Ka-Band MMIC Receiver with Ion-Implanted Technology for High-Volume and Low-Cost Application

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Abstract—**An MMIC receiver in ion-implantation technology, with LNA and mixer, shows 4.7 dB noise figure and 6.8 dB conversion gain at 35 GHz with a low IF frequency of 10–50 MHz.**

I. Introduction

HIGH volume applications such as phased array antennas and smart ammunitions dictate a cost-effective MMIC technology. A key component in these systems is a receiver or down-converter consisting of a low-noise amplifier (LNA) and a mixer to translate the RF frequency to a lower IF frequency for signal processing. At Ka-band frequencies the material technology used in fabricating the receiver can have a strong influence on receiver cost and performance. Ion-implantation technology was chosen for fabricating the receiver for the following reasons:

- cost effective,
- high yield,
- highly manufacturable,
- $1/f$ noise lower than in HEMT technology,
- selective implantation allows high level of integration.

In actual application (e.g., FMCW radars), an IF frequency of 10–60 MHz called for a mixer with low $1/f$ noise. A passive MESFET mixer (i.e., no drain current) is chosen instead of an active mixer to keep this $1/f$ noise down. Also, a P-HEMT passive mixer in our lab has shown higher low-frequency noise than passive MESFET mixers. Measurement on a similar P-HEMT-based (LNA + mixer) combination has shown a low-frequency (IF $\leq$ 20 MHz) noise of 6.5 dB (DSB) and a high-frequency (IF $\geq$ 80 MHz) noise of 3.5 dB (DSB). So although the P-HEMT receiver has a lower noise figure than an ion-implanted receiver at high IF frequencies, the ion-implanted receiver has an advantage at low IF frequencies. Adjusting LO-power level (e.g., lowering it) may somewhat improve the low-frequency noise at a cost of higher insertion loss and high-frequency noise. A comparison table is included in the measurement section.

Good results have been reported [1] for a hybrid LNA in Q-band, which uses discrete devices fabricated on ion-implanted, graded heterostructure $In_xGa_{1-x}As$ substrate. The grading, which could adversely affect the yield for high-volume and low-cost applications, was necessary to stop gate leakage [1]. The same group [2] reported one MMIC amplifier in Q-band with no noise data. The data reported in this article are for a receiver using only ion-implanted technology in Ka-band. A simplified block diagram of the system is given in [3]. The results discussed here are for two separate amplifier and mixer IC's combined to form a receiver or downconverter. The two chips can also be integrated, resulting in a single chip receiver.

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II. Fabrication

The LNA and mixer IC's are based on 0.25-μm ion-implanted FET technology fabricated on a 3-inch wafer using a hybrid e-beam/stepper lithography process. All lithography except the 0.25-μm gate level is done with a Censor 10$\times$ optical stepper. The gate lithography uses e-beam direct-write exposure. Both IC's use identical dual-channel implants of Si^{29} 1e13 cm^{-3} at 100 kev and 50 kev with a buried p implant of Be 6e11 cm^{-3} at 80 kev to improve transconductance of the FET's when they are biased near pinchoff. Backside processing includes thinning the wafers to 4 mils, reactive ion etching of via holes, gold plating the backside, and etching of streets for chip separation.

III. Design and Results

A resistive FET mixer [4] is selected to minimize receiver $1/f$ noise at low IF frequencies (10–100 MHz). In this FET mixer design the LO and RF signals are applied to the gate and drain, respectively, through appropriate matching networks. The IF output is taken from a low-pass filter attached to the source. The mixer design is based on a 0.25-μm by 200-μm gate interdigital FET with four gate fingers. A unique resonant loop approach provides good LO-to-RF isolation by resonating the gate-to-drain capacitance at the LO and RF frequencies. A similar single-FET unbalanced mixer is described in [5]. This mixer is comparable in many respects to a diode balanced mixer in the case where the LO and RF frequencies are very close and the IF frequency is low (10–100 MHz). The comparable diode balanced mixer uses an FET with source and drain shorted to form the diode. Electrical evaluation of diode mixers of this type in our laboratory shows the performance differs from the FET mixer mainly in a lower LO drive requirement. On the other

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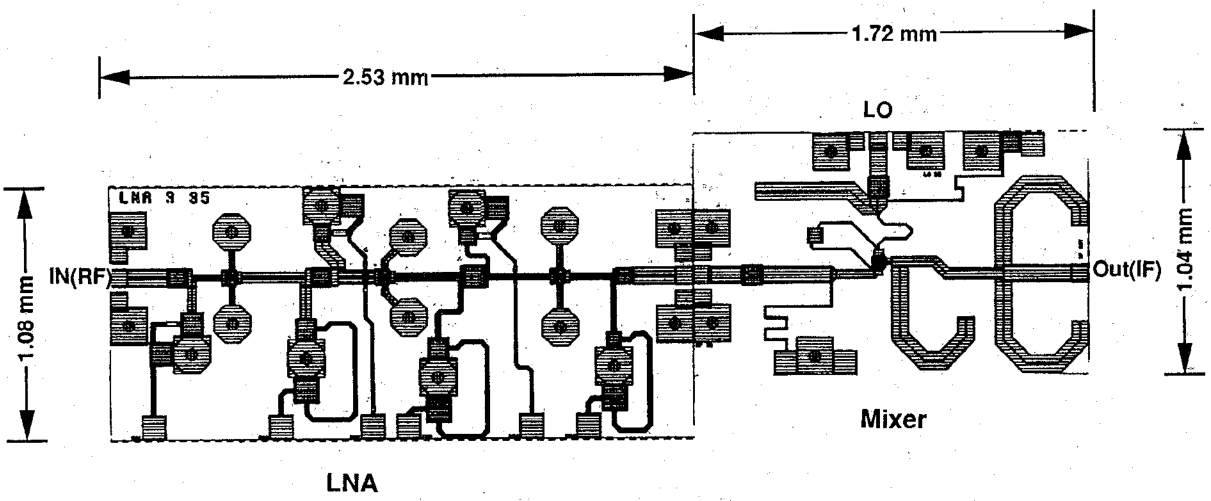

Fig. 1. Mixer and three-stage low noise amplifier circuits (mixer: 1.0×1.7 mm^2; LNA: 1.08×2.53 mm^2).

hand, the diode balanced mixer chip occupies an area of 6.2 mm^2 compared to 1.9 mm^2 for the FET mixer. Balanced mixers with improved microdot diode structures [6] based on special doping profiles offer an additional advantage of lower noise figure, but the approach increases process complexity if integration with FET-based circuits is a consideration.

The LNA has three stages, each employing a 0.25×100-μm^2 device. Each stage has series feedback to bring input match and optimum noise match together. All the bias filters are included on-chip. No external bias circuitry is needed for this chip. The gates have series stabilizing resistors; the drains are biased over RF-shorted quarter-wave lines at the lowest impedance (dc floating) point. This ensures stable operation of the amplifier. Fig. 1 shows the combined layout of amplifier and mixer. Fig. 2 shows the combined performance of LNA and mixer. We have plotted double sideband NF and gain with a different LO drive. Since the traces in Fig. 2 for different LO levels lie close to one another, we describe in the caption of Fig. 2, which trace belongs to which LO drive level. The IF frequency is taken from 10 MHz to 110 MHz. No on-chip tuning was necessary to achieve these results. For the best performance (Fig. 3), only the bias of the LNA was changed. All the measurements are made with a HP8970B noise figure meter in which LNA + mixer form the receiver under test. The LO drive during testing derives from a GUNN source to minimize the low frequency noise. Even then we observed for some LO frequencies (e.g., 33 GHz of LO) at low IF (< 15 MHz), the noise tends to increase slightly for higher LO drive (> 11 dBm). This slight increase in NF, however, does not affect system performance, so the cause has not been fully investigated. Our assumption at this point is the mixer FET might be overdriven at some frequencies, and the higher LO drive could cause an increase in gate current and also this slight increase in NF [7]. Fig. 2(a)–2(c) depict the performance at three LO frequencies. At 34 and 35 GHz, the low IF frequency (< 15 MHz) noise is much flatter.

The LO drive levels are 7 dBm, 9 dBm, 11 dBm, and 13 dBm. Even though overall gain improves with LO drive, the total NF is almost unchanged; it is determined mainly by the front-end low-noise and high-gain amplifier. At 35 GHz with an LO drive of 11 dBm, the total gain is approximately 6.8 dB and NF is 4.7 dB. At 33 GHz (the center of the LNA band) with the same LO drive, the total gain is 6.8 dB and NF is 4.5 dB. After readjusting the bias of the LNA (VDS = 2 V, VGS1 = 0.8 V, VGS2 = −0.8 V, VGS3 = −0.5 V), we achieved the best result over a narrower band. The best performance at the center of the LNA band (33 GHz) is shown in Fig. 3. The NF dropped to 4.2 dB and the gain is ~10 dB with a nominal 9 dBm LO drive level to the mixer. The individual chip performance for LNA is 14.5 dB gain with 3.8 dB NF @ 35 GHz (nominally), and for the mixer it is approximately 5 dB conversion loss and noise figure (DSB) at 35 GHz. The individual LNA performance is being reported in [8]. The results presented here are for a system of LNA and mixer, which does not have a sideband rejection filter. In actual practice the RF signal will be present in only one sideband, so the detection ability of the signal will degrade by 3 dB. The SSB noise figure for this system will be 3 dB higher, and the gain should be read 3 dB lower.

Finally in Table I, we show a performance comparison between P-HEMT-based (LNA + mixer) and I^2 MESFET-based (LNA + mixer). The lower gain of the HEMT receiver is mainly due to the fact that the MESFET receiver has a three-stage LNA preceding the mixer, while the HEMT receiver LNA has only two stages; however, the 1-dB compression point for the HEMT receiver is already lower than the MESFET receiver. Increasing the HEMT amplifier gain by adding an additional stage would further reduce the power for 1 dB compression.

It is also interesting to notice the P-HEMT had a lower high-frequency (IF = 100 MHz) noise than the I^2 MESFET; on the other hand, at low IF frequency (IF ≤ 20 MHz), I^2 MESFET did better in terms of noise figure. A part of this low-frequency noise in P-HEMT is due to overdriving with LO and a part is due to the material itself. This is not, however, investigated mainly because the I^2 MESFET showed better results for our applications. The performance of the P-HEMT mixer was observed by varying the LO drive; lowering the LO drive was able to improve the low-

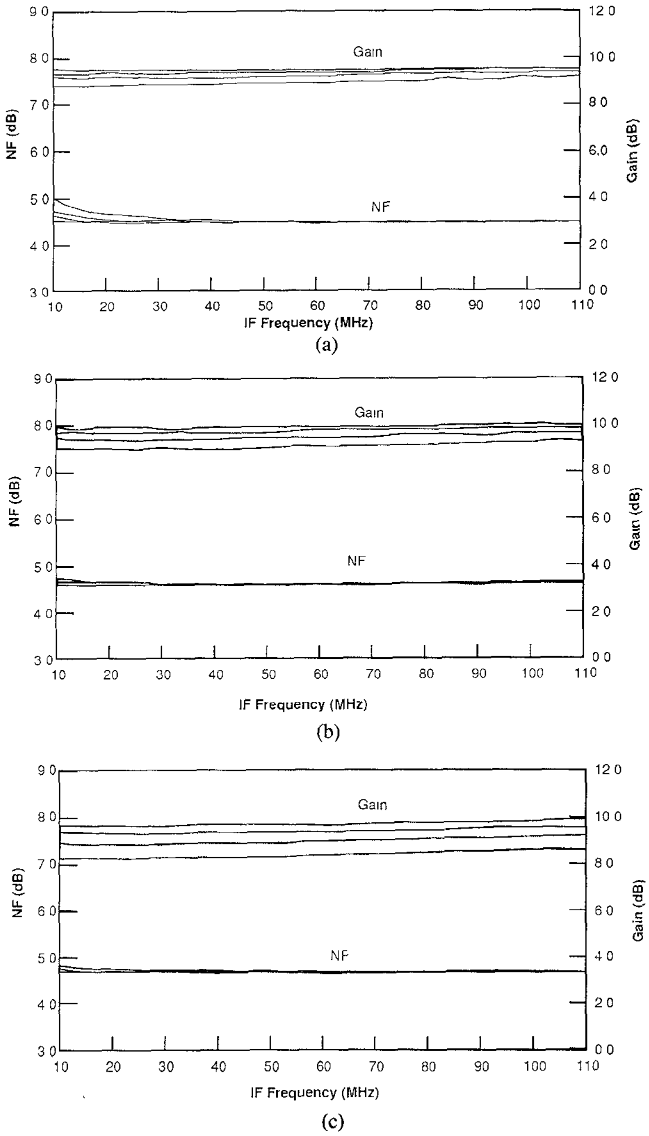

Fig. 2. Gain and NF (DSB) performance of LNA and mixer at three frequencies (33 GHz, 34 GHz, and 35 GHz). LO drive is varied from 7 dBm to 13 dBm in steps of 2 dB. Upper trace for gain plot is with 13 dBm of LO; the lower trace is with 7 dBm of LO. Bias point for LNA: VDS = 2 V, VGS1 = −1.07 V (~ 20% Idss); VGS2 = −1.00 V (~ 25% Idss), VGS3 = −0.83 V (~ 35% Idss). Bias for mixer: VGS = −2.0 V. Since the gain and NF were measured directly from the noise figure meter that measures noise from two sidebands, the gain should be read 3 dB lower and SSB noise figure will be 3 dB worse. (a) 33 GHz LO. (b) 34 GHz LO. (c) 35 GHz LO.

frequency noise at a high cost of insertion loss and high-frequency (IF ≥ 80 MHz) NF. The yield performance of ion-implantation and MBE MESFET technology developed under this program for Ka-band high-volume applications is being reported in a separate article [9]. These are produced in high volume for system insertion (smart ammunitions) the unit cost of which is to be bought as low as $3000.

IV. Conclusion

We have successfully demonstrated viable and manufacturable technology, useful in Ka-band for high-volume, cost-effective applications. The measured results show the technology is able to deliver high performance with good yield. At this time, comparison with HEMT technology in our lab

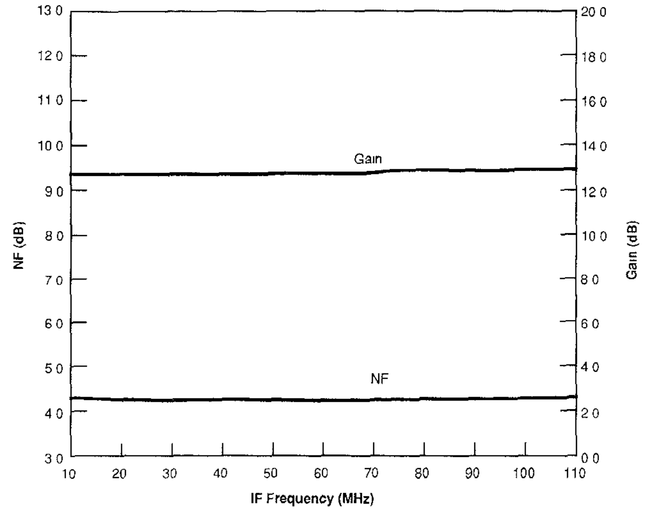

Fig. 3. Best performance obtained by readjusting the bias point of the LNA (VDS = 2.0 V, VGS1 = −0.8 V, VGS2 = −0.8 V and VGS3 = −0.5 V). LO frequency is 33 GHz at 9 dBm drive.

TABLE I
Comparison of HEMT-Based (LNA + mixer) and MESFET-Based (LNA + mixer) at 35 GHz

	HEMT	I^2 MESFET
Gain (SSB)	3.0 dB	6.8 dB
NF (SSB) @ 10 MHz	9.5 dB	7.7 dB
NF (SSB) @ 100 MHz	6.5 dB	7.7 dB
RF Return Loss	−30.0 dB	−9.0 dB
LO Return Loss	−30.0 dB	−15.0 dB
RN IN for 1 dB Compression	−15.0 dB	−6.0 dBm
LO Drive	9.0 dBm	9.0 dBm

Values are nominal. These are measured at Honeywell Lab. Both use equal gate widths per stage. P-HEMT LNA is a two-stage amplifier while the MESFET LNA has three stages.

shows that for FMCW applications (e.g., smart munitions), where the detected IF frequency is less than 60 MHz and noise in the IF band of 10–60 MHz plays an important role, the mixer based on P-HEMT technology seems to have no advantage over the mixer based on ion-implanted technology. It should be pointed out that the LNA with P-HEMT is superior to that with ion-implanted material in terms of NF. The material or device improvement with P-HEMT technology should be able to improve the low-frequency noise in the mixer. We have, however, become aware of work [10] based on P-HEMT technology. Unfortunately, no information is given in terms of SSB noise figure, SSB gain, and 1-dB compression point at low IF frequency (< 20 MHz) for direct comparison with the results in Table I.

Acknowledgment

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