A Ka-band tunable LNA for MB-OFDM application

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Abstract
In this paper a novel tuneable LNA is presented. This LNA is designed with two separated structures which both of them utilize noise cancellation technique and some other approaches such as gain boosting and T-transformer feedback. Each proposed LNA has two stages that the first stage is designed based on noise cancellation and the second stage uses common gate structure. The proposed LNA type (A) utilises the switched capacitance in the first stage to tune the centre frequency and a gain boosting in the second stage to increase the gain. The second proposed LNA type (B) has implemented the parallel networks to decrease the change in the gain values of the LNA in different channels. The T-transformer approach is used in each parallel network to decrease the inductors value and improve the input matching. In the second stage, the negative feedback is also employed to control the bandwidth. The proposed LNA is simulated in ADS software with TSMC 130 nm CMOS technology and the layout is designed by Cadence. The LNA type (A) has 22.7 dB gain in 28.8 GHz and the noise figure of 2 dB. The IIP3 for this LNA is 0 dBm in 25.42 GHz. For the LNA type (B), the gain and noise figure standard deviations are 0.25 and 0.057 respectively which shows minimum variations by frequency tuning. For this LNA, the maximum gain is 20.5 dB and the noise figure is 2 dB at 31.42 GHz. Finally the performances of the proposed LNAs have been compared with those of LNAs which have been recently published.

1 INTRODUCTION

The new generation of the mobile communication (5G) require the high data rate signals. For this generation, two frequency bands are proposed that involve the sub 6 GHz and above 24 GHz. Due to wideband requirement for high data rate applications, the millimetre wave spectrum is a good candidate for this application [1]. However, due to the atmospheric absorption of mm-wave spectrum, international telecommunication union (ITU) proposed some bands that include 24.25-27.5, 31.8-33.4, 37-40.5, 40.5-42.5 GHz etc. [2]. One of the most significant part of a 5G receiver is low noise amplifier (LNA). The LNA boosts the input signal while keeps the system noise figure at a low value. However, there are some other parameters in addition to gain and noise figure such as linearity, bandwidth, power etc. Therefore the researchers have been studying to improve the LNA performances. Also, finally a trade-off between these parameters is necessary.

The multi band orthogonal frequency division multiplexing (MB-OFDM) is one of the techniques to improve the quality of high date rate systems in wireless communication [3]. Although there are some standards in frequency range less than 10 GHz like IEEE 802.15.3a [4], the proposed LNA in this paper has been designed to be used in the mm-wave frequency range.

The choice of an appropriate technology for the implementation of a LNA is important. Because of its high level of integration, low cost and low power consumption, the CMOS silicon on insulator (SOI) is a good choice for LNA design [5–7]. Some recent research works carried out in LNA for MB-OFDM at mm-wave frequency range are as follows.

In [8], Qin and Xue presented a novel LNA using the transformers based on the source degeneration approach. Due to
utilizing a transformer gate-drain feedback technique, the proposed LNA has achieved the 10.2 dB gain at high frequency from 15.8 to 30.3 GHz. In [9], Lee and Nguyen applied a novel transformer feedback single ended to the differential dual-band load to design a new LNA which had flexibility in controlling the stop-band frequency. In [10], Zhou et al. employed the gm-boosting approach based on capacitor cross-coupled to reduce the noise figure and increase the gain in their proposed LNA. In [9] a transformer-based noise reduction with neutralization approaches has been used to achieve 23.5 dB gain and 3.3 dB noise figure at 24 GHz. In [11], Hajiri et al. proposed a new three stages high gain low power consumption, using the current reuse approach. In [12], design of a new receiver front-end which consists of a modified cascade LNA with two gain stages using a negative feedback structure and a current-bleeding active mixer with tunable loads has been presented.

The need for a new LNA to be used in high data rate systems is a motivation to propose a design method in this paper. Therefore in this paper a new tuneable LNA based on noise cancelation technique for MB-OFDM application is presented. The proposed LNA is designed with TSMC 130 nm CMOS at Ka band.

In the following section, the design procedure for the proposed LNA is discussed.

2 LNA DESIGN

2.1 Conventional noise cancellation

The noise figure is one of the most important parameters in LNA design. Based on Friis formula [13], the gain and noise figure of the first block in a receiver determines the system noise figure. The noise cancelation technique using two approaches can decrease the noise figure while maintaining the gain at maximum [14]. Two approaches are based on common gate and common source topologies. The CG is more common for design in mm-wave because of its good input impedance matching (Figure 1(a)) [15, 16].

The base structure of a CG noise cancellation is shown in Figure 1(a). In this structure, the thermal noise current produced by $M_1$ passes through two paths. In the first path, the average thermal noise voltage in node A ignoring the resistance $r_s$ is obtained by (1). In the second path, the thermal noise current passes through the source resistor $R_s$. For a CS structure and assuming the zero-input current in $M_2$, the squared average thermal noise voltage in node B is expressed by Equation (2):

$$ \tilde{v}_{n,1}^2 = \frac{\tilde{i}_2^2}{g_m} \xi_1^2 $$

$$ \tilde{v}_{n,B}^2 = \frac{\tilde{i}_2^2}{g_m} R_s^2 $$

The path through $M_2$ changes the phase of the noise $M_1$ while the voltage in $\tilde{v}_{n,1}$ has positive phase. Finally the input squared average thermal noise voltage of $M_1$ is calculated as Equation (3):

$$ \tilde{v}_{n,\text{in}}^2 = \tilde{v}_{n,1}^2 - A^2 \tilde{v}_{n,B}^2 R_s^2 $$

The noise $M_1$ is omitted in the output provided that:

$$ \frac{\tilde{v}_{n,1}^2}{g_m} - A^2 \frac{\tilde{v}_{n,B}^2}{g_m} R_s^2 = 0 $$

$$ \xi_1 = AR_g $$

![Figure 1](image-url) (a) The principle of a typical noise cancellation based on CG structure. (b) A tuneable LNA structure based on noise cancellation topology
2.2 Tuneable LNA structure

As discussed in the previous section, because of high data rate property of MB-OFDM system, it is necessary to design a new LNA for these systems in mm-wave. Figure 1(b) shows a tuneable LNA based on noise cancellation technique while its small signal model is shown in Figure 2.

Assuming matched input, the circuit gain ignoring the switch capacitor and also internal resistor of transistor $r_o$, can be calculated by Equation (6) using Equation (5) as:

$\begin{align*}
&v_{out} = -Z_L^2 i_3 \\
&i_3 = i_1 - i_2 = \\
&\frac{1}{2} g_m v_{in} + \frac{1}{2} g_m g_{m3}(Z_{L1} \parallel Z_{Cgs}) v_{in}
\end{align*}
$

From Equation (5), the total gain can be expressed as follows:

$A = -\frac{1}{2} Z_{L2}(g_m + g_{m1} g_{m3}(Z_{L1} \parallel Z_{Cgs}))$

The centre frequency is determined by gate-source capacitance of $M_3$ and $L_1$. Therefore, the centre frequency is changed by adding some capacitors in node A to control the node capacitance.

Each switch uses an NMOS transistor which is biased in triode region. When the transistor is off, the equivalent circuit is a capacitor and when it is on, it is replaced by a couple of capacitor and resistor as shown in Figure 2 [17].

In the next section two tuneable LNAs based on noise cancellation technique are proposed. One of LNAs has approximately equal gain for different channels while for another LNA the maximum gain is changed by changing its centre frequency.

2.3 Gain boosting approach

The gain of amplifier can be increased by implementing a gain booster shown in Figure 3. In fact by adding inductor to the gate of transistor, the drain current is increased which in turn increases the gain [18]. For Figure 3, the amplifier gain neglecting $r_o$ is expressed as:

$A = g_m Z_L g_m + Z_{Cgs} (7)$

where $Z_{L2}$ is the gain boosting impedance. If we define $K = \frac{Z_{L2}}{Z_{L2} + Z_{Cgs}}$ then one can write:

$K = \frac{Z_{L2}}{Z_{L2} + Z_{Cgs}} = \frac{L_2}{L_2 - \frac{1}{a^2 C_{gs}}} > 1$

From Equation (8) it is clear that $K > 1$ and so based on Equation (7) the gain increases.
The first novel tuneable LNA for MB-OFDM applications in mm-wave is shown in Figure 4. This amplifier is 2-stage amplifier. The first stage is designed based on noise cancellation technique to reduce the total noise of the system. This stage is also tuneable which is tuned by switch capacitor. The second stage is CG amplifier as this stage should be wide-band because the centre frequency of the first stage changes in a wide frequency range. In addition, the second stage should have enough gain to boost the first stage output signal. The \( L_g \) acts as a gain booster to increase the gain.

For Figure 4, the amplifier gain is expressed as:

\[
A = \frac{1 + \frac{j\omega L_g}{1 - \omega^2 C_g L_g}}{1 + \frac{Z_L}{Z_L}}
\]
As can be seen from Equation (9), one can change $L_g$ such that $1 - \omega^2 C_{gs} L_g$ become much less than 1 which boosts the amplifier gain. Figure 5 shows the effect of $L_g$ on the LNA gain. From Figure 5 it is also seen that changing $L_g$ value has no effect on amplifier noise figure.

The input impedance of Figure 4 taking into account the resistor $r_s$ is expressed as Equation (10):

$$Z_{in} = \frac{Z_t + r_s}{1 + \frac{\omega C_{gs}}{r_s}} = \frac{Z_t + r_s}{Z_t + \frac{Z_r}{Z_s}}$$

where $Z_j$ and $Z_i$ are expressed by Equation (11) as:

$$Z_j = Z_{Ld} + \left( Z_{L1} \parallel Z_{sw} \right)$$

$$Z_j = \frac{L_{L1}}{C_{gs} g_{m2}} + j(\omega L_{L1} - \frac{1}{\omega C_{gs}^2})$$

$L_{L1}$ and $L_{L2}$ can be obtained from Equation (12).

$$\omega_0 = \frac{1}{\sqrt{L_{L1} C_{gs}}}, \quad \omega_0 = \frac{1}{\sqrt{L_{L2} C_{gs}}}$$

where $\omega_0$ is the centre frequency of the amplifier. The small signal model of the amplifier is shown in Figure 6.

The proposed tuneable LNA type (A) is simulated in ADS software with TSMC 130 nm CMOS technology. The values of proposed circuit components are presented in Table 1 and also the Q-factor of components is chosen to be 14.

The LNA type (A) has three channels at 25.4, 26.9 and 28.8 GHz. For selecting the channel 1, the switch 1 and switch 2 must be on. Also, for selecting the channel 2, the switch 1 is on and the switch 2 is off and for the channel 3 both switches must be off. With changing the capacitance of $C_1$ and $C_2$, the resonance frequency will change.

The biasing voltages VDD and $V_b$ are 1.2 and 0.6 V respectively. Figure 7 shows the gain of proposed tuneable LNA type...
Due to implementation of noise cancellation technique in the first stage, the expected noise figure is 2 dB. The IIP3 for this channel is 0 dBm which shows the linearity of the amplifier. Figures 8 and 9 show other S-parameters and IIP3 for all channels.

Table 1 shows the element values of the proposed LNA type (A). For this design, IIP3 is around $-1 \text{ dBm}$, the gain is 22.7 dB and the noise figure is 2 dB in Ch3 while for ch1, the bandwidth is 3.67 GHz.

However, tuning the center frequency for the proposed LNA, changes other LNA parameters. This is due to this fact that when the switches turns on, the transistors behaves as a resistor (dynamic and statics) and changes the gain and other parameters. A new tuneable LNA design is then proposed that tuning the centre frequency, has small effects on the other parameters.

### 2.5 Proposed LNA type (B)

For a good design of tuneable amplifier, tuning the center frequency should not affect other parameters. Based on the above discussion, a novel tuneable LNA is proposed that tuning its centre frequency has minimum effects on other amplifier parameters. As Figure 10 shows, this design (LNA type (B)) has 2 stages similar to that of LNA type (A). However, for this LNA, the parallel networks is implemented for tuning in the
second stage while the T-transformer structures in used in the first stage.

The proposed tuneable LNA type (B) has been tuned for three channels. For selecting each channel, only one of three parts in parallel network (A or B or C) must be turned on. The centre frequency is tuned by changing the capacitance of the capacitor.

In the first stage a T-transformer is used for introducing smaller inductors for tuning and also improve the input matching. As Figure 11 shows, for tuning the centre frequency around 31 GHz, the inductor $L_1$ should be 89 pH with coupled inductors (T-transfer) and is 149 pH without coupled inductor. This smaller inductor reduces the noise figure and total size. As can be seen from Figure 11, using 89 pH non-coupled inductor increases the centre frequency of amplifier to around 37 GHz. In the second stage a gain boosting inductor, $L_g$ increases the CG gain and also a transformer feedback controls the bandwidth.

For simulation of the proposed LNA type (B) an ADS simulator with TMSC 130 nm CMOS technology has been used. The Q-factors of the inductors are assumed to be 14. The biasing voltage $V_{DD}$ and $V_b$ are chosen to be 1.2 and 0.5 V respectively. The coupling coefficient $K$ for T-transformer and feedback transformer is 0.5. Table 2 shows the component values of LNA type (B).

As Figure 13 shows, the noise figure is as low as 2 dB due to implementation of noise cancellation network. Also $S_{11}$ is better than −10 dB. Furthermore the linearity (IIP3) is $−7 \text{ dBm}$ in 31.42 GHz (Figure 14).
RESULTS AND COMPARISON

Table 3 compares the proposed LNA type (A) and LNA type (B) post-layout results with those of recently research works. As can be seen in this Table, the LNA type (A) has highest gain (22.7 dB) and lowest noise figure (2 dB) in 28.8 GHz. The IIP3 of our proposed LNA type (A) which is one of the most significant parameters in LNA design is 0 dBm which shows the good linearity of the amplifier. The LNA type (A) has 14.5% bandwidth at centre frequency of 25.4 GHz. Also, for our proposed LNA type (B), the gain and noise figure standard deviations are 0.25 and 0.057 respectively since the gain and noise figure variations with frequency tuning is low. However, for LNA type (A), the gain and noise figure standard deviations are 2.3 and 0.6 respectively. The LNA type (B) has a 20.5 dB gain at 31.42 GHz and 2 dB noise figure in 29.7 GHz. The power consumption of LNA type (B) is 40.2 mW

However, for LNA type (A) the power consumption is 33.6 mw. Tables 4 and 5 show the parameters of the proposed LNA A and B for each channel.

The figure of merits listed in Table 3 are defined by Equations (13) and (14). The layout of the proposed LNA type (A&B) obtained by Cadence are shown in Figure 15 and the stability factors of LNAs are presented in Figures 16 and 17. Beside the noise contribution of each switch capacitor to the total noise of circuit is presented in Figure 18 which depicts the proposed LNA type A noise figure for different switch capacitor conditions.

\[
FO_M = \frac{Gain \times BW}{(NF - 1)}
\]  

(13)
TABLE 3  
Comparison between this work and the LNAs that have been published recently

| Reference | Single band | Multiband |
|-----------|-------------|-----------|
|           | [16] | [19] | [20] | [5] | [21] | [4] | [11] | This work | This work |
| Year      | 2018 | 2018 | 2019 | 2016 | 2019 | 2008 | 2016 | 2020 | 2020 |
| Frequency (GHz) | 23-30 | 33 | 30-34.5 | 35.5-41.9 | 24 | 3.4 | 4.2 | 28.8 | 29.7 |
| Topology  | 2-Noise cancellation and CS | 2-Cascode | 2- diff | 5- CS | 3- cascode | 2-diff | 3- CS & CG | 2-Noise cancellation and CG | 2-Noise cancellation and CG |
| Process (CMOS) | 28 nm | 28 nm | 65 nm | 130 nm | 130 nm | 180 nm | 180 nm | 130 nm | 130 nm |
| Gain(dB)  | 17.7 | 24.5 | 20.8 | 13.8 | 31.2 | 16 | 25 | 22.7 | 20.13 |
| NF(dB)    | 4.8 | 4 | 3.71 | 4.2 | 4.9 | 2.7 | 4.3 | 2 | 2 |
| IIP3(GBm) | * | −15.9 | −10.8 | * | * | −8.8 | * | −3 | −8 |
| PDC(mW)   | 22.2 | 27.6 | 26.7 | 30.9 | 22.3 | 11.9 | 3.4 | 33.6 | 40.2 |
| Area (mm²) | 0.31 | 0.23 | 0.39 | 0.98 | 0.53 | * | * | 0.67 | 0.55 |
| BW(GHz)   | 7 | 4.4 | 4.5 | 6.4 | 1.7 | 0.5 | 0.5 | 2.52 | 3.5 |
| FOM1      | 32.6 | 35.9 | 34.5 | 27 | 13.6 | 4.7 | 3.7 | 57.2 | 70.45 |
| FOM2      | 5 | 4.8 | 6.68 | 3.06 | 6.2 | * | * | 11.46 | 13.94 |

TABLE 4  
The results of the proposed tuneable LNA type (A)

| CH1 | CH2 | CH3 |
|-----|-----|-----|
| Gain(dB) | 18.1 | 20.1 | 22.7 |
| NF(dB) | 3.2 | 2.6 | 2 |
| IIP3(GBm) | 0 | −1 | −3 |
| $P_{DC}$(mW) | 33.6 | 33.6 | 33.6 |
| BW(GHz) | 3.67 | 3.27 | 2.52 |
| $f_0$ (GHz) | 25.42 | 26.95 | 28.8 |

TABLE 5  
The results of the proposed tuneable LNA type (B)

| CH1 | CH2 | CH3 |
|-----|-----|-----|
| Gain(dB) | 19.93 | 20.13 | 20.5 |
| NF(dB) | 2.1 | 2 | 2 |
| IIP3(GBm) | −9 | −8 | −7 |
| $P_{DC}$(mW) | 40.2 | 40.2 | 40.2 |
| BW(GHz) | 3.52 | 3.5 | 3.34 |
| $f_0$ (GHz) | 28.21 | 29.7 | 31.42 |

4  CONCLUSION

In this paper two new tuneable LNAs based on noise cancellation technique implementing gain booster, T-transform and transformer feedback have been presented. The first proposed LNA type (A) utilized the switched capacitor to tune the centre frequency of the amplifier. For this amplifier, the gain and noise figure are 22.7 and 2 dB respectively in the centre frequency of 28.8 GHz with excellent IIP3. The second proposed LNA type (B) is presented to decrease the change in the LNA parameters with tuning the centre frequency of the amplifier. The LNA type (B) implements the parallel network so that only one part of network is active for each channel. In addition, the LNA type (B) utilizes T-transformer to reduce the inductor and also implements the transformer feedback to control the bandwidth. The gain boosting is also used in this LNA to boost the gain. For LNA type (B), the gain and noise figure are 20.5 and 2 dB respectively in the centre frequency of 31.42 GHz.

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How to cite this article: Hosseini, S.A., et al.: A Ka-band tunable LNA for MB-OFDM application. IET Commun. 1–10 (2021). https://doi.org/10.1049/cmu2.12242