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PHASE NOISE ANALYSIS FOR HIGH SPEED VOLTAGE CONTROL RING OSCILLATOR

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AUTHORS' CONTRIBUTIONS

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ABSTRACT

Voltage controlled oscillators (VCOs) are an important part of transceivers. Phase noise is an important characteristic of oscillator design and is defined as the spectral density of the oscillator spectrum at an offset from the center frequency of the oscillator relative to the power of the oscillator. The effect of the oscillator's noise is one of the most important items in the designing of modern RF telecommunication systems. In this paper, we present the design and performance analysis of a 15 GHz voltage-controlled ring oscillator using the 130nm CMOS technology for operating in high-speed applications. For improving the efficiency of the ring oscillator in the transceiver, different techniques such as transistor sizing are employed. In comparison to other publications, the author's ring oscillator design is optimized with reference to the central frequency and phase noise.

Keywords: Ring oscillator; high speed; phase noise.

1. INTRODUCTION

Due to the significant growth in applications of wireless technology, the need for systems with low costs, high flexibility, and the ability to handle high data rates has recently increased. Furthermore, due to the increase in demand for small-sized, portable, and low-powered wireless devices with multiple applications, the process of designing hardware and software that will result in those benefits has become harder. In order to meet these demands, the goal is to move towards a software-defined radio, which can enable us to make telecommunication applications and standards embedded, and reconfigurable. In order to achieve this goal, we need to design a RF circuit using CMOS that can meet these requirements, and among them the voltage-controlled ring oscillator is one of the fundamental circuits. Voltage-Controlled Oscillators (VCOs) have a variety of applications such as RF transceivers, modulators and demodulators, radio frequency identification devices (RFID), and transponders. Analysis and designing a low-phase noise VCO is a major direction in VCO research works. In this regard, many theories and topologies have emerged in the literature [1,2].

In all voltage-controlled ring oscillators, the frequency of the output oscillation can be changed by the biasing of a controlled voltage signal and reducing the supply voltage leading to an increase in the phase noise. Therefore, it is necessary to find a solution for achieving high-phase noise performance under a low-voltage supply and power.

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Many researches have been done with the aim of improvement of phase noise behavior in the VCOs, through employing different techniques such as: the Colpitts VCO with improvement using gm -enhanced and current-reuse techniques [3], 0.12 μm SiGe Bic MOS for a cross-coupled design VCO [4], a cascade CMOS VCO with a source-damping-resistance technique [5] and the PMOS cross- coupled pair and gm- boosting topology [6].

Motivated by the above arguments, in this paper, a five-stage voltage-controlled ring oscillator is proposed for operating in high frequencies. We employ differential topologies to handle as less capacitance as possible to achieve a fast oscillation frequency with low phase noise. In the proposed circuit, we use the voltage-controlled active load to get rid of the current source and help boosting the output swing, maintain the tuning range and control gain [7]. In addition, the authors employ a transistor sizing technology to propose a circuit that demonstrates the high speed with low power consumption and low phase noise.

The rest of the paper is organized as follows. In Sections II and III, phase noise will be introduced and the importance of Phase Noise in Communication Systems will be considered. The Barkhausen Criteria are analyzed in Section IV. section V provides VCO topologies and in section VI, the phase noise analysis and some evaluation using simulation to confirm our analysis. Finally, in Section VII, an overview of the results and some conclusions are presented.

2. PHAS NOISE

Passive and active components in an oscillator cause noise to be applied to the system, including shot noise, flicker noise, and thermal noise [7]. When the noise is added to the output signal of an oscillator, it leads to changes in the frequency and amplitude of the output. These random changes in the frequency of the oscillator are called random change in the position of the zero crossings or phase of the oscillator signal. Since all oscillators have a mechanism to control amplitude, it does not allow the oscillation amplitude to be changed more than a certain value.

Due to this reason, it is observed that the amplitude noise is not significant since the oscillator will automatically remove it. Hence only the phase noise is significant to consider in designing an ″VCO″ since it does not get removed, and it is a serious matter that needs to be investigated in the VCO design.

From the frequency domain perspective, phase noise means that output signals contain significant energy at other frequencies rather than the desired fundamental frequency. The output signal of an ideal sinusoidal oscillator is shown in Fig. 1. (a) that operates at frequency f_o. It is observed from this figure that the shape of the spectrum is characterized as an impulse function. As shown in Fig. 1. (b), in any practical oscillator, the spectrum has power distributed around the frequency of oscillation [1]. Also, the phase noise can be expressed as the ratio of power at a specific offset frequency

(Δω) from the carrier to the power at the central frequency. According to this definition, the phase noise is expressed as decibels below the carrier per hertz (dBc/Hz). The oscillator phase noise, denoted by $\mathcal{L}(\Delta\omega)$, is mathematically defined as [8]:

$$\mathcal{L}(\Delta\omega) = 10 \log \left(\frac{p_{\text{sideband}}(\omega_0 + \Delta\omega, 1HZ)}{p_c}\right),$$

where p_c is the power in the fundamental carrier ω_0 and p_{sideband} represents the power distributed around the carrier. According to the above definition, the phase noise may be reduced by increasing p_c at the cost of an increase in the power consumption.

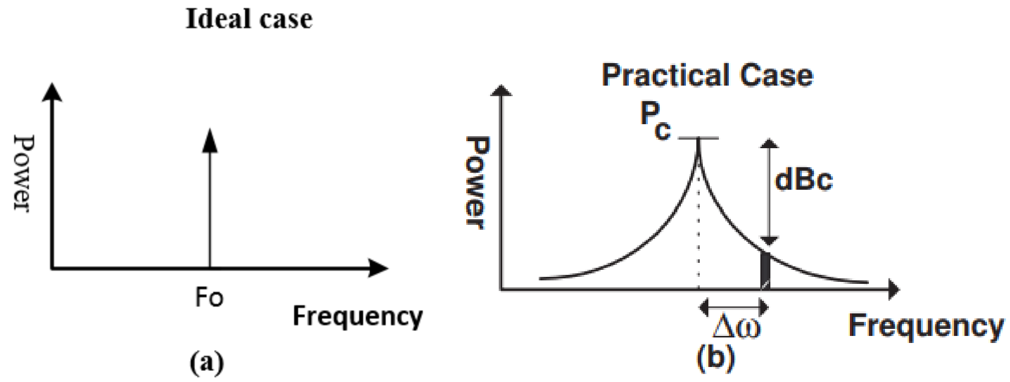


Fig. 1. Frequency spectrum of (a) an ideal oscillator, (b) a practical oscillator

The phase noise is a critical parameter that can use for compression the performance of VCO. The output of a practical oscillator can be written as:

$$V_{out}(t) = Acos(\omega_0 t + \phi),$$

where A is the amplitude of oscillator, ω_0 is the oscillation frequency, and φ is the inherent phase. However, the oscillator is affected by internal and external noises which make an amplitude and phase fluctuations. The output of an actual oscillator can be written as:

$$V_{out}(t) = A(t)f(\omega_0 t + \phi).$$

The function f is periodic in 2π, *A(t)* and φ(t) are modeled as the fluctuation of amplitude and phase, respectively. The amplitude fluctuation naturally will be rejected by the oscillator. The value of phase noise can be varied according to the offset frequency. To achieve the low phase noise, power of the noise in the unit bandwidth should be small and the power of the carrier should be large.

3. IMPORTANCE OF PHASE NOISE IN COMMUNICATION SYSTEMS

Most wireless communication devices extensively depend on frequency conversion using local oscillators. In addition, spectral purity is one the most challenging items in the transmitter and receiver that make limitations in the number of channels. A generic transceiver consists of a band-pass filter, a low noise amplifier, a down-conversion mixer, an up-conversion mixer, a band-pass filter, and a power amplifier as shown in Fig. 2. The local oscillator (LO) provides the carrier signal for both the transmitter and receiver. The phase noise from LO will be transferred to both the upconverted and the down-converted signals and then both will be corrupted.

In the ideal case, an impulse function will be implicated with the signal band of interest in the frequency domain and is translated to a higher frequency, but lower frequency will remain in its shape. A large interferer in an adjacent channel will accompany the desired signal and the local oscillator shows a finite phase noise. When the signal and the interferer are mixed with the LO output, two overlapping spectra will appear in the down-converted band as shown in Fig. 3.

The signal always suffers from significant noise, which is the result of the tail of the interferer. Here, the end portions of the interferer's frequency spectrum which leak into the adjacent channels have been referred to as the tails of the interferer. This effect is called as reciprocal mixing.

To minimize the effects of the noise in transceivers, LO should have a sharp output spectrum. To achieve this goal, it is vital to include ring oscillators in communication systems, but their phase noise is approximately high due to the lack of passive resonant elements in the ring VCO structure. Therefore, it is necessary to have ring oscillator phase noise models that are accurate at the circuit level to be able to optimize the parameters of communication systems containing ring oscillators.

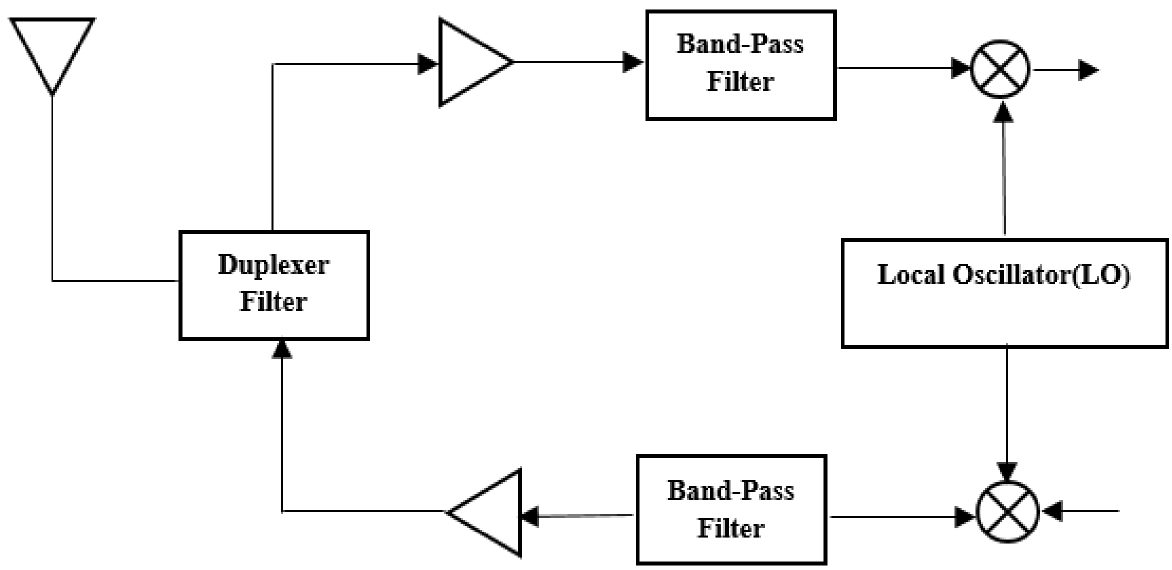


Fig. 2. Block diagram of a generic transreceiver

4. BARKHAUSEN CRITERIA

The barkhausen criteria [7] is a mathematical formula to determine when a linear electronic circuit will oscillate. The criteria treat the oscillator as a linear positive feedback loop, where the forward gain $H_1(j\omega)$ represents the voltage transfer function of the amplifier and

$H_2(j\omega)$ is the voltage transfer function of the feedback network. Obviously, the transfer function of the complete network is given by:

$$\frac{V_{out}}{V_{in}} = \frac{H_1(j\omega)}{1 - H_1(j\omega)H_2(j\omega)}.$$

To make the system unstable, the root of the denominator should be located at the right-hand side of the complex axis, given:

$$|H_1(j\omega)||H_2(j\omega)| \geq 1,$$

and to keep the amplitude constant, it should be

$$|H_1(j\omega)||H_2(j\omega)| = 1.$$

The phase shift around the loop is zero or an integer multiple of 2π, i.e.,

$$\phi_{H_1(j\omega)} + \phi_{H_2(j\omega)} = 0 + 2\pi k, k = 1,2, \dots .n.$$

The above equations represent the well-known Barkhausen criteria, where $\phi_{H_1(j\omega)}$ and $\phi_{H_2(j\omega)}$ donate the phase shift of $H_1(j\omega)$ and $H_2(j\omega)$, respectively. Note that these criteria pose a necessary condition but are not enough. In some circuits, the criteria are fulfilled, however, those do not oscillate. To guarantee the start-up, the loop gain $|H_1(j\omega)||H_2(j\omega)|$ is usually greater than one, leading to an increase in the amplitude. Then, the gain will fall back to one as a result of the nonlinearity of the circuit.

5. VCO TOPOLOGIES

There are two kinds of main RF VCOs, which are LC- tank VCO [9,10], and ring VCO [11,12].

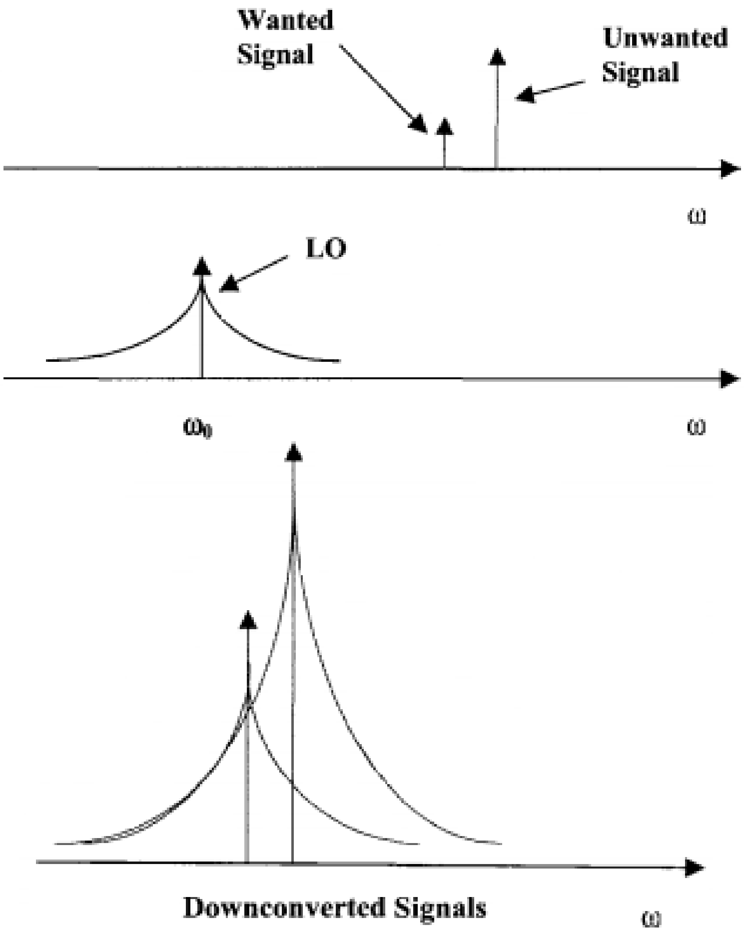


Fig. 3. Effect of the phase noise on the receive path

LC-Tank VCO: This type of VCO is constructed by an inductor and a capacitor in which the resonant frequency is $\omega = 1/(\sqrt{LC})$, which means at frequency ω, the impedance of the LC-tank is infinite. If some energy is stored in the tank, it will generate a periodic signal with frequency ω. In this case, the quality factor Q can be defined as [13]:

$$Q = 2\pi \frac{E_{stored}}{E_{dissipated}},$$

where E_{stored} denotes the amount of energy stored and $E_{dissipated}$ represents the amount of energy lost in the components such as inductor and circuit. The LC-tank VCO has a higher oscillation frequency and a better phase noise performance than other topologies, because of the higher quality factor Q of the LC-tank. However, the frequency tuning ability of this type of VCO is realized by on-chip variable capacitors. In addition, the variable range of on-chip integrated capacitors are limited, which leads to a very narrow frequency adjustment range of the LC-tank VCO. Moreover, using multiple on-chip inductors leads to a relatively large chip area of the LC-tank VCO [12]. Totally, this kind of VCO cannot display a wide tunability, since inductors and varactors are not effortlessly tuned.

Ring VCO: These oscillators consist of an odd number of single-ended inverters or an even/odd number of differential delay cell (inverter) where the output of the last stage is fed back to the input of the first stage. To achieve a sustained oscillation, the ring oscillator must provide the phase shift of 2π and the unity voltage gain. The phase shift is equally divided between each delay cell. The oscillation frequency of the ring VCO is determined by the propagation delay of the cell and the number of delay stages.

Taking the above considerations into account, the ring oscillator is a better choice for the implementation of RF VCOs, because on-chip inductors are not necessary, and the occupied chip area is smaller than the LC-tank VCO for fabrication and it is a very cost-effective [14]. In the ring oscillators, by adjusting the bias current of delay cells, it is possible to tune frequency, and ring oscillators provide a much better tuning range. Ring oscillators have a wider range of frequency adjustment in comparison with the LC-tank VCO and the bias current can be freely controlled. Moreover, the ring oscillator can generate both quadrature and in-phase outputs for an even number of delay cells [13].

In comparison with other types of oscillators, though the LC-tank VCO shows a good phase noise performance, it is not good in other features described as follows. The frequency of operation is lower than that of ring oscillators and owing to the attendance of spiral inductors which occupy a big area on the chip, the cost is increased. In addition, the phase noise performance depends on the inductor’s quality factor, while a good quality LC oscillator comes at a high cost.

6. PHASE NOISE ANALYSIS

In this paper, we consider several VCOs in terms of phase noise. A five-stage voltage-controlled ring oscillator for operating in 15GHZ frequency is introduced that uses CMOS in 130nm technology. The delay cell circuit that is used in the proposed VCO has been shown in Fig. 4. In this design, we use a voltage-controlled load device for controlling the gain. In this VCO, identical delay cells are connected back to back and the output of each cell is fed to the next delay cell’s input.

As previously mentioned, the phase noise evaluates the noise and power of a carrier signal. In other words, it is the ratio of the noise and carrier signal powers. In addition, the random noise and systemic noise generate the noise power. Fig. 5 displays the phase noise of the introduced ring oscillator at 15 GHZ. It can be seen from the diagram that the phase noise in frequency offset 1MHZ and 15.04 GHZ are equal to -103.460 and -186.701, respectively.

The output waveform of the delay cell in V=1.2v as well as the FFT diagram (technique to analyze signal in the frequency domain to find out how many frequency components are present) have been shown in Fig. 6. The performance comparison of this VCO with recently reported circuits in terms of the phase noise have been mentioned in Table 1. The frequency of the proposed VCO is 15 GHZ and shows a premiere performance in phase noise as compared to circuits presented in [3,4].

In [3], a Colpitts VCO is presented for low-power and low-phase-noise applications. The current efficiency of the proposed VCO is improved through gm -enhanced and current-reuse techniques. The VCO is implemented in a 0.18-μm CMOS process and is shown to operate at frequencies of 2.34 to 2.55 GHz. The prototype has a power dissipation of 1.4 mW and achieves a phase noise of -122.85 dBc/Hz at a 1 MHz frequency offset.

In [4], a 9.9-12.45 GHz VCO is designed in 0.12 μm SiGe Bic MOS with a focus on achieving the lowest possible phase noise using only a single core and maintaining the recommended V_{dd} of the technology. The oscillator consists of a cross-coupled design utilizing a transformer-coupled resonant tank, which takes the advantage of tank parasitic to create harmonic resonances. A phase noise of -122 dBc/Hz is measured at 1 MHz offset from the carrier resulting in a figure of merit (FoM) -183 and -190 dBc/Hz, respectively. The VCO is incorporated into a type-II charge-pump-based phase-locked loop (PLL) with intent to be used as the local oscillator (LO) generation in a potential fifth generation (5G) communication system.

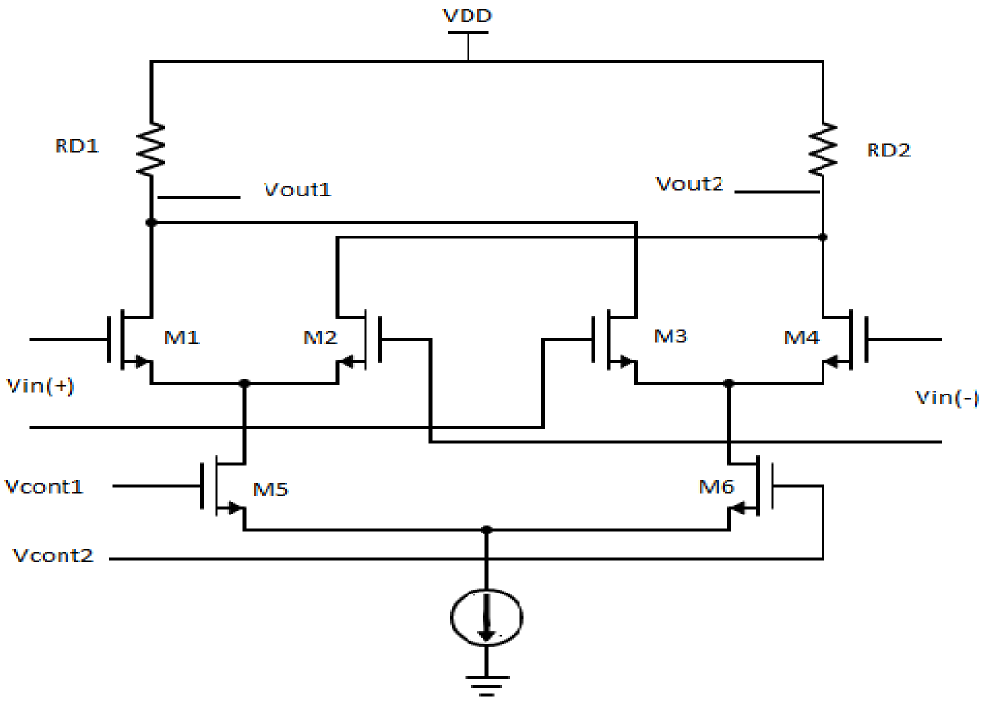
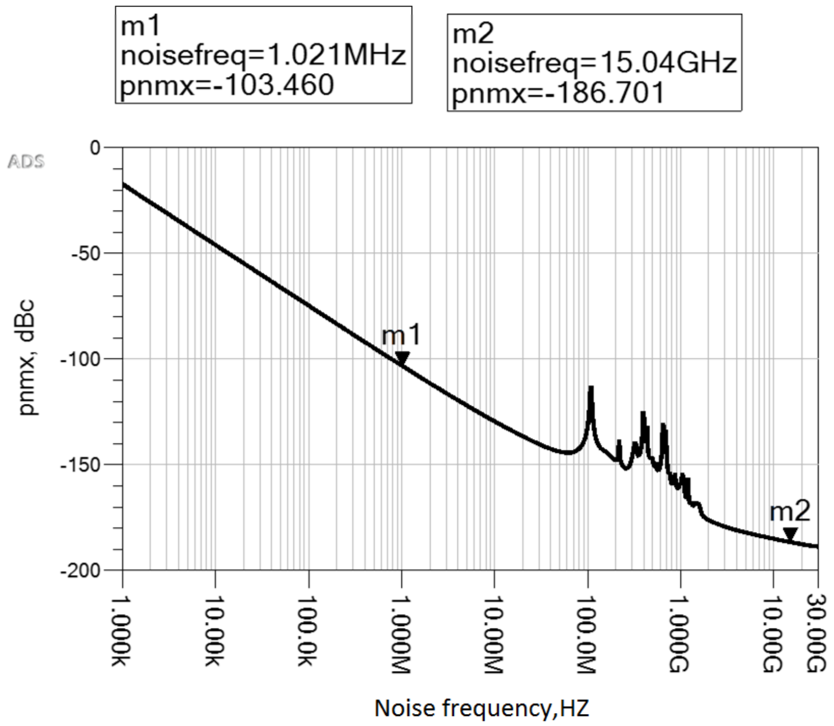


Fig. 4. Proposed delay circuit in each stage of the ring VCO

a.



b.

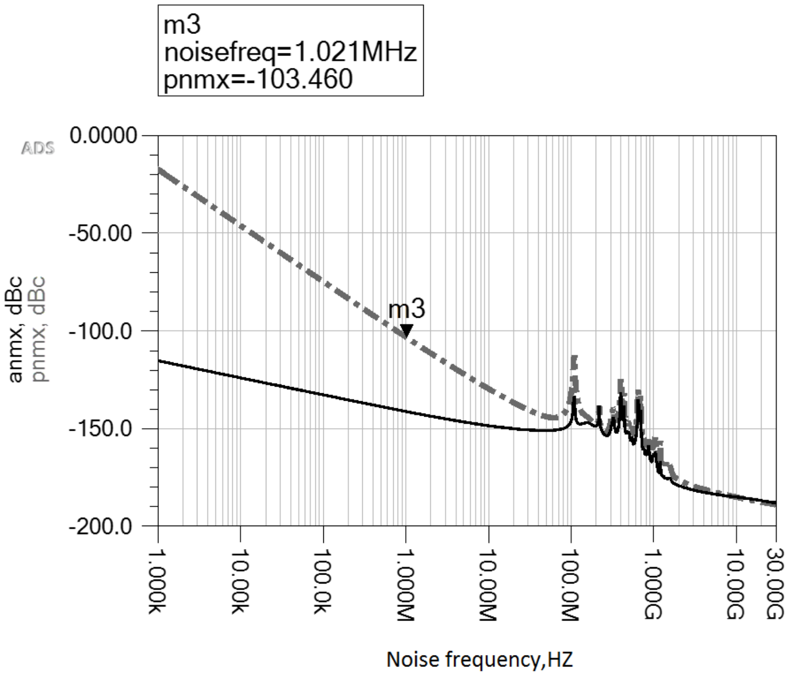


Fig. 5. a. Phase noise diagram in frequency offset =1MHZ and 15.04 GHZ; b. Phase noise and amplitude in frequency offset =1MHZ

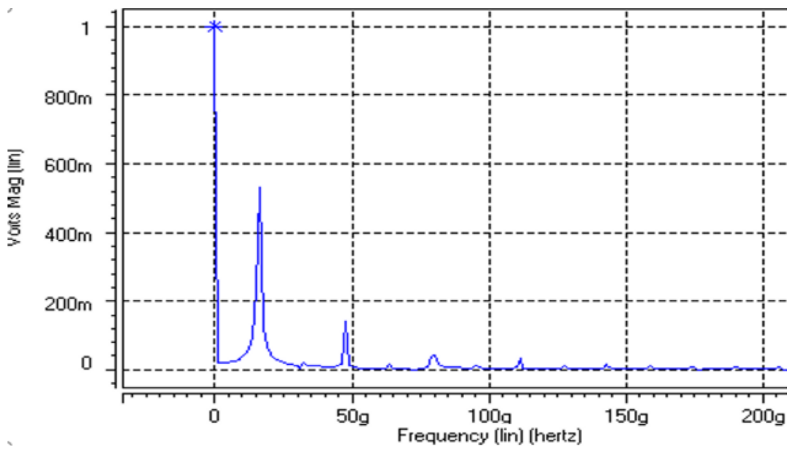


Fig. 6. FFT output of the introduced VCO at 15 GHZ and V=1.2 v

Table 1. Comparison between the performance of the proposed VCO with that of four recent VCO designs in [3-6]

Item	f_{osc} GHz	Phase noise	*FOM*	Power dissipation
[3]	2.34- 2.55 GHz	-122.85 dBc/Hz	-	1.4 mW
[4]	9.9-12.45 GHz	-122 dBc/Hz	-190 dBc/Hz	-
[5]	2.26 -2.14 GHz	-125.9 dBc/Hz	-187.6 dBc/Hz	3.0mW
[6]	5 GHz	117.4 dBc/Hz	-	2.92 mW
Introduced VCO	15 GHZ	-103.460 dBc/Hz	-209.6 dBc/Hz	2.4734m

In [5], a cascade CMOS VCO with a source-damping-resistance technique is proposed to reach low phase noise. Measured oscillation frequency is from 2.26 GHz to 2.14 GHz. The measured phase noise at 1 MHz offset is -125.9 dBc/Hz at 2.14 GHz, and the core power consumption is 3.0mW from a supply voltage of 1.5V. A FOM of -187.6 at 1MHz offset is obtained. Two different phase noise improvement techniques merged simultaneously are demonstrated.

In [6], a low- power and low- phase- noise 5GHz VCO is proposed in a standard CMOS 0.18- μm process. To design this VCO, authors use the PMOS cross- coupled pair and gm- boosting topology. The VCO consumed a dc power of 2.92 mW with the supply voltage of 1 V. The measured phase noises were − 104.6 dBc/Hz and − 117.4 dBc/Hz at 1 MHz offset frequency with switched off and on capacitances, respectively, which demonstrated 12.8- dB improvement.

7. CONCLUSION

In this paper, we have designed a ring VCO based on a five-stage inverter (CMOS differential) connected in a ring topology to achieve the desired frequency in oscillation. The ring oscillator was designed based on the TSMC 0.13 μm technology. We used powerful simulation software, ADS to analyze the phase noise, simulate and verify the predicted phase noise performance of the designed VCO. As a result, the theoretical simulations have provided a range of control voltage between 1V and 1.8 V, which corresponds to an oscillation frequency in 15 GHz and higher. To demonstrate the advantages of the designed scheme, it was demonstrated a low phase noise and power dissipation such as -103.640 dBc/Hz mw in 2.4734m. To the best of our knowledge, this VCO achieves high speed performance (15 GHZ), small chip area with lack of a LC- tank, and lower phase noise, which is critical among the VCOs reported to date. It was demonstrated the potential of the designed scheme for high speed, low phase noise oscillator applications in modern telecommunication industry, medical industry, and the applications in which a sharp and accurate clock generation is necessary.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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