A High-Performance Monolithic Q-Band InP-Based HEMT Low-Noise Amplifier

Dennis C. W. Lo, Richard Lai, *Member, IEEE*, Huei Wang, *Member, IEEE*, Kin L. Tan, *Member, IEEE*, Rosie M. Dia, Dwight C. Streit, *Member, IEEE*, Po-Hsin Liu, James Velebir, Barry Allen, *Member, IEEE*, and John Berenz

Abstract—**We report a Q-band two-stage MMIC low-noise amplifier based 0.1-μm pseudomorphic InAlAs–InGaAs–InP HEMT technology. The amplifier has achieved an average noise figure of 2.3 dB with associated gain of 25 dB over the band from 43 to 46 GHz. This noise figure is the best result ever reported for a monolithic amplifier at this frequency range. In addition, this InP-based amplifier consumes only 12 mW, which is at least three times lower than a GaAs-based counterpart, indicating that InP-based pseudomorphic HEMT's are well suited for very high density monolithic integration or an application where ultra low power consumption is required.**

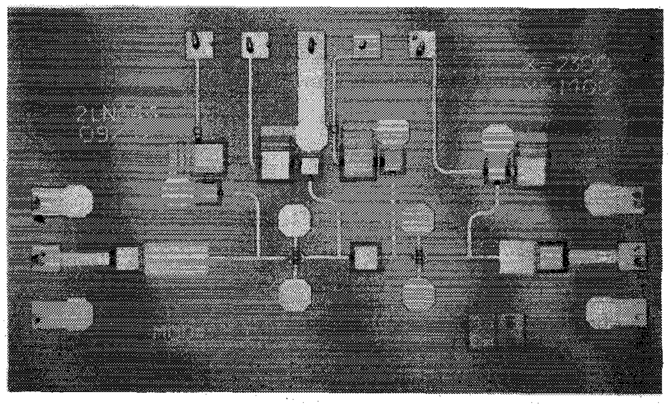

Fig. 1. Photomicrograph of the monolithic two-stage Q-band LNA.

I. Introduction

CONSIDERABLE effort recently has been focused on the development of solid-state millimeter-wave (MMW) components for applications in communications, smart munitions, electronic warfare, and radiometry. Monolithic microwave/millimeter-wave integrated circuits (MMIC's) are particularly attractive for such systems due to its potential advantages of high reliability, performance, functionality, compactness and low cost in comparison to hybrid counterparts [1]. Among MMIC's, the front-end low noise amplifier (LNA) is a key component in a receiver system. For example, in future airborne phased arrays a serious issue driving system array size, and therefore cost, is the noise figure of the front-end LNA. For a constant RF carrier-to-noise ratio, the number of required antenna elements can be decreased with lower LNA noise figure [2].

Most of the demonstrated MMIC's to date utilize GaAs-based devices due to the mature state of their material and process technologies. Recently, InP-based pseudomorphic (PM) InAlAs–InGaAs high electron mobility transistor (HEMT) technologies have been developed and demonstrated the lowest noise figure and highest gain at MMW frequencies among three-terminal devices [3]–[7]. These results are attributed to a high Indium mole fraction in the PM InGaAs channel, which results in a low-band gap, high-electron mobility and high-electron peak drift velocity. MMIC's using InP-based HEMT devices have also demonstrated a low noise figure of 0.78 dB at Ku band and 4.2 dB at V band [8], [9]. In this letter, we present a monolithic Q-band LNA based on PM InAlAs–$In_{0.60}Ga_{0.40}As$–InP HEMT technology. The LNA has achieved an average noise figure of 2.3 dB with associated gain of 25 dB over the band from 43 to 46 GHz, and has a minimum noise figure of 1.8 dB at 46 GHz. These noise figures are the best values ever reported for monolithic LNA's at this frequency range. In addition, the LNA consumes only 12mW dc power, which is at least three times lower than comparable Q-band amplifiers using GaAs-based PM HEMT's.

Manuscript received April 19, 1993. This work was supported by TRW Independent Research and Development Projects.

The authors are with TRW, Electronic and Technology Division D1/1050, One Space Park, Redondo Beach, CA 90278.

IEEE Log Number 9211461.

II. Amplifier Design and Fabrication

Fig. 1 shows a photomicrograph of a complete two-stage LNA with a chip size of 2.3 mm × 1.4 mm. The two-stage LNA used a 0.1-μm HEMT with four gate fingers and total gate width of 80 μm at each stage. A small-signal equivalent circuit model, including the noise model [10], for the PM HEMT device was first extracted from the measured device scattering and noise parameters over 2 to 26 GHz. Fig. 2 shows the extracted device small-signal equivalent circuit model for a 80-μm wide device biased at V_{ds} = 1 V, I_{ds} = 8 mA. Based on the model, the 80-μm wide device shows a maximum available gain of 13 dB and a minimum noise figure of 1.2 dB at 44 GHz. In the LNA, input noise matching is accomplished by a series transmission line for the best noise figure and good associated gain. The interstage and output matching networks are designed to give the best gain. Series source inductive feedback in both stages is used to improve the broad-band noise and gain match as well as circuit stability. The circuit was grounded by wet-etched vias through the 3-mil thick semi-insulating (SI) substrate. The via front pad size is 120 um × 120 um. Metal-insulator-metal capacitors are used for dc blocking and RF bypass in the matching and bias networks.

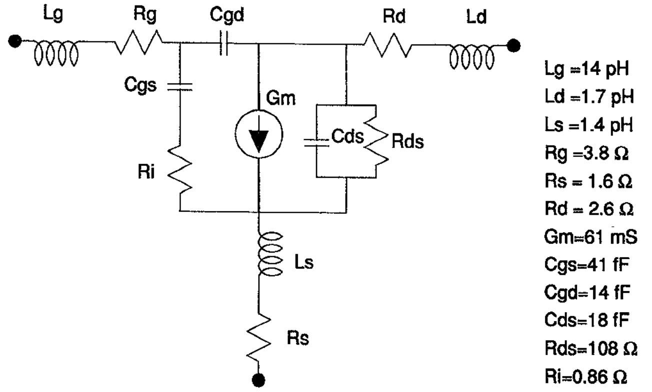

Fig. 2. Small signal equivalent circuit model of a 0.1-μm long 80-μm wide InAlAs–InGaAs–InP HEMT.

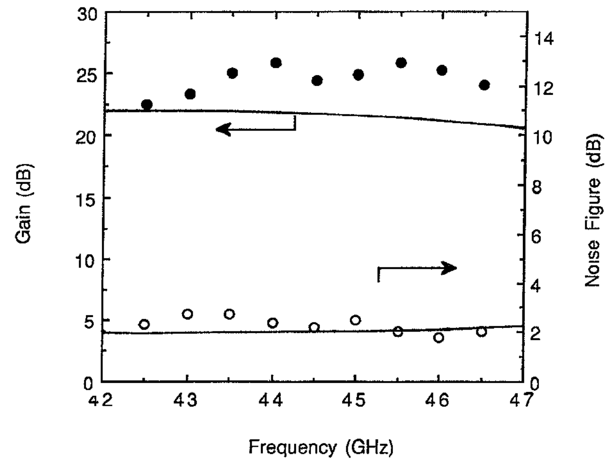

Fig. 3. Simulated (——) and measured (o) noise figure and associated small signal gain (•) of the Q-band two-stage LNA.

Thin-film NiCr resistors are used in the gate bias network for isolation as well as circuit stability.

The LNA was fabricated on epitaxial layers grown on a 2-inch Fe-doped SI InP substrate by molecular beam epitaxy. The InAlAs layer was planer doped with silicon to achieve a high-channel aspect ratio as well as high-electron transfer efficiency. Doping levels and layer thickness were optimized for low noise and high gain at high-frequency operation. The InP MMIC process is adapted from our baseline 0.1-μm PM AlGaAs–InGaAs–GaAs HEMT MMIC process that has shown high yield, high reproducibility as well as high performance [11]. Details of the InAlAs–$In_{0.60}Ga_{0.40}$ As–InP HEMT device structure and MMIC process have been reported elsewhere [5], [6].

III. Measured Performance

The 0.1-μm PM InAlAs–$In_{0.60}Ga_{0.40}As$ HEMT typically shows a maximum dc transconductance, g_m, of 800–1000 mS/mm and an unity current gain frequency, f_T, of 180–210 GHz. Performance of the two-stage LNA was measured on-wafer by Cascade Microtech RF probes. The measured gain (solid circles) and noise figure (open circles) of the LNA as a function of input frequency are shown in Fig. 3 and compared with simulated performance. Over the band from 43 to 46 GHz, the amplifier has achieved an average NF of 2.3 dB with an associated gain of 25 dB; a minimum NF of 1.8 dB is achieved at 46 GHZ. These noise figures are the best values ever reported for monolithic LNAs at this frequency range. Note that, based on the measured data of a GaAs-based LNA, the noise figure measured on-wafer in this frequency range agrees with that measured on a waveguide test fixture to within 0.1 dB.

The high-electron mobility in the PM $In_{0.60}Ga_{0.40}As$ channel layer also results in a low-drain saturation voltage, V_{dsat}, which corresponds to the applied drain voltage when the electrons in the channel reach the peak drift velocity [12]. Such a low V_{dsat} allows the device to be biased at low drain voltage and hence, consumed low dc power. During RF measurement, the amplifier was biased at $V_d = 0.75$ V and $I_d \sim 8$ mA at each stage, corresponding to a total dc power consumption of 12 mW. Such low dc power consumption is at least three times lower than Q-band amplifiers using GaAs-based HEMT's, which are typically biased at $V_d = 2$ V or above [13]. This result indicated that InP-based PM HEMT's are efficient and suitable for very high density monolithic integration where low-power dissipation is required due to thermal constraints.

IV. Conclusion

We have demonstrated a high-performance monolithic Q-band PM InAlAs–InGaAs–InP HEMT LNA. The two-stage LNA has achieved an average noise figure of 2.3 dB with associated gain of 25 dB over the band from 43 to 46 GHz and a minimum noise figure of 1.8 dB at 46 GHz. The noise figure of the amplifier is the best value ever reported for a monolithic amplifier at this frequency band. In addition, the dc power consumption of the LNA is three times lower than GaAs-based HEMT counterparts. This result demonstrates the potential of InP-based pseudomorphic HEMT MMIC's for very high density monolithic integration, such as applications in active phased arrays and passive imaging arrays [14]. The low power consumption also makes InP-based pseudomorphic HEMT's attractive for applications in personal portable communication equipment as well as cryogenic deep-space radiometry [7].

Acknowledgment

The authors would like to thank G. S. Dow for his encouragement, D. C. Yang, C. C. Yang, J. Lin, and S. Kam for support in testing, G. Coakley and C. Sieg-Fostvelt in layout, A. Freudenthal in EBL process, and members of the Advanced Microelectronics Laboratory and RF Product Development Laboratory for their excellent technical support.

References

[1] R. A. Pucel, "Technology and design considerations of monolithic microwave integrated circuits," in *Gallium Arsenide Technology*, D. K. Ferry, Ed. Indianapolis, IN: SAMS, 1985.
[2] R. M. Gagliardi, *Satellite Communications*, 2nd ed. New York: VNR, 1991
[3] U. K. Mishra, A. S. Brown, M. J. Delaney, P. T. Greiling, and C. F. Krumm, "The AlInAs–GaInAs HEMT for microwave and millimeter-wave applications," *IEEE Trans. Microwave Theory Tech.*, vol. 37, p. 1279, 1989.

[4] K.H.G. Duh, P.C. Chao, S.M. J. Liu, P. Ho, M.Y. Kao, and J.M. Ballingall, "A super low-noise 0.1 um T-gate InAlAs–InGaAs–InP HEMT," *IEEE Microwave Guided Wave Lett.*, vol. 1, p. 114, May 1991.

[5] K.L. Tan, D.C. Streit, P.D. Chow, R.M. Dia, A.C. Han, P.H. Liu, D. Garske, and R. Lai, " 140 GHz 0.1 um gate-length pseudomorphic $In_{0.52}Al_{0.48}As/In_{0.60}Ga_{0.40}As/InP$ HEMT," in *IEEE IEDM Tech. Dig.*, p. 239, 1991.

[6] D. Chow, K.L. Tan, D.C. Streit, D. Garske, P.H. Liu, and R. Lai, "W- and D-band low noise amplifiers using 0.1 um pseudomorphic AllnAs/InGaAs/InP HEMTs," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1992, p. 807.

[7] M.W. Pospiezalski, W.J. Lakatosh, R. Lai, K.L. Tan, D.C. Streit, P.H. Liu, R.M. Dia, and J. Velebir, " Millimeter-wave cryogenically-coolable amplifiers using AllnAs/GalnAs/InP HEMTs," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1993, p. 515.

[8] S.E. Rosenbaum, K. Litvin, C.S. Chou, L.E. Larson, L.D. Nguyen, C. Ngo, M. Lui, J. Henige, M.A. Thompson, U. Mishra, and D. Pierson, "AllnAs/GalnAs on InP HEMT low noise MMIC amplifiers, in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1991, p. 815.

[9] R.T. Webster, A.J. Slobodnik, and G.A. Roberts, "Monolithic InP HEMT V-band low-noise amplifier," *IEEE Microwave Guided Wave Lett.*, vol. 2, p. 236–238, June 1992.

[10] R.A. Pucel, H.A. Haus and H. Statz, " Signal and noise properties of GaAs microwave FETs," in *Advances in Electronics and Electron Physics*, vol. 38, L. Martin, Ed. New York: Academic, 1975, p. 195.

[11] K.L. Tan, P.H. Liu, D.C. Streit, R. Dia, A.C. Han, A. Freudenthal, J. Velebir, K. Stolt, J. Lee, M. Biedenbender, R. Lai, H. Wang, and B. Allen, "A high performance 0.1 um pseudomorphic AlGaAs/InGaAs HEMT process for W-band MMICs, " in *IEEE GaAs IC Symp.*, 1992, p. 251.

[12] D.C. W. Lo and S.R. Forrest, "Performance of InGaAs and InP juncton field-effect transistors for optoelectronic integrated circuits. I. Device analysis," *IEEE J. Lightwave Technol.*, vol. 7, p. 957, 1989.

[13] C. Yuen, C. Nishmoto, S. Bandy, and G. Zdasiuk, "A monolithic 40-GHz HEMT low-noise amplifier," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1988, p. 117.

[14] G.S. Dow, T.N. Ton, H. Wang, D.C.W. Lo, W. Lam, B. Allen, K.L. Tan, and J. Berenz, "W-band MMIC direct detection receiver for passive imaging system," to be published in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1993, p. 163.