International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 2 Issue 8, August - 2013

Design and Implementation of CMOS Differential VCO using Back-Gate Transformer Feedback

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***Abstract*—For an effective communication among varioustransponders in a wireless communication system, the signals must be noiseless. The function of reducing the noise-levels in a transponder is carried out using a Voltage Controlled Oscillator (VCO). This project describes the designs of differential LC tank VCOs used conventionally viz., Front-Gate and Source-fed feedback circuits, along with their operational limitations. The in-built deficiencies of the existing VCOs hinder their ability to reduce the noise-levels significantly. The proposed Back-Gate feedback system, which is a combination of the conventional designs, has better operational characteristics. A circuit model has been developed and simulated using AWR Microwave Office software and the proposed hardware model has been given. From the results obtained, it can be concluded that the noise reduction in the proposed system is higher than in the conventional designs.**

***Keywords*—Voltage Controlled Oscillator (VCO),LC tank, Front-Gate, Source-fed, Back-Gate, AWR Microwave Office.**

I. INTRODUCTION

Oscillators are circuits that produce specific, periodic waveforms such as square, triangular, saw-tooth, and sinusoidal. They generally use some form of active device, lamp, or crystal, surrounded by passive devices such as resistors, capacitors, and inductors, to generate the output. Feedback oscillator circuits can be classified according to the type of frequency selective filter they use in the feedback loop as RC oscillators, LC oscillators and Crystal oscillators. In this paper, we use LC oscillators.

Any practical implementation of an LC circuit will always include loss resulting from small but non-zero resistance within the components and connecting wires. The purpose of an LC circuit is usually to oscillate with minimal damping, so the resistance is made as low as possible. While no practical circuit is without losses, it is nonetheless instructive to study this ideal form of the circuit to gain understanding and physical intuition. Most of the VCOs using LC oscillators were designed for an operating frequency of less than 8 GHz, due to design constraints in the conventional models. In this paper, a new transformer-based differential VCO is presented by utilizing a back-gate feedback operating at a frequency range of 11 GHz to 14 GHz.

II. TRANSFORMER FEEDBACK DIFFERENTIAL VCO

Figure 1 shows a CMOS differential VCO with transformer feedback to the front-gate of the MOSFET. The input current and voltage are given through a FPGA kit, which is used to produce the necessary frequency level. The drain voltage feeds back to the front-gate. Since the impedance seen at the gate of the switching transistor is relatively high, the turns-ratio of the transformer can be optimized with a smaller number of turns. However in this design, the parasitic capacitances of the transformer directly couple to the tank, and lower the oscillation frequency significantly. Thus, as the operational frequency increases, the use of front-fed model becomes insignificant due to the necessity of larger lumped circuit and the resulting losses.

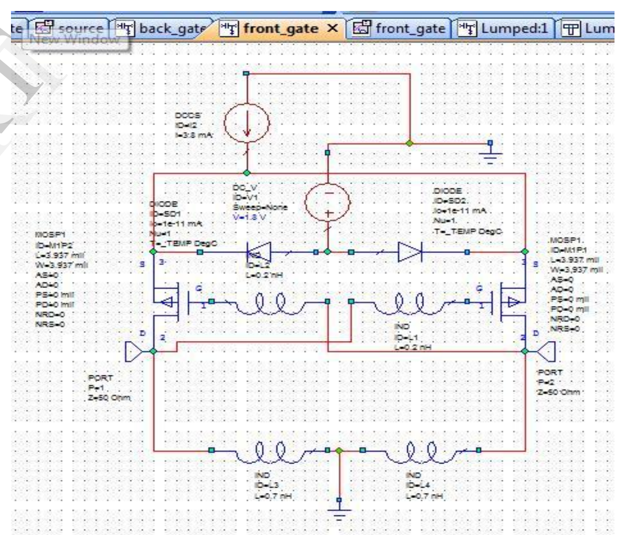

Figure 1 Differential VCO with transformer feedback to the Front Gate

Figure 2 shows a CMOS differential VCO with transformer feedback to the source. The drain voltage feeds back to the source terminal with an impedance transformation of n^2/g_m , where n is the number of turns of the primary winding and g_m is the trans-conductance of the switching transistor, M_{sw}. Since the impedance seen at the source terminal is $1/g_m$, a relatively high turns-ratio is required for the transformer to make an impedance transformation from the drain to the source, thereby entailing complexity in transformer design, making it possible to lower the oscillation frequency. So, due to mechanical design constraints, the source-fed model also cannot be used for high frequency operations.

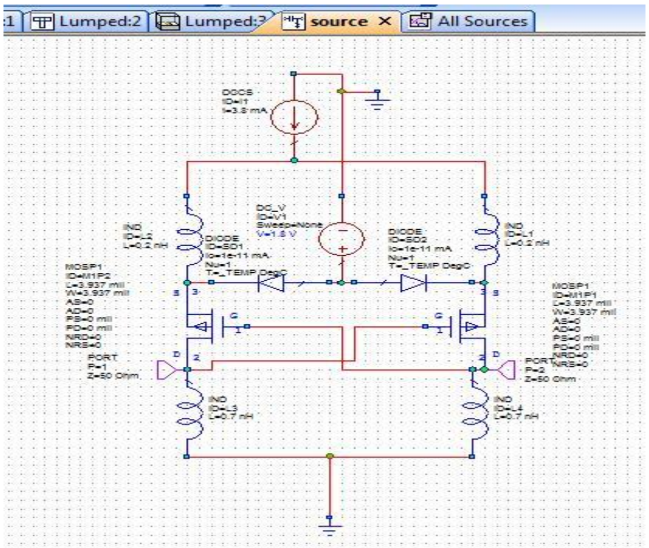

Figure 2 Differential VCO with transformer feedback to the Source

To obtain both higher frequency and simplify the transformer design (smaller number of turns-ratio), the front-gate feedback path in Figure 1can be modified to have a feedback to the back-gate. The block diagram of the proposed model, along with input and output elements is shown in Figure 3.

The topology (in Figure 3) can oscillate at higher frequency while keeping comparable performances compared to those of the other topologies discussed. Figure 3 shows the proposed VCO in which the inductors, L_d and L_s, form a transformer with a coupling coefficient, k_m. To optimize the turns-ratio and size of the transformer, a circuit simulation is investigated. The turns-ratio of the transformer is determined with an ideal transformer by varying the number of turns for each topology. About a 2:1turns-ratio is chosen which has sufficient feedback in the VCO. A lumped-element compact model is adopted to estimate the figures of merit (coupling coefficient (k_m), self-inductances of the individual windings, and self-resonant frequency) of the designed monolithic transformer. The equivalent compact model can be implemented using inductors, resistors, capacitances, and an ideal transformer. Since a transformer fabricated in CMOS technology has a parasitic signal loss mechanism, the model includes parasitic capacitances and dissipation in the substrate represented by shunt elements of C_{ox}, $C_{sub}$and $R_{sub}$where $C_{ox}$is the parasitic capacitance in the oxide layer,$C_{sub}$is thesubstrate capacitance and R_{sub} is the substrate resistance. Also,

it includes inter-winding capacitances between the primary and secondary windings.

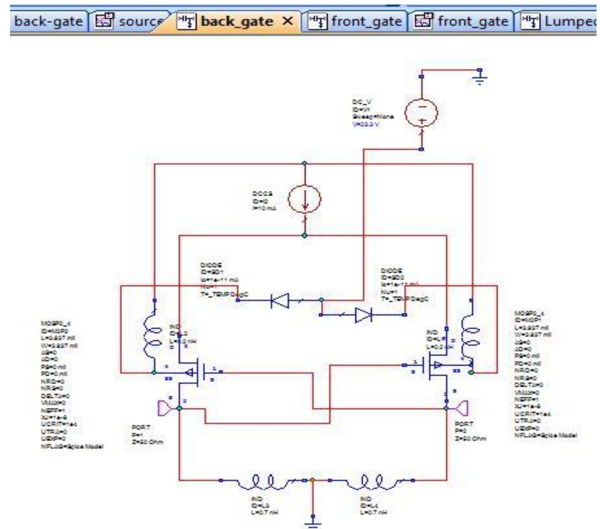

Figure 3. Differential VCO with transformer feedback to the Back-Gate

III. SIMULATION RESULTS

A combination of results of the 3 VCO designs is shown below, for comparison.

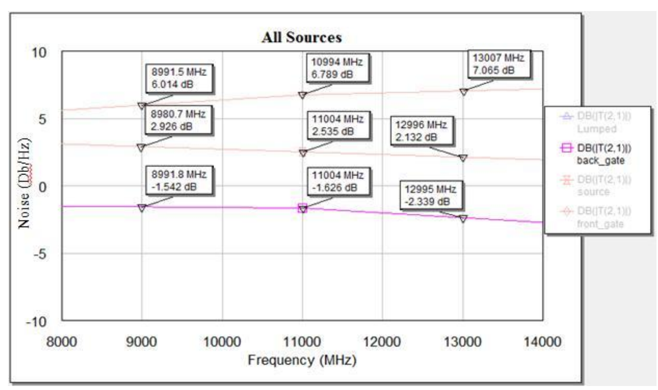

Figure 4 Combined result of Noise vs. Frequency curves for all models

The following conclusions can be drawn from the above table:

A. In the Front-Gate model, we notice that the noise level keeps rising continuously above 8 GHz. This is because, the effect of the parasitic capacitance in the circuit elements reduce the efficiency of the entire circuit.
B. In the Source-fed model, we see that the noise-level control is slower than the back-gate model. This is because of the trans-conductance effect in the circuit starts increasing as the operating frequency increases.
C. In the Back-Gate model, the noise levels continue to drop almost similar to the way as in Front-Gate model. But it is to be noted that in this model, the effect of parasitic capacitance of various elements and the trans-conductance effect of the lumped elements is significantly reduced, thereby making it more efficient in controlling the noise levels.

The table below shows the comparison of noise-levels for the three models.

Frequency (GHz)	Noise in Feedback Circuits (dB/Hz)		
	Source-fed	Front-gate	Back-gate
8	3.10	3.58	-1.50
9	2.92	3.60	-1.54
10	2.72	3.63	-1.58
11	2.54	3.65	-1.62
12	2.33	3.72	-1.97
13	2.13	3.78	-2.33
14	1.93	3.84	-2.68

Table 1 Noise-levels at various frequencies for the simulated designs

Thus, from the above results, we can say that the ability of the Back-Gate model to control the noise levels is comparatively higher than that of Front-Gate and Source-fed models. Figure of Merit (FOM) for oscillators summarizes the important performance parameters, i.e., phase noise and power consumption P, to make a fair comparison. Figure of Merit is a quantity used to characterize the performance of a VCO relative to other VCOs of the same type. It is given by,

$$FOM = L(\Delta\omega) + 10\log_{10}(\Delta\omega/\omega_0)^2 + 10\log_{10}(P/1mW) \quad \text{(Eqn 1)}$$

where $\Delta\omega$ is change in frequency, ω is the operating frequency, P is the power consumed by VCO and $L(\Delta\omega)$ is the phase noise.

Let input voltage be 1.8V, input current is 3.8mA and the phase noise is 200dB/m. The change in frequency is assumed to be about 1GHz. Then from Eqn 1 we can say that at 11 GHz, FOM is 187 dBc/Hz and at 14 GHz, FOM = 185 dBc/Hz.

IV. CONCLUSION

In this paper, the software simulation of the conventional models (Front-Gate feedback and Source-fed feedback circuits) and the proposed model (Back-Gate feedback circuit) has been shown for operational frequencies greater than 8GHz, while maintaining a high FOM. The results obtained from the 3 circuit models were compared.

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