Wide tuning range CMOS Colpitts VCO based on tunable active inductor

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ABSTRACT:
In this paper, a new differential Colpitts voltage-controlled oscillator (VCO) is presented. The VCO is based on the gm-boosted structure to relax the oscillation start-up current requirement and reduce the DC power consumption in comparison to conventional Colpitts structures. In the proposed VCO, a tunable active inductor is utilized as a part of LC tank instead of passive inductor with constant inductance. The proposed VCO is designed and simulated in ADS in a 0.18μm CMOS process. Simulation results indicate that the proposed VCO has a wide tuning range in comparison to other reported designs while consumes less DC power.

KEYWORDS: CMOS, Colpitts, Tunable Active Inductor, voltage-controlled oscillator (VCO), Wide Tuning Range.

1. INTRODUCTION

Frequency of the voltage-controlled oscillators (VCOs) based on LC tank is tuned by changing the capacitance of the tank; because in a fully integrated architecture, changing the inductance value is not possible. Tunable capacitors are based on pn-junction varactors or accumulation-mode MOS varactors in which the value of capacitance is changed by tuning the DC bias of the varactor. However, the VCOs based on this kind of tuning system suffer from limited tuning range between 10%-30% [1], [2]. Using a tunable active inductor instead of passive one is a suitable choice to enhance the tuning range of the VCO.

Today, tunable active inductors have attracted great attention in designing filters, phase shifters, VCOs, and injection-locked frequency dividers (ILFDs) [3]-[5]. At low gigahertz, passive inductors occupy large chip area and increase the cost. So, using the active inductor helps to achieve lower cost and wide tuning range chip. Although, the active inductor-based VCO has a wide tuning range, it has higher phase noise in comparison to its passive inductor-based one. But, due to the fact that this kind of VCO is the core of the wide locking range ILFD, designing an active inductor-based VCO should be taken into consideration [6], [7].

This paper presents the design procedure of a new differential Colpitts VCO based on active inductor. Simulation results indicate that the proposed VCO has a wide tuning range and high output power in comparison to other reported designs while consumes less DC power. The proposed architecture is capable to be used as the core of the wide locking range ILFDs.

2. CIRCUIT DESIGN

2.1. Active Inductor

The block diagram of the active inductor based on the gyrator-C theorem is shown in Fig. 1(a). Two transconductors connected in back-to-back, form a gyrator. The transconductor in the forward path has a negative transconductance and the one in the feedback path has a positive transconductance. By replacing the common-source and common-drain architectures for the transconductors, the circuit level realization of the active inductor can be achieved as shown in Fig. 1(b) [8]. Mn and Mp act as current sources for biasing the circuit. But, this active inductor suffers from fixed low inductance, low quality factor, and limited tuning range. To enhance the performance of the circuit, an active tunable resistor ($R_f^{\prime}$) can be used at the gate of M2. This resistor consists of the parallel connection of a NMOS transistor MR and a passive resistor (R_f) which its resistance is usually large (Fig. 2(a)) [9]. The resistance of the active tunable resistor can be controlled by changing the gate-source voltage of the parallel transistor. The tuning capability of the active resistor versus control voltage V_{tune} in 0.18μm CMOS process is shown in Fig. 2(b).

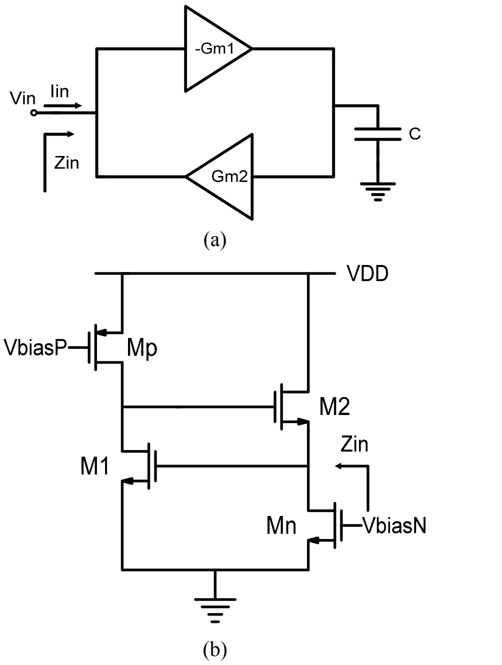

Fig. 1. (a) Block diagram, (b) circuit level realization

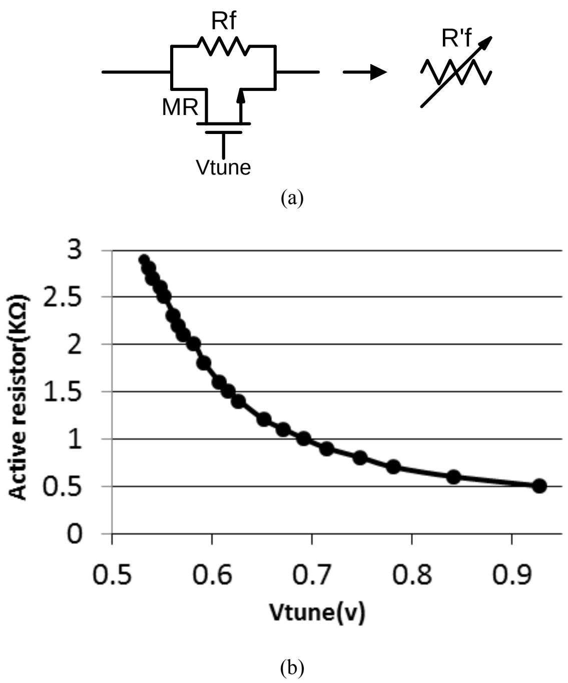

Fig. 2. (a) Active resistor structure, (b) tuning capability of the active resistor versus control voltage

As it is obvious from Fig. 2, the resistance will be decreased when V_{tune} is increased.

For deep consideration of how the active inductor works, the complete schematic of the inductor and its equivalent circuits are shown in Fig. 3 [10]. As it can be seen, the active inductor of Fig. 3(a) can be modeled as a RLC network of Fig. 3(b) and its small signal model is shown in Fig. 3(c) where g_{dsp} and g_{dsn} are output conductance of transistors Mp and Mn, respectively, g_{m1} and g_{m2} are transconductance of the gyrator main transistors M1 and M2, and C_{gs1} and C_{gs2} are their gate-source capacitance.

The relations of equivalent RLC model are as below [10]:

$$R_{eq} = \frac{g_{dsp}}{(g_{m1}g_{m2} + g_{m2}g_{dsp} + g_{dsn}g_{dsp})} \quad (1)$$

$$L_{eq} = \frac{C_{gs2}(1 + R'_f g_{dsp})}{(g_{m1}g_{m2} + g_{m2}g_{dsp} + g_{dsn}g_{dsp})} \quad (2)$$

$$C_{eq} = \frac{C_{gs2}[g_{m1} + g_{dsp} + g_{dsn}(1 + R'_f g_{dsp})] + C_{gs1}g_{dsp}}{(g_{m1}g_{m2} + g_{m2}g_{dsp} + g_{dsn}g_{dsp})R_{eq}} \quad (3)$$

According to (2), when the control voltage V_{tune} is increased which is equivalent to decreasing the tunable resistor R'_f, the equivalent inductance L_{eq} will be decreased. So, this issue is suitable for designing a new VCO with tunable active inductor.

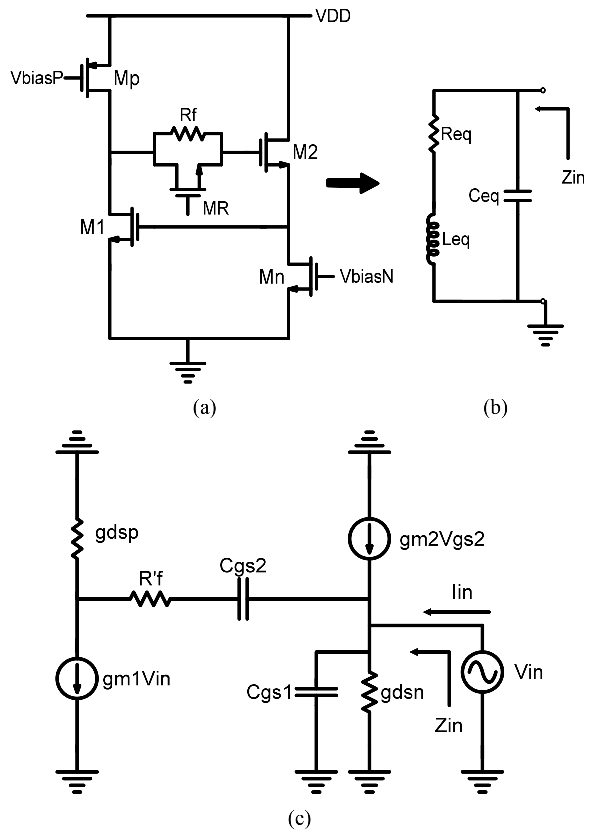

Fig. 3. Tunable active inductor, (a) circuit level, (b) equivalent RLC model, (c) small signal model

2.2. Voltage-controlled Oscillator

The proposed VCO based on the tunable active inductor is shown in Fig. 4. In this circuit, transistors M1-M6 in conjunction with active resistors form a differential tunable active inductor to realize a fully differential VCO. The oscillation frequency of the VCO depends on the equivalent inductance of the active inductor, capacitors C1-C5, and parasitic capacitance of transistors M7-M10. The frequency can be tuned by changing the control voltage V_{tune}. When V_{tune} is increased, the inductance of the LC tank will be decreased and hence the oscillation frequency will be increased.

The frequency tuning range of the VCO is as bellow:

$$Tuning\ Range = \frac{f_{max} - f_{min}}{(\frac{f_{max} + f_{min}}{2})}\% \qquad (4)$$

where f_{max} and f_{min} are maximum and minimum oscillation frequency of the VCO.

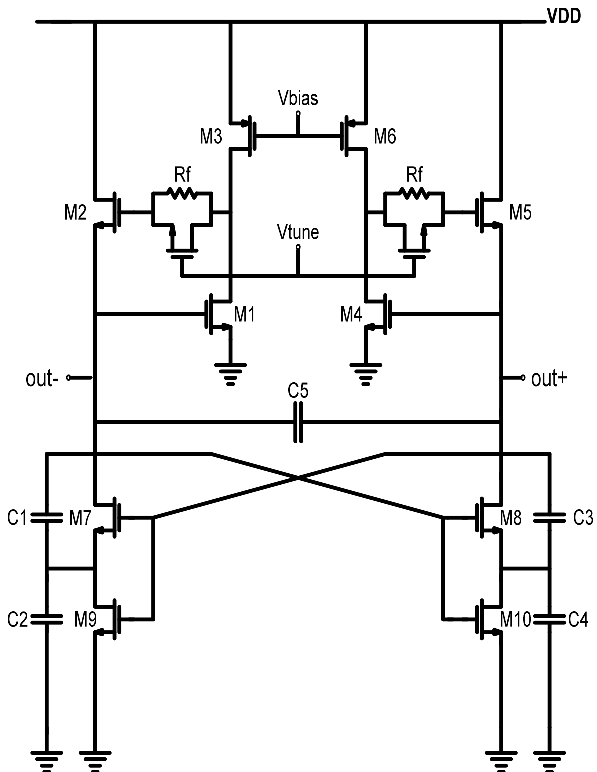

Fig. 4. The proposed VCO

The core of the VCO is based on a differential Colpitts architecture which consists of the transistors M7-M10 and capacitors C1-C5. This structure not only generates the differential output signals and negative resistance, but also acts as the current source Mn for biasing the gyrator main transistors, as shown in Fig. 3(a). Since the start-up conditions for conventional Colpitts VCOs are more difficult than the cross-coupled architectures, the proposed VCO is based on the gm-boosted structure, which is realized by cross-coupled connections between the gate terminal of M7 (M8) to the drain terminal of M8 (M7), to relax the oscillation start-up current requirement and reduce the DC power consumption in comparison to conventional Colpitts structures [11]. The proposed VCO is designed in a self-bias mode and the transistors M9 and M10 act as bias sources where their gate terminal is connected to the output port to reduce the needed bias voltage.

The transconductance of the designed VCO is increased by the factor of $(1+\frac{C_2}{C_1})$ in comparison to conventional one, therefore these capacitors should be chosen carefully.

3. SIMULATION AND DISCUSSION

The proposed Colpitts VCO is simulated in a 0.18μm CMOS process. Supply voltage of circuit is 1.8V.

The output waveforms of the VCO at $V_{tune} = 0.617V$ and 1.5GHz frequency is shown in Fig. 5. Fig. 6 shows the oscillation frequency of the VCO for different values of V_{tune} from 0.53V to 0.93V. As it can be seen, the output frequency of the VCO has a range of 3250MHz which corresponds to 149% tuning range from 550MHz to 3.8GHz. The output power of the VCO versus V_{tune} is shown in Fig. 7, which is from +3dBm to -11dBm.

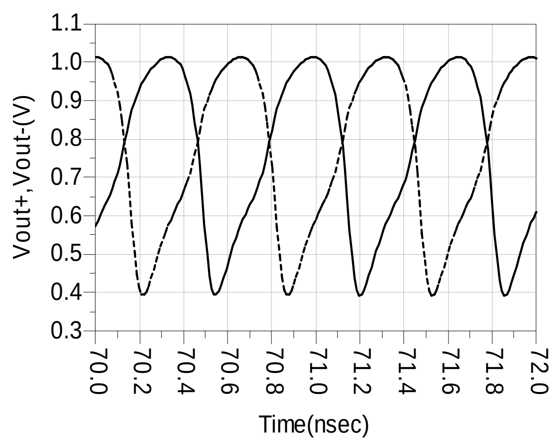

Fig. 5. Output waveforms of the VCO at 1.5GHz

Fig. 8 shows the phase noise of the proposed VCO at 1.1GHz frequency for $V_{tune} = 0.572V$. The output power spectrum of the VCO at $V_{tune} = 0.762V$ is shown in Fig. 9.

A brief summary of the specifications of the proposed VCO is provided in Table I.

Table II provides a comparison of the proposed VCO and recently works [12]-[14]. As it can be seen, the proposed VCO has much wider tuning range of 149% and higher output power in comparison to other designs while it dessipates less DC power. Also, its phase noise is comparable with some works.

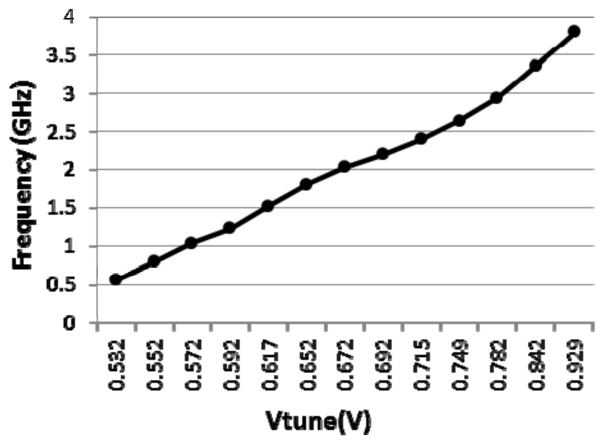

Fig. 6. Oscillation frequency of the VCO versus V_{tune}

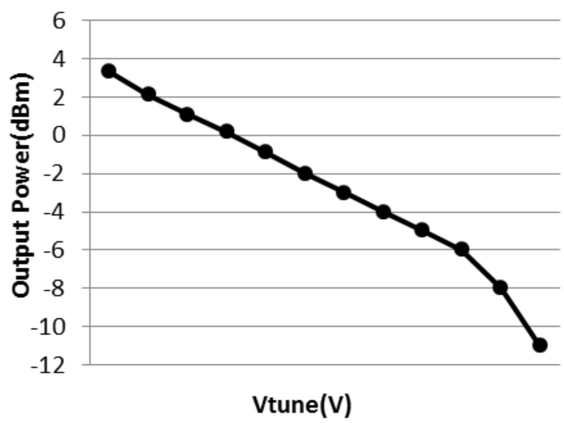

Fig. 7. Output power of the VCO versus V_{tune}

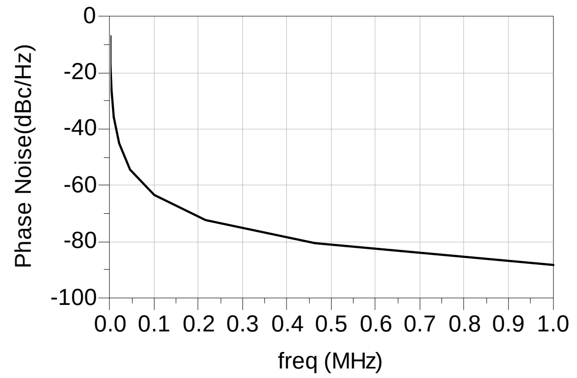

Fig. 8. Phase noise of the VCO at 1.1GHz for $V_{tune} = 0.572V$

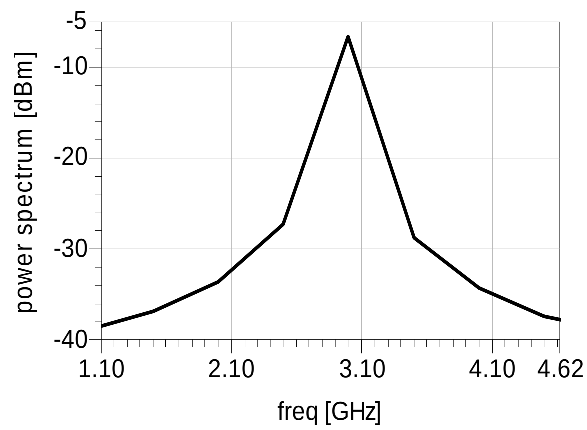

Fig. 9. Output power spectrum of the VCO at $V_{tune} = 0.782V$

Table I. Brief summay of the specifications

Supply Voltage	1.8V
DC Power	11.9mW
Control Voltage (V_{tune})	0.532-0.929 V
Freq. Tuning Range	0.55-3.8 GHz
Output Power	+3 ~ -11 dBm
Phase Noise @ 1MHz Offset	-89 dBc/Hz

Table II. Performance comparison of the proposed VCO and recently works

Parameter	Unit	This Work	[12]	[13]	[14]
Technology	µm-CMOS	0.18	0.18	0.18	0.18
Supply Voltage	V	1.8	1.8	1.8	1.8
Tuning Range	GHz	0.55-3.8	0.5-3	0.5-2	0.4-1.6
	%	149	143	120	120
Power Dissipation	mW	11.9	6-28	13.8	26
Output Power	dBm	+3 ~ -11	-14 ~ -22	-21 ~ -29	N.A.
Phase Noise @ 1MHz Offset	dBc/Hz	-78 ~ -89	-101 ~ -118	-78 ~ -90	-88 ~ -95
Wide Tuning Range Technique	-	Active Inductor	Active Inductor	Active Inductor	Ring Oscillator

4. CONCLUSION

A new wide tuning range Colpitts VCO in 0.18µm CMOS process is introduced in this paper. In order to achieve a wide tuning range and small die area, in this structure, a tunable active inductor is used as a part of LC tank. Simulation results indicate that the proposed VCO has a wide tuning range of 149% and is a good choice for design wide locking rang ILFDs.

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