# A 21-to-54.5GHz Transformer-Coupled Varactorless 45nm CMOS VCO

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**Abstract — A dual-resonance mode millimeter-wave VCO with a transformer-coupled resonator in 45nm SOI CMOS is presented that achieves a record tuning range of 88.5% and generates frequencies in 21.1-to-54.5GHz range while consuming only 8-16mW from a 1V supply. Switched capacitor banks and a switched coupled inductor provide coarse tuning, while fine frequency tuning is performed with current-mode tuning. With phase noise lower than -107dBc/Hz at 10MHz offset, the $FOM_T$ of this VCO is better than-185.4 dB.**

**Index Terms — CMOS integrated circuits, dual band, mutual coupling, phase noise, transformers, millimeter-wave, voltage-controlled oscillators.**

## I. INTRODUCTION

Interest in the millimeter-wave (mm-wave) bands is currently surging due to emerging applications in communication, radar and imaging. A key requirement in transceivers for such applications is the need to tune over extremely wide frequency ranges – with 20% being barely adequate – thus creating enormous challenges in frequency synthesis. As the center frequency of a VCO increases, fixed transistor and wiring parasitic capacitances become comparable to the variable capacitance and cause the tuning range to shrink. Conventional approaches to this problem include using multiple VCO's or frequency multiplication, which suffer from other shortcomings including large area, high power consumption, spur generation etc.

In order to extend the tuning range of a fundamental frequency VCO beyond what is attainable with conventional second-order L-C resonators, a fourth-order network based on a transformer-coupled resonator is employed in this work. This property of dual resonance can be exploited to generate large frequency jumps [1,2,3]. This paper presents a mm-wave VCO that operates over an 88.5% tuning range from 21.1GHz to 54.6GHz – the widest tuning range reported to date. Designed in a 45nm SOI CMOS technology, the VCO demonstrates phase noise lower than -84 dBc/Hz at 1MHz and -107 dBc/Hz at 10MHz offset across the entire tuning range. The VCO consumes only 8-16mW from a 1V supply and the output buffer, which is designed to be reconfigurable to a double-balanced down-conversion mixer for test purposes, consumes 11mW from a 1.1V supply.

## II. CIRCUIT DESIGN

A schematic of the transformer-coupled VCO is illustrated in Fig. 1. To achieve fine-grained "coarse" frequency tuning, the VCO employs switched capacitor banks connected across the primary and secondary inductors of the transformer. Since

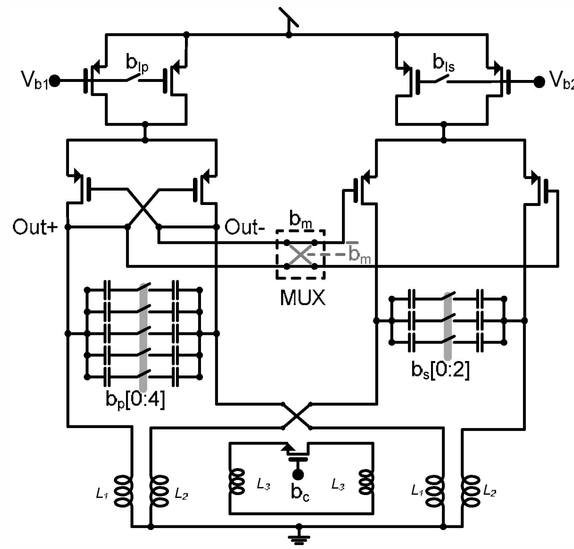



Fig. 1: Schematic of transformer coupled VCO.

capacitive tuning alone was not sufficient to cover the wide frequency gap between the high and low resonance modes, a shunt coupled inductor, which is switched on or off, is incorporated to change the effective mutual inductance between the primary and secondary, thereby providing an additional mechanism for coarse tuning. Fig. 2 shows the layout of the stacked/interwound transformer where $L_1$ and $L_3$ are one-turn inductors in the topmost and the two layers below the topmost metal layer, respectively, and $L_2$ is a two-turn inductor using both metal layers below the topmost one. Since varactors suffer from very poor quality factors at mm-wave frequencies, they are avoided as a means of fine frequency tuning. Instead, current-mode tuning is used to achieve continuous frequency tuning by changing the bias current on the secondary side. This scheme has the benefit of not compromising the tank $Q$.

A PMOS cross-coupled pair forms the oscillator core, while a PMOS transconductance stage controls the current coupled in the secondary of the transformer. Using the model of Fig. 3, in which the transformer is modeled as a Z-parameter two-port network, the loop gain is calculated to be $T(s) = G_{m1}Z_{11} \pm G_{m2}Z_{12}$. The closed-loop system with the characteristic equation $1\text{-}T(s)\text{=}0$ has two complex conjugate pole pairs and can potentially exhibit dual resonance (oscillation) modes. Assuming $L_1C_1 = L_2C_2 = 1/\omega_0^2$ the two resonance modes are located at $\omega_H = \omega_0/\sqrt{1-k}$ and $\omega_L = \omega_0/\sqrt{1+k}$. With a coupling factor $k$ = 0.6, the resonance frequency can be changed by a factor of two ($\omega_H/\omega_L = 2$). In this VCO, in order to excite each resonance mode individually, the direction of the current in the secondary inductor is switched to be either in phase or out of phase with the current in the primary [3].

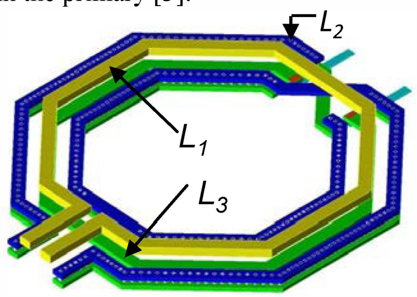
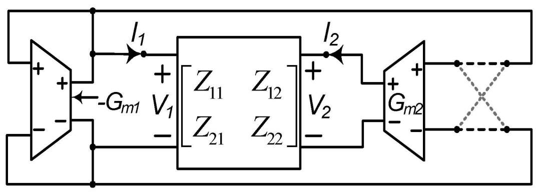



Fig. 2: 3D layout of the transformer.




$$T(s)=G_{m1}Z_{11}\pm G_{m2}Z_{12}=G_{m1}\underbrace{(Z_{11}\pm G_{m2}/G_{m1}\cdot Z_{12})}_{Z_{eq}}$$

$$Z_{eq}(s)=\frac{s^3C_2(L_1L_2-M^2)+s(L_1\pm G_{m2}/G_{m1}\cdot M)}{s^4C_1C_2(L_1L_2-M^2)+s^2(L_1C_1+L_2C_2)+1}$$

Fig. 3: Block digram of transformer coupled VCO with the equation for loop gain T(s) assuming high Q.

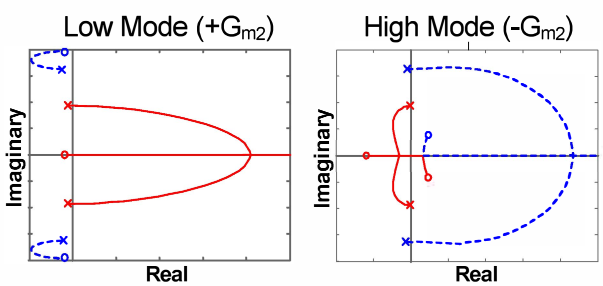



Fig. 4: Root locus plots of characteristic equation $1\text{-}T(s)=0$ obtained by sweeping $G_{m1}$ in the two case of +,- coupling.

The root locus plots in Fig. 4 show that when the coupling is positive, the low-resonance poles are in the RHP, and when negative, the high-resonance poles are in the RHP. A MUX is used to select high/low modes by changing the polarity of coupling as shown in Fig. 1.

Discrete tuning is performed using the binary weighted capacitor banks (5/3-bits in primary/secondary) and the switched coupled inductor. Continuous frequency tuning is performed by reducing the secondary-side current to as low as 10% of its nominal value; this results in a frequency change of more than 2 LSB of primary switched capacitors, where the LSB ranges from 42 to 270MHz.

A two-stage output buffer shown in Fig. 5 is used to drive 50Ω measurement loads. A balun at the output of the buffer converts the output from differential to single-ended for measurement purposes. The output buffer can also be reconfigured as a double-balanced mixer to down convert the VCO output for phase noise measurement. When the buffer is in mixer mode, a differential LO is supplied to the mixer through a balun and a matching network. The two-stage buffer consumes 11mW from a 1.1V supply.

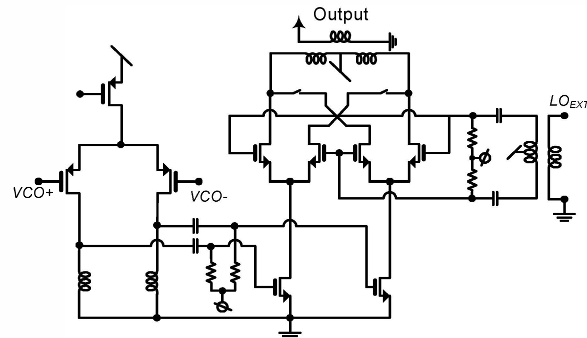



Fig. 5: Schematic of the two-stage buffer with the output stage reconfigurable as a double-balanced mixer.

## III. Measurement Results

Fabricated in 45nm SOI CMOS technology, the VCO occupies an area of 120μm x 180μm. A chip photograph of the VCO and output buffer is shown in Fig. 6. The VCO was characterized through wafer probing. Waveguide harmonic mixers were used to extend the frequency range of a 26GHz spectrum analyzer up to 60GHz.

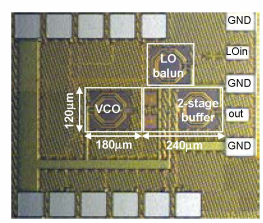



Fig. 6: Chip micrograph.

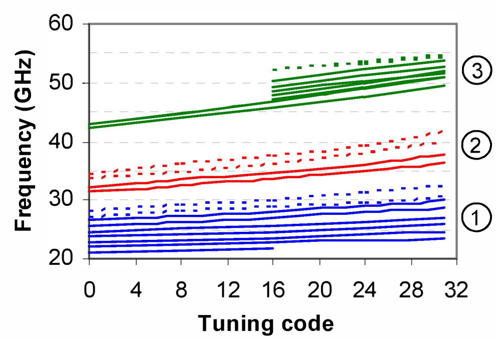



Fig. 7: Measured VCO tuning characteristic versus primary tuning code.

The oscillation frequency is digitally tuned with 10 control bits: 5 bits $b_p[4:0]$ for the primary-side switched capacitors, 3 bits $b_s[2:0]$ for the secondary-side switched capacitors, 1 bit $b_c$ for the switched coupled inductor, and 1 bit $b_m$ for mode select. Two additional bits are used to control the primary-side and secondary-side bias currents. The measured tuning characteristic of the VCO is plotted in Fig. 7 versus the code to the primary-side capacitor bank. Three different frequency

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regions can be distinguished from the plot: (1) low-resonance mode, with coupled inductor switch *OFF* ($b_c$=0), ranges from 21.16 to 32.19GHz (2) low-resonance mode, with the coupled inductor switch ON ($b_c$=*1*) ranges from 31.37 to 41.61GHz. (3) high-resonance mode ranges from 42.31 to 54.61GHz. Although high and low modes were designed to overlap, process variation and unaccounted parasitics introduced a 700MHz gap between regions (2) and (3).

The solid lines in the tuning curve represent the frequency band corresponding to the secondary capacitor bank code $b_s[2:0]$. The dashed lines show frequency change effected by switching the secondary bias current to as low as 10% of nominal value. In the high-mode, the switched coupled inductor does not change the frequency significantly since the stronger magnetic field in the secondary is already in the opposite direction. Insufficient gain for start-up causes some codes to be missing, e.g. in the high-mode, for secondary codes greater than 3, oscillation starts up only for the upper half of the primary-side codes ($b_p[4]$=1).

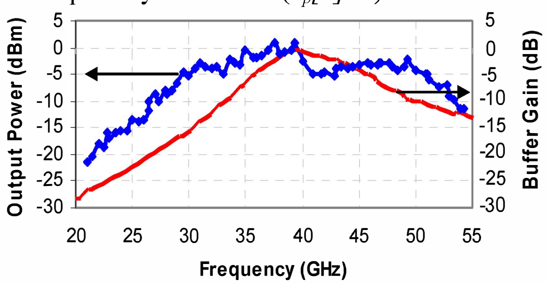


Fig. 8: Output power from VCO buffer and measured buffer gain.

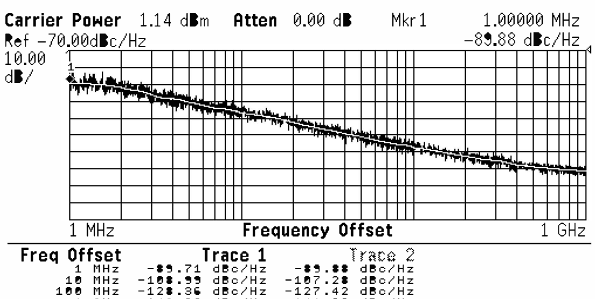


Fig. 9: Measured phase noise at center frequency 37.78GHz.

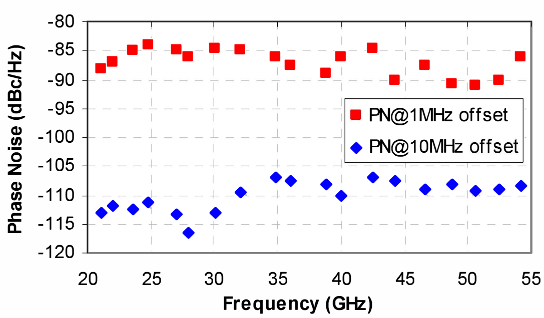


Fig. 10: Phase noise at 1MHz and 10MHz offset over entire tuning range.

Fig. 8 shows the measured output power from the buffered VCO after de-embedding the loss of waveguide harmonic mixers and cables; the measured buffer gain is overlaid on the same plot to illustrate the limited buffer bandwidth compared to the VCO tuning range. After de-embedding the buffer gain, the VCO output swing is greater than 500mVpp. The phase noise was measured after direct down-conversion of the VCO output to below 26GHz (the maximum measurement frequency of spectrum analyzer) with an external low phase noise signal applied to the output stage configured in mixer mode. Fig. 9 shows the phase noise plot measured at the center frequency 37.78GHz. The performance of this VCO is summarized and compared with recently published state-of-the-art wideband mm-wave VCOs in Table I. With 88.5% frequency tuning range the $FOM_T$ (1) at 10MHz offset ranges from -185.4 to -194.5 dBc, which is one of the highest $FOM_T$ reported for a VCO operating at mm-wave frequencies.

TABLE I PERFORMANCE SUMMARY AND BENCHMARKING

| Ref. | [4] | [5] | [6] | [7] | **This** |
|---|---|---|---|---|---|
| Tech. (nm) | 130nm* | 45nm | 65nm | 45nm | **45nm** |
| Supply [V] | 3 | 1.1 | 1 | 0.9 | **1** |
| $f_c$ [GHz] | 52.4 | 65 | 58.2 | 24.77 | **37.8** |
| Tuning [%] | 26.5 | 24.6 + | 7.4 | 24.9 | **88.5** |
| PN @ 1MHz | -108 | -75 | -95 | -101 | **-90** |
| Power [mW] | 132 | 14** | 11** | 12 | **8-16** |
| $FOM_T$ | -189.6 | -167.6 | -177.2 | -186 | **-188.4** |

$$FOM_T = L(\Delta f) - 10\log\left(\frac{1}{P_{dc}}\left(\frac{f_o}{\Delta f}\right)^2\right) - 20\log\left(\frac{FTR}{10\%}\right) \quad (1)$$

*: SiGe $^+$; Two QVCOs used; **: QVCO power was divided by 2

## IV. CONCLUSION

The VCO presented here employs a transformer coupled tank to generate dual resonance modes and hence large frequency jumps. Switched capacitor banks along with a switched coupled inductor provide fine discrete frequency tuning in each resonance mode, while current mode tuning provides continuous frequency tuning without the need for varactors. This VCO achieves the widest tuning range 21.2–54.6 GHz and an excellent $FoM_T$ of -188.4 while consuming only 8–16mW from 1V.

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