A Dual-band VCO using Inductor Splitting for Automotive Radar System at W-band

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***Abstract*— A dual-band VCO (Voltage Controlled Oscillator) for automotive radar system is proposed by 65nm CMOS process. The proposed VCO is splitting inductor and NMOS cross-coupled differential LC type and includes output matching buffer. The output frequencies of VCO are 76.4~77.1GHz and 78.5~ 80GHz. These frequency bands are proper to long-range and short-range radar sensor system of automotive radar at W-band. The simulation results show the output power of -8.4dBm and the phase noise of –90.8dBc/Hz at 1MHz offset and -113.3dBc/Hz at 10MHz offset. The power consumption of the proposed VCO is 30mW at the supply voltage of 1.2V. The proposed VCO shows good figure of merit (FOM) of –176.6dBc/Hz.**

***Keywords*—Automotive Radar System, CMOS, Frequency Synthesizer, VCO(Voltage Controlled Oscillator), Inductor splitting**

I. INTRODUCTION

Recently, automotive radar system using CMOS process is in progress in the field of millimeter waves because of the development of CMOS process technology. Researches on frequency synthesizer at W-band have been actively carried out widely through dramatic development. A VCO is an inevitable component for the frequency synthesizer of the automotive radar [1-3]. The 77GHz frequency range is related to long-range and 79GHz frequency range is related to short-range radar sensor system in automotive radar. So the dual-band VCO design is useful for automotive radar system. Though the VCO with large tuning range for frequency synthesizer is also possible to operate in both range but large K_{VCO} leads to large phase noise. Many researches are in progress to get low phase noise [3] but it is very difficult to get good phase noise performance in W-band. So we optimized inductor by using CAD tools such as EM-simulator to get high quality factor (Q-factor) of inductor [4]. This is because the high Q-factor can improve the phase noise performance of VCO. And we used the splitting inductor method to obtain dual-band operation [5]. The inductor tuning structure in ISSCC 2013 has ultra-wide tuning range in high-end process [5], but the realization is difficult in general process. It is also important that the circuit is implemented to meet the specifications for automotive radar system. The qualified inductors improve output swing and adjust the oscillation frequency of the VCO.

This paper introduces the dual-band CMOS VCO which is suitable for automotive radar and describes the post-simulation results. In Section II, the proposed VCO topology and the circuit design are presented. The post-simulation results of the VCO and the performance comparison between the proposed VCO and the previous VCO's are provided in Section III. Finally, summary and conclusions are given in Section IV.

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II. VCO ARCHITECTURE

The schematic of the proposed dual-band VCO is shown in Fig. 1.

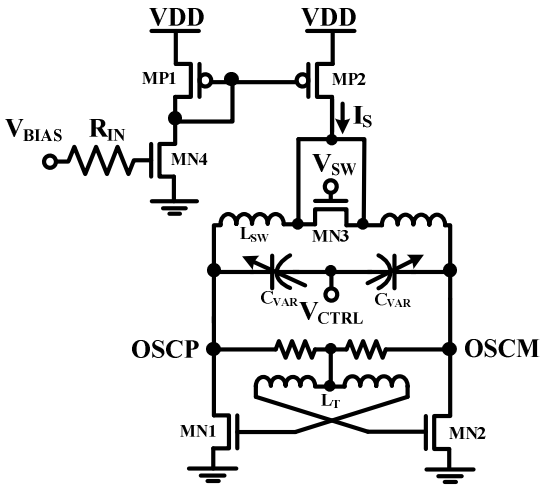

Fig. 1. The proposed VCO schematic

The architecture is NMOS cross-coupled differential LC type and inductor tuning structure [3]. MN1 and MN2 are used to ensure the differential mode operation and compensate the losses from the passive components due to negative resistance.

And a current source is added for the VCO to widen frequency tuning range and we get good phase noise performance. Because the surface mobility of PMOS transistors is slower than that of NMOS, so PMOS transistors are used in the bias circuit to reduce the flicker noise for better phase noise performance. V_{BIAS} can control I_S, then I_S adjusts the oscillation frequency because the oscillation frequency depends on not only inductance and capacitance but also the resistance of the VCO. V_{CTRL} also changes the oscillation frequency by changing the capacitance of varactor. R_{IN} is the internal resistor that could protect unexpected damage to the circuit because an external input signal current to the circuit in automobile circumstance could be limited by the resistor.

A VCO based on waveguide or transmission line is possible to oscillate at W-band, but it requires high power consumption and eventually leads to large parasitic capacitance because the low resistance of output load requires high g_m of transistor. So we used native inductor layer structure with modified shape by using simulator. Research on inductance and capacitance with the shape of inductor was carried out because of limited values in width and diameter of the inductor given by the process. The optimized width and diameter with highest Q-factor in 77~79GHz were selected from simulation. We use upper two metal layers in inductor layout to guarantee the skin depth of metal at high frequency. For high output swing, two pairs of the inductors have mutual inductance by placing each other closely. And this layout technique also results in area reduction. The output buffer is added for 50Ω impedance matching and isolation to the next stage. The schematic of output buffer is shown in Fig. 2.

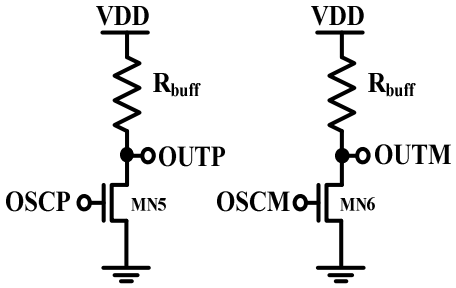

Fig. 2. Schematic of output buffer

If the sizes of MN5 and MN6 are large, OUTP and OUTM have larger swing but the operating frequency goes down. This is because MN5 and MN6 have to pass high current. Otherwise in order to get high operating frequency, the parasitic capacitances of the VCO should be minimized and the switching role of transistor is more important. So the sizing of MN5 and MN6 should be very careful to trade between the large output swing and high operating frequency. We use low-V_t NMOS transistor for high operating frequency and large output swing is obtained by high input swing (OSCP and OSCM) from the inductors connected to MN1 and MN2.

III. Post-Simulation Results

The proposed dual-band VCO is implemented by 65nm CMOS process and Fig. 3 shows the chip layout and microphotograph of the VCO. The area is $0.15\times0.21mm^2$ and CADENCE Spectre RF is used for simulation.

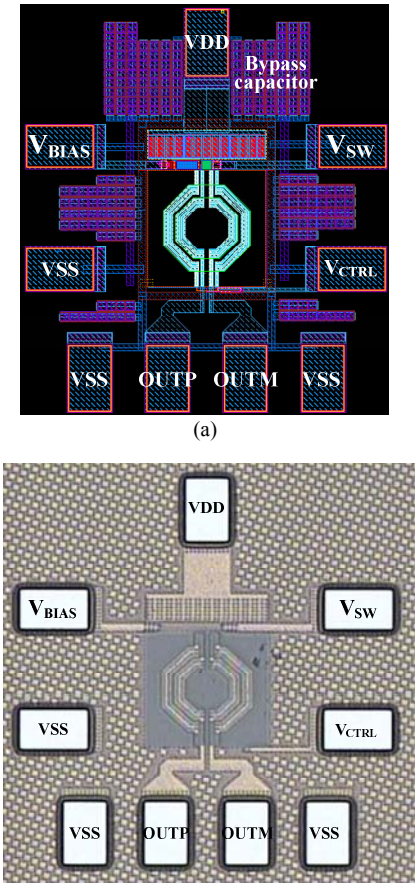

Fig. 3. (a) Layout of VCO (b) Die microphotograph

The simulation is accomplished by the post-layout parameters and similar measurement environment. Fig. 4 shows the simulation results of the output frequency versus V_{CTRL} and V_{BIAS}. If V_{SW} is 1.2V, NM3 is ON as switch and the output frequency is decreased because the capacitance between drain and source of NM3 is bigger than C_{VAR}. On the contrary, If V_{SW} is 0V, C_{VAR} does not affect the operation frequency. This is because the capacitance of drain and source of MN3 and C_{VAR} are connected in series. So the output frequency increases. We designed the VCO for two bands, 77GHz and

79GHz, and K_{VCO} is 0.67GHz/V and 1.5GHz/V, respectively. Additionally V_{BIAS} could widen the tuning range of the VCO by controlling I_S and shown in Fig. 4.(b).

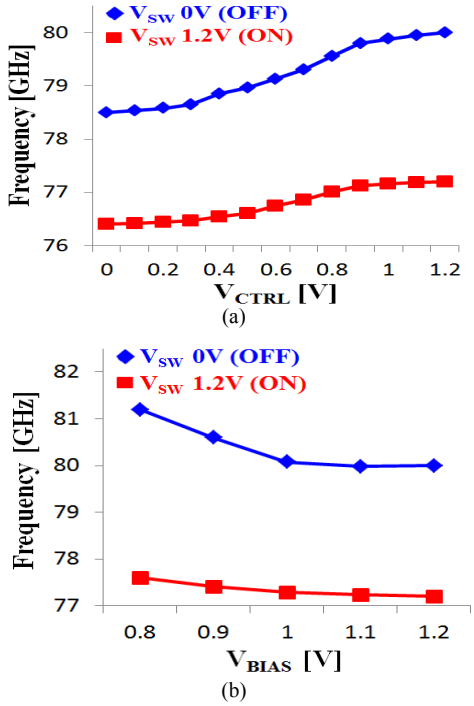

Fig. 4. Simulation results of the frequency versus (a)V_{CTRL} and (b)V_{BIAS}

If V_{SW} is 1.2V, the drains of NM1 and NM2 are short from DC point of view. So the resistance between NM1 and NM2 is low. This leads to low output swing. These simulation results are shown in Fig. 5. If V_{SW} is 0V, the drains of NM1 and NM2 are split and the capacitance between drain and source of MN3, C_{SW}, is remained [5]. Then, C_{VAR} and C_{SW} seem like series and the total capacitance is smaller than C_{SW} because C_{VAR} is larger than C_{SW} [5]. The operating frequency increases because the capacitance of LC resonator of the VCO is lower.

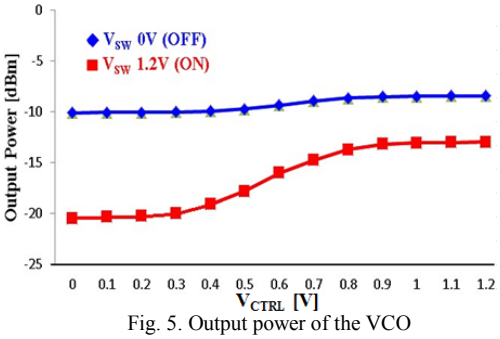

Fig. 5. Output power of the VCO

The maximum output power of the VCO is about -8.4dBm when MN3 is OFF and V_{CTRL} is 1.2V. And the phase noise is –90.8dBc/Hz at 1MHz offset and -113.3dBc/Hz at 10MHz offset and shown in Fig. 6.

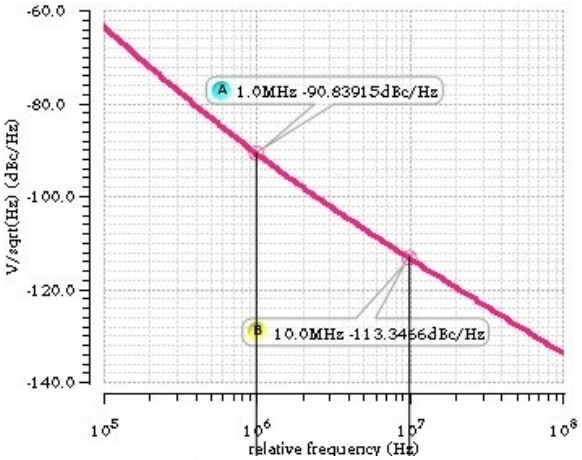

Fig. 6. Phase noise of the VCO

For the performance comparison with other VCO's, the following FOM characteristics equation (1) is used.

$$FOM = PN\{\Delta f\} - 20\log\left(\frac{f_0}{\Delta f}\right) + 10\log\left(\frac{P_{DC}}{1mW}\right) \quad (1)$$

Where PN{Δf} is phase noise in dBc/Hz at the offset frequency of Δf. P_{DC} is the power consumption of the VCO in mW. If FOM is smaller, it means that the performance of the VCO is better. The FOM of the proposed dual-band VCO is -176.6dBc/Hz and shows superior performance to other VCO's in similar frequency band and process. And the phase noise from small K_{VCO} is excellent compared with other VCO's. In Table 1, the performance of the proposed VCO and previous VCO's are summarized.

TABLE I. THE PERFORMANCE COMPARISON WITH PREVIOUS WORKS

	[1]ISOCC 2011	[2]RFIC 2011	[5]ISSCC 2013	*this work
Process	65nm CMOS	65nm CMOS	32nm CMOS	65nm CMOS
Tuning Range [GHz]	69.6~81	77~81	33.6~46.2	ON:76.4~77.2 OFF:78.5~80
Phase Noise [dBc/Hz]	*-85@1M	-88@1M	-118@10M	-90.8@1M -113.3@10M
Output Power [dBm]	*-5	6	N/A	-8.4
P_{DC}[mW]	*100	190	9.8	30
FOM [dBc/Hz]	-163	-162.9	-178.4	-176.6

*Simulation Results

IV. CONCLUSIONS

For the automotive radar system, the dual-band VCO at W-band was proposed by 65nm CMOS process. The architecture of the proposed VCO is NMOS cross coupled differential LC type with splitting inductor for high frequency inductor tuning. So the proposed VCO operate at 77GHz long-range and 79GHz short-range radar sensor system. Low K_{VCO} design and the PMOS current source are used to obtain good performance of phase noise. Also the PMOS current source widens the tuning range of the VCO by controlling the current of the VCO. The post-simulation results show that the precise dual-band operation from inductor tuning split technique. The output power is -8.4dBm and the phase noise are –90.8dBc/Hz at 1MHz and -113.3dBc/Hz at 10MHz offset. The power consumption of the VCO is 30mW at the supply voltage of 1.2V. The VCO shows good FOM of –176.6dBc/Hz. So the proposed VCO shows superior performance to other VCO's in similar frequency band and process.

This work enables high performance frequency synthesizer as realization of automotive radar. The frequency synthesizer using the proposed VCO will form the basis for automotive radar development. CAD tools are supported by IDEC.

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