A D-Band Balanced Subharmonically-Pumped Resistive Mixer Based on 100-nm mHEMT Technology

Y. Campos-Roca, A. Tessmann, H. Massler, and A. Leuther

A D-band subharmonically-pumped resistive mixer has been designed, processed, and experimentally tested. The circuit is based on a 180° power divider structure consisting of a Lange coupler followed by a $\lambda/4$ transmission line (at local oscillator (LO) frequency). This monolithic microwave integrated circuit (MMIC) has been realized in coplanar waveguide technology by using an InAlAs/InGaAs-based metamorphic high electron mobility transistor process with 100-nm gate length. The MMIC achieves a measured conversion loss between 12.5 dB and 16 dB in the radio frequency bandwidth from 120 GHz to 150 GHz with 4-dBm LO drive and an intermediate frequency of 100 MHz. The input 1-dB compression point and IIP3 were simulated to be 2 dBm and 13 dBm, respectively.

Keywords: Metamorphic HEMT (mHEMT), monolithic microwave integrated circuit (MMIC), millimeter-wave frequency conversion, resistive mixer, D-band, subharmonically-pumped (SHP) mixer.

I. Introduction

Millimeter-wave systems operating beyond 100 GHz are receiving an increasing interest due to different applications, such as remote atmospheric sensing, wideband communications, and automotive radar. Downconverters are key components of these millimeter-wave systems.

Different technologies and operation modes have been proposed for millimeter-wave mixers. Beyond 100 GHz, mixers are mostly based on Schottky-diodes [1]-[3].

Compared to the diode-based type, field-effect transistor (FET)-based resistive mixers have the advantage that they achieve lower distortion and lower noise figure [4]. In comparison to FET gate mixers, FET resistive mixers require no DC power consumption and show also higher linearity.

Downconverters can be fundamentally-pumped or subharmonically-pumped (SHP). Compared to the former type, SHP mixers require lower local oscillator (LO) frequency, which is especially interesting in the upper millimeter-wave range, where LO power and phase noise requirements are difficult to achieve. Additionally, a better LO-to-radio frequency (RF) isolation can be obtained due to the important frequency difference between the two signals.

To the knowledge of the authors, very few FET-based SHP mixers with operating frequencies beyond 100 GHz have been published. A fourth harmonic SHP resistive mixer based on an InP-high electron mobility transistor (HEMT) technology is presented in [5]. Despite the excellent high-frequency and low-noise properties, InP has important disadvantages, such as material cost and mechanical fragility. These obstacles have been overcome by the GaAs metamorphic HEMT (mHEMT) technology [6]. An active dual-gate SHP mixer based on a GaAs mHEMT technology is shown in [7]. In [8], resistive SHP I/Q mixers are presented.

The coplanar SHP resistive mixer presented here achieves quite broadband performance (the conversion loss keeps between 12.5 dB and 16 dB in the RF bandwidth between 120 GHz and 150 GHz) having low LO drive requirements (4 dBm at half of the LO frequency).

II. Technology

The mHEMT processing technology used in this work has been developed at the Fraunhofer Institute for Applied Solid

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State Physics (IAF). The mHEMT structures are grown on 4" semi-insulating GaAs substrates by molecular beam epitaxy. The monolithic microwave integrated circuit (MMIC) is based on an $In_{0.52}Al_{0.48}As/In_{0.65}Ga_{0.35}As/In_{0.53}Ga_{0.47}As$ HEMT process with 100-nm T-shaped gates. Gate definition is performed using electron beam lithography in a three-layer (PMMA) resist process. A Pt-Ti-Pt-Au layer sequence is used for the gate metallization. An extrinsic transit frequency, f_T, of 220 GHz and a maximum oscillation frequency, f_{max}, of 300 GHz have been achieved for a 2 ×30 μm common source device. At a drain-source bias of 1.2 V, a maximum extrinsic transconductance of 1,200 mS/mm has been obtained. The off-state breakdown voltage of the transistors is 4.3 V, and the on-state breakdown voltage is approximately 3 V. The on-resistance for these devices is 0.65 Ω×mm.

The mixer has been realized in coplanar waveguide (CPW) technology. Afterwards, a full backside metallization process was carried out, including wafer thinning to a final thickness of 50 μm. Also, via holes were etched for increased suppression of parasitic substrate modes. More details about this technology can be found in [9].

III. SHP Resistive Mixer Design

In a resistive FET mixer, the transistor is operated in its linear ohmic region with zero DC drain bias. The SHP resistive mixer presented here was designed to downconvert the D-band RF signal by mixing with the second harmonic of a LO signal.

The schematic circuit diagram is shown in Fig. 1. The mixer uses a singly-balanced topology. The LO is applied to a Lange coupler, followed by a λ/4-length CPW line, to generate the required 180° phase shift at the transistor gates [10]. The drains are connected together. The connection point of the two drains is a virtual ground for the LO. In comparison to an ideal coupler, providing exactly 180° phase difference in a wide bandwidth and a perfect amplitude balance, the structure based on a Lange coupler followed by a λ/4 line limits the achievable LO suppression. However, the results are still sufficiently good (see section IV).

The matching networks for the LO and RF inputs at the gates and drains of the mHEMTs, respectively, are based on shunt metal-insulator-metal (MIM) capacitors and CPW lines. The intermediate frequency (IF) signals were extracted from the drain of both devices through low-pass filters (also based on CPW lines and shunt MIM capacitors) to provide RF and LO filtering. The current prototype has two IF outputs to be able to investigate the effect of non-perfectly-balanced branches on mixer performance. However, both IF outputs can be directly connected when the mixer is further integrated with other MMIC functions to complete a whole receiver. In the case of the current prototype, the combining of both IF signals has been performed by using an off-chip power combiner.

The transistors have 2 ×30 μm geometry. For the simulation of them, an in-house analytical large-signal model from the Fraunhofer IAF has been used. All simulations were performed using the commercial software Advanced Design System from Agilent.

IV. Mixer MMIC Performance

A chip photograph of the MMIC is shown in Fig. 2. The active chip area is 1.2 mm×1.5 mm. Due to the resistive operation mode, the circuit consumes no DC power.

The MMIC conversion gain performance has been tested on-wafer. The LO signal was obtained by an Agilent E8257D signal generator, whose output was multiplied in an HP source module, resulting in a maximum of 5-dBm LO power at the chip level. The RF input was driven from another Agilent E8257D signal generator applied to an Oleson-S06MS (110 GHz to 170 GHz) source module. The RF power measurement was performed in-house by using a D-band power sensor (DPM-06 from the company ELVA-1), which was calibrated with an Erickson calorimeter. The two IF output signals were externally combined and measured with a

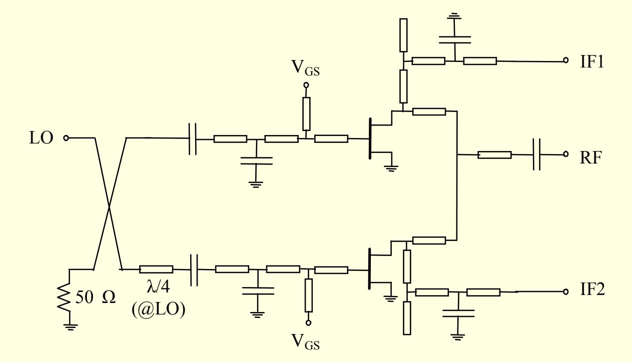

Fig. 1. Schematic circuit diagram of SHP mixer.

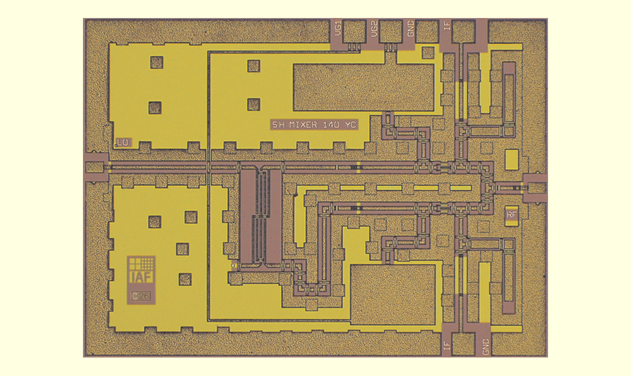

Fig. 2. Chip photograph of SHP mixer MMIC.

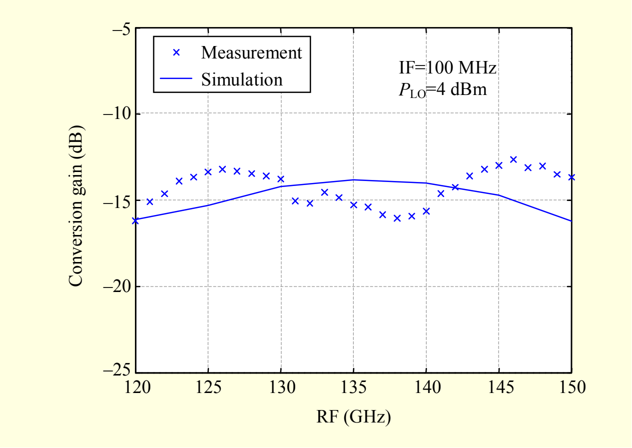

Fig. 3. Conversion gain of SHP mixer as function of RF.

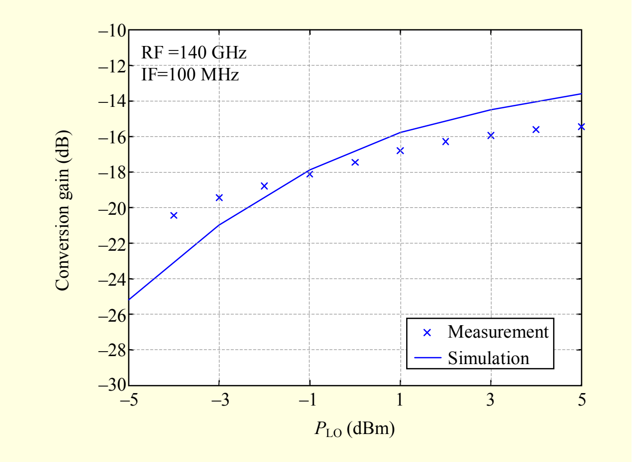

Fig. 4. Conversion gain of mixer versus LO power.

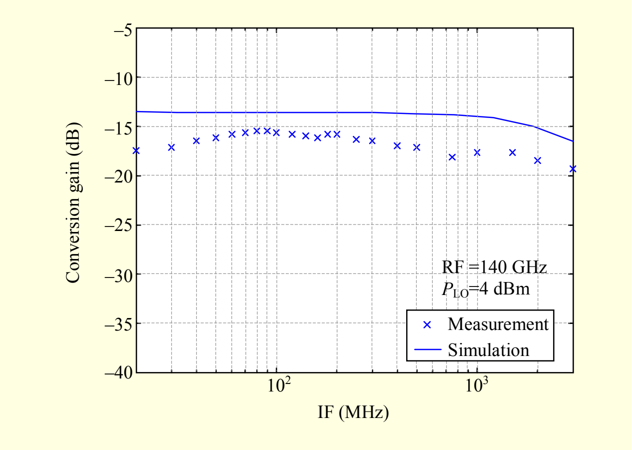

Fig. 5. Conversion gain of SHP mixer as function of IF.

spectrum analyzer.

To maximize the conversion gain of the mixer, the gate DC bias voltage was set to –0.1 V, close to the threshold voltage of the transistors. The measured and simulated performances of the MMIC are shown in Figs. 3 to 5. Figure 3 shows the conversion gain of the mixer as a function of the RF. The IF is set to 100 MHz, and the LO power was 4 dBm. As shown, the circuit achieves a best conversion loss of 12.5 dB at 146 GHz. In the RF range between 120 GHz and 150 GHz, the conversion loss keeps quite flat (between 12.5 dB and 16 dB).

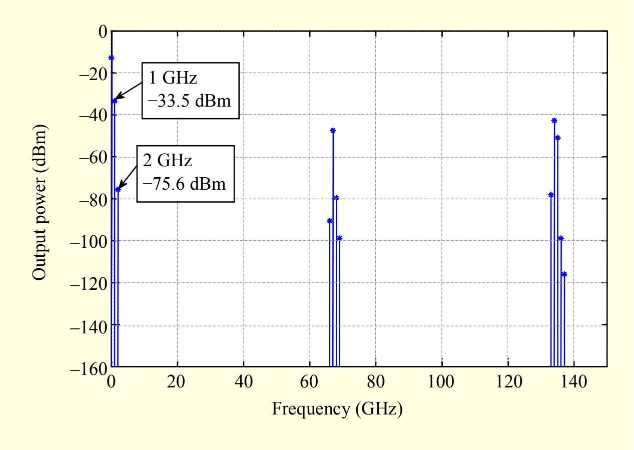

Fig. 6. Output spectrum of SHP mixer.

Figure 4 shows the conversion gain as a function of the LO power. At the maximum available LO power (5 dBm), the conversion gain curve has not reached the maximum value yet, although saturation is already close. Finally, Fig. 5 shows the conversion gain versus the IF. From DC to 2 GHz, the conversion gain keeps also quite flat with a variation smaller than 3 dB.

Figure 6 shows the simulated output spectrum of the mixer for an RF input power of –20 dBm (at 135 GHz) and an LO power of 5 dBm (at 67 GHz). The most harmful spurious term (at 2 GHz) has an output power of –75.6 dBm, that is, about 42 dB lower than the IF term. The other terms (RF and LO feedthrough and mixing products) represent no problem because they could be easily reduced by better filtering at the output. In the RF bandwidth between 120 GHz and 150 GHz, the port isolations were simulated to have values in the following ranges: 29 dB to 33.4 dB (LO-RF), 15.6 dB to 24.7 dB (2LO-RF), 39.7 dB to 56.6 dB (LO_IF), 46.5 dB to 55.5 dB (2LO-IF), and 30 dB to 32 dB (RF-IF). Regarding linearity, the input 1 dB compression point and IIP3 were simulated to be 2 dBm and 13 dBm, respectively. Table 1 compares the performance of this MMIC with other state-of-the-art SHP mixers above 100 GHz.

V. Conclusion

A D-band second harmonic singly-balanced resistive mixer has been designed and realized in a 100-nm mHEMT process.

Table 1. State-of-the-art subharmonic mixers above 100 GHz. N.A. means 'Not Available' (not provided by authors).

Devices, technology, mixer type, harmonic number	Conversion loss in the specified RF bandwidth (dB)	LO power (dBm)	DC power (mW)	RF bandwidth (GHz)	Noise temperat. (K)	IIP3	P_{1dB}
Schottky diodes, x2 [1]	12 to14	4 to 10	N.A.	520 to 590	3,000 to 4,000 (DSB)	N.A.	N.A.
Schottky diodes, x2 [2]	10 to 11 (simulation)	8.5 to 10.5	N.A.	320 to 360	3,400 to 5,000 (SSB)	N.A.	N.A.
Schottky diodes, x2 MMIC [3]	12.7 to 16.5	7 to 8	0.2	200 to 215	5,000 to 10,000 (SSB)	N.A.	N.A.
InP HEMT, x4 [5]	25 to 40	18	N.A.	176 to 200	N.A.	N.A.	N.A.
Dual-gate MHEMT, x2 [7]	5.1 to 9.5	10	36	180 to 210 or higher	N.A.	N.A.	N.A.
MHEMT I/Q mixer, x2 Resistive [8]	IF-Q: 19 to 22	2	0	182 to 202	N.A.	N.A.	N.A.
MHEMT I/Q mixer, x2 Resistive [8]	IF-Q: 18.5 to 21.5	2	0	206 to 220 or higher	N.A.	N.A.	N.A.
MHEMT, x2 Resistive [this work]	12.5 to 16	4	0	120 to 150	N.A.	13 dBm (simulation)	2 dBm (simulation)

With no DC power consumption and low LO drive requirements, the circuit achieves a best measured conversion loss of 12.5 dB and quite broadband performance (the conversion loss keeps between 12.5 dB and 16 dB in the RF bandwidth between 120 GHz and 150 GHz). A review of the literature reveals a general lack of information concerning linearity and noise figure of HEMT-based mixers in this frequency range. Thus, the study of these aspects from an experimental point of view should be an important goal in future investigations.

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