A 4.2–5 GHz, low phase noise LC-VCO with constant bandwidth and small tuning gain

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Abstract: As the tuning frequency of an integrated LC-voltage controlled oscillator (LC-VCO) increases, it is difficult to co-design the active negative resistance core and the varactor to achieve wideband frequency range, low phase noise, constant bandwidth and small tuning gain together. The presented VCO solves the problem by designing a set of changeable varactor units. The whole VCO was implemented in a 0.18 μm CMOS process. The measured result shows –120 dBc/Hz phase noise at 1 MHz offset. The measured tuning range is from 4.2 to 5 GHz and the tuning gain is 8–10 MHz/V. The VCO draws 4 mA from a 1.5 V supply voltage.

Key words: VCO; low phase noise; switched varactor array; tuning gain; constant bandwidth

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1. Introduction

Voltage controlled oscillators (VCOs) are essential building blocks of communication systems. The VCO performance determines the tuning range and phase noise of a transceiver. With the development of modern communications, a high working frequency, wideband frequency range and low phase noise local oscillator (LO) signal are needed, which applies a stringent requirement to the VOC design.

To achieve the strict phase noise specifications, most RF transceiver ICs use LC-VCOs. The frequency tuning band of LC-VCOs is often controlled by changing the capacitor value or the inductor value in the resonant tank. As the phase noise performance of the phase-locked loop (PLL) is often determined by the tuning gain ($K_{\rm VCO}$) of the VCO[1], the latter must be kept relatively low. On the other hand, phase noise optimization of the PLL requires a certain bandwidth with respect to the given VCO circuit. For every different output frequency of the VCO, the bandwidth must be kept constant to minimize phase noise variation and guarantee loop stability of the PLL.

Compared with switched inductor designs[2], which have difficulty in limiting the deterioration of the phase noise performance caused by the insertion of the switches, switched capacitor designs are more frequently applied. A mixed discrete/continuous tuning method is especially widely chosen[3, 4]. The large steps are realized by digitally switching varactor units in and out of the resonant tank and small analog varactor units are used for continous tuning.

However, as the working frequency of the VCO increases, the tuning gain and the bandwidth become more sensitive to the change of the capacitors in the resonant tank. Several papers have been published concerning this issue. Nevertheless, the phase noise is not ideal[5], the tuning gain is too high[6, 7] and the bandwidth varies greatly[6]. This paper proposes a set of changeable varactor units, which achieves constant bandwidth across the whole output frequency range and keeps the tuning gain small. The circuit design of the VCO, which includes the architecture, the active negative resistance core and the switched varactor array, is also given.

2. Design considerations

2.1. Start-up condition

In the target frequency range (< 5 GHz), MOS varactor units in modern CMOS processes achieve quite high quality factors of 40 or even higher. As the result, the losses in the oscillator tank are usually dominated by the inductor loss. The required negative resistance is given by[8]

$$G_{\rm m} = \frac{R_{\rm S}}{(\omega L)^2}, \tag{1}$$

where $R_{\rm S}$ is the series resistance of the inductor, L is the tank inductance, and ω is the oscillation frequency. The required $G_{\rm m}$ increases with decreasing ω. In the traditional design the most rigorous condition should be met, which means that the active core should make $G_{\rm m}$ big enough to guarantee oscillation at the lowest target frequency.

2.2. Phase noise

There are, broadly speaking, two working regimes. In the current-limited regime, the voltage amplitude in the tank is proportional to the total current of the VCO, defined as $I_{\rm B}$. In the voltage-limited regime, the voltage amplitude saturates to a plateau limited by the available headroom from the supply

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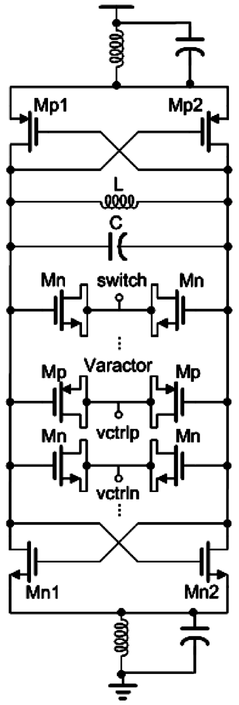

Fig. 1. The proposed VCO architecture.

voltage, defined as V_0. Many papers have described the treatment of phase noise in VCOs. Some of the most important dependences could be presented as

$$\text{PN} \approx \frac{\overline{i_n^2}}{V_0^2}\frac{R_T^2}{4Q_T^2}\left(\frac{\omega}{\Delta\omega}\right)^2, \quad (2)$$

where Q_T is the quality factor of the inductor, $\overline{i_n^2}$ is the noise current of the tank, and $\Delta\omega$ is the frequency offset from the carrier.

The optimum phase noise performance occurs at the beginning of the voltage-limited regime. The proposed VCO architecture is shown in Fig. 1. The current of the VCO can adjust itself according to the change of the target oscillating frequency. As $V_0 = I_B R_T$ is always met, Equation (2) could be rewritten as

$$\text{PN} \approx \frac{\overline{i_n^2}}{I_B^2}\frac{1}{4Q_T^2}\left(\frac{\omega}{\Delta\omega}\right)^2, \quad (3)$$

where I_B automatically increases with decreasing ω. Thus, the maximization of the quality factor Q_T is the key to improving the phase noise performance of the VCO.

2.3. Switch varactor array

In order to suppress noise from the power supply and substrate, the VCO is differentially configured. As illustrated in Fig. 1, a change in the differential control voltage V_{crtlp} and V_{crtln} results in a change of the analog varactor capacitance C. This causes a change in frequency Δf, which can be expressed as

$$f = \frac{1}{2\pi\sqrt{LC}}, \quad (4)$$

$$\frac{\Delta f}{\Delta C} = \frac{-1}{4\pi C\sqrt{LC}}. \quad (5)$$

Due to the nonlinearity of frequency to the capacitor, K_{VCO} will change and the band step will vary if the equal capacitor is switched in and out of the tank. To cover a wideband frequency range with constant bandwidth and small K_{VCO}, a number of varactor units are used in Fig. 1. These varactor units are used in two ways. Some of them are controlled by the voltage V_{crtlp} and V_{crtln} for analog continuous tuning. The other units are used for discrete tuning, connected either to the power supply or to ground. The size of these varactor units is changeable. As the sensitivity is relatively high at high frequency, a minority of analog varactor units are connected to the analog control voltage, and others are connected to the power supply or ground to get minimum fixed capacitance at the higher frequency band. In contrast, at the lower frequency band a majority of varactor units are switched in. To obtain equal frequency bandwidth, the size of the varactor units used for discrete tuning is also changeable[5, 9].

3. Circuit implementation

Figure 1 shows a simplified view of the complete VCO circuit implementation. The VCO is roughly composed of an active core, a main inductor, a switchable discrete varactor array and a switchable analog varactor array.

The inductor value is chosen to be small (0.86 nH) and the quality value is optimized to be 13.43 at a frequency of 5 GHz. Discrete frequency tuning is realized by an array of 64 inversion MOS varactor units. The analog varactor units consist of 4 small units. A six bit word is applied to control these varactor units.

To ensure the bandwidth remains constant, 64 inversion MOS varactor units are designed with different sizes. All varactor units are connected to the power supply when the VCO works at the highest frequency. While the varactor units are switched in one by one, the whole capacitance in the tank becomes larger and larger to make the working frequency decrease. The same principle is applied to 4 analog varactor units. The analog varactor units are switched in one by one with the decrease of frequency to keep the tuning gain constantly small.

However, the parasitic capacitance should be considered as the varactor units are switched out of the tank. Then the capacitance in the tank can be written as

$$C_{tol,min} = C_P + (\alpha_1 + ... + \alpha_{64})C_{v,discrete} + (\delta_1 + ... + \delta_4)C_{v,continous}, \quad (6)$$

$$C_{tol,max} = C_P + (\beta_1 + ... + \beta_{64})C_{v,discrete} + (\gamma_1 + ... + \gamma_4)C_{v,continous}, \quad (7)$$

where the parameters α, δ, β, γ determine the value of 64 discrete varactor units and 4 analog varactor units when they are switched in and out of the tank, respectively.

The tail inductors and capacitors are added in Fig. 1. With the aid of this design, the second order harmonic waves caused by the oscillation are isolated from the voltage supply and the

Table 1. Comparison with previous work.

Reference	Frequency range (GHz)	Core power (mW)	Max K_{VCO} (MHz/V)	Phase noise (dBc/Hz)	Technology
[5]	3.14–5.2	9.2	N.A.	–114.6 @ 1 MHz	0.13 μm CMOS
[6]	3.23–4.57	11.2	42	–121 @ 1 MHz	0.25 μm BiCMOS
[7]	3.21–4.02	18	33	–127 @ 400 kHz	0.13 μm CMOS
This work	4.2–5.03	6	8–10	–120 @ 1 MHz	0.18 μm CMOS

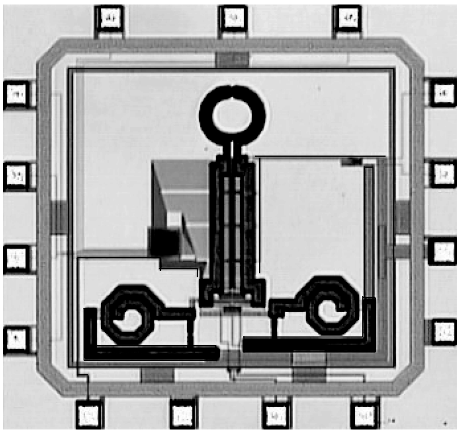

Fig. 2. Micrograph of the proposed VCO.

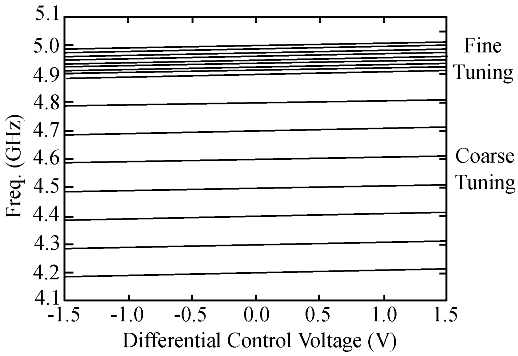

Fig. 3. Selected set of measured frequency responses.

ground. The phase noise performance of the VCO can be further improved[10].

4. Experimental results

The VCO is implemented in an SMIC 0.18 μm RF process. A micrograph of this proposed VCO is shown in Fig. 2. The complete circuit occupies 0.8 mm^2 (excluding bond pads).

In Fig. 3, a selected set of the measured frequency responses of the VCO is shown. The tuning range is from 4.2 to 5 GHz. The detailed fine tuning steps are also illustrated in the upper frequency range, where only one of the 4 small analog varactor units is controlled. Eventually the whole frequency band can be constructively covered with 64 coarsely discrete bands with constant bandwidth and the desired tuning gain is about 8–10 MHz/V.

The measured phase noise of the VCO at 5 GHz for offset frequencies ranging from 10 kHz to 1 MHz is illustrated in Fig. 4. As explained in Eq. (2), the phase noise deteriorates mostly at the highest frequency and indicates –120 dBc/Hz at

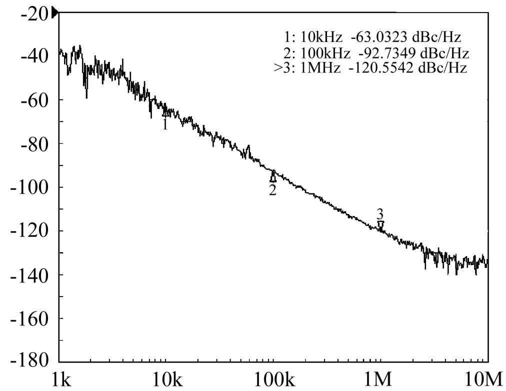

Fig. 4. Measured phase noise of the proposed VCO.

1 MHz. Beyond offset of about 3 MHz, the measurement is limited by the noise floor of the spectrum analyzer.

Table 1 compares the power consumption, the frequency range, the maximum tuning gain and the phase noise performance with previous work. The presented VCO achieves much smaller tuning gain than previous results. At the same time, the bandwidth remains constant across the whole output frequency range.

5. Conclusion

The proposed VCO is special for constant bandwidth, small tuning gain and low phase noise. To achieve these performance levels, a set of changeable analog varactor units are used and the same method is applied to the discrete varactor units. To further improve the phase noise performance, tail inductors and capacitors are added in order to isolate the second order harmonic waves from the voltage supply and the ground. Compared with previous work, the proposed VCO realizes very small tuning gain and constant bandwidth. The core consumes only 4 mA at 1.5 V, the tuning gain is about 8–10 MHz/V, and the phase noise is lower than –120 dBc/Hz at 1 MHz.

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