Improved HBT Linearity With a "Post-Distortion"-Type Collector Linearizer

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***Abstract*—An HBT amplifier with a "post-distortion"-type linearizer utilizing a base-collector junction diode shows more than 8-dB improvement of adjacent channel power ratio, and the collector linearizer comprising a reverse biased base-collector junction diode requires no additional dc power consumption and makes no deterioration of RF performances. The linearization technique of post-distortion compensates the nonlinearity of HBTs, which arises from the C_{bc} variation due to a large-signal swing.**

I. Introduction

EFFICIENCY and linearity of RF amplifiers become the vital specifications required in mobile communication systems, and the linearity performance is especially emphasized for CDMA and wideband CDMA (W-CDMA) with nonconstant envelope modulation schemes. RF amplifiers for mobile phones, however, have strict constraints on the size and price; therefore, linearization techniques utilized to meet the stringent linearity requirements for the RF amplifiers should be implemented small in size and cheap in cost.

Although several predistortion-type linearization techniques have been proposed, insertion losses of the predistorters lead to gain losses of the overall RF amplifiers with predistorters [1]–[4].

Utilization of a forward biased base-collector junction as a predistorter [5] can avoid the undesirable gain loss arising from predistorters and showed much improvement of the HBT linearity. However, the forward biased diode junction has an exponential nature dependent on the base-collector voltage, and its nonlinear characteristics are very different from the nonlinearity of the reverse biased RF HBT base-collector junction, which makes effective nonlinearity cancellation between the forward biased junction of the predistorter and the base-collector junction of the HBT amplifier under reverse bias condition difficult [6]–[9].

Several studies have shown that epi-layer structures with a low collector punch-through voltage are suitable for HBTs with highly linear performance [10]–[12], partly from weak nonlinearities arising from the weakly nonlinear behavior of conductances and capacitances, the punch-through collector structures cannot be always an effective remedy for strong nonlinearities resulting from a large-signal RF swing [7].

In this work, a new linearization technique of post-distortion utilizing a reverse biased base-collector junction diode is proposed to reduce the C_{bc} variation due to a large-signal swing of RF operation. The linearization technique requires no additional dc current consumption and makes no degradation of RF performances such as RF output power, gain, and efficiency.

Manuscript received July 1, 2002; revised August 19, 2002. The review of this letter was arranged by Associate Editor Dr. Arvind Sharma.

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Digital Object Identifier 10.1109/LMWC.2003.810113

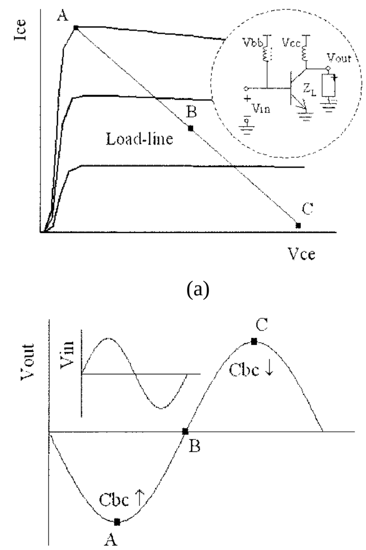

Fig. 1. (a) Load-line of CE HBT amplifier and bias-points A to C on the load-line and (b) correlation between C_{bc} variation and the large-signal swing of V_{out} for the sinusoidal input V_{in}.

II. Cancellation Mechanism for the C_{bc} Variation

Simplified class-A operation of a HBT amplifier in the common-emitter (CE) configuration that is one of the configurations widely adopted for RF amplifiers is described in Fig. 1. Under the simplified situation where the influences of all reactances are excluded, there is a phase difference of 180° between the input voltage (V_{in}) and output voltage (V_{out}) of the CE amplifier as follows:

$$A_v = \mathrm{Vout}/\mathrm{Vin} = -\mathrm{g_m} \cdot \mathrm{R_L} \tag{1}$$

where g_m is the transconductance of the HBT and R_L is the real part of the load impedance Z_L.

Fig. 1(a) shows the load-line for the CE HBT amplifier in class-A operation and A, B, and C are the bias points on the load-line. During RF operation of the CE HBT along the load-line, C_{bc} approaches its largest magnitude near bias point A and decreases as the operation point passing through B goes close to bias point C in the cutoff region [13]. The correlation between V_{out} of the CE HBT amplifier and C_{bc} variation is shown in

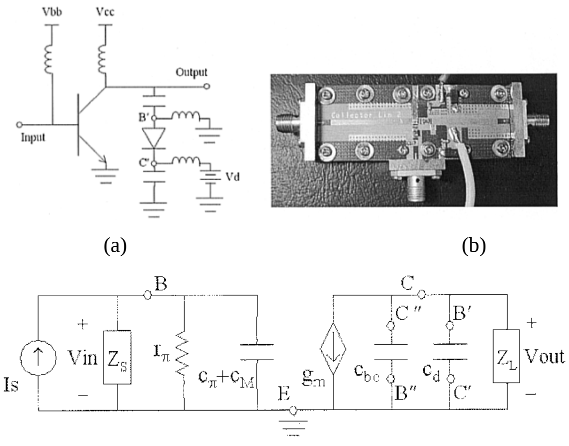

Fig. 2. (a) Schematic and (b) photograph of CE HBT amplifier with the collector diode linearizer and (c) its simplified small-signal equivalent circuit model by Miller's theorem.

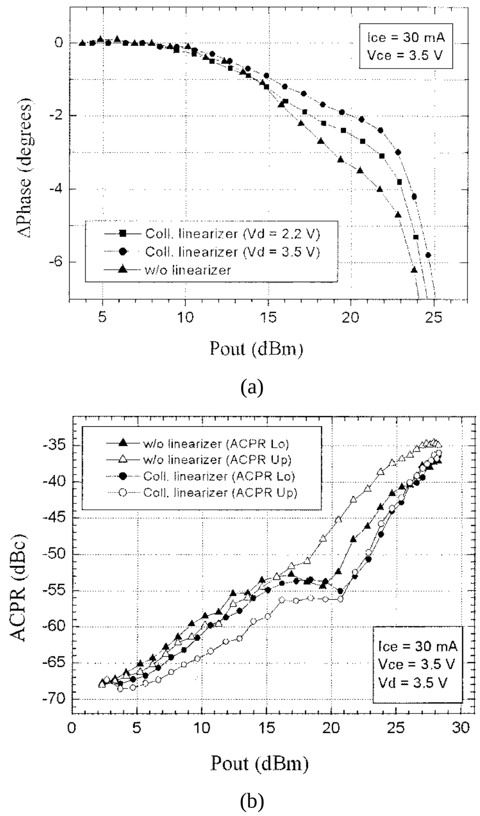

Fig. 3. Measured linearity performances for CE HBT amplifier with the collector diode linearizer at $Vd = 2.2$ and 3.5 V, and CE HBT amplifier alone. (a) Phase deviation; (b) ACPR.

Fig. 1(b). When V_{out} makes a negative swing along the load-line, C_{bc} increases and has its maximum near point A. After passing through bias point B, V_{out} begins a positive swing and C_{bc} becomes decreasing and has its smallest magnitude near the cut-off bias point C.

In order to reduce the variation of C_{bc} due to a large-signal swing, the phase difference between V_{in} and V_{out} can be utilized (1). When a reverse-biased base-collector junction diode is connected to the CE HBT in the same polarity as in Fig. 2(a), the diode capacitance C_d decreases and has the smallest value near the bias point A, here, C_{bc} has its maximum, and on the contrary, C_d has its greatest value near the bias point C, at which C_{bc} has the smallest in its magnitude.

A clearer viewpoint about the cancellation between C_{bc} and C_d can be obtained by the help of the small-signal equivalent circuit model of the CE HBT including the base-collector junction diode linearizer. Employing Miller's theorem [14], C_{bc} in the connection of shunt-feedback between base and collector can be converted into an equivalent form more convenient for analysis. The voltage gain Av of a CE HBT amplifier is usually much greater than unity. With this assumption, the small-signal equivalent circuit in Fig. 2(c) can be acquired, and the C_{bc} contribution toward base is expressed by $C_M = (1+g_m \cdot R_L) \cdot C_{bc}$. The relationship between V_{in} and V_{out} derived from the equivalent circuit model in Fig. 2 (c) is given by the expression

$$\begin{aligned} V_{out} &= -g_m \cdot V_{in} \cdot (j\omega C_{bc}//j\omega C_d//Z_L) \\ &= \frac{-g_m}{G_L + j[\omega(C_{bc}+C_d)+B_L]} \cdot V_{in} \end{aligned} \quad (2)$$

where Z_L is $1/(G_L + jB_L)$.

Equation (2) shows that the variation of C_{bc} due to a large-signal swing can be compensated by C_d, and as a consequence, the variation of the total capacitance $C_{total} = C_{bc} + C_d$ is reduced and the phase distortion appearing in Vout decreases, which leads to improvement of HBT linearity.

Also, with the aid of weakly nonlinear analysis, the capacitances, C_d and C_{bc} are connected in the opposite polarity, as in Fig. 2 (c); hence, the coefficients for them in the Volterra series expansion appear with opposite signs, and resultantly, nonlinearity compensation between C_d and C_{bc} can be proven again.

III. Measurement Results and Discussions

The devices tested in this work are AlGaAs/GaAs HBTs with the total emitter area 880 μm^2 comprising 16 unit-cells, and each unit-cell includes two emitter fingers with the emitter area 55 μm^2. The collector epi-layer structure for the HBTs were designed to be fully depleted at low collector voltages. The base-collector junction with the identical epi-layer structure and emitter area is used for the collector linearizer. RF characteristics were measured utilizing automatic load-pull tuner system at 1.8 GHz under maximum power matching condition, where the source impedances of both the CE HBT amplifiers with and without the collector linearization were tuned to 2.8-j8.3 Ω, and the load impedances for them were set to 13.3-j4.5 Ω and 10.8-j6.4 Ω, respectively. The slight difference in the load impedances comes mainly from the reactance of the collector diode.

Fig. 3 (a) shows the measured phase deviations of the CE HBT amplifier with the collector linearizer for different V_d and of the CE HBT amplifier alone for comparison purpose. It is expected that for $V_d = 2.2$ V, the linearized amplifier would have the best linear phase characteristics. Because GaAs HBTs in active bias regime have about 2.2 V voltage drop across the base-collector junctions with about 1.3 V allotted for the base-emitter turn-on voltage at $V_{ce} = 3.5$ V, hence, the diode linearizer biased with $V_d = 2.2$ V would be expected to best compensate the Cbc variation. However, the phase measurement re-

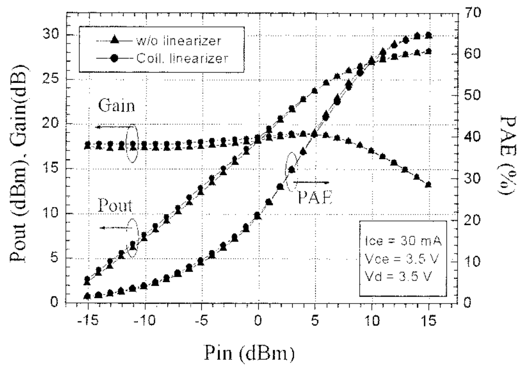

Fig. 4. Measured RF performances for CE HBT amplifier with the collector diode linearizer and CE HBT amplifier alone.

veals that the linearizer gives better linear phase characteristics with $V_d = 3.5$ V than with $V_d = 2.2$ V. The discrepancy between the expectation and the measurement results comes from the different bias condition of the collector linearizer which is reverse biased and has no dc current flow, but the base-collector junction of the HBT has a certain amount of dc collector current during the RF operation. The current flow across the base-collector junction results in the ionized donor charge compensation in the collector depletion region by the injected mobile charges and leads to increase of the collector depletion width and resultant decrease of Cbc [8]. In order to make better compensation of the Cbc variation, the diode linearizer should be further reverse biased than the expected value of $Vd = 2.2$ V. At the output RF power level of $P_{out} = 20$ dBm, the phase deviations of the linearized HBT amplifier with $V_d = 3.5$ V and the CE HBT amplifier alone are 2.0° and 3.4°, respectively.

Fig. 3 (b) shows the measured ACPR of the HBT amplifier with the collector linearizer and the HBT amplifier without linearization. The ACPR was measured in ±1250 KHz offset frequency bands using an offset quadrature phase shift keying (OQPSK) signal with a chip rate of 1.2288 Mcps at 1.8 GHz. The worst-case ACPR for which the worse data is chosen from the ACPR measured in both the upper and lower offset bands at $P_{out} = 20$ dBm is −54.4 dBc for the linearized amplifier with $V_d = 3.5$ V. This is an improvement of ACPR by more than 8 dB in comparison with that of the HBT amplifier alone. The RF power performances for the linearized and unlinearized amplifiers are shown in Fig. 4. Both the amplifiers give almost identical RF power characteristics, and no deterioration in the RF performances is observed for the linearized amplifier, which proves the collector diode linearizer can improve the linear characteristics of HBTs without sacrificing any RF performances. The linearization technique of the collector diode linearizer is very simple in its structure, and the compactness of the collector linearizer when it is integrated into the MMIC together with a HBT power amplifier makes this linearization technique suitable for power amplifiers of mobile phones with high linearity requirements.

IV. Conclusion

A new linearization technique of the collector diode linearizer has been developed to reduce the C_{bc} variation due to a large-signal swing of RF operation, hence to improve the HBT linearities. Utilization of the collector diode linearizer improves the phase deviations of HBTs and the worst-case ACPR is improved by more than 8 dB for the linearized HBT amplifier in comparison with the unlinearized HBT amplifier. The collector linearizer requires no additional dc current consumption and makes no deterioration of RF performances, such as output power, gain, and efficiency. The linearizer is simple in its structure and can be compactly integrated into MMICs together with RF power amplifiers. The technique of the collector diode linearizer is considered to be suitable for the power amplifiers of mobile phones with the requirements of high linearity and compactness in size.

Acknowledgment

The authors would like to thank Prof. B. Kim of Pohang University of Science and Technology for his helpful advices concerning the HBT nonlinearities.

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