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Fully Balanced 60 GHz LNA with 37 % Bandwidth, 3.8 dB NF, 10 dB Gain and Constant Group Delay over 6 GHz Bandwidth

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Abstract — This paper presents a two-stage fully integrated 60 GHz differential Low Noise Amplifier implemented in a TSMC bulk CMOS 65 nm technology. Implementation of a voltage-voltage feedback enables the neutralization of the Miller capacitance and the achievement of flat gain with a deviation of ± 0.25 dB over the entire 6 GHz bandwidth. It features a transducer gain (Gt) of 10 dB along with a noise figure (NF) of 3.8 dB, NFmin of 3.7 dB and a constant delay time. IIP3 is 4 dBm. It consumes 35 mW from a 1.2 V supply and only occupies 330 x 170 µm.

Index Terms — Millimeter wave amplifiers, transformers, broadband amplifiers, CMOS analog integrated circuits, 60 GHz, LNA.

I. INTRODUCTION

The market demand for RF transceivers providing communication links of several Gb/s data rate motivates the use of the broadband WPAN ISM band at 60 GHz. These systems require receivers with a low noise figure (NF) and flat band response because of the complex modulation scheme. Combination of low NF, sufficient bandwidth, high gain and low voltage operation are important properties of LNAs.

The design of mm-wave LNAs in CMOS causes many challenges because of lossy passives and the Miller capacitance. Several LNAs have been reported in recent years [5]-[9]. To defeat the loss in the passives, SOI technology [6] has been used and in order to neutralize the Miller capacitance, cascode has been applied [7], [9].

This paper describes a fully differential 60 GHz LNA (Fig. 1) in bulk CMOS employing transformer feedback resulting in a flat and broadband response. Miller effect is defeated using gate-drain capacitance neutralization [1], which is achieved when the following equation is satisfied (n is the transformer turn ratio and k is its coupling factor):\

\[
\frac{n}{k} = -\frac{C_{gs}}{C_{gd}}, \quad n = \sqrt{\frac{L_t}{L_s}}
\]

The circuit design procedure and the transformer design are discussed in section II and III. Section IV discusses the layout. The simulation results pre and post layout are shown in section V and section VI shows the measurement and verification results. In section VII the presented LNA is benchmarked against 60 GHz LNAs found in literature.

II. DESIGN PROCEDURE

Main design goal for the LNA is low NF combined with a high gain. Both are a function of MOS transistor bias and width, passives choices, and source impedance Zsrc. The MOS transistor bias was chosen as a compromise between noise and gain performance. The small signal circuit is shown in Fig. 2.

A. Transformer Specifications and Voltage Gain

To achieve Cgs neutralization, the transformer turn ratio n divided by the coupling factor k should be equal to the ratio between Cgd and Cgs with a negative sign (1), which is approximately 2.3 in the used technology.

To maximize gain, the turn ratio should be as high as possible and Ls should resonate with (n²Cgs + Cgd) to tune out these parasitic capacitances. The former leads along with (1) to a high |k| (which is ±1 at maximum), and the latter sets the inductance value for the inductors used in the transformer. The resulting voltage gain then converges to n. Given a certain MOS transistor width at the chosen bias the transformer properties are thereby known.
B. Input Impedance

The input impedance with $k \approx -1$ is shown in (2):

$$Z_{in} = 2 \left( R_g + \frac{1}{j \omega C_{gs} (1+n)} + j \omega L_g \right)$$  \hspace{1cm} (2)

To create a resistive input impedance, $L_g$ is chosen to resonate with $(1+n)C_{gs}$. This also maximizes the gain.

C. Noise Figure

The calculated noise factor $F$ is given below, in which $\gamma$ is a process dependent variable:

$$F \approx 1 + 2 \frac{R_g}{R_{src}} + \frac{2 \gamma^2 g_m}{R_{src}} \left( \frac{\omega^2}{(1+n) \omega^2} + \frac{j \omega}{\omega} \right) + \frac{1}{g_m} - \frac{j \omega}{g_m (1+n) \omega^2}$$

Approximated as:

$$F \approx 1 + 2 \frac{R_g}{R_{src}} + \frac{2 \gamma^2 g_m}{R_{src}} \left( \frac{\omega^2}{(1+n) \omega^2} + \frac{j \omega}{\omega} \right) + \frac{1}{g_m}$$

$L_{g,opt,NF}$ and $R_{src,opt,NF}$ are, after differentiating (3):

$$\frac{\partial F}{\partial L_g} = 0 \Rightarrow L_{g,opt,NF} = \frac{1}{\omega} \left( \frac{1}{g_m} + \frac{1}{g_m} \right)$$  \hspace{1cm} (4)

$$\frac{\partial F}{\partial R_{src}} = 0 \Rightarrow R_{src,opt,NF} = \sqrt{\frac{R_g}{\gamma g_m}}$$  \hspace{1cm} (5)

Combining equations (2), (4) and (1) with $k \approx -1$ it is seen that $X_{src,opt,NF} = X_m = 0$ can be created at the center frequency resulting in low NF and high $G_t$. Comparing equations (2) and (5) it follows $R_{src,opt,NF} \neq R_m$ so a tradeoff is made between NF and $G_t$. Two stages were cascaded. The $F_{min}$ of the LNA is equal to:

$$F_{min} = 1 + \frac{2 \gamma g_m}{\theta_k} \sqrt{R \gamma g_m}, \text{at } 60\text{GHz} \rightarrow 1 + \sqrt{R \gamma g_m}$$  \hspace{1cm} (6)

III. TRANSFORMER DESIGN

The transformer used in the LNA was constructed using EM simulation software (ADS Momentum). The resulting structure is shown in Fig. 3. The transformer has been optimized to have high $|k|$ and high Q-factor inductors [4]. To satisfy equation (1) a turn ratio $n$ of 1.8 has been chosen along with a coupling factor $k$ of -0.76.

The simulated Q-factors of the inductors are higher than 10 at the frequency of interest. Simulated values for $L_d$ and $L_s$ are respectively 137 pH and 42 pH. A patterned shield has been placed underneath the transformers to reduce substrate coupling.

IV. LAYOUT

In Fig. 4 the layout of the core of the LNA is shown. At the left the differential input of the first stage is shown and at the right the differential output of the second stage. The two stages are connected to each other with a DC-blocking capacitor between the output of TF1 and the input of $L_g2$. All RF interconnects longer than 10µm used were simulated in ADS Momentum and Cadence RC-extraction was used for all other structures. $L_{d1}$ and $L_{d2}$ are approximately 110 pH and 150 pH respectively.

The transistors are indicated in Fig. 4 and are situated underneath the metal lines connecting the transformer structures. Transistor width stage 1 is 35 µm and stage 2 is 25 µm. The vertical lines surrounding the transformers...
are the DC power lines and biasing of the LNA. Coplanar waveguides with shielding have been used to connect the different components to each other. This results in low coupling to the substrate and between components.

The input and output of the LNA are connected to bondpads using CPWs (see Fig. 5). This results in losses and an impedance shift. The resulting source and load impedance of the circuit at the input and output indicated in Fig. 4 is approximately \(37 + j10\ \Omega\). Open-short-load structures are added to de-embed the circuit. A lot of effort has been put into making the design as symmetrical as possible to reduce common mode.

V. SIMULATION RESULTS

The design consisted of an iterative process between circuit simulations, EM simulations and RC-extraction. After the first circuit simulation a \(G_t\) of 13 dB with a NF of 3.1 dB was simulated at 61 GHz. The IIP3 of the LNA was approximately 2.6 dBm with a 1 dBc of -11.8 dBm.

After EM-simulation and RC-extraction the performance changed due to the parasitic effects. \(G_t\) decreased by 2.3 dB to 10.7 dB and the NF increased by 0.5 dB to 3.6 dB. These simulation results are shown in Fig. 6. The IIP3 increased to 4 dBm and the 1 dB compression point increased to -9.8 dBm. The simulated \(G_t\) variation in the band of interest is smaller than ± 0.15 dB and the 3 dB bandwidth is approximately 50 - 73 GHz which is approximately 37 % of the center frequency at 61 GHz. The simulated power consumption is 35 mW at 1.2 V supply and 0.8 V gate bias.

All simulations were performed using a source impedance of 30 \(\Omega\), which was chosen as a compromise between NF and \(G_t\), see Fig. 7. This is not equal to the conventional 100 \(\Omega\) for a differential topology. This is because the antenna could be connected directly to the LNA, allowing a different antenna (source) impedance.

VI. MEASUREMENTS AND VERIFICATIONS

To verify the behavior of the LNA a number of measurements were performed using a differential measurement setup. DC power consumption is seen to be equal to the simulated value of 35 mW. The NF and s-parameters are verified independently by the Technical University Eindhoven and NXP Research.

A. S-Parameters

The S-parameters were measured using Agilent E8361A PNA. Calibration was verified using WinCal XE software. After de-embedding the measured \(G_t\) with \(Z_{src} = 30\ \Omega\) is 10 dB at 61 GHz (Fig. 6). The measured in-band deviation is ± 0.25 dB. The \(s_{12}\)-parameter is below -47 dB over the entire measured band of 55 - 67 GHz and the group delay is \(\approx 20\ \text{ps}\) and behaves constant over the band of interest. The differential stability factor (K-factor) stays above 30 in the measured band.

In common mode, the maximum transducer gain is equal to -2 dB resulting in a CMRR of 12 dB. The \(s_{12}\)-parameter is below -42 dB, and K-factor stays above 70 in this case.

Fig. 6. Measured and simulated performance (post layout).
B. Noise Figure

NF was measured in the band 59.5 – 66 GHz (Fig. 6). $Z_{src}$ during this measurement is equal to $37 + j10 \, \Omega$, while the input reflection coefficient for the noise source stays below -15 dB. The average measured value in this band is equal to 3.8 dB. To the author’s knowledge this is the lowest value found in literature around 60 GHz. NF$_{\text{min}}$ of the circuit is found to be 3.7 dB using a load-pull setup in NXP. During this measurement the source impedance for NF$_{\text{min}}$ was also verified with the simulated value.

C. Large Signal Measurements

The measured IIP$_3$ is equal to 5 dBm at 57.5 GHz and 4 dBm at 60 GHz which is in close agreement with the simulation. Measured 1 dBc is -4.6 dBm and deviates from the simulated value because in simulation a $Z_{\text{load}}$ of 100 $\Omega$ was used.

VII. BENCHMARKING

The performance of existing 60 GHz LNAs is compared with this work in table 1. The LNAs presented in [5]-[7] are single ended, and [8] has a differential output. It is seen the work presented in this paper shows the lowest NF along with the highest bandwidth. The relative low gain is because only 2 CS stages are used. The use of feedback results in a high IIP$_3$.

VIII. CONCLUSION

A 60 GHz differential LNA was realized and measured exhibiting the lowest NF and highest bandwidth to date. High IIP$_3$ was measured, resulting in a high dynamic range. EM simulations were used to simulate transformers and interconnect and are proven accurate enough. Measurements are in close agreement with simulations.

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