A Q-Band Monolithic Linear Amplifier Using AlGaAs/GaAs HBT's

Youngwoo Kwon, *Member, IEEE*, Wu-Jing Ho, *Member, IEEE*, and J. Aiden Higgins, *Senior Member, IEEE*

***Abstract*— This letter reports on a Q-band monolithic heterojunction bipolar transistor (HBT) amplifier demonstrating high gain, efficiency, excellent linearity, and low added phase noise. The amplifier used 40 μm^2 CB-HBT's in a balanced configuration. The monolithic microwave integrated circuit (MMIC) amplifier showed a peak gain of 13.5 dB at 38 GHz and a 3-dB bandwidth of 10 GHz. Under class-A bias conditions, the circuit exhibited $P_{1\,dB}$ higher than 15 dBm from 35–41.5 GHz and a peak PAE of 32% at 35 GHz. Two-tone tests showed an IP_3 of 30 dBm at 44 GHz and IMD_3 ratios better than 20 dBc at 1-dB gain compression point. Amplifier phase noise measurement showed added phase noise of −148 dBc/Hz at 10 kHz away from the carrier at $P_{1\,dB}$. This circuit demonstrates a great potential for the HBT MMIC's for mm-wave high-efficiency linear applications.**

I. Introduction

AlGaAs/GaAs heterojunction bipolar transistors (HBT's) have been used successfully for high-power, linear, and low near-carrier noise applications at microwave frequencies. Monolithic amplifiers producing more than 1 W output power have been demonstrated with high efficiency [1]–[3]. High IP_3 (third-order intercept point) has also been reported [4]. HBT linearity characteristics have recently been studied at device levels up to X-band [5]. A low intermodulation ratio of −20 dBc was demonstrated at 1-dB compression point for common-emitter HBT's.

Application of HBT's in millimeter-wave frequencies has been limited so far, however, due to their modest gain characteristics. Emerging millimeter-wave applications such as automotive radars and wireless local area networks (LAN's), as well as military systems, require ultralinear amplification. One such example is the linear amplifier with minimum added phase noise for automotive radar transmitters.

In this work, we present a monolithic single-stage linear HBT amplifier showing a peak gain of 13.5 dB at 38 GHz with 10-GHz 3-dB bandwidth and −20 dBc IMD_3 (third-order intermodulation) ratio at 1-dB compression point from 35–44 GHz.

II. Circuit Design

The design goal was to build a Q-band amplifier with high gain, good linearity, and medium output power. The center frequency was 38.5 GHz, which was one-half the automotive radar frequency of 77 GHz.[1] Two different configurations can be employed for HBT amplifiers—common emitter (CE) and common base (CB). Both types of the devices have been characterized using on-wafer probing up to 40 GHz. CE HBT's had a maximum available gain (MAG, $K > 1$) of 10 dB at 40 GHz while CB HBT's showed a maximum stable gain (MSG, $K < 1$) of 14 dB at 40 GHz. CB HBT's are more unilateral and show significantly higher gain at the expense of low K-factor. Higher gain makes them better suited to millimeter-wave applications. On the other hand, the IMD_3 level of CB-HBT's was reported to be higher than those of CE-HBT's [5]. Hence, a compromise has to be made between the gain and linearity in choosing the device configuration. Considering the operation frequency, CB-HBT's were chosen in this work.

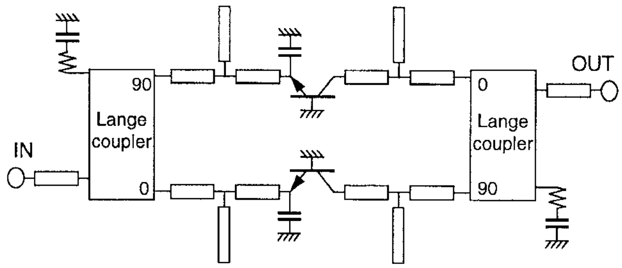

Fig. 1. Equivalent circuit schematic of a balanced HBT amplifier

The devices used in the circuit had two 2 $\mu m \times 10$ μm emitter fingers (40 μm^2 emitter area) and employed common-base configuration. CB devices often present design challenges in matching and stability. The input and output impedances tend to have high Q factors, and S_{22} and S_{11} are close to the edge of the Smith chart. Furthermore, they are inherently unstable and present very low K factors. As a result, achieving broad-band and high-gain characteristics while assuring good stability is difficult. In this work, we have employed a balanced configuration to overcome these difficulties and achieve high gain with low VSWR over a wide frequency range.

The circuit schematic is shown in Fig. 1 and the photograph of the monolithic circuit is shown in Fig. 2. Lange couplers were used for both input and output for balanced operation. The matching circuits were designed for maximum gain, not for maximum power. All the bias circuitry was integrated on-chip and the chip size was about 2 mm × 1.5 mm. No attempt was made to minimize the chip size at this first design iteration.

[1] Amplifiers are followed by the multiplier for a 77-GHz transmitter.

Manuscript received November 13, 1995.
The authors are with the Rockwell Science Center, Thousand Oaks, CA 91360 USA.
Publisher Item Identifier S 1051-8207(96)02579-2.

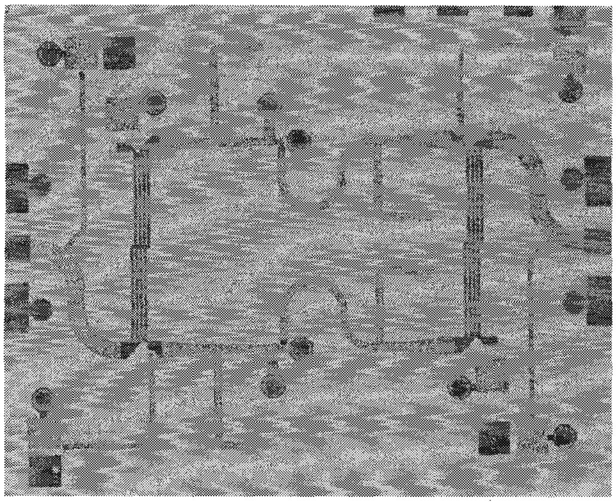

Fig. 2. Photograph of a Q-band monolithic balanced HBT amplifier (chip size = 2 mm × 1.5 mm).

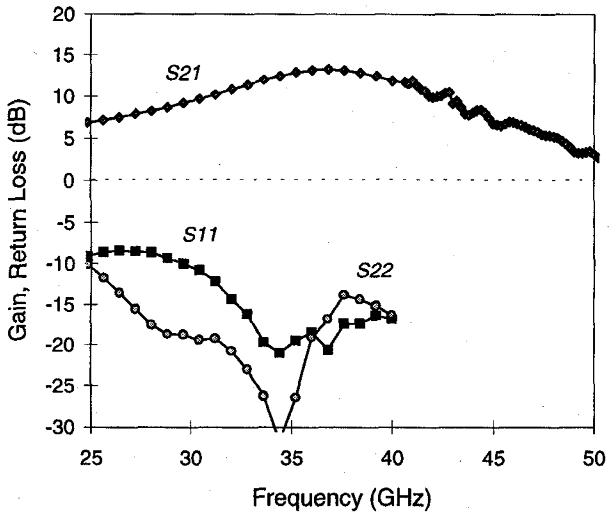

Fig. 3. Measured small-signal gain and return loss of the amplifier. Measurement up to 40 GHz was performed using on-wafer probing. Gain measurement above 40 GHz was done in a test fixture.

III. Experimental Result

The circuit was tested for small-signal gain up to 60 GHz. The MMIC chip was first characterized by on-wafer probing up to 40 GHz and was later mounted in a test jig for 40–60 GHz waveguide test. The measured small-signal gain is shown in Fig. 3. Also shown in Fig. 3 is the input and output return loss up to 40 GHz as measured by on-wafer probing. The amplifier shows broadband characteristics and good return loss thanks to balanced configuration. The peak gain was 13.5 dB and occurs around the design frequency of 38 GHz. The 3-dB bandwidth was about 10 GHz. To the best of our knowledge, this is believed to be the highest gain ever achieved out of a single-stage monolithic HBT amplifier at these frequencies. Fifteen circuits out of four wafers have been tested on-wafer under the same bias conditions ($I_c = 36$ mA, $V_{cb} = 1$ V). Measured gain variation was less than 1 dB, which demonstrates good uniformity of the HBT process.

The jig-mounted MMIC chip was also tested for power and intermodulation from 35–44 GHz. Two different waveguide setups (WR-28 and WR-19) were used for this purpose. For the entire test, the amplifier was biased for class-A operation for better linearity. Measured $P_{1\,\mathrm{dB}}$, P_{sat}, IP_3, and IMD_3 level at 1-dB compression point are shown in Fig. 4. $P_{1\,\mathrm{dB}}$ was higher than 15 dBm from 35–41.5 GHz. Corresponding power added efficiency (PAE) was as high as 32% at 35 GHz and decreased to 20% at 41.5 GHz. Third-order intercept point (IP_3), which is commonly used as a linearity measure, was better than 24 dBm from 35–44 GHz. A peak IP_3 of 30 dBm was achieved at 44 GHz. Another important linearity measure is the intermodulation level at 1-dB gain compression point [5]. Third-order intermodulation product was at least 20 dB lower than the signal level at 1-dB compression point from 35–44 GHz.

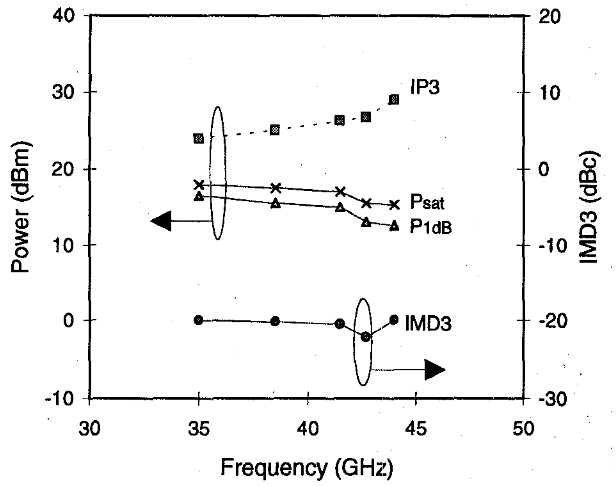

Fig. 4. Measured frequency characteristics of saturation power (P_{sat}), 1-dB compression power ($P_{1\,\mathrm{dB}}$), third-order intercept point (IP_3), and intermodulation ratio (IMD_3) at 1-dB gain compression point.

Finally, the amplifier was measured for added phase noise. At 1-dB gain compression point, the added phase noise was -148 dBc/Hz at 10 kHz away and -153 dBc/Hz at 100 kHz away from the carrier. This demonstrates excellent linearity of the mm-wave HBT amplifier and low $1/f$ noise characteristics of HBT's.

IV. Conclusion

A broadband HBT amplifier has been developed for Q-band linear applications. The single-stage MMIC amplifier showed a record high gain of 13.5 dB at 38 GHz. Measured intermodulation level was at least 20 dB lower than the signal level at 1-dB compression point, demonstrating excellent linearity. The amplifier also exhibited a high PAE of 32% at 35 GHz under class-A bias and low added phase noise of -148 dBc/Hz at 10 kHz away from the carrier. This work demonstrates that with proper device and circuit design, the HBT MMIC's are very promising for high-efficiency linear applications at frequencies as high as Q-band.

References

[1] J. J. Komiak and L. W. Yang, "5 watt high efficiency wideband 7 to 11 GHz HBT MMIC power amplifier," in *Tech. Dig. IEEE Monolithic Microwave and Millimeter-Wave Circuits Symp.*, May 1995, pp. 17–20.

[2] A. Khatibzadeh, W. Liu, T. Henderson, J. Sweder, and S. Pierce, "High-efficiency X-band HBT power amplifier," in *Tech. Dig. IEEE Monolithic Microwave and Millimeter-Wave Circuits Symp.*, May 1994, pp. 117–120.

[3] N. L. Wang, W. J. Ho, and J. A. Higgins, "4 W, 7–12 GHz, compact CB HBT MMIC power amplifier," in *Tech. Dig. 1992 IEEE GaAs IC Symp.*, pp. 301–304, Oct. 1992.

[4] M. E. Kim, A. K. Oki, G. M. Gorman, D. K. Umemoto, and J. B. Camou, "GaAs heterojunction bipolar transistor device and IC technology for high-performance analog and microwave applications," *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 1286–1303, Sept. 1989.

[5] N. L. Wang, W. J. Ho, and J. A. Higgins, "AlGaAs/GaAs HBT linearity characteristics," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1845–1850, Oct. 1994.