Effect of collector bias current on the linearity of common-emitter BJT amplifiers*

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Abstract: Using a Volterra series, an explicit formula is derived for the connection between input 3rd-order intercept point and collector bias current (I_{CQ}) in a common-emitter bipolar junction transistor amplifier. The analysis indicates that the larger I_{CQ} is, the more linear the amplifier is. Furthermore, this has been verified by experiment. This study also integrates a method called dynamic bias current for expanding the dynamic range of an LNA (low noise amplifier) as an application of the analysis result obtained above. IMR3 (3rd-order intermodulation rate) is applied to evaluate the LNA's performance with and without adopting this method in this study.

Key words: IIP3; collector bias current; BJT; dynamic bias current
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1. Introduction

More and more bandwidth efficient modulation techniques have been employed in recent years, such as QAM16 and QAM64. Hence, there has been an extensive requirement for more linear amplifiers in the transmitters as well as the receivers[1−3]. This paper focuses on the linearity of the receivers, especially the LNA, since it has a considerable influence on the performance of the bit error rate[4].

Generally, Volterra series are effective in analyzing the nonlinearity of amplifiers[5−7]. Besides providing insights into the nonlinear mechanism, Volterra series can handle memory elements with greater speed than the Harmonic Balance approach. In this study, a Volterra series is applied to calculate the nonlinearity of the low noise amplifier (LNA), which is a weakly nonlinear common-emitter (CE) BJT amplifier operating in class-A mode. And the Volterra series is truncated to 3rd-order to keep the analysis tractable.

In addition to other influencing factors on the nonlinearity of the CE BJT (bipolar junction transistor) amplifier, the effect of the collector bias current (I_{CQ}) has been paid great attention. Furthermore, the input 3rd-order intercept point (IIP3) is used to estimate the nonlinearity of the amplifier and it is calculated in two steps: the nonlinear transfer function is derived via a Volterra series; IIP3 is calculated through the nonlinear transfer function. With the expression of IIP3, the effect of I_{CQ} on IIP3 can be specified explicitly, and it has been verified by experiment.

In this study, based on the effect of the I_{CQ} on nonlinearity, a method called dynamic bias current is proposed to improve the linearity of the CE BJT amplifier. Experimental results show that the IMR3 of the LNA is reduced by more than 35 dB with this method when the input power is –35 dBm.

2. Volterra model of the CE BJT amplifier

A simplified schematic of a typical CE BJT is shown in Fig. 1(a), and its equivalent nonlinear circuit for a Volterra series calculation is shown in Fig. 1(b). The base–emitter resistance ($R_{b'e}$) is considered to be the main source of nonlinearity, while the remaining elements, such as C_{BE}, β_F are taken to be linear components. It has been proved that the nonlinearity of $R_{b'e}$ dominates the 3rd-order intermodulation[8]. Therefore, the assumption for the nonlinear components in the schematic (Fig. 1(b)) is reasonable.

The nonlinear element $R_{b'e}$ depends on both the quiescent bias current I_{CQ} and the RF signal. Therefore, the value of $R_{b'e}$ is determined under large-signal conditions. Based on the BJT's EM model, the transient current I_b can be expressed as

$$I_b = \frac{I_S}{\beta_F} \exp \frac{V_{b'e}}{V_T}, \tag{1}$$

where V_T is the thermal voltage ($V_T = kT/q$) and I_S is the

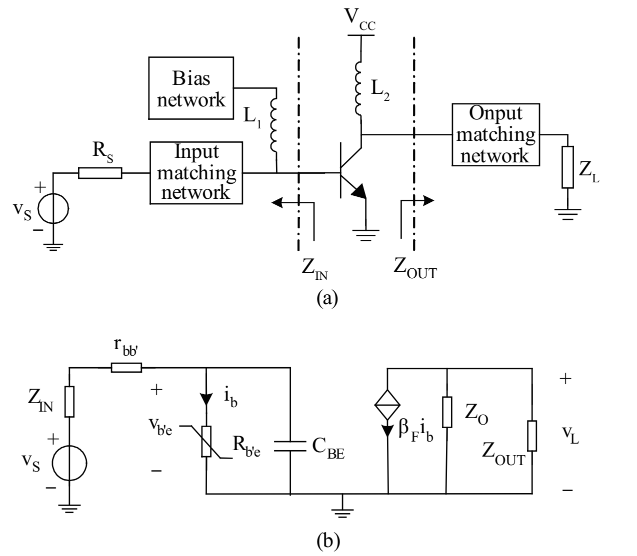

Fig. 1. (a) Typical CE BJT amplifier schematic and (b) its equivalent nonlinear circuit for a Volterra series calculation.

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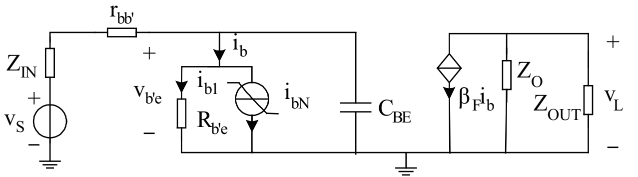

Fig. 2. Linearized circuit for the CE BJT amplifier.

reverse saturation current.

The transient current $I_{\rm b}$ consists of two parts, DC and AC. Furthermore, the exponential function can be expressed with a Taylor series. Then $I_{\rm b}$'s expression can be obtained as

$$\begin{aligned} I_{\rm b} &= \frac{I_{\rm S}}{\beta_{\rm F}} \exp\frac{V_{\rm B'E}+v_{\rm b'e}}{V_{\rm T}} = \frac{I_{\rm S}}{\beta_{\rm F}} \exp\frac{V_{\rm B'E}}{V_{\rm T}} \exp\frac{v_{\rm b'e}}{V_{\rm T}} \\ &= \frac{I_{\rm S}}{\beta_{\rm F}} \exp\frac{V_{\rm B'E}}{V_{\rm T}} \left(1+\frac{v_{\rm b'e}}{V_{\rm T}}+\frac{1}{2}\left(\frac{v_{\rm b'e}}{V_{\rm T}}\right)^2+\frac{1}{6}\left(\frac{v_{\rm b'e}}{V_{\rm T}}\right)^3+\cdots\right) \\ &= \frac{I_{\rm CQ}}{\beta_{\rm F}}+\frac{I_{\rm CQ}}{\beta_{\rm F}}\left(\frac{v_{\rm b'e}}{V_{\rm T}}+\frac{v_{\rm b'e}^2}{2V_{\rm T}^2}+\frac{v_{\rm b'e}^3}{6V_{\rm T}^3}+\cdots\right), \end{aligned} \tag{2}$$

where $I_{\rm CQ}$ is the static bias current on the collector [$I_{\rm CQ} = I_{\rm S}\exp(V_{\rm B'E}/V_{\rm T})$].

It should be noted that the AC part of $I_{\rm b}$, named $i_{\rm b}$, is derived as

$$i_{\rm b} = \frac{I_{\rm CQ}}{\beta_{\rm F}} \times \left(\frac{v_{\rm b'e}}{V_{\rm T}}+\frac{v_{\rm b'e}^2}{2V_{\rm T}^2}+\frac{v_{\rm b'e}^3}{6V_{\rm T}^3}+\cdots\right). \tag{3}$$

A linearized circuit for the CE BJT combined with a nonlinear current source is shown in Fig. 2. Using a Volterra series approach, the nonlinear transfer functions ($H_1(s_1)$, $H_2(s_1, s_2)$, $H_3(s_1, s_2, s_3)$) can be derived. A detailed process of derivation of the nonlinear transfer function is given in the Appendix.

Instead of solving the whole kernel, the repose of interest frequency can be calculated by substituting the variables s_1, s_2 and s_3 for the desired signal frequencies. In this paper, a lower 3rd-order intermodulation signal (IM3) which is at the frequency $2\omega_1 - \omega_2$ is computed with $s_1 = s_2 = {\rm j}\omega_1$ and $s_3 = -{\rm j}\omega_2$.

3. IIP3 analysis

IIP3, a common parameter for measuring the nonlinearity of an amplifier, has a close relationship with the intermodulation product: the larger the IIP3 is, the more linear the amplifier is. According to the definition of IIP3, the value of IIP3 is derived as

$$\text{IIP3 (dB)} = P_{\rm IN}\,(\text{dBm}) + \frac{1}{2}P_{\rm OUT1}\,(\text{dBm}) - \frac{1}{2}P_{\rm OUT3}\,(\text{dBm}), \tag{4}$$

where $P_{\rm IN}$ is the input power of the amplifier, and $P_{\rm OUT1}$ and $P_{\rm OUT3}$ represent the power level of output base-band signal and 3rd-order intermodulation, respectively.

IIP3 can also be expressed in numerical (not in dB) form,

Table 1. Extracted parameters of 2SC5010.

Parameter	$\beta_{\rm F}$	$r_{\rm bb'}$	$V_{\rm T}$	$C_{\rm b'e}$
Value	130	19.9 Ω	26 mV	5 pF

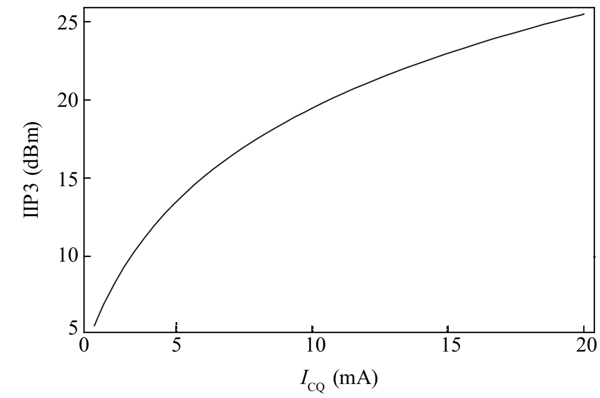

Fig. 3. Calculation curve of IIP3 versus $I_{\rm CQ}$.

$$\text{IIP3} = P_{\rm IN}\sqrt{\frac{P_{\rm OUT1}}{P_{\rm OUT3}}} = v_{\rm b'e} i_{\rm b1}\sqrt{\frac{v_{\rm L1}^2/2Z_{\rm OUT}}{v_{\rm L3}^2/2Z_{\rm OUT}}} = v_{\rm b'e} i_{\rm b1}\frac{v_{\rm L1}}{v_{\rm L3}}, \tag{5}$$

where $v_{\rm L1}$ and $v_{\rm L3}$ are the output voltage at frequency of ω_1 and $2\omega_1 - \omega_2$. $i_{\rm b1}$, $v_{\rm L1}$ and $v_{\rm L3}$ can be calculated from nonlinear transfer functions (Appendix). Then IIP3's expression could be transformed to

$$\begin{aligned} \text{IIP3} =& \frac{I_{\rm CQ}}{\beta_{\rm F} r_{\rm bb'} V_{\rm T}^2} \\ &\times \left\{ \left(1 - \frac{r_{\rm bb'} I_{\rm CQ}}{r_{\rm bb'} I_{\rm CQ} + \beta_{\rm F} V_{\rm T}(1 + {\rm j}(2w_1 - w_2) C_{\rm b'e} r_{\rm bb'})}\right) \right. \\ &\times \left[1 + 2V_{\rm T}^2 \left(\frac{1}{V_{\rm T} + \dfrac{r_{\rm bb'} I_{\rm CQ}}{\beta_{\rm F}} + 2{\rm j}w_1 C_{\rm b'e} r_{\rm bb'} V_{\rm T}} \right.\right. \\ &+ \left. \frac{2}{V_{\rm T} + \dfrac{r_{\rm bb'} I_{\rm CQ}}{\beta_{\rm F}} + {\rm j}(w_1 - w_2) C_{\rm b'e} r_{\rm bb'} V_{\rm T}} \right) \\ &\times \left. \left. \left(V_{\rm T} + \frac{r_{\rm bb'} I_{\rm CQ}}{\beta_{\rm F}} - {\rm j}w_2 C_{\rm b'e} r_{\rm bb'} V_{\rm T} \right) \right]^{-1} \right\}^{-1}. \end{aligned} \tag{6}$$

Equation (6) gives the relationship between IIP3 and $I_{\rm CQ}$. The other parameters in Eq. (6), such as $r_{\rm bb'}$ and $\beta_{\rm F}$, can be extracted from measuring an actual BJT. In this work, these parameters were extracted from 2SC5010 and the results are shown in Table 1.

By calculating Eq. (6), the curve of IIP3 versus $I_{\rm CQ}$ is derived (Fig. 3).

4. Experiment verification

To validate the conclusion drawn above, a two-tone test was employed for measuring the IIP3 of a commercial BJT (2SC5010) at 860 MHz. The experimental network is shown

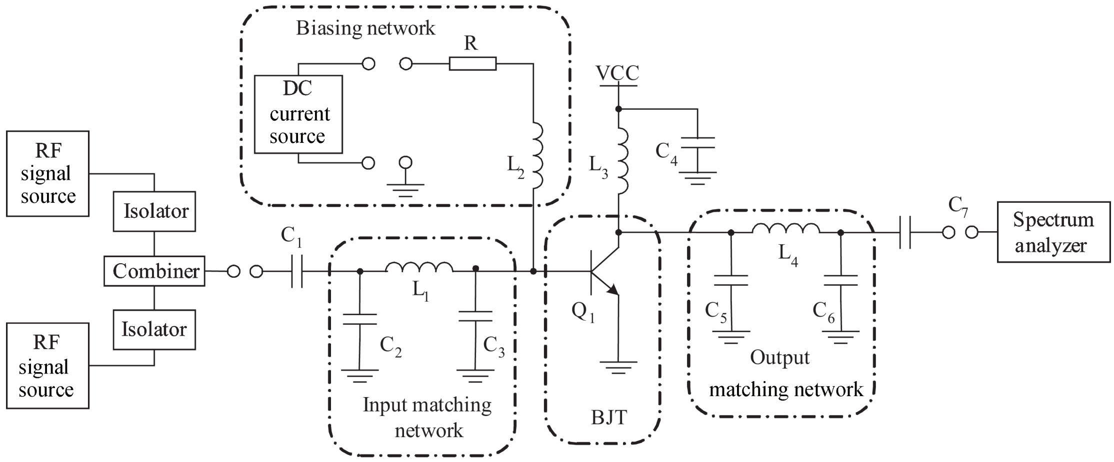

Fig. 4. Circuit used in two-tone test.

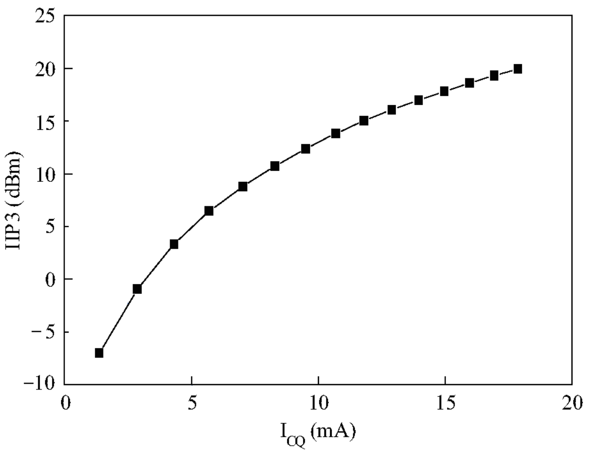

Fig. 5. Measurement curve of IIP3 versus I_{CQ}.

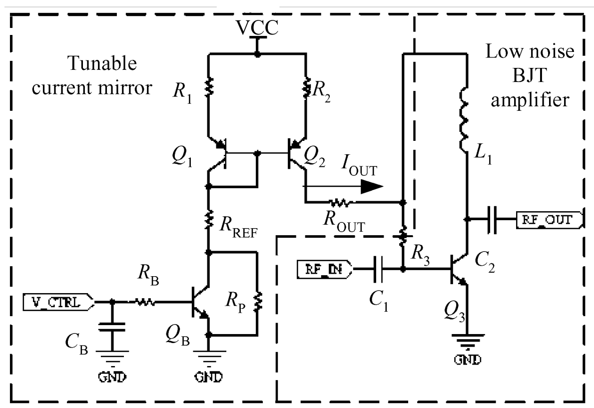

Fig. 6. Schematic of dynamic bias current LNA.

in Fig. 4, which consists of a DC current source to provide the adjustable quiescent bias current. The two-tone signals provided by two RF signal sources (HP8657A) were combined by two isolators and one combiner. A spectrum analyzer (Agilent 9320A) was employed to measure the power level of the output base-band signal and the intermodulation product.

During the experiment, every time the bias current was changed, the input and output matching network was adjusted with a vector network analyzer (Agilent N5070B) to ensure that the whole network was well matched.

Figure 5 shows the measurement result of IIP3, which has the same variation trend with the calculation result in Section 3.

The IIP3 calculated (Fig. 3) is a little higher than the IIP3 measured (Fig. 5). This difference may be explained as follows. In calculation, just the main nonlinear element ($R_{b'e}$) is taken into account, while other weakly nonlinear components are considered to be linear. As a result, the circuits calculated seem to be more linear than the real one.

5. Application

In this section, a method called dynamic bias current (DBC), which is based on the connection between IIP3 and I_{CQ}, is introduced to improve the linearity of LNA. The idea of DBC is to adjust the bias current (I_{CQ}) of LNA dynamically according to the strength of the receiving signals. In detail, the I_{CQ} increases when receiving strong RF signals. As a larger I_{CQ} leads to a higher IIP3, the power level of the intermodulation product will decrease. On the other hand, when the received RF signals are weak, the I_{CQ} will decrease to a normal value, ensuring the low noise performance of the LNA.

This method has already been applied in a wireless handset where the value of I_{CQ} was designed into two levels (2 mA and 10 mA). Figure 6 shows the LNA's circuit, which consists of two parts: a tunable current mirror (CM) and a low noise BJT amplifier.

As the provider of the collector bias current of the LNA, the CM's output current (I_{OUT}) is controlled by the signal V_{CTRL}, a digital signal coming from the MCU (micro controller unit). When V_{CTRL} is low, I_{OUT} = 2 mA; and I_{OUT} = 10 mA when V_{CTRL} is high.

The measured power level of output base-band signal and intermodulation under different bias currents are presented in Fig. 7. IMR3 which means the rate between intermodulation and base-band is easily figured out. Apparently, the IMR3 under I_{CQ} = 10 mA is reduced by more than 35 dB compared to that under I_{CQ} = 2 mA when the input power is –35 dBm. Therefore, the receiver with DBC has a much better perfor-

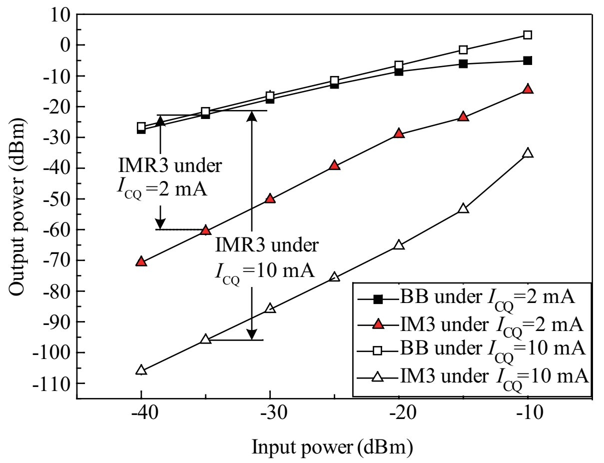

Fig. 7. Comparison of power level of output base-band signal and intermodulation product under different bias currents. BB means baseband signal, while IM3 means 3rd-order intermodulation.

mance (lower intermodulation distortion) when dealing with strong signals.

6. Conclusion

The effect of I_{CQ} on IIP3 of a CE BJT amplifier is presented. With a Volterra series approach, the analysis is carried out on the basis of a simplified large-signal model of a BJT. It is shown that the larger the I_{CQ} is, the higher the IIP3 is, which also means the more linear the amplifier is. Experiment and analysis results agree with each other very well.

Based on this analysis, a method called dynamic bias current is proposed for expanding the dynamic range of a wireless receiver. The comparison between IMR3 with and without adopting this method has validated this approach.

Appendix A: Calculation of the nonlinear transfer function

According to the circuit shown in Fig. 2, it is easy to obtain the equations set below,

$$\begin{cases} v_{b'e} + r_{bb'}\left(i_{bN} + sC_{BE}v_{b'e} + \dfrac{v_{b'e}}{R_{b'e1}}\right) = 0, \\ v_L = \beta_F i_b \dfrac{Z_O Z_L}{Z_O + Z_L}. \end{cases} \tag{A1}$$

$v_{b'e}$ and v_L can be expressed as:

$$\begin{aligned} v_{b'e} = {} & F_1(s_1)v_{in}(s_1) + F_2(s_1, s_2)v_{in}(s_1)v_{in}(s_2) \\ & + F_3(s_1, s_2, s_3)v_{in}(s_1)v_{in}(s_2)v_{in}(s_3), \end{aligned} \tag{A2}$$

and

$$\begin{aligned} v_L = {} & H_1(s_1)v_{in}(s_1) + H_2(s_1, s_2)v_{in}(s_1)v_{in}(s_2) \\ & + H_3(s_1, s_2, s_3)v_{in}(s_1)v_{in}(s_2)v_{in}(s_3), \end{aligned} \tag{A3}$$

where the $F_1(s_1)$, $F_2(s_1, s_2)$ and $F_3(s_1, s_2, s_3)$ are the terms for the transfer function for $v_{b'e}$, and $H_1(s_1)$, and $H_3(s_1, s_2, s_3)$ are the terms for the transfer function for v_L.

Substituting Eqs. (17) and (18) into Eq. (16), the nonlinear transfer functions can be obtained as

$$F_1(s) = \frac{V_T}{\dfrac{I_C r_{bb'}}{\beta_F} + sV_T C_{BE} r_{bb'} + V_T}, \tag{A4}$$

$$F_2(s_1, s_2) = -\frac{I_C r_{bb'}}{2\beta_F V_T^2} F_1(s_1)F_1(s_2)F_1(s_1 + s_2), \tag{A5}$$

$$\begin{aligned} & F_3(s_1, s_2, s_3) = \\ & -\frac{I_C r_{bb'}}{\beta_F}\left(\frac{6\overline{F_1(s_1)F_2(s_2, s_3)}}{V_T^2} + \frac{F_1(s_1)F_1(s_2)F_1(s_3)}{V_T^3}\right) \\ & \times F_1(s_1 + s_2 + s_3), \end{aligned} \tag{A6}$$

$$\begin{aligned} H_1(s) = \frac{v_{L1}(s)}{v_{in}(s)} & = \frac{I_C}{V_T}\frac{Z_O Z_L}{Z_O + Z_L}F_1(s) \\ & = \frac{I_C}{\dfrac{I_C r_{bb'}}{\beta_F} + sV_T C_{BE} r_{bb'} + V_T}\frac{Z_O Z_L}{Z_O + Z_L}, \end{aligned} \tag{A7}$$

$$\begin{aligned} & H_2(s_1, s_2) = \frac{v_{L2}}{v_{in}(s_1)v_{in}(s_2)} \\ & = \frac{I_C}{V_T^2}\frac{Z_O Z_L}{Z_O + Z_L}F_1(s_1)F_1(s_2)\left[1 - \frac{I_C r_{bb'}}{2V_T\beta_F}F_1(s_1 + s_2)\right], \end{aligned} \tag{A8}$$

$$\begin{aligned} & H_3(s_1, s_2, s_3) = \frac{v_{L3}}{v_{in}(s_1)v_{in}(s_2)v_{in}(s_3)} \\ & = \frac{Z_O Z_L I_C r_{bb'}}{Z_O + Z_L}\left[\frac{6\overline{F_1(s_1)F_2(s_2, s_3)}}{V_T^2} + \frac{F_1(s_1)F_1(s_2)F_1(s_3)}{V_T^3}\right] \\ & \quad \times \left[1 - \frac{I_C r_{bb'}}{V_T\beta_F}F_1(s_1 + s_2 + s_3)\right]. \end{aligned} \tag{A9}$$

With the transfer functions, we could derive some useful parameters for calculating IIP3.

$$i_{b1} = \frac{I_C}{\beta_F}\frac{v_{b'e1}}{V_T} = \frac{I_C}{\beta_F\left(\dfrac{I_C r_{bb'}}{\beta_F} + sV_T C_{BE} r_{bb'} + V_T\right)}v_{in}(s), \tag{A10}$$

$$v_{L1}(s) = \frac{I_C}{\dfrac{I_C r_{bb'}}{\beta_F} + sV_T C_{BE} r_{bb'} + V_T}\frac{Z_O Z_L}{Z_O + Z_L}v_{in}(s), \tag{A11}$$

$$\begin{aligned} v_{L3} = {} & \frac{Z_O Z_L I_C r_{bb'}}{Z_O + Z_L} \\ & \times \left(\frac{6\overline{F_1(s_1)F_2(s_2, s_3)}}{V_T^2} + \frac{F_1(s_1)F_1(s_2)F_1(s_3)}{V_T^3}\right) \\ & \times \left[1 - \frac{I_C r_{bb'}}{V_T\beta_F}F_1(s_1 + s_2 + s_3)\right]v_{in}(s_1)v_{in}(s_2)v_{in}(s_3). \end{aligned} \tag{A12}$$

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