MILLIMETER-WAVE LOW-NOISE HEMT AMPLIFIERS

K.H.G. Duh, P.C. Chao, P.M. Smith, L.F. Lester,
B.R. Lee, J.M. Ballingall,and M.Y. Kao

GE Electronics Laboratory
Syracuse, New York 13221

ABSTRACT

Short-gate-length high electron mobility transistors(HEMTs) developed in our laboratory have exhibited state-of-the-art low noise performance at millimeter-wave frequencies: minimum noise figure of 1.2 dB at 32 GHz and 1.8 dB at 60 GHz from 0.25µm HEMTs. At Ka-band, a two-stage low noise amplifier has demonstrated an average noise figure of 2 dB from 26.5 GHz to 37 GHz with a gain of 17 dB at 32 GHz. At V-band, a two-stage amplifier yielded noise figure of 3.2 dB at 61 GHz with flat gain 12.7 ± 0.5 dB from 59 GHz to 65 GHz. The results clearly show the potential of the short-gate-length HEMTs for high performance millimeter-wave receiver applications.

INTRODUCTION

Recent developments in heterostructure transistor technology have advanced very rapidly in both the high speed and high frequency areas. HEMT devices have shown superb low noise and power results in microwave and millimeter-wave frequency regions[1-3]. HEMT amplifiers have been demonstrated at 35 GHz[4] and V-band[5-7]. In this paper, we report the development of 0.25µm HEMT Ka-band and V-band amplifiers achieving record low noise performance, and discuss the potential for future improvement.

DEVICE DESCRIPTION

The devices were fabricated on selectively doped AlGaAs/GaAs heterostructures grown by molecular beam epitaxy(MBE). These HEMTs employed large cross-section T-shaped gates, one of which is shown in Figure 1, to minimize the parasitic gate resistance[8]. DC extrinsic transconductance, g_m, of 0.25 µm HEMTs is typically 450 mS/mm, although values as high as 600 mS/mm have been obtained. We have developed a very effective screening technique based on the device parameters(g_m, C_{gs}, I_{ds}), and low frequency thermal noise measurements[9] for selecting devices for the amplifier work. Table 1 displays the 0.25 µm AlGaAs/GaAs HEMT noise performance from 8 to 60 GHz. These HEMTs gave minimum noise figure of 1.2 dB with associated gain of 10 dB at 32 GHz and 1.8 dB noise figure with 6.4 dB gain at 60 GHz - these are the best device results yet reported for any microwave transistor. F_∞ in Table 1 is defined as the noise figure of an infinite chain of cascaded single-stage amplifiers. It is a useful figure of merit that closely approximates the noise figure attainable in a multi-stage, high gain (> 15 dB) amplifier.

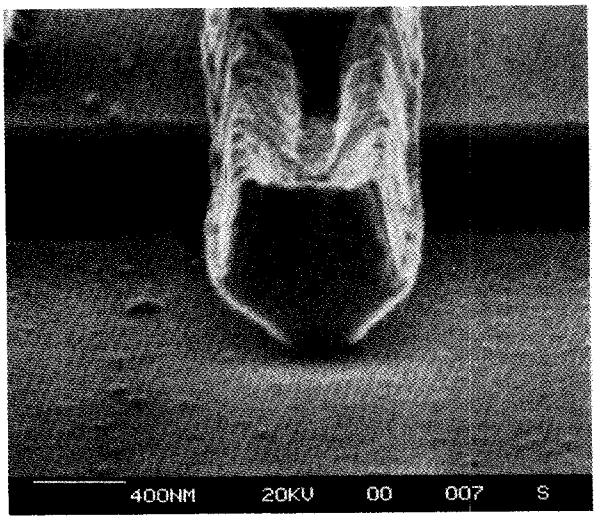

Figure 1. Low resistance 0.25 µm gate structure.

Frequency (GHz)	NF (dB)	Ga (dB)	F_∞ (dB)
8	0.4	15.2	0.41
18	0.7	13.8	0.73
32	1.2	10.0	1.31
60	1.8	6.4	2.22

$$F_\infty = F + \frac{F-1}{G} + \frac{F-1}{G^2} + \ldots\ldots = \frac{FG-1}{G-1}$$

Table 1. Noise Performance of 0.25µm AlGaAs/GaAs HEMTs at 300K.

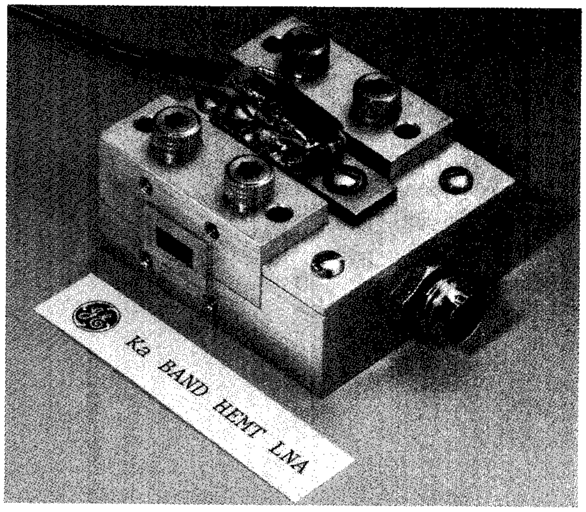

Figure 2. Ka-band 2-stage HEMT LNA.

KA-BAND HEMT LNA

Figure 2 is a photograph of the Ka-band two-stage HEMT low noise amplifier(LNA). A simple, stepped ridge to microstrip transition was utilized in the amplifier. The amplifier design was based on 0.25 x 75 µm HEMTs. The input and output networks included the waveguide to microstrip transitions. The device equivalent circuit model was obtained from fitting S parameters measured at low noise bias condition from 2 to 20 GHz using Super-Compact. We then selected the equivalent circuit topology and determined some element values for the Ka-band LNA design based upon the good agreement between calculated and measured millimeter wave gain performance. The input, output, and inter-stage matching circuits were designed on 10 mil quartz substrate with TaN thin film resistors and TiWAu metallization. The edge-coupled symmetric microstrip DC blocking circuit(two finger) was used to provide low loss DC isolation and improve stability out of band functioning as a band-pass filter.

The LNA fixture and DC bias circuits were designed with the consideration of cryogenic operation. Diode protection was included in both the gate and drain bias circuits. Two LEDs were mounted on top of the cover for the purpose of determining the light sensitivity of HEMTs at low temperature. No noticeable difference had been observed in the measurement with or without the light.

The amplifier broadband performance is shown in Figure 3. It exhibited average noise figure of 2 dB from 26.5 GHz to 37 GHz. At 32 GHz, it demonstrated 1.7 dB noise figure with 17 dB associated gain. The gain is 17.0 dB ± 0.5 dB from 29 to 34 GHz. Figure 4 displays the noise performance upon cooling at 32 GHz. At -60°C, the amplifier yielded 0.9 dB noise figure with a gain of 18 dB. The noise measurement was performed by the hot/cold method. For the room temperature swept frequency measurements, the ENR values of the solid state noise source were calibrated using hot/cold standards. It appears that the improvement caused by cooling of the HEMTs is more pronounced than that of the conventional GaAs FETs.

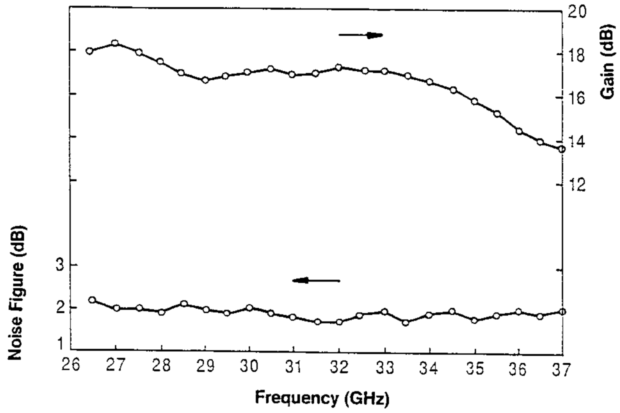

Figure 3. Gain and noise performance of Ka-band 2-stage HEMT LNA.

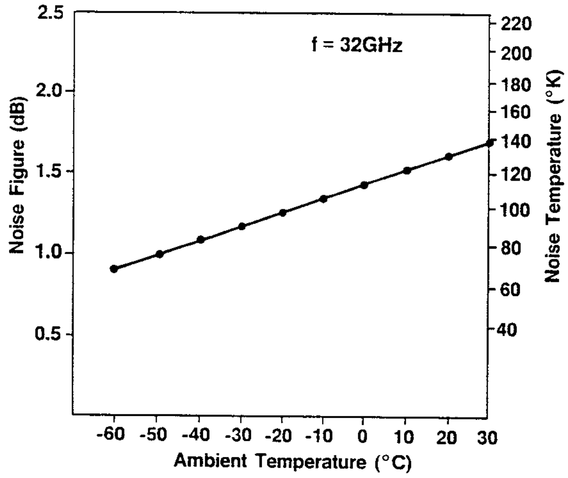

Figure 4. Cooled temperature dependence of noise performance for Ka-band 2-stage HEMT LNA.

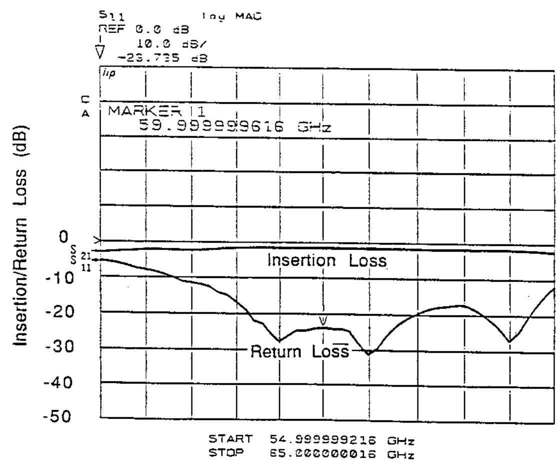

Figure 5. Measured performance of V-band E-field probe fixture with a 50 ohm through line.

V-BAND HEMT LNA

E-field probes were used for the V-band waveguide to microstrip transition. Microstrip circuits and adjustable backshorts were also included in the fixture to optimally match the radiation impedance to 50 ohm to achieve best transition performance. The V-band fixture with a 50 ohm through line containing two edge-coupled lines(necessary to provide DC blocking) has a measured insertion loss of 1 dB from 58 to 62 GHz as shown in Figure 5. The input return loss is approximately 20 dB in the test band.

0.25 x 50 µm HEMT devices selected for the V-band LNA work were determined on the trade-off between optimum impedance matching, power handling capability, intermodulation distortion, and power dissipation. The parasitics, tee/cross junctions, steps, and gaps of the circuit elements were carefully analyzed and modelled using Super-Compact and Jansen full wave analysis. The gate and drain bias circuits which consisted of high and low impedance quarter-wavelength transmission line network, bonding wires, chip capacitors and resistors, were designed to be unconditionally stable from low frequency(megahertz range) to 94 GHz.

The two-stage HEMT low noise amplifier performance from 55 to 65 GHz is shown in Figure 6. The minimum noise figure is 3.2 dB with 12.7 dB at 61 GHz. The flat gain response of the LNA is 12.7 dB ± 0.5 dB from 58 GHz to 65 GHz with a noise figure of less than 4 dB across the band. The input return loss of the LNA is approximately 10 dB from 56 GHz to 64 GHz, which is significantly better than that of a GaAs FET LNA. This is because the optimum source impedances of HEMTs for minimum noise and for gain match are closer than those of the FETs. The noise source used in this measurement was also calibrated by the hot/cold method.

FUTURE IMPROVEMENT

In addition to conventional HEMTs based on AlGaAs/GaAs heterostructures, new structures such as InGaAs HEMTs have shown great promise. Theoretical investigation[10] has shown that the FET performance can be improved by reducing the gate length if the ratio of gate length to channel thickness can be maintained. We minimized the short channel effect in the 0.1 µm HEMT device by adopting an AlGaAs/InGaAs/GaAs planar doped structure[11] and were able to obtain the extrinsic g_m as high as 930 mS/mm from 0.1 x 50 µm devices. The device structure is described in Figure 7. A maximum gain of 19.3 dB has been measured at 18 GHz.

The 0.1 µm HEMT device with a normal triangular-shaped gate has a very high gate resistance, approximately 20 times higher than the 0.25 µm T-shaped device. In spite of the high gate resistance, a single stage amplifier using 0.1 µm HEMT has demonstrated a noise figure of 3.1 dB and gain of 7.4 dB at 59 GHz as compared with 2.4 dB noise figure with 5.4 dB gain obtained using a 0.25 µm HEMT(not correcting for fixture loss). Figure 8 displays the measured results of both single-stage amplifiers from 58 GHz to 62 GHz. By employing the multi-finger air-bridged gate or T-shaped gate to reduce the gate resistance, our calculations indicate that a noise figure of less than 2.4 dB with gain of 10 dB at 60 GHz can be achieved in single-stage amplifier using 0.1 µm HEMT.

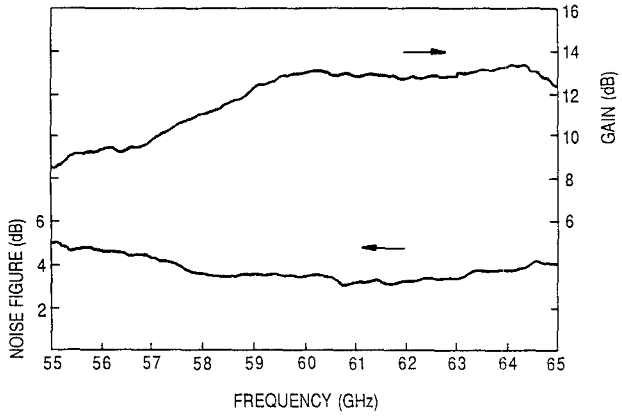

Figure 6. Gain and noise performance of V-band 2-stage HEMT LNA.

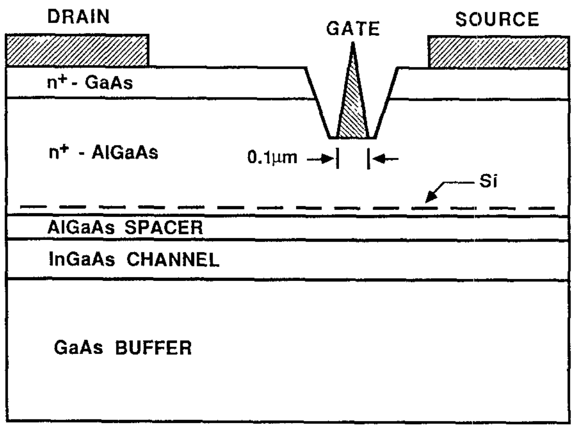

Figure 7. The cross-sectional view of 0.1 µm AlGaAs/InGaAs/GaAs HEMT.

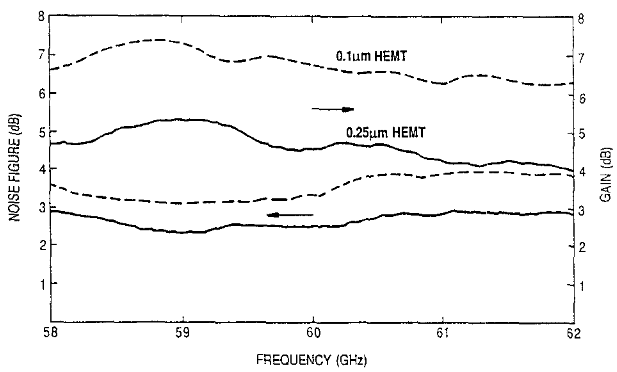

Figure 8. Comparison of single-stage amplifiers using 0.1 µm and 0.25µm HEMTs: dotted line for 0.1µm HEMT and solid line for 0.25µm HEMT.

CONCLUSION

We have demonstrated state-of-the-art Ka-band and V-band low noise amplifier performance using our 0.25 μm HEMT devices. The results clearly show their great potential for millimeter-wave low noise receiver applications. Due to HEMTs' large gain-bandwidth product and large noise bandwidth, the HEMT LNA is well suited for broadband applications. Further advances in transistor technology will lead to improved performance at all frequencies, and will also make it possible to develop transistor amplifiers at frequencies through 94 GHz. The low minimum noise figure and broad bandwidth of HEMTs will also make low-noise HEMT MMICs very attractive for high performance receiver applications.

ACKNOWLEDGMENT

GE Ka-band HEMT development was supported in part by JPL. The authors acknowledge the contributions of A. Jabra, and W. Kopp, and the support of A.W. Swanson and W.J. Butler. Useful discussions with M.W. Pospieszalski, and S. Weinreb are gratefully acknowledged.

REFERENCES

[1] K.H.G. Duh, M.W. Pospieszalski, W.F. Kopp, P. Ho, A.A. Jabra, P.C. Chao, P.M. Smith, L.F. Lester, J.M. Ballingall, and S. Weinreb, "Ultra-Low-Noise Cryogenic High-Electron-Mobility Transistors," IEEE Trans. Electron Devices, Vol.ED-35, pp.249-256, 1988.

[2] P. Saunier and J.W. Lee, "High-Efficiency Millimeter-Wave GaAs/AlGaAs Power HEMTs," IEEE Electron Device Lett., Vol. EDL-7, pp. 503-505, 1986.

[3] P.M. Smith, P.C. Chao, K.H.G. Duh, L.F. Lester, B.R. Lee, and J.M Ballingall, "Advances in HEMT Technology and Applications," 1987 IEEE MTT-S Digest, pp.749-752, 1987.

[4] J.M. Schellenberg, M.V. Maher, S.K. Wang, K.G. Wang, and K.K. Yu, "35 GHz Low Noise HEMT Amplifier," 1987 IEEE MTT-S Digest, pp.441-442, 1987.

[5] J. Berenz, K. Nakano, T.-I. Hsu and J. Goel, "HEMT 60 GHz Amplifier," Electron. Lett., vol. 21, pp. 1028-1029, 1985.

[6] K.H.G. Duh, P.C. Chao, P.M. Smith, L.F. Lester and B.R. Lee, "60 GHz Low-Noise High-Electron-Mobility Transistors," Electron. Lett., Vol.22, pp. 647-649, 1986.

[7] W. Yau, E.T. Watkins, S.K. Wang, K. Wang, and B. Klatskin, "A Four Stage V-Band MOCVD HEMT Amplifier," 1987 IEEE MTT-S Digest, pp.1015-1018, 1987.

[8] P.C. Chao, P.M. Smith, S.C.Palmateer, and J.C.M. Hwang, "Electron-Beam Fabrication of GaAs Low-Noise MESFETs Using A New Tri-Layer Resist Technique," IEEE Trans. Electron Devices, Vol.ED-22, pp.1042-1046, 1985.

[9] K.H.G. Duh, S.M.J. Liu, L.F. Lester, P.C. Chao, P.M. Smith, M.B. Das, B.R. Lee, and J.M. Ballingall, "Ultra-Low Noise Millimeter-wave High Electron Mobility Transistors," to be submitted to IEEE Electron Device Lett.

[10] M.B. Das, "Millimeter-Wave Performance of Ultrasubmicron-Gate FETs: A Comparison of MODFET, MESFET, and PBT structures," IEEE Trans. Electron Devices, Vol.ED-34, pp.1429-1440, 1987.

[11] P.C. Chao, P.M. Smith, K.H.G. Duh, J.M. Ballingall, L.F. Lester, B.R. Lee, A.A. Jabra, and R.C.Tiberio, "High Performance 0.1 μm Gate-Length Planar-Doped HEMTs," 1987 IEDM, Paper 17.1, 1987.