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Implementation And Comparison of Different Stages of Current Starved CMOS Ring Oscillator – A Study

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Abstract

The ring oscillators serves as the fundamental building blocks in both digital and analog circuit design, as its extensive use is found in various electrical systems, including phase-locked loops, frequency dividers, and clock generators. This study gives a general overview of the ring oscillator circuit, including its workings, uses, and important design considerations. The ring oscillator generates timing signals for synchronous operation and is often employed as a clock generator in digital systems. It may also be used as a frequency divider to separate higher frequencies into lower ones. A closed loop is used to connect an odd number of inverting stages to create the ring oscillator circuit. An inverter, which is often built using complementary metal-oxide-semiconductor (CMOS) technology, is a component of every stage. By adding a delay to each step, the ring oscillator creates a self-sustaining oscillation. The development and comparison of 3, 5, and 7 stage ring oscillators for different performance metrics, as well as corner analysis for propagation delay and the effect of temperature on the operation of the ring oscillator was performed using Cadence Virtuoso with 90nm technology. This comparison of several phases of a current-starved (CS) ring oscillator offers an advantage to the best design with innovation based on the technology employed and outcomes from the corner analysis, which hasn't been done in any of the more recent researches.

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1. Introduction

In both digital and analog circuit design, ring oscillators are fundamental building blocks. They are also extensively used in various electrical systems, including phase-locked loops, frequency dividers, and clock generators. A closed loop is used to connect an odd number of inverting stages to create the ring oscillator circuit. In each stagean inverter, that is built using complementary metal-oxide-semiconductor (CMOS) technology [1,8] is included.. The delay added to each step enables the ring oscillator to create a self-sustaining oscillation.

The propagation delays of the various stages and the overall delay imposed by the whole loop are the main factors that affect the ring oscillator's oscillation frequency [10]. The oscillation frequency can be increased by including more stages, however decreasing the number of stages lowers the frequency. By adjusting the transistors' sizes or including additional capacitive elements, the oscillation frequency may be further altered. The ring oscillator generates timing signals for synchronous operation and is often employed as a clock generator in digital systems. It may also be used as a frequency divider to separate higher frequencies and the lower ones. In addition, since it provides a trustworthy reference signal for frequency synthesis, the ring oscillator is a crucial part of phase-locked loops [4].

When building a ring oscillator, factors such transistor size, supply voltage, and load capacitance must be considered with great care. These factors directly affect the circuit's power consumption, frequency stability, and signal integrity. Establishing consistent performance is also challenging due to process heterogeneity and noise sources. The ring oscillator, a versatile circuit with several uses in electrical systems, is the last point. It is a crucial element in many digital and analog systems because of its self-oscillating nature, simplicity, and scalability. In order to enhance the performance of ring oscillator circuits in forthcoming technologies and applications, future research will concentrate on tackling concerns with power consumption, frequency stability, and noise immunity.

The primary goal of this work is to;

- Examine the operation of the 3, 5, and 7 stage Current starved Ring oscillators for various parameters and analysis.
- Compare and evaluate the results, faults, and describe the best result with supporting documentation.

2. Performance Parameters

This section identifies and explains the many performance standards and analyses and clarifies the numerous operational concepts. A person can rapidly understand the relevance and select the best method to finish their work by segmenting according to many categories. The applications of the ring oscillator as well as performance measures have been evaluated in order to fully analyse the work.

2.1 Performance Parameters of Ring Oscillators

Performance Parameters of the ring oscillator [3], which is a type of oscillator circuit is commonly used in electronic systems, can vary depending on the specific design and application. However, here are some common parameters associated with a ring oscillator:

A. Frequency (in MHz): The frequency of a ring oscillator refers to the oscillation rate at which the circuit generates a continuous waveform. It is typically measured in megahertz (MHz). The frequency is determined by the number of stages or inverters in the ring and the propagation delay through each stage.

B. Average Power (in mW): The average power consumption of a ring oscillator represents the average amount of power required to sustain the oscillations. It is usually measured in milliwatts (mW). The power consumption depends on various factors such as the technology used, supply voltage, operating temperature, and circuit design.

C. Total Harmonic Distortion (THD): THD is a measure of the distortion present in the output waveform compared to the input waveform. In the case of a ring oscillator, THD quantifies the extent to which the generated oscillation deviates from a perfect sinusoidal waveform. THD is typically expressed as a percentage or in decibels (dB).

D. Output Noise (in dB): The output noise of a ring oscillator indicates the amount of unwanted noise present in the output signal. It is typically measured in decibels (dB). Noise in a ring oscillator can arise from various sources, such as power supply fluctuations, thermal noise, process variations, and coupling effects.

These parameters are essential for evaluating the performance of a ring oscillator circuit. Designers aim to optimize these parameters based on the specific requirements of the application. For example, higher frequencies may be desirable in some cases, while lower THD and output noise are generally preferred for improved signal quality. The choice of technology, circuit topology, and biasing conditions play significant roles in determining these parameters.

2.2 Performance Parameters of a Voltage Controlled Oscillator (VCO):

Ring oscillator is a type of voltage-controlled oscillator (VCO) [1,8,13] that can be implemented using a current-starved circuit. It consists of an odd number of inverters connected in a ring configuration. The delay through each inverter creates a positive feedback loop, causing the circuit to oscillate. Figure 1 depicts the usage of Ring Oscillator as a Voltage Controller oscillator.

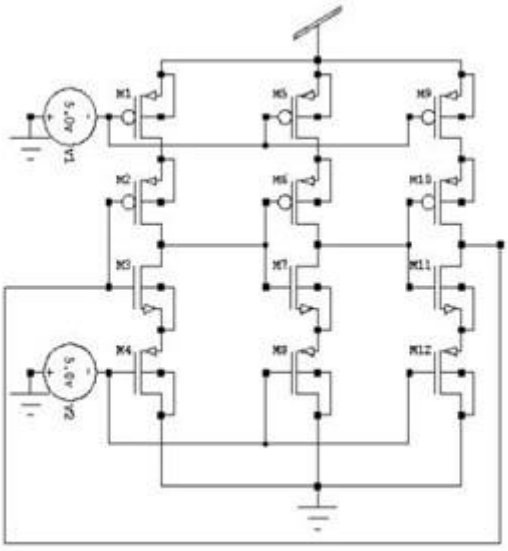

Figure 1. Schematic of a Ring Oscillator as a VCO [7]

The performance parameters of a ring oscillator implemented using a current-starved circuit include [7]:

A. **Frequency Range:** The range of frequencies over which the oscillator can operate. It depends on the characteristics of the inverters and the current-starved circuitry.

B. **Frequency Tuning Range:** The extent to which the output frequency of the VCO can be adjusted by varying the control voltage. It is typically specified as a percentage of the center frequency.

C. **Linearity:** The linearity of the VCO refers to how linearly the output frequency changes with variations in the control voltage. A higher linearity indicates a more predictable relationship between the control voltage and the output frequency.

D. **Phase Noise:** Phase noise is an important parameter that characterizes the quality of the generated signal. It measures the random phase fluctuations in the output signal and is typically specified in decibels relative to the carrier power at a specific frequency offset.

E. **Power Supply Sensitivity:** The sensitivity of the VCO's frequency to variations in the power supply voltage. Ideally, the output frequency should be minimally affected by power supply fluctuations.

These performance parameters can be optimized by carefully designing the current-starved circuit and selecting appropriate transistor sizes, biasing conditions, and component values. The trade-offs between these parameters depend on the specific requirements of the application and the available design constraints.

3. Methodology

A voltage-controlled oscillator (VCO) may be created utilizing a ring oscillator and a current-starved circuit. A circuit with an odd number of inverter stages linked in a loop is known as a ring oscillator. Each inverter stage consists of a transistor pair with a positive feedback loop (usually a complementary metal-oxide-semiconductor, or CMOS, pair). The current-starved approach includes biasing the transistors with a continuous current source to reduce their operational current. A control voltage (V_ctrl) is supplied to the ring oscillator [5] to enable it to function as a VCO. In the current-starved circuit, this control voltage modifies the bias current. The propagation delay and the oscillation frequency of the ring oscillator

[2]are modified by altering the control voltage, which also affects the bias current. As a result, the output frequency of the VCO [13] is precisely proportional to the control voltage. Each inverter stage's positive feedback loop makes sure that the input signal is regenerated. When an inverter stage's output is linked to the input, the signal constantly inverts as it travels around the loop. Sustained oscillations result from this positive feedback.

3.1 Software Requirement

Cadence Virtuoso is a widely used electronic design automation (EDA) tool suite developed by Cadence Design Systems. It is primarily used for designing and verifying complex integrated circuits (ICs) and semiconductor devices. Virtuoso offers a comprehensive set of tools for various stages of the IC design process, including schematic entry, layout design, simulation, physical verification, and design rule checking (DRC).

Figure 2. Cadence Virtuoso Tool

Cadence Virtuoso provides a comprehensive set of tools and features for designing, simulating, and verifying complex integrated circuits. It is widely used in the semiconductor industry and offers an extensive ecosystem of tools and technologies to support the entire IC design flow.

3.2 Implementation of 3 Stage Ring Oscillator

A three-stage ring oscillator is a circuit that consists of three inverters connected in a ring configuration. The inverters provide positive feedback to create an oscillating signal. The output of the third inverter is fed back to the input of the first inverter, completing the loop. Figure 3 depicts the schematic of 3 stage ring oscillator implemented on the CADENCE Virtuoso tool.

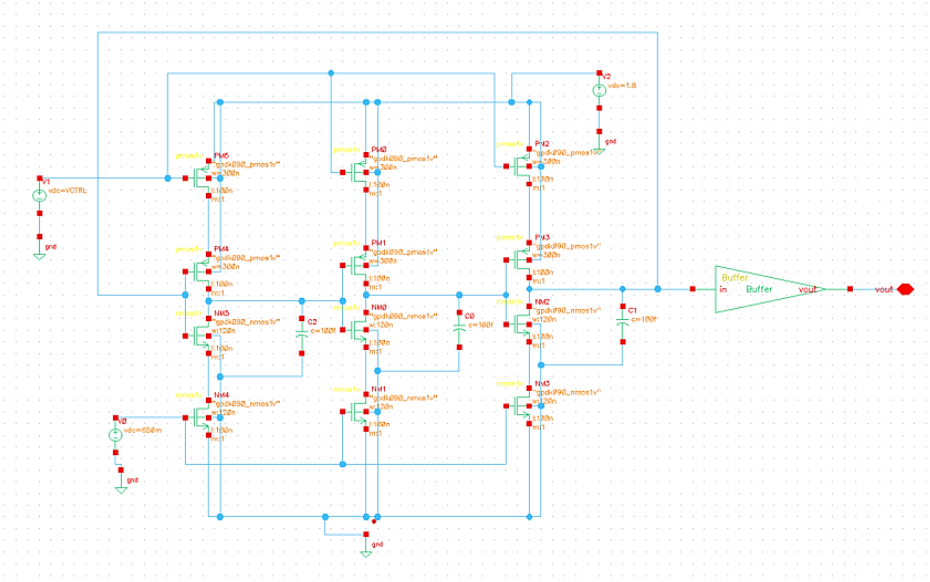

Figure 3. Schematic of 3 Stage Ring Oscillator

Table 1. Design Parameters of 3, 5 & 7 Stage Ring Oscillator

Parameters	Design Value
Wp(nm)	300
Wn(nm)	120
L(nm)	100
Initial Control Voltage	0V
VDD	1V
V bias	0.65V
Capacitor	100f

The circuits are designed in Cadence Virtuoso Analogue Design Environment's schematic editor using the gpdk090 library. These circuits are simulated in Cadence's Spectre simulator for performance study. The transistor sizes obtained as previously stated for a set of parameters are utilized to create the necessary ring oscillator circuit. The first ring oscillator is intended for use with 3 stages of CMOS inverters and a W/L ratio of 90nm CMOS technology.

The width of an NMOS transistor is denoted by Wp, whereas the width of an NMOS transistor used to build a current-starved ring oscillator is denoted by Wn.

3.3 Implementation of 5 Stage Ring Oscillator

A five-stage ring oscillator[6] is made up of five inverters linked in a loop. Each inverter has an input and an output. Each inverter's output is linked to the input of the next inverter in the series, and the last inverter's output is connected back to the input of the first inverter, completing the feedback loop. This feedback loop permits the oscillation to continue and produces a continuous oscillating signal. Figure 4 shows the schematic of 5 stage ring oscillator with parameters as mentioned in Table 1.

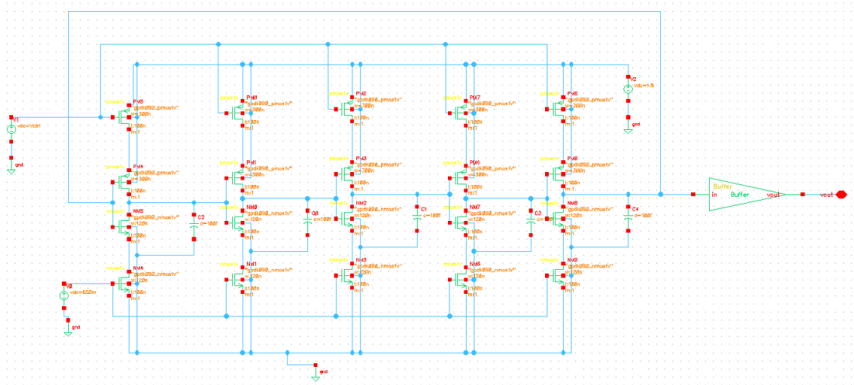

Figure 4. Schematic of 5 Stage Ring Oscillator

Each inverter is made up of a pair of complementary NMOS (n-channel metal-oxide-semiconductor) and PMOS (p-channel metal-oxide-semiconductor) transistors. The NMOS transistor is a pull-down switch, whereas the PMOS transistor is a pull-up switch. The propagation delay across each step determines the frequency of the oscillation. Several variables impact the delay, including transistor properties, the capacitance of the load linked to each inverter output, and the overall resistance and capacitance of the circuit. The ring oscillator's oscillation period is equal to twice the total of all of the stage delays.

3.4 Implementation of 7 Stage Ring Oscillator

A seven-stage ring oscillator is a circuit that consists of seven inverters connected in a ring configuration, forming a feedback loop that generates an oscillating signal. Each inverter stage amplifies and inverts the signal before passing it to the next stage. Figure 5 depicts the

block diagram of the proposed 7 stage ring oscillator and Figure 6 is the schematic of 7 stage ring oscillator using an additional inverter as a buffer in the circuit.

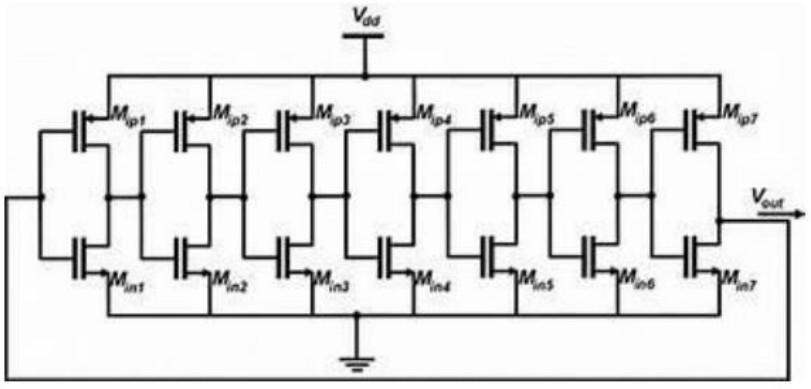

Figure 5. Block Diagram of the 7 Stage Ring Oscillator [14]

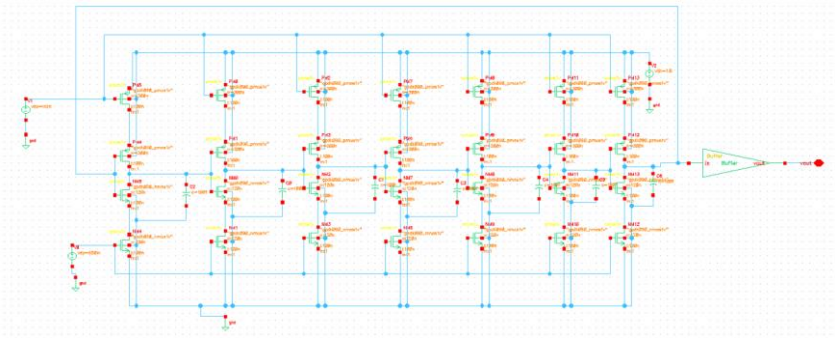

Figure 6. Schematic of 7 Stage Ring Oscillator

- Stage 1: An input signal is applied to the first inverter (Inv 1). It amplifies and inverts the signal, providing an output to the second stage (Inv 2).
- Stages 2-6: The output of each inverter stage is fed into the next inverter stage, following the same pattern. Each stage amplifies and inverts the signal, passing it along to the subsequent stage.
- Stage 7: The output of the sixth stage (Inv 6) is fed back to the input of the first stage (Inv 1). This connection completes the feedback loop.

It's important to keep in sight that a ring oscillator's stage count has an impact on the oscillation's frequency and stability.

4. Results and Discussions

In the context of performance parameters, the terms NN, SS, FS, SF, and FF are often used to represent the process corners or conditions under which performance characteristics of a device or system are evaluated. These terms are commonly associated with integrated circuits (ICs) and semiconductor manufacturing Here's what each term represents:

1. **NN (Nominal-Nominal):** NN represents the nominal or typical operating conditions for a device. It refers to the performance characteristics evaluated under normal operating conditions without any specific variations or deviations from the standard specifications. NN conditions assume that the manufacturing process is operating within its expected tolerances.

2. **SS (Slow-Slow):** SS represents the worst-case or slowest operating conditions for a device. It refers to performance characteristics evaluated under conditions where the device operates at the slowest possible speeds or exhibits the highest delays. This condition helps determine the device's performance in situations where timing is critical, such as in high-frequency or highspeed applications.

3. **FS (Fast-Slow)**: FS represents performance characteristics evaluated under the condition where one part of the device operates at its fastest speed (fast corner), while another part operates at its slowest speed (slow corner). This condition is used to assess the device's performance under asymmetric operating conditions.

4. **SF (Slow-Fast):** SF represents performance characteristics evaluated under the condition where one part of the device operates at its slowest speed (slow corner), while another part operates at its fastest speed (fast corner). Similar to FS, SF is used to assess the device's performance under asymmetric operating conditions, but with the opposite combination of fast and slow corners.

5. **FF (Fast-Fast):** FF represents performance characteristics evaluated under the best-case or fastest operating conditions for a device. It refers to the condition where all parts of the device operate at their fastest speeds (fast corner). This condition helps determine

the device's performance when operating optimally or at its highest possible performance levels.

By evaluating performance parameters under different process corners, designers and manufacturers can gain insights into the device's behaviour and performance across a range of operating conditions. This information is useful for designing robust systems and ensuring that the device meets the required performance specifications under various scenarios.

4.1 3 Stage Ring Oscillator

From Figure 7, the variation of frequency on impact of temperature can be verified. As the temperature rose from 25 to 100 degrees, the frequency decreased from 42.25 to 34.45 Mhz. Temperature variations are inversely proportional to frequency.

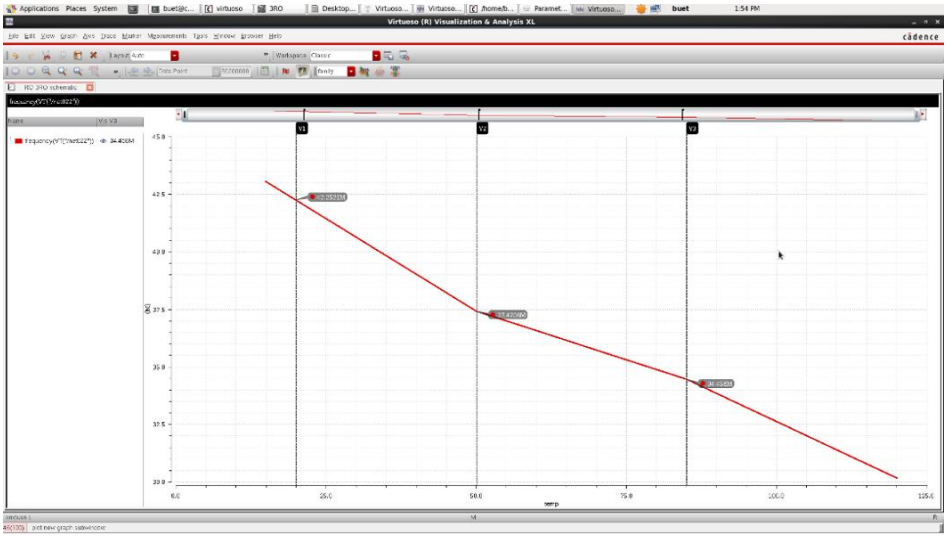

Figure 7. Temperature v/s Frequency for 3 Stage Ring Oscillator

Frequency is steady until Vctrl hits a threshold value of 0.67V, at which frequency starts to decrease as control voltage rises. This variation of control voltage v/s frequency can be seen in Figure 8.

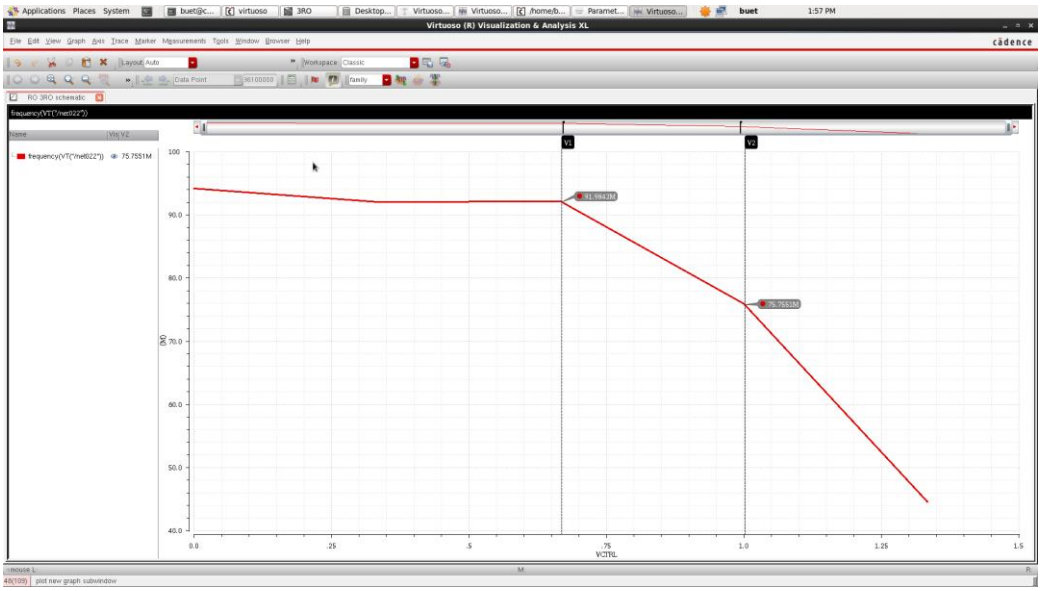

Figure 8. Control Voltage v/s Frequency for 3 Stage Ring Oscillator

Voltage and Power decreases from 22.4dB (20mW) respectively to 0 (zero) as frequency reaches to the power of 9 (Giga hertz), seen in Figure 9.

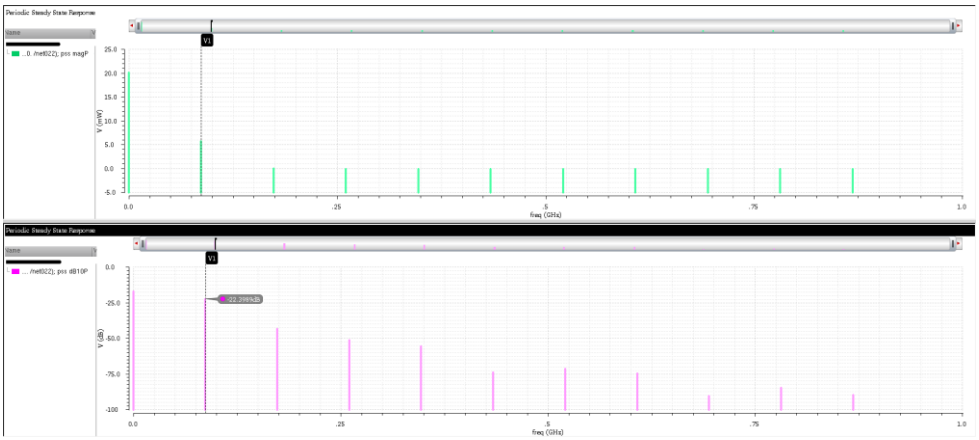

Figure 9. Periodic Steady-State (PSS) Analysis of 3 Stage Ring Oscillator.

Table 2 gives a complete picture of 3 stage ring oscillator for different performance parameters for different corner analyses.

Table 2. Performance Parameters of 3 Stage Ring Oscillator

Parameters	NN	SS	FS	SF	FF
Frequency (in MHz)	86.69	58.96	89.381	81.09	115.84
Average Power (in mW)	6.48	6.43	7.62	4.07	6.56
THD	65.983	66.621	56.202	91.136	65.159
O/P Noise (in dB)	-65.36	-61.97	-52.5	-65.18	-66.72

4.2 5 Stage Ring Oscillator

An evaluation of a 5-stage ring oscillator's performance would normally require modeling and simulation. This entails investigating the oscillator's stability and noise characteristics as well as the output waveforms, oscillation frequency, propagation delay, and waveform measurements. Studying the output waveforms enables accurate oscillation and assesses elements such signal quality, rise/fall durations, and duty cycle. While the propagation delay sheds light on the oscillator's speed, the oscillation frequency is tested to see if it falls within the appropriate range.

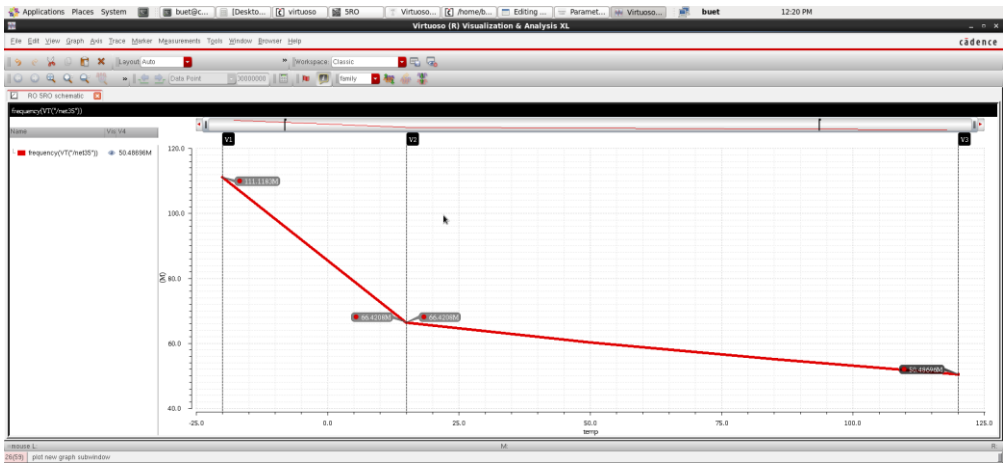

Figure 10. Temperature v/s Frequency for 5 Stage Ring Oscillator

The frequency dropped from 66.42 to 50.48 MHz when the temperature increased from 15 to 100 degrees. Figure 10 illustrates how temperature changes are inversely related to frequency.

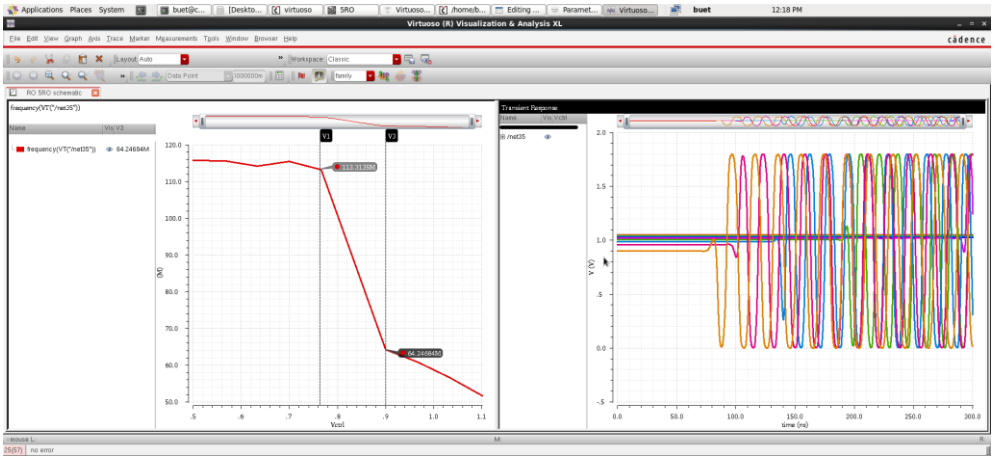

Figure 11. Control Voltage v/s Frequency for 5 Stage Ring Oscillator

As control voltage fluctuates, frequency decreases from 113.3 to 64.4MHz and stays stable up to 0.76V, as shown in Figure 11. Additionally, oscillation amplitude ranges from 0 to 1.8V, has a 90ns delay before stabilizing, and oscillates indefinitely.

Figure 12. PSS Analysis of 5 Stage Ring Oscillator

As frequency increases to higher frequencies (Giga Hertz), voltage and power continue to decrease from 20.4dB and 16.2mW, respectively, to zero. When compared to a 3-stage Ring Oscillator, the 5-stage version uses less power, depicted in Figure 12.

Table 3. Performance Parameters of 5 Stage Ring Oscillator

Parameters	**NN**	**SS**	**FS**	**SF**	**FF**
Frequency (in MHz)	50.70	34.296	52.48	44.805	115.84

Average Power (in mW)	8.22	8.24	8.55	7.07	6.56
THD	49.86	49.94	47.13	54.63	49.728
O/P Noise (in dB)	-65.88	-62.79	-63.56	-65.82	-66.45

4.3 7 stage Ring Oscillator

7-stage ring oscillator's performance parameters and attributes are examined as part of the outcome analysis. Higher oscillation frequency and shorter propagation latency may result from the 7-stage ring oscillator's extra stages as compared to the 5-stage oscillator. It might, however, lead to higher power use and perhaps more sensitivity to changes or noise. When comparing the two oscillators, great consideration must be given to trade-offs between the intended frequency range, power use, and stability.

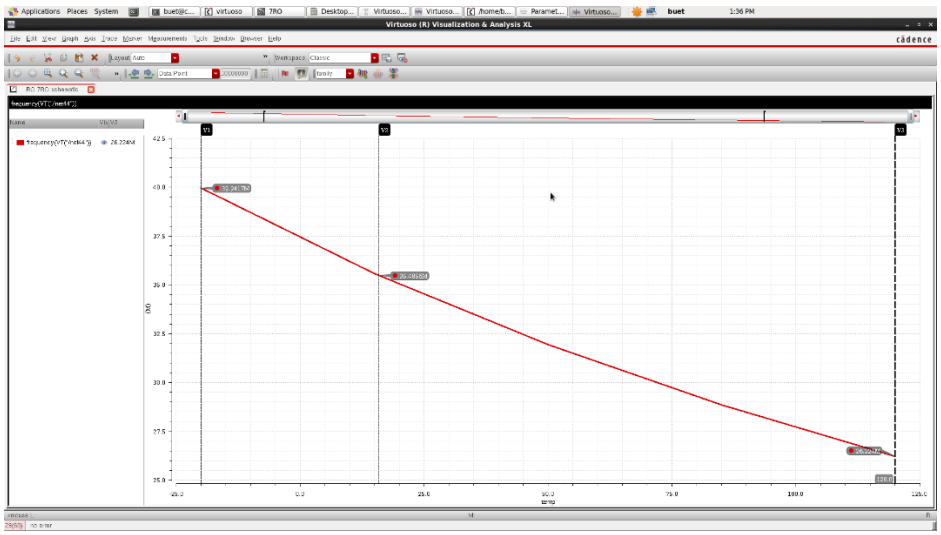

Figure 13. Temperature v/s Frequency for 7 Stage Ring Oscillator

The frequency dropped from 39.94 to 26.22 MHz when the temperature increased from -20 to 100 degrees. Figure 13 shows that temperature changes are inversely related to frequency.

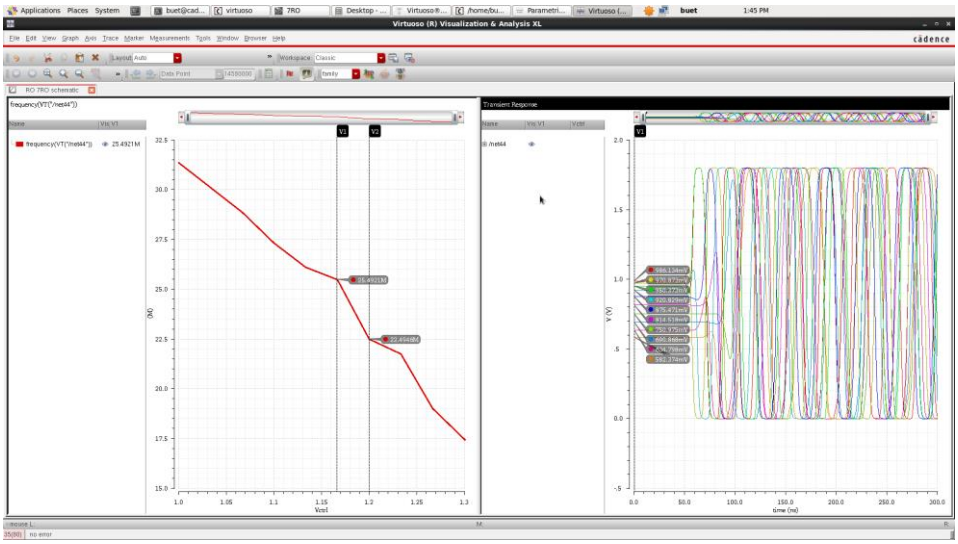

Figure 14. Control Voltage v/s Frequency for 7 Stage Ring Oscillator

Until Vctrl reaches a threshold value of 1.17 volts, frequency remains constant. After that point, frequency begins to drop from 31.5 to 22.5 MHz as Control voltage increases. This can be verified with the image shown in Figure 14.

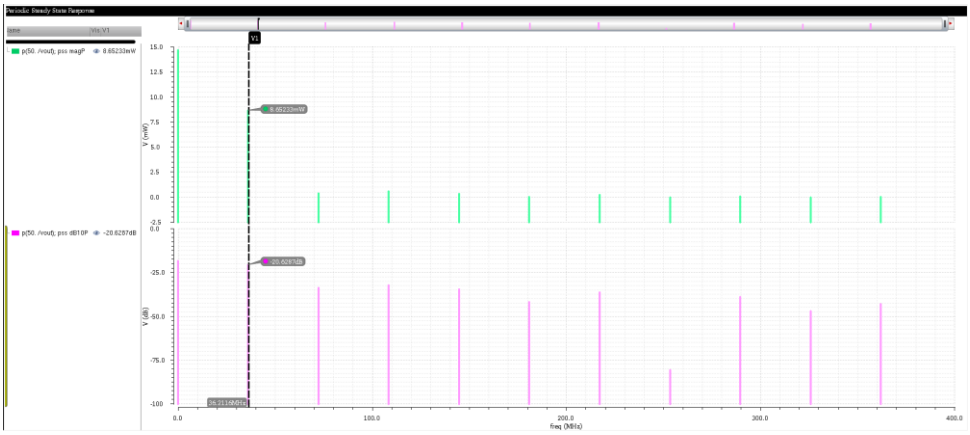

Figure 15. PSS Analysis of 7 Stage Ring Oscillator

Voltage and power continue to fall as frequency increases to higher frequencies (Mega Hertz), from 20.62 dB and 14.8 mW, respectively, until zero. As shown in Figure 15, the power consumption of the 7-stage ring oscillator is lower than that of the 3-stage and 5-stage oscillators. Table 4 compares the corner analyses results obtained for different performance parameters of a 7-stage ring oscillator.

Table 4. Performance Parameters of 7 Stage Ring Oscillator

Parameters	**NN**	**SS**	**FS**	**SF**	**FF**
Frequency (in MHz)	36.211	24.502	37.52	31.95	48.55
Average Power (in mW)	8.65	8.65	8.82	8.38	8.65
THD	46.717	46.759	45.453	48.743	46.652
O/P Noise (in dB)	-57.39	-63.86	-60.62	-52.12	-65.17

5. Advantages

- **Large Frequency Range**: A ring oscillator VCO [11] may provide a large frequency range utilizing current-starved methods, making it appropriate for a variety of applications.
- **Low Power Consumption:** Current-starved designs have a reputation for using less power, which makes them energy-efficient and appropriate for battery-operated gadgets.
- **Simple Circuitry:** The ring oscillator VCO [12] may be built with a reasonably simple circuit employing current-starved methods, which lowers design complexity and production costs.
- **Compact Size:** The circuitry's simplicity permits a compact architecture, making it appropriate for incorporation into system-on-chip (SoC) designs and integrated circuits.

6. Conclusion

Utilizing current-starved methods, a Ring Oscillator may be constructed as a VCO and provides advantages including a broad frequency range, low power consumption, simplicity, and small size. To achieve best performance for the purpose, however, factors including frequency linearity, phase noise, control voltage range, and power supply rejection must be taken into account. The CMOS ring oscillator with 3,5,7 stages Using the CMOS 90nm

technology method, a current-starved circuit has been designed and developed simultaneously in the Cadence Virtuoso environment. Numerous performance factors, including noise, delay, temperature, power, and glitches, were also analysed, tallied, and lowered as appropriate in order to enhance the efficiency of the ring oscillator. From the analysis it was found that;

- Temperature and Frequency have an inverse relation.
- Control Voltage and frequency also have an inverse relation.
- Power consumption reduces with increase in number of stages.
- Delay between each stage is dependent on the number of stages.

References

[1] Sharma, P., & Sachan, V. K. (2022, January). “Performance Analysis of Ring Oscillators and Current-Starved VCO” in 45-nm CMOS Technology.

[2] Preeti Kumari, Madhuresh Suman, "Design of a Nine Stage Ring Oscillator using PSO", International Journalod Innovative Trends in Engineering (IJITE), July 2020, 91(67), pp 44-47.

[3] Preston, D. J., Jiang, H. J., Sanchez, V., Rothemund, P., Rawson, J., Nemitz, M. P., ... & Whitesides, G. M. (2019). “A soft ring oscillator”. Science Robotics, 4(31), eaaw5496.

[4] Gurwinder Kaur, Abhilasha Sharma, Shanu Sood, "Design and Performance Analysis of CMOS based Ring Oscillator", Journal of Emerging Technologies and Innovative Research (JETIR), April 2018, 5(4), pp 543-547

[5] Masten, H. (2016). “Ring oscillator design in 32nm CMOS with frequency and power analysis for changing supply voltage”. Department of Electrical Engineering and Computer Science, Auburn University.

[6] Rasaily, D., Mehra, R., & Rai, U. (2016, March). “CMOS design of 5-stage ring oscillator as temperature sensor”. In 2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT) (pp. 2371-2375). IEEE.

[7] Suman, S., Bhardwaj, M., & Singh, B. P. (2012, January). “An improved performance ring oscillator design”. In 2012 Second International Conference on Advanced Computing & Communication Technologies (pp. 236-239). IEEE.

[8] Jovanovic, G., Stojcev, M., & Stamenkovic, Z. (2010). “A CMOS voltage-controlled ring oscillator with improved frequency stability”. Scientific Publications of the State University of Novi Pazar, Series A: Applied Mathematics, Informatics and mechanics, 2(1), 1-9.

[9] Kumar, S., & Kaur, G. (2012). “Design and performance analysis of nine stages CMOS based ring oscillator”. International Journal Of VLSI Design & Communication Systems, 3(3), 57.

[10] Mandal, M. K., and Bishnu Charan Sarkar. "Ring oscillators: Characteristics and applications." (2010).”.

[11] Halesh, M.R., Rasane, K.R., Rohini, H. (2011). Design and Implementation of Voltage Control Oscillator (VCO) Using 180nm Technology. In: Unnikrishnan, S., Surve, S., Bhoir, D. (eds) Advances in Computing, Communication and Control. ICAC3 2011. Communications in Computer and Information Science, vol 125. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-18440-6_60

[12] Gui, Xiaoyan, Renjie Tang, Yanlong Zhang, Dan Li, and Li Geng. "A voltage-controlled ring oscillator with VCO-gain variation compensation." IEEE microwave and wireless components letters 30, no. 3 (2020): 288-291.

[13] Choi, Jaehyouk, Kyutae Lim, and Joy Laskar. "A ring VCO with wide and linear tuning characteristics for a cognitive radio system." In 2008 IEEE Radio Frequency Integrated Circuits Symposium, pp. 395-398. IEEE, 2008.

[14] Nayak, Rajendra, Iman Kianpoor, and Pydi Ganga Bahubalindruni. "Low power ring oscillator for IoT applications." Analog Integrated Circuits and Signal Processing 93 (2017): 257-263.