A 25MHz-6.44GHz LC-VCO Using a 5-port Inductor for Multi-band Frequency Generation

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***Abstract* — This paper proposes a wide tuning range VCO for multi-band frequency generation. The wide band oscillator consists of a dual-mode LC-VCO using a 5-port inductor, and a divider chain. The proposed 5-port inductor provides two different inductances, which could support two resonances in a compact chip area. Thus, for LC-VCO, two operation modes are obtained to increase the tuning range. The experimental results achieve 25MHz-to-6.44GHz of continuous tuning range with a FoM_T of -209 dBc/Hz.**

***Index Terms* — 5-port inductor, LC-VCO, multi-band, wide tuning range.**

I. INTRODUCTION

Software-defined radios (SDR) and cognitive radios (CR) [1][2] have recently emerged for radio systems with frequency-agility property, so as to dynamically adapt to different modulation standards. Almost all communication standards for consumer applications, *e.g.*, DTV, GSM, UMTS, LTE, WiMAX, GPS, Bluetooth, IEEE 802.11 a/b/g/n, use several frequency ranges spreading in heavily used band from 100-MHz to 6-GHz. In order to support the frequency agility, synthesizers for SDR and CR are required to provide all necessary local-oscillator frequencies with proper channel spacing. Thus, being an indispensable component for synthesizer, wide-band voltage-controlled oscillators (VCOs) are necessary for multi-band frequency generation.

Conventionally, switched capacitor resonators [3] in Fig. 1(a) and switched inductor [4] in Fig. 1(b) have been proposed to increase the available tuning range of VCO. However, the limitation of these methods is the switch loss, which could degrade the phase noise considerably. Although switches with large size can be chosen to reduce their resistive loss contribution, the tuning range of VCO would decrease due to large parasitic capacitance.

Other approaches, like switched coupled inductor based resonator [5][6] in Fig. 1(c) and self-switching inductor based resonator [7] (that is using switch to vary the number of turns in a spiral inductor), still suffer from the trade-off between phase noise and available tuning range due to the employment of Q-degrading switches at resonators.

Recently, several wide-band VCOs using switch-less resonant tanks have been reported. For example, in [8] a high-order resonator is proposed to extend the tuning range of VCO. However, this approach may introduce the issue of potential instability over a wide frequency band. Alternatively in [9], a triple-mode VCO using three coupled inductors is proposed to enable wide-band frequency generation. To save chip area, each inductor in this design is realized in vertical dimensions. Thus, quality factor for inductors are typically degraded due to resistance loss.

In this paper, a different method to achieve multi-band frequency generation is proposed. This frequency generation circuit consists of dual-mode core-VCO and divider chain. Two modes of oscillation are built by a 5-port inductor-based resonator as shown in Fig. 1(d) without any switch connected to the resonator tank which could decrease the resonator Q. Combing dual-mode operation with switched capacitors, the frequency from 3.14-GHz to 6.44-GHz for core-VCO can be achieved. As a result, the proposed frequency generation circuit achieves 25MHz-to-6.44GHz of continuous tuning range with the following divider chain.

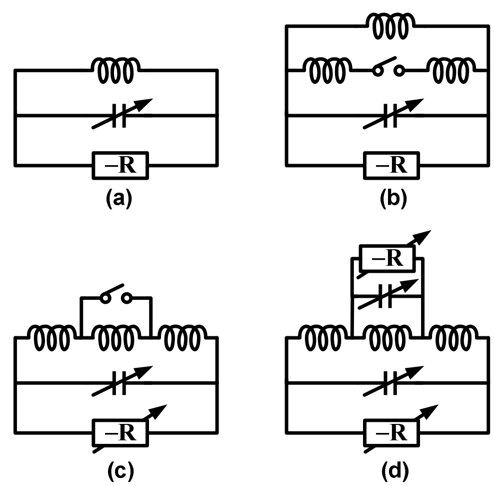

Fig.1. Simplified models for oscillator using (a) only variable capacitor; (b) series switch; (c) short switch; and (d) no switch (proposed).

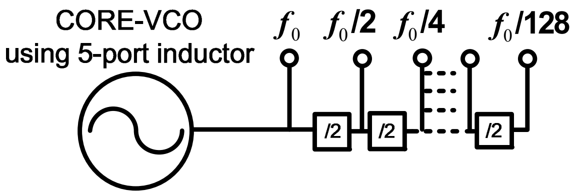

Fig.2. The simplified diagram of proposed architecture.

This paper is organized as follows. Section II presents the design consideration of the proposed switch-less 5-port inductor-based VCO. The following section describes the measurement results of the VCO. Finally, conclusion is summarized in Section IV.

II. Wide Band VCO Design

As illustrated in Fig. 2, the proposed VCO architecture consists of wide tuning range core-VCO and divider chain. The core-VCO has two modes of oscillation. By activate the proper negative feedback mechanism either of two oscillation modes can be selected. Thus, dual band operation is achieved by core-VCO using a 5-port inductor.

The fundamental frequency f_o is generated by the dual-mode core VCO, which is tuned from 3.14-to-6.44GHz. Since the tuning range of dual-band core-VCO is larger than 50%, lower frequency range from 0.025-to-3.22GHz can be generated by the divider chain.

This wide VCO architecture has the following advantages: (1) Layout area can be considerably saved since this proposed dual-band VCO could sustain two resonances while only occupies layout area of typical single resonance LC-VCO. (2) The trade-off between phase noise and tuning range can be relieved by the reason that no Q-degrading switches connect to LC resonant tank, compared with different types of inductor switching technique.

A. 5-port Inductor Design

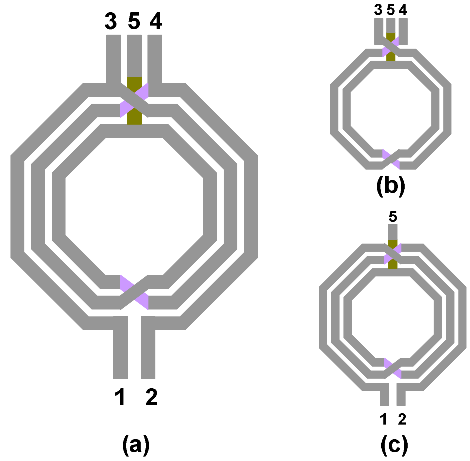

Fig.3. Layout of proposed (a) 5-port inductor, (b) its inner 2-turn inductor as a small inductor for high frequency operation mode and (c) 3-turn inductor as a large inductor for low frequency operation mode.

The layout of a 5-port inductor is shown in Fig. 3(a). Generally speaking, this inductor can be considered as the combine of two inductors with different inductance. If differential signal are applied to port 3 and port 4, the 5-port inductor is equivalent to a two-turn 3-port inductor with port 5 as the center tap, as sketched in Fig. 3(b). Similarly, if differential signal are applied to port 1 and port 2, the 5-port inductor is equivalent to a three-turn 3-port inductor with port 5 as the center tap, as plotted in Fig. 3(c). Thereby, larger inductor, formed by connecting port 1 and port 2 to resonance tank, can be applied for low frequency oscillation mode. Smaller inductor, built by connecting port 3 and port 4 to resonance tank, can be reused for high frequency oscillation mode.

In order to obtain high *Q*, the top thick metal layer is employed for the 5-port inductor implement and lower thin metal layers are only used for metal crossing. The 5-port inductor is simulated by a 3D electromagnetic simulator HFSS.

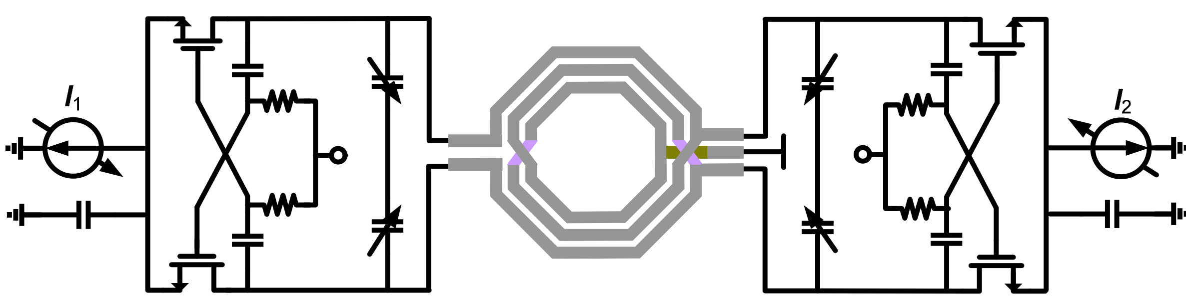

Fig.4. Detailed schematic of the dual-band core-VCO using a 5-port inductor.

B. Core-VCO Design

The detailed schematic of the VCO is depicted in Fig. 4. The active parts at each core are cross-coupled class-C differential pair [16] with tail current source. The left part in Fig. 4 indicates the low frequency operation mode and the right part in Fig. 4 indicates the high frequency operation mode, respectively. The two modes can be selected by activating and deactivating tail current source I_1 and I_2 alternatively. Only one active core is enabled at any given moment. The corresponding part has the largest oscillation swing. Meanwhile, oscillations can also be observed in the other part with small oscillation swing at the same oscillation frequency. The port 5 as the center tap is connected to the supply voltage, equal to 1.2-V.

In order to tune frequency for each mode of oscillation, switched capacitors are required. In this design, a 4-bit binary-weighted switched capacitor has been employed for coarse tuning in low frequency operation mode. Similarly, in high frequency operation mode, a 3-bit binary-weighted switched capacitor is used for coarse tuning. For fine tuning, one varactor is employed at high frequency active part, but it is also effective to tune the frequency at low frequency oscillation mode.

III. Experimental Results

To validate the analysis and design in Section II, the VCO is implemented in a 180nm CMOS process. Fig. 5 shows the microphotograph of fabricated VCO. The core chip size is only 470μm×760μm, benefiting from the proposed dual-band core-VCO using a 5-port inductor.

The measured low frequency oscillation mode covers the tuning range of 3.14-to-5.06GHz, and the measured high frequency oscillation mode covers the tuning range of 4.71-to-6.44GHz. Combing the two oscillation modes, lower frequency band ranging from 25MHz-to-3.22GHz is obtained by the divider chain. As a consequence, the resulting tuning range (25MHz-to-6.44GHz) is achieved in the experimental results. The measured phase noise characteristic at 1.3GHz, 4.4GHz and 6.1GHz are plotted in Fig. 6. The proposed VCO achieves -120 dBc/Hz phase noise at a 1-MHz offset from a 4.4-GHz carrier, and the corresponding power dissipation is 8.8-mW. The total power consumption including divider chain is 7.1mW-16.3mW depending on output frequency.

To evaluate frequency tuning range along with phase noise, FoM_T [17] is utilized:

$$\mathrm{FoM_T} = \mathcal{L}(f_{\mathrm{offset}}) - 20\log\left(\frac{f_0}{f_{\mathrm{offset}}}\frac{\mathrm{FTR}}{10}\right) + 10\log\left(\frac{P_{\mathrm{DC}}}{1\mathrm{mW}}\right) \quad (1).$$

where $\mathcal{L}(\mathrm{f_{offset}})$ is phase noise, f_{offset} is offset frequency, f_0 is oscillation frequency and P_{DC} is power consumption. FTR is frequency tuning range, which is defined as $(f_{\max} - f_{\min})/((f_{\max} + f_{\min})/2)$ in percent figures. Table I summarizes the comparison to other published wide band VCOs with performances. The proposed VCO achieves wide tuning range and good FoM_T, which is

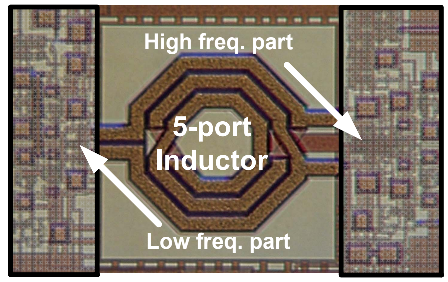

Fig.5. The die photo of proposed VCO.

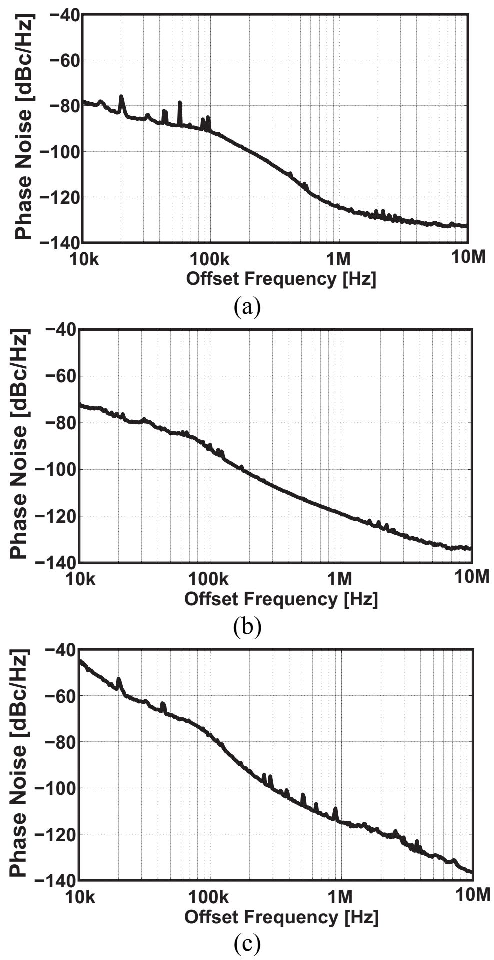

Fig.6. Measured phase noise characteristic versus the offset frequency at (a) 1.3GHz, (b) 4.4GHz, and (c) 6.1GHz, respectively.

TABLE I
PERFORMANCE COMPARISON BETWEEN WIDEBAND VCOS

Reference	CMOS Technology	Chip Area	Phase Noise @1MHz Offset	Power	Tuning Range		FOM_T
Unit	-	mm^2	dBc/Hz	mW	GHz	%	dBc/Hz
[3]	0.18µm	1.7	-127 @1.8GHz	2.6-10	1.14-2.46	73	-202
[9]	0.13µm	0.295	-117 @4.5GHz	6.5	1.3-6	128	-203
[10]	90nm	0.05	-117 @5.6GHz	5.9-11.2	0.009-5.7	199	-210
[11]	0.18µm	0.65	-119 @4.6GHz	1-8	3.4-7	69	-201
[12]	90nm	0.05	-118 @4.1GHz	9.5-15.6	0.011-7.0	199	-204
[13]	0.18µm	0.585	-124 @1.2GHz	N.A	1.2-3.27	92.6	N.A
[14]	SOI 0.13µm	0.299	-122 @3.8GHz	14	4.5-7.1	45	-189
[15]	65nm	0.11	-116 @12.8GHz	22.5	10.8-14.8	31.3	-194
This work	0.18µm	0.36	-120 @4.4GHz	7.1-16.3	**0.025-6.44**	**199**	**-209**

comparable to the-state-of-the-art wide-band VCOs [3] [9-15] for multi-band frequency generation.

IV. CONCLUSION

In this paper, a novel wide band VCO using a 5-port inductor for multi-band frequency generation is designed and implemented. With careful design, the proposed VCO can be well suited for wideband frequency synthesizer in future software-defined radios and cognitive radios.

ACKNOWLEDGEMENT

This work was partially supported by MIC, SCOPE, MEXT, STARC, NEDO, Canon Foundation, and VDEC in collaboration with Cadence Design Systems, Inc., and Agilent Technologies Japan, Ltd.

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