K-Band Receiver Front-Ends in a GaAs Metamorphic HEMT Process

Babak Matinpour, Neeraj Lal, Joy Laskar, *Member, IEEE*, Robert E. Leoni, III, *Member, IEEE*, and Colin S. Whelan, *Member, IEEE*

***Abstract*—In this paper, we present K-band receiver blocks fabricated in a state-of-the-art 0.18-μm GaAs metamorphic high electron-mobility transistor (MHEMT) process using 60% indium-content InGaAs channel. Several circuits are developed to demonstrate the superior noise performance and successful integration of K-band receiver components in such a process. We show a low-power three-stage low-noise amplifier (LNA) with a gain of 23 dB and a noise figure (NF) of less than 1.6 dB at 30 GHz. This LNA shows InP-like performance on a GaAs substrate with a high RF yield of 84%. This is the first report of a statistical yield analysis of an MHEMT integrated circuit. We also demonstrate on-chip integration of a single-stage amplifier with a diode subharmonic mixer for low-power and broad-band receiver performance. This down-converter exhibits a conversion loss of 3 dB, overall NF of 5 dB, and third-order input intercept point of −5 dBm from 26 to 30 GHz.**

***Index Terms*—Frequency conversion, microwave circuits, microwave frequency conversion, microwave mixers, microwave receivers, MMIC mixers, MMIC receivers, MMICs, receivers.**

I. Introduction

THE increasing demand for existing millimeter-wave wireless systems, such as local multipoint distribution systems (LMDS) and emerging applications such as wireless local area networks (WLAN), has given rise to the development of low-power and high-performance millimeter-wave transceivers. Most commercial millimeter-wave transceivers have utilized GaAs-based high electron-mobility (HEMT) and pseudomorphic HEMT processes for their reasonable performance and cost of fabrication. Until recently, the only alternative for higher performance was the more expensive InP-based processes. However, due to the high cost of InP substrates and fabrication, InP-based technology had been limited to high-end applications for specialized commercial and military markets. To address this cost limitation, many researchers have pursued the development of metamorphic HEMT (MHEMT) technology, in which high indium material is grown on a GaAs substrate [1]–[3]. Devices fabricated in the MHEMT process exhibit superior InP-like frequency and noise performance, while providing the inherent cost advantage of fabrication on a large-diameter and high-volume GaAs substrate.

In this paper, we present the implementation of several K-band receiver front-ends fabricated in a 0.18-μm GaAs MHEMT process. We show a low-power three-stage low-noise amplifier (LNA) with a gain of 23 dB and noise figure (NF) of less than 1.6 dB at 30 GHz. This LNA shows such InP-like performance with a high RF yield of 84%. We also demonstrate the integration of a single-stage amplifier with a diode subharmonic mixer for low-power and broad-band receiver performance.

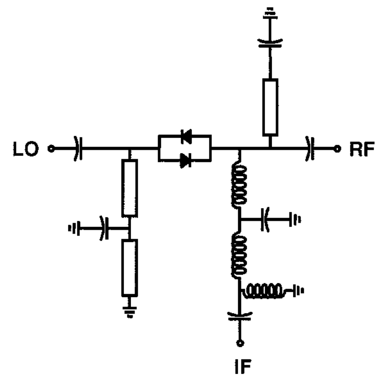

Fig. 1. Circuit schematic of the mixer.

II. Circuit Design

Three monolithic microwave integrated circuits (MMICs), i.e., a subharmonic mixer, a subharmonic down-converter, and a three-stage LNA, have been designed and fabricated for K-band applications between 23–30 GHz.

A. Subharmonic Mixer

A subharmonic mixer topology was chosen to allow for the use of a lower local oscillator (LO) frequency that not only relaxes the constraints of the LO source, but also alleviates the concern for LO to RF isolation.

As shown in Fig. 1, the antiparallel diode pair is used to generate simultaneous doubling and frequency conversion in the mixer [4]. Each diode is implemented by shorting the source and drain of a 4 $\times$ 12.5 μm MHEMT. The diodes have been connected in an antiparallel configuration and terminated by two transmission-line stubs that were designed to be a quarter-wavelength long at the LO frequency. The transmission lines were designed using a quasi-lumped transmission-line

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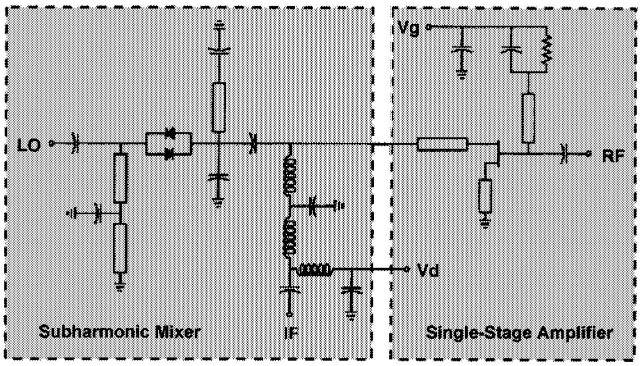


Fig. 2. Circuit schematic of the down-converter.

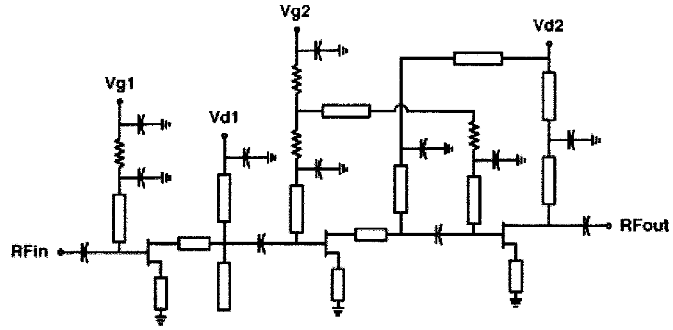
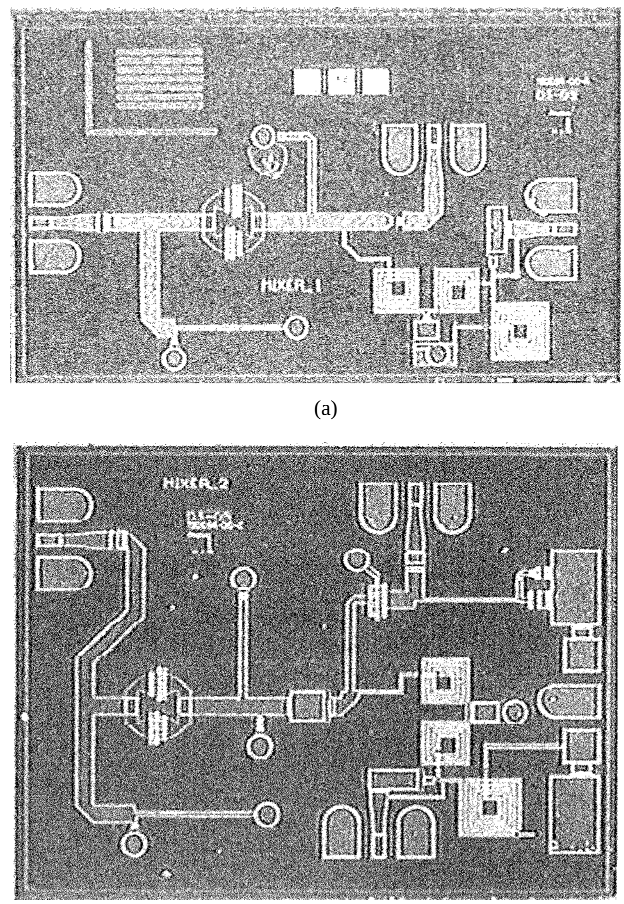


Fig. 3. Circuit schematic of the three-stage LNA.



(a)

(b)

Fig. 4. (a) Subharmonic mixer. (b) Down-converter MMICs.

technique in order to reduce the physical length while maintaining the quarter-wave electrical length [5]. The stub at the LO port was designed to act as a shorted quarter-wavelength line so that it exhibits high impedance at the LO and low impedance at the RF frequency. The stub at the RF port was designed in the opposite manner to act as an open quarter-wavelength so that it exhibits low impedance at the LO and high impedance at the RF frequency. The IF signal is tapped from the RF side through a low-pass filter that allows for rejection of RF and LO signals. The IF port is matched using a high-pass *LC* network for an IF frequency range of 0.7–1.3 GHz.

B. Subharmonic Down-Converter

As shown in Fig. 2, the down-converter is composed of a single-stage amplifier followed by a modified version of the subharmonic mixer described earlier. By taking advantage of the low noise and high gain of a 100-μm periphery MHEMT, a single-stage amplifier with an NF of 1.5 dB and gain of 11 dB at 26 GHz is implemented without the use of additional input noise matching. The MHEMT is biased at a drain voltage of 1.5 V and a drain current of 10 mA. Source degeneration is used to stabilize the amplifier, and simple input matching is used to improve return loss. The amplifier is mated with the mixer with minor modifications that includes the addition of a blocking capacitor to isolate the diodes from the dc bias of the amplifier.

As shown in Fig. 2, the drain bias of the amplifier is fed through the IF matching network and the gate bias is applied through the RF input matching stub of the amplifier.

C. Low-Noise Amplifier

Fig. 3 shows the circuit schematic of this three-stage LNA. In this design, we have cascaded three 75-μm MHEMTs to achieve 23 dB of gain at 30 GHz. Each device uses source inductive degeneration to stabilize the stage. This configuration also helps to shift the input noise matching closer to a 50-Ω termination [6]. The first stage uses separate bias lines to bias the gate and drain of the device, while the last two stages share the same bias. The first stage device is matched for noise at the input by the combination of the gate feed and the ac coupling capacitor. Open and shorted stubs are used for inter-stage matching throughout the gain stages. Large bypass capacitors are used on the drain lines to provide proper grounding while resistors are used in the gate bias lines to isolate the device from the dc supply.

III. Experimental Results

All MMICs are fabricated in a 0.18-μm MHEMT process using a 60% indium content InGaAs channel. The single-pulse doped MHEMT devices exhibit characteristics similar to InP-based HEMTs with room-temperature sheet densities and mobilities of 3.2×10^{12} cm^{-2} and 10 500 cm^2/V $\cdot$ s [2].

A. Subharmonic Mixer and Down-Converter

Fig. 4 shows the photographs of the fabricated mixer and down-converter MMICs. The die size of the mixer and down-converter are 2.4×1.1 mm^2 and 2.3×1.7 mm^2, respectively. The chips were evaluated using on-wafer coplanar RF probes for

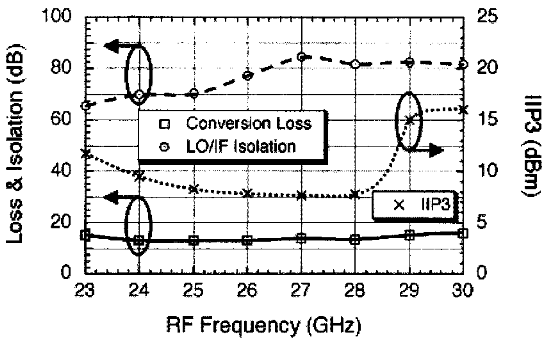


Fig. 5. Performance of the subharmonic mixer with LO power range of 8–12 dBm.

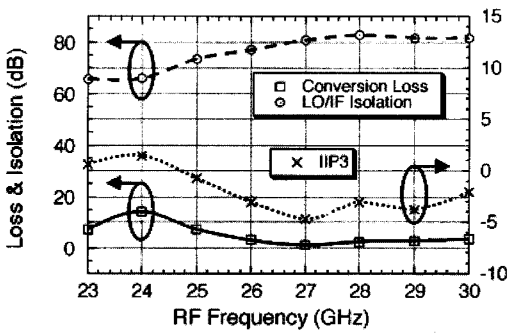


Fig. 6. Performance of the down-converter with LO power of 6–11 dBm.

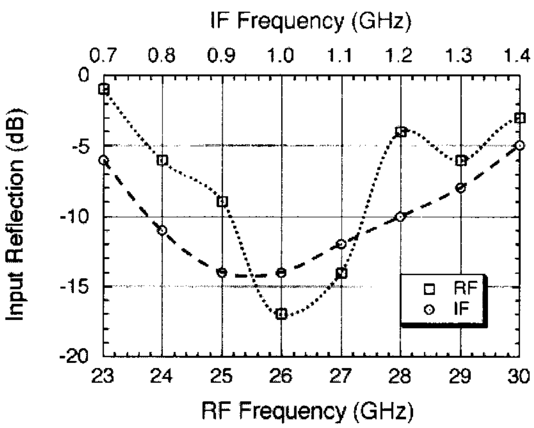


Fig. 7. IF and RF input reflection of the down-converter.

a RF input frequency range of 23–30 GHz, which corresponds to an LO frequency of 10.5–14.5 GHz with an IF frequency of 1 GHz. Single- and two-tone measurements were performed to characterize the conversion characteristic and linearity. Fig. 5 shows the conversion loss, LO to IF isolation, and third-order input intercept point (IIP3) of the subharmonic mixer.

Our measurements show a conversion loss of 14 dB, IF return loss of 15 dB, LO to IF isolation of 65 dB, and out-of-band LO to RF isolation of better than 15 dB. In addition, a 650-MHz conversion bandwidth was observed, proving the mixer to be very suitable for high bandwidth wireless systems.

For the testing of the down-converter, an additional signal–ground–signal dc probe is used to provide the dc bias for the amplifier. The dc probe incorporates 0.1-μF capacitors that help

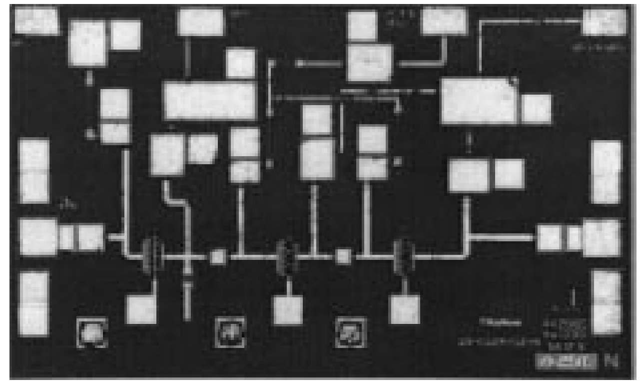


Fig. 8. Three-stage LNA MMIC.

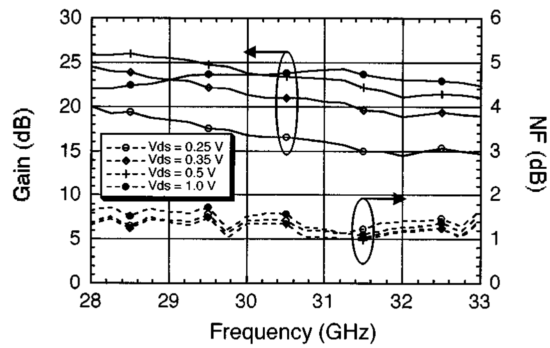


Fig. 9. Measured gain and NF of the LNA for various dc bias points.

improve RF grounding and prevent low-frequency oscillations. Fig. 6 shows the conversion loss and IIP3 of the subharmonic down-converter. Fig. 7 shows the input reflection of the IF and RF ports. The NF of the down-converter is measured to be below 5 dB from 26 to 30 GHz, showing more than 9 dB of improvement over the standalone mixer results.

B. *Low-Noise Amplifier*

Fig. 8 shows a photograph of the fabricated LNA occupying a die area of 2.0 $\times$ 1.25 mm^2. The LNA is mounted and wire bonded on a test fixture for measurements. The bias lines are properly grounded using off-chip bypass capacitors to eliminate low-frequency oscillations. Noise and s-parameter measurements are performed at various bias points for a frequency range of 28–33 GHz. Fig. 9 shows a plot of the small-signal gain and NF as a function of frequency for various bias points. A gain of more than 23 dB and an NF of less than 1.57 dB is observed at 30 GHz for the total dc power consumption of 15 mW at 1-V drain voltage. Lower drain voltage biases down to 0.25 V are achieved while maintaining the low NF, however, the gain match shifts to lower frequencies. To study the RF performance statistics, these measurements are repeated for a total of 310 LNA MMIC samples from the same wafer. Figs. 10 and 11 show the gain and NF distribution of all the samples measured at this bias. The gain distribution shows an average gain of 23.45 dB with standard deviation (STDEV) of 0.82, while the noise distribution shows an average NF of 1.56 with a STDEV of 0.095 at 30 GHz. This translates to an RF yield of 84% for this specific design.

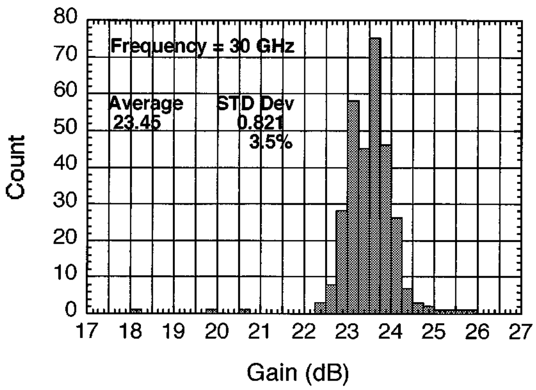


Fig. 10. Distribution of measured small-signal gain for 310 samples.

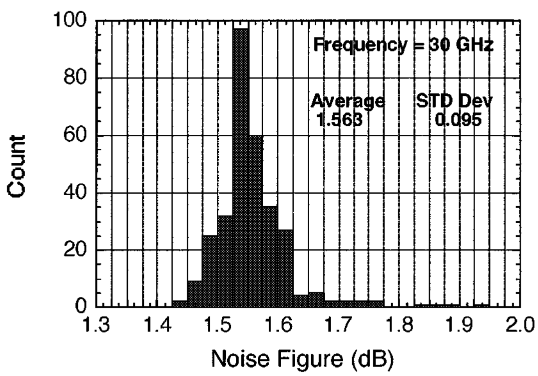


Fig. 11. Distribution of measured NF for 310 samples.

IV. Conclusions

In this paper, we have presented several K-band receiver front-end blocks fabricated in a 0.18-μm GaAs MHEMT process. Low-noise and high-gain characteristics of the MHEMT devices have been utilized to integrate a single-stage amplifier with a subharmonic mixer for low-power broad-band performance suitable for LMDS and WLAN applications. The subharmonic mixer has exhibited a conversion loss of 13 dB and an IIP3 of $+8$ dBm from 23 to 30 GHz. With the addition of the single-stage amplifier, the down-converter has exhibited a conversion loss of 3 dB, an NF of 5 dB, and an IIP3 of -5 dBm from 26 to 30 GHz. We also show a low-power three-stage LNA with a gain of 23 dB and an NF of less than 1.5 dB at 30 GHz. This LNA shows such InP-like performance with an RF yield of 84%. This is the first report of a statistical yield analysis of an MHEMT IC.

References

[1] C. S. Whelan, W. F. Hoke, R. A. McTaggart, M. Lardizabal, P. S. Lyman, P. F. Marsh, and T. E. Kazior, "Low noise $In_{0.32}AlGa_{0.68}AsIn_{0.43}Ga_{0.57}As$ metamorphic HEMT on GaAs substrate with 850 mW/mm output power density," *IEEE Electron Device Lett.*, vol. 21, pp. 5–8, Jan. 2000.

[2] C. S. Whelan, P. F. Marsh, W. E. Hoke, R. A. McTaggart, P. S. Lyman, P. J. Lemonias, S. M. Lardizabal, R. E. Leoni, III, S. J. Lichwala, and T. E. Kazior, "Millimeter-wave low-noise and high-power metamorphic HEMT amplifiers and devices on GaAs substrates," *IEEE J. Solid-State Circuits*, vol. 35, pp. 1307–1311, Sept. 2000.

[3] D.-W. Tu, S. Wang, J. S. M. Liu, K. C. Hwang, W. Kong, P. C. Chao, and K. Nichols, "High-performance double-recessed InAlAs/InGaAs power metamorphic HEMT on GaAs substrate," *IEEE Microwave Guided Wave Lett.*, vol. 9, pp. 458–460, Nov. 1999.

[4] M. Cohn, J. E. Degenford, and B. A. Newman, "Harmonic mixing with an antiparallel diode pair," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 667–673, Aug. 1975.

[5] T. Hirota, A. Minakawa, and M. Muragchi, "Reduced-size branch-line and rat-race hybrids for uniplanar MMIC's," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 270–275, Mar. 1990.

[6] S. Yoo, M. R. Murty, D. Heo, and J. Laskar, "A C-band low power high dynamic range GaAs MESFET low noise amplifier," *Microwave J.*, vol. 43, no. 2, pp. 90–106, Feb. 2000.

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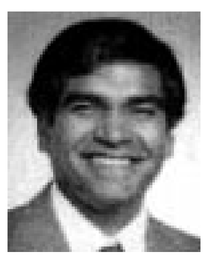

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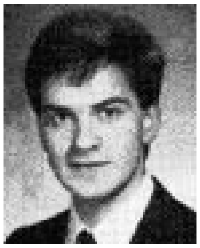

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