathrm{f}) - 10\log_{10}\mathrm{P_{DC}}(\mathrm{mW})$. $FoM_A = FoM + 10\log_{10}(Area/1mm^2)$.

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