A Low-Power *W*-Band SiGe-HBT Double-Balanced Up-Conversion Mixer With an Integrated Second-Order IF Low-Pass Filter

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***Abstract*—A low-power W-band (75–110 GHz) double-balanced up-conversion mixer using a 0.13 μm SiGe:C BiCMOS technology with f_T/f_{max} = 250/370 GHz is presented. The mixer includes ON-chip transformer baluns at the LO and RF ports for on-wafer characterization. At 91.3 GHz, the active mixer achieves a single sideband (SSB) power conversion gain of 4.1 dB with a 3-dB RF bandwidth (BW) of 30 GHz from 78.1 to 108.3 GHz, covering almost the entire W-band. The linearity performance, characterized by OP_{1dB} and P_{sat}, is 0.6 and 1.8 dBm, respectively while consuming only 11 mW from a 1.8 V supply. Moreover, a second-order IF LC low-pass filter (LPF) with a cutoff frequency of 1.4 GHz is integrated to provide an additional spurious suppression of ∼12 and ∼19 dB at the second and third harmonic of the fundamental IF (i.e., 1.25 GHz). The overall chip area, including the IF LPF is 990 × 540 μm (0.53 mm^2). To the best of authors' knowledge, the active up-conversion mixer achieves the lowest power consumption along with the highest OP_{1dB}/P_{sat} and 3-dB RF BW reported among all prior published W-band SiGe-HBT up-conversion mixers.**

***Index Terms*—BiCMOS, double-balanced, integrated filter, low-power, millimeter-wave, silicon-germanium (SiGe), up-conversion mixer, W-band.**

I. Introduction

E-BAND (60–90 GHz) and W-band (75–110 GHz) fixed wireless access (e.g., wireless backhauls and point-to-multipoint (PtMP) links) is expected to become increasingly prevalent due to its large available bandwidth (BW) (i.e., >5 GHz) and superior network capacity (>10 Gbps) compared to its sub-7 GHz counterpart [1], [2]. Moreover, there is a growing interest in multibeam phased-array systems based on digital beamforming architecture as it offers several advantages including precise amplitude/phase control and scalability/reconfigurability that supports simultaneous generation of multiple beams (e.g., mMIMO) [3], [4]. However, one major drawback of such architecture in the RF-domain is the increased dc power consumption associated with the hardware within each dedicated transmit (TX) and receive (RX) channel, along with power penalties and increased complexity of the digital front-end (DFE). For instance, the number of required up-conversion mixers directly scales with the number of TX channels in a phased array, necessitating the minimization of mixer power consumption while ensuring sufficient conversion gain and linearity performance for higher-order modulation schemes. To date, there have only been a limited number of SiGe active up-conversion mixers [8], [9], [10], [11], [12] reported with marginal OP_{1dB} and considerably higher power consumption.

In this letter, a W-band double-balanced active up-conversion mixer is presented that achieves low-power yet linear operation while mitigating potential spurious tones and harmonics (e.g., sampling clock spurs from DAC and/or nonlinear distortions from TX VGA and active baseband filter) using an integrated second-order IF low-pass filter (LPF). Compared to the conventional approach where a single high-order active filter (e.g., fifth-order Gm-C) is typically employed in the TX baseband lineup [5], the implemented second-order LC LPF can provide further suppression of spurs/harmonics along with a low-order tunable active filter with reduced complexity, noise, linearity, and power consumption penalties while meeting out-of-band (OOB) spurious emission requirements.

II. Up-Conversion Mixer Design

The schematic of the proposed W-band double-balanced up-conversion mixer with integrated RF and LO matching networks (MNs) and a second-order IF LPF is shown in Fig. 1. The up-conversion mixer is fabricated in B11HFC, a 0.13 μm SiGe:C BiCMOS production technology of Infineon AG with six copper metal layers. The process offers a high-speed n-p-n device with a peak f_T/f_{max} collector current density ($J_{C,peak}$) of ∼11 mA/μm^2. The transconductance (g_m) stage (Q_1–Q_2) is based on a resistive-degenerated common emitter (CE) topology with a base-emitter-collector (BEC) device configuration. The emitter length (l_E) of 10 μm is chosen to provide sufficient current driving capability for linearity (OP_{1dB} and P_{sat}). The CE is biased at $J_C = 2.3$ mA/μm^2 for low current consumption. Moreover, degeneration resistors (10 Ω) are added for dc stability and to further improve linearity of the g_m stage at the expense of conversion gain.

A second-order LC LPF at the input of the g_m stage is implemented not only to provide impedance matching at IF but more importantly, to further reject/suppress any spurious

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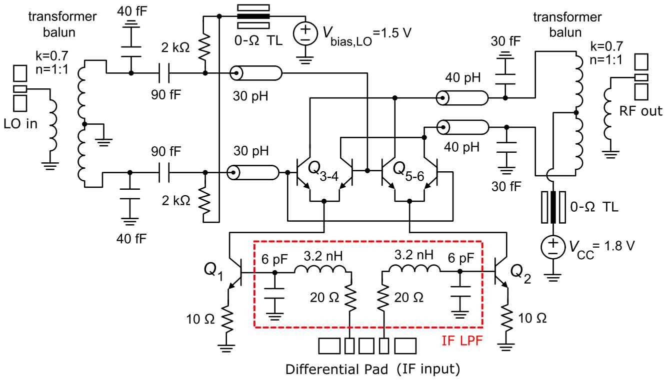
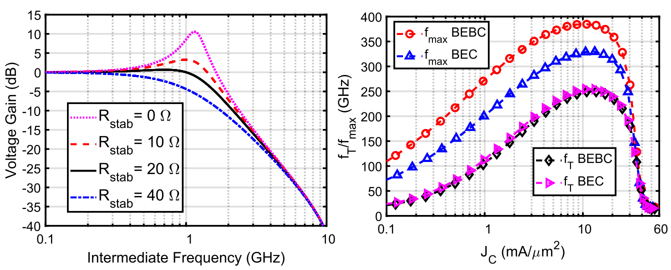


Fig. 1. Schematic of the proposed W-band double-balanced up-conversion mixer with the integrated IF LPF.



(a) (b)

Fig. 2. (a) Simulated voltage gain of the second-order IF LPF loaded with the differential g_m stage for various stabilization resistor values. (b) Measured f_T/f_{max} of devices with BEC and BEBC configuration (l_E = 3 μm and $V_{BC} = -0.3$ V).

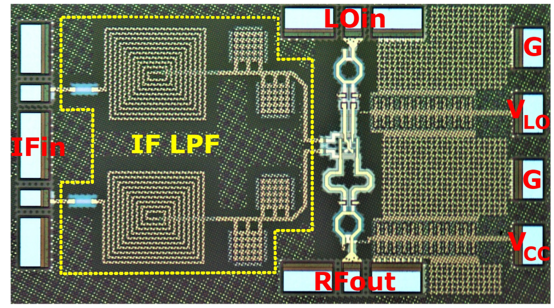


Fig. 3. Chip micro-graph of the up-conversion mixer.

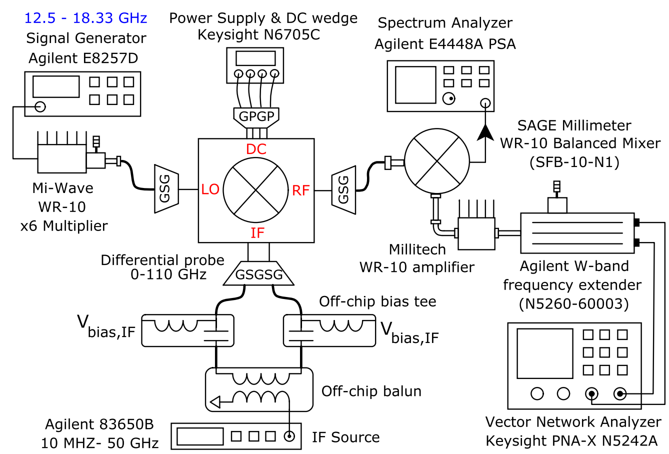


Fig. 4. Large-signal measurement setup.

tones and harmonics generated from the baseband circuitry that could potentially give rise to an undesired OOB emission. The LPF is designed to achieve a cutoff frequency of 1.4 GHz, targeting an RF channel BW of up to 2.5 GHz (corresponding to a baseband BW of 1.25 GHz per E-band block arrangements [6]). The simulated voltage gain is shown in Fig. 2(a) where the differential input and output are taken at the IF input pads and the base nodes of Q_1 and Q_2, respectively. Due to the resonant condition at the LPF cutoff frequency of 1.15 GHz when $R_{stab} = 0\ \Omega$, a peaking of ~10 dB is observed. The amount of peaking is determined by the quality factor (Q) of the filter and is dominated by the series resistance (5.2 Ω) of the inductor. In order to achieve a maximally flat gain response without peaking, a damping resistance of 20 Ω is added for stabilization which reduces the Q of the filter to ~1 and extends the 3-dB cutoff frequency to 1.4 GHz (in simulation), allowing the mixer to operate up to 1.25 GHz (baseband BW) with a 150 MHz margin for process variations. The LC filter has a −40 dB/decade slope which provides an additional 12 dB and 19 dB spurious rejection at the second (2.5 GHz) and the third (3.75 GHz) harmonic of the IF, respectively.

The switching quad transistors (Q_3–Q_6) in BEBC configuration are designed with an l_E of 3 μm and a J_C of 7.7 mA/μm^2. As shown in Fig. 2(b), this selection significantly reduces the base resistance (r_b) with a modest increase in the total input capacitance (C_{be} and C_{bc}) of ~8 fF while maintaining sufficiently high f_T and f_{max} to ensure fast switching for linear operation. Moreover, the required LO power level is also relaxed, thereby simplifying the LO buffer design. Multisection LO and RF MNs which include an LC section (30 pH/40 fF for the LO MN and 40 pH/30 fF for the RF MN) and a vertically-coupled transformer balun (k ~0.7) are used to realize a flat conversion gain response with a wide 3-dB RF BW. The RF MN is also carefully optimized to achieve high linearity (OP_{1dB} and P_{sat}) for a given dc power budget (~10 mW per I- or Q-path). The two transformer baluns (RF and LO) achieve simulated insertion loss of 1–1.5 dB across W-band with an amplitude and phase imbalance of ~0.05 dB and ~0.7°, respectively.

Lastly, the 0-Ω transmission line (TL) utilizes all the metal layers as interdigitated metal-oxide-metal (MOM) capacitors with embedded MIM capacitors along the length of the line [7] to provide broadband ac grounding from 3 to 500 GHz. The entire circuit including the pads is EM-simulated with the 2.5-D ADS Momentum.

III. Measurement Setups and Results

The micro-graph of the fabricated chip is shown in Fig. 3 with an area of 990 × 540 μm including the pads. The large-signal measurement setup is illustrated in Fig. 4 where the LO signal is generated with a signal generator and a ×6 multiplier. The waveguide-to-coaxial adapter, 1-mm cable, and probe losses are de-embedded to calibrate the LO power at the pad. Due to the limited BW of the spectrum analyzer, the output is down-converted using an external WR-10 mixer which has a conversion loss of ~9 dB. A W-band frequency extender along with a WR-10 power

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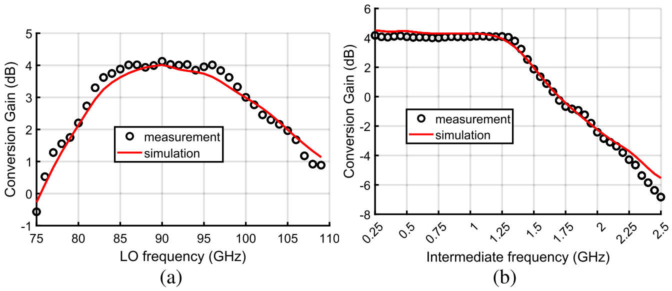

Fig. 5. (a) Measured and simulated SSB CG over LO frequency with $f_{\mathrm{IF}} = 1.25$ GHz and $P_{\mathrm{LO}} = 3$ dBm. (b) Measured and simulated SSB CG over IF with $f_{\mathrm{LO}} = 90$ GHz and $P_{\mathrm{LO}} = 3$ dBm.

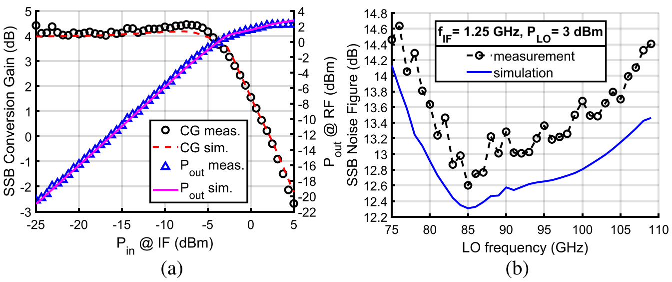

Fig. 6. Measured and simulated (a) SSB CG and output power at $f_{\mathrm{LO}} = 90$ GHz, $P_{\mathrm{LO}} = 3$ dBm, $f_{\mathrm{IF}} = 1.25$ GHz and (b) SSB NF.

amplifier is used to provide the required LO drive for the external down-converter. An OFF-chip balun (500 kHz–40 GHz) and bias-tees (100 MHz–65 GHz) are used to generate and feed the differential IF signals. The calibration of the OFF-chip IF chain is performed separately with respect to the IF using a power meter. S-parameter measurements for port matching are performed with the vector network analyzer and W-band extender. The IF source in Fig. 4 is replaced with a noise source (Agilent 346C 10 MHz–26.5 GHz) at the IF port to measure the single sideband (SSB) noise figure (NF) using the Y-factor method.

The measured conversion gain (USB) over the LO frequency is illustrated in Fig. 5(a) where the peak CG of 4.1 dB is achieved at $f_{\mathrm{LO}} = 90$ GHz with an LO power of 3 dBm. The mixer achieves a wide 3-dB RF BW of 30 GHz from 78.1 to 108.3 GHz thanks to the broadband RF and LO MNs. As shown in Fig. 5(b), the SSB CG over the intermediate frequency demonstrates a flat gain response up to the fundamental frequency of 1.25 GHz with an additional suppression (∼12 dB) at the second harmonic, validating the effectiveness of the second-order LC filter with a −12 dB/octave slope. The large-signal performance of the mixer is depicted in Fig. 6(a) where a measured $\mathrm{OP}_{1\mathrm{dB}}$ of 0.6 dBm and P_{sat} of 1.8 dBm are achieved at $f_{\mathrm{LO}} = 90$ GHz. Excellent agreement between simulation and measurement has been obtained. Fig. 6(b) demonstrates a minimum measured SSB NF of 12.6 dB at 85 GHz and <14 dB from 79 to 106 GHz.

The measured RF and LO port return losses are better than 10 dB across the entire W-band, as shown in Fig. 7(a). The discrepancy between measurement and simulation at the midband is attributed to extra passive component losses in the LO and RF MNs. The LO-to-RF isolation is determined based on the

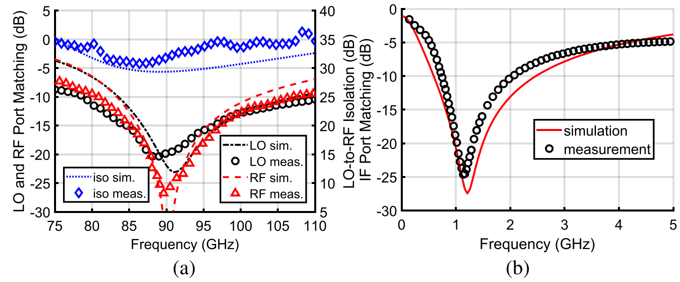

Fig. 7. Measured and simulated (a) LO/RF port matching and LO-to-RF isolation. (b) Measured and simulated IF port matching.

TABLE I

COMPARISON OF THE STATE-OF-THE-ART W-BAND SiGe-HBT ACTIVE UP-CONVERSION MIXERS

Ref.	Tech. $f_T/f_{\max}$ (GHz)	Output Freq. (GHz)	SSB CG (dB)	$\mathrm{BW}_{3\mathrm{dB}}$ (GHz)	LO-to-RF Isolation (dB)	P_{DC} (mW) @V_{DC}	$\mathrm{OP}_{1\mathrm{dB}}$ (dBm)
[8]	180 nm 200/200	80	3.2	72-79 [a]	21.4	104[d]@3.3	-7.3
[9]	180 nm 200/200	80	3.8	72-81 [a]	21.1	107[d]@3.3	-5.8
[10]	130 nm 200/250	71	3.9	71-86 [a]	33 [b]	80@2.7	1 [c]
[11]	130 nm 200/250	81	1 [a]	71-84 [a]	27 [b]	140@2.7	-7
[12]	130 nm 250/370	82	6	76-86 [a]	34	23@2.2	N/A
This work	**130 nm 250/370**	**91.3**	**4.1**	**78.1-108.3**	**32**	**11@1.8**	**0.6**

[a] estimated from plot. [b] estimated from LO power and leakage data.
[c] outside of W-band (at 71 GHz). [d] including output buffers.

difference between the LO leakage at the RF output spectrum (e.g., −29 dBm for $f_{\mathrm{LO}} = 90$ GHz) and the actual LO drive (i.e., 3 dBm at the LO port). Measured isolation is >30 dB across the W-band. Fig. 7(b) shows the IF port matching which demonstrates the dual purpose of the IF LPF for impedance matching and harmonic filtering. Table I summarizes and compares the performance of prior published W-band SiGe-HBT active up-conversion mixers [8], [9], [10], [11], [12].

IV. CONCLUSION

In this letter, the design and characterization of a low-power W-band double-balanced up-conversion mixer is reported. At 91.3 GHz, the mixer achieves a peak CG of 4.1 dB, 3-dB RF BW of 30 GHz, and $\mathrm{OP}_{1\mathrm{dB}}/P_{\mathrm{sat}}$ of 0.6/1.8 dBm while consuming only 11 mW from a 1.8 V supply. With the integrated second-order IF LC LPF, the mixer provides an additional spurious suppression of ∼12 and ∼19 dB at the second and third harmonic, respectively. To the best of authors' knowledge, this work demonstrates the lowest power consumption with the highest $\mathrm{OP}_{1\mathrm{dB}}/P_{\mathrm{sat}}$ and 3-dB RF BW reported among all prior published W-band SiGe-HBT up-conversion mixers.

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