A Monolithic HEMT-HBT Direct-Coupled Amplifier with Active Input Matching

K. W. Kobayashi, *Member, IEEE,* D. C. Streit, *Senior Member, IEEE,* D. K. Umemoto, *Member, IEEE,* T. R. Block, *Member, IEEE,* and A. K. Oki, *Member, IEEE*

***Abstract*— We have achieved the first active input matching of a monolithic microwave integrated circuit through the use of a common-gate (CG) HEMT directly coupled to the input of an HBT Darlington feedback amplifier. The HEMT and HBT devices were monolithically integrated on the same chip using selective MBE. This circuit features an active impedance match technique that eliminates the need for large microstrip matching components. The novel amplifier obtains greater than 10-dB gain over a dc-5 GHz band, a maximum IP3 of 27 dBm, and a minimum noise figure of 3.7 dB. In comparison with a HBT-ONLY Darlington feedback design, the employment of the CG HEMT results in a 6-dB improvement in IP3 and a 1.5–2 dB reduction in noise figure. By adjusting the common-gate HEMT bias, the input return-loss can be tuned for near ideal 50 Ω match (>20 dB). The actively matched HEMT-HBT amplifier demonstrates an active circuit technique, which can reduce the chip area and cost of HEMT-HBT MMIC's while improving their performance.**

I. Introduction

The capability of integrating HEMT and HBT devices on the same substrate offers MMIC designers the flexibility to take advantage of the unique performance characteristics of FET and bipolar devices that complement each other in terms of performance and functionality. While HEMT's offer high gain and low noise figures, HBT's offer low 1/f noise, high linearity, high efficiency, and excellent output drive capability. In addition to optimizing RF circuit performance, a monolithic HEMT-HBT IC technology offers additional circuit functionality, with combinations of circuit topologies never before attainable with III-V semiconductors. This multitechnology integration capability will lead to higher complexity multifunctional MMIC's, which will reduce part-count and associated cost and weight of satellite communications payloads while improving performance and reliability. Several MMIC's fabricated using selective MBE and a merged process technology have been recently reported that demonstrate key circuit functions and performance [1]–[3]. Here, we report for the first time on a unique employment of HEMT's and HBT's to construct an actively matched direct-coupled amplifier with improved performance over an HBT-only equivalent design without HEMT active matching.

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The authors are with TRW Electronics Systems and Technology Division, Redondo Beach. CA 90278 USA.

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II. HEMT Actively Matched HBT Amplifier

The HEMT-HBT actively matched direct-coupled MMIC employs a low-noise common-gate HEMT, M1, which is directly coupled to an HBT Darlington feedback amplifier consisting of transistors Q_1 and Q_2, shown in Fig. 1. The common-gate HEMT provides active impedance matching that can be electronically tuned for optimum return-loss or noise figure. This active FET matching circuit is a common technique that has previously been used in MESFET IC's [4]. At frequencies reasonably lower than the FET device f_T, the input impedance can be expressed as the series combination of the source resistance r_s and a resistance equal to the reciprocal of the HEMT device transconductance. This is given in (1) below

$$Z_{\text{in}}(s) \approx r_s + \frac{1}{G_{m\text{HEMT}}}. \quad (1)$$

For a 0.2 × 200 μm^2 HEMT (M1), $r_s \approx 0.5\ \Omega$, and G_m can range from 0 to ≈120 mS. A near ideal match to 50 Ω would require a HEMT $G_m \approx 20$ mS, which occurs at an $I_{\text{ds}} \approx$ 2–4 mA for our 0.2 × 200 μm^2 HEMT device. The common-gate HEMT active match technique provides good amplifier input return-loss performance without the use of large, cumbersome passive matching components. This technique offers an advantage for applications that are intimately driven by chip size and cost. Furthermore, the HEMT active match allows the amount of feedback of the HBT output stage to be independently adjusted for optimal IP3 performance without compromising the input return-loss of the amplifier. In practice, the resistive parallel feedback amplifier cannot be independently optimized for gain, bandwidth, and input/output return-loss by simply adjusting the amount of resistive feedback.

The HBT Darlington feedback stage consisting of 2 × 10 μm^2 HBT quad-emitter transistors Q_1 and Q_2, provides the output drive capability of the amplifier. Each HBT transistor is biased at an $I_c \approx 16$ mA. The HEMT-HBT amplifier is biased through a single 12-V supply that draws 34.6–44 mA. Fig. 2 shows the fabricated chip that illustrates the negligible impact on size as a result from integrating the common-gate HEMT with the HBT Darlington amplifier. The total chip size is 0.9 × 0.7 mm^2.

Fig. 3 gives the measured gain and input return-loss for various common-gate HEMT bias conditions. The HEMT-HBT amplifier obtains between 10–13 dB gain from dc-5

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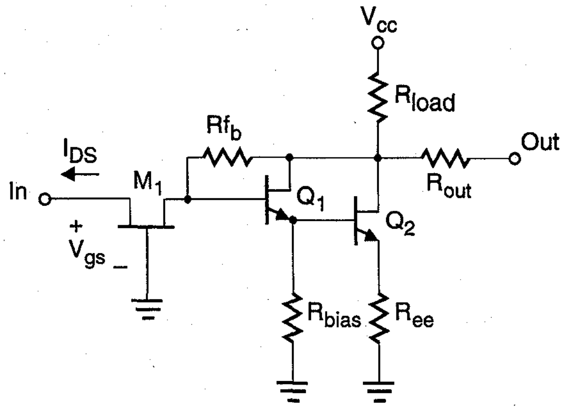

Fig. 1. Circuit schematic of the actively matched direct-coupled HEMT-HBT amplifier.

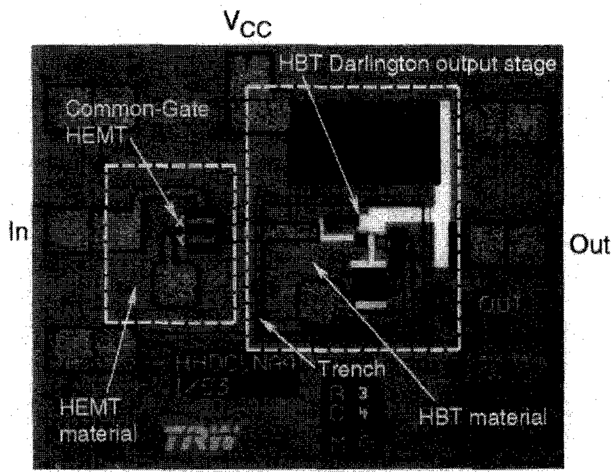

Fig. 2. Microphotograph of the HEMT-HBT MMIC. The chip size is 0.9 × 0.7 mm².

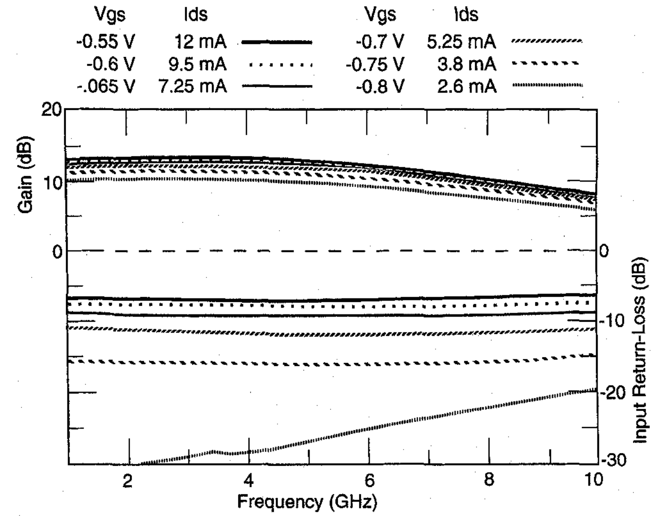

Fig. 3. Measured gain and input return-loss as a function of common-gate HEMT active bias (V_{gs}, I_{ds}).

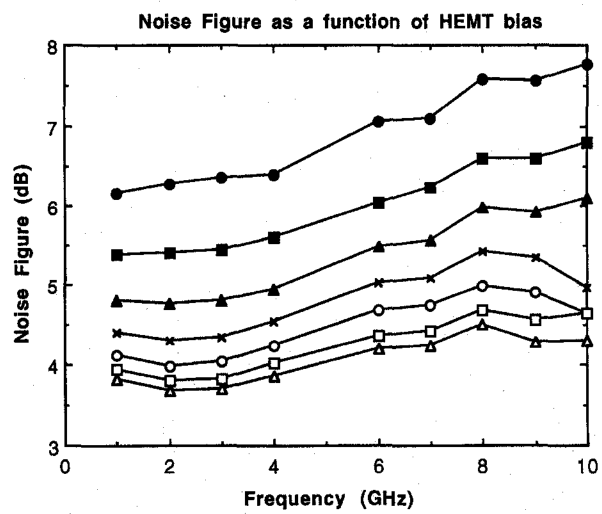

Fig. 4. Measured noise figure as a function of common-gate HEMT active bias (V_{gs}, I_{ds}).

GHz and reasonable return-loss performance that can be electronically adjusted. At a CG HEMT $I_{ds} = 2.6$ mA, the amplifier obtains near ideal 50 Ω match with a input return-loss of >20 dB over the 1–10 GHz band and a corresponding gain of 10 dB. At a higher CG HEMT bias of $I_{ds} = 5.25$ mA, the amplifier achieves slightly higher gain ≈12 dB but at the expense of a poorer return-loss of ≈11 dB. As the CG HEMT bias current I_{ds} is further increased, the gain increases while the input return-loss degrades below 10 dB. The associated noise figure performance as a function of the CG HEMT bias is given in Fig. 4. A noise figure <4.5 dB across the 1–10 GHz band and a minimum noise figure of 3.7 dB is achieved at an $I_{ds} = 14.5$ mA, however this bias corresponds to poor input return-loss performance. A trade-off between low noise figure and good input return-loss is observed. As the bias current is reduced the noise figure increases but the input return-loss improves. At a bias of $I_{ds} = 9.25$ mA, the noise figure is better than 4.7 dB and the input return-loss is 7.5 dB across a 1–5 GHz band. At this bias, the associated IP3 is between 25–27 dBm and is illustrated in Fig. 5, which gives the output IP3 performance at other CG HEMT bias currents as well. These curves indicate that higher IP3 is achieved for lower CG HEMT bias.

The HEMT active matching circuit enables the amplifier to be electronically adjusted for an optimum combination of IP3, noise figure, and input return-loss performance. For example, at a CG HEMT I_{ds} bias of 9.25 mA, the amplifier achieves ≈12 dB gain, 25–27 dBm IP3, <4.7 dB noise figure, and a reasonable input return-loss of 7.5 dB across a 1–5 GHz band. Compared to an HBT-ONLY Darlington feedback amplifier of equivalent design that achieves 11 dB gain, 18–20 dBm IP3, and a 6–6.5 dB noise figure [5], the HEMT actively matched HBT Darlington amplifier achieves a 6 dB improvement in IP3 and a 1.5–2 dB reduction in noise figure.

In retrospect, the HEMT-HBT amplifier performance could be further improved by employing a smaller gate-width CG HEMT in the design. This would result in a reduction in noise figure performance of the CG HEMT stage at the lower CG HEMT current bias where the amplifier has already demonstrated optimal IP3 and return-loss performance. A resulting noise figure below 3 dB is estimated.

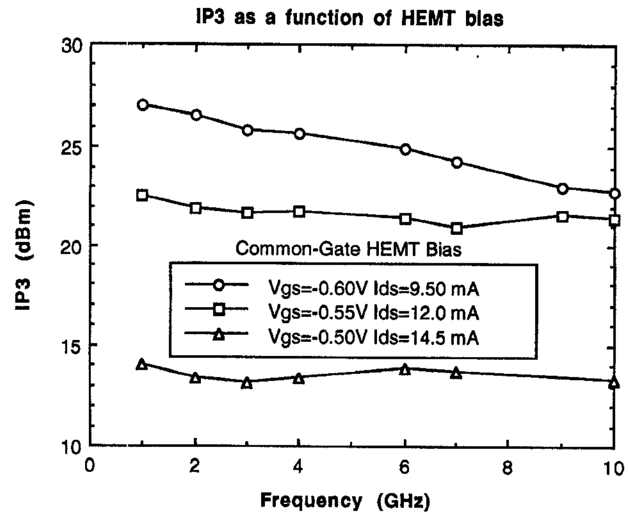

Fig. 5. Measured IP3 as a function of common-gate HEMT active bias (V_{gs}, I_{ds}).

III. Conclusion

A HEMT actively matched HBT amplifier was demonstrated using selective MBE. A HEMT common-gate input device that is directly coupled to an HBT Darlington amplifier provides active input matching which can be realized in a small chip area. The use of the active HEMT matching allows the amount of resistive feedback of the HBT Darlington amplifier to be independently optimized for IP3 without compromising the return-loss performance. As a result, a 6-dB improvement in IP3 and a 1.5–2 dB reduction in noise figure performance was demonstrated in comparison to an HBT-ONLY Darlington feedback amplifier of equivalent design. The resulting HEMT-HBT MMIC demonstrates an active circuit technique that can be used to improve the performance of other HEMT-HBT IC's while minimizing chip size and cost.

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