Noise Analysis for low-voltage low-power CMOS RF low noise amplifier

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Abstract— In this paper, a noise analysis to a 1 V , 1.5 GHz CMOS low-noise amplifier (LNA) was done. The Circuit is simulated in 90 nm CMOS MOSIS. The LNA gain is 18dB , noise figure (NF) is 2dB , reverse isolation (S_{12}) is -36dB , input return loss (S_{12}) is -12.6dB , output return loss (S_{22}) is -17dB , and the power consumption is 5.4 mA from a single 1 V power supply.

Index Terms— Low-noise amplifier (LNA); RF front end; Global system for mobile communication (GSM); Global positioning system (GPS); Wireless local area network (WLAN); Advanced Design system (ADS).

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1 INTRODUCTION

THE development of the high-speed wireless communication systems puts increasing request on integrated low-cost RF devices with multi-GHz bandwidth operating at the lowest power consumption and supply voltage. A wideband LNA [1], which is a key block in the design of broadband receivers for multiband wireless communication standards. One of the important blocks in the receiver is the LNA. Still the challenge is CMOS radio frequency (RF) front end circuit is for high performance, low cost, low power consumption [4,5]. Today the present goal is to reduce the power consumption, which leads to an increase of the battery-use time and of cost as well [2].

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2 CIRCUIT ANALYSIS

As the first active stage of receivers, LNAs play a critical role in the overall performance and their design is governed by a trade off among the following parameters[3].

1) Power Dissipation
2) Noise Figure
3) Linearity
4) Gain
5) Bandwidth
6) Input Matching (antenna-LNA matching)

Doing the analysis for many circuits and calculate the gain, the input referred noise and the noise figure trying to minimize the noise figure as can as possible to achieve higher performance for the overall design then studying the S-parameter for each design to know the incident, reflected power and the power loss in order to do matching then checking stability and enhance it by adding a source inductor.

2.1 Circuit analysis of Shaeffer Low Noise Amplifier

Fig. 1 is the most popular narrow-band LNA. It is narrowband because impedance matching is only established within a very narrow frequency range due to the resonant nature of the reactive matching network. Impedance matching is established by inductive degeneration. Around the operation frequency

$$\omega_o = 1/\sqrt{C_{gs}(L_s + L_g)}$$

the input impedance only presents a real part $Z_{in} = g_m/C_{gs}L_s$; detailed analysis is found in [4].

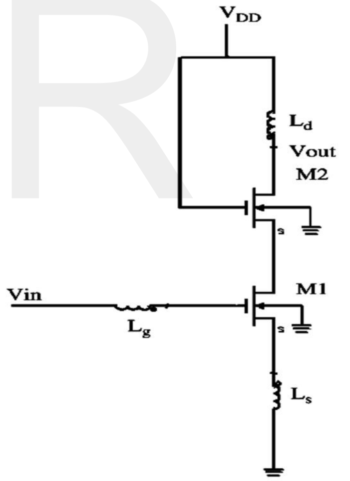

Fig. 1. CMOS low noise amplifier [4].

2.2 Noise analysis for Low-voltage low-power CMOS RF LNA

To reduce the cascode number of elements, the mutual inductance properties between two inductors were used as shown in Fig. 2, the LNA differs by one additional capacitor C2 compared to the typical cascode LNA. The insertion of this capacitance adds a degree of freedom to play with the noise performance in addition to the gain at low-power consumption [2]. Also the input is applied on the M1 source instead of the M1 gate, which makes the body effect increase the equivalent transconductance of the stage [6].

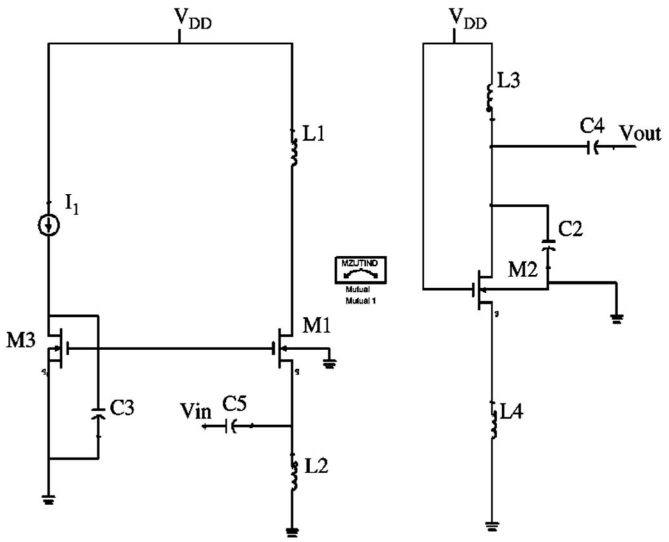

Fig. 2. Modified cascade low noise amplifier [2].

1. Gain analysis

The voltage transfer function of the proposed circuit can be written as follows:

$$A_v = \frac{V_{out}}{V_{in}} = A_1 * A_2$$

$$A_1 = \frac{a_2 s^4 + b_2 s^3 + c_2 s^2 + d_2 s + e_2}{f_2 s^2 + g_2 s + h_2}$$

$$A_2 = \frac{f_1 s^2 + g_1 s + h_1}{a_1 s^3 + b_1 s^2 + c_1 s + d_1}$$

$$A_v = \frac{\alpha}{\beta}$$

$$\alpha = s^6 a_2 f_1 + s^5(a_2 g_1 + f_1 b_2) + s^4(a_2 h_1 + b_2 g_1 + c_2 f_1)$$

$$+s^3(d_2 f_1 + b_2 h_1 + c_2 g_1) + s^2(h_1 + g_1 d_2 + h_1 c_2)$$

$$+s(g_1 e_2 + h_1 d_2) + h_1 e_2$$

$$\beta = s^5 a_1 f_2 + s^4(b_1 f_2 + a_1 g_2) + s^3(c_1 f_2 + b_1 g_2 + a_1 h_2)$$

$$+s^2(d_1 f_2 + c_1 g_2 + b_1 h_2) + s(d_1 g_2 + c_1 h_2) + d_1 h_2$$

The mutual inductance M1 between L1 and L4 helps in giving extra freedom for controlling the conversion gain taking into account the layout fabrication limitation. Also the body effect affects positively the LNA conversion gain.

The hand analysis equations are done using MATLAB R2010a tool.

The Matlab results that the gain at 1.5 GHz without including load resistance nor source resistance is 29 dB as shown in Fig. 5.

2. Noise performance simulation result

The NF of the presented LNA is 2.079 dB at frequency 1.5 GHz as presented in Fig. 3.

The Matlab results that the noise figure at 1.5 GHz is 2.32 dB as shown in Fig. 6.

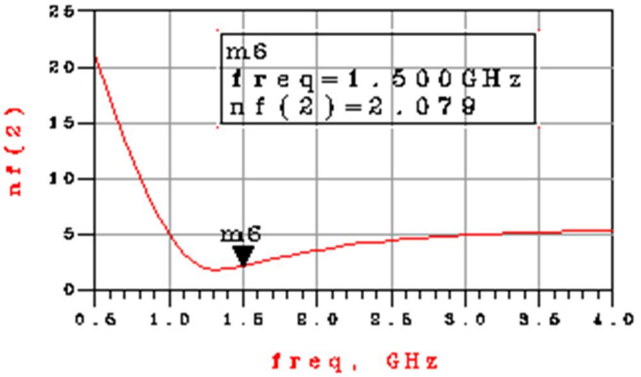

Fig. 3. Noise Figure

3. S-parameters simulation result

The low-voltage low-power CMOS RF LNA shown in Fig. 2 is simulated using the ADS simulation tools. As shown in Fig. 4 at 1.5 GHz frequency the input return loss S_{11} = -12.6 , the output return loss S_{22} = -17 , the reverse isolation S_{12} = -36 .

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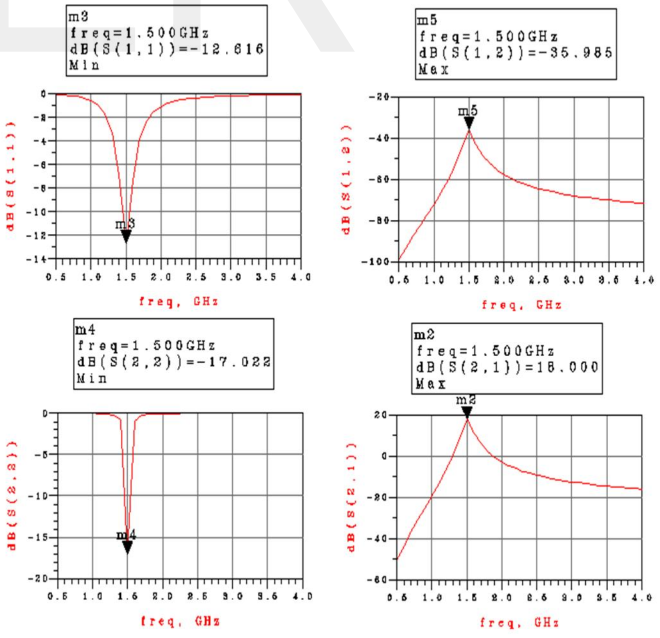

Fig. 4. S-parameter.

3 COMPARISON

Table 1. Comparison of LNA performances

Ref.	Tech. (CMOS) (*µm*)	Freq. (*GHz*)	Supply voltage (*V*)	Gain (*dB*)	NF (*dB*)	Power (*mW*)
[2]	0.25	2	1	25.67	4	5.13
[7]	0.2	1.9	2.25	19.7	2.37	23
[8]	0.18	2	0.29	26.25	2.2	0.96
[9]	0.18	3.1	1.8	14	2.66	23.7
[10]	0.09	58	1.5	14.6	5.5	24
[11]	0.18	2	1.2	14.8	3.1	13.4
[12]	0.09	1.76	2	23	2	2.8
[13]	0.18	5.06	0.7	20.8	3	8
[14]	0.13	2	1.5	14.5	2.6	17.4
[15]	0.18	2.4	5	14.951	1.5	300
[16]	0.09	1.76	2	23	2	5.6
[17]	0.13	2.4	1.2	28	2.2	4.8
[18]	0.18	3	1.8	14.49	1.89	11.7
This paper	0.09	1.5	1	18	2	5.4

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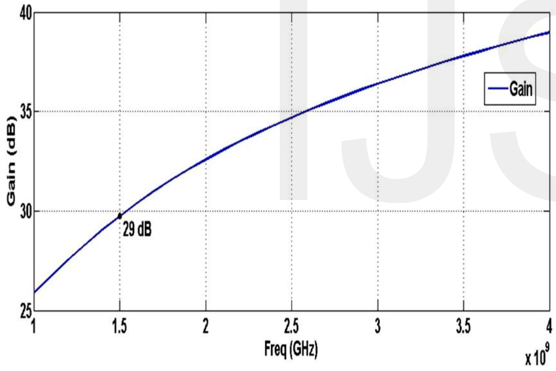

Fig. 5. Gain from Matlab calculations.

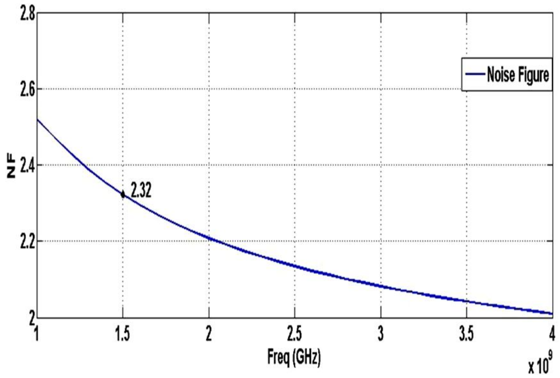

Fig. 6. Noise analysis from Matlab calculations.

4 CONCLUSION

low-voltage CMOS LNA based on a modification done to the traditional cascode LNA was presented. Using cascode elements of the reduction technique based on the two transistors limitation to reduce the supply voltage that leads to reduce the power consumption, which is essential today to increase the battery life time on most applications. The input signal is inserted in the M1 source to take the advantage of the body effect to help increase the conversion gain. The insertion of the capacitor C2 gives another degree of freedom to control the LNA gain. The LNA is simulated in standard 90nm . The LNA presented here is useful in RF signal-processing applications, in the front-end transceiver, WLAN.

The results from calculations is done using Matlab is so close to simulation results.

Comparison of LNA performances is shown in Table 1.

Appendix A

Input Impedance

$$V_{in} = I_{in} sL_g + \frac{I_{in}}{sC_{gs}} + \left(I_{in} + g_m V_{gs1}\right) sL_s \, , V_{gs1} = \frac{I_{in}}{sC_{gs}}$$

$$V_{in} = I_{in}\left(sL_g + sL_s + \frac{1}{sC_{gs}} + \frac{g_m L_s}{C_{gs}}\right)$$

$$Z_{in} = s\left(L_s + L_g\right) + \frac{1}{sC_{gs}} + \left(\frac{g_m L_s}{C_{gs}}\right)$$

To do matching in the input impedance it will be only a real part $Z_{in} = R_s$

$$j\omega\left(L_s + L_g\right) - \frac{j}{\omega C_{gs}} = 0$$

$$\omega\left(L_s + L_g\right) = \frac{1}{\omega C_{gs}}$$

$$\omega^2 = \frac{1}{C_{gs}\left(L_s + L_g\right)}$$

The resonance frequency is

$$\omega_o = \frac{1}{\sqrt{C_{gs}\left(L_s + L_g\right)}}$$

Noise Analysis

neglecting flicker noise, involving source resistance R_s

$$\overline{V_{n_o}^2} = 4KT\gamma g_{m1} R_{out}^2$$

$$\overline{V_{n_i}^2} = 4KTR_s$$

$$Gain = G = G_m R_{out}$$

$$G_m = \frac{i_o}{V_{in}} = \frac{g_{m1} V_{gs}}{V_{in}}$$

$$V_{gs} = \frac{I_{in}}{sC_{gs}}, V_{in} = I_{in}\left(R_s + Z_{in}\right)$$

$$G_m = \frac{g_{m1}\, I_{in}/sC_{gs}}{I_{in}\left(R_s + Z_{in}\right)}$$

$$G_m = \frac{g_{m1}}{sC_{gs}\left[R_s + s\left(L_s + L_g\right) + \frac{1}{sC_{gs}} + \frac{g_{m1}L_s}{C_{gs}}\right]}$$

$$G_m = \frac{g_{m1}}{1 - \omega^2 C_{gs}\left(L_s + L_g\right) + j\omega\left(R_s C_{gs} + g_{m1} L_s\right)}$$

at resonance frequency ω_o, $1 - \omega^2 C_{gs}\left(L_s + L_g\right) = 0$

$$|G_m| = \frac{g_{m1}}{\omega C_{gs}\left(R_s + \frac{g_{m1}L_s}{C_{gs}}\right)}$$

$$|G_m| = \frac{\omega_T}{\omega R_s\left(1 + \frac{\omega_T L_s}{R_s}\right)}$$, where $\omega_T = \frac{g_{m1}}{C_{gs}}$

The Noise Figure $NF = 1 + \frac{\overline{V_{n_o}^2}}{G\overline{V_{n_i}^2}}$

$$\left(\frac{\overline{V_{n_o}^2}}{G\overline{V_{n_i}^2}}\right)^2 = \frac{4KT\gamma g_{m1} R_{out}^2 \omega^2 R_s^2 \left(1 + \frac{\omega_T L_s}{R_s}\right)^2}{4KTR_s R_{out}^2 \omega_T^2}$$

$$\left(\frac{\overline{V_{n_o}^2}}{G\overline{V_{n_i}^2}}\right)^2 = \frac{\gamma g_{m1} \omega^2 R_s \left(1 + \frac{\omega_T L_s}{R_s}\right)^2}{\omega_T^2}$$

$$NF = 1 + \frac{\omega}{\omega_T}\left(1 + \frac{\omega_T L_s}{R_s}\right)\sqrt{\gamma g_{m1} R_s}$$

Appendix B

$$V_{gs1} = V_{bs1}$$

$$V_{gs2} = V_{bs2}$$

$$V_{in} = -V_{gs1}$$

$$A_1 = 1 + r_{o1}\left(g_{m1} + g_{mb1}\right)$$

$$A_2 = 1 + r_{o2}\left(g_{m2} + g_{mb2}\right)$$

$$\frac{1}{Z} = sC_{gs1} + sC_{sb1} + \frac{1}{R_2 + sL_2}$$

$$= \frac{1 + sR_2\left(C_{gs1} + C_{sb1}\right) + s^2\left(C_{gs1}L_2 + C_{sb1}L_2\right)}{R_2 + sL_2}$$

$$Z = \frac{R_2 + sL_2}{1 + sR_2\left(C_{gs1} + C_{sb1}\right) + s^2\left(C_{gs1}L_2 + C_{sb1}L_2\right)}$$

$$\frac{1}{Z_1} = sC_{gd1} + sC_{db1} + \frac{1}{R_1 + s\left(\frac{L_1 L_4 M_1^2}{L_4 - M_1}\right)}$$

$$\frac{1}{Z_1} = sC_{gd1} + sC_{db1} + \frac{\left(L_4 - M_1\right)}{R_1\left(L_4 - M_1\right) + s\left(L_1 L_4 M_1^2\right)}$$

$$\frac{1}{Z_1} = \frac{X_1}{Y_1}$$

$$X_1 = L_4 - M_1 + s\left[R_1\left(C_{gd1} + C_{db1}\right)\left(L_4 - M_1\right)\right]$$

$$+ s^2\left[\left(C_{gd1} + C_{db1}\right)\left(L_1 L_4 - M_1^2\right)\right]$$

$$Y_1 = R_1\left(L_4 - M_1\right) + s\left(L_1 L_4 - M_1^2\right)$$

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$$Z_1 = \frac{Y_1}{X_1}$$

$$\frac{1}{Z_2} = sC_{gs2} + sC_{sb2} + \frac{1}{R_4 + s\left(\frac{L_1L_4 - M_1^2}{L_1 - M_1}\right)}$$

$$Z_2 = \frac{Y_2}{X_2}$$

$$Y_2 = R_4(L_1 - M_1) + s(L_1L_4 - M_1^2)$$

$$X_2 = L_1 - M_1 + s\left[R_4\left(C_{gs2} + C_{sb2}\right)(L_1 - M_1)\right]$$

$$+s^2\left[\left(C_{gs2} + C_{sb2}\right)(L_1L_4 - M_1^2)\right]$$

$$I_{r_{o2}} = \frac{V_{out} + V_{gs2}}{r_{o2}}$$

$$V_{out} = -\left(g_{m2}V_{gs2} + g_{mb2}V_{bs2} + \frac{V_{out} + V_{gs2}}{r_{o2}}\right)(R_3 + sL_3)$$

$$V_{out}\left[1 + \frac{R_3 + sL_3}{r_{o2}}\right]$$

$$= -V_{gs2}\left(g_{m2} + g_{mb2} + \frac{1}{r_{o2}}\right)(R_3 + sL_3)$$

$$V_{out}[r_{o2} + R_3 + sL_3]$$

$$= -V_{gs2}(1 + g_{m2}r_{o2} + g_{mb2}r_{o2})(R_3 + sL_3)$$

$$\frac{V_{out}}{V_{gs2}} = \frac{-A_2(R_3 + sL_3)}{r_{o2} + R_3 + sL_3} \qquad (1)$$

$$V_{out1} = I_3Z_1$$

$$I_3 = I_2 - I$$

$$I = I_{r_{o1}} + g_{m1}V_{gs1} + g_{mb1}V_{bs1}$$

$$I = \frac{V_{out1} + V_{gs1}}{r_{o1}} + g_{m1}V_{gs1} + g_{mb1}V_{gs1}$$

$$I_2 = g_{m2}V_{gs2} + g_{mb2}V_{gs2} + \frac{V_{out} + V_{gs2}}{r_{o2}} + \frac{V_{gs2}}{Z_2}$$

$$I_3 = V_{gs2}\left(g_{m2} + g_{mb2} + \frac{1}{r_{o2}} + \frac{1}{Z_2}\right) + \frac{V_{out}}{r_{o2}}$$

$$-\frac{V_{out1}}{r_{o1}} - V_{gs1}\left(\frac{1}{r_{o1}} + g_{m1} + g_{mb1}\right)$$

from equation (1)

$$V_{out1}\left[1 + \frac{Z_1}{r_{o1}}\right] = \frac{V_{out}Z_1}{r_{o2}}$$

$$+V_{in}Z_1\left(\frac{1}{r_{o1}} + g_{m1} + g_{mb1}\right)$$

$$-V_{out}\frac{(r_{o2} + R_3 + sL_3)Z_1\left(g_{m2} + g_{mb2} + \frac{1}{r_{o2}} + \frac{1}{Z_2}\right)}{A_2(R_3 + sL_3)}$$

$$V_{out1}\left[1 + \frac{Z_1}{r_{o1}}\right]$$

$$= V_{out}\left[\frac{Z_1}{r_{o2}} - \frac{(r_{o2} + R_3 + sL_3)Z_1\left(g_{m2} + g_{mb2} + \frac{1}{r_{o2}} + \frac{1}{Z_2}\right)}{A_2(R_3 + sL_3)}\right]$$

$$+V_{in}Z_1\left(\frac{1}{r_{o1}} + g_{m1} + g_{mb1}\right)$$

$$V_{out1}\left(\frac{1}{Z_1} + \frac{1}{r_{o1}}\right) = V_{out}\left[\frac{1}{r_{o2}} - \frac{(r_{o2} + R_3 + sL_3)\left(A_2 + \frac{r_{o2}}{Z_2}\right)}{r_{o2}A_2(R_3 + sL_3)}\right]$$

$$+V_{in}\frac{A_1}{r_{o1}} \qquad (2)$$

$$V_{in} = \left(g_{m1}V_{gs1} + g_{mb1}V_{bs1} + \frac{V_{out1} - V_{in}}{r_{o1}}\right)$$

$$* \frac{(R_2 + sL_2)}{1 + sR_2\left(C_{gs1} + C_{sb1}\right) + s^2\left(C_{gs1}L_2 + C_{sb1}L_2\right)}$$

$$V_{in}\left[1 + \frac{\left(g_{m1} + g_{mb1} + \frac{1}{r_{o1}}\right)(R_2 + sL_2)}{1 + sR_2\left(C_{gs1} + C_{sb1}\right) + s^2\left(C_{gs1}L_2 + C_{sb1}L_2\right)}\right]$$

$$= V_{in}\left[\frac{r_{o1}\left[1 + sR_2\left(C_{gs1} + C_{sb1}\right) + s^2\left(C_{gs1}L_2 + C_{sb1}L_2\right)\right] + A_1(R_2 + sL_2)}{r_{o1}\left[1 + sR_2\left(C_{gs1} + C_{sb1}\right) + s^2\left(C_{gs1}L_2 + C_{sb1}L_2\right)\right]}\right]$$

$$V_{out1} = V_{in}r_{o1}$$

$$* \left[\frac{\left[1 + sR_2\left(C_{gs1} + C_{sb1}\right) + s^2\left(C_{gs1}L_2 + C_{sb1}L_2\right)\right]}{(R_2 + sL_2)} + \frac{A_1}{r_{o1}}\right] \qquad (3)$$

from equation (3) in equation (2)

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$$V_{out}\left[\frac{A_2(R_3 + sL_3) - (r_{o2} + R_3 + sL_3)\left(A_2 + \frac{r_{o2}}{Z_2}\right)}{r_{o2}A_2(R_3 + sL_3)}\right]$$

$$= V_{in}\left\{1 + \frac{1}{r_{o1}}\right\}$$

$$*\left\{\frac{1 + sR_2\left(C_{gs1} + C_{sb1}\right) + s^2\left(C_{gs1}L_2 + C_{sb1}L_2\right)}{R_2 + sL_2} + \frac{A_1}{r_{o1}}\right\}$$

$$-V_{in} * \frac{A_1}{r_{o1}}$$

$$A_v = \frac{V_{out}}{V_{in}} = A_1 * A_2$$

$$A_1 = \frac{a_2s^4 + b_2s^3 + c_2s^2 + d_2s + e_2}{f_2s^2 + g_2s + h_2}$$

$$A_2 = \frac{f_1s^2 + g_1s + h_1}{a_1s^3 + b_1s^2 + c_1s + d_1}$$

$$A_v = \frac{\alpha}{\beta}$$

$$\alpha = s^6a_2f_1 + s^5(a_2g_1 + f_1b_2) + s^4(a_2h_1 + b_2g_1 + c_2f_1)$$

$$+s^3(d_2f_1 + b_2h_1 + c_2g_1) + s^2(h_1 + g_1d_2 + h_1c_2)$$

$$+s(g_1e_2 + h_1d_2) + h_1e_2$$

$$\beta = s^5a_1f_2 + s^4(b_1f_2 + a_1g_2) + s^3(c_1f_2 + b_1g_2 + a_1h_2)$$

$$+s^2(d_1f_2 + c_1g_2 + b_1h_2) + s(d_1g_2 + c_1h_2) + d_1h_2$$

Notes:

$$a_1 = L_3r_{o2}(L_1L_4 - M_1^2)\left(C_{gs2} + C_{sb2}\right)$$

$$b_1 = r_{o2}^2\left(C_{gs2} + C_{sb2}\right)(L_1L_4 - M_1^2)$$

$$+L_3r_{o2}R_4\left(C_{gs2} + C_{gb2}\right)(L_1 - M_1)$$

$$+r_{o2}R_3\left(C_{gs2} + C_{sb2}\right)(L_1L_4 - M_1^2)$$

$$c_1 = A_2r_{o2}(L_1L_4 - M_1^2) + r_{o2}^2R_4\left(C_{gs2} + C_{sb2}\right)(L_1 - M_1)$$

$$+r_{o2}R_3R_4\left(C_{gs2} + C_{sb2}\right)(L_1 - M_1) + r_{o2}L_3(L_1 - M_1)$$

$$d_1 = R_4A_2r_{o2}(L_1 - M_1) + r_{o2}^2(L_1 - M_1) + r_{o2}R_3(L_1 - M_1)$$

$$f_1 = r_{o2}A_2L_3(L_1L_4 - M_1^2)$$

$$g_1 = r_{o2}R_3A_2(L_1L_4 - M_1^2) + r_{o2}A_2L_3R_1(L_1 - M_1)$$

$$h_1 = r_{o2}A_2R_3R_1(L_1 - M_1)$$

$$a_2 = r_{o1}^2L_2(L_1L_4 - M_1^2)\left(C_{gs1} + C_{db1}\right)\left(C_{sb1} + C_{gs1}\right)$$

$$b_2 = r_{o1}^2R_2(L_1L_4 - M_1^2)\left(C_{gs1} + C_{db1}\right)\left(C_{sb1} + C_{gs1}\right)$$

$$+L_2r_{o1}(L_1L_4 - M_1^2)\left(C_{sb1} + C_{gs1}\right)$$

$$+r_{o1}^2\mathrm{L_2R_1(L_4 - M_1)}\left(C_{gs1} + C_{db1}\right)\left(C_{sb1} + C_{gs1}\right)$$

$$+A_1r_{o1}L_2(L_1L_4 - M_1^2)\left(C_{db1} + C_{gs1}\right)$$

$$c_2 = r_{o1}^2(L_1L_4 - M_1^2)\left(C_{db1} + C_{gs1}\right)$$

$$+r_{o1}R_2(L_1L_4 - M_1^2)\left(C_{sb1} + C_{gs1}\right)$$

$$+r_{o1}^2R_1R_2(\mathrm{L_4 - M_1})\left(C_{gs1} + C_{db1}\right)\left(C_{sb1} + C_{gs1}\right)$$

$$+r_{o1}L_2R_1(\mathrm{L_4 - M_1})\left(C_{sb1} + C_{gs1}\right)$$

$$+r_{o1}^2L_2(\mathrm{L_4 - M_1})\left(C_{sb1} + C_{gs1}\right)$$

$$+r_{o1}R_2(L_1L_4 - M_1^2)\left(C_{db1} + C_{gs1}\right) + L_2A_1(L_1L_4 - M_1^2)$$

$$+r_{o1}L_2R_1A_1(\mathrm{L_4 - M_1})\left(C_{db1} + C_{gs1}\right)$$

$$d_2 = r_{o1}(L_1L_4 - M_1^2) + r_{o1}^2R_1(\mathrm{L_4 - M_1})\left(C_{db1} + C_{gs1}\right)$$

$$+r_{o1}R_1R_2(\mathrm{L_4 - M_1})\left(C_{sb1} + C_{gs1}\right)$$

$$+r_{o1}^2R_2(\mathrm{L_4 - M_1})\left(C_{sb1} + C_{gs1}\right) + A_1R_2(L_1L_4 - M_1^2)$$

$$+r_{o1}A_1R_1R_2(\mathrm{L_4 - M_1})\left(C_{db1} + C_{gs1}\right) + L_2A_1R_1(\mathrm{L_4 - M_1})$$

$$+\mathrm{r_{o1}L_2A_1(L_4 - M_1)}$$

$$e_2 = R_1r_{o1}(\mathrm{L_4 - M_1}) + \mathrm{r_{o1}^2(L_4 - M_1) + A_1R_1R_2(L_4 - M_1)}$$

$$+\mathrm{A_1R_2r_{o1}(L_4 - M_1)} - \frac{\mathrm{A_1}}{\mathrm{r_{o1}}}$$

$$\mathrm{f_2} = L_2r_{o1}(L_1L_4 - M_1^2)$$

$$g_2 = r_{o1}R_2(L_1L_4 - M_1^2) + R_1L_2r_{o1}(\mathrm{L_4 - M_1})$$

$$\mathrm{h_2 = r_{o1}R_2R_1(L_4 - M_1)}$$

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