A 1.8 GHz CMOS VCO with reduced phase noise

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A 1.8 GHz CMOS VCO with Reduced Phase Noise

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Abstract

A 2 V, 6 mA, 15% tuning range, 1.8 GHz VCO implemented in a standard 0.35μm CMOS process is presented. The phase noise of the VCO has been greatly reduced by means of on-chip filters and one off-chip low frequency inductor. The phase noise measured at 3 MHz offset from the carrier is between −141.5 dBc/Hz and -138.5 dBc/Hz over the whole tuning range.

Introduction

The theoretical analysis and practical implementation of LC-tank CMOS voltage-controlled oscillators (VCO's) has recently made some important progresses. A closed expression for the phase noise of this kind of VCO's with nMOS-only switch transistors has been presented in [1] (under simplifying assumptions). This work has elucidated the mechanisms by which the noise from the different components in the VCO is converted into phase noise. Thus, it was recognized that the dominating contribution to phase noise is due to the tail transistor, whose noise at twice the frequency of oscillation is down-converted into phase noise by the switch transistors, while its low frequency noise (both white and 1/f) is up-converted into phase noise through the nonlinearities of the LC-tank, which transform amplitude noise into phase noise. The use of an on-chip LC filter has proven very effective to suppress the high frequency noise of the tail transistor [2], and an additional off-chip low frequency inductor removed all low frequency tail current noise as well [3], both white and 1/f, starting from frequencies below 100 kHz.

The present work applies the above ideas to the symmetrical implementation (i.e., with both nMOS and pMOS switches) of the LC-tank VCO, together with an additional on-chip inductive degeneration to suppress the noise from the pMOS switches. The combined filtering techniques dramatically improve the phase noise behavior of the VCO.

VCO design

The schematic of the VCO is shown in Fig. 1. It is the standard symmetric implementation of the LC-tank VCO, with the addition of: 1) inductor L_{lf} between the tail transistor and ground; 2) low pass L_{flt}-C_{flt} filter between the tail transistor and the nMOS switches; 3) inductors L_{top} between each pMOS switch and the power supply. The VCO is tuned by accumulation-mode MOS varactors combining low losses and wide tuning range. Dimensions and values for all components are given in Table I.

The off-chip inductor L_{lf} degenerates the tail transistor M_{src}, eliminating its low frequency noise (both white and 1/f) for frequencies above $\omega_l = (g_m L_{lf})^{-1}$ (where g_m is the transconductance of M_{src}) and below (roughly) the self-resonance frequency of L_{lf} [3]. It is worth noting that the 1/f noise of M_{src} could in principle be reduced at pleasure by making M_{src} very large; its white noise, however, can be reduced only by reducing its g_m. For a constant tail current, this implies an increase of the transistor overdrive, and consequently an increase of the minimum drain-source voltage for which M_{src} still acts as a current source. The maximum voltage amplitude of the oscillations would then decrease, with a net increase of the phase noise as a result. The on-chip low pass filter L_{flt}-C_{flt} filters off the high frequency noise of M_{src} [2]. L_{flt} also has another function: to turn the common source of the nMOS switch pair (M_{na}, M_{nb}) into a high impedance node for high frequencies (it is already for low frequencies). This reduces the amount of noise from these transistors flowing into the tank. The same approach was followed to reduce the noise from the pMOS switch transistors (M_{pa}, M_{pb}), whose sources are usually directly connected to the power supply. Thus, the on-chip inductors L_{top} are designed to resonate at twice the frequency of oscillation in parallel with the parasitic capacitance at the source of each pMOS. Interestingly, a single inductor placed between the power supply and the common source node of both pMOS transistors results in an almost negligible phase noise reduction. It must be added that the mechanisms by which the noise in the switches is converted into phase noise are at the moment rather obscure.

The phase noise of the VCO was simulated with spectreRF and the MOS model bsim3v.3. The noise factor γ for the transistors was about 0.75, possibly too optimistic a value. The overall phase noise reduction at 3 MHz offset from the carrier yielded by the filtering techniques discussed above was approximately 3.5 dB at carrier frequencies close to the middle of the tuning range, 4.5 dB at lower carrier frequencies, and no less than 7 dB at the highest carrier frequency. On average, the largest reduction was due to the external inductor L_{lf}, which reduced the phase noise by as much as 5 dB at high carrier frequencies (the smallest reduction due to L_{lf} was about 1 dB). The L_{flt}-C_{flt} filter and the L_{top} inductors contributed 1 to 2 dB and 0.5 to 1.5 dB phase noise reduction, respectively, again depending on the carrier frequency. At lower offset frequencies the effect of L_{lf} was even more dominating, as the 1/f noise of M_{src} becomes increasingly important. Finally, at all offset frequencies of interest the LC-tank losses are responsible for roughly 65% of the phase noise, while the white noise in the switches generates approximately 30%. The 1/f noise of all transistors is negligible, contributing no more than 2% (the pMOS switches being responsible) at 100 kHz offset.

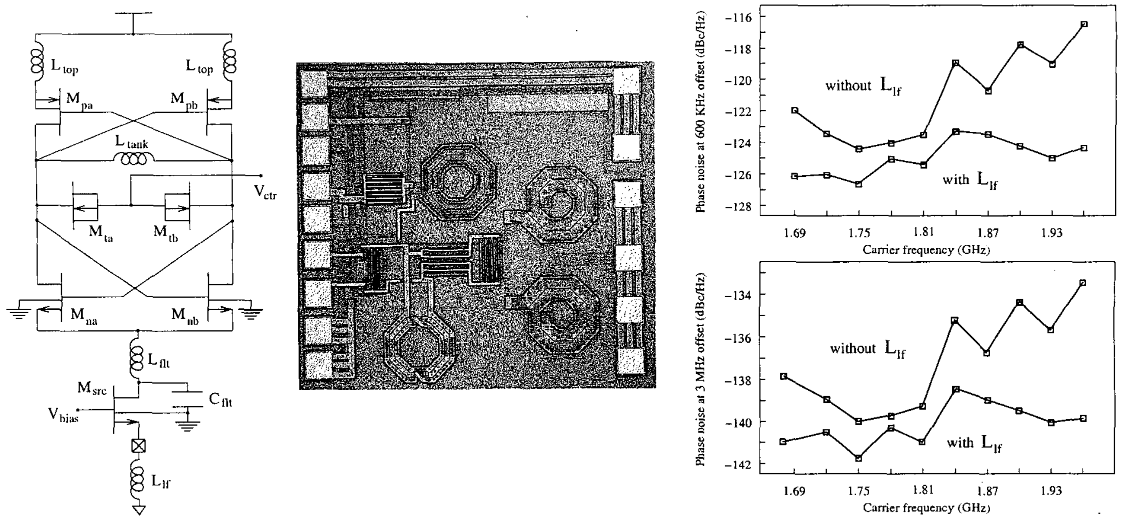

Fig. 1. Left: Schematic view of the VCO. Center: Die photograph of the VCO (VCO size: 1100μm $\times$ 850μm). Right: Measured phase noise of the VCO at 600 kHz (top) and 3 MHz offset frequency from the carrier.

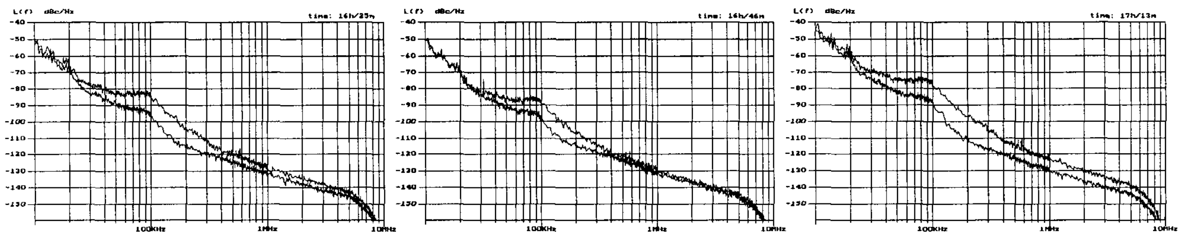

Fig. 2. Phase noise of the VCO at 1.69 GHz (left), 1.81 GHz (center), and 1.96 GHz carrier frequency, with $L_{lf} = 0$ (higher phase noise) and $L_{lf} = 100\mu$H.

Table I. Dimensions and values of the on-chip VCO components.

Transistors (W×L in μm)		Reactors	
M_{src}	2000×1.0	L_{tank}	≈ 2.3 nH
M_{na}, M_{nb}	300×0.35	Q_{tank}	≈ 8 at 1.8 GHz
M_{pa}, M_{pb}	800×0.35	L_{flt}, C_{flt}	≈ 3.0 nH, 10 pF
M_{ta}, M_{tb}	1600×0.35	L_{top}	≈ 0.7 nH

Measurement results

The VCO was fabricated in a 0.35μm CMOS process with three metal layers, a substrate resistivity of $5\,\Omega$·cm, and no special RF features. A die photograph of the VCO is shown in Fig. 1. All measurements presented here were taken with a 2.0 V supply voltage and a 6 mA supply current. The frequency of oscillation could be tuned from 1.69 GHz to 1.96 GHz, for a tuning range of about 15%. The phase noise of the VCO was measured at ten different carrier frequencies with 30 MHz intervals. Each measurement was performed both with and without the off-chip $100\,\mu$H inductor L_{lf}, to show in a robust way the phase noise reduction due to the inductive degeneration of M_{src}. It must be remarked that measurements and simulations match very closely, particularly when the phase noise difference between two different VCO implementations is considered. Fig. 1 shows the phase noise displayed by the VCO at two different offset frequencies, 600 kHz and 3 MHz, as a function of the carrier frequency. It is evident that L_{lf} has a dramatic influence on the phase noise, which is both (much) lower and much less dependent on the carrier frequency when L_{lf} is present. The combined filtering techniques secure a phase noise below -123 dB at 600 kHz offset, and below -138 dB at 3 MHz offset, fulfilling the specifications for GSM-1800. The phase noise versus the offset frequency at three different carrier frequencies is shown in Fig. 2, again both with and without L_{lf}. The beneficial effect of L_{lf} is particularly clear at the extreme carrier frequencies, as well as at lower offset frequencies (the phase noise peaking at 100 kHz offset, the steep slope below 100 kHz offset, and the roll-off at 5 MHz offset are artifacts of the measurement system).

Concluding, it has been shown that a symmetric LC-tank VCO with mediocre phase noise behavior can be turned into a high performance VCO by the application of suitable noise filtering techniques.

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