4 - 20 GHz low noise amplifier MMIC with on-chip switchable gate biasing circuit

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Abstract: A broadband low-noise amplifier (LNA) MMIC with a novel on-chip switchable gate biasing circuit is proposed. The biasing circuit is able to switch on/off the low noise amplifier and compensate the variation of threshold voltage (Vth) and temperature, hence improving the robustness of the amplifier over a wide operating frequency range. The switching frequency is up to 1 MHz, and the fluctuations of on-state quiescent current and power gain of the amplifier are within ±7.9% and ±0.8% when the threshold voltage varies from -0.15 V to 0.15 V. The power gain variation is stabilized within ±1.25 dB by the biasing network, while the temperature changes from -55°C to 125°C. Realized in 0.15 μm E-mode pHEMT technology with size of 2.0 mm×1.3 mm, the LNA provides a typical gain of 24 dB while maintaining input and output return loss better than 10 dB and the noise figure (NF) of the LNA smaller than 1.6 dB from 4 GHz to 20 GHz.

Keywords: LNA MMIC, gate biasing circuit, Vth compensation, temperature compensation

Classification: Electron devices, circuits and modules (silicon, compound semiconductor, organic and novel materials)

References

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1 Introduction

Wideband low noise amplifiers with low DC power dissipation have been playing a crucial role in various applications like ultra-wideband (UWB) communication, imaging, and software-defined radios [1][2][3]. Over the past few years, a new class of MMIC amplifiers have emerged based on pHEMT technology, with the advantage of both low noise figure and high gain performance [4][5][6]. However, MMICs based on pHEMT technology are sensitive to the threshold voltage variation due to fabrication process fluctuation and temperature variation [7]. One of the most important factors, which determines the yield of amplifiers, is the threshold voltage of the utilized transistors, so it’s necessary to compensate the effect of the threshold voltage variation in order to improve the robustness and yield [8]. For low power applications, LNA is also required to be conveniently turned off when the receiver system is inactive [9]. For some extreme environmental applications, the compensated temperature range offered by existing gate biasing circuit is not enough [8][10]. In this letter, we propose and verify a novel on-chip gate biasing circuit which enables the low noise amplifier with switchable ability and stable RF performances over threshold voltage and
wide temperature variations.

2 Proposed gate biasing circuit

A switchable gate biasing circuit (Fig.1) is proposed to enable switchable ability and compensation of threshold voltage and temperature variations for LNA MMIC, as illustrated in Fig.3. The switchable gate biasing circuit consists of five resistors \((R_1, R_2, R_3, R_4\) and \(R_5\)) and three transistors \((Q_1, Q_2\) and \(Q_3\)). \(Q_2\) and \(Q_3\) serve as switches which not only control the state of transistors \(Q_1\) and \(Q_{\text{LNA}}\), but also form a compensation structure together with transistor \(Q_1\) for threshold voltage and temperature variations. Transistors \(Q_1\) and \(Q_{\text{LNA}}\) are fed with DC voltage \(V_D\), and transistors \(Q_2\) and \(Q_3\) are fed with a TTL voltage \(V_{\text{ctrl}}\) which enables transistors \(Q_1\) and \(Q_{\text{LNA}}\) on/off.

The DC current through transistors \(Q_1, Q_2\) and \(Q_3\) are denoted as \(I_{D1}\), \(I_{D2}\), \(I_{D3}\) respectively and the drain, source and gate voltage of transistors \(Q_X\) are denoted respectively as \(V_{DX}, V_{SX}, V_{GX}\) \((X=1,2,3)\). The gate current of each transistor is so small that can be ignored in the latter analysis.

\[
\begin{align*}
\text{Fig. 1 The topology of proposed switchable gate biasing circuit}
\end{align*}
\]

3 Compensation of threshold voltage variation

A current feedback circuit includes transistor \(Q_1\) and transistor \(Q_2\) with its gate connected to the drain of the first transistor \(Q_1\) and its drain connected to \(V_D\). When \(V_{th}\) slightly decreases due to fabrication process variation, the current \(I_{D1}\) of \(Q_1\) increases, resulting in current \(I_{D2}\) decreasing of \(Q_2\), and \(V_{G3}\) linearly decreases as \(I_{D1}\) increases, as follows:

\[
V_{G3} = V_D - I_{D1}(R_1 + R_2)
\]  

(1)

Adjusting \(R_1\) and \(R_2\) to make the following equation:

\[
\Delta V_{G3} = -\Delta I_{D1}(R_1 + R_2) = 2\Delta V_{th}
\]  

(2)

Considering \(Q_3\) and \(R_5\) as a source coupled FET circuit, the relationship between \(V_{G3}\) and \(V_{S3}\) \((V_{G})\) is as follows:

\[
\Delta V_{G3} = \Delta V_{th} + \Delta V_{S3} = \Delta V_{th} + \Delta V_G
\]  

(3)

Combining (2) and (3):

\[
\Delta V_G = \Delta V_{th}
\]  

(4)

The quiescent current \(I_Q\) is determined by the following equation:

\[
I_Q = k[(V_G + \Delta V_G) - (V_{th} + \Delta V_{th})]^2
\]  

(5)

Where \(k\) is a process related parameter. Finally, the quiescent current \(I_Q\) of LNA, and the RF performances will be kept stable theoretically while \(V_{th}\) varies.

4 Compensation of temperature variation

One of the aims of compensation biasing network is to stabilize small signal gain.
of LNA against temperature variation from -55°C to 125°C. Generally, when ambient temperature increases, both the small signal gain of LNA and $\Delta V_{th}$ decrease. Based on this fact, the proposed circuit also has the ability of compensating temperature variation by performing the same analysis as the previous section. In addition, a positive temperature coefficient mesa resistor $R_6$ is utilized instead of thin film resistor, which lifts the internal operation voltage and further reduces the variation of small signal gain against temperature variation. The relationship between $V_G$ and $R_6$ is described as follows:

$$V_G = I_{D3}R_6 + (I_{D1} + I_{D2} + I_{D3})R_6$$  \hspace{1cm} (6)

$V_G$ changes slightly ($\Delta V_G=0$) when the sum of $I_{D1}$, $I_{D2}$ and $I_{D3}$ decreases but $R_6$ increases with increasing temperature. Finally, the current $I_Q$ in (5) increases as temperature increases to compensate the gain reduction of LNA, and similar analysis can be performed for the case of temperature decrease.

Fig. 2 shows the simulated quiescent current $I_D$ with the proposed gate biasing circuit of $V_D=5\,\text{V}$ and direct bias of $V_G=0.49\,\text{V}$ against threshold voltage variation from -0.15V to 0.15V and also with the comparison between mesa resistor and thin film resistor against temperature variation from -55°C to 125°C. With the proposed gate biasing circuit of $V_D=5\,\text{V}$, the quiescent current $I_Q$ ranges from 34mA to 29mA exhibiting little change of 15.8% ($\Delta I_D=5\,\text{mA}$) with $V_{th}$ varied from -0.15V to +0.15 V, indicating an excellent compensation of threshold voltage variation with gain fluctuation of 0.4 dB. This is much better than direct biasing of $V_G=0.49\,\text{V}$ with gain fluctuation of 20 dB. Also, after applying the mesa resistor, the quiescent current $I_Q$ increases from 24mA to 35mA with temperature changing from -55°C to 125°C, providing good compensation of temperature variation with gain fluctuation from 24.5 dB to 22.2dB. This is better than applying thin film resistor with gain fluctuation from 25.4dB to 21.2dB.

5 Measurements
The low noise amplifier with the proposed gate biasing circuit is fabricated using a commercial 0.15 µm GaAs Enhanced mode pHEMT MMIC technology, with a die size of 2.0 mm × 1.3 mm, and demonstrated in Fig. 3. The chip is typically biased with a +5 V \( V_D \) supply and TTL control voltage, which consumes only 32 mA and has a typical P-1dB of 2 dBm. Fig. 4 shows the noise figure (NF) and small signal gain with temperature varies from -55°C to 125°C. When temperature is 25°C, the measured NF is lower than 1.6 dB over the bandwidth 4 to 20 GHz with a best NF of 0.6 dB at 4 GHz and the measured gain is higher than 23.8 dB over 4 to 20 GHz. When temperature is varied form -55°C to 125°C, the fluctuations of NF and gain are about 1.0 dB and 2.4 dB respectively which can be well adapted for different applications. The jitters of NF and gain are due to the possible mismatch between noise source and noise figure analyzer. Fig.5 demonstrates the switching performances of LNA MMIC with gate biasing circuit in a typical radar application. Fig.5 (a) shows the pulse width of 100 us and pulse period of 110 us, and the ratio is about 90% which meets the application requirement. The overshoot of the pulse is less than 0.05 dB as showed in Fig.5 (b). The rising time and falling time are 50 ns and 25 ns respectively as showed in Fig.5 (c) and (d).

![Fig. 3 Photograph of LNA MMIC with gate biasing circuit](image)

![Fig. 4 The NF and Gain of LNA MMIC at different temperatures](image)
Fig. 5 Measured switch performances of the LNA MMIC with pulse width of 100 us, pulse period of 110 us

Table 1 compares the performance of the state-of-the-art wide band pHEMT low noise amplifiers. To the best of our knowledge, the chip adopting the proposed gate biasing circuit in this letter has the widest operating temperature ranging from -55°C to 125°C compared with references [11]-[15] while $\Delta NF$ and $\Delta Gain$ normalized with temperature are excellent and also owns a quite low power consumption of 160 mW while keeping an excellent RF performance such as NF and Gain.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Freq (GHz)</th>
<th>NF (dB)</th>
<th>Gain (dB)</th>
<th>$\Delta NF$ (dB/°C)</th>
<th>$\Delta Gain$ (dB/°C)</th>
<th>Operate Temp. (°C)</th>
<th>Power (mW)</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>[11]</td>
<td>1.2~18</td>
<td>3</td>
<td>13.3</td>
<td>-</td>
<td>-</td>
<td>-500</td>
<td>GaN</td>
<td></td>
</tr>
<tr>
<td>[12]</td>
<td>3~15</td>
<td>2.5</td>
<td>28</td>
<td>-</td>
<td>-</td>
<td>200</td>
<td>GaAs</td>
<td></td>
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<tr>
<td>[13]</td>
<td>6~18</td>
<td>1.6</td>
<td>19</td>
<td>0.007</td>
<td>0.013</td>
<td>-55~85</td>
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<td>GaAs</td>
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<td>0.020</td>
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</tr>
<tr>
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<td>16</td>
<td>0.007</td>
<td>0.01</td>
<td>-25~75</td>
<td>60</td>
<td>GaAs</td>
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<tr>
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<td>1.6</td>
<td>24</td>
<td>0.006</td>
<td>0.014</td>
<td>-55~125</td>
<td>160</td>
<td>GaAs</td>
</tr>
</tbody>
</table>

6 Conclusions
In this paper, a switchable gate biasing circuit which can compensate threshold voltage and wide temperature variations is proposed and it can be applied to a 4~20 GHz LNA MMIC successfully. The fabricated LNA MMIC has excellent performances and can be fully powered on/off according to the requirement of application. The switchable gate biasing circuit is attractive to MMIC applications since it can offer wide temperature compensation and switchable ability and be easily integrated on MMICs with little occupying area.

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