Highly linear fundamental up-converter in InP DHBT technology for W-band applications

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Abstract
A fundamental up-converter with high linearity is presented, realized as full Gilbert cell (GC) mixer using a 800 nm transferred substrate (TS) InP-DHBT technology. The LO input of the Gilbert cell conducts from 75 to 100 GHz and requires 5 dBm of input power. The GC attains a single sideband (SSB) conversion gain of 10 ± 1 dB within the frequency from 82 to 95 GHz with a saturated output power of −1 dBm at 86 GHz and >5 dB conversion gain between 75 and 100 GHz. The up-converter exhibits 25 GHz of IF bandwidth. The DC power consumption is only 51 mW.

KEYWORDS
Local oscillator (LO), indium phosphide double heterojunction bipolar transistor (DHBT), single sideband (SSB), upper side band (USB), lower side band (LSB), transferred-substrate (TS) process, Gilbert cell (GC) mixer

1 | INTRODUCTION

The frequency range 75-110 GHz and above allows larger bandwidth for high-speed communications as well as shorter wavelength for sensors and imaging applications. At present, several applications for W-band are being explored, such as radar for space,1,2 imaging,3 and high-speed communication4 systems. All these systems require accurate frequency conversion for transmit and receive signal processing. An important component for such systems is the up converter mixer in the transmitter, which translates the baseband signal to RF signal. Necessary performance such as conversion gain, IF bandwidth, linearity (OP1dB, OIP3), and isolation (LO-to-RF). Specially, wideband intermediate frequency (IF) of functioning is necessary for high bit-rate data transmission and enhanced imaging and radar system performance. From a system perspective, the SSB up-converter should shows a conversion gain more than unity; a high conversion gain not only improves the linearity performance of the mixer, but also relaxes the gain requirements of the power amplifier design at mm-wave frequencies. It is difficult to achieve conversion gain beyond 0 dB by using diode-based up-converters and, therefore, at present MMIC based up-converters have increasing interest in W-band and beyond.

In recent years, only a few passive as well as active W-band up-converters for high-speed communications and automotive radars have been reported, most of all implemented in CMOS/BiCMOS process.5-7 However, it is a challenging task to realize all the above-mentioned performance in a single design. The presented up-converter in this letter is compact in size and shows decent value of all the performance.

This letter present here a fundamental up-converter in InP DBHT technology performing over the full W-band. It comprises input and output W-band Marchand baluns together with a balanced GC as mixing circuit.

The letter is formulated as follows: Section 2 shortly illustrates the process and Section 3 describes the MMIC design. Section 4 shows the implemented circuit as well as the measured results, followed by a discussion, while Sec. V consists of the conclusions.
2 | TRANSFERRED-SUBSTRATE PROCESS

The up-converter mixer circuit is realized on the transferred-substrate (TS) InP-DHBT MMIC process as shown in Figure 1. Devices are one and two fingers InP/InGaAs HBTs with 500 nm and 800 nm emitter width. There are three gold metal layers G1, G2, and GD with 2, 4, and 2.5 μm thicknesses, respectively, MIM capacitors (sheet capacitance of 0.3 fF/μm²) and NiCr resistors (sheet resistance of 25 Ω/sq.). Interconnects are established by dry etched vias in the BCB to connect the ground plane, base, collector and the host substrate. After processing the base and emitter layers, the InP wafer is bonded to a host substrate by BCB wafer bonding and then the remaining process steps are performed. A high value of resistivity silicon substrate with prefabricated through silicon vias (TSVs) were used as host substrate, which could also be replaced with a complete processed BiCMOS wafer. The TSVs are implemented to suppress unwanted modes in the host substrate. A single finger 0.8 × 6 μm² transistor exhibits cut-off frequencies $f_t$ and $f_{max}$ of about 350 GHz, with BVCEO = 4 V.

3 | MMIC DESIGN

The circuit diagram of the entire up-converter is shown in Figure 2. At the LO input, a W-band Marchand balun (BLN1) translates the single-ended output signal from the LO to an input signal for the Gilbert mixer cell. The core Gilbert mixer is realized in double-balanced topology using $T_1$, $T_2$, $T_3$, $T_4$, $T_5$, and $T_6$ (6 HBTs), with an emitter area of 0.8 × 5 μm² each. For on wafer measurement purposes as well as for further amplification in the transmitter unit, the differential output of the mixer is converted to a single-ended output using a second Marchand (BLN2). In order to have simple layout, base and collector biasing of $T_1$, $T_2$, $T_3$, $T_4$ is fed through the Marchand baluns (BLN1, BLN2) using $V_{b_{mix1}}$ and $V_{c_{mix}}$. Base biasing ($V_{b_{mix2}}$) and the differential IF input signal for $T_5$, $T_6$ are inserted using an external balun with bias tees (see Figure 2).

The Marchand baluns (BLN1, BLN2) presented in this letter is realized as a modified version of the conventional topology. The Marchand balun is employing two quarter-wavelength coupled line sections with a compensation transmission line connects the two coupled line sections. Figure 3 shows the simplified schematic diagram of the modified Marchand balun. Symmetrical analysis is done by using even-mode and odd-mode equivalent circuits of the modified Marchand balun. More detail design can be found in. The EM simulation results of the Marchand baluns exhibit <0.5 dB of amplitude imbalance and 180°–1° of phase difference between 75 and 102 GHz. All the microstrip lines including the Marchand baluns layout was optimized using a 2.5-D EM simulator.
PERFORMANCES

The on-wafer circuit test setup is shown in Figure 4. The output power has been measured using ground-signal-ground (GSG) W-band Cascade waveguide probes with a pitch of 100 μm, an RPG sub-harmonic mixer (SHM), and a spectrum analyzer (FSW) from R&S. The differential IF input signal is introduced using a GSGSG coaxial probe, a signal generator (SG) and an external balun with bias tees. The single-ended local oscillator (LO) input signal is fed through a ground-signal-ground coaxial probe from GGB with a pitch of 150 μm.

The chip photograph of the entire MMIC circuit is presented in Figure 5. The chip area including RF and DC pads with Marchand baluns is 1 × 0.75 mm² (core area only 0.13 × 0.13 mm²).

Figure 6, shows the measured characteristics of IF input power, the RF output power at the USB as well as conversion gain (CG) as a function of RF output frequency. The LO frequency is unchanged at 75 GHz with input power of 2 dBm, while IF is swept from 1 to 26 GHz (it implies the USB frequencies from 76 to 101 GHz). After correcting probe losses at the output (provided by vendor), one achieves USB conversion gain values between 12 and 5 dB in the frequency range from 75 to 101 GHz. The measured isolation (LO input to LO output) of approximately 44 dB, the LO-RF suppression is more than 30 dBc. Figure 6 also presents the simulated conversion gain as a function of RF frequency. It can be seen that the measured values agree quite well with simulated values, except some values frequency range from 85 to 95 GHz; this can be explained by the input/output on chip Marchand balun as well as external IF balun from the vendor.

Figure 7, depicts the measured and simulated USB output power as a function of IF input power, while the IF frequency kept constant at 11 and 20 GHz. One reaches output \( P_{1dB} \) values between −5 and −7 dBm at 86 GHz and 95 GHz, respectively. In Figure 6 also presents measured output power at the LO frequency vs IF input power, which is always below −25 dBm at the output port. Evaluating the deviation in the linearity characteristics of the up-converter, one can expect several possible reasons. First, the large signal HBTs modeling is not performed for both common emitter and common base transistors. In addition, the Marchand balun insertion loss and frequencies shift due to process variation, which has been already shown in Figure 6.

In Figure 8, the measured USB and lower side band (LSB) conversion gain and output power at LO frequency is shown as a function of LO input power, for fixed LO frequencies of 80, 90, 100, and 2 GHz IF frequency. The values in Figure 8 indicate that one can achieve higher conversion gain by injecting more LO input power.
The results demonstrate that the converter covers the bandwidth from 75 to 102 GHz also at the LO input. The IF bandwidth was limited to 27 GHz by the external IF balun and the bias tees (<27 GHz).

Table 1 benchmarks the result with recently reported 75-110 GHz up-converters using different technologies. From the table one can see, the presented up-converter achieves remarkable performance regarding conversion gain, OP1dB, and DC consumption. Conversion gain is at the same level as, but at much lower DC power. The referenced presents a higher value for OP1dB, but with an additional output buffer stage, which increases DC power consumption and decreases considerably the bandwidth of operation. The circuit presented in this article consumes only 51 mW DC power. Also, LO-to-RF isolation is excellent.

Table 1

| Ref. | Technology | Frequency | IF BW (GHz) | PDC (mW) | CG (dB) | OP1dB (dBm) | LO- RFISO (dB) | Chip size (mm²) |
|------|------------|-----------|-------------|-----------|---------|-------------|----------------|----------------|
| 10   | 800 nm InP DHBT | 350/550 | Two stages LO buffer + mixer | 81–102 USB | 10 | 1.1×107 | 0.83×0.7 | 2.5×1.5 |
| 6    | 90 nm GaAs | 104/106 | Mixer + buffer | 75–82 USB | 8 | 2.18 | 0.74×0.6 |
| 11   | 150 nm GaAs | 89/92 | Single-balanced resistive mixer | 90–102 USB | 10 | 41.3 | >30 | 0.74×0.6 |
| 12   | 800 nm/250 nm InP-on-BiCMOS HBT | 200 | VCO + doubler + mixer | 75–102 USB to LSB | 25 | 8.5×104 | 4.2×105 |
| This Work | 800 nm TS InP-DHBT | >300 | Passive balun + mixer | USB | 26 | 512 | 92 | 44 |

a Differential input/single ended output correction.

b Differential input/single ended output.

c Isolation 2×LO-RF.

The measured conversion gain as a function of LO input power. IF frequency is fixed at 2 GHz, LO frequencies are 80, 90, and 100 GHz. The output power at LO frequency is included [Color figure can be viewed at wileyonlinelibrary.com]
CONCLUSIONS

This letter shows a highly linear W-band fundamental up-converting Gilbert mixer in 0.8 μm TS InP-DHBT technology. It presents up-conversion gain of 10 ± 1 dB in the frequency from 82 to 95 GHz, with output P1dB values of −5.5 dBm at 86 GHz and low DC power consumption. The combined performance in conversion gain, linearity, bandwidth, and output power is clearly superior to previous published results and makes the converter interesting for various kinds of W-band system application.

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