Novel Single Device Balanced Resistive HEMT Mixers

Klas Yhland, Niklas Rorsman, and Herbert H. G. Zirath

***Abstract*— A family of novel single device balanced resistive HEMT mixers has been designed and characterized. The RF is fed through a 180° balun. The IF is extracted either by a 180° balun or single ended. The main advantages of this type of mixer are that no device pairing is necessary, since only one HEMT is used and that no RF and LO grounding is necessary. These advantages make the described topology particularly suitable for microstrip MIC's, MMIC's, crossbar, fin-line and quasi optical mixers. The mixers are designed for RF 17.5–20 GHz, the LO is wideband and the IF is 1–2 GHz. Measurements show a conversion loss of 6 to 8 dB and an LO to RF isolation of up to 37 dB (typically 20 dB).**

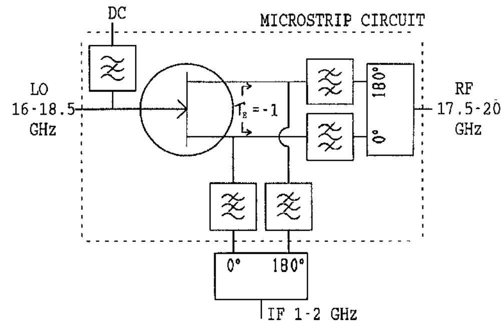

Fig. 1. Block diagram of mixer 1, the source of the FET is DC-connected to ground through a bias tee outside the IF balun and gate-source voltage is applied between the DC connection and ground.

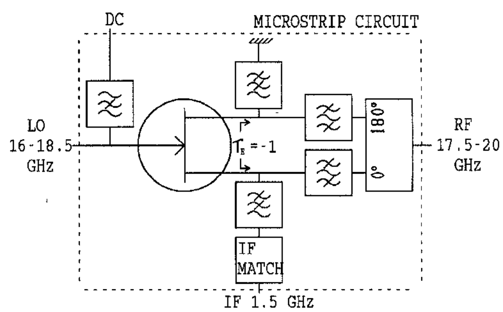

Fig. 2. Block diagram of mixer 2, the gate-source voltage is applied between the DC connection and ground.

I. Introduction

BALANCED MIXERS are widely used to minimize unwanted frequencies like the leakage of the local oscillator (LO) signal to the radio frequency (RF) port, the LO signal to the intermediate frequency (IF) port, as well as intermodulation (IM) products. A number of different MESFET and HEMT-based mixers operating in the resistive mode, working at frequencies up to F-band have been presented recently [1]–[10]. The resistive mixer has a number of advantages like low intermodulation, zero DC-consumption, natural separation between the LO and RF/IF-ports. Also low conversion loss (CL) can be obtained at a very low LO-power using advanced InP based HEMT-devices [8].

II. Mixer Operation

The block diagrams of the balanced mixers are shown in Figs. 1 and 2. The mixers are operated as resistive mixers, i.e., no DC voltage is applied over the FET channel. The LO is fed to the FET gate, resulting in a change of channel resistance between high and low values. In order for the LO voltage to open and close the FET channel effectively the LO signal has to see a ground at the source and the drain, i.e., the reflection coefficient seen from the drain and the source into the RF balun should be -1 at even mode excitation ($\Gamma_e = -1$). The LO ground is achieved by selecting the proper transmission line length between the FET and the RF balun. Simulations show that the LO power requirement of the mixer increases 20–30 dB as Γ_e approaches 1. The RF signal, which is fed equally in amplitude and opposite in phase to the drain and the source of the FET, is modulated by the LO, generating an IF signal in the channel. Since the RF is applied balanced to the source and drain, the RF will have a virtual ground in the middle of the channel. The IF signals will have opposite phase at the drain and the source. The IF can be extracted with a 180° balun as in mixer 1, Fig. 1, or at the drain of the FET when the source is grounded as in mixer 2, Fig. 2. The gate to source voltage (V_{gs}) is close to the pinch-off voltage for optimum operation.

III. Mixer Design

The layouts of the mixers are shown in Figs. 3 and 4. The mixers were fabricated on RT Duroid 5870 with a thickness of 0.38 mm (15 mil). In both mixers the RF balun was realized as a ratrace with the sum port omitted at a center frequency of 18 GHz. The ratrace was optimized for 50 Ω impedance

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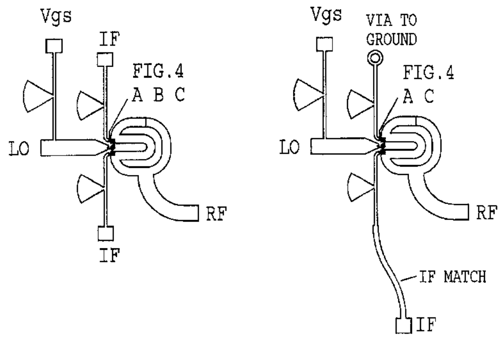

Fig. 3. Layout of the two mixers, at left mixer 1 and at right mixer 2.

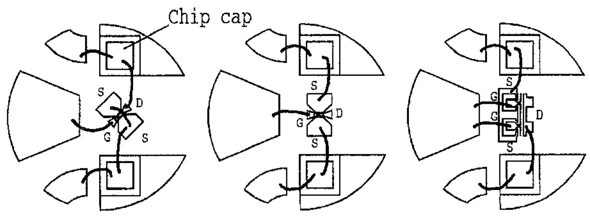

Fig. 4. Zoom of the device mountings (a) InP device asymmetrically mounted. (b) InP device symmetrically mounted. (c) NE324 device asymmetrically mounted.

level. The LO port was not matched in this design. The IF blocking filters were realized with 0.8 pF chip capacitors. Radial stubs were used as RF and LO blocking filters. In mixer 1 the IF balun was placed outside the planar circuit in order to simplify the design. A commercially available balun covering 1–2 GHz was used at the IF. The balun has 50 Ω port impedances and no further matching was used. In mixer 2, an impedance transforming network from the 50 Ω IF port-impedance to a device IF-impedance of 100 Ω was utilized.

In order to make the mixer well balanced the drain and source parasitics should be identical or negligible. This is done by making the drain and source symmetric around the gate finger.

Two different kinds of HEMT's were used in this work. One commercially available GaAs HEMT (NE324) and one in-house fabricated InP HEMT.

The InP HEMT is configured as two paralleled devices with a common drain and separate sources, Fig. 5. It is possible to mount the InP device in both an asymmetric and a symmetric way. In Fig. 4(a) the two sources are bonded to the same RF-IF connection and the drain pad to the other RF-IF connection resulting in an asymmetric device mounting. In Fig. 4(b) the drain pad of the HEMT was left unconnected while the two source pads were bonded to individual RF-IF connections resulting in symmetric parasitics. For NE324 only asymmetrical mounting was possible due to the layout of the device, Fig. 4(c). Mixer 1 was assembled with an asymmetrically mounted InP HEMT, Fig. 4(a), a symmetrically mounted InP HEMT, Fig. 4(b) and a NE324, Fig. 4(c). Mixer 2 was assembled with an asymmetrically mounted InP HEMT, Fig. 4(a) and an NE324, Fig. 4(c).

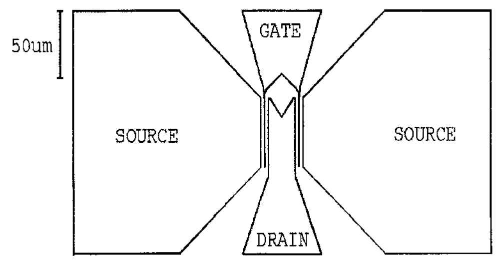

Fig. 5. The layout of the InP HEMT. The chip size is $290 \times 400\ \mu m^2$.

IV. HEMT Fabrication and Characteristics

Two types of HEMT's were investigated in this study, our own developed InP-based HEMT and a commercially available GaAs HEMT.

The InP-based HEMT is fabricated on a material with a strained $In_{0.60}Ga_{0.40}As$ channel on InP. The room temperature Hall mobility is 8600 cm^2/Vs (28500 cm^2/Vs at 77 K) and the electron density is $1.8 \cdot 10^{12}\ cm^{-2}$ ($2.0 \cdot 10^{12}\ cm^{-2}$ at 77 K). The HEMT was fabricated with standard photolithography for the isolation and ohmic contact definition. The ohmic metalization is Au/Ge/Ni, and RTA (rapid thermal annealing) was used for annealing. The resulting ohmic contact resistivity was 0.2 Ω·mm. T-gates (mushroom shaped) were defined with electron beam lithography (EBL) using a three-layer resist system. A selective citric acid based etch was used for recess etching. The gate metalization (Au/Pt/Ti) was electron beam evaporated. The gate length is approximately 0.15 μm. A thick gold layer was evaporated on the bonding pads and the devices were then passivated with polyimide. Finally, the wafer was lapped to a thickness of 150 μm and diced with a diamond saw. The layout of the HEMT is shown in Fig. 5. In this work we have used devices with $2 \times 50\ \mu m$ and $2 \times 75\ \mu m$ gate width for the asymmetric and symmetric device mounting respectively. The DC transconductance is 350 mS/mm and the saturated drain to source current is 400 mA/mm. The minimum resistance between the source and the drain terminals, which is a key parameter for this type of mixer, is 1.5 Ω· mm. The extrapolated maximum frequency of oscillation, $f_{\max}$, is 380 GHz and the extrinsic transit frequency f_T is 110 GHz. This HEMT was previously found to be suitable in resistive mixers [8] requiring very little LO-power and giving a comparatively low CL. This is due to the effective modulation of the channel charge versus gate voltage.

The GaAs-based HEMT is a NE324 from NEC. This device also has a mushroom shaped gate and a pseudomorphic channel, the gatewidth is approximately 200 μm and the gatelength 0.25 μm. The measured on-resistance is approximately 1.5 Ω· mm which makes it comparable with the InP-HEMT.

V. Mixer Characterization

The mixer characterization includes CL versus RF, CL versus LO power, LO to RF isolation, 1 dB compression point versus LO power, and two tone 2nd and 3rd order intermodulation products. Optimum CL was found at $V_{gs} = -0.75$ V for the asymmetric mounted InP devices and at $V_{gs} = -0.65$ V for the symmetric mounted device, at 0

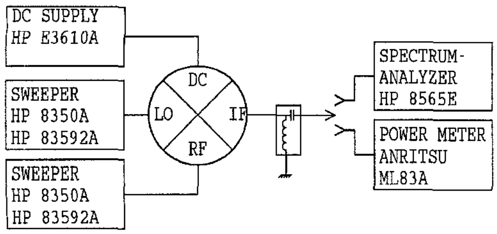

Fig. 6. Set-up for the conversion loss measurements.

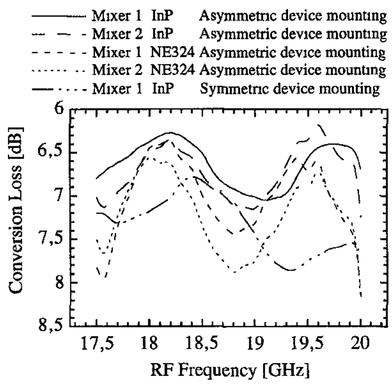

Fig. 7. Conversion loss versus RF, $P_{RF} = -15$ dBm, $f_{IF} = 1.5$ GHz. $P_{LO} = 0$ dBm and $V_{gs} = -0.75$ V for the asymmetrically mounted InP devices. $P_{LO} = 0$ dBm and $V_{gs} = -0.65$ V for the symmetrically mounted InP device. $P_{LO} = 3$ dBm and $V_{gs} = -0.80$ V for the NE324 devices.

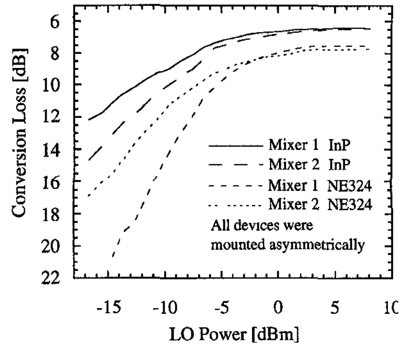

Fig. 8. Conversion loss versus LO power, $f_{LO} = 17$ GHz, $f_{RF} = 18.5$ GHz and $P_{RF} = -21$ dBm. $V_{gs} = -0.75$ V for the InP devices. $V_{gs} = -0.80$ V for the NE324 devices.

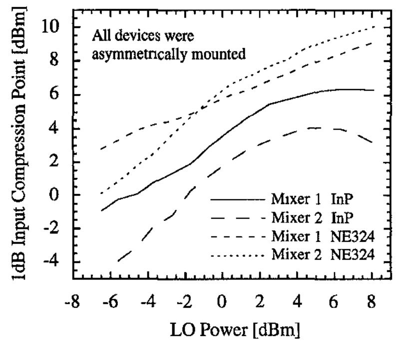

Fig. 9. 1 dB Input Compression Point versus LO power, $f_{LO} = 17$ GHz and $f_{RF} = 18.5$ GHz. $V_{gs} = -0.75$ V for the InP devices. $V_{gs} = -0.80$ V for the NE324 devices.

dBm LO power. For the NE324, optimum CL was found at $V_{gs} = -0.80$ V, at 3 dBm LO power. All measurements were performed at these bias points. For the symmetrically mounted InP device mixer, the measurements are restricted to LO to RF isolation and CL.

A. Conversion Loss

The set-up for the CL measurements is shown in Fig. 6. Fig. 7 shows the CL versus RF fort all five mixers. The minimum CL is 6.2 dB for the asymmetric InP device mounting in both mixer 1 and mixer 2, 6.8 dB for the symmetric InP device mounting, 6.4 dB for the NE324 in mixer 1 and 6.6 dB for the NE324 in mixer 2. The mixer with symmetrically mounted InP device has a higher CL than the mixer with the asymmetrically mounted InP device because it has higher on state resistance. In the mixer with the symmetrically mounted InP device the drain pad is left unconnected and one of the sources is used as drain instead, i.e., the HEMT is operated with the two unit cells in series instead of parallel, causing the on state resistance of the channel to be approximately 40 Ω instead of 15 Ω. Fig. 8 shows the CL versus LO power for the mixers with the asymmetrically mounted InP devices and the mixers with the NE324 devices. Fig. 9 shows the 1 dB Input Compression Point ($P_{1\,dB}$) versus LO power for the mixers with the asymmetrically mounted InP devices and the mixers with the NE324 devices.

B. Noise Figure

The noise figure was measured for mixer 1 with NE324 under the same bias conditions as in Fig. 7. The noise figure was approximately 1 dB higher than the CL which is in agreement with [4].

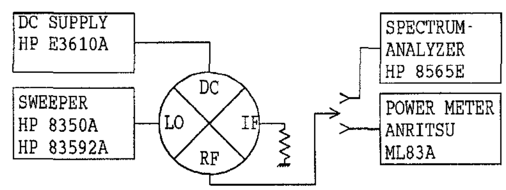

Fig. 10. Set-up for the LO to RF isolation measurement.

C. LO to RF Isolation

The set-up for the LO to RF isolation measurement is shown in Fig. 10. Fig. 11 shows the LO to RF isolation of all five mixers. The symmetric mounting of the InP HEMT gives superior performance over the asymmetric mounting. The relatively low LO to RF isolation at 16 GHz is caused by imbalance in the RF balun.

D. Intermodulation

Two tone 2nd and 3rd order InterModulation (IM) levels were measured for the mixers with the asymmetrically mounted InP devices and the mixers with the NE324 devices. The set-up for the two tone IM measurements is shown in

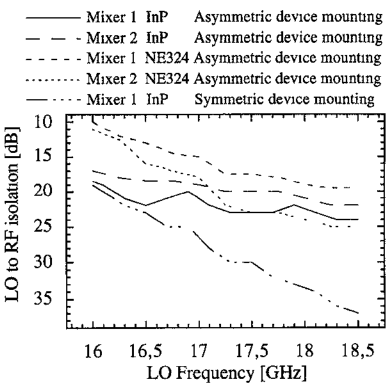

Fig. 11. LO to RF isolation at $f_{\mathrm{LO}} = 16$–18.5 GHz. $P_{\mathrm{LO}} = 0$ dBm and $V_{gs} = -0.75$ V for the asymmetrically mounted InP devices. $P_{\mathrm{LO}} = 0$ dBm and $V_{gs} = -0.65$ V for the symmetrically mounted InP device. $P_{\mathrm{LO}} = 3$ dBm and $V_{gs} = -0.80$ V for the NE324 devices.

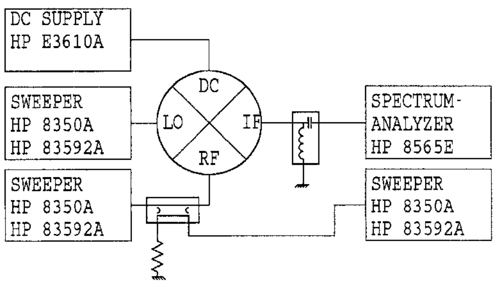

Fig. 12. Set-up for second and third order two tone intermodulation measurements.

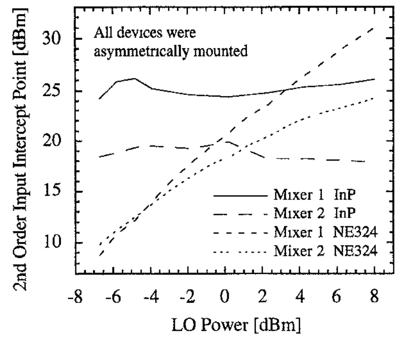

Fig. 13. Second order input intercept point versus LO power, $f_{\mathrm{LO}} = 17$ GHz, $f_{\mathrm{RF1}} = 18.5$ GHz and $f_{\mathrm{RF2}} = 19.99$ GHz. $V_{gs} = -0.75$ V InP devices. $V_{gs} = -0.80$ V for the NE324 devices.

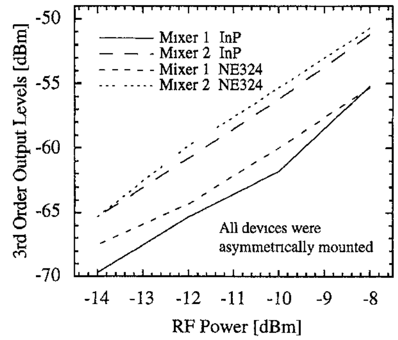

Fig. 14. Third order intermodulation products versus RF power, $f_{\mathrm{LO}} = 17.5$ GHz, $f_{\mathrm{RF1}} = 19$ GHz and $f_{\mathrm{RF2}} = 19.01$ GHz, $P_{\mathrm{LO}} = 0$ dBm. $V_{gs} = -0.75$ V for the InP devices. $V_{gs} = -0.80$ V for the NE324 devices.

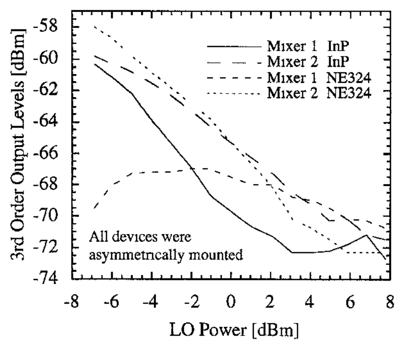

Fig. 15. Third order intermodulation products versus LO power, $f_{\mathrm{LO}} = 17.5$ GHz, $f_{\mathrm{RF1}} = 19$ GHz and $f_{\mathrm{RF2}} = 19.01$ GHz, $P_{\mathrm{RF1}} = P_{\mathrm{RF2}} = -14$ dBm. $V_{gs} = -0.75$ V for the InP devices $V_{gs} = -0.80$ V for the NE324 devices.

Fig. 12. Fig. 13 shows the 2nd order input intercept point (IIP2) versus LO power. The 2nd order output levels have a 2 dB/dB slope which makes it possible to extract the IIP2. From Fig. 13 it is clear that mixer 1 with the NE324 device has a higher IIP2, compared to mixer 2 with the NE324 device, at high LO powers. The InP HEMT based mixers have the same characteristic but almost independent on the LO power. The 3rd order IM levels versus RF power have a slope varying between 2 and 2.6 for different LO powers. We show therefore the actual 3rd order levels versus RF power at a fixed LO power. In Fig. 14. Mixer 1 shows better 3rd order intermodulation levels, but the difference between the two types of HEMT's is small. In Fig. 15, the 3rd order IM-product levels versus LO power are shown. For the mixer 2 type, this IM-product decreases approximately 1 dB per 1 dB increase in LO power over a relatively broad LO-power range.

VI. Conclusion and Discussion

A family of new single device balanced resistive HEMT mixers has been successfully demonstrated. Two different types of HEMT's were investigated experimentally, InP-based and GaAs-based HEMT's. The mixers are realized with 180° baluns at the RF-port. The IF can be either single ended or balanced. Measurements show a total mixer CL of 6–8 dB and an LO to RF isolation of typically 20 dB and as best 37 dB. It was found that at least 4 dB less LO-power is needed to pump the InP-based HEMT compared to the GaAs HEMT for similar conversion loss. Other measured characteristics include conversion loss versus LO power, IF output power versus RF power, 2nd and 3rd order intermodulation products. The effects of device asymmetry were also investigated, the CL and LO to RF isolation were measured for two different device mountings, one symmetric and one asymmetric. It was shown that the device symmetry is important. From intermodulation point, the balanced IF configuration is favorable. If space is of major concern, the IF balun can be omitted.

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REFERENCES

[1] S. A. Maas, "A GaAs MESFET mixer with very low intermodulation," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 425–429, 1987.

[2] ——, "A GaAs MESFET Balanced mixer with very low intermodulation," in*IEEE-MTT Int. Microwave Symp. Dig.*, Las Vegas, 1987, pp. 895–898.

[3] K. W. Chang *et al.*, "Zero bias GaInAs MISFET mixers," in *IEEE-MTT Int. Microwave Symp. Dig.*, Long Beach, 1989, pp. 1027–1030.

[4] J. Geddes, P. Bauhahn, and S. Swirhun, "A millimeter wave passive FET mixer with low $1/f$ noise," in *IEEE-MTT Int. Microwave Symp. Dig.*, Boston, 1991, pp. 1045–1047.

[5] K. W. Chang *et al.*, "High performance resistive EHF mixer using InGaAs HEMT's," in *IEEE-MTT Int. Microwave Symp. Dig.*, Albuquerque, 1992, pp. 1409–1413.

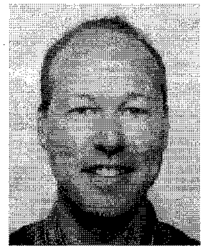
[6] H. Zirath, I. Angelov, and N. Rorsman, "An HFET millimeter resistive mixer," in *22nd European Microwave Conf. Proc.*, Helsinki, 1992, pp. 614–619.

[7] I. Angelov, H. Zirath, N. Rorsman, C. Karlsson, and R. Weikle, "An F-band resistive mixer based on heterostructure field effect transistor technology," in *IEEE-MTT Int. Microwave Symp.*, Atlanta, 1993, pp. 787–790.

[8] H. Zirath, C.-Y. Chi, N. Rorsman, and G. Rebeiz, "A 40 GHz integrated quasi optical slot HFET mixer," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 2492–2497, 1994.

[9] A. A. Saleh, "Theory of resistive mixers," Research Monograph #64, The MIT Press, Cambridge, MA.

[10] K. Yhland, N. Rorsman, and H. Zirath, "A novel single device balanced resistive HEMT mixer," in *IEEE-MTT Int. Microwave Symp. Dig.*, Orlando, 1995, pp. 1411–1414.



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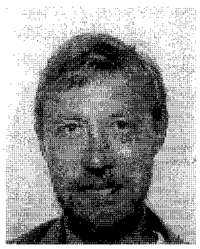

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