A DC-10 GHz High Gain-Low Noise GaAs HBT Direct-Coupled Amplifier

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***Abstract*—An AlGaAs/GaAs HBT wide-band low noise amplifier has been achieved using a direct-coupled amplifier topology. A nominal gain of 22.5 dB and a noise figure of 3.0–3.65 dB has been achieved over a dc-10 GHz band, while consuming less than 55 mW of dc power through a 5 V supply. This result benchmarks the lowest noise figure so far reported for a direct-coupled HBT amplifier at X-band frequencies. In addition, an approximate expression for the amplifier noise figure is given that predicts the noise figure to within 0.3 dB over bias and frequency. The amplifier can be compacted into a 0.3×0.3 mm^2 area and can yield as many as 30 000 die per 3-in. GaAs wafer. The broadband gain and noise figure, low dc power, and miniature die size makes this design attractive as a standard off-the-shelf microwave product for high volume commercial applications.**

I. Introduction

LOW noise direct-coupled microwave amplifiers are useful for Gigabit-per-second (Gpbs) high data-rate optical communications, instrumentation, commercial industrial-scientific-medical (ISM) wireless applications, cellular telephone, as well as satellite receiver applications. GaAs HBT technology is well suited for these types of applications because of its low $1/f$ corner frequency (<100 KHz) characteristic of bipolar devices and its microwave f_T performance (>20 GHz), which is comparable to GaAs MESFET devices. These inherent performance properties allow GaAs HBT's to achieve low noise figure performance over a multi-decade frequency range from baseband to microwave. A family of HBT direct-coupled LNA's have been previously reported that demonstrated high gain (>24 dB), low noise figure (<2.5 dB) and low dc power performance (<60 mW) up to 6 GHz [1]. In this work we reveal a new addition to the HBT LNA family that extends the 3-dB frequency of operation beyond 10 GHz. The present work achieves an 60% improvement in bandwidth while maintaining 3–3.65 dB of noise figure, which benchmarks the lowest noise figure reported for an HBT amplifier at X-band frequencies. Furthermore, this work will present a simple expression for the amplifier noise figure, which can be used to optimize the noise performance in terms of device size, bias current, and amplifier feedback.

II. HBT LNA Process Technology

The HBT LNA's are based on our standard GaAs/AlGaAs 2- and 3-μm Self-aligned Base Ohmic Metal (SABM) HBT process technology, which has been described elsewhere [2]. The 2-μm emitter width HBT transistors have a typical f_T and $f_{\max}$ of 24 and 50 GHz, respectively, at a current density of $J_c = 20$ kA/cm^2. The device breakdown voltage, BV_{ceo}, is greater than 18 V. Minimum device noise figures of 1.3 dB, 2.5 dB, and 3.5 dB are obtained at 2, 6, and 10 GHz, respectively.

III. Direct-Coupled Low Noise HBT Amplifier

A schematic of the direct-coupled amplifier is shown in Fig. 1. This topology has previously demonstrated sub-2.5 dB noise figure and 3-dB bandwidths up to 6 GHz [1]. The direct-coupled amplifier topology consists of two gain stages. The first stage is a common-emitter amplifier comprised of a $2 \times 10\,\mu$m^2 HBT transistor, Q_1. The second stage is a feedback amplifier comprised of $2 \times 10\,\mu$m^2 HBT Darlington connected transistors, Q_2 and Q_3, series feedback resistor R_{ee}, shunt feedback resistor Rf_1, bias resistor R_{bias}, load resistor R_{load}, and output matching resistor R_{out}. Transistors Q_1 and Q_3 are nominally biased at a collector current of 4 mA while transistor Q_2 is biased at a collector current of 2 mA. The first stage acts as a low noise common-emitter amplifier stage which determines the noise figure of the overall 2-stage amplifier. The second stage Darlington feedback amplifier provides wideband gain and output drive capability. The bandwidth characteristics of the Darlington feedback stage can therefore be optimized by changing the series and parallel feedback resistors without degrading the noise figure of the overall amplifier. The shunt feedback resistor Rf_1 of the Darlington stage can be adjusted for gain-bandwidth performance. Rf_1 also provides a current source for biasing transistor Q_1 of the first stage. The shunt feedback resistor, Rf_2, connected between the emitter of transistor Q_2 and the base of transistor Q_1, can be adjusted to change the effective impedance looking out of the base of transistor Q_1 toward the source, and therefore, optimized for minimum noise match. In addition, Rf_2 provides rf shunt feedback, which impacts the gain-bandwidth response and determines the input impedance match of the amplifier to 50 Ω. Thus, feedback resistor Rf_2, can be adjusted to obtain optimal noise figure as well as input return-loss performance.

In order to predict the amplifier noise figure performance as a function of bias, frequency, device parameters, and amplifier feedback, a simple expression for amplifier noise figure was derived. The following expression is based on the assumption that the main source of noise contribution comes from the collector and base shot noise sources of the first stage transistor, Q_1. This is a fair assumption, since the voltage gain of the input common-emitter stage is large (>10 dB) and reduces the noise contribution of the succeeding Darlington stage by approximately a factor of the first stage

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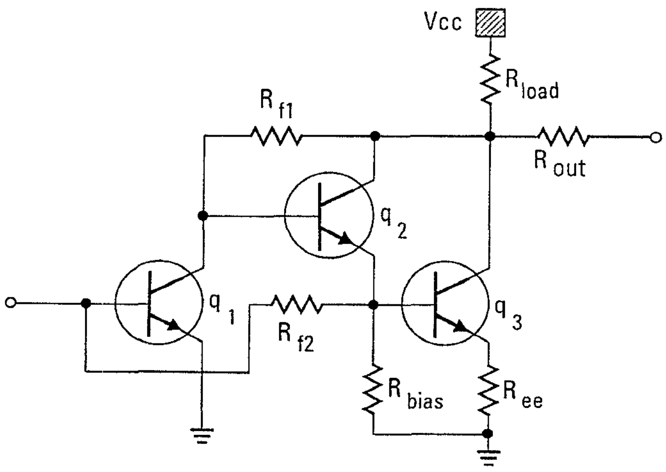

Fig. 1. Schematic of the direct-coupled HBT amplifier.

voltage gain. In addition, thermal noise sources attributed to the feedback resistors, Rf_1 and Rf_2, transistor parasitic resistors r_b and r_e, intrinsic device dynamic resistance r_d = 1/Gm, and source resistance R_s, were also included in the analysis. The expression for noise figure ratio is

$$F_{NF}(\omega) = \frac{1}{R_s}\left(R_s + r_b + \frac{1}{2G_m} + r_e\right) \cdot \left[1 + \frac{R_s^2}{Rf_2^2}\right] + \frac{R_s}{4KT}\left[2qI_B + \frac{2qI_c + \dfrac{4KT}{Rf_1 + R_s}}{|\beta(\omega)|^2} + \frac{4KT}{Rf_2}\right] \quad (1)$$

where

$$|\beta(\omega)| = \frac{\beta_0}{\sqrt{1 + \left(\dfrac{\omega}{\omega_\beta}\right)^2}}.$$

From this simple expression, it is easy to see that the bias current dependence of noise figure comes from Q_1's base and collector shot noise (I_B and I_C in last term) while the frequency dependence is related to the collector shot noise frequency dependence, which is a function of the ac beta, $|\beta(\omega)|$. The circuit feedback resistor Rf_1 is not very sensitive to the overall noise figure for reasonable values of first stage load resistance (>100 Ω). The second feedback resistor, Rf_2, can significantly impact the overall amplifier noise figure due to its relative magnitude with respect to the source resistance, R_s.

Because the HBT direct-coupled LNA design consists of only three active transistors and six Thin Film Resistors (TFR), the amplifier can be compacted into a small 0.3 × 0.3 mm^2 chip area, not shown, which includes bond pads and one backside via. As many as 30 000 die can be yielded on a 3-in. GaAs wafer. The fabrication cost is only a few pennies per die after the wafer has been scribed.

IV. Measured Results

The gain and noise figure of the HBT direct-coupled amplifier was characterized on-wafer for various bias conditions.

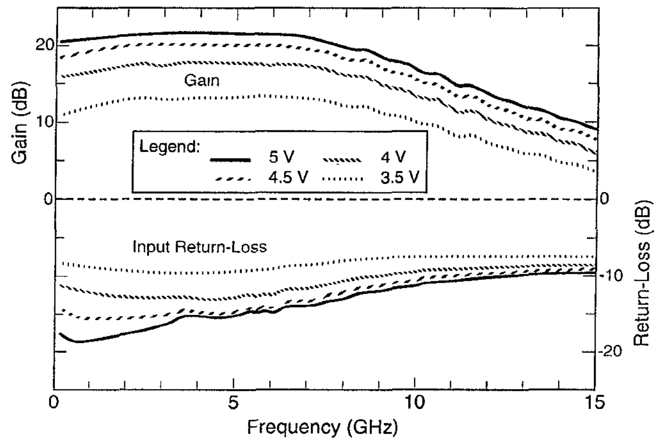

Fig. 2. Broadband gain and input return-loss performance for supply voltages of 5, 4.5, 4.0, and 3.5 V.

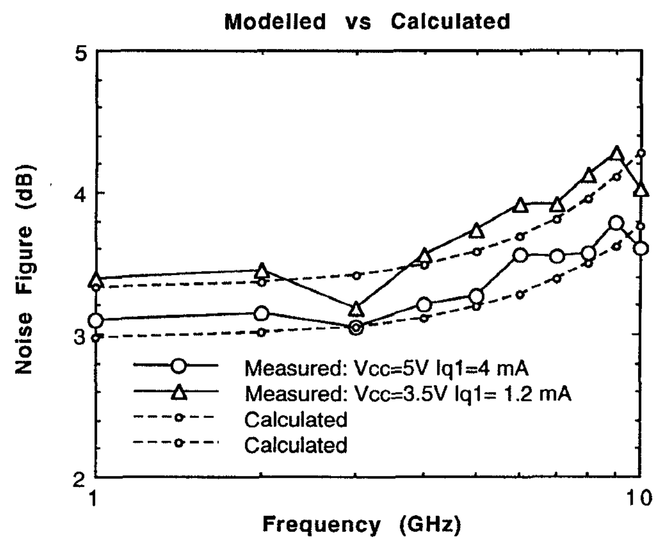

Fig. 3. Measured and calculated amplifier noise figure for 5 and 3.5 V supply voltages.

Fig. 2 gives the gain and input return-loss for supply voltages of 5, 4.5, 4.0, and 3.5 V. At a supply voltage of 5 V and 10.6 mA, The amplifier achieves 22.5 dB gain, 9.1 GHz bandwidth and a minimum input return-loss of 10 dB across the band. The total dc power consumption is 53 mW. For lower supply voltages the gain reduces while the 3-dB bandwidth increases. At a supply of 3.5 V, the nominal gain is 11.5 dB with a 11.5 GHz bandwidth. The corresponding dc power is only 24 mW. As the supply voltage is reduced from 5 to 3.5 V, the input return-loss steadily degrades. A minimum input return-loss of 7.5 dB is measured at 11 GHz for the 3.5 V bias condition.

Fig. 3 illustrates the measured noise figure performance of the amplifier swept over a 1–10 GHz frequency band for the 5 V and 3.5 V supply bias conditions. The corresponding HBT input transistor's (Q_1) collector bias current is also given in the legend of the graph. For the 5 V and 3.5 V supply, the collector bias current of the input transistor, Q_1, is 4 mA and 1.2 mA, respectively. Using hybrid-π model parameters extracted from s-parameters for the two bias currents of transistor Q_1, calculated amplifier noise figure can be obtained over frequency and bias, which is shown in Fig. 3. For a supply voltage of 5 V, the measured noise figure increases from 3.1 dB at 1 GHz to 3.65 dB at 10 GHz. This is believed to be the lowest noise figure so far obtained for an HBT direct-coupled amplifier at X-band frequencies. For a supply voltage of 3.5 V, the measured noise figure increases from 3.4 dB at 1 GHz to 4 dB at 10 GHz. The corresponding noise figure as calculated from (1) shows an accuracy to within 0.3 dB over the 1–10 GHz frequency band and two octaves of transistor bias current. This validates the assumptions made for our simple noise figure expression given earlier. Thus, the noise figure expression of (1) can be useful in exercising performance trades based on device model parameters and bias, as well as the amplifier design parameters such as feedback resistors, RF_1 and RF_2.

V. Conclusion

A dc-10 GHz HBT direct-coupled amplifier obtained 22.5 dB of gain, a 3–0–3.65 dB noise figure, with less than 55 mW of dc power consumption through a 5 V supply. This benchmarks the lowest noise figure so far reported for an HBT amplifier at X-band frequencies. The amplifier uses a direct-coupled topology that can achieve multidecade frequency performance from baseband to X-band. A simple expression for amplifier noise figure was derived that can predict the noise figure to within 0.3 dB over frequency and two octaves of bias current. The miniature amplifier is useful for commercial wireless, electrooptical communication, instrumentation, as well as satellite receiver applications that require baseband to microwave frequency detection, receiving, and signal processing.

References

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