A CMOS Fully Integrated 1 GHz and 2 GHz Dual Band VCO with a Voltage Controlled Inductor

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Abstract

A fully integrated voltage controlled oscillator with a wide tuning range from 978 MHz to 2010 MHz is presented. The LC-VCO was designed in INFINEON low-cost 0.25 μm 4 metal standard CMOS process, using an integrated fully symmetrical coil. The frequency of the presented LC-VCO is both capacitance- and inductance-controlled. A novel voltage controlled fully differential inductor is introduced. Testchip results using the inductance tuning to implement a dual band VCO are presented. At 1GHz the VCO consumes 7.5 mA from a 1.5 V supply voltage and features a measured phasenoise of -138 dBc/Hz at 3 MHz offset. At 2 GHz 9 mA from a 1.5 V supply is consumed and the VCO features a measured phasenoise of -132 dBc/Hz at 3 MHz offset.

1. Introduction

Fully integrated voltage controlled oscillators (VCO) are widely used in wire based and wireless telecommunication systems for the implementation of clock-circuitry and frequency synthesizers. An LC-VCO implementation is normally preferred over ring-oscillator circuits for its better phasenoise/jitter performance at a much lower power consumption. The main disadvantage of an LC-VCO is the limited tuning range. Solutions to extend the tuning range based on switched capacitor banks [1] or switching VCO-inductors [2] have been presented.
The capacitor switching solution suffers from the large switches needed for the Q of the coil. It furthermore decreases the tank-inductance for a specified center frequency leading to higher power consumption and phasenoise as described in [3] and shown in [4, 5].
Switching the inductors is severely limited by the switches. If the switches are designed for minimal series resistance in order not to deteriorate the Q of the tank, huge capacitances are introduced at the RF-nodes of the oscillator, leading again to higher power consumption and phasenoise.
More generally, the systematic low power low phasenoise design approach of [3] maximizes the tank inductance and minimizes the varactor size to the limit given by the tuning range specification. This design tradeoff problem between low power and tuning range obviously vanishes completely, if the varactor could be omitted and the VCO could be frequency controlled over its inductor.

2. A fully differential voltage controlled inductor

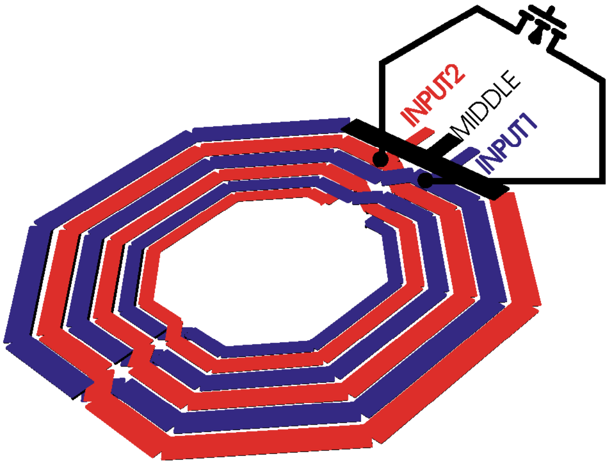

Figure 1. Differential voltage controlled coil layout

The proposed voltage controlled inductor is based on the special coil layout already used and discussed in [4]. The layout of the staggered winding width coil is shown in Fig. 1. As the RF-nodes are put at the inside of the coil, the outer winding of the coil is at common mode in differential mode and its winding width can be increased to reduce its series resistance without any disadvantage of the increased capacitance into substrate. The influence of any additional capacitance connected to the other windings is proportional to the respective differential voltage. The differential voltage across a winding is proportional to the inductance and varies quadratically with the winding number from the inside to the outside of the layout. Thus the largest differential RF voltage swing is found at the inner windings of the coil and only a minor voltage swing occurs at the outer windings. The proposed inductor exploits this effect and adds a large MOS-switch between the outer windings of the coil. The rather large parasitic capacitances from the MOS device only marginally affect the self-resonance of the coil as they are placed at nodes with a small voltage swing. Also the series resistance of the coil is not deteriorated as the MOS-switch can be made very wide. If the MOS switch is off, the proposed inductor has an inductance and self-resonance similar to the the layout without the MOS switch. If the MOS switch is on, the proposed structure is reduced to a smaller inductor consisting of the inner windings, with a smaller inductance. The differential selfresonance is clearly increased, as the not-used windings are at common-mode and the resulting smaller coil layout has less winding to winding and winding to substrate capacitance. If the MOS transistor is used as variable resistance, the effective inductance of the structure can be tuned continuously over its gate voltage. A simplified lumped model for this differential voltage controlled inductor is presented in Fig. 2. As a fully

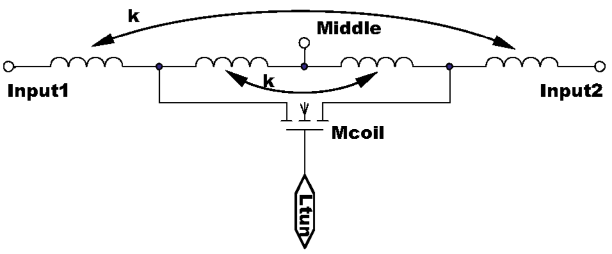

Figure 2. Differential voltage controlled coil lumped model

integrated VCO is very sensitive to coil series resistance and self-resonance, the proposed tunable coil was implemented in a VCO to demonstrate its feasibility and usability. Of course, this structure is not only useful for dual band VCO-applications, but it can also be very usefull to switch the gain of inductively loaded LNA's or mixers.

3. VCO-design

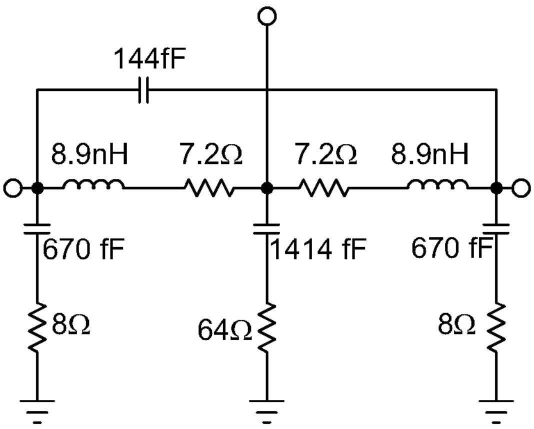

Figure 3. Extracted coil lumped model, $Mcoil$ omitted

The VCO-design is based on the design described in detail in [4]. Only the coil was replaced. Three more staggered windings were added to its six windings coil layout, resulting in an inductance of 17.8 nH. Metal 2,3 and 4 were put in parallel for a total thickness of $1.7\mu m$ Al to reduce the series resistance. Total metal thickness in [2] is $4\mu m$. The nine windings coil, without the inductor controlling transistor, was separately characterized using s-parameter structures, the resulting lumped model is presented in Fig. 3. Differential self resonance frequency is 1.7 GHz, differential bandwidth Q is about 7 in the 1 GHz VCO frequency range.

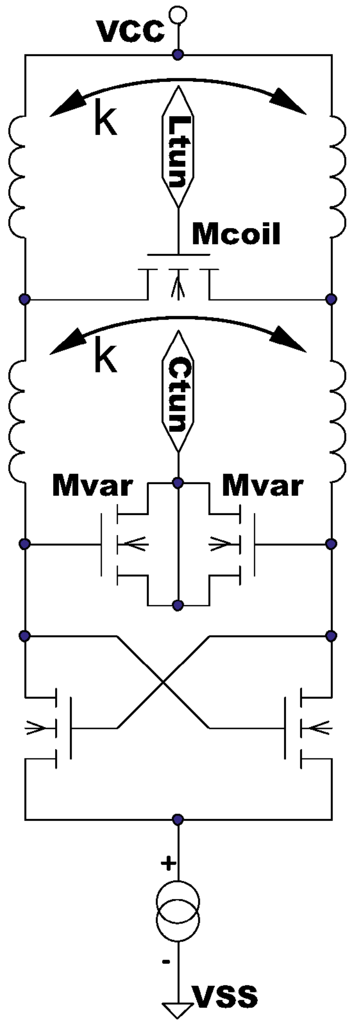

Figure 4. VCO schematic, MOS-bulks are connected to vss.

Fig. 4 presents the VCO schematic. The VCO has two frequency control inputs. One input, $Ctun$, tunes the NMOS varactor and provides classical capacitive tuning. the second input, $Ltun$, tunes the inductance through the MOS-transistor $MCoil$. This very large NMOS transistor is clearly visible in the chip photograph Fig. 5. The odd winding count of the coil is optimal for the floorplan of the layout as the big transistor Mcoil is situated automatically at the opposite side of the RF-nodes. A 50 Ω output buffer completes the design.

4. Measurements

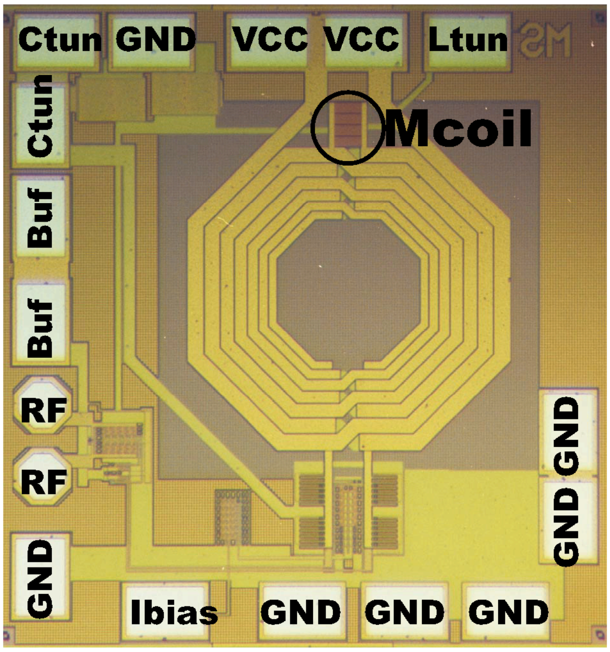

Figure 5. Chipfoto of VCO.

The chipfoto is shown in Fig. 5, die size is 850 μm by 850 μm, coil size is 500 μm by 500 μm.
The capacitive dual band tuning-characteristic of the VCO is presented in Fig. 6, setting the the coil tuning $Ltun$ at minimum and maximum value. This curves represent a typical dual band application. The inductive tuning-characteristic of the VCO is presented in Fig. 7, setting the varactor tuning $Ctun$ at minimum and maximum value. The steep frequency response in this mode limits severely the usability of this continuous inductance tuning.
The upper VCO frequency range of ca. 2 GHz of the VCO clearly exceeds the 1.7 GHz self-resonance of the separately measured nine windings coil from Fig. 3 without the inductance tuning. This clearly demonstrates the inductance decrease and self-resonance increase as discussed in section 2.

Phasenoise is measured with EUROPTEST PN9000 equipment at the respective minimal and maximal frequencies of the capacitive and inductive tuning ranges (Fig. 8, 9, 10, 11), corresponding to the typical frequency ranges in a dual band application. The phasenoise performance of the coil-tunable VCO is very comparable to the design [4]. This clearly shows that the coil tuning not deteriorates the Q of the tank. The VCO-measurements are summarized in Table 5. The widely used VCO figure of merit (definition e.g. in [3]) of -178 dBc/Hz is very state of the art, especially considering the standard CMOS process with thin metals and low-resistivity substrate used for this design.

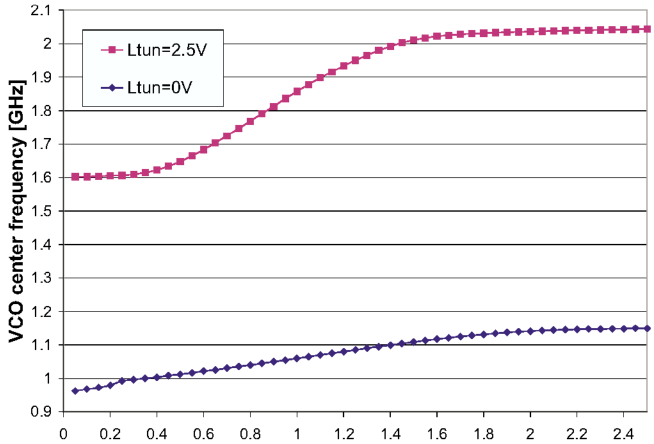

Figure 6. VCO varactor tuning.

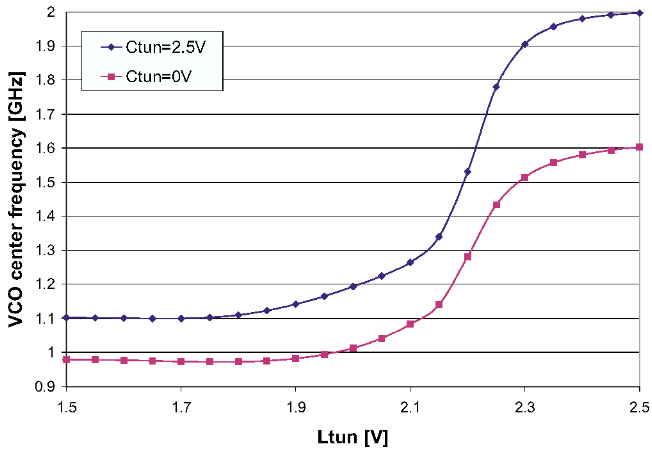

Figure 7. VCO inductor tuning.

5. Summary

A novel fully integrated voltage controlled inductor is introduced. The proposed structure is used to implement a fully integrated dual band voltage controlled oscillator with a wide tuning range from 978 MHz to 2010 MHz. A testchip was produced in low-cost 0.25 μm 4 metal standard CMOS process. At 1 GHz center frequency the VCO features a phasenoise of -138 dBc/Hz at 3 MHz offset, at 2 GHz a phasenoise of -132 dBc/Hz at 3 MHz offset. The frequency tuning above 2GHz exceeds the self-resonance of the same inductor layout without tunability by 300 MHz. The phasenoise and frequency tuning measurements clearly demonstrate that Q and self-resonance of voltage controlled inductor is not affected by its tunability.

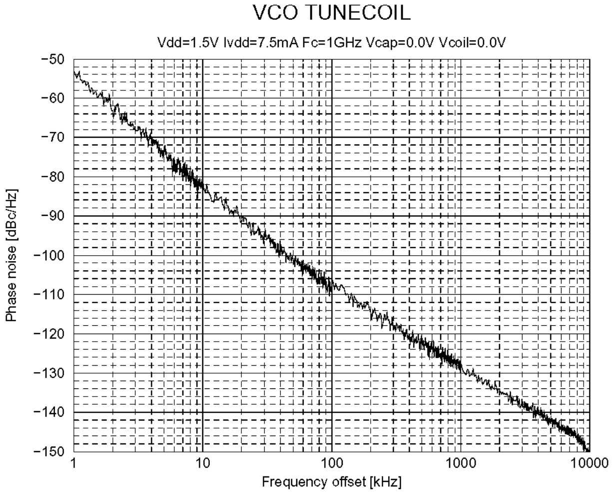

Figure 8. Measured phasenoise at 1.5V power supply, 7.5mA core current, frequency=1GHz.

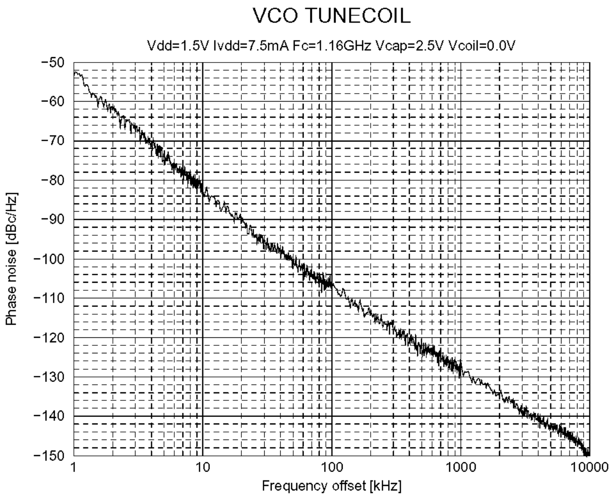

Figure 9. Measured phasenoise at 1.5V power supply, 7.5mA core current, frequency=1.16GHz.

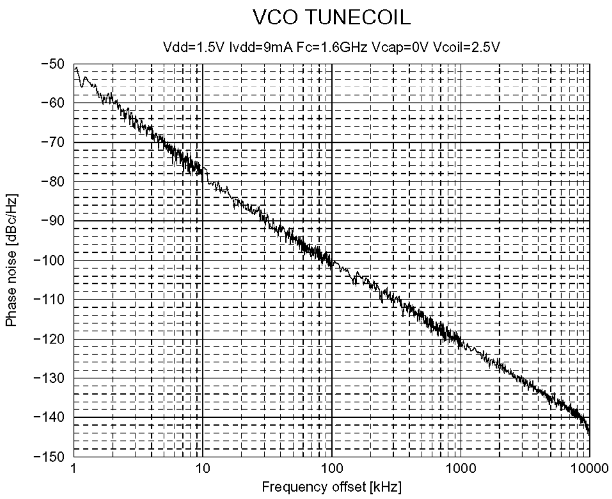

Figure 10. Measured phasenoise at 1.5V power supply, 9mA core current, frequency=1.6GHz.

Table 1. Measurement summary

	Low range	High range
Freq [MHz]	978-1160	1600-2010
Phasenoise [dBc/Hz] @3MHz offset	-138	-132
FOM [dBc/Hz]	-178 (1GHz)	-177 (2GHz)
Supply [V]	1.5	1.5
Current [mA]	7.5	9

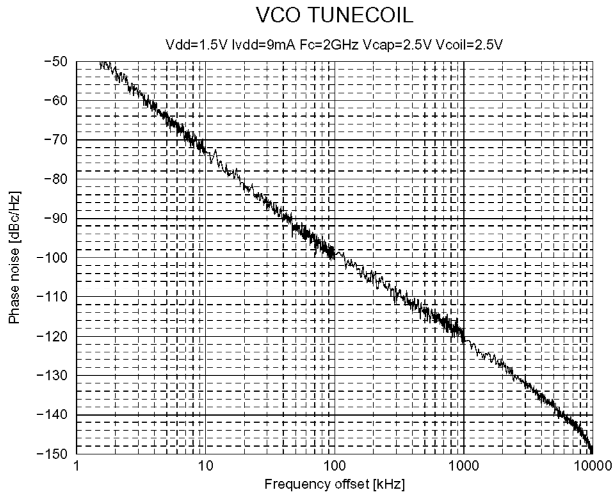

Figure 11. Measured phasenoise at 1.5V power supply, 9mA core current, frequency=2GHz.

6. References

[1] A. Kral, F. Behbahani and A.A. Abidi, "RF-CMOS oscillators with switched tuning," in *Proc. of the Custom Integrated circuits conference*, May 1998, pp. 555–558.

[2] S. Yim, K.K. O, "Demonstration of a switched resonator concept in a dual-band monolithic CMOS LC-tuned VCO," in *Proc. of the Custom Integrated circuits conference*, May 2001, pp. 205–208.

[3] M. Tiebout, "Low power, low phasenoise, differentially tuned quadrature VCO-Design in standard CMOS," *IEEE J. Solid-State Circuits*, vol. 36, July 2001.

[4] M. Tiebout, "A Fully Integrated $1.3GHz$ VCO for GSM in $0.25\mu m$ Standard CMOS with a Phasenoise of $-142dBc/Hz$ at $3MHz$ Offset," in *Proc. of the 30th European Microwave Conference*, Paris, Oct 2000, EUMW'00.

[5] M. Tiebout, H.-D. Wohlmuth and W. Simbuerger, "A 1V 51GHz Full-Integrated VCO in $0.12\mu m$ CMOS," in *ISSCC98 Digest of Technical Papers*. 2002 IEEE International Solid-State Circuits Conference, February 200, pp. 300–301.