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Design and Linearity Analysis of a Dual Control 5-Stage CSR-VCO for RF Applications

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***Abstract*— This paper presents dual control voltage in the conventional 5-stage current-starved ring voltage-controlled oscillator (CSR-VCO) to provide a wider tuning range and fine-tuning possibilities for radio frequency (RF) applications. The circuit is implemented using 45nm CMOS 1V process technology. The conventional circuit is found to have an oscillation frequency range from 6.51 GHz to 13.66 GHz for the first control voltage (0.8 V-1.8 V). On the other hand, the second control voltage (1 V-1.8 V) demonstrates a better linear frequency range, spanning from 5.65 GHz to 13.66 GHz when the first control voltage is fixed at 1.8V. Modifying the first control voltage, in conjunction with the second, results in slight changes in the frequency level, providing the potential for fine-tuning in radio frequency applications. The 1 MHz offset phase noise of the VCO at the maximum output frequency of 13.6 GHz is found to be -55.3 dBC/Hz and the corresponding power consumption is found to be 2.68 mW.**

Keywords*— *CSR-VCO, dual-control VCO, frequency gain, linear frequency range, phase-noise.

I. Introduction

The Voltage-Controlled Oscillator (VCO) is a crucial part of Radio Frequency (RF) applications that are highly valued for low power consumption, wide frequency range, and high integration capability. A CMOS VCO can be constructed using an LC resonant circuit, relaxation circuit or ring structure. While LC design has the best frequency performance within a small tuning range, ring oscillators can be designed for a wide range within less die area. A VCO is generally designed to generate a consistent oscillating signal with a linear frequency response through voltage adjustments. However, the linear frequency characteristics of a Ring VCO (R-VCO) might not be as good as the LC design [1]. Maintaining the linearity of a VCO is crucial for various communication systems, including Phase-Locked Loop (PLL), frequency synthesizers, clock frequency multiplication, oversampling analogue to digital converters, wireless communication etc [2]. Non-linearity in the VCO can lead to signal distortion and interference in these applications.

This study analyses the linearity of the conventional 5-stage Current-Starved Ring VCO (CSR-VCO) and introduces a second control voltage that provides a better linear frequency range by the change of voltage. Conventional CSR-VCO is described in section II. Linear frequency VCO is demonstrated in section III. Section IV presents the proposed dual-controlled VCO and its analyses followed by the conclusion in section V.

II. Basic VCO

A VCO is a type of oscillator whose frequency is controlled by an input voltage. VCOs are commonly used in electronic music synthesizers, communication systems and PLL circuits.

A. Conventional Ring VCO

A conventional ring VCO consists of an odd number of inverters connected in series, forming a chain where the output is fed back to the input as shown in Fig. 1. Each inverter stage introduces a 180° phase shift, ensuring that the Barkhausen criterion for oscillation is satisfied [2][3].

The oscillation frequency (f_{osc}) of this ring VCO is determined by the delay time (t_d) of each inverter stage. If there are N stages, the oscillator completes the total cycle after traversing $2Nt_d$ times. The formula for calculating the oscillation frequency is given by:

$$f_{osc} = \frac{1}{2Nt_d} \quad (1)$$

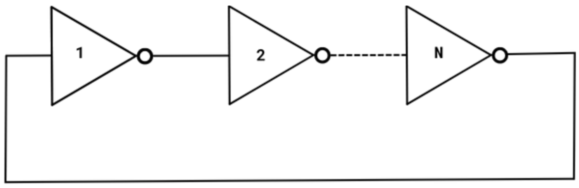

Fig. 1. Basic block diagram of a ring VCO

B. Conventional CSR-VCO

Fig. 2 presents a schematic diagram of a conventional CSR-VCO, which operates on the principle of a ring oscillator with a current source at the beginning. The architecture comprises multiple delay stages, where the oscillation frequency relies on the delay introduced by each inverter stage. The key feature of this design is the ability to control the delay by modulating a DC voltage.

The control voltage, serving as the means to influence the delay, is finely tuned through a current mirror, affecting the turn-on resistances of the pull-down and pull-up transistors. This turn adjustment regulates the available current for charging or discharging the capacitive load in each transistor stage. The mechanism is such that higher control voltage values permit large current flow, resulting in reduced resistance and consequently smaller delays [3]. The blue colored line in Fig. 2 indicates an initial trigger voltage is needed in this node to generate oscillation.

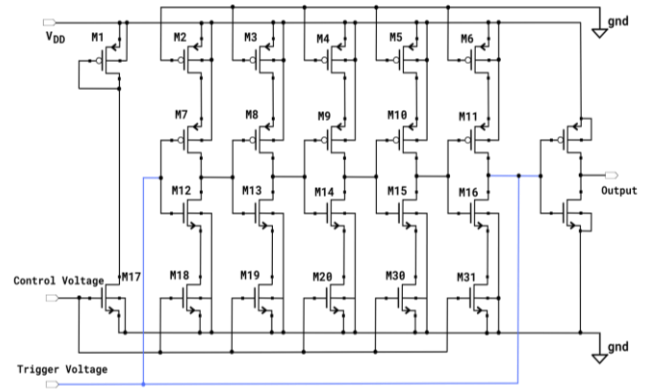

Fig. 2. Basic circuit of 5-stage CSR VCO

In the configuration, the inner transistors (M7–M16) function as inverters, while the upper (M2-M6) and lower (M18-M31) transistors operate as current sources and sinks, respectively. The current sources play a crucial role in limiting the current supplied to the inverters, effectively "starving" them. The drain currents of the initial 2 transistors (M1 and M17) are set to be identical and are determined by the control voltage. The inverter transistors at the end are for scaling the amplitude at a fixed level. This current-starved ring VCO offers to control oscillation frequency by finely manipulating the available current through the ingenious use of current sources and sinks, contributing to the overall stability and versatility of the ring oscillator. As a result, CSR-VCO has a higher frequency range than a conventional ring oscillator.

III. Linearity Analysis

The term "linearity" in this context refers to the degree to which the relationship between the input voltage and the output frequency follows a straight, predictable, and proportional pattern. In a linear VCO, changes in the input voltage should result in consistent and proportional changes in the output frequency, often known as "frequency gain". Determining the linear characteristics of a VCO is important for maintaining output precision [4].

Fig. 3 shows the relation between the frequency and control voltage of the conventional CSR-VCO circuit at V_{DD} 1.8V. The purple line shows the V_{DD} and the green line shows the control voltage level. The red color shows the oscillation and the oscillated frequency in the figure below. It is found that minimum oscillation starts from 0.5V.

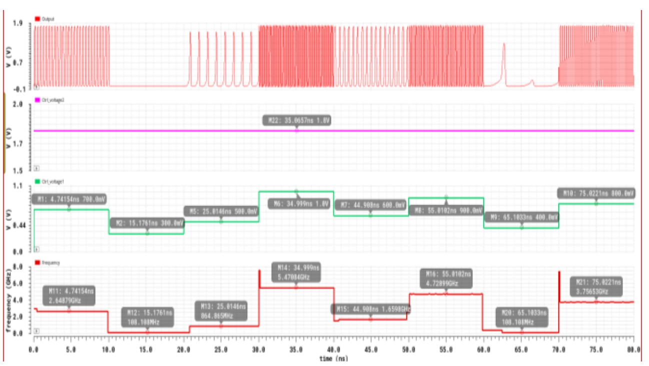
Fig. 3. Frequency relation by the change of voltage

The linearity of the frequency or frequency gain can be determined by the derivative of the frequency curve. If the frequency (f) increases linearly with voltage (V), the relationship can be expressed as:

$$f = mV + b \tag{2}$$

where,

- f is the frequency,
- V is the voltage,
- m is the slope of the line,
- b is the y-intercept (the frequency at zero voltage).

Now, The frequency gain curve, on the other hand, represents the gain or sensitivity of the system to changes in the input parameter. It describes how much the output frequency changes in response to a small change in the input voltage in VCO. Mathematically, if G represents the gain and V represents the input voltage, the frequency gain curve is represented as:

$$\mathrm{G} = \left(\frac{df}{dV}\right) = \mathrm{m} \tag{3}$$

So, the derivative of the frequency with respect to voltage is a constant value equal to the slope of the line, if the frequency increases or decreases linearly. This means that the rate of change of frequency with respect to voltage remains constant, indicating a linear relationship between frequency and voltage. However, the linear characteristic of a VCO can be straight or exponential.

Fig. 4 demonstrates the frequency curve and frequency gain curve (derivative) with respect to the voltage. The frequency gain curve illustrates that the frequency increased randomly from 0.5V to 0.8V and then the increasing rate decreased non-linearly, most likely exponentially decaying until 1.8V. In that case, this circuit can be useful within the range of 0.8V to 1.8V in different RF applications that allow exponential decay frequency gain, such as envelope generators in synthesizers, musical synthesis or as an exponential vibrator in modulations for its decay-like behavior. It is important to detect the linear characteristics or frequency gain curve of a VCO to apply in any RF applications to control tuning.

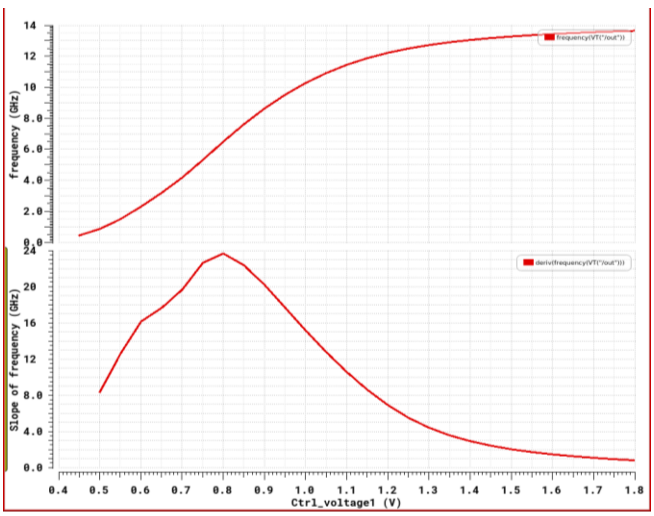

Fig. 4. Frequency and frequency gain vs control voltage curve

This study introduces a second control voltage besides the conventional control voltage in this 5-stage CSR-VCO that provide better result in frequency gain.

IV. Dual-Control CSR-VCO

The introduction of dual control in a VCO serves various purposes, providing additional flexibility and functionality, especially for pitch and timbre control of musical sound. Fig. 5 shows the dual-controlled CSR-VCO schematic implemented in Cadence Virtuoso. Control voltage-1 is the conventional control node for the circuit, shown in the lower left corner and control voltage-2 shown in the upper left corner in Fig. 5.

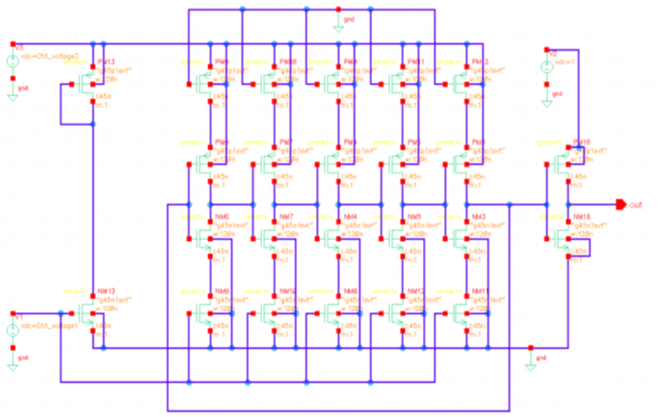

Fig. 5. Schematic implementation of dual-controlled CSR-VCO

This dual control enables simultaneous change of both frequency level and gain by employing different control voltages. Fig. 6 shows the frequency variation with different control voltages, including the frequency gain. While the control voltage-2 is connected to the input signal, control voltage-1 can be used for fine-tuning. The frequency curve shows the frequency range from 5.32GHz to 11.46GHz for 1.1V at control voltage-1 within 1V to 1.8V at control voltage-2. Applying the control voltage-1 equal to 1.8V can achieve a frequency range of 5.65GHz to 13.66GHz. The detailed variation of frequency variation and power consumption for the change of control voltage is shown in Table I.

The frequency gain curve in Fig. 6 is a straight downward line, which predicts the frequency curve as a square function. The gain curve is represented by the derivative of the frequency curve:

$$G = \left(\frac{df}{dV}\right) = -mV + b \tag{4}$$

This straight downward line in the derivative suggests a linear relationship between the control voltage and the rate of change of frequency. Integrating the derivative, we find the frequency curve:

$$f(v) = -\frac{m}{2}V^2 + bV + C \tag{5}$$

This is a quadratic function with a downward concavity, consistent with the behaviour of the VCO where frequency may vary slightly quadratically with the control voltage. This type of VCO might produce noise in strict linearity-required applications. However, that type of VCO can be useful for non-linear signal processing, chirp radar systems, sweep generators or synthetic aperture radar.

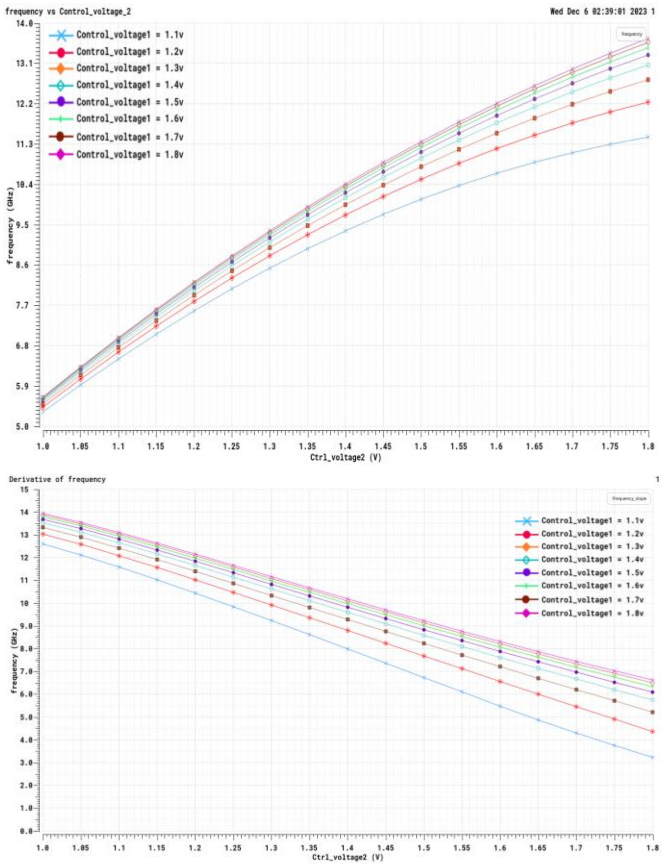

Fig. 6. Frequency and frequency gain vs control voltage-2 curve for different values of control voltage-1.

This study has further simulated the phase noise for the proposed dual control CSR-VCO. The phase noise is found at -75.96 dBc/Hz at the 3dB point and -55.3 dBc/Hz at the 1MHz offset frequency when both the control voltage is at 1.8V. Fig. 7 shows the phase noise curve at the 3dB point.

Table I demonstrates a discernible correlation between power consumption and operational parameters. The data unequivocally reveals an escalation in power consumption simultaneously with increments in both frequency and control voltage.

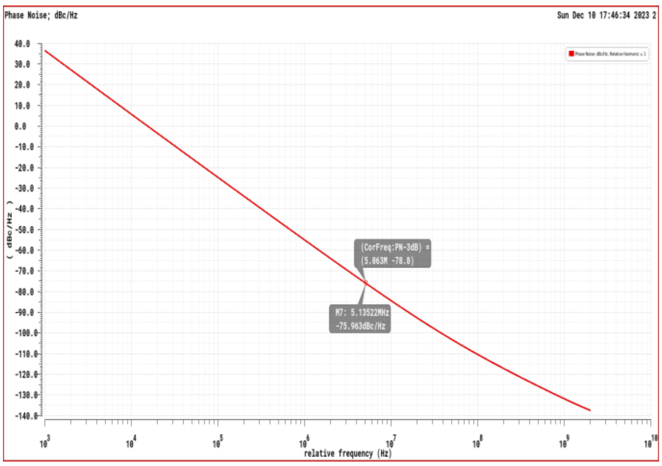

Fig. 7. Phase noise of dual-controlled CSR-VCO at 3dB

TABLE I. FREQUENCY AND POWER CONSUMPTION OF THE CSR-VCO

		Control Voltage-2									
		1.0 (V)	**1.1 (V)**	**1.2 (V)**	**1.3 (V)**	**1.4(V)**	**1.5(V)**	**1.6(V)**	**1.7(V)**	**1.8(V)**	
Control Voltage-1	**1.1 (V)**	5.32	6.51	7.58	8.54	9.37	10.07	10.65	11.11	11.46	***Frequency (GHz)***
		35.5	50.4	67.2	85.7	105.6	126.5	148.7	172.1	196.8	***Power (μW)***
	1.2 (V)	5.43	6.66	7.79	8.81	9.72	10.52	11.20	11.77	12.24	***Frequency (GHz)***
		36.9	52.7	70.8	91.2	113.6	137.9	163.5	190.6	219	***Power (μW)***
	1.3 (V)	5.50	6.77	7.93	8.99	9.95	10.80	11.55	12.19	12.74	***Frequency (GHz)***
		37.9	54.2	73.2	94.7	118.7	145	173.5	203.8	235.7	***Power (μW)***
	1.4 (V)	5.55	6.84	8.03	9.12	10.10	10.99	11.78	12.47	13.06	***Frequency (GHz)***
		38.5	55.3	74.9	97.1	122.1	149.8	180	212.6	247.4	***Power (μW)***
	1.5 (V)	5.59	6.89	8.10	9.21	10.22	11.13	11.94	12.66	13.29	***Frequency (GHz)***
		39	56.1	76.1	98.9	124.6	153.1	184.5	218.6	255.3	***Power (μW)***
	1.6 (V)	5.62	6.93	8.15	9.28	10.30	11.23	12.06	12.80	13.45	***Frequency (GHz)***
		39.4	56.7	76.9	100.1	126.3	155.5	187.7	222.8	260.8	***Power (μW)***
	1.7 (V)	5.64	6.96	8.19	9.33	10.36	11.30	12.14	12.90	13.57	***Frequency (GHz)***
		39.7	57.1	77.6	101.1	127.7	157.3	190.1	225.9	264.8	***Power (μW)***
	1.8 (V)	5.65	6.98	8.22	9.37	10.41	11.36	12.21	12.98	13.66	***Frequency (GHz)***
		39.9	57.5	78.1	101.8	128.6	158.6	191.8	228.2	267.8	***Power (μW)***

V. CONCLUSION

In conclusion, the dual-controlled 5-stage Current-Starved Ring Voltage-Controlled Oscillator (CSR-VCO) emerges as a tailored solution for RF applications. We've simulated for linearity concerns and introduced a second control voltage, that significantly expands the linear frequency range. This dual-controlled CSR-VCO impressively spans frequencies from 5.32GHz to 13.66GHz. Delving into phase noise analysis, we find commendable performance, hitting -75.96 dBc/Hz at the 3dB point and -55.3 dBc/Hz at the 1MHz offset frequency with both control voltages set at 1.8V. The power consumption is found between 35.5μW to 267.8 μW for both control voltage. Quantifying the relationship between control voltage and frequency gain reveals a controlled non-linear behavior. These results solidify the dual-controlled CSR-VCO as a promising contender for nuanced RF applications like chirp radar, sweep generators, synthetic aperture radar etc. that effortlessly balancing precise frequency control with controlled non-linearity.

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