Proceedings of the 9th European Microwave Integrated Circuits Conference

6-12 GHz Double-Balanced Image-Reject Mixer MMIC in 0.25μm AlGaN/GaN Technology

M. van Heijningen, J.A Hoogland, A.P. de Hek, F.E. van Vliet
Radar Technology Group
TNO
The Hague, The Netherlands
Marc.vanHeijningen@tno.nl

***Abstract*— The front-end circuitry of transceiver modules is slowly being updated from GaAs-based MMICs to Gallium-Nitride. Especially GaN power amplifiers and TR switches, but also low-noise amplifiers, offer significant performance improvement over GaAs components. Therefore it is interesting to also explore the possible advantages of a GaN mixer to complete a fully GaN-based front-end. In this paper the design-experiment and measurement results of a double-balanced image-reject mixer MMIC in 0.25 μm AlGaN/GaN technology are presented. This design features an integrated LO amplifier and active IF balun. The measured conversion loss is less than 8 dB from 6 to 12 GHz, at 0 dBm LO power.**

Keywords— Mixers, Gallium Nitride, MMICs

I. INTRODUCTION

Gallium-Nitride (GaN) semiconductor technology is well known for power amplifier and switch applications, due to its high power-density and breakdown levels. Also for low noise amplifiers GaN technology can be interesting because of the high input-power handling capability, which could eliminate the use of a limiter in front of the LNA. One function that has not been addressed much in GaN technology is the mixer. Most publications on GaN mixers focus on technology demonstration, using only a single transistor as mixer element, such as in [1][2]. Only a few publications deal with complete GaN mixer MMICs [3][4]. In [3] a single-balanced cold-FET mixer is presented. The Ku-band design features 9 dB conversion loss at 10 dBm LO power with 10 dBm input power compression point (P1dBin). In [4] a single quad FET ring mixer is presented with 13 dB conversion loss at 23 dBm LO power and also about 10 dBm P1dBin. On the wide band-gap semiconductor material Silicon-Carbide (SiC) mixers have been presented with high input power compression point, but at the same time requiring a large LO power, such as in [5].

Main drawback of the use of GaN technology for mixers is that the required passive elements, such as the baluns and hybrids, consume a large part of the expensive layout area. An advantage of using GaN is the possibility to realize a fully integrated receive chain in one technology. Other advantages are the possibility to easily integrate an LO amplifier and the inherent robustness of the design against damage due to overdrive conditions.

In order to explore the possibilities and limitations of a GaN mixer, a double-balanced image-reject FET quad ring mixer MMIC has been designed in 0.25 μm AlGaN/GaN technology of UMS (GH25-10 technology). This design features an integrated LO amplifier, very compact 90° hybrid, RF baluns and active IF baluns. The design of the mixer and the passive components is discussed in section II. Section III shows the measurement results on a test structure of the mixer core. Section IV shows the measurement results of the mixer MMIC, compared with the simulation results and finally the results are discussed in section V.

II. MIXER DESIGN

The following specifications for the mixer have been defined:

- Image rejection > 25 dB
- X-band RF frequency
- 1-2 GHz IF frequency
- 0 dBm LO power
- Conversion gain > 0 dB
- High LO-RF isolation
- Low spurious output signals

As mixing core a diode or a cold-FET mixer can be used. A cold-FET quad ring mixer core has been selected because this is more efficient than a diode ring mixer in terms of required LO power and can provide better linearity. The quad ring core also enables a relatively easy wideband matching. The selection of the optimum switch-transistor is a trade-off between the on-state resistance and the off-state capacitance. Analysis performed on the available cold-FET sizes in the design kit has shown that a low off-state capacitance is more important than a low on-state resistance. Therefore the smallest available cold-FET in the design kit, the 2x75 μm, has been used. The switching transistors are biased at the threshold voltage (about -3 V). The layout of the quad ring structure is shown in fig. 1.

Since the LO frequency range falls inside the RF frequency range no external LO filtering can be applied. To achieve high LO-RF isolation a double balanced mixer structure has been chosen. The RF and LO baluns have been realized using very compact Marchand-type baluns. The LO balun is also used to supply the gate voltage to the mixing transistors. The ground connection for the transistors is realized via the RF balun. The complete mixing core is shown in fig. 1.

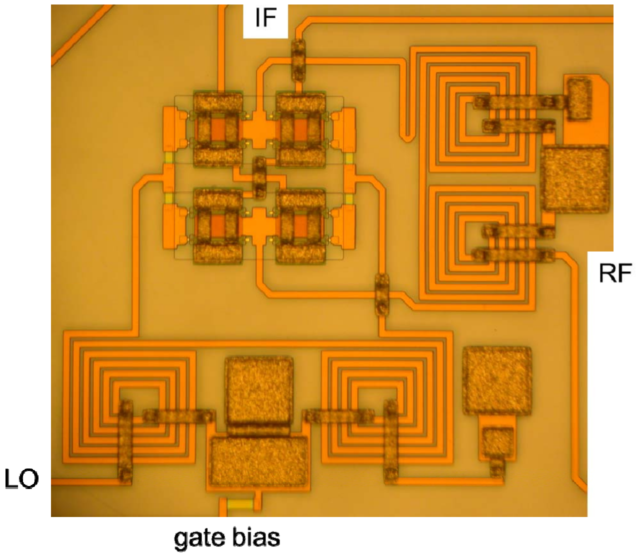

Fig. 1. Photograph of the mixer core with the quad ring FETs, LO balun, RF balun and differential IF output (layout area about 1 mm^2).

To realize the image-rejection function two mixers are needed that operate in quadrature. Therefore a 90° hybrid is needed in the LO or RF path. To minimize the conversion loss this hybrid has been placed in the LO path. The phase and amplitude accuracy of this hybrid will determine the maximum achievable image-rejection. A coupled inductor transformer [6] has been used as compromise between performance and layout area. The layout of this hybrid is shown in fig. 2. To divide the RF signal over the two mixers, a lumped-element Wilkinson splitter has been used.

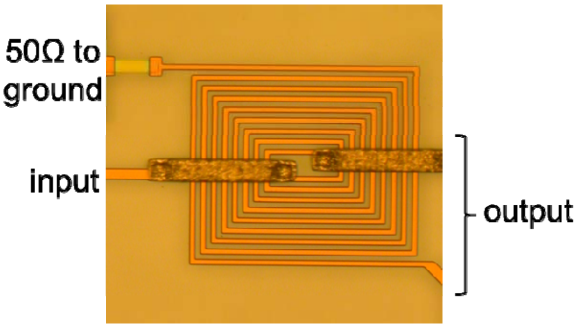

Fig. 2. Photograph of the coupled inductor 90° hybrid to realize the two LO signals.

The most difficult part of the design has been the IF path. To realize a single ended IQ-output an IF balun is needed. Because of the relatively low IF frequency a passive balun will become quite large and lossy. An example of a possible IF balun has been shown in [4], where a so called Triformer [7] structure has been used at an IF frequency around 2 GHz. The amplitude and phase balance performance of this structure is good, but the insertion loss is high (> 6 dB, including the splitting loss) and increases rapidly for lower frequencies. To overcome this loss and to compensate for the conversion loss of the mixer core additional IF amplification would be needed, which will also require a large layout area. Instead of a passive IF balun an active IF balun has been included to combine the balun function and IF amplification. This balun is realized with a stack of two 2x75 µm transistors, like a half-bridge. The simulated power gain is higher than 10 dB, from 0.1 to 2 GHz. An additional LC filter has been added in the output to further reduce any spurious signals. The drain bias is 10 V and the current consumption ranges from 17 to 33 mA depending on the gate bias voltage. The schematic of this active IF balun is shown in fig. 3 and the layout in fig. 4.

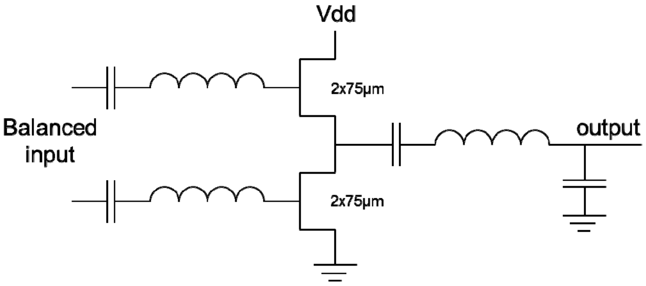

Fig. 3. Schematic of the active IF balun (gate bias connection not shown).

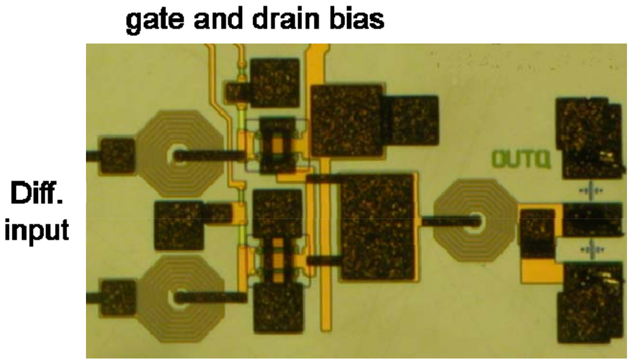

Fig. 4. Photograph of the active IF balun.

Finally an LO amplifier has been included. The mixer core needs approximately 15 to 20 dBm LO power for optimum conversion loss. The specified external LO power is 0 dBm. Therefore a two-stage amplifier has been added, consisting of a 2x30 µm input stage and 4x30 µm output stage. The transistors have been stabilized using RC feedback from drain to gate and an additional shunt resistor from the gate to ground. The simulated power gain is higher than 15 dB and the output power is higher than 15 dBm from 6 to 10.5 GHz for an input power of 0 dBm. Drain bias is 10 V and the current consumption is about 20 mA.

The complete architecture of the image-reject mixer is shown in fig. 5 and fig. 6 shows a photograph of the realized MMIC. All parts of the layout have been optimized using 2D EM simulations to obtain maximum overall performance for conversion gain and image rejection. As can be seen the actual mixer core uses about one third of the total layout area. The IF baluns and the LO amplifier each use also about one third of the area. An option in the layout has been included to bypass the LO amplifier, since simulation has shown that the bandwidth of this amplifier is limiting the bandwidth of the overall circuit. The chip dimension was not optimized, and could have been smaller, but was dictated by other designs on a multi-project wafer run.

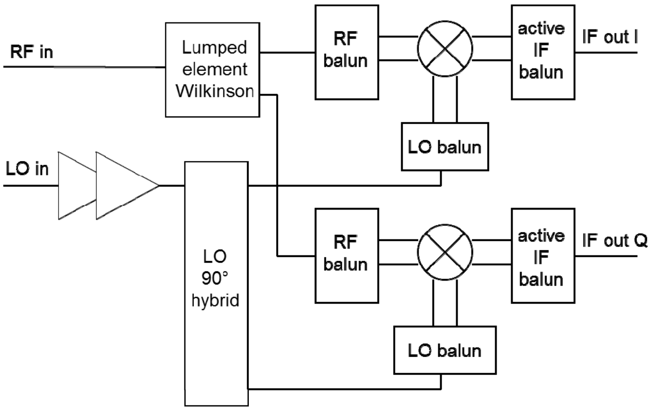

Fig. 5. Architecture of the double-balanced image-reject mixer.

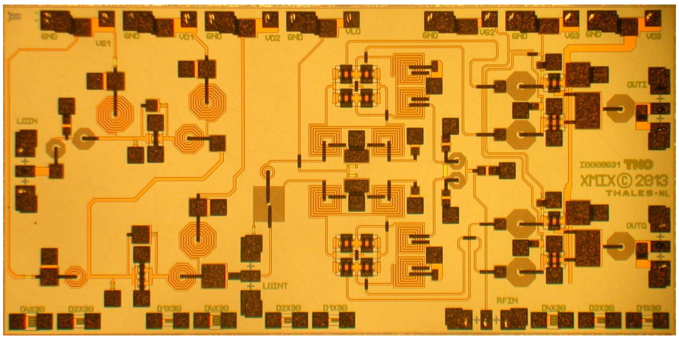

Fig. 6. Photograph of the GaN mixer MMIC (4.1 x 2.0 mm^2).

III. MIXER CORE TEST STRUCTURE

To analyze the performance of the double-balanced mixer core, a test structure has been designed consisting of only one passive mixer with a Triformer IF balun to allow single-ended IF measurements. The layout of this test structure is shown in fig. 7.

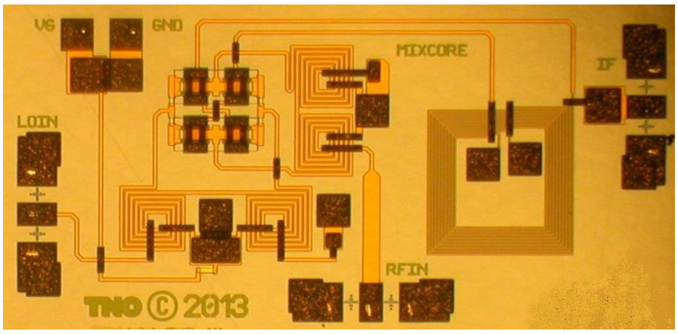

Fig. 7. Photograph of the GaN mixer core test structure (2.0 x 1.0 mm^2).

The conversion gain of this test structure has been measured versus RF frequency at IF frequencies from 1.0 to 3.0 GHz and 15 dBm LO power. At 1.5 GHz IF frequency fig. 8 shows that the measurement result compares very well with the simulation, indicating the accuracy of the EM simulation of the passive elements and the quad ring structure. The performance at the other IF frequencies is very similar.

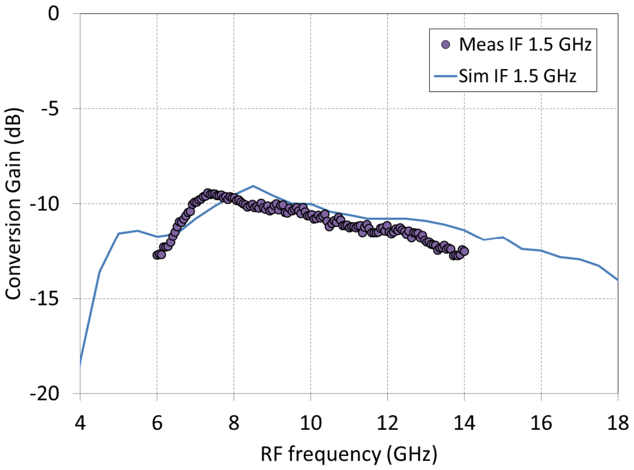

Fig. 8. Measured and simulated conversion gain at 15 dBm LO power at 1.5 GHz IF frequency.

IV. SIMULATION AND MEASUREMENT RESULTS

The mixer MMIC has been measured using a 4-port PNA-X network analyzer, in order to measure both the IF-I and IF-Q output. The total conversion gain and image rejection have been calculated from the I and Q data as if an ideal IF hybrid has been included. Measurements have been performed at two different bias settings: the default bias for the mixing FETs and IF balun and a maximum conversion gain bias. Power dissipation in the case of the default bias is around 170 mW for the IF balun. For the maximum gain bias the power dissipation increases to 330 mW. In both cases the additional power dissipation for the LO amplifier is 200 mW.

Fig. 9 shows the measured and simulated conversion gain at 0 dBm LO power for 1.0 and 2.0 GHz IF frequency at the default bias. Apart from 3 dB additional loss, the measured performance corresponds well with the simulations. Since this additional loss is not seen in the mixer core test structure it is expected that it is caused in the IF part of the circuit.

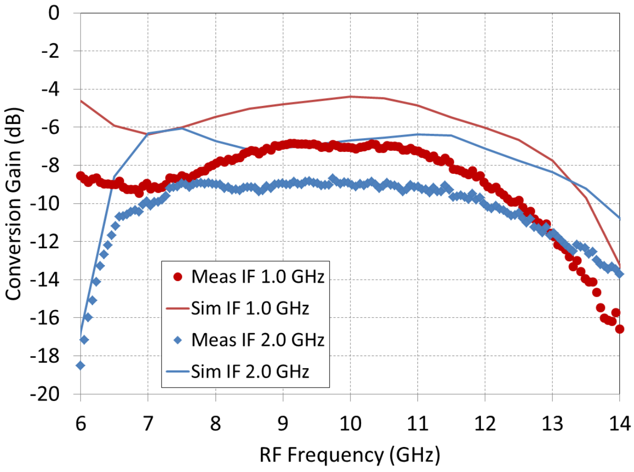

Fig. 9. Measured and simulated conversion gain at 0 dBm LO power for 1.0 and 2.0 GHz IF frequency.

Fig. 10 shows the measured conversion gain over a wider IF frequency range, from 0.5 to 3.0 GHz IF, at the maximum gain bias setting. The best performance is obtained between 0.5 to 1.0 GHz IF, with a conversion loss of less than 8 dB from 6 to 12 GHz RF. At higher IF frequency and low RF frequency the bandwidth of the LO amplifier is limiting the performance. This has been confirmed by measurement of the conversion gain, while bypassing the LO amplifier.

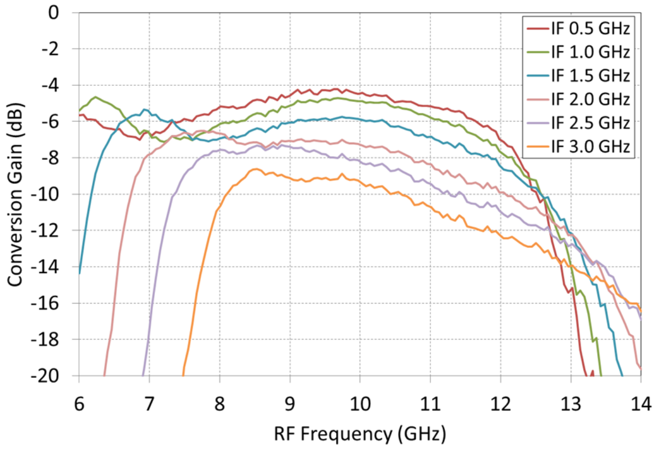

Fig. 10. Measured conversion gain at 0 dBm LO power for 0.5 – 3.0 GHz IF frequency at maximum gain bias setting.

The measured 1 dB input power compression point at 10 GHz RF frequency and 0 dBm LO power is 7 dBm. At 5 dBm LO power this compression point increases to 12 dBm. Fig. 11 shows the calculated image-rejection response from the measured I and Q data, compared to the simulation, for 0 dBm LO power and 1.0 and 2.0 GHz IF frequency. The measured image rejection in the X-band is better than 25 dB and shows good agreement with the simulation.

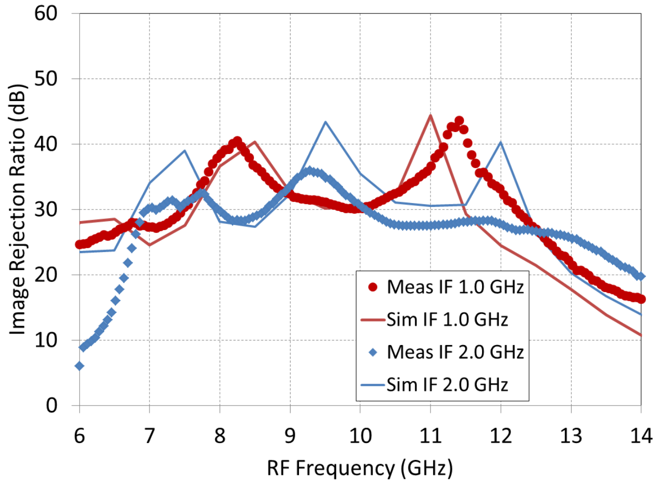

Fig. 11. Measured and simulated image-rejection ratio at 0 dBm LO power for 1.0 and 2.0 GHz IF frequency.

Spectrum measurements at a single IF output, before a 90° IF hybrid, have shown that the LO and RF suppression are respectively -70 dBc and -55 dBc, at 10 dBm LO power and -18 dBm RF power. Measured LO to RF isolation is better than 20 dB in X-band, at 0 dBm LO power. Without the on-chip LO amplifier this isolation increases to about 40 dB. No damage or change in performance has been observed when overdriving the RF input up to at least 35 dBm, demonstrating the robust performance of the GaN technology. Finally, the measured Noise Figure is less than 13 dB in X-band.

V. DISCUSSION AND CONCLUSION

In this work, the first GaN integrated double-balanced image-reject mixer has been demonstrated. The design uses an integrated LO amplifier and has demonstrated good performance over a wide frequency range. As also demonstrated by others, the performance of the mixer core is comparable to existing GaAs designs. Because of the extensive use of 2D EM simulations the measured performance shows good agreement with the simulations. This design experiment has shown the possibility of including the mixer function in a robust, fully GaN-based, LNA/down-converter combination. In case the additional cost of the GaN chip area is a major concern, the passive parts (i.e. baluns and hybrids) could be integrated on GaAs-based or other passive technologies.

ACKNOWLEDGMENT

The authors would like to thank the support of Thales Nederland and the European Defence Agency (EDA) project MAGNUS.

REFERENCES

[1] V.S. Kaper, R.M. Thompson, T.R. Prunty, J.R. Shealy, "Signal generation, control, and frequency conversion AlGaN/GaN HEMT MMICs," IEEE Trans. Microwave Theory Tech., vol.53, no.1, pp.55-65, Jan. 2005

[2] M. Sudow, M. Fagerlind, M. Thorsell, K. Andersson, N. Billstrom, P.-A. Nilsson, N. Rorsman, "An AlGaN/GaN HEMT-Based Microstrip MMIC Process for Advanced Transceiver Design," IEEE Trans. Microwave Theory Tech., vol.56, no.8, pp.1827-1833, Aug. 2008

[3] M.N. Do, M. Seelmann-Eggebert, R. Quay, D. Langrez, J.-L. Cazaux, "AlGaN/GaN mixer MMICs, and RF front-end receivers for C-, Ku-, and Ka-band space applications," 2010 European Microwave Integrated Circuits Conference (EuMIC), 27-28 Sept. 2010

[4] B. Mallet-Guy, L. Darcel, J.-P. Plaze, Y. Mancuso, "First 0.25µm GaN MMICs dedicated to compact,wideband and high SFDR receiver," 2012 7th European Microwave Integrated Circuits Conference (EuMIC), 29-30 Oct. 2012

[5] M. Sudow, K. Andersson, P.-A. Nilsson, N. Rorsman, "A highly linear double balanced Schottky diode S-band mixer," IEEE Microwave and Wireless Components Letters, vol.16, no.6, pp.336-338, June 2006

[6] R.E. Fisher, "Broad-Band Twisted-Wire Quadrature Hybrids (Short Papers)," IEEE Trans. Microwave Theory Tech., vol.21, no.5, pp.355-357, May 1973

[7] A. Boulouard, M. Le Rouzic, "Analysis of rectangular spiral transformers for MMIC applications," IEEE Trans. Microwave Theory Tech., vol.37, no.8, pp.1257-1260, Aug 1989