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A 1.8-V 2.4/5.15-GHz Dual-Band *LC* VCO in 0.18-μm CMOS Technology

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***Abstract*—A dual band, fully integrated, low phase-noise and low-power *LC* voltage-controlled oscillator (VCO) operating at the 2.4-GHz industrial scientific and medical band and 5.15-GHz unlicensed national information infrastructure band has been demonstrated in an 0.18-μm CMOS process. At 1.8-V power supply voltage, the power dissipation is only 5.4 mW for a 2.4-GHz band and 8 mW for a 5.15-GHz band. The proposed VCO features phase-noise of -135 dBc/Hz at 3-MHz offset frequency away from the carrier frequency of 2.74 GHz and -126 dBc/Hz at 3-MHz offset frequency away from 5.49 GHz. The oscillator is tuned from 2.2 to 2.85 GHz in the low band (2.4-GHz band) and from 4.4 to 5.7 GHz in the high band (5.15-GHz band).**

***Index Terms*—CMOS, dual-band voltage controlled oscillator (DVCO), low phase-noise, low-power consumption.**

I. INTRODUCTION

As WIRELESS applications proliferate, demands for radios which can support multiple bands and multiple standards with minimal hardware implementations are rapidly increasing. One of the major issues in a dual-band transceiver is the implementation of a dual-band voltage controlled oscillator (DVCO). The most popular implementation method of a DVCO is to use switching devices in the tank to change either capacitance [1] or inductance [2]. The resistance of the switching devices, however, is likely to cause the degradation of the tank quality factor (Q) and, consequently, the oscillator's phase-noise. A wide tuning range VCO can be another choice to cover the dual bands [3], but the required varactors with wide tuning range are not usually available in a standard process and the relatively large VCO gain (K_{vco}) can easily lead to severe phase-noise degradation [4]. A set of multiple VCOs can support multiple bands [5], however, this could be unaffordable in portable devices due to the overwhelming circuit overheads. In spite of these endeavors, the design of integrated dual band *LC* VCOs still poses many challenges.

Inspired by the reasons mentioned, a dual-band *LC* VCO based on the frequency multiplication method in a commercial 0.18-μm CMOS technology is presented. It operates at the 2.4-GHz industrial scientific, medical (ISM) band and the 5.15-GHz unlicensed national information infrastructure (UNII) band. The tuning ratio is 25.6% for dual bands, respectively. Low dc-voltage and power consumption, simple circuit scheme, and good phase-noise performance are design goals.

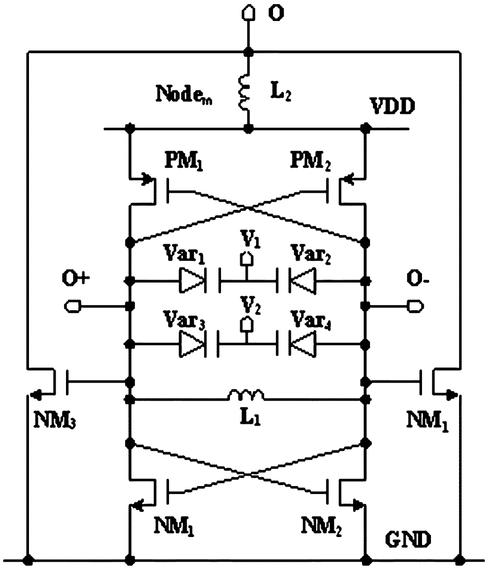

Fig. 1 Schematic of the dual-band VCO.

II. VCO DESIGN AND IMPLEMENTATION

The 2.4/5.15-GHz dual-band *LC* VCO architecture is illustrated in Fig. 1. The complementary cross-couple *LC* tank VCO as the core circuit forms a 2.4-GHz band, a differential multiplier followed the core circuit covers the 5.15-GHz band. Therefore, the differential output (O+ and O$-$) in Fig. 1 generates the 2.4-GHz band frequencies (f_{o}), while the single end output (O) produces the 5.15-GHz band frequency ($2f_{\mathrm{o}}$).

A. 2.4-GH Band

The VCO core of the 2.4-GHz band is based on a standard *LC* tank complementary cross-coupled topology, being chosen primarily for its ability to achieve low phase-noise and for its high headroom and low parasitic compared other configurations. The *LC*-tank in Fig. 1 is formed by the on-chip spiral inductor (L_1) and two pairs of symmetric AMOS varactors arrays (Var_1 and Var_2, Var_3 and Var_4). The Q-factor of the tank circuit is primary limited by the inductor of which the Q value is about seven at the frequency of 2.45 GHz. Inductors of 2 nH are implemented by using three tunes spirals with two AlCu metals (metal 6 and 5 in a 0.18-μm process). MOS varactors are used in the accumulation-mode because of the wide capacitor variation that can be obtained with a low variation of the source to gate bias voltage [6]. Consequently, the use of AMOS varactors

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is consistent with the new CMOS technologies because of the low supply voltage required. Two pairs of varctors, of 2 pF, are utilized to improve the tuning range of the oscillation frequency, in which Var_3 and Var_4 provide the coarsely tuning steps and Var_1 and Var_2 are designed to get fine tuning steps.

The cross-coupled devices (NMOS_1, NMOS_2, PMOS_1, and PMOS_2) form a positive feedback to serve as the negative resistance in order to compensate for the energy loss in the LC tank. The oscillation will occur at the frequency when the loop transfer function is exactly one. This is known as the Barkhausen Criterion [7]. The oscillation frequency $(f_0 = (1/2\pi\sqrt{L_1C})$ can easily be obtained because the imaginary part of the transfer function has to be exactly zero. Where L_1 is the inductance of the LC tank and C is the capacitance of the LC tank, includes the capacitances of varactors and the parasitical capacitances, located at the two sides of the LC tank. The cross-coupled VCO operates as periodical switches [8]. The W/L of the cross-coupled NMOS and PMOS devices is chosen based on the oscillation startup requirements at the low-end (worst-case) of the tuning range. Since the drain noise currents of the complementary cross-coupled devices are the dominant noise contributors in this design, the lengths are made larger than the minimal-size to limit short-channel induced excess noise [9].

B. 5.15-GHz Band

It is well known that a nonlinear effect is exiting during the operation of a multiplier. It can be modeled with polynomials empirically as

$$V(x) = A_0 + A_1x + A_2x^2 + A_3x^3 + A_4x^3 \cdots\cdots \quad (1)$$

where $V(x)$ is the output of the multiplier, A_n $(n = 0,1,2,\ldots N)$ are the harmonic coefficients and x is the input signal. Here, it is assumed that $x = \cos(\omega t + \theta)$, substituting x into (1) and we have

$$\begin{aligned}\mathrm{V}(\omega\mathrm{t}+\theta) &= \left(\mathrm{A}_0 + \frac{\mathrm{A}_2}{2} + \frac{\mathrm{A}_4}{2}\right) + \left(\mathrm{A}_1 + \frac{3}{4}\mathrm{A}_3\right)\cos(\omega\mathrm{t}+\theta)\\ &+ \left(\frac{\mathrm{A}_2}{2} + \frac{\mathrm{A}_4}{2}\right)\cos(2\omega\mathrm{t}+2\theta) + \frac{\mathrm{A}_3}{4}\cos(3\omega+3\theta) + \cdots\cdots \quad (2)\end{aligned}$$

From Fig. 1, we know that the differential outputs of the 2.4-GHz band are the inputs of the differential multiplier, whose phase difference is 180°. According to (2), we have

$$\begin{aligned}\mathrm{V}_0(2\omega\mathrm{t}+\varphi) &= \mathrm{V}_{\mathrm{o}+}(\omega\mathrm{t}+\theta) + \mathrm{V}_{\mathrm{o}-}(\omega\mathrm{t}+\theta) \approx 2\left(\mathrm{A}_0 + \frac{\mathrm{A}_2}{2}\right)\\ &+ \mathrm{A}_2\cos(2\omega\mathrm{t}+2\theta) + \cdots\cdots \quad (3)\end{aligned}$$

Therefore, the fundamental frequency components are canceled out and the second harmonic frequencies $(2f_0)$ are obtained theoretically. Thus, a simple high band circuit is formed by two differential NMOS devices and one inductor (L_2) as depicted in Fig. 1. L_2 of 8 nH with a Q factor of 5.85 is utilized to lower the dc cutoff of the output, block the RF signal, and match 50 Ω. The differential outputs (O+ and O−) inject the signals to the input of the second harmonic circuit to generate the high band output through the node "Node_m" as in Fig. 1, which also means that the node "Node_m" is pulled up at the time when each of the differential NMOS transistors turns on, the node "Node_m" moves at two times that of the frequency of the low band. It is obvious from (3), that the tuning range of the high band VCO is twice that of the low band and the phase-noise performance $(\varphi = 2\theta)$ of the high band is higher $(20\log 2 = 6$ dB) than that of the low band. Thus, the exact phase difference of 180° and low-power consumption are the design goals of the high band VCO. In the application, a single-end to differential-end circuit [10] is implemented at the high frequency band in order to avoid the corresponding sensitivity on substrate coupling.

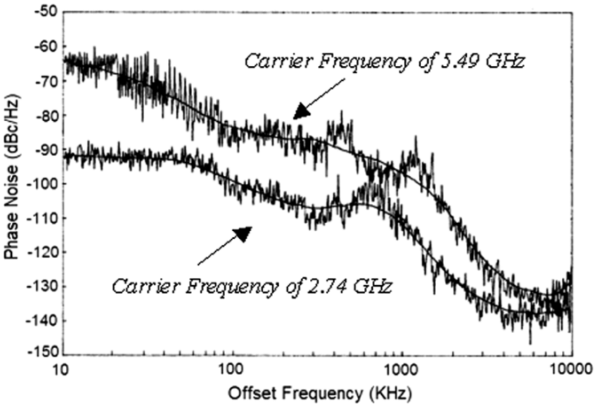

Fig. 2. Measured phase-noise at the 3-MHz offset frequency away from 2.74 and 5.49 GHz, respectively.

III. MEASURED RESULTS AND DISCUSSIONS

The VCO was fabricated in a commercially 0.18-μm CMOS process. HP8563E spectrum analyzer is used to measure the spectral density of the proposed VCO. The measured spectral densities give the fundamental frequency of 2.74 GHz and the output power is around −0.33 dBm. In addition, the output frequency of the high band is 5.49 GHz, and the second harmonic is $(2f_\mathrm{o})$. The output power is −10.5 dBm at 5.49 GHz. With a 1.8-V power supply, the measured phase-noise is −134 dBc/Hz at a 3-MHz offset frequency from a 2.47-GHz carrier as shown in Fig. 2. This is 4-dB better than that of the reported CMOS VCOs operating in the 2∼3-GHz range [11], [12]. At 5.49 GHz, the phase-noise performance of −126 dBc/Hz at the offset frequency of 3 MHz is achieved. The phase-noise is better than those reported in [13] and [14] which are designed for around 5-GHz operations frequency VCOs or multiband VCOs. In addition, the phase-noise difference of 8 dBc between two bands, compared with the ideal value of 6 dBc, is in an acceptable range.

The VCO is intentionally designed with smaller gain or a smaller tuning range to achieve low phase-noise. The measured tuning ranges in the low band and high band are 65 and 130 MHz as shown in Fig. 3, respectively. The output powers are measured with the variation of the controlled voltages and shown

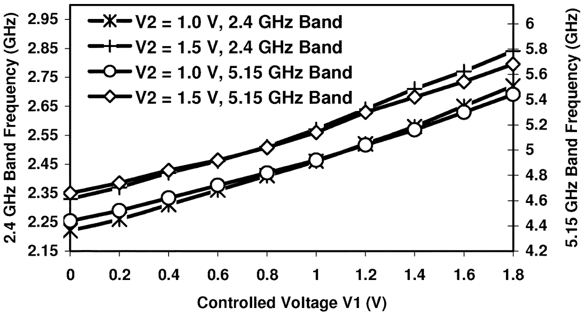

Fig. 3. Tuning characteristics of the 2.45-GHz VCO and 5.15-GHz VCO.

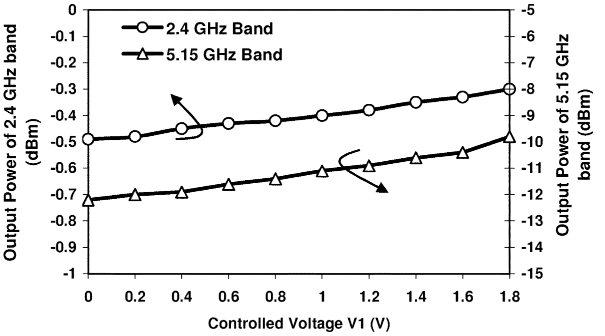

Fig. 4. Measured output power distribution versus the controlled voltage V_1 when $V_2 = 1.5$ V.

TABLE I
COMPARISON WITH RECENTLY PUBLISHED VCOS

Ref.	Tech. (μm)	Power diss. (mW)	Δf/f₀ (M/GHz)	Phase-noise (dBc/Hz)	FOM (dBc/Hz)
This work	CMOS 0.18	5.4	3/2.74	-135	-188.3
		8	3/5.49	-126	-183.7
[11]	CMOS 0.35	12.6	3/2.37	-131	-177.9
[12]	CMOS 0.18	1.5	3/2.5	-124.2	-181
[13]	CMOS 0.13	2.0	3/5.6	-122	-183
[14]	CMOS 0.25	7.0	3/5.35	-123	-181

in Fig. 4. Thus, the average output power is around -0.41 dBm and -10.9 dBm at the low band and the high band, respectively.

A widely used figure of merit (FOM) for the VCO is defined as [13]

$$\mathrm{FOM} = \mathrm{L}\{\mathrm{f_{offset}}\} - 20\log\left(\frac{\mathrm{f_o}}{\mathrm{f_{offset}}}\right) + 10\log\left(\frac{\mathrm{P_{DC}}}{1\ \mathrm{mW}}\right) \quad (4)$$

where $L\{f_{\mathrm{offset}}\}$ is the measured phase-noise at offset frequency f_{offset} from the carrier frequency f_o. P_{DC} is VCO power consumption in mW. Table I shows the performance summary and comparisons to those VCOs recently published.

A die photograph of the VCO is shown in Fig. 5. The chip size is 0.8×0.5 mm^2. This should be around 25% smaller than the area that would have occupied by two separate VCOs operating near the 2.4-GHz band and 5.15-GHz band.

IV. CONCLUSION

A fully integrated dual-band LC VCO at 2.4 GHz/5.15 GHz fabricated in a CSM 0.18-μm process was presented. Typical measured phase-noise at 3-MHz offset is -126 dBc/Hz and -135 dBc/Hz in the 5.49-GHz and 2.47-GHz bands with 3.6 and 5.4-mW power consumption, respectively. The dual band VCO achieves PFTN phase-noise FOMs of 188.3 and 183.7 at a 3-MHz offset frequency, which is one of the highest reported to date. These results also demonstrate that by using a complementary cross-coupled LC tank VCO, which followed a frequency doubler to operate, up to 5 GHz can be implemented and the phase-noise is better than that of the 5-GHz single band VCOs.

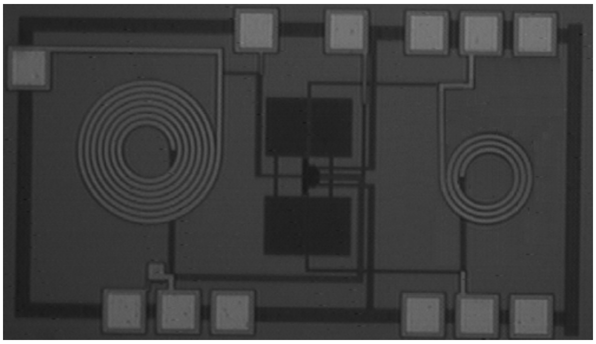

Fig. 5. Die of the dual band LC tank VCO.

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