A mm-Wave $40\,$nm CMOS Subharmonically Injection-Locked QVCO with Lock Detection

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***Abstract*—This paper demonstrates a $40\,$nm CMOS mm-wave subharmonically injection-locked QVCO with a lock detection mechanism. The locking range is more than $2\,$GHz over the 55-$63\,$GHz tuning range. An envelope detector simplifies the calibration of the QVCO. In addition, the lock detector, based on passive mixing, detects the lock condition simply by a change in the DC operating point. The large locking range, the large tunability and the combination of envelope detector and lock detector offer a simple approach for robust mm-wave frequency synthesis based on subharmonic injection locking.**

I. Introduction

Subharmonic injection locking has recently been investigated for mm-wave frequency synthesis phase-locked loops (PLLs), [1], [2]. It avoids the use of mm-wave frequency dividers while phase noise is shaped by the injected signal. In addition, for mm-wave phased-array transceivers with phase shifting at baseband or in the local oscillator (LO) path, the mm-wave oscillators can be positioned close to the mixers while only an n-times lower-frequency injection-locking signal instead of a mm-wave LO signal has to be distributed to the different antenna paths. This leads to a lower power consumption and a more robust LO distribution.

On the other hand, the locking range (LR) of mm-wave subharmonically injection-locked oscillators is typically narrow (just a few hundreds of MHz). Consequently, disturbances can easily bring the system out of lock. Because of this, a runtime control is often needed. A frequency-tracking control is proposed in [1]. A simplified scheme of frequency tracking is shown in Fig. 1.a. This approach becomes complex at mm-wave frequencies because a mm-wave frequency divider is needed. Such a complexity is relaxed in [3], where the mm-wave frequency divider is substituted by a mixer and a high-frequency doubler, as shown in Fig. 1.b.

The robustness of subharmonic injection locking can be improved by making the LR so wide that no runtime control is needed and only an off-line calibration is sufficient [2], [4].

This paper proposes a 55-$63\,$GHz subharmonically injection-locked QVCO (SHIL-QVCO) with a calibration circuitry. A large LR ($>2\,$GHz) is achieved by using coupled resonators [4]. The calibration circuitry is based on an envelope detector and a lock detector (LD), hereby avoiding the need for high-frequency dividers and doublers (see Fig. 1.c). In addition, the output of such detectors is at DC and this can relax the digital calibration requirements. All this makes the proposed approach simpler than the state-of-the-art approaches.

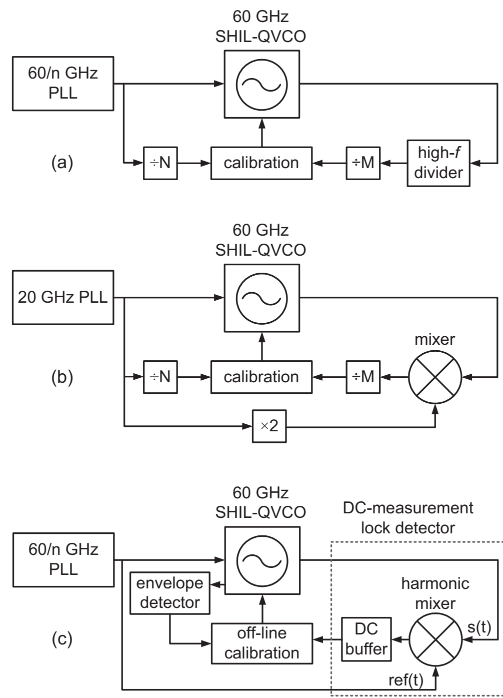

Figure 1. Different calibration methods for a mm-wave SHIL-QVCO: (a) frequency-tracking, (b) method in [3], (c) proposed method.

The outline of the paper is as follows. Section II explains the LD working principle, section III focuses on the system implementation, section IV reports measurement results and section V draws conclusions.

II. Mixer-based lock detector

The LD takes as input the SHIL-QVCO output signal and the subharmonic injected signal, and assumes either a *high* state or a *low* state whether the SHIL-QVCO is either locked or not. It can be seen as a lock-in amplifier [5] mixing a sinusoidal source signal (the SHIL-QVCO output) with a sinusoidal quadrature reference (the subharmonic signal), as depicted in Fig. 2. We define the source signal as

$$s(t) = V_S sin(\omega_s t + \theta_s), \tag{1}$$

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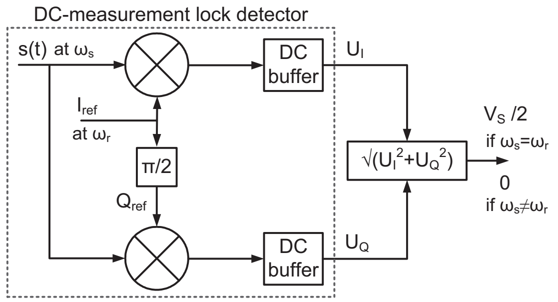

Figure 2. A quadrature mixer used as lock detector. This is a single-ended equivalent of the differential circuit.

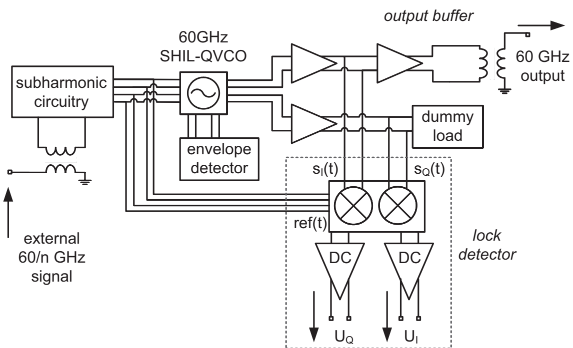

Figure 3. System block diagram.

and the quadrature reference as

$$I_{ref}(t) = sin(\omega_r t), \quad Q_{ref}(t) = sin(\omega_r t + \pi/2). \quad (2)$$

Considering the (differential) DC voltage outputs of the lock-in amplifier (Fig. 2), it can be shown that

$$\begin{aligned} \omega_s \neq \omega_r &\Rightarrow U_I = U_Q = 0 \quad (i), \\ \omega_s = \omega_r &\Rightarrow \sqrt{U_I^2 + U_Q^2} = \frac{V_S}{2} \quad \forall \theta_s \quad (ii). \end{aligned} \quad (3)$$

We can thus define condition (i) as *low* state and condition (ii) as *high* state. Because of DC offset, condition (i) may not be zero. However, *high* state and *low* state can be distinguished. In this work the LD uses harmonic mixing. Given the SHIL-QVCO oscillating at ω_{osc}, then with a subharmonic injected signal at $\omega = \omega_{SH}$, the LD assumes the *high* state when

$$\omega_{osc} = n \times \omega_{SH}. \quad (4)$$

III. System implementation

The system presented in this paper consists mainly of three parts (see block diagram of Fig. 3): a 60 GHz SHIL-QVCO, a LD based on passive mixers, a subharmonic circuitry (operated at 60 GHz$/n$, with n an odd integer).

A. 60 GHz *SHIL-QVCO*

The 60 GHz SHIL-QVCO (see Fig. 4) consists of two differential LC-tank oscillators coupled to each other through transconductors $M_{3,4}$. Coupled resonators ($L_1C_1 - L_2C_2$) are used to achieve a large LR [4]. The output signal is taken

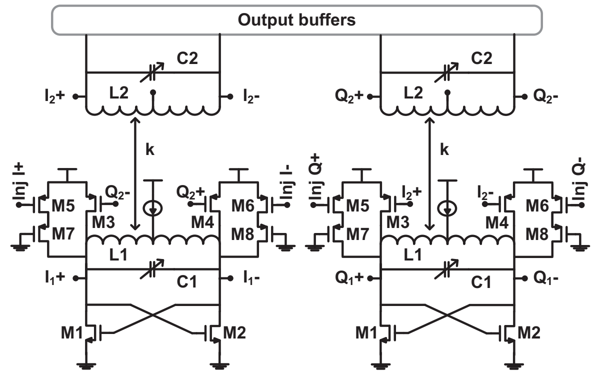

Figure 4. SHIL-QVCO schematic.

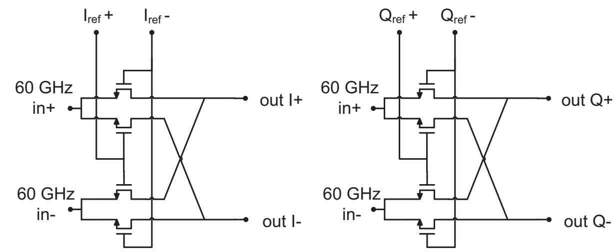

Figure 5. LD mixer implemented by a passive harmonic mixer.

from the secondary (L_2C_2). The coupling factor k is 0.2 and L_2=103 pH is larger than L_1=75 pH in order to boost the output signal. The transformer Q factor is around 13.5. The cross-coupled pairs $M_{1,2}$ provide the negative conductance necessary for the oscillation. The subharmonic signal is injected into both differential oscillators through cascodes $M_{5,7}$ and $M_{6,8}$. The cascode topology is chosen to emphasize the n-th harmonic of the injected signal.

The SHIL-QVCO needs to be calibrated to allow a large LR. First, C_1 is chosen for the desired coarse value of the output frequency. Then, C_2 has to be tuned for a particular ratio C_2/C_1. This can be done by sweeping C_2 and measuring the relative minimum of the free-running oscillation amplitude [4]. For this task an envelope detector is implemented, which monitors the oscillation at the primary resonator (L_1C_1) and provides a DC output proportional to the oscillation amplitude. The setting of C_2, which gives a peak in the envelope response, implies a large LR (Fig. 8).

B. *Lock detector*

The LD mixes the SHIL-QVCO quadrature output, denoted as $s_I(t)$ and $s_Q(t)$ in Fig. 3, with the subharmonic quadrature injected signal $ref(t)$. Since the quadrature mixer in Fig. 2 has a differential source input $s(t)$, two mixers are used for $s_I(t)$ and $s_Q(t)$ respectively. In this way, the load of the SHIL-QVCO quadrature buffer is balanced. The LD mixers are implemented as passive harmonic mixers consisting of switched MOS resistors (see Fig. 5). The nonlinearity of these MOS devices is necessary for harmonic mixing.

C. *Subharmonic circuitry*

The subharmonic circuitry (see Fig. 6) distributes and injects a subharmonic signal of frequency 60/n GHz into

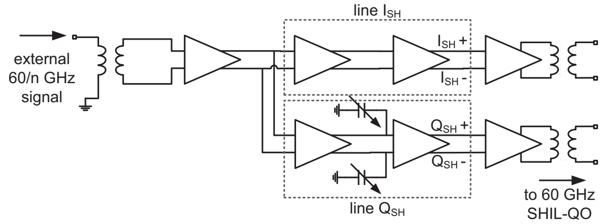

Figure 6. Subharmonic circuitry block diagram.

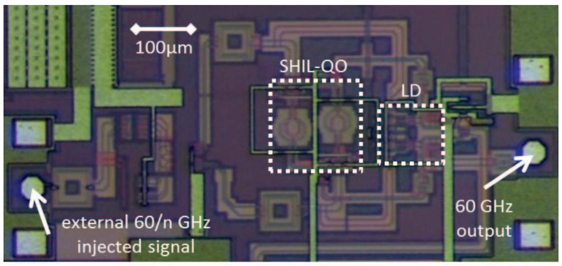

Figure 7. Chip photograph where the SHIL-QVCO and the LD are indicated.

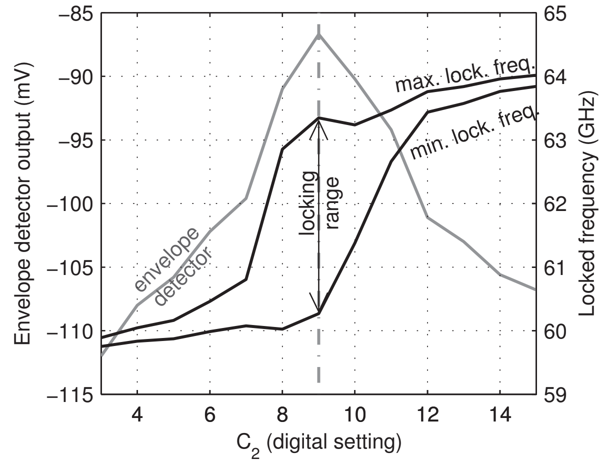

Figure 8. Measured envelope detector output and LR, with C_1 fixed and C_2 swept. The envelope detector output is taken when the SHIL-QVCO is free-running. C_2=9 gives a peak in the envelope response, which corresponds to a relative minimum of the free-running oscillation amplitude and to a large LR [4].

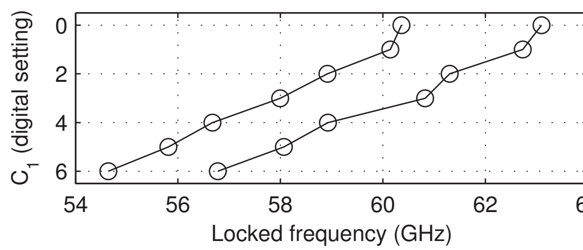

Figure 9. LR moved over the frequency. The LR is larger than 2 GHz, covering the range of 55 to 63 GHz, under injection of 20 GHz.

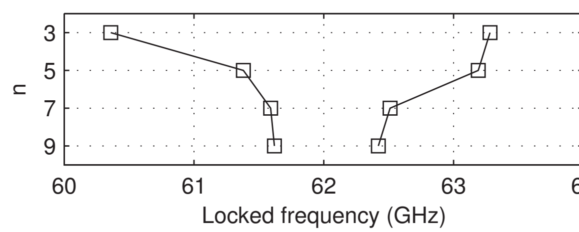

Figure 10. LR for different orders of subharmonic injection.

the 60 GHz SHIL-QVCO, converting it from single-ended to quadrature. Only n odd integer is used since the circuits are differential. An external 60/n GHz signal is converted from single-ended to differential by an on-chip balun. This differential signal is buffered by two pseudodifferential lines (I_{SH} and Q_{SH}) consisting of cascades of CMOS inverters. Line Q_{SH} is delayed with respect to line I_{SH} by a variable capacitive load. The resulting signals (I^+_{SH}, I^-_{SH}, Q^+_{SH} and Q^-_{SH}) are then buffered and injected into the SHIL-QVCO.

For an optimal injection-locking efficiency, the phase difference between I_{SH} and Q_{SH} should match the IQ phase of the SHIL-QVCO, which is $\pi/2$ at 60 GHz. Therefore, the variable capacitive load is tuned so that

$$\angle I_{SH} - \angle Q_{SH} = \frac{\pi}{2} \text{ at } 60\,\text{GHz} \equiv \frac{\pi}{2n} + \frac{2k\pi}{n} \text{ at } \frac{60}{n}\text{GHz}, \quad (5)$$

with k an integer.

IV. Measurement Results

The system is realized in 40 nm digital CMOS (see Fig. 7). An external signal generator provides the single-ended subharmonic signal. The SHIL-QVCO (together with buffers, envelope detector and bias circuitry) consumes 35mA from a 0.9 V supply.

A. SHIL-QVCO

The SHIL-QVCO needs to be calibrated in order to obtain a large LR. As mentioned above, this is done through the envelope detector. First, C_1 is chosen for the desired coarse value of the output frequency, then C_2 is swept and the free-running oscillation amplitude is monitored. The value of C_2 which gives a peak in the envelope detector's response, is the one to be chosen for large LR, as measured and reported in Fig. 8.

The LR can be moved over the frequency by changing C_1. Fig. 9 shows a LR of more than 2 GHz over a tuning range of 55-63 GHz under an injection of 20 GHz (estimated single-ended amplitude of 450 mVpp at $M_{5,6}$ gates).

Different frequencies at 60/n GHz can lock the SHIL-QVCO, with n an odd integer. Fig. 10 shows the LR under injection with n = 3, 5, 7 and 9. Thanks to the use of coupled LC resonators, the LR is relatively large (0.8 GHz) even with $n = 9$. The LR decrease from n=3 to n=9 can be explained by the fact that the 9th harmonic generation is not so efficient as the 3rd harmonic one.

B. Lock detector

The LD detects the lock condition with a *high* state of $\sqrt{U_I^2 + U_Q^2}$. Fig. 11 shows a case with a 20 GHz injection (n=3) and C_2/C_1 tuned for large LR. Fig. 12 reports a case with n=3 and C_2/C_1 not tuned for large LR. Fig. 13 shows a case with a 12 GHz injection (n=5). In all these cases the lock condition is detected. Therefore this LD can be used also

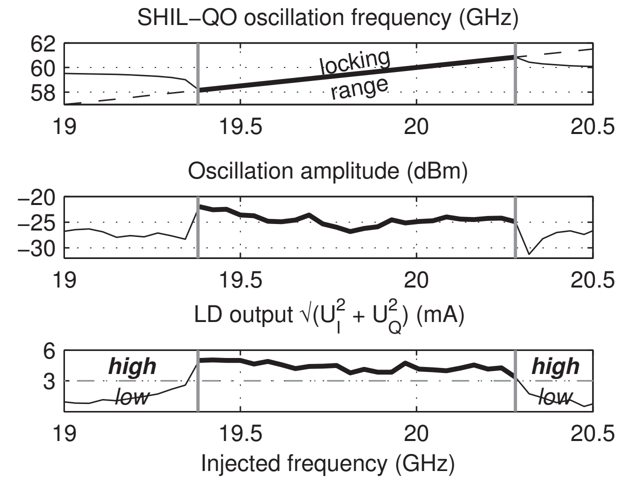

Figure 11. SHIL-QVCO and LD outputs for a particular case of 20 GHz injection (n=3), where C_2/C_1 is tuned for large LR. The lock condition (thick line) is detected as *high* state of the LD output. The oscillation amplitude is taken from the 60 GHz output buffer (cable loss not deembedded).

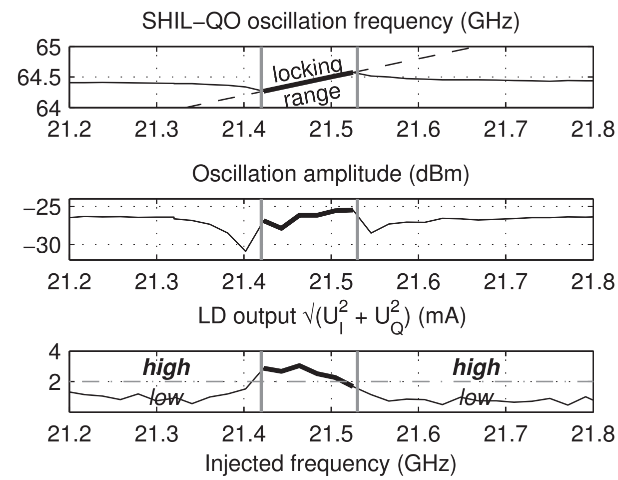

Figure 12. SHIL-QVCO and LD outputs for a particular case of 20 GHz injection (n=3) and narrow LR. The lock condition is in thick line.

for narrow LRs and different n, given that the n-th harmonic generation is efficient in both the LD passive mixer and the SHIL-QVCO.

C. Proposed calibration

The SHIL-QVCO can be calibrated through the envelope detector and the LD. Like in [3], the subharmonic signal frequency is assumed to be known. We propose the following: (i) set C_1; (ii) tune C_2 for large LR through the envelope detector (Fig. 8); (iii) sweep the subharmonic signal frequency and record, through the LD, whether the SHIL-QVCO is locked or not (Figs. 11-13). Reapeating these steps for each C_1 setting, the LR is known over the frequency (Fig. 9). Such a calibration requires no frequency measurement. Only the DC outputs of the detectors need to be processed by a digital circuitry, which is not implemented in this work.

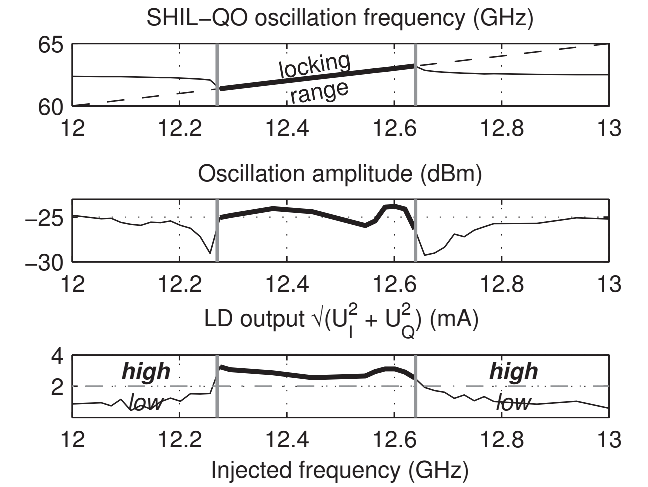

Figure 13. SHIL-QVCO and LD outputs for injection of 12 GHz (n=5). The lock condition is in thick line.

V. CONCLUSIONS

We demonstrate a $40\,$nm CMOS mm-wave subharmonically injection-locked QVCO with large locking range and simple calibration. Under a $20\,$GHz injection, the locking range is more than $2\,$GHz over the 55-$63\,$GHz tuning range. The SHIL-QVCO can operate also under other injection frequencies (60/n GHz with n = 5, 7, 9), still achieving a locking range larger than $0.8\,$GHz. Calibration is performed through an envelope detector and a lock detector. This simplifies the system with respect to state-of-the-art approaches since nor high-frequency dividers neither high-frequency doublers are needed. Further, the proposed lock detector can work with different injected frequencies (60/n GHz, n = 3, 5) and narrow locking ranges as well. The large locking range, the large tunability and the simple calibration offer a simple and robust approach for mm-wave frequency synthesis based on subharmonic injection locking.

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