1.8V RF AGC and Mixer Implemented with a Novel Four-Terminal HBT (FHBT)

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Abstract - **A recent discovery indicates that the current gain of AlGaAs/GaAs HBTs can be externally modulated by biasing an extra Schottky electrode that contacts the emitter passivation ledge directly. This discovery leads to the possibility of implementing complex RF AGC (automatic-gain-control) and signal mixing functions within a 4-terminal HBT (FHBT) at relatively low power supply voltages (down to V_{cc}=1.8V). This low voltage operation has been extremely difficult for the conventional Gilbert-cell mixer design based on regular 3-terminal HBTs. The demonstrated FHBT AGC has 24dB gain control up to 6GHz and the mixer has 7dB conversion gain and -12.5dBm IIP3 without emitter or base degeneration.**

I. INTRODUCTION

We have recently observed that the current gain of AlGaAs/GaAs HBTs can be externally modulated by biasing a Schottky electrode that contacts the emitter passivation ledge directly [1]. This observation leads to possible designs to realize RF AGCs and mixers within a single Four-terminal HBT (FHBT). Currently, most AGCs and mixers are designed based on a Gilbert cell structure that requires stacked stages and is particularly difficult to operate at low supply voltages.

The presented FHBT RF AGC and mixer employ only one stage and a single transistor. It depends on the control of the emitter ledge potential within the device itself to realize the required circuit functions. Therefore, the FHBT AGC and mixer are uniquely suitable for low voltage operations. The measurement at V_{cc}=1.8V shows that the FHBT AGC offers very extensive gain control (>24dB) up to 6GHz and the FHBT mixer provides 7dB conversion gain and – 12.5dBm in IIP3 without degenerating the device.

II. FHBT DC CHARACTERISTICS

The AlGaAs/GaAs FHBTs, used in AGC and mixer design, have an emitter area of 2x2 μm^2 and a simplified cross section as shown in Fig.1. The 4^{th} electrode is formed by using a Ti/Pt/Au Schottky diode which contacts the emitter ledge directly. As described in [1], the emitter ledge must be thin (< 500Å) and fully depleted to be completely isolated from the emitter. As a result, the collector current of the FHBT can be modulated by either biasing the base as typically in conventional HBTs or biasing the additional ledge. The operation of the FHBT becomes more evident in Fig.2 when biasing the device under a constant base current I_B=200µA and measuring the collector current I_C and ledge current I_L versus the ledge bias V_L at V_{cc}=1.8V.

When the ledge bias V_L is low (1.25-1.37V), the base current mostly flows out of the ledge instead of flowing into the intrinsic base. The effective base current of the FHBT is therefore very small and so is the collector current. As the ledge bias becomes sufficiently high (>1.37V), the ledge current reduces, leading to increased intrinsic base and collector currents. Since the ledge is fully depleted, the potential of the underlying base tracks very well to the external ledge bias (V_L) according to the measured relationship in Fig.2:

$$I_C = Is\exp(\frac{V_L}{nV_T}) \quad (1)$$

where I_C is the collector current, V_L is the ledge voltage, V_T is the thermal voltage, I_S and n are constants which can be determined by fitting the collector current as a function of V_L as

$$Is = 1.8\times10^{-24}\,A$$
$$n = \begin{cases} 1.1 & 1.25 < V_L < 1.4 \\ 1.8 & 1.4 < V_L < 1.45 \end{cases} \quad (2)$$

The n factor is larger at high ledge bias 1.4< V_L<1.45, possibly due to the high injection effect of the FHBT and the more significant IR drop at the high bias.

III. FHBT RF CHARACTERISTICS

According to Eqs.1 and 2, the small signal transconductance of the FHBT, g_m, can be written as:

$$g_m = \frac{I_C}{V_T} = \frac{Is}{V_T}\exp(\frac{V_L}{nV_T}) \qquad (3)$$

When taking into account of the input diffusion capacitance of the base-emitter junction, which is proportional to the collector current, the RF voltage gain, can be derived as [2]:

$$
\begin{aligned}
Gain(dB) &= 20\log[g_m Z_L C \exp(\frac{-aV_L}{nV_T}) f^{-a}] \\
&= \frac{334(1-a)V_L}{n} - 20a \log f + 20\log\frac{CIsZ_L}{V_T}
\end{aligned} \quad (4)
$$

Where V_T is 26mV at room temperature, Z_L is the load impedance, f is the frequency, a represents the effect of the diffusion capacitance, which is estimated to be about 0.4 in the frequency range of 2 to 10 GHz and C is a constant. Inserting n factors in Eq.2 into the equation above, the *Gain Control Range* of the designed FHBT AGC at 2GHz is estimated to be:

$$
Range = \begin{cases} 27dB & V_L: 1.25-1.4 \\ 5.5dB & V_L: 1.4-1.45 \end{cases} \quad (5)
$$

At higher frequencies (>2GHz), the gain control range reduces due to the decrease of the amplifier *Gain (dB)* under high ledge bias ($1.4<V_L<1.45$). The control range may further reduce when considering the signal feed-through via the base-collector capacitance of the FHBT at the low ledge bias ($1.25< V_L<1.4$). In this bias range, the output of the amplifier is dominated by the signal feed–through instead of the amplifier gain, which increases as the signal frequency increases.

Based on the same principle, we may also derive the ideal conversion gain G_C of a single-balanced mixer (linear time-variant type) based on a single FHBT as [3]:

$$
G_C = \frac{2}{p} g_m \quad (6)
$$

which is approximately 4dB lower than the RF voltage gain as calculated in Eq.4.

IV. FHBT RF AGC, MIXER CIRCUITS DESIGN AND MEASUREMENT RESULTS

The schematic of a designed FHBT AGC circuit is shown in Fig.3. In order to prevent the ledge current from flowing into the control voltage source at the low ledge voltage, two resistors are used in the ledge bias loop. R_1 is designed for current limiting and R_2 is designed to carry most of the ledge current. Its value is selected as:

$$
R_2 = \frac{V_{L,lowest}}{I_B} \quad (7)
$$

When the ledge control voltage is low, the voltage source provides no output current. As the ledge voltage increases, the voltage source injects more current into R_2. Since the injected current is relatively small, it does not affect the control voltage source. The constant base current (200μA) can be easily supplied by using a silicon PNP transistor. Since the current is small, Vce=0.35V is sufficient for the PNP device to stay within the active region at V_{cc}= 1.8V.

Fig.4 shows the measured results of the FHBT AGC with 50Ω output. At 2GHz, the gain control range is 28dB for V_L=1.25-1.4V (roughly, 9.3dB/50mV) and reduced to 4dB as V_L=1.4-1.45V, which is consistent with the calculated values from Eq.5. The control range decreases to 24dB at 6GHz and 16dB at 10GHz, respectively. The reduced control range with the increased operating frequency is anticipated based on the analysis in section III. As shown in Fig.4, at the low ledge voltage (1.25V-1.3V), the RF *Gain (dB)* is less than unity and increases with the increase of frequency. The g_m is low due to the very small collector current (<100μA) of the FHBT. Nevertheless, the input signal is still coupled to the AGC output through the B-C capacitance and increases as the operating frequency increases. This is why at low ledge voltage the *Gain (dB)* does not follow the trend as Eq.4 describes. At the high ledge voltage (1.4V-1.45V), the g_m is high and *Gain (dB)* becomes significant. With the increase of frequency, the *Gain* drops primarily due to the increase of the B-E diffusion capacitance as the collector current increases. As a result, higher frequency signal is attenuated more significantly at the AGC input, therefore achieving lower *Gain (dB)*. According to Eq.4, at 10GHz the *Gain (dB)* can be calculated to be 5.6dB, which is lower than that at 2GHz and consistent with the measured result of 5.1-6.5dB as shown in Fig.4.

The schematic of a FHBT mixer is shown in Fig.5. It differs from the AGC circuit primarily in the LO part. A small NPN HBT is added to isolate the LO driver and RF source and provide a light load for LO driver with its small driving current (2μA) and input capacitance. The sensitivity of the LO is also improved in this design. When LO is low, the FHBT amplifies the RF input signal;

When LO is high, the base current is drained by the ledge to turn off the FHBT. In this manner, the output is a product of RF and LO multiplication.

To test the function of an FHBT mixer, LO (0.9GHz) and RF (1GHz) signals are applied. The output signal spectrum is shown in Fig.6. A very strong IF signal appears at the intended 100MHz. No spur is measured around IF within 30dBc. The conversion gain is measured to be 7dB, which is close to the predicted value in Eq.6, 4db less than RF voltage gain (12dB). IIP3 is about – 12.5dBm without any device degeneration. The two-tone measurement result is shown in Fig.7.

The LO and RF leakage indicated in Fig.6 is primarily caused by the signal feed-through of the single-balanced and single-ended mixer topology, which can be easily removed through filtering. To improve the efficiency, it is better to make the mixer double-balanced and differential. Since our purpose is to build a down-conversion mixer based on a simplest architecture, a single FHBT scheme is chosen and the high frequency output products are left unconcernedly as they are very far away from the IF.

V. SUMMARY

In summary, simple RF AGC and mixer are implemented by using a novel Four-terminal HBT (FHBT) for the first time. Both circuits perform excellently under low power supply voltages (down to Vcc=1.8V), which is extremely difficult for the conventional stacked Gilbert cell design with regular three-terminal HBTs. To prove the concept, the demonstrated FHBT AGC achieves 24dB voltage gain control up to 6GHz. Mixer attains 7dB conversion gain and -12.5dBm IIP3 without any device degeneration.

REFERANCES

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[2] Adel S. Sedra and Kenneth C. Smith, *Microelectronic Circuits (Fourth Edition)*, Oxford University Press, 1998

[3] Thomas. H. Lee, *The Design of CMOS Radio-Frequency integrated Circuits*, Cambridge University Press, 1998

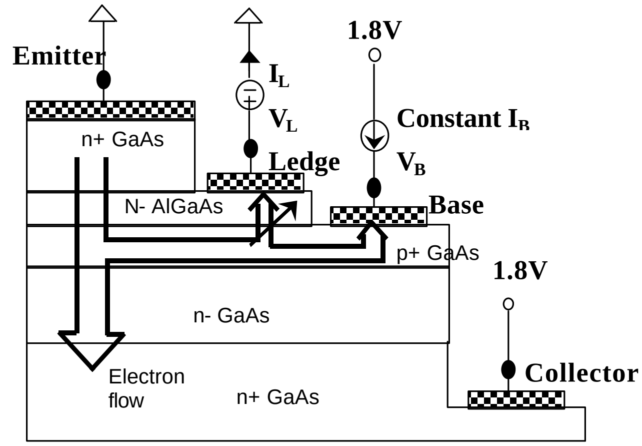

Fig.1 Four-terminal HBT (FHBT) with an extra ledge electrode

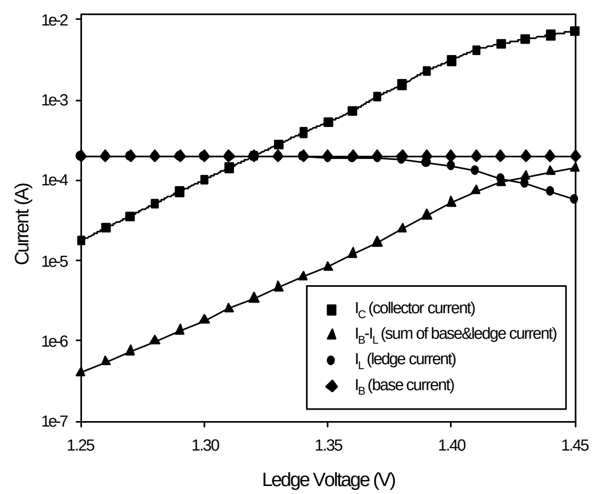

Fig.2 FHBT DC characteristics

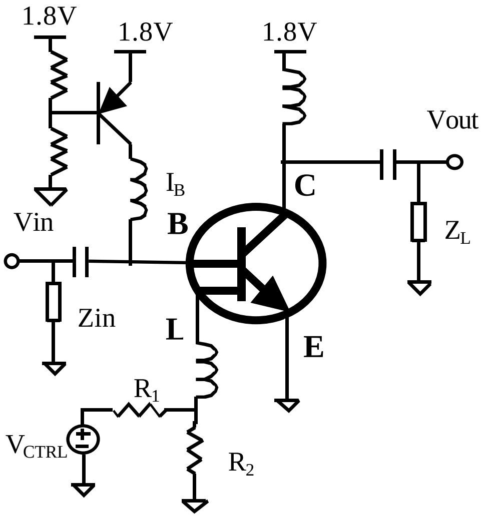

Fig.3 RF AGC based on FHBT

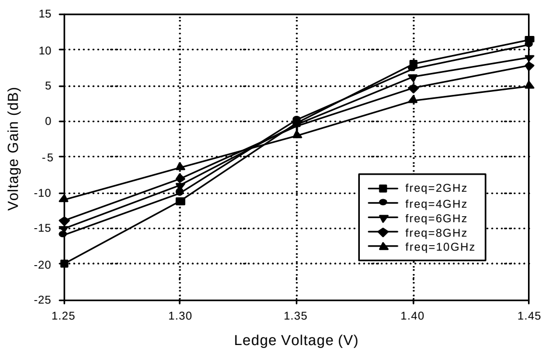

Fig.4 The RF measurement result of FHBT AGC

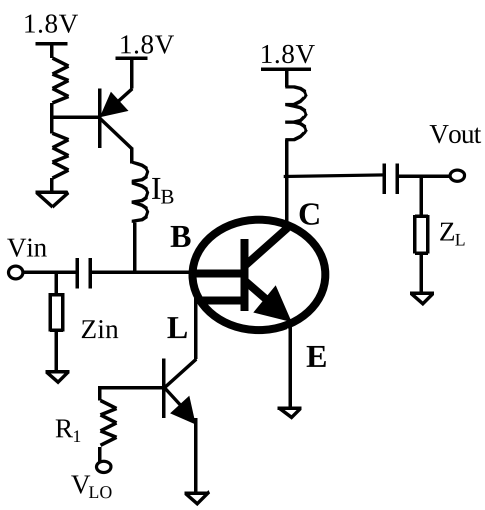

Fig.5 RF Mixer based on FHBT

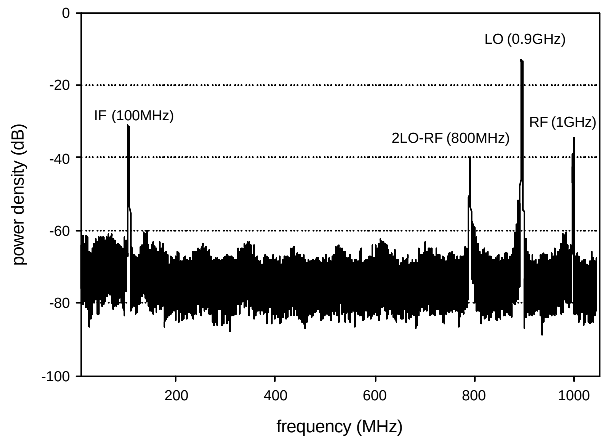

Fig.6 Output spectrum of an FHBT down-conversion mixer

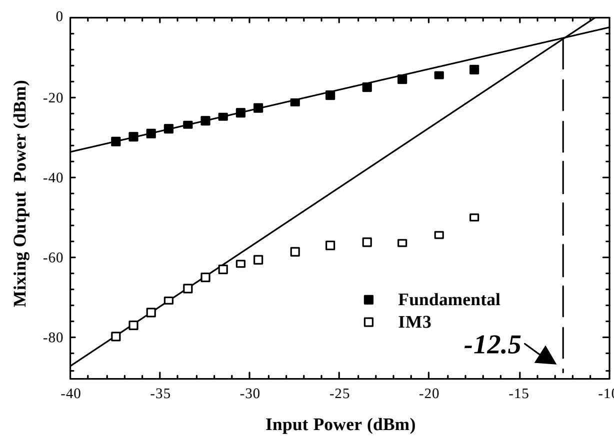

Fig.7 Measured IIP3 of an FHBT mixer without degeneration