

Development of Accurate BSIM4 Noise Parameters for CMOS 0.13- μm Transistors in Below 3-GHz LNA Application

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ABSTRACT

Accurate transistor thermal noise model is crucial in IC design as it allows accurate selection of transistors for specific frequency application. The accuracy of the model is represented by the similarity between the simulated and the measured noise parameters (NPs). This work was based on a problem faced by a foundry concerning the dissimilarities between the measured and simulated NPs, especially minimum noise figure (NF_{\min}) for frequencies below 3 GHz. Hence, this work looks into the BSIM4 charge-based (TNOIMOD 0) and holistic (TNOIMOD 1) thermal noise models of a 0.13- μm CMOS device to determine the most accurate settings between them. As such, both the simulated and measured data for the transistors were retrieved from four NPs; NF_{\min} , noise resistance (R_N), $|\Gamma_{\text{opt}}|$ and $\Gamma_{\text{opt}}^\circ$. The findings exhibit optimum parameters for the TNOIMOD 1 at $TNOIA=1.5$, $TNOIB=3.5$, $RNOIB=0.5164$ and $RNOIA = 1.477$ for best NF_{\min} and $\Gamma_{\text{opt}}^\circ$, and $RNOIA = 0.577$ for best $|\Gamma_{\text{opt}}|$ and R_N . Meanwhile, as for the TNOIMOD 0, the proposed setting is $NTNOI=5$ (above 4 GHz), $NTNOI=10$ (below 3 GHz), and either 5 or 10 for 3 to 4 GHz. On top of that, the noise figure (NF) performance of a low-noise amplifier (LNA) was chosen to verify the transistor's new NP settings. As a result, it was found that for application below 3 GHz, the TNOIMOD 0 at $NTNOI=10$ supersedes the accuracy of the TNOIMOD 1.

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1. INTRODUCTION

For any semiconductor foundry, it is of utmost importance to provide transistors with accurate noise models to allow accurate selection of transistors during integrated circuit (IC) design. The accuracy of the noise model is assessed by the closeness of the measured with the simulated noise parameters (NPs). In this work, the problem statement is concerning an issue highlighted by a semiconductor foundry on the inaccuracy between the measured and simulated minimum noise figure (NF_{\min}) of an existing 0.13- μm CMOS RF device for below 3 GHz frequency region. Hence, this work was focused on the BSIM4 noise modeling of the mentioned 0.13- μm CMOS RF device.

Two modes of the BSIM4 thermal noise model had been employed in this work, which were the TNOIMOD 0 and TNOIMOD 1 [1], [2]. With that, in order to provide a more accurate transistor model device, an LNA design was selected as the test circuit to verify the new noise model.

In this work, the data had been obtained from both simulation and measurement for four noise parameters, such as NF_{min} , noise resistance (R_N), gamma optimum in magnitude ($|\Gamma_{opt}|$) and gamma optimum in phase (Γ_{opt}°) [3],[4],[5], for frequencies between 1 GHz to 10 GHz. Next, the measured and the simulation results were compared and as such, suggestions are offered based on the comparisons made on the noise parameters, which had been set based on frequency application. This exemplifies the most accurate noise model for the particular frequency application. The accuracy of the new noise parameters were later tested on an inter-stage LNA. The LNA was tested with varied settings at both TNOIMOD 0 and TNOIMOD 1.

This paper is outlined as follows: Section 1 is on the introduction to the study described in this paper. Next, Section 2 elaborates in detail the theory of the two BSIM4 thermal noise models applied in this study. After that, the methodology employed in this study is explained in section 3, while the results and discussion are elaborated in section 4. Finally, the conclusion is depicted in section 5.

2. THEORETICAL BACKGROUND

This section explains in detail the two BSIM4 thermal noise models highlighted in this study. Moreover, relevant equations pertaining to the significant noise parameters in these models are described.

2.1. Charge Based Thermal Noise Model (TNOIMOD 0)

The noise current is given by [1], [2], [6], [7], [8];

$$i_d^2 = \frac{4k_B T \Delta f}{R_{ds}(V) + \frac{L_{eff}^2}{\mu_{eff} |Q_{inv}|}} \cdot NTNOI \quad (1)$$

where $R_{ds}(V)$ is the bias-dependent lightly doped drain (LDD) source to drain resistance, k_B is the Boltzman's constant ($k_B = 1.38 \times 10^{-23} \text{J/K}$), T is the thermal temperature, Δf is the frequency difference, L_{eff} is the effective length of transistor, μ_{eff} is the effective mobility, Q_{inv} is the quality factor of the input stage, and the parameter NTNOI is introduced for more accurate fitting of short-channel devices.

2.2. Holistic Thermal Noise Model (TNOIMOD 1)

In this thermal noise model, all the short-channel effects and velocity saturation effect are considered. Hence, it is named as "Holistic Thermal Noise Model".

The noise voltage source partitioned to the source side is given by [9], [10],

$$v_D^2 = 4k_B T \cdot \theta_{tnoi}^2 \cdot \frac{V_{dseff} \Delta f}{I_{ds}} \quad (2)$$

$$F = F_{min} + \frac{R_N}{G_s} \left[(G_s - G_{opt})^2 + (B_s - B_{opt})^2 \right] \quad (3)$$

where, v_D^2 is the noise voltage, θ_{tnoi} is one of the TNOIMOD parameters, V_{dseff} is the source-drain effective voltage, I_{ds} is the source-drain current, F is the noise factor, F_{min} is the minimum noise factor, G_{opt} is the optimum conductance, G_s is the source conductance, B_{opt} is the optimum susceptance and B_s is the source susceptance. In addition, gamma optimum, $\Gamma_{opt} = G_{opt} + jB_{opt}$ and gamma source, $\Gamma_s = G_s + jB_s$. Equation (3) indicates that the most influential parameter of F is F_{min} .

Both noise parameters, i.e. minimum noise figure, NF_{min} , and R_N , are derived below to comprehend the effects upon holistic thermal noise [11], [12],

$$NF_{min} = 1 + 2R_N (\Gamma_{opt} + \Gamma_s) \quad (4)$$

$$R_N = \left| -\frac{1}{G_m} \right|^2 \frac{i_d^2}{4k_B T \Delta f} \quad (5)$$

Where, Γ_{opt} and Γ_s are the ratio of the incident to the reflected wave along a transmission line, and G_m is transconductance. Substituting equation (5) into equation (4), we have;

$$NF_{min} = 1 + 2 \left| -\frac{1}{G_m} \right|^2 \frac{i_d^2}{4k_B T \Delta f} (\Gamma_{opt} + \Gamma_s) \tag{6}$$

Equation (6) shows that NF_{min} is directly proportional to i_d^2 . Meanwhile, Equation (2) can be simplified and expressed in terms of R_N as [13],

$$v_D^2 = 4k_B TR_N \Delta f \tag{7}$$

Hence, it is noted that v_D^2 is directly proportional to R_N . On the other hand, the noise current is expressed as,

$$\overline{i_d^2} = 4K_B T \frac{V_{dseff} \Delta f}{I_{ds}} [G_{ds} + \beta_{tnoi} (G_m + G_{mbs})]^2 - \overline{v_d^2} (G_m + G_{ds} + G_{mbs})^2 \tag{8}$$

where, β_{tnoi} is one of the TNOIMOD 1 parameters, G_{ds} is drain to source conductance and G_{mbs} is the body to source tranconductance. To determine v_D^2 in Equation (2) and i_D^2 in Equation (8), the following parameters are defined as [1],

$$\theta_{tnoi} = RNOIB \cdot \left[1 + TNOIB \cdot L_{eff} \cdot \left(\frac{V_{gsteff}}{E_{sat} L_{eff}} \right)^2 \right] \tag{9}$$

and

$$\beta_{tnoi} = RNOIA \cdot \left[1 + TNOIA \cdot L_{eff} \cdot \left(\frac{V_{gsteff}}{E_{sat} L_{eff}} \right)^2 \right] \tag{10}$$

where, V_{gsteff} is the gate-source effective threshold voltage, E_{sat} is the critical electrical field. β_{tnoi} is one of the TNOIMOD 1 parameters while RNOIA and RNOIB are model parameters with the default values of 0.577 and 0.5164, respectively. These default values for the model parameters were set by the foundry.

2.3 Low-Noise Amplifier (LNA)

LNA is a type of amplifier that is extremely sensitive to noise (as indicated vividly in its name – ‘‘Low Noise Amplifier’’). In fact, one of the most important performance metric of the LNA is the NF [14]. Thus, the LNA had been opted as the test circuit to verify the new noise model.

As a test circuit, a simple LNA will be favorable. If a more complex circuit is chosen, it would mean the effects of parasitic and integrated components might influence the NF performance more rather than the transistor’s noise model. Hence, the chosen LNA for this work has a dual-stage topology [15], [16], [17] as shown in Figure 1.

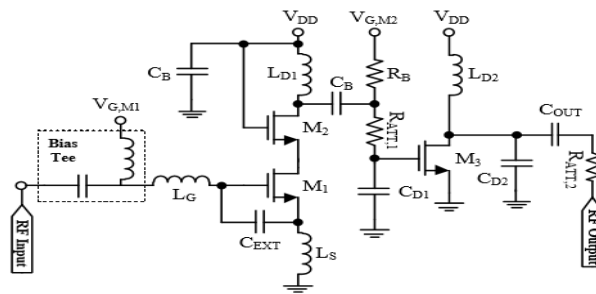


Figure 1. Schematic of a dual-stage narrowband LNA. [15], [16], [17]

3. METHODOLOGY

For TNOIMOD 0, the default value for NTNOI was 5, while in TNOIMOD 1, the default value for the parameters were TNOIA = 1.5, TNOIB = 3.5, RNOIA = 0.577, and RNOIB = 0.5164. The default values were obtained from the foundry. In this work, these parameters were varied to obtain optimum settings.

3.1 BSIM4 Thermal Noise Model

CMOS 0.13- μm transistors (DUT) were fabricated and characterized. Next, the NPs obtained from the measured DUT were compared to the NPs obtained from the HSPICE simulation using the BSIM4 TNOIMOD 0 and TNOIMOD 1 thermal noise models. This comparison will determine which noise model is more accurate in modeling the transistor.

3.2 Low Noise Amplifier

Figure 2 shows the layout of the dual-stage narrowband LNA that was fabricated and used as the test circuit to verify the accuracy of the TNOIMOD 0 and TNOIMOD 1 thermal noise models in modeling the transistors.

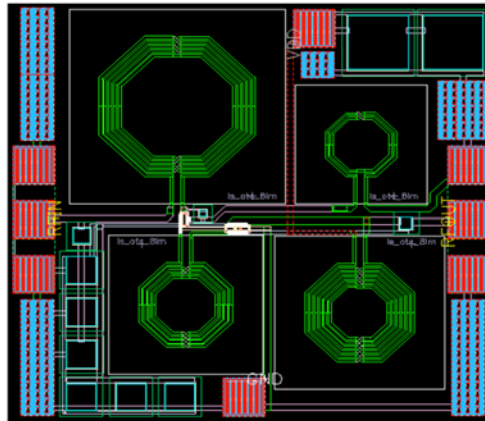


Figure 2. The layout of the dual-stage narrowband LNA used in this work

4. RESULTS AND DISCUSSION

Section 4.1 describes the results obtained for all NPs under varied parameters for TNOIMOD 0 and TNOIMOD 1. Section 4.2 displays the results achieved for NF_{\min} and NF for the inter-stage LNA under varied NTNOI for TNOIMOD 0 and the results achieved for NF under varied RNOIA for TNOIMOD 1.

4.1 BSIM4 Thermal Noise Model

This section show and describe the results when the device was under different NTNOI for the TNOIMOD 0 thermal noise model. The NTNOI was varied at 1, 5, 10 and 15. For the TNOIMOD 1, the RNOIA was varied while the other three parameters were at their default values.

4.1.1 Noise parameters obtained for TNOIMOD = 0 under various conditions

Figure 3 shows the results retrieved from the four noise parameters that had been set at varied NTNOI, i.e. NTNOI 1, 5, 10 and 15. The graphs plotted point out the variances between the simulated and the measured results. Observation recorded from Figure 3 are as follows:

- (i) As the NTNOI increases, NF_{\min} , R_N , and $|\Gamma_{\text{opt}}|$ increase as well. $\Gamma_{\text{opt}}^{\circ}$ does show similar trend but at NTNOI = 5, 10 and 15, the difference is insignificant.
- (ii) Simulated R_N and $|\Gamma_{\text{opt}}|$ at NTNOI = 1, offer near similar values to those of measured data.
- (iii) NF_{\min} simulated results are closest to the measured results when NTNOI = 5 (for frequencies exceeding 4 GHz) and NTNOI = 10 for frequencies below 3 GHz.
- (iv) $\Gamma_{\text{opt}}^{\circ}$ at NTNOI = 5, 10 and 15 display 64% to 79% of the measured value while $\Gamma_{\text{opt}}^{\circ}$ at NTNOI = 1 is showing 54% to 75% of the measured value.
- (v) Figure 3, in general, portrays that the best value to set the parameters under TNOIMOD = 0 for 2-3 GHz operation is NTNOI = 10. Although NTNOI = 1 shows better results for R_N and $|\Gamma_{\text{opt}}|$, the NF_{\min} is the parameter that mostly affected the NF . At NTNOI = 10, NF_{\min} displays the closest results to those of measured at this frequency range.
- (vi) In general, NTNOI should be set at 5 for frequencies above 4 GHz and at 10 for frequencies below 3 GHz. As for 3 to 4 GHz frequency range, the NTNOI can be set at either 5 or 10.

4.1.2 Noise parameters obtained for TNOIMOD = 1 under various conditions.

For this experiment, it was found that the variation of TNOIA, TNOIB and RNOIB did not make significant changes to the NPs. The graphs showing these results are not included here due to the page limitation. The variation in RNOIA, on the other hand, did show some changes to the NPs.

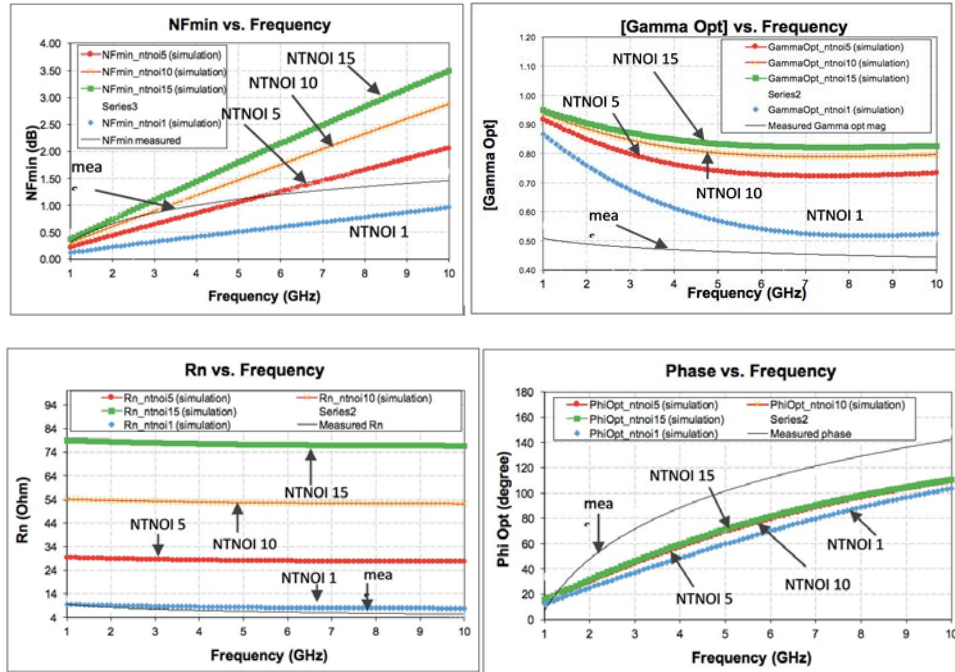


Figure 3. Simulation vs measured results for all noise parameters when NTNOI is varied for TNOIMOD = 0

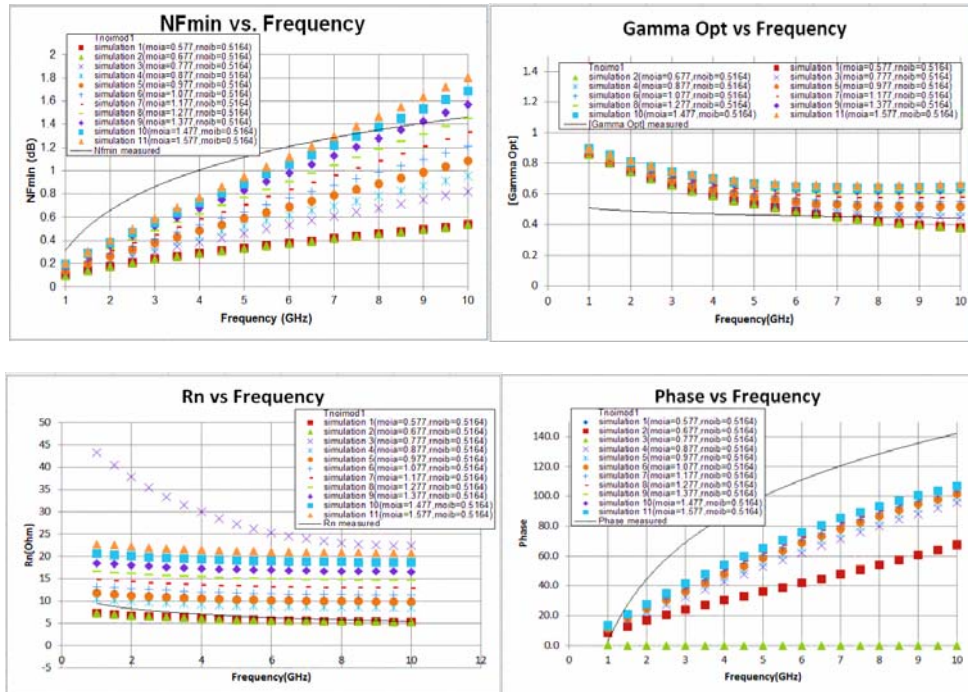


Figure 4. Results from simulation and measurement when TNOIMOD = 1, with RNOIA varied and TNOIA, TNOIB and RNOIB remained constant at their default values

Figure 4 displays the noise parameters for BSIM4 CMOS transistor, when only RNOIA was varied and the other parameters' settings were made constant at their default values. RNOIA was varied from 0.577 to 1.577.

For NF_{min} , the increase in RNOIA had increased NFmin. When RNOIA = 1.477 and 1.577, the NF_{min} had been closest to the measured data.

For $|\Gamma_{opt}|$, the RNOIA at 0.577 or 0.677 was the nearest to the measured data at frequency below 7 GHz. Meanwhile at frequency above 7 GHz, RNOIA at 0.877 gave the closest display.

As for parameter R_N , increment in RNOIA had increased the R_N and moved it further up away from the measured data. As an example, for RNOIA = 1.477, R_N was 20 Ω as compared to the measured 8 Ω at frequency 2 GHz.

For Γ_{opt}° , the increase in RNOIA will increase the phase and moved it closer to the measured results. The RNOIA at 1.377 to 1.577 had been the nearest to the measured data.

From the above mentioned results and observations, the most accurate RNOIA settings for the specific NP are as follows:- NF_{min} : RNOIA = 1.577 (< 7 GHz) and 1.477 (> 7 GHz), $|\Gamma_{opt}|$: RNOIA = 0.577 or 0.677 (< 7 GHz) and 0.877 (> 7 GHz), R_N : RNOIA = 0.577 and Γ_{opt}° : RNOIA = 1.377 to 1.577. However, for practicality and to be implemented during IC simulation, RNOIA can be set at 1.477 for most accurate NF_{min} and Γ_{opt}° and at 0.577 for most accurate $|\Gamma_{opt}|$ and R_N . For circuit like LNA, the design might be targeting for very good NF performance and thus, the accuracy of the NF_{min} becomes critical. This has been highlighted by equation (3). For such a design, RNOIA can be set at 1.477.

4.2 Low Noise Amplifier

The dual-stage LNA, designed for operation at 2.5 GHz, was simulated with variation in the BSIM4 thermal noise model parameters. Initially, TNOIMOD 0 was used with NTNOI varied at 1, 5, 10 and 15. The evaluated NF and NF_{min} are illustrated in Figure 5.

- (i) The simulated NF at NTNOI = 10 is very close to the measured NF for frequencies between 1 to 3 GHz. This corresponds well with the observation in 4.1.1.
- (ii) As NTNOI increases, both NF and NF_{min} display increment as well.
- (iii) The LNA was designed for a 2.5 GHz operation, explaining the closest resemblance between the simulated NF and NF_{min} (at NTNOI = 10) with the measured data at this frequency.

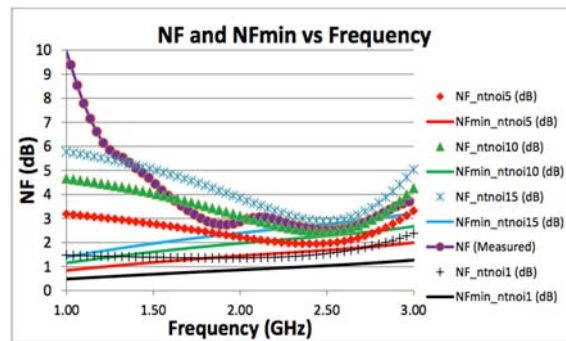


Figure 5. NF and NF_{min} of the dual-stage LNA at varied NTNOI values, in comparison to those obtained from measurement

Figure 6 shows the NF trend when TNOIMOD 1 was applied. With reference to Figure 4, there is no RNOIA that can provide closest simulation to measured data for all NPs. No doubt that the closest to measured NF_{min} data was generated by RNOIA = 1.477 or 1.577, but these values were also the ones that gave the furthest from the measured R_N . Due to this, in order to compare the LNA's measured versus simulated NF, RNOIA = 1.177 was chosen as it shows moderate performance for the NF_{min} and R_N . Besides RNOIA = 1.177, the NF of the LNA was also simulated at RNOIA = 0.577, i.e. the default value.

At RNOIA = 1.177 and other parameters at their default values (i.e. TNOIA = 1.5, TNOIB = 3.5, RNOIB = 0.5164), the simulated data gave the results closest to the measured data. On the other hand, when all parameters were set at their default values (i.e. RNOIA = 0.577), the results showed that the simulated data gave the results furthest away from the measured data. These findings confirm that the higher the RNOIA, the closer is the simulated to the measured NF. Referring to Figure 4, where increment of RNOIA

had also increased NF_{min} (moving closer to measured data) and increased R_N (moving further away from measured data), these findings also prove that the NF_{min} affects NF more than R_N .

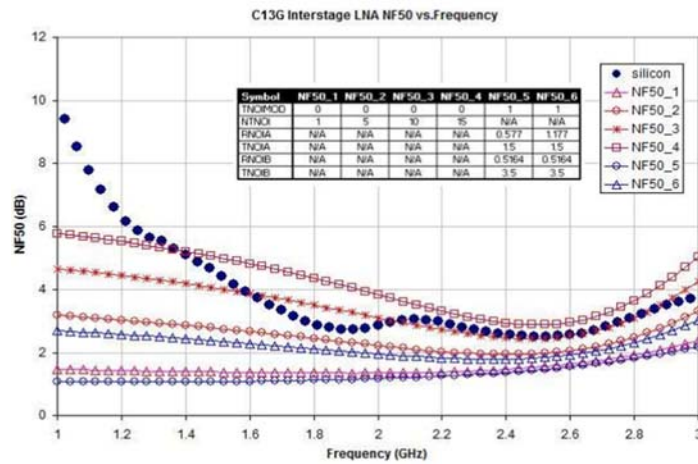


Figure 6. NF of the dual-stage LNA at varied TNOIMOD 0 and TNOIMOD 1 parameters compared with those of measurement

5. CONCLUSION

As a conclusion, the findings obtained from the simulation of thermal BSIM4 noise model portray changes with variation in the noise parameters. For instance, as for $TNOIMOD = 0$, the value of $NTNOI$ should be set at value 5 for application of frequency above 4 GHz and value 10 for application of frequency below 3 GHz. It is also suggested that the best values to set the parameters for $TNOIMOD = 1$ are $TNOIA = 1.5$, $TNOIB = 3.5$, $RNOIB = 0.5164$ and $RNOIA = 1.477$ for most accurate NF_{min} , $RNOIA = 0.577$ for most accurate $|\Gamma_{opt}|$, $RNOIA = 0.577$ for most accurate R_N and $RNOIA = 1.477$ for most accurate Γ_{opt}° . Hence, the choice of $RNOIA$ will be based on the application and focus of the designed circuit utilizing the device. For the design and simulation of circuits like the LNA where NF might be the focused metric, the IC designer might want to set the $RNOIA$ to 1.477 since NF_{min} will be the most affecting parameter.

Other than that, the dual-stage LNA, which had been selected to test the new noise model settings for $TNOIMOD 0$ and $TNOIMOD 1$, confirmed that the performance exerted by the NF was indeed the most accurate, when the parameters were set at the suggested values. It was also found that for applications below 3 GHz, $TNOIMOD 0$ at $NTNOI = 10$ had been the closest to the NF measured data, in comparison to $TNOIMOD 1$ with the suggested parameter values. This might be insinuating that the holistic model is overestimating the thermal noise of the device.

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