60 GHz Low-Noise Amplifier for Detection Systems

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Abstract. This paper presents a 60 GHz low-noise amplifier (LNA) to improve detection systems performance. The considered system is based on impulse radar technology. The LNA is designed in GaAs metamorphic High Electron Mobility Transistor (m-HEMT) technology. Three stages common source transistors are used with inductive degeneration for a good trade-off between gain and noise. The post-layout simulation results show a noise factor of 2.06 dB and a gain of 14.5 dB at 60.2 GHz, for a power consumption of 13.5 mW. The simulated non-linear characteristics show an $I_{1dB}$ (Input 1 dB compression Point) of -10 dBm and an $I_{IP3}$ (Input third-order Intercept Point) of -4.4 dBm. The LNA occupies an area of $1.56 \times 1.29 \text{ mm}^2$.

1. Introduction
With the evolution of standards and technologies, the millimeter-wave frequencies are attracting more and more interest. The availability of unlicensed bandwidth around 60 GHz in several regions of the world can facilitate frequency harmonization and massive deployment of systems. The use of large bandwidth allows to achieve high data rates (several gigabits/second at a few meters) for communication systems and high range resolutions (a few cm) for detection systems. These opportunities create a need for broadband, low noise, low power consumption and small size amplifiers to improve systems performance.

This study is part of the development of an ultra-wideband (UWB) millimeter wave short-range detection system. Monostatic radar is considered (figure 1), with two co-located antennas and a cylindrical target of radius $r$ and height $h$, located at a range $R$. The incidence angle $\theta$ is determined by the orientation of the target with respect to the antennas boresight.

The rest of this paper is structured in four main parts. The detection principle and LNA specifications are presented in Section 2. Section 3 details the description of the technology used and the design of the 60 GHz LNA. The layout and the electromagnetic simulation results are presented in Section 4. And finally, a conclusion and future work are presented in Section 5.

2. Principle of detection and LNA specifications
The detection principle is based on the impulse technique, using a dual-band approach [1], to improve the angular detection coverage of the target. Frequencies around 60 GHz were chosen for spectrum availability, but also for short wavelengths to detect small objects. Due to the frequency dependence of the radar cross section (RCS), we use frequency diversity [2], to maximize the received radar echo according to the target orientation angle $\theta$.

The choice of frequencies is based on the UWB millimeter wave standardization, but also on the dimensions of the targets to be detected. It has been optimized for metal plates and cylinders whose largest dimension doesn’t exceed 10 cm. In addition, it is based on the RCSs of targeted objects, which are determined using the physical optics method [3].
The architecture associated to the detection principle is shown in figure 1 for a dual-band system. Its operation consists in simultaneously transmitting pulses in both frequency bands and recombining their echoes in reception. More details are given in [1], including DSPA (Differential Structure Power Amplifier) part. This architecture can be extended to \( N \) frequency bands.

![Figure 1. Example of dual band detection architecture.](image)

The design of the system is based on the radar equation [4], which can be in the form:

\[
R_{\text{max}}^4 = \frac{P_t G^2 \sigma \lambda^2}{(4\pi)^3 \cdot kT \Delta f \cdot F \cdot SNR_r}
\]

where \( P_t \) is the transmitted power, \( G \) the antenna gain, \( \sigma \) the RCS of the target, \( k \) the Boltzmann constant, \( T \) the temperature, \( \Delta f \) the receiver bandwidth, \( F \) its noise factor and \( SNR_r \) the signal-to-noise ratio required to ensure detection. By setting the objective to detect a cylinder (\( r = 0.6 \) cm; \( h = 5.4 \) cm) up to 2 m at \( \theta = 0^\circ \), we will determine the specifications of the LNAs. To do this, we consider a quad-band system in 57-66 GHz, around the frequencies 57.8 GHz, 60.2 GHz, 62.8 GHz and 65.2 GHz. The output power of each channel of the DSPA\( _2 \) is set at 15 dBm, taking into account the standardization and antennas gain (12 dBi). The bandwidth of each band is 1.6 GHz and the filter losses are set to 3.5 dB [5]. For a single pulse, the \( SNR_r \) for a detection probability of 90% and a false alarm probability of \( 10^{-6} \) is 13.2 dB for a non-fluctuating target. With a non-coherent integration of 4 pulses in the 4 frequency bands, the \( SNR_r \) is 8.3 dB for the same probabilities. Based on non-coherent integration and using equation (1), the specifications of the LNAs are at least 12.5 dB of gain and at most 3 dB of noise factor.

3. Technology description and circuit design

The 60.2 GHz LNA is designed in OMMIC’s D007IH technology, which has a 70 nm gate length. This technology has a \( f_T/f_{\text{max}} \) of 300 GHz/450 GHz. It offers a depletion transistor m-HEMT with \( V_{\text{DS, max}} \) of 3 V and \( I_{\text{DSS, max}} \) of 400 mA/\( \mu \)m. The choice of this technology is based in part on its low losses, 0.22 dB/mm at 60 GHz. The technology process consists of a 3.5 \( \mu \)m metal on its underside, a 100 \( \mu \)m thick GaAs substrate above which there are different metal layers.

The LNA is designed with Keysight Advanced Design System (ADS). It consists of a three stages structure using identical transistors. The size of the transistor (2 × 25 \( \mu \)m of gate) is chosen for a better trade-off between gain and noise [6]. The optimal bias point corresponds to a voltage \( V_{\text{DS}} = 1 \) V for an \( I_{\text{DS}} \) current of about 4.1 mA. Unconditional bias point has been ensured both by inductive degeneration of the source, but also by the use of resistors in the bias circuits. The first two stages are almost identical and are matched with a good trade-off between gain and noise. Matching of the third stage is optimized in gain because its influence is less significant on the whole structure noise factor.

Figure 2 presents the schematic of the LNA. All bias circuits are made with quarter-wave transmission lines. They include GaAs implanted resistors (\( R_D \) and \( R_G \)) and bypass capacitors \( C_D \). The degeneration of the transistor source is made by the transmission line TL\( _S \), \( C_1 \), TL\( _1 \)
and TL₂ form the input matching network. C₂, TL₃ and C₃ on the one hand, and C₄, TL₄ and C₅ on the other hand, form the inter-stages matching networks between stages 1 and 2 and stages 2 and 3 respectively. The output maching network is formed by C₆ and TL₅.

4. Layout and simulation results
The layout of the LNA is shown in figure 3 and occupies 1.56 × 1.29 mm². It includes RF (Radio Frequency) and DC (Direct Current) pads. All ground connections are made by vias holes.

The post-layout simulation results with ADS Momentum Microwave solver are presented in figures 4-6. The circuit is unconditionally stable up to 200 GHz as shown in figure 4.

Figure 2. Schematic of the LNA design.

Figure 3. Layout of the LNA.

Figure 4. Stability of the LNA.

Figure 5. S-parameters of the LNA.

Figure 6. Gain and P₁dB.

Our LNA achieves a gain of 14.5 dB and a noise factor 2.06 dB at 60.2 GHz. The reflection coefficients S₁₁ and S₂₂ are less than -15 dB in the band of interest 59.4-61 GHz. In this band,
we observed a gain ripple of 0.9 dB and a noise factor ripple less than 0.1 dB. The non-linear characteristics of the LNA present an $IP_{1dB}$ of -10 dBm (figure 6) and an $IIP_{3}$ of -4.4 dBm.

The performance of the designed LNA compared to other LNAs in the state-of-the-art are given in table 1. Compared to [7] and [8], our LNA presents a better noise factor, a good gain with a moderate power consumption and occupies less space. Its non-linear characteristics are much better than those of references [8]- [10]. Note that CMOS technologies are generally more suitable for miniature and low-power consumption components compared to HEMT technologies.

| Ref. | Technology | Freq. (GHz) | Gain (dB) | NF (dB) | $P_{DC}$ (mW) | Area (mm$^2$) |
|------|------------|-------------|-----------|---------|---------------|--------------|
| [7]  | 50 nm GaAs* | 50-90       | 27        | 2.6     | 45            | 2.3 $\times$ 1.6 mm$^2$ |
| [8]  | 100 nm GaAs* | 60-90      | 19        | 2.5     | 56            | 3.5 $\times$ 1.0 mm$^2$ |
| [9]  | 40 nm CMOS | 60         | 12.5      | 3.8     | 20.4          | 0.63 $\times$ 0.31 mm$^2$ |
| [10] | 65 nm CMOS | 60         | 20.2      | 5.2     | 28            | 0.54 $\times$ 0.80 mm$^2$ |
| This Work | 70 nm GaAs* | 60.2       | 14.5      | 2.06    | 13.5          | 1.56 $\times$ 1.29 mm$^2$ |

+ Measures, * m-HEMT

5. Conclusion and future work

A 60 GHz LNA designed in GaAs m-HEMT technology was presented. This design was done for a multi-band system using a frequency diversity to improve detection coverage. Our designed LNA offers good performance with only 2.06 dB noise factor at 60.2 GHz. With three stages, it achieves a gain of 14.5 dB, while consuming 13.5 mW. With this performance, the range and overall detection coverage are improved compared to conventional single-band system.

As future work, we can mention the realization and characterization of the designed LNA.

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