

A Simulated Design of a Ring Oscillator with Phase Noise of -104.3 dBc/Hz@1MHz

Shuyi Wang

*Nanjing University of Information Science and Technology, Nanjing, China
15862845902@163.com*

Abstract. This paper presents the design of a fifth-order ring voltage-controlled oscillator (VCO) featuring low phase noise, based on the TSMC 65nm CMOS RF process. The design employs a low-noise inverter amplifier to replace the conventional inverter, thereby enhancing the performance of the ring oscillator. Simulations were carried out using Cadence Virtuoso. The results show that under a tunable control voltage ranging from 0.7V to 1.3V, the oscillator achieves a frequency tuning range of 108 MHz to 203 MHz. At a resonant frequency of 203 MHz, the phase noise is -83.6 dBc/Hz@100 kHz and -104.3 dBc/Hz@1 MHz. The typical power consumption at room temperature is 30.3 μ W.

Keywords: Ring Oscillator, Voltage-controlled Oscillator, Phase Noise, TSMC 65nm

1. Introduction

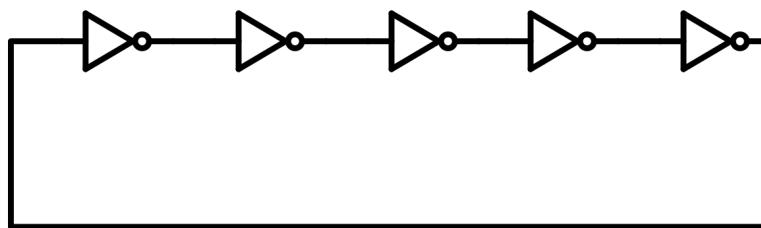
In modern applications such as wireless communication, satellite navigation, and precision measurement, the ring oscillator—serving as the core component of frequency sources—plays a critical role in determining signal integrity, communication range, and positioning accuracy. Traditional quartz crystal oscillators (e.g., quartz VCXOs) have dominated the mainstream market due to their excellent frequency stability. However, their high cost, large size, and limited tuning range fail to meet the emerging requirements of Internet of Things (IoT) devices and miniaturized radar modules. In recent years, dielectric resonator oscillators (DROs) and integrated phase-locked loop (PLL) technologies have made progress in terms of miniaturization and cost reduction. Nevertheless, in frequency bands above 10 GHz, their phase noise performance still generally falls short of -100 dBc/Hz@1 kHz. Additionally, these technologies suffer from challenges such as temperature sensitivity and process variation.

Multistage ring oscillators based on inverters offer significant advantages in terms of high performance and low cost. By tuning key electrical parameters—such as the output current, output impedance, and the number of cascaded inverter stages—precise, low-noise frequency output can be achieved under specific voltage conditions. Optimized electrical characteristics not only improve the oscillator's noise performance and frequency stability but also enhance its adaptability to temperature-sensitive components and its applicability in constructing high-precision encrypted communication networks. In recent years, ring oscillators have attracted considerable academic attention. In [1], the phase noise was reduced to -113.1 dBc/Hz by increasing the number of delay stages, achieving a 7 dB improvement at the cost of increased power consumption, which rose to

100.3 mW without optimization. In [2], the switching speed of the oscillator's delay unit was enhanced by adding MOS transistors and incorporating a positive feedback structure, resulting in a frequency increase of up to 300%. In [3], a five-stage ring oscillator model was developed to analyze phase noise and power consumption, followed by transistor sizing optimization. The resulting VCO achieved a phase noise of -111 dBc/Hz at 1 MHz offset from a 400 MHz center frequency, with power consumption of only 158 μ W. Reference [4], utilizing the 65nm CMOS process, reduced total channel thermal noise injected into the VCO output node during output voltage transitions. At 645 MHz, it achieved a phase noise of -110.8 dBc/Hz at 1 MHz offset, with a power consumption of 10 mW under a 1-V supply. In [5], a VCO fabricated using a 0.35 μ m CMOS process and composed of five delay units plus an output buffer demonstrated improved phase noise performance and linear tuning characteristics. The proposed VCO-based PLL sensor interface achieved a signal-to-noise ratio (SNR) of 88.4 dB over a 1 kHz bandwidth.

2. Circuit design

The schematic of a conventional ring oscillator based on inverter amplifiers is shown in Figure 1(a), while the schematic of a single inverter amplifier is illustrated in Figure 1(b). Five inverter amplifiers are connected in a closed loop to form an oscillation ring. The oscillation frequency of the loop is determined by the propagation delay of the ring; the frequency is inversely proportional to the total delay. Therefore, increasing the delay of the inverters leads to a reduction in oscillation frequency, and vice versa. Generally, there are two methods to increase the overall delay of the loop. The first is to increase the number of cascaded inverter stages, thereby increasing the total delay. However, this approach is not suitable when chip area and power consumption are constrained. The second method is to increase the delay of each individual inverter stage, which effectively increases the total loop delay without significantly impacting area or power. As shown in Figure 1(b), the inverter consists of a PMOS and an NMOS transistor connected in series. The gates of both transistors serve as the input terminal, while the drains are connected to form the output terminal. The W/L ratios of the PMOS and NMOS transistors are carefully designed to ensure that the output impedances of both transistors are matched.



(a)

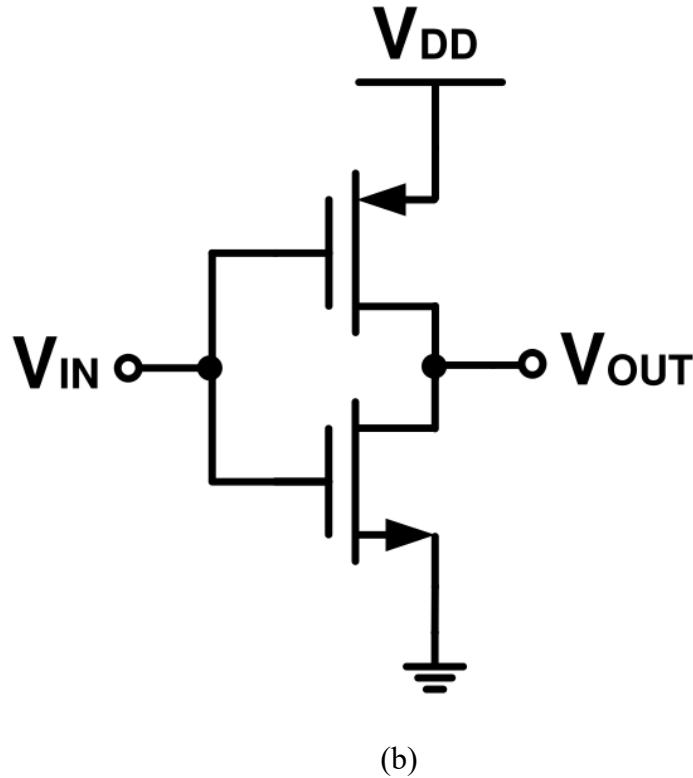


Figure 1: (a) Fifth-order ring voltage-controlled oscillator; (b) conventional inverter amplifier

The proposed low-noise inverter amplifier is shown in Figure 2. A parallel RC network, consisting of a resistor R and a capacitor C , is inserted between the PMOS and NMOS transistors. On one hand, this RC network functions as a first-order low-pass filter, which effectively reduces the noise generated by the inverter amplifier. The output noise of a first-order low-pass filter formed by R and C is given by kT/C , where k is Boltzmann's constant and T is the absolute temperature in Kelvin. Therefore, the thermal noise introduced by the resistor R is negligible. On the other hand, the resistor R increases the output impedance of the inverter amplifier, thereby enhancing the robustness of the ring oscillator without contributing to additional power consumption. As a result, replacing the traditional inverter amplifier with the proposed low-noise design as the delay cell in the voltage-controlled ring oscillator can further improve the oscillator's overall performance.

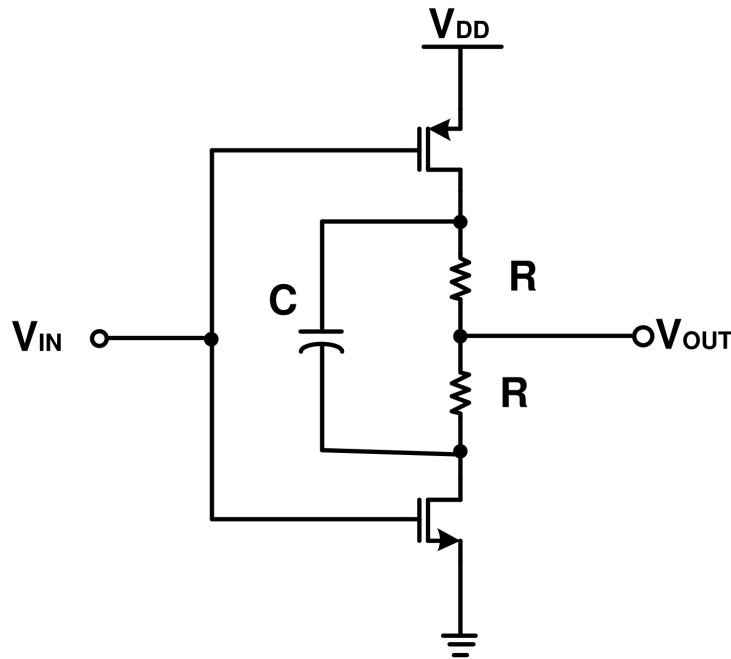


Figure 2: Low-noise inverter amplifier

3. Simulation results

The proposed low-phase-noise ring oscillator was simulated using the Cadence Virtuoso platform based on the TSMC 65nm CMOS RF process. The simulation results are shown in Figure 3~5.

The oscillation waveform of the proposed oscillator circuit is shown in Figure 3. The startup time of the oscillation is approximately 10ns, and the peak-to-peak voltage of the waveform is about 700mV_{pp}.

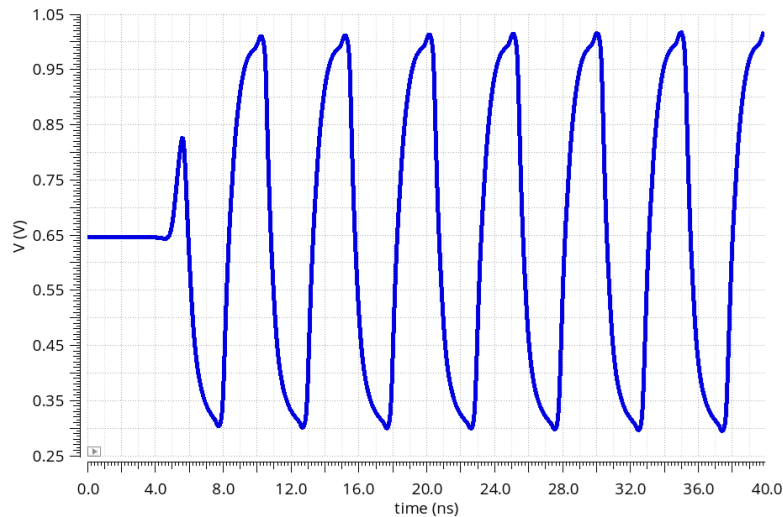


Figure 3: Oscillation waveform of the proposed oscillator circuit

The simulated phase noise performance of the proposed oscillator circuit is shown in Figure 4. The phase noise is -83.6 dBc/Hz at a 100 kHz offset, -104.3 dBc/Hz at a 1 MHz offset, and -124.5 dBc/Hz at a 10 MHz offset.

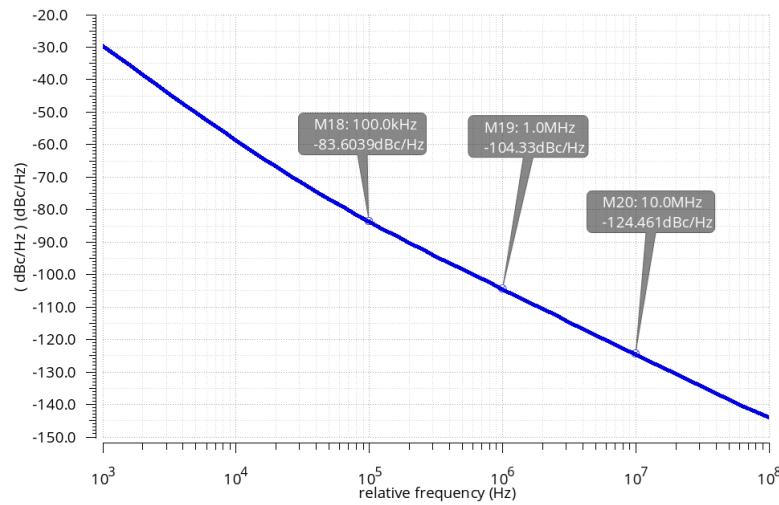


Figure 4: Simulated phase noise results

The simulated frequency tuning range of the proposed oscillator circuit under a control voltage varying from 0.7 V to 1.3 V is shown in Figure 5. The tunable frequency range extends from 108 MHz to 203 MHz.

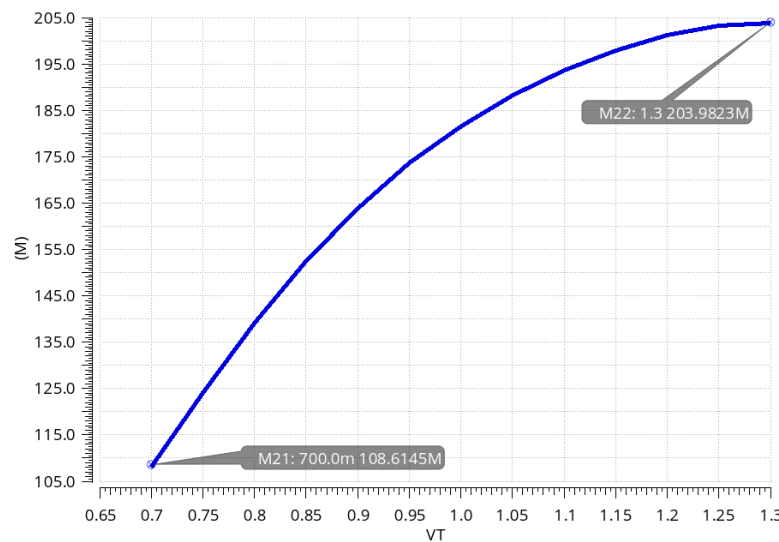


Figure 5: Simulated frequency tuning range

4. Conclusion

Based on the TSMC 65nm CMOS RF process, a low-phase-noise fifth-order ring voltage-controlled oscillator (VCO) based on inverter circuits was designed. By adding two delay cells to the conventional three-stage inverter amplifier structure, the oscillation frequency of the loop was increased. Additionally, a parallel RC network was introduced between the PMOS and NMOS transistors, which effectively reduced the noise of the inverter amplifier. This design also enhanced the robustness of the ring oscillator by increasing the output impedance without incurring additional power consumption, thereby addressing the high power consumption issue of traditional amplifiers. Simulation results demonstrate that under a control voltage range of 0.7 V to 1.3 V, the proposed

fifth-order ring VCO achieves a tunable frequency range from 108 MHz to 203 MHz. The phase noise performance is -83.6 dBc/Hz at a 100 kHz offset, -104.3 dBc/Hz at a 1 MHz offset, and -124.5 dBc/Hz at a 10 MHz offset. Compared to traditional ring oscillators, the proposed design exhibits improved phase noise performance with a typical power consumption of 30.3 μ W, indicating promising application potential.

References

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