A 7.5 mW −43 dB LO leakage source-driven wideband CMOS millimeter-wave mixer

Jiafu Lin,1 Chirn Chye Boon,2 Roc Berenguer,3 and Gui Liu1✉

1College of Electrical and Electronic Engineering, Wenzhou University, Wenzhou, Zhejiang, China
2School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, Singapore
3Department of Electric and Electronics Engineering, School of Engineering of the University of Navarra, Pamplona, Spain

✉Email: itgliu2@gmail.com

This paper presents a millimeter-wave (mm-wave) V-band mixer. The source-driven transformer-coupled up-converter topology can alleviate the local oscillator (LO) leakage problem. The proposed V-band up-converter has been implemented on 65 nm CMOS technology. The experimental results show that the LO leakage level can be reduced to −43.1 dB. The up-converter occupies 0.11 mm² in area excluding signal pads.

Introduction: In a mm-wave transmitter, the up-conversion mixer converts a lower intermediate frequency (IF) signal to a higher radio frequency (RF) to provide efficient power transmission. The local oscillator (LO) leakage on the spectrum of transmitter output can degrade error vector magnitude (EVM) performance substantially. In addition, the LO leakage further mixes with output signals and generates intermodulation output around desired frequency band, which further deteriorates EVM performance.

Frequency conversion circuit can generate significant LO leakage, especially for CMOS technology because of the lossy substrate [1]. Due to the increased parasitic effects at mm-wave frequencies, the demand of large LO-driven power would further contribute to the LO leakage. Meanwhile, path mismatch of mm-wave LO signal can inevitably lead to amplitude and phase imbalance. The amplitude and phase imbalance directly result in non-linearity and LO leakage at the output [2,3]. Therefore, double-balanced structure is preferred over other topologies in terms of LO leakage performance [4–7].

In this work, we investigate a transformer-coupled topology for the up-conversion circuit to eliminate non-linearity trans-conductance stage and minimize parasitic capacitance between LO source and RF output. The mixer core is as symmetrical as possible to avoid LO leakage to the output. Therefore, the LO leakage can be minimized and the linearity can be improved significantly.

Design principle: As shown in Figure 1, a source-driven transformer-coupled up-conversion mixer is proposed. The LO signal is provided by a 1:1 vertical-coupled on-chip transformer with a radius of 26 µm. The simulated insertion loss of transformer is approximately 0.8 dB. A 1:1 transformer based balun with radius of 22 µm is employed at the RF output. The size of the transistors is properly selected to trade off the required LO power and switching loss. All transistors (M1, M2, M3 and M4) are of the same size (the width is 10 µm and the length is 65 nm).

During switching operation, output impedance of switching pair is approximate to the impedance of transistor output. An impedance matching network is designed using transformer to maximise the output power. The proposed up-converter employs a passive transformer for transconductance stage, which has several advantages. First, no voltage drop is required to maintain the transconductance stage operating in the saturation region. Therefore, the distortion owing to transconductance (gm) can be fully eliminated. Second, the common gate input for the LO signal has a wide input bandwidth, which is approximately 1/gm. Therefore, the matching effort in the LO path can be greatly reduced. The 1:1 ratio on-chip transformer can simultaneously provide impedance matching and perform single-ended to differential conversion in a compact size. In contrast, conventional Gilbert mixer requires impedance matching in the LO path, otherwise a large drive power is required. By reducing LO drive power, the LO leakage can also be minimized. Last but not least, non-linearity due to device mismatch of transconductance is avoided due to the elimination of the transconductance transistors.

Therefore, employing LO signal at the source terminals instead of gate terminals shows superior RF performance for the following reasons. Since the IF signal is employed at gate terminal of up-conversion circuit and IF frequency is usually far lower than RF output frequency, the IF signal cannot directly contribute to LO leakage. Although the input balun itself brings phase-and-amplitude mismatches, those mismatches can be cancelled out due to double-balanced operation.

Figure 2a shows a source-drain switching cell employing an interleaved layout. The intrinsic non-symmetry of three-port circuit is carefully planned in layout. An overview of core area of the proposed mixer is given in Figure 2b. The DP and DN ports are differential RF outputs, while LOP and LON ports are differential inputs from the transformer. Both the LO and RF paths are carefully designed to minimize the mismatch. The IFP and IFN are provided from the left side, which are perpendicular to the RF-LO path as shown in Figure 2b. Each four transistors form an interleaved pair in the order of D1-G1-S1-G2-D2-G1-S2-D1. G1 and G2 are connected to IFP and IFN, and S1 and S2 are connected to LOP and LON, respectively. The output D1 and D2 are combined into DP and DN, respectively.

Experimental setup and results: The proposed mm-wave up-converter is fabricated on GlobalFoundries 65 nm CMOS technology. The die photo diagram is shown in Figure 3. The up-converter occupies 280 µm × 280 µm. The experimental results show that the LO leakage level can be reduced to −43.1 dB. The up-converter occupies 0.11 mm² in area excluding signal pads.
400 µm in an area excluding signal pads. The input and output transformers perform single-ended to differential and differential to single-ended conversion, respectively. Additional transmission with transformer is employed for impedance transform at the output. Both LO and RF terminals employ G-S-G pads with pitch distance of 150 µm, while IF signal employs G-S-S-G pads to minimize the die area. The fabricated chip is measured by Cascade Elite 100 on-wafer probe station system. The S-parameter measurement is carried out to check the impedance matching at the input and output without applying any LO and IF signals, and the biasing for switching transistor is approximately 0.6 V. In the setup, 100 measurement points and -30 dBm calibration has been carried out with frequency extension unit Agilent N5260-6003 which can extend the frequency up to 110 GHz.

Figure 4 depicts the measured –10 dB input impedance bandwidth of LO port is 54 GHz, ranging from 38 GHz to 92 GHz. The best matching condition occurs at frequencies from 58 to 68 GHz that the reflection coefficients are less than –20 dB. Therefore, the measurement results well match with the simulation. The measured –10 dB output impedance bandwidth of RF port is 30.8 GHz, ranging from 37.5 to 68.3 GHz. The measured results indicate a wide-band capability of the proposed up-conversion mixer.

Conversion gain (CG) has also been characterized using R&S ZVA67 vector network analyzer and a V-band amplifier to generate LO power from –6 to 6 dBm, as shown in Figure 5. The IF signal is generated from Agilent 81180A arbitrary waveform generator with a maximum allowable IF frequency up to 250 MHz. The output is evaluated by Agilent N5247A PNA-X Microwave Network Analyzer. A maximum –14 dBm output has been achieved with –3 dBm LO power and a conversion gain approximately –11 dB which is 3 dB less than the simulation results. The measured output power can be as large as –5 dBm with 6 dBm LO power.

Figure 6 shows the LO leakage is measured over IF input power from –16 to 5 dBm due to the difference between output power at the LO frequency and input LO power level. The measured LO leakage is –43 dB at –6 dBm LO output or –3 dBm LO input with –16 dBm IF input. The worst case happens when the mixer is under 6 dBm LO power and 5 dBm IF input. The leakage is less than –35 dB when the mixer is working in the target power range.

A comparison over state-of-the-art CMOS mm-wave up-conversion mixer is given in Table 1. The comparison table shows the passive source-driven mixer exhibits better performance in terms of bandwidth and power consumption as well as LO leakage. Although conversion gain between RF output and IF input is smaller than that of other works, the large input voltage range of IF signal is achievable from on-chip IF amplifier, thus will not limit the practical application of source-driven mixer in a transmitter. Compared with the mixers presented in [3–5] that employ active LO buffer, the proposed mixer obtains excellent LO leakage suppression without any digital calibration in a compact layout size. This work shows that the source-driven mixer can operate without additional LO buffer which results in lower power consumption, less LO leakage and smaller chip area when employed in a fully integrated transceiver system.

**Conclusion:** This work has demonstrated a wide-band CMOS mm-wave up-converter in 65 nm CMOS technology. The proposed source-driven transformer coupled up-converter alleviates the LO leakage problem. The elimination of employing active transconductance also reduces power consumption. The proposed source driven up-converter has achieved an excellent LO leakage performance.
Table 1. Millimetre-wave up-conversion mixer comparison

| Reference | Topology | RF freq. (GHz) | IF freq. (GHz) | CG (dB) | LO leakage (dB) | DC power (mW) | Area (mm²) | CMOS process (nm) | LO power (dBm) |
|-----------|----------|----------------|---------------|---------|-----------------|---------------|------------|-------------------|----------------|
| [3]       | Gilbert-cell with active balun | 53–65 | 1 | 0.78 | −30.8 | 27.8 | 0.75 | 90 | 0 |
| [4]       | Gilbert-cell with dual negative R compensation | 77–81 | 0.1 | 2.1 (w/o buffer) | −35.9 | 13.6 | 0.599 | 90 | 0.2 |
| [5]       | Fundam-ental drain/Gate pumped | 30–90 | 0.5 | −8.7 ± 1.5 (at LO=90 GHz) | −30.2 | 0.6 | 0.389 | 65 | 4.42 |
| [6]       | Modified Gilbert stacked LO | 34–56 | 0.1 | −4.8 ± 1.5 | >−43 | 7 | 0.5 | 65 | (75–90 GHz) |
| This work | Source- drive | 45.8–90 | 0.25 | −10 | −43.1 | 7.46 | 0.114 | |

Abbreviations: RF, radio frequency; IF, intermediate frequency; CG, Conversion gain; LO, local oscillator.

Acknowledgments: This work was supported in part by the National Natural Science Foundation of China under Grant No. 61671330, the Science and Technology Department of Zhejiang Province under Grant No. LGG19F010009, and Wenzhou City Key Science and Technology Innovation Team Program under Grant No. C20170005.

References

1. Liu, R., et al.: EVM estimation by analyzing transmitter imperfections mathematically and graphically. *Analog Integr. Circuits Signal Process.* 48(3), 257–262 (2006)
2. Tsai, T., Lin, Y.-S.: 15.1 mw 60 GHz up-conversion mixer with 4.5 dB gain and 57.5 dB LO-RF isolation. *Electron. Lett.* 48(14), 844–845 (2012)
3. Chou, M.-L., et al.: A 60 GHz CMOS up-conversion double-balanced mixer with wide IF bandwidth. *Microwave Opt. Technol. Lett.* 58(3), 546–549 (2016)
4. Lin, Y.-S., et al.: 13.6 mW 79 GHz CMOS upconversion mixer with 2.1 dB gain and 35.9 dB LO-RF isolation. *IEEE Microw. Wireless Compon. Lett.* 24(1), 495–497 (2014)
5. Wu, Y.-C., et al.: A novel 30-90-GHz singly balanced mixer with broadband LO/IF. *IEEE Trans. Microw. Theory Tech.* 64(12), 4611–4623 (2016)
6. Zhu, F., et al.: A reconfigurable low-voltage and low-power millimeter-wave dual-band mixer in 65-nm CMOS. *IEEE Access* 7(7), 33359–33368 (2017)
7. Lin, J., et al.: A millimeter-wave CMOS injection-locked BPSK transmitter in 65-nm CMOS. *Electronics* 10(5), 598–604 (2021)