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A Triple-Band Voltage-Controlled Oscillator Using Two Shunt Right-Handed 4th -Order Resonators

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***Abstract*—A triple-band (TB) oscillator was implemented in the TSMC 0.18 μm 1P6M CMOS process, and it uses a cross-coupled nMOS pair and two shunt 4th order LC resonators to form a 6th order resonator with three resonant frequencies. The oscillator uses the varactors for band switching and frequency tuning. The core current and power consumption of the high (middle, low)- band core oscillator are 3.59(3.42, 3.4) mA and 2.4(2.29, 2.28) mW, respectively at the dc drain-source bias of 0.67V. The oscillator can generate differential signals in the frequency range of 8.04-8.68 GHz, 5.82-6.15 GHz, and 3.68-4.08 GHz. The die area of the triple-band oscillator is 0.835× 1.103 mm^2.**

***Index Terms*—0.18 μm CMOS, 6th LC resonator, 4th right-handed LC resonator, triple-band, differential oscillator**

I. INTRODUCTION

Oscillators are widely used and crucially important in modern microwave transceivers for up-converting and down-converting base-band data, voice, and video signals. The design of fully-integrated oscillator requires trade-offs among many design parameters such as phase noise, frequency band and power consumption. Recent commercial communication products require a radio with flexible multi-band/multi-mode /multi-function operation and the multiple band service demands frequency-agile RF transceivers with wide-band or multiband oscillator circuits. Lots of techniques have been proposed to design multi-band oscillators in the past. A straight-forward multi-band oscillator is using multiple LC-tank oscillators [1], each oscillator is dedicated to each frequency band, and this approach has best performance. However, the product cost is expensive and with large form factor. The second approach uses wide-tuning range ring oscillator, which has worse phase noise and high power consumption. Other approach uses switchable and tunable LC-tank [2, 3]. In the switching method the resonance frequency of oscillator is modified by adding L and C elements to the tank via MOS switches, which reduces the tuning range and increases phase noise. One alternative uses multi-resonant LC resonator, varactors are used as tuning elements for frequency-band switching and tuning [4]. And various dual-band oscillators [5-7] using 4th order LC resonator have been presented in the past, these oscillators can be extended to design a triple-band oscillator using a 6th order LC resonator. As many options for the resonators can be configured. This letter uses two shunt resonators approach however there are still many options. The 0.18 μm oscillator can generate differential signals in the frequency range of 8.04-8.68 GHz, 6.74-6.86 GHz, and 4.22-4.47 GHz and this TB oscillator uses varactor switch [11] to select frequency band.

II. CIRCUIT DESIGN

Fig. 1 shows the schematic of the proposed triple-band (TB) VCO, which is composed of a 6th order resonator and a cross-coupled pair (M_1, M_2) to generate negative resistance. Two common-source amplifiers are used for

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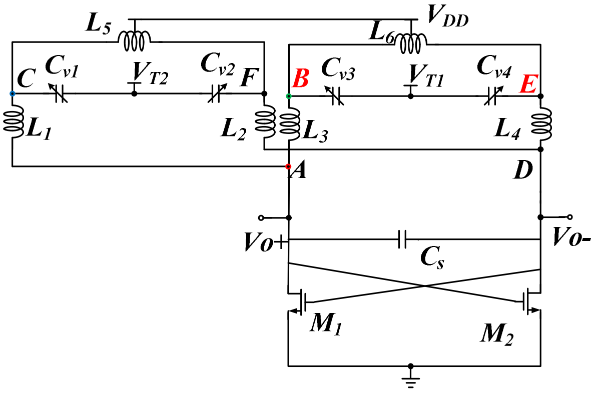


Fig. 1. Schematic of the triple-band oscillator.

measurement purpose. The 6th order LC resonator consists of two 4th order right-handed LC resonators in shunt. The first 4th order LC resonator consists of inductors L_6, (L_3, L_4), varactors (C_{v3}, C_{v4}) and parasitic active capacitor C_s across the drains of the switching pair. The second 4th order LC resonator consists of inductors L_5, (L_1, L_2), varactors (C_{v1}, C_{v2}) and parasitic active capacitor C_s. The voltages V_{T1} and V_{T2} are used to vary the capacitance of varactors. Simple operation principle is as follows. When the capacitances of (C_{v1}-C_{v4}) are small (say, at V_{t2}=2 V, V_{t1}=2 V), the varactors are considered as open circuit; L_3+L_6+L_4 are in shunt with L_1+L_5+L_2; the oscillator is at the low-frequency band. The voltages at the nodes A, B, C are in-phase. When the capacitances of (C_{v1}-C_{v4}) are large (say, at V_{t2}=0 V, V_{t1}= 0 V), (C_{v1}-C_{v2}) and (C_{v3}-C_{v4}) are considered as shorted circuit, L_2+L_4 and L_1+L_3 are in shunt; the oscillator is at the high-frequency band. At V_{t2}=2 V, V_{t1}= 0 V, the capacitances of (C_{v3}-C_{v4}) are small and the capacitances of (C_{v1}-C_{v2}) are large, L_3+L_4 are in shunt with L_1+L_5+L_2; the oscillator is at the middle-frequency band. The voltages at the nodes A, C are in-phase and the voltages at the nodes A, B are out-of-phase. The hard points are propose best performance results with tuning Vdd to 0.67 V in triple-band and optimized layout from this design.

There are two resonant frequencies for the two 4th order resonators shown in Fig. 1. Neglecting the lossy parasitic, the input admittance Y_{in} looking into the 4th order right-hand side resonator from the nodes A and D is given by

$$Y_r = \frac{1 + s^2\{L_{6h}C_{v3} + [L_{6h} + L_4]C_s\} + s^4 L_{6h}C_{v3}L_4C_s}{s[L_{6h} + L_4] + s^3 L_{6h}C_{v3}L_4} \tag{1}$$

where $2C_s$ is the parasitic active capacitance of (M_1, M_2). The subscript h in L_{ih} is used to denote half of L_i. The input admittance Y_{in} looking into the left-hand side resonator from the nodes A and D is given by

$$Y_L = \frac{1 + s^2\{L_{5h}C_{v1} + [L_{5h} + L_2]C_s\} + s^4 L_{5h}C_{v1}L_2C_s}{s[L_{5h} + L_2] + s^3 L_{5h}C_{v1}L_2} \tag{2}$$

The net input admittance Y_{in} looking into the whole 6th order composite resonator from the nodes A and D is given by

$$Y_{in} = Y_r + Y_L \tag{3}$$

This equation indicates if the first 4th order resonator and the second 4th order resonator have the same components the whole resonator is a 4th order resonator. Switching from (V_{t2}=V_{t1}=0 V) to (V_{t2}=V_{t1}=2 V), the oscillator switches from high-frequency band to low-frequency band. However, if the components are different in the two 4th order resonators or the tuning biases are different, the oscillator circuit uses higher-order resonator.

III. EXPERIMENTS

The triple-band oscillators were designed and fabricated in the TSMC 0.18 μm CMOS process. Fig. 2 shows the micrograph of the proposed triple-band oscillator with a chip area of 0.835×1.103 mm^2 including all test pads and dummy metal. The right-hand side shows inductors (L_3, L_6, L_4) and the left-hand side shows inductors (L_1, L_5, L_2). With the supply voltage of V_{DD} = 0.67 V, the current and power consumption of the high (middle, low)- band core oscillator are 3.59(3.42, 3.4) mA and 2.4(2.29, 2.28) mW, respectively. Fig. 3 shows the tuning ranges of the oscillation frequency as varying V_{t1} and V_{t2}. At V_{t2}= 1.8 V, the triple-band (TB) oscillator operates between 3.68-4.08 GHz at low band as the control voltage V_{t1} is tuned from 0.8 V to 1.8 V; the TB oscillator operates between 5.96-6.15 GHz at middle band, as the control voltage V_{t1} is tuned from 0 V to 0.7 V. At V_{t1} = 0 V, the TB oscillator operates between 8.04-8.68 GHz at high band as the control voltage V_{t2} is tuned from 0 V to 1.0 V; the TB oscillator operates between 5.82-5.96 GHz at middle band, as

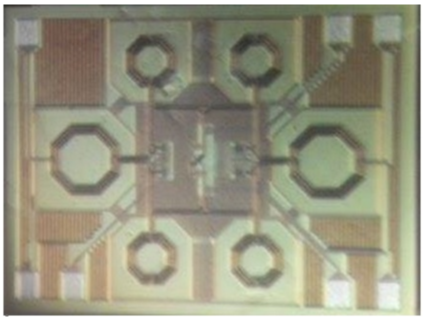


Fig. 2. Chip photograph of the proposed TB oscillator.

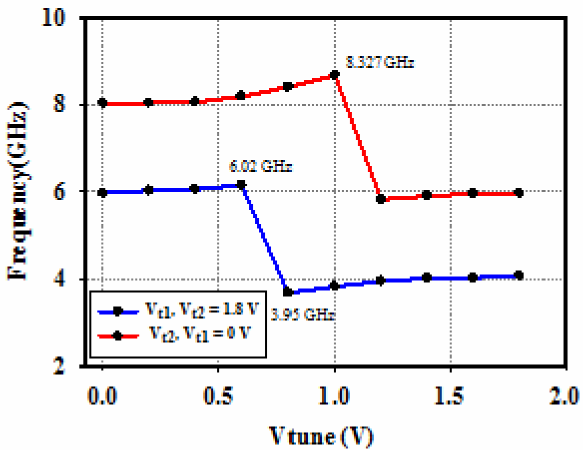
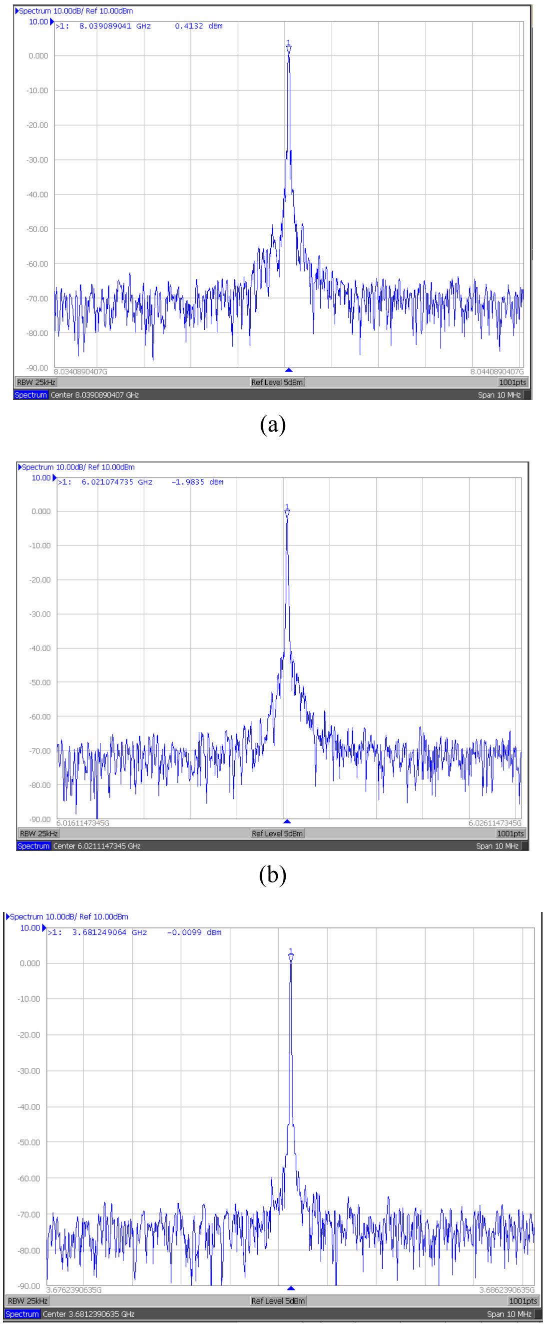


Fig. 3. Measured tuning range of the VCO. (a) (blue line) V_{t2}=1.8 V,V_{t1}= 0~2 V. (b). (red line) V_{t1}=0 V ,V_{t2}= 0~2 V. V_{DD} = 0.67 V.



(a)

(b)

(c)

Fig. 4. Measured spectra of (a) the high-band VCO (a) the high-band VCO at V_{t1}=V_{t2}=0 V, (b) the middle-band VCO at V_{t1}=0 V ,V_{t2}=1.2 V, (c) the low-band VCO at V_{t1}=0.8 V ,V_{t2}= 1.8 V. V_{buffer}=1.2 V, V_{DD}=0.67 V.

Fig. 4(a) shows the high-band output spectrum at 8.04 GHz, with 0.41 dBm output power. Fig. 4(b) shows the middle-band output spectrum at 6.02 GHz, with -1.98 dBm output power. Fig. 5(c) shows the low-band output spectrum at 3.68 GHz, with 0 dBm output power. The phase noises were measured using the Agilent E5052B signal source analyzer plus E5053A microwave down converter. Fig. 5 shows the measured high (middle, low)-band phase noise. The measured high (middle, low)-band phase noise and the phase noise is -113.27(-15.2, -123.09) dBc/Hz at 1 MHz offset frequency from the carrier frequency of 8.04(6.02, 3.68) GHz. The phase noise has the dependence of $1/\Delta\omega^2$ ($\Delta\omega^3$) due to the thermal (flicker) noise. The figure of merit (FOM) is calculated using the following equation

$$\mathrm{FOM} = L\{\Delta\omega\} + 10\cdot\log\left(P_{DC}\right) - 20\cdot\log\left(\frac{\omega_o}{\Delta\omega}\right) \quad (5)$$

where $L\{\Delta\omega\}$ is the SSB phase noise measured at $\Delta\omega$ offset from ω_o carrier frequency and P_{DC} is DC power consumption in mW. Table 1 is the performance comparison of the VCOs.

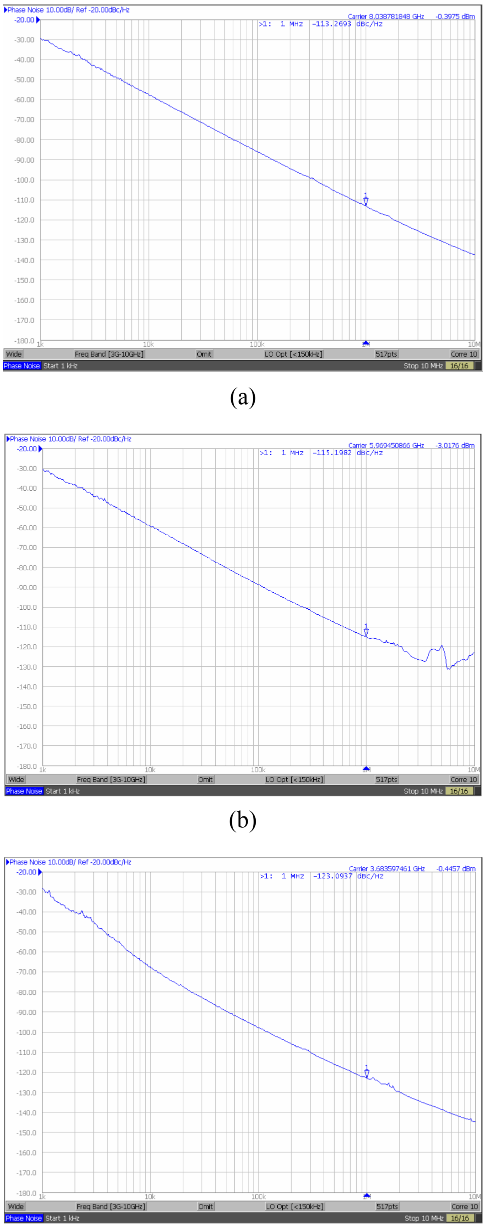


Fig. 5. Measured phase noises of (a) the high-band VCO at $V_{t1}=V_{t2}=0$ V, (b) the middle-band VCO at $V_{t1}=0$ V, $V_{t2}= 1.2$ V, (c) the low-band VCO at $V_{t1}= 0.8$ V ,$V_{t2}=1.8$ V. $V_{buffer}=1.2$ V, $V_{DD} = 0.67$ V.

IV. CONCLUSIONS

This letter proposes a novel triple-band cross-coupled oscillator by using 4th order right-handed LC resonators to form a 6th order resonator. Two pairs of varactors are used to tune and switch the frequency band. The TB oscillator uses two identical resonators in shunt at the high-frequency and low-frequency bands. The chips were successfully implemented in the 0.18 μm CMOS process. According the comparison table, this work shows lower power consumption and higher frequency than reference [8]. After calculation, FOM results show better than others published papers from Eq. (5) and listed in Table 1. The high band frequency is at 8.3 GHz, the middle-band frequency is at 6.0 GHz, and the low-band frequency is at 3.9 GHz. The high (middle, low)-band FOM is -191.45(-187.2, -189.87) dBc/Hz. The performance is better than other TB oscillators.

Table 1. Performance Comparison of LC-VCOs

Ref.	Proc. (um)	Vdd. (V)	fo (GHz)	P (mW)	PN @1M (dBc/Hz)	FOM, dBc/Hz
[9]	0.18	1.8	6	3.24	-106	-176.5
			9	3.24	-104	-177.98
[6]	0.18	0.8	4.48	4.93	-113.25	-179.29
			7.43		-121.28	-191.25
[5]	0.09	-	21	14	-100.8	-175.8
			55		-86.7	-170.0
[10]	0.13	1.5	1.28	4.35~ 9.15	-120	-177.4
			-		-119	-181
			-		-117	-181.5
[8]	0.18	0.8	3.453	3.9	-117.19	-183.0
			5.679		-113.74	-183.0
			6.995		-111.44	-183.84
This	0.18	0.67	3.95	2.28	-123.1	-191.45
			6.02	2.29	-115.2	-187.2
			8.327	2.4	-115.28	-189.87

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