A 150 to 220 GHz Balanced Doubler MMIC Using a 50 nm Metamorphic HEMT Technology

C. Schwörer, Y. Campos Roca*, A. Leuther, A. Tessmann, M. Seelmann-Eggebert, H. Massler, M. Schlechtweg and G. Weimann

Fraunhofer-Institute for Applied Solid State Physics
Tullastrasse 72, D-79108, Germany, Phone: ++49 761 5159 486
*University of Extremadura, Avda. de la Universidad, s/n, E-10071 Caceres, Spain

***Abstract* — A coplanar millimeter wave doubler MMIC covering the entire G-band was developed. Based on a 50 nm metamorphic HEMT technology, the circuit demonstrates an output power of more than –12 dBm between 150- and 220 GHz for an input power of 0 dBm. By increasing the input power to 12 dBm an output power exceeding 0 dBm was obtained in the frequency range between 180- and 220 GHz. Good fundamental rejection was ensured by using a Marchand Balun for balancing the design. The doubler was also used to provide the LO signal for a 170 to 200 GHz resistive FET mixer, yielding a conversion loss of 10 dB.**

I. Introduction

Active and passive millimeter and submillimeter-wave sensors penetrate the frequency range up to 1 THz. Applications are radiometric imagers focused on the atmospheric windows at 94 GHz, 140 GHz and 220 GHz as well as atmospheric sounders and environmental sensors at frequencies where characteristic resonance frequencies of molecules exist [1]. Also, next generation automotive collision avoidance radars and short range industrial sensors come into play in environmentally harsh conditions were optical and ultra-sonic sensors fail due to dust and pollution. Not all of these systems are realizable with direct detection systems where the RF signal is directly rectified to DC and then processed. Local oscillator sources are needed in RADARs, spectrometers, synthetic aperture systems to provide phase synchronous down conversion, to measure absorption, or simply as illumination to enhance the contrast of a scene to be observed. Frequency generation beyond 100 GHz is generally a demanding task, which is mostly solved with varactor multipliers. As InP based HEMT transistors advance in performance, there is the possibility of realizing active FET frequency multipliers monolithically up to frequencies as high as 220 GHz. The advantages of active FET multipliers are their broad bandwidth and good conversion efficiency, in contrast to resistive diode multipliers which are broadband but inefficient or varactor multipliers which demonstrate good conversion properties only over a narrow bandwidth [2]. A narrow band HEMT doubler at 164 GHz was already demonstrated in [3].

In this paper, we describe the development of a balanced broadband frequency doubler in a coplanar environment based on a highly advanced 50 nm MHEMT technology.

II. Technology

The technology employed is a metamorphic HEMT structure, grown on semi-insulating 4” GaAs substrates. The metamorphic buffer layer consists of a linear $In_xAl_{0.48}Ga_{0.52-x}As$ ($x = 0 \rightarrow 0{,}52$) grading, that finally yields the InP lattice constant. The layer structure comprises a composite channel consisting of an 80 % In main channel for high carrier velocity. Furthermore, a 53 % indium content sub-channel was introduced, which helps to reduce impact ionization and thus improves the breakdown behavior. The on-state breakdown voltage achieved with the described layer structure is 1.5 V, and the off-state breakdown voltage is about 2.0 V. E-beam lithography with a four layer PMMA resist was used to pattern the T-shaped gate with a final foot print length of 50 nm. The Pt-Ti-Pt-Au gates are fully passivated using a CVD deposited silicon-nitride. The active device area is mesa defined using a chemical wet etch.

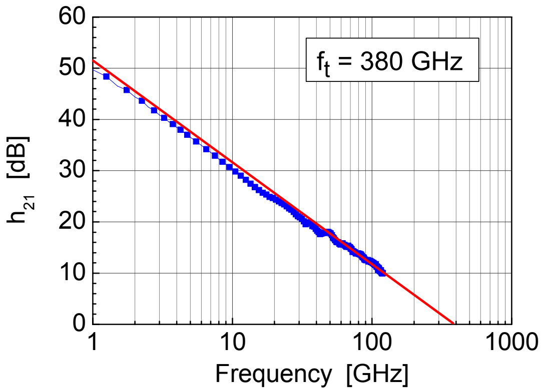

Fig. 1. Current gain for a 2×30 µm MHEMT with extra-polated f_t.

Using this process technology a maximum extrinsic trans-conductance of 1600 mS/mm was measured, resulting in an equal transit frequency (f_t) and maximum frequency of oscillation (f_{max}) of 380 GHz for a 2×30 µm device as displayed in Fig. 1. The maximum current of the device structure is 1300 mA/mm. Accelerated life time tests in air were performed at 200, 220 and 240 °C channel temperature and at 1 V drain bias. The failure criterion was a 10 % degradation of the maximum trans-conductance. Based on a log-normal distribution, an activation energy of 1.6 eV and a median life time of 2×10^6 hours at a channel temperature of 125 °C were calculated. More details on our metamorphic HEMT technology can be found in [4].

III. Circuit Design

The circuit topology employs a balanced design using coplanar line technology as shown in Fig. 2. The MMIC consists of a planar Marchand balun at the input to divide the incoming signal equally onto two branches with 180 degrees of phase-shift. The advantages of a Marchand balun are the broadband frequency response, exact phase difference and very good amplitude balance throughout the entire band of operation. The balun used in this circuit comprises of two coupled line sections of 155 µm length. The performance was verified with electro magnetic (EM) simulations using Agilent Momentum and Ansoft HFFS. It is important to mention that the resistivity of the used metal layer has to be taken into account in EM simulations because of significant loss. This is due to the fact, that design rules allow only a thin metal layer to layout tight spacing of the lines, needed, to achieve sufficient coupling. The balun is followed by the gate bias section which is also used for matching at the input of the FETs.

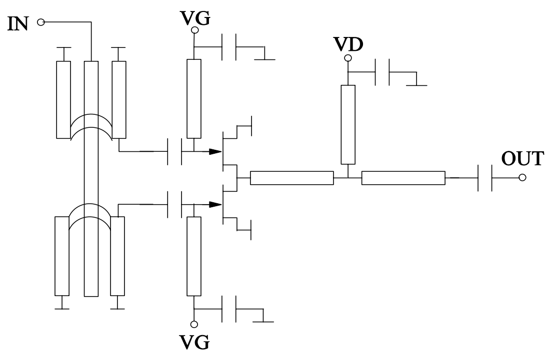

Fig. 2. Circuit diagram of the balanced G-band doubler.

The active devices have a gate width of 2×30 µm and are biased in a class B manner. The FET's layout is realized by truncating the gate bus of a 4×30 µm transistor layout into two halves. This way, the drain connection of the two FETs is as short as possible which in turn guarantees the cancellation of the fundamental signal at the drain. The second harmonic frequency matching is done by the drain bias network. It is straight forward because the shorting of the fundamental frequency at the output is implemented by the balanced design [5]. Simply spoken, the difficulties in achieving the right load conditions at the output was circumvented by putting more effort on the input side at half of the frequency. A photograph of the doubler MMIC is shown in Fig. 3.

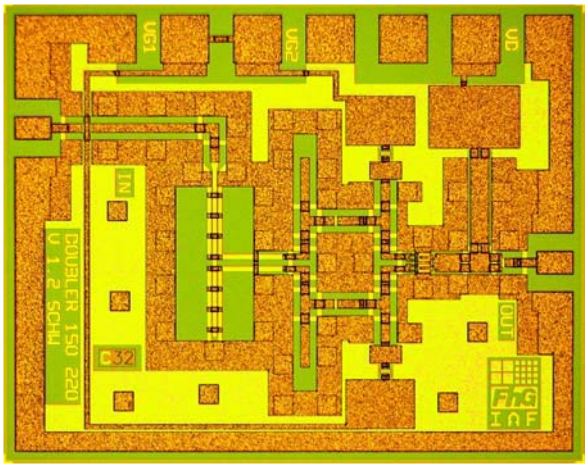

Fig. 3. Chip photograph of the balanced doubler MMIC. The chip size is 1×1.25 mm^2.

IV. Experimental Results

The circuit was characterized on-wafer, the wafer was thinned down to 140 µm without backside processing. First, a HP83558A W-band source module was used as an input source, giving roughly 0 dBm of output power over the entire W-band at the input of the MMIC. All the connections were done with WR-10 waveguides at the input and WR-5 waveguides at the output of the circuit. The output power was measured with a G-band Picoprobe tip and fed directly into an ELVA-1 DMP-05 power meter. The cutoff frequency of the WR-5 waveguide is 118 GHz, assuring that no fundamental power could leak into the power meter. A schematic of the test setup is illustrated in Fig. 4.

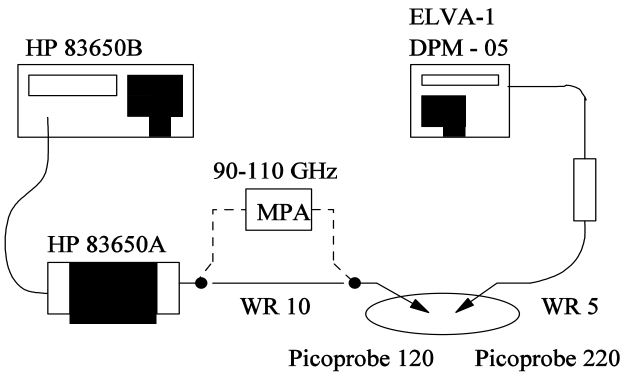

Fig. 4. Schematic of the test bench used to characterize the doubler MMIC.

For this configuration an output power of more than -12 dBm was achieved from 150 to 220 GHz, with a maximum output power of –6 dBm at 180 GHz, as shown in Fig. 5.

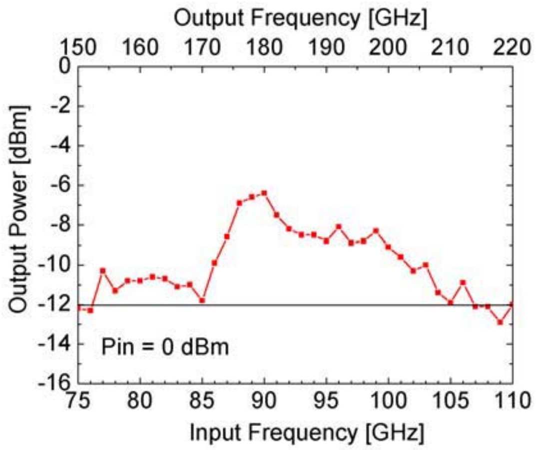

Fig. 5. Output power of the G-band doubler MMIC for 0 dBm input power.

The gate voltage was adjusted to 0 V and the drain voltage to 0.8 V resulting in a 25 mA quiescent current. More input drive power of approximately 12 dBm was available between 90 GHz and 110 GHz from an in-house build medium power amplifier module. By using this module to increase the input power, the output power at the doubled frequency could be kept above 0 dBm, again having the maximum power level at 180 GHz with 4 dBm as shown in Fig. 6.

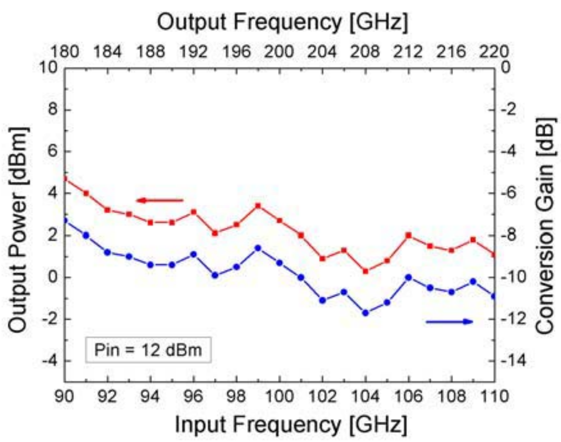

Fig. 6. Output power and conversion gain of the G-band doubler for 12 dBm input power.

At 12 dBm input power, the gate voltage was reduced to -0.2 V to achieve the best conversion properties. With 1 V drain bias, the circuit consumes 25 mA of drain current in operation, which is equal to a current density of 200 mA/mm. Additionally, input power sweeps at 90, 100 and 110 GHz were performed. The smooth behavior of the multiplied signal over the input power variation implies stable operation, as indicated in Fig. 7. Also, with no input signal applied, no output power is measured. This is important as sometimes multipliers with high conversion efficiencies show oscillations and are therefore acting as sub-harmonic injection locked oscillators.

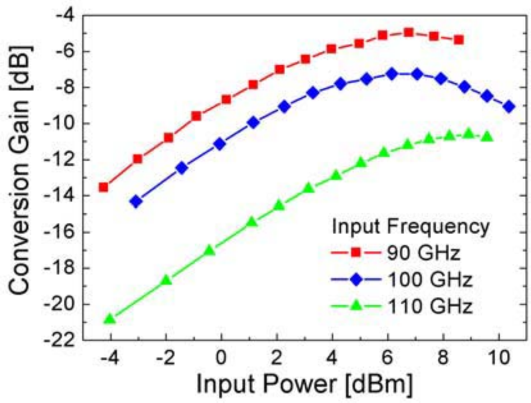

Fig. 7. Conversion gain versus input power of the G-band doubler MMIC for frequencies of 90, 100 and 110 GHz .

To evaluate the yield of the circuit across one wafer, the power level at 220 GHz output frequency was measured for an input power of 0 dBm at 110 GHz at the input of the chip. The DC yield was exceeding 90 %. If a minimum output power of -13.5 dBm was chosen for selection criteria, the RF yield accounted to 50 %.

V. Application of the Doubler Chip as LO Source for a Downconverter

To approve the applicability of the developed doubler MMIC, it was used as a local oscillator source for a single ended resistive FET mixer. A resistive FET mixer was chosen because of its ability to perform well at very high frequencies with low LO power [6].
A doubler and a mixer chip were mounted on a silicon substrate with the doubler's output and the mixer's LO input placed as close as possible to keep the connecting bond wires short. The mounted chips are shown in Fig. 8.

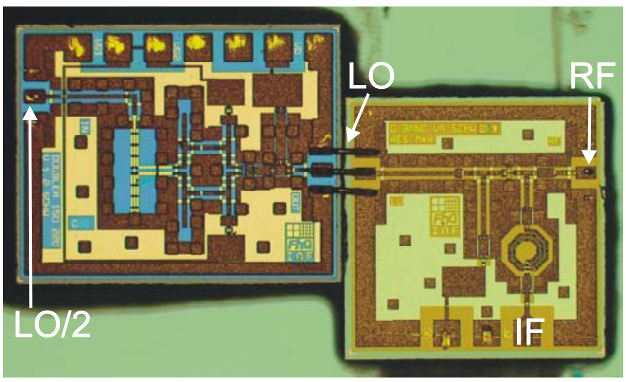

Fig. 8. Doubler MMIC left, and mixer MMIC right, mounted on a silicon substrate with interconnecting bond wires.

To contact the chips during the measurement, DC and RF on-wafer probes were used. The input signal of the doubler was provided using again the W-band HP source module and the MPA module to provide approximately 12 dBm input power at the doubler input. The RF signal was supplied using a G-band S-parameter extension module from Oleson, operated in CW mode. The output power of the Oleson module was characterized before the measurement using the ELVA-1 G-band power sensor. The down converted signal was measured with a spectrum analyzer. To calculate the conversion loss of the mixer, probe and cable losses were accounted for. The doubler mixer combination showed good conversion properties between 170 and 200 GHz with a conversion loss of around 10 dB for a single-side-band (SSB) measurement and an IF frequency of 1 GHz. Above 200 GHz, the mixer conversion loss dropped off sharply, as can be seen in Fig. 9.

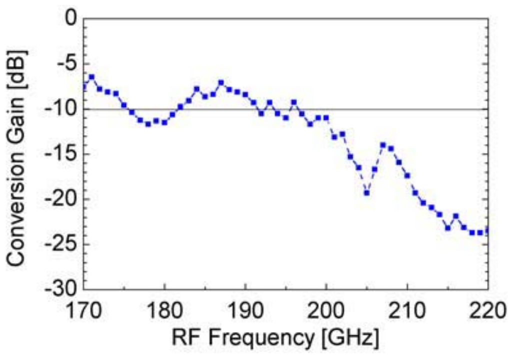

Fig. 9. Measured conversion loss of the doubler–mixer combination from 170 to 220 GHz at an IF frequency of 1 GHz.

VI. CONCLUSION

A broadband doubler MMIC, covering the frequency range from 150 GHz to 220 GHz was realized. The balanced FET multiplier chip was fabricated using a 50 nm gate-length metamorphic HEMT technology and demonstrated a conversion loss better than 12 dB over the entire G-band for an input power of 0 dBm. With 12 dBm of input power, an output power of more than 0 dBm could be achieved between 180 GHz and 220 GHz. Also, the ability of the doubler to serve as a LO source for a mixer was demonstrated, yielding a SSB conversion loss of approximately 10 dB between 170 and 200 GHz.

VII. AKNOWLEDGEMENTS

The authors would like to thank M. Riessle and H. Walcher for dicing and the mounting of chips.
The authors acknowledge the support of the German Federal Ministry of Defence (BMVg), the German Federal Office of Defence Technology and Procurement (BWB), Koblenz, and the Bundeswehr Technical Centre for Information Technology and Electronics (WTD 81), Greding, in the framework of the TeraKomp program.

REFERENCES

[1] P. Siegel, "Terahertz Technology", *IEEE Transactions on Microwave Theory and Techniques*, vol.50, no. 3, March 2002.

[2] S. A. Maas, "*Nonlinear Microwave and RF Circuits*" Artech House, 2nd Edition, 2003.

[3] V. Radisic, M. Micovic, M. Hu, P. Janke, C. Ngo, L. Nguyen, L. Samoska and M. Morgan, "164-GHz MMIC HEMT Doubler," *IEEE Microwave and Wireles Components Lett.*, vol. 11, no. 6, pp. 241-243, 2001.

[4] A. Leuther, A. Tessmann, M. Dammann, W. Reinert, M. Schlechtweg, M. Mikulla, M. Walther, G Weimann, "70 nm Low Noise Metamorphic HEMT Technology on 4 Inch GaAs Wafers", *Indium Phosphide and Related Materials Conference,* IPRM, May2003, pp. 215-218.

[5] B. Lefebvre, A. Bessemoulin, C. Schwoerer, V. Lehoue, O. Vaudescal, "A Highly Integrated Double Conversion Mixer MMIC for Ka-band VSAT Communication Systems", *12th GAAS Symposium,* Amsterdam, October 2004, pp. 91-94.

[6] A. R. Barnes, P. Munday, R. Jennings and M.T. Moore. "A Comparison of W-Band Monolithic Resistive Mixer Architectures", *IEEE MTTS 2002*, pp. 1876-1870.