A Dual-band LO Generation System Using a 40GHz VCO with a Phase Noise of -106.8dBc/Hz at 1-MHz

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***Abstract* — This paper demonstrates a dual-band LO generation system using a low phase noise single-band 40GHz VCO as the signal source. The LO generation system has two outputs: single-band LO1 at 20GHz and dual-band LO2 switchable between 10GHz and 15GHz. Implemented in 0.25-µm SiGe:C BiCMOS, the VCO achieves a phase noise of -106.8dBc/Hz at 1-MHz offset from 40GHz with a frequency tuning range of 9.7%.**

***Index Terms* — VCO, LO generation, dual-band, phase noise, frequency divider, mixer**

I. Introduction

The demand for reconfigurable microwave and millimeter-wave radio transceivers which can support multiple bands and multiple standards has increased recently. One of the challenges in multi-band radio frequency (RF) front-ends is the design of a low phase noise voltage-controlled oscillator (VCO) that can cover multiple distinct frequency bands. Switched capacitors and/or inductors in the resonant tank can be used [1]. However, designing switches at microwave and millimeter-wave frequencies is extremely difficult due to the trade-offs between insertion-loss and isolation [2]. For microwave and millimeter-wave frequencies, instead of switching the resonant tank values other techniques have been developed to cover multiple distinct frequency bands, like changing the core current [3], and switching the transistor's g_m [4]. However, their phase noises are not low enough for systems that require a low phase noise such as wireless back-haul and radar applications.

In this paper, using a low phase noise single-band 40GHz VCO as the signal source, a new approach is proposed to design a dual-band local oscillator (LO) generation system suitable for 30/35GHz dual-band transmitter applications. The dual-band LO system is intended for point-to-point (P2P) base stations back-haul at 30GHz and radar applications at 35GHz.

II. System Architecture

The circular polarization is widely used in modern P2P back-haul and radar systems. In order to form a circular

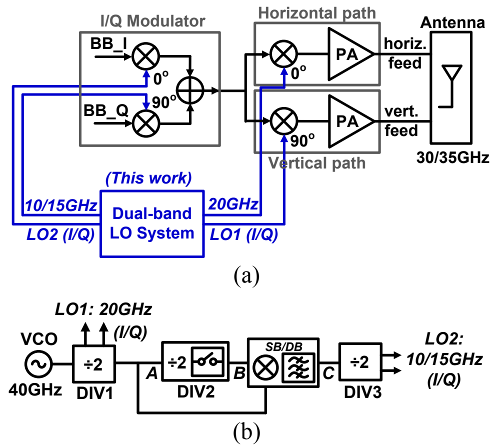

Fig. 1. (a) 30/35GHz transmitter with the dual-band LO system (b) Block diagram of the dual-band LO system.

polarization, the antenna requires horizontal and vertical polarized signal feeds. Fig. 1(a) shows the overall 30/35GHz transmitter architecture with the proposed dual-band LO system, suitable for a circular polarization. The in-phase (I) and quadrature-phase (Q) signals of LO1 (single-band at 20GHz) drive the mixers in the horizontal polarized and vertical polarized signal paths respectively to output the required feeds to the antenna. The baseband (BB) I/Q modulator is driven by the dual-band LO2 (switchable between 10GHz and 15GHz). The quadrature phases of the LO2 signal are required by the BB I/Q modulator. Typically a 40dB image rejection is sufficient for P2P back-haul. The intermediate frequency (IF) is 10/15GHz, and the RF is therefore dual-band (i.e. 30/35GHz). Fig. 1(b) shows the block diagram of the proposed dual-band LO generation system. A 40GHz VCO is used as the signal source. The quadrature outputs of LO1 at 20GHz are generated with the first divide-by-two frequency divider (DIV1). The second divide-by-two (DIV2) is turned on if 15GHz is selected as the frequency of LO2. The 20GHz signal is now again divided by two resulting in a 10GHz signal at node B, which serves as one of the two inputs of the mixer. The 20GHz signal at node A is the other input of the mixer. The output of the mixer therefore consists of a wanted signal at 30GHz and an image signal at 10GHz. The filtering embedded in the mixer suppresses the image signal at 10GHz, resulting in

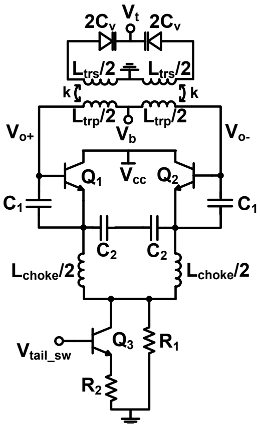

Fig. 2. Circuits diagram of the 40GHz VCO.

a 30GHz signal at node C. When the upper-band of LO2, i.e. 15GHz, is selected, the mixer operates in a double-balanced (DB) mode to suppress the LO1 feedthrough of 20GHz. The 30GHz output from DIV2 is divided by the third div-by-two (DIV3) to generate LO2 at 15GHz as a quadrature signal. If the lower-band (i.e. 10GHz) of LO2 is selected, DIV2 is turned off and the mixer operates in single-balanced (SB) mode to pass the 20GHz signal directly to node C. DIV3 divides the 20GHz to generate an LO2 of 10GHz, again as a quadrature signal.

III. CIRCUIT DESCRIPTION

A. 40GHz VCO

As shown in Fig. 2, the chosen VCO topology is a common-collector Colpitts architecture. Capacitors C_1 (215fF) and C_2 (180fF) form a positive feedback to generate sufficient negative resistance to compensate the loss in the transformer-coupled resonant tank that consists of a transformer and a differential varactor. The main advantage of using the transformer-coupled tank is that the highest quality factor (Q-factor) of a differential varactor can be realized using a common-cathode structure without additional grounding resistors [5]. A differential choke inductor L_{choke} is used to minimize the noise contributions from the tail bias. The tail biasing circuit consists of a resistor R_1 in parallel with an additional biasing branch formed by Q_3 with the emitter degenerated by R_2. This additional biasing branch can be switched on or off by the voltage V_{tail_sw}.

In order to achieve a low phase noise, the resonant tank is designed with a low impedance (i.e. small inductances of the transformer) allowing more current to flow through the tank for a fixed tank voltage swing. The swing is limited by the break-down voltage of transistors Q_1 and Q_2 or by the supply voltage. With a higher current

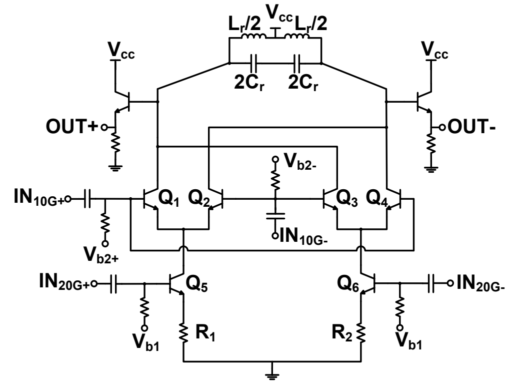

Fig. 3. Circuits diagram of the reconfigurable mixer.

through the tank, a higher carrier power can be achieved, resulting in a better signal-to-noise ratio (and thus phase noise). However, too small inductances of the transformer can result in a too low Q-factor, which may offset the phase noise improvement. Hence, the tank impedance must be optimized for the optimum phase noise. The lateral-coupled transformer uses the top metal layer for both the primary and secondary windings to achieve a higher Q-factor. The primary inductance L_{trp}, and the secondary inductance L_{trs} of the transformer are 114pH and 162pH, respectively with a coupling factor k=0.6. The simulated Q-factor of the transformer is 22 at 40GHz.

To compensate for process and temperature variations, the VCO has to provide sufficient tuning range. However, a large continuous tuning range would result in a degraded phase noise performance. Switching a capacitor array bank is widely used at lower frequencies as way of coarse tuning. However, switches are difficult to realize at 40GHz. Therefore, instead of switching the resonant tank to compensate unwanted frequency variations, two other methods are used in this design to provide coarse tunings. A combination of switching the tail current by V_{tail_sw} and switching the base voltage V_b has been applied. Both methods change the oscillation frequency by changing the intrinsic capacitances of the transistors. By switching the tail current from 21mA to 29mA, the oscillation frequency decreases by 1.3%. By switching V_b from 2.65V to 3.15V, the oscillation frequency decreases by 3.3%. Therefore, for the coarse tunings V_{tail_sw} is used as the least significant bit (LSB), while V_b is used as the most significant bit (MSB). Note that unlike in [3] where the change in core current is used to switch the VCO frequency between two distinct bands, in this work the change in tail current only needs to provide a coarse frequency tuning. To achieve two distinct frequency bands, the mixing action in the LO generation system is used. Therefore, the needed change in current is much smaller than in [3], which reduces phase noise

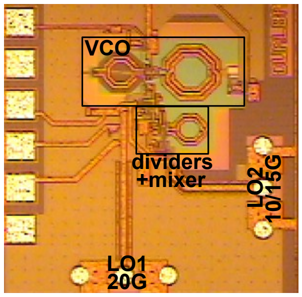

Fig. 4. Die photo of the core circuits.

degradation due to large current change. The continuous fine tuning is achieved by changing V_t to vary the varactor's capacitance. The fine tuning covers around 4% of the continuous frequency tuning range.

B. Reconfigurable mixer and frequency dividers

The reconfigurable mixer is based on the double-balanced Gilbert topology (see Fig. 3), where Q_1~Q_4 are switched by the 10GHz signal. The 20GHz signal inputs to Q_5 and Q_6. When the upper-band is selected, the mixer operates in the double-balanced mode, which suppresses the 20GHz feed through to the output. When the lower-band is selected, one half of the mixer is turned off by setting V_{b2-}=0V. The mixer operates then in the single-balanced mode to pass directly the 20GHz to the output.

The output of the mixer is loaded with an LC resonant tank formed by L_r and C_r to provide band-pass filtering. The center frequency of the LC tank is chosen to be between 20GHz and 30GHz to have a higher suppression to the 10GHz image signal at the output of the mixer while not suppressing too much on the wanted signal at 20GHz (lower-band selected) or 30GHz (upper-band selected). The requirement on image suppression is not too stringent; the image signal amplitude at the output of DIV3 should be too weak to drive the mixer in the signal path of the corresponding transmitter or receiver. An attenuation of 20dB will be sufficient. The mixer including the output buffers consumes 33mW DC power.

The frequency dividers are straight-forward master-slave current-mode-logic (CML) dividers with resistive loading [6]. The currents of the succeeding divide-by-two dividers are scaled according to its operating frequency to lower the overall power consumption.

IV. MEASUREMENT RESULTS

The micrograph of the fabricated LO system is shown in Fig. 4. The chip is implemented in a 0.25-µm SiGe:C BiCMOS. The area of the core circuits excluding pads is 400µm×450µm. From a 3.3V supply, the VCO core consumes 69.3~105.6mW depending on the tail current

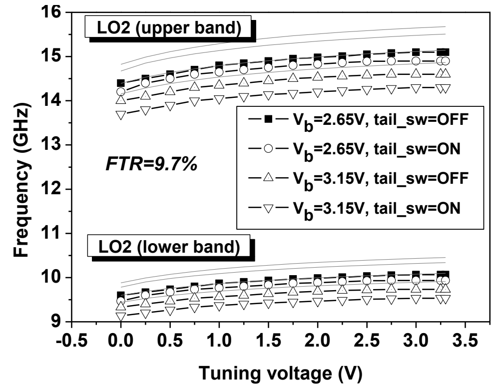

Fig. 5. Measured frequency tuning at LO2 of the LO system (simulated results shown as straight lines).

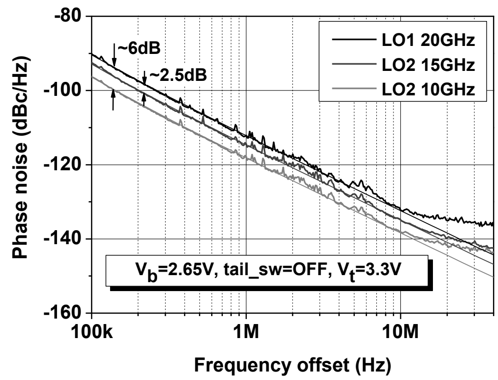

Fig. 6. Measured phase noise at LO1 and LO2 of the LO system (simulated results shown as straight lines).

and the rest of the system consumes 105.6~125.4mW depending on the frequency band selection of LO2.

The measured frequency tuning at LO2 is shown in Fig. 5. Note that the frequency tuning curves at LO1 are identical, only with a frequency shift. By combining the coarse tuning and the varactor's fine tuning, the measured frequency of LO2 can be tuned from 13.7GHz to 15.1GHz when the upper-band is selected and from 9.13GHz to 10.07GHz when the lower-band is selected. The frequency tuning range is therefore 9.7% that is sufficient to cope with process spread and temperature-dependent frequency drift. The oscillation frequency of the 40GHz VCO is tunable from 36.5GHz to 40.3GHz.

The measured phase noise behavior at LO1 and LO2 is shown in Fig. 6. The phase noise of LO2 when the lower-band is selected (10GHz) is 6dB lower than the phase noise of LO1 (20GHz), which is in agreement with a frequency division by 2. For an LO2 of 15GHz, the frequency division ratio is 4/3 or 2.5dB. The measured phase noise of LO2 at 15GHz is indeed 2.5dB lower than that of LO1 (see Fig. 6). These observations also indicate that the phase noise degradation due to the frequency dividers and the mixer is negligible. Therefore, based on

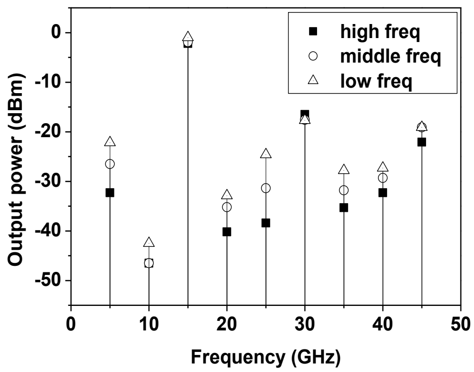

Fig. 7. Measured spectrum at LO2 (upper-band selected).

the measured phase noise of LO1, the phase noise of the 40GHz VCO is found to be -84.1dBc/Hz and -106.8dBc/Hz at 100-kHz and 1-MHz offsets respectively. It is noted that the phase noise roll-off is -20dB/dec between 100-kHz and 1-MHz offsets, which indicates superior close-in noise performance of the 40GHz VCO.

The measured frequency spectrum at LO2, when the lower-band of 10GHz is selected, shows only the harmonics of LO2. This is expected as only integer frequency division takes place in the LO system. When the upper-band of 15GHz is selected, the suppression of the spurs due to the image signal at the mixer's output (i.e. 5GHz) is -20dBc~-30dBc (see Fig. 7). The spurious tone at 5GHz and 10GHz are too weak to cause frequency mixing issues in a transmitter/receiver signal path.

Table I compares the performance with other single-band and dual-band VCOs. For performance comparison, the normalized phase noise (PN_{norm}), the phase noise's figure of merit (FOM_{PN}) and the figure of merit considering phase noise with tuning range (FOM_T) are used. Note that PN_{norm} is used to assess only the phase noises at different frequencies. The proposed dual-band LO system achieves superior PN_{norm}, FOM_{PN} and FOM_T.

V. Conclusion

Using a low phase noise single-band 40GHz VCO as the signal source, a dual-band LO generation system is proposed for a 30/35GHz dual-band transmitter. The LO system achieves outstanding phase noise and FOMs.

Acknowledgement

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TABLE I
PERFORMANCE COMPARISON WITH SINGLE-BAND AND DUAL-BAND VCOS

	[7]	[8]	[3]	[4]	This work
Freq (GHz)	35.3	45	45/60	24/60	VCO: 38.4 [LO1: 19.2; LO2: 9.6/14.4]
Technology	0.13-µm BiCMOS	0.12-µm BiCMOS	0.25-µm BiCMOS	0.13-µm CMOS	0.25-µm BiCMOS
PN @1M (dBc/Hz)	-97	-91	-99/-93 (@10M)	-120/-114 (@10M)	VCO: -106.8 [LO1: -112.8; LO2: -118.7/-114.8]
FTR (%)	8.2	6.5	8.5/4.1	10.8/7.2	9.7
P_{DC}(mW)	50	13.8	32.5/17.5	11/24	VCO: 69.3~105.6 other: 105.6~125.4
PN_{norm} (dBc/Hz)	-188	-184.1	-172.1/-168.6	-187.6/-189.6	-198.9
FOM_{PN}	171.4	173	158/156	177/176	178.7~180.5
FOM_T	169.7	169.3	156.6/148.3	177.7/173.1	178.4~180.2
Remarks	single-band VCO	single-band VCO	dual-band VCO	dual-band VCO	dual-band LO system

$PN_{norm} = L\{\Delta f\} - 20log\frac{f_{osc}}{\Delta f}$; $FOM_{PN} = -L\{\Delta f\} + 20log\frac{f_{osc}}{\Delta f} - 10log\frac{P_{DC,core}}{1mW}$; $FOM_T = FOM_{PN} + 20\log(10 \cdot FTR)$