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CMOS Circular Geometry VCOs for Microwave Magnetic Field Generation

Tolga Yalcin[1,2], Volkan Sahin[3], Giovanni Boero[1] and Radivoje S. Popovic[1]

[1]Ecole Polytechnique Federale de Lausanne, IMM-LMIS3, CH-1015, Lausanne, Switzerland
[2]Fachhochschule Zentralschweiz, School of Engineering+Architecture, CH-6048, Horw, Switzerland
[3]Decicon Inc., San Jose, CA 95112, U.S.A.

Abstract — **In this paper, we present 6 and 8 GHz CMOS VCOs capable of equi-phase microwave magnetic field generation for magnetic sensor applications. The VCOs are implemented in a balance-scale shaped circular-geometry structure, and prototyped using a standard 0.35 µm CMOS technology. Both VCOs can generate magnetic fields of up to 1 mT within an on-chip 300 µm diameter coil. Simulated phase noise is better than -120 dBc at 1 MHz. Measured frequency tuning ranges are 1.1 and 0.6 GHz for the 6 and 8 GHz VCOs, respectively.**

Index Terms — **CMOS, VCO, magnetic field generation, magnetic sensors.**

I. Introduction

Magnetic sensor applications require precise measurement of changes in a magnetic field, which can be either absolute or relative depending on the application, and for practical reasons can only be observed after conversion to a corresponding current or voltage [1], [2].

For relative field comparisons, two sensor measurements are taken from a reference and a sensing field. Initially, both fields are generated exactly in the same manner so that difference between two measurements is below minimum required sensor resolution. Introduction of a magnetic field disturbing quantity (sample under observation) affects the sensing field, resulting in a shift from its initial value. This shift is measured relative to the reference field which retains its initial value, or shifts in the opposite direction.

This approach is relatively simple and highly accurate for low frequency applications [3], where phase differences between reference and sensing fields can be tolerated to a certain degree. For radio frequency or microwave applications it is crucial to ensure equi-phase between the two fields. Any phase difference between them will result in an offset in the sensor measurement.

Another critical point is the field strength. Even micro-scale magnetic sensor applications require relatively strong magnetic fields (in the mT range) [3], [4]. This, together with equi-phase magnetic field generation requirement, makes it crucial to incorporate intelligent solutions for magnetic sensing applications in RF and microwave frequencies.

A basic magnetic sensor microsystem operating in high frequency is shown in Fig. 1, where excitation field is generated by a local oscillator, and amplified by a power amplifier driving an excitation coil or coils. Magnetic fields observed by the reference and sense detection coils are then converted to a current or voltage, and subtracted from each other. Depending on the operating frequency, subtracted signal is down-converted to an intermediate frequency and amplified again.

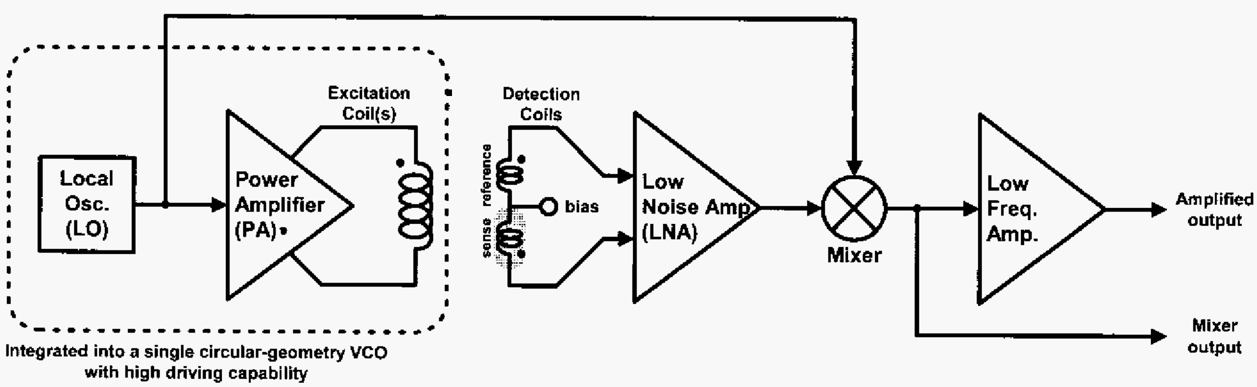

Fig. 1. Magnetic sensor microsystem block diagram.

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In his study, local oscillator, power amplifier, and excitation coils are integrated into a single balance-scale shaped circular-geometry oscillator, which provides a very suitable solution for equi-phase magnetic field generation in microwave frequencies. Rest of the sensor electronics is also implemented providing a means of observing VCO functionality in addition to sensing capability.

II. Balance-Scale Shaped Circular-Geometry VCO

From the very beginning of the design, we investigated ways of integrating the oscillation and power amplification stages, and excitation coils into a single block, in order to minimize the total area and number of inductors. This would make it possible to minimize total magnetic interaction on the chip, and maximize sensor precision.

The most straightforward solution was to use oscillator inductors as excitation coils. Geometrically it was possible to design inductors in such a way to hold any sample whose magnetic characteristics would be measured. For example, inductance of a 300 μm diameter octagonal coil is below 1 nH, resulting in a tank capacitor of 0.5-2 pF for frequency generation above 5 GHz.

The next problem to be solved was the equi-phase magnetic generation. For this purpose, circular-geometry oscillator structure was chosen [5]. Circular-geometry oscillators are similar to distributed amplifiers in operating principle [6]. Main idea is to implement as many identical oscillators as needed (two in our case), and connect them in a configuration where each oscillator shares half of an inductor with its neighbor oscillator. In other words, inductors are distributed among identical oscillator cores in a geometrically circular configuration.

Evolution of the balance-scale shaped circular-geometry VCO with two oscillator cores is illustrated in Fig. 2. We first start with two identical back-gate differential LC VCOs connected in parallel. In this case, even if the two oscillators are perfectly identical, equi-phase of RF currents on the oscillator inductors can not be guaranteed. Therefore one oscillator uses left inductor of its own and right inductor of its neighbor, while the other oscillator does the opposite geometrically.

Electrically, this corresponds to a larger RF current loop that covers both oscillators, instead of two separate RF current loops. This guarantees that an equi-phase RF current flows though the inductors of both oscillators regardless of process variation and/or layout mismatches. Equi-phase magnetic fields within both inductors are also obtained this way.

The final VCO layout has the shape of a balance-scale, as shown in Fig. 3 for the 8 GHz case. The large coils on

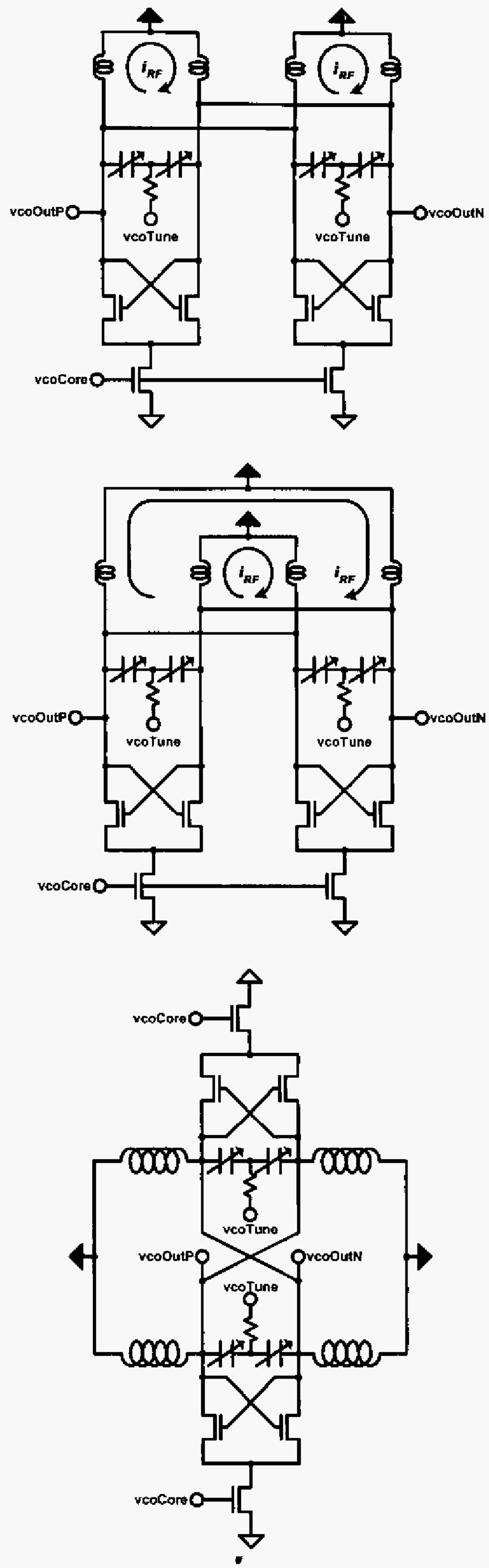

Fig. 2. Circular-geometry oscillator evolution: The initial two parallel-connected VCOs are finally arranged to form a balance-scale shaped circular-geometry VCO.

the left and right are the oscillator inductors, and are responsible of magnetic field generation. Two oscillator cores are located on the top and bottom of the layout. The top oscillator core uses the top halves of the left and right inductors, while the bottom oscillator core uses the bottom halves. Supply is connected from the mid-points of both inductors, which act as virtual grounds at high frequencies.

Sensor electronics is implemented in the middle area between the two oscillator cores. Smaller inductors inside the oscillator inductors act as pick-up (sensing) coils for the generated magnetic fields. The smallest inductors on the corners are the matching inductors required for the sensor electronics.

During the design, special care was paid to sense and matching inductors, in order to minimize their loading on the excitation coils. Quality factors of the excitation coils had to be kept at the maximum possible value, since they also act as the inductors of LC tanks. The matching inductors are also placed in a perfectly symmetric manner in order to ensure identical loading on both top and bottom halves of the oscillator inductors.

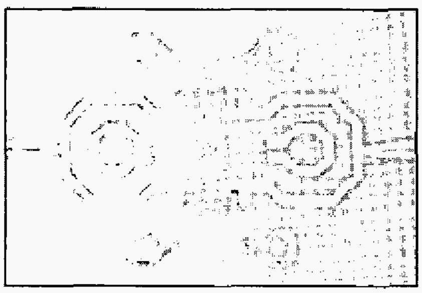

Fig. 3. Layout of the 8 GHz circular-geometry VCO.

The VCO inductors are implemented using the thick metal (2.5 μm) option available with the chosen CMOS process, and simulated using a 2.5-D electromagnetic field solver. A complex equivalent lumped-element network, which incorporates all the inductors, their coupling, and their parasitic capacitances and resistances, is formed, and values of lumped elements were tuned to match S-parameters obtained from the field solver.

The inductance values and quality factors are 0.67 nH and 0.50 nH, with quality factors above 12, for the 6 and 8 GHz VCO inductors, respectively.

Values of the varactors and hence the oscillation frequency of the VCOs are controlled via the vcoTune input. Generated magnetic field strength is directly proportional to the RF current on the inductors, and controlled by the vcoCore input. Measurements show that both VCOs are capable of generating linear magnetic fields up to 1 mT.

III. VCO Prototype

The 6 and 8 GHz CMOS circular-geometry VCOs were implemented using a 0.35 μm standard CMOS process with a thick metal option. Die photo of the prototype chip is given in Fig. 4. Area of the prototype chip is 8.3 mm^2 (2.6×3.2 mm). The upper and lower blocks are the 6 and 8 GHz VCOs, respectively.

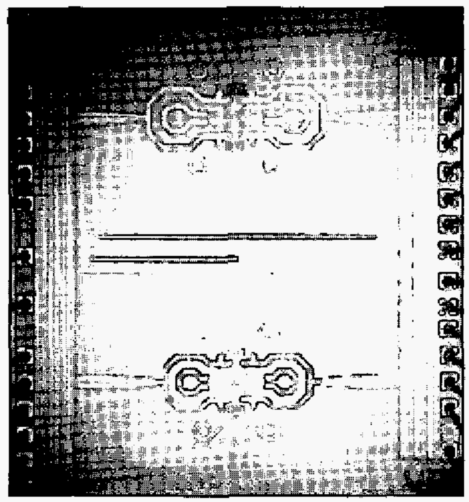

Fig. 4. Die photo of the prototype chip.

All the pins of the chip are low frequency I/O and supply/ground pins. There are no RF I/Os going in and out of the chip. Due to practical limitations, it was not possible to place any test pads on the chip. Instead, the sensor electronics shown in Fig. 1 was implemented.

For frequency measurements of the VCOs, a simple loop antenna is designed and microwave broadcast from the VCO coils are measured with this antenna. Frequency measurements were done for various magnetic field strengths. Results for 0.1 and 0.6 mT magnetic field strengths are shown in Fig. 5. Although voltage dependencies of oscillation frequencies are not linear, this is not a strict requirement for sensor applications. Instead, a wide frequency tuning range is preferable, which is clearly achieved with the implemented VCOs.

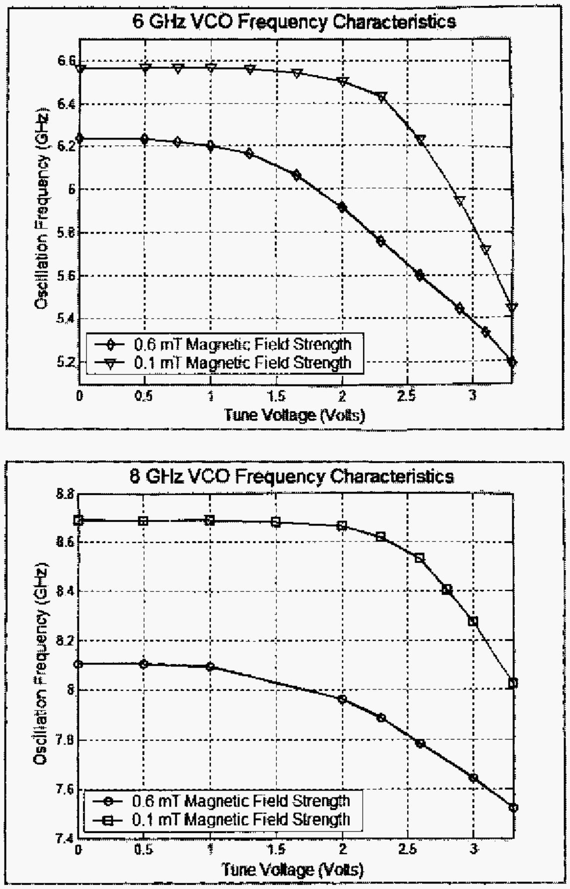

Fig. 5. Frequency characteristics for the 6 GHz (top) and 8 GHz (bottom) VCOs.

Lack of direct contact with oscillator outputs makes it impossible to measure the exact phase noise. But indirect measurement results obtained via sensor electronics show the phase noise to be lower than -100 dBc at 100 KHz.

In a similar manner, there is no easy way to measure the exact strengths of the generated magnetic fields. They were also measured indirectly, and proved to be proportional to the current drawn from the supply. The current drawn by each VCO is 30 mA and 85 mA for 0.1 mT and 0.6 mT magnetic field strengths, respectively, which is very close to the simulation results.

For the equi-phase verification, the down-converted mixer output was observed. It is supposed to be zero in case excitation coils on both sides of the VCO are loaded equally, in a similar manner to a balance-scale with no weights on both arms. This case is verified successfully. Then variations in the down-converted output were recorded for different magnetic samples placed into one side of the VCOs. Known characteristics of the magnetic samples were used to characterize the VCO behaviors.

IV. Conclusion

Two CMOS circular-geometry VCOs for magnetic field generation were designed and implemented using a standard CMOS process. Operation and frequency behavior of the VCOs have been successfully verified. It has been shown that CMOS circular-geometry VCOs present perfect solutions for magnetic sensor applications where radio frequency and microwave equi-phase magnetic field generation is required. They provide compact and reliable solutions, without need to separate field coils and amplification stages.

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