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Performance Evaluation of Matching Networks in Low Noise Amplifiers for GPS Application

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Abstract

This paper introduces the design and performance of a Low Noise Amplifier (LNA) aimed at Global Positioning System (GPS) applications operating at the L1 band (1.575 GHz). The LNA was developed using an AT41511 transistor from Avago Technologies, employing three different matching networks: lumped element, quarter-wave, and single-stub matching networks. Using Microwave Office Software for simulation, performance parameters such as noise figure and gain were evaluated. The single-stub matching network demonstrated the best performance, achieving a noise figure of 2.175 dB and a gain of 14.57 dB, surpassing the minimum design requirements for GPS systems. These findings highlight the superiority of the single-stub matching network for LNA design in GPS receivers.

Keywords: Low Noise Amplifier (LNA), GPS, matching networks, gain, noise figure, AT41511 transistor.

Introduction

Global Positioning System (GPS) technology has become integral to a wide range of applications, including navigation, surveying, and location-based services. GPS operates by receiving signals transmitted from a constellation of satellites orbiting Earth, which allows precise location determination by calculating the time delay between signal transmission and reception. The primary frequency band used for civil GPS applications is the L1 band, operating at 1.575 GHz. Given the weak nature of the received signals due to atmospheric and environmental conditions, low noise amplification is essential in ensuring signal clarity and integrity for accurate positioning (Navidpour et al., 2019; Wang et al., 2019)

At the front end of a GPS receiver is the Low Noise Amplifier (LNA), a critical component tasked with amplifying weak signals received from GPS satellites while introducing minimal additional noise Wingh et al., 2021; Yang and Yoon, 2020). This is particularly important because any degradation in the signal-to-noise ratio (SNR) at this stage would severely affect the accuracy of the system.

Numerous studies have explored different approaches to LNA design, with the goal of improving performance while minimizing size and power consumption. For instance, in (Lee et al.,, 2021), a low-power LNA was developed for GPS applications, achieving a noise figure of 1.8 dB and a gain of 13.5 dB using a combination of lumped elements and microstrip lines. Similarly, (Kang et al., , 2019) presented an LNA design for GPS receivers that utilized a quarter-wave matching network, achieving a noise figure of 2.1 dB and a gain of 14.2 dB. These studies highlight the importance of matching network design in optimizing LNA performance.

In recent years, advancements in transistor technologies have led to the development of LNAs with improved performance metrics. For example, the introduction of GaAs and GaN transistors has enabled the design of LNAs with lower noise figures and higher gains than traditional silicon-based devices (Wu et al., 2020; Park et al.,, 2020). In 2020, a GaN-based LNA for GPS applications achieved a noise figure of 1.5 dB, significantly outperforming silicon-based designs (Zhang and Zang, 2022). Additionally, Hasan demonstrated that GaAs transistors could achieve gains of up to 15 dB, making them highly suitable for GPS receivers (Hasan et al., 2021).

Consequently, the performance of the LNA is typically evaluated based on two key parameters: noise figure (NF) and gain (Lin, 2020; Rahim et al., 2021). The noise figure represents the degradation in SNR caused by the LNA, while gain refers to the amplification of the signal's power. In GPS applications, the desired noise figure is typically less than 2.5 dB, and the gain should exceed 10 dB to ensure reliable signal reception (Noor et al, 2018; Kuo and Lai, 2020).

Given the increasing demand for high-performance GPS receivers in applications such as autonomous vehicles, drones, and smart cities, there is a growing need for LNAs that offer both high gain and low noise figure while maintaining a compact form factor. This study aims to compare the performance of three different matching networks which is lumped element, quarter-wave, and single-stub, in the design of an LNA for GPS applications using the AT41511 transistor. The goal is to identify the optimal matching network that meets the stringent performance requirements of modern GPS systems, including a noise figure below 2.5 dB and a gain exceeding 10 dB. The design process and simulation results for each matching network are discussed in detail in the following sections.

Three matching network configurations were considered in this study: lumped element, quarter-wave, and single-stub matching. The lumped element matching network uses discrete components such as inductors and capacitors to achieve impedance matching. The quarter-wave matching network, on the other hand, relies on transmission lines of a specific length to match the impedances. Finally, the single-stub matching network employs a transmission line with an open or shorted stub to achieve the desired impedance transformation. For each matching network, the design parameters were optimized to achieve the best possible performance in terms of gain and noise figure.

Research Motivation

The motivation for this research stems from the growing reliance on Global Positioning System (GPS) technology across a broad range of applications, including navigation, autonomous vehicles, and location-based services. GPS receivers must amplify weak satellite signals while minimizing noise to maintain accuracy and reliability. Low Noise Amplifiers (LNAs) play a critical role in this process, as they are the first stage in the receiver chain, directly influencing the quality of the received signal.

However, designing an LNA that meets the stringent requirements for GPS systems, such as a noise figure below 2.5 dB and gain exceeding 10 dB, presents significant challenges. Achieving optimal performance requires precise impedance matching between the LNA and the GPS receiver. This research explores different matching network designs—lumped element, quarter-wave, and single-stub matching networks—to determine which approach yields the best noise figure and gain for GPS applications.

With the advent of new technologies, including advanced transistors like the AT41511, and increasing demands for compact, high-performance GPS systems in modern industries such as autonomous transportation, the need for efficient, reliable LNA designs is more critical than ever. This study aims to contribute to these advancements by identifying the most effective matching network for optimal LNA performance in GPS receivers.

Methodology

The LNA design process begins with the selection of the AT41511 transistor, which offers a noise figure of less than 2.5 dB at 1.575 GHz. The transistor's performance is characterized using S-parameters, which are essential for understanding the behavior of the LNA in terms of gain, stability, and noise figure. The S-parameters of the AT41511 transistor were obtained from the manufacturer's datasheet and used to design the matching networks.

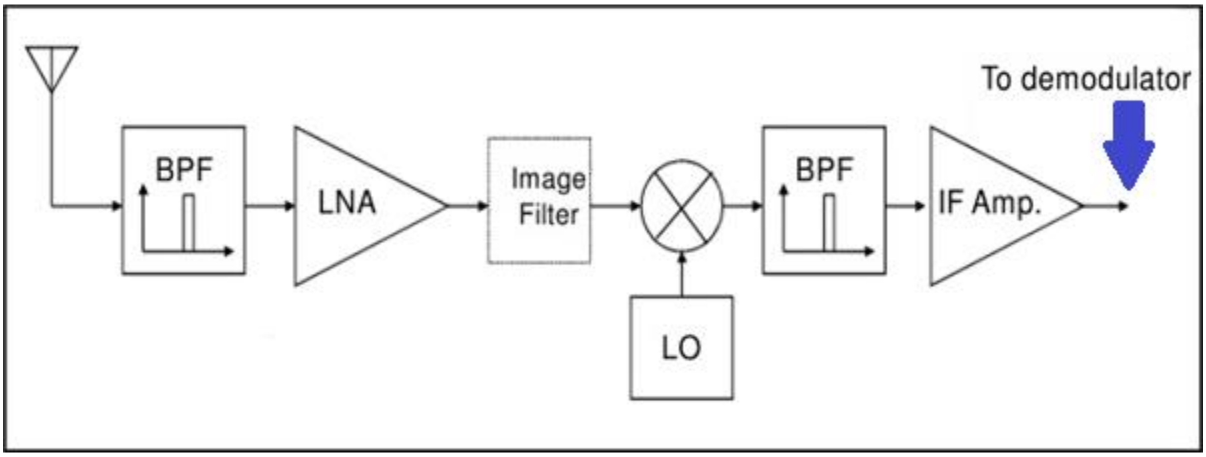

Figure 1: GPS receiver architecture

For GPS receivers, the AT41511 transistor, a low-noise, high-gain device manufactured by Avago Technologies, has been widely used due to its low noise figure and excellent linearity, see Figure 1. The performance of the LNA can be further optimized by designing appropriate impedance matching networks that minimize signal reflection and maximize power transfer between the source and load (Ahmed, 2020). Three types of matching networks are typically used in LNA designs: lumped element, quarter-wave, and single-stub matching networks. Each of these techniques offers different trade-offs in terms of design complexity, physical size, and performance characteristics (Hassan et al, 2021). Table 1 shows the design specification for the proposed LNA.

Table 1

LNA specification

Parameter	Value
Frequency	1.575 Ghz
Gain	> 10 dB
Noise Figure	< 2.5 dB
Return Loss	< -10 dB

Transistor is considered unconditional stability, checked using *Rollet's condition, K* and *Auxiliary condition,* Δ.

$$K = \frac{1 + |\Delta|^2 - |S_{11}|^2 - |S_{22}|^2}{2|S_{12}S_{21}|}, K > 1 \tag{1}$$

$$|\Delta| = |S_{11}S_{22} - S_{12}S_{21}| > 1 \tag{2}$$

The AT-41511 transistor is selected with a V_{CE} of 2.7V and I_C of 10 mA, as these operating conditions result in a low noise figure. The gain and noise figure values can be derived from the S-parameters at 1.575 GHz, which were obtained through simulations using AWR software and calculated using the relevant equations.

$$\text{Power gain, } G = \frac{|S_{21}|^2\left(1 - |\Gamma_L|^2\right)}{\left(1 - |\Gamma_{in}|^2\right)|1 - S_{22}\Gamma_L|^2} \tag{3}$$

$$\text{Available gain, } G_A = \frac{|S_{21}|^2\left(1 - |\Gamma_S|^2\right)}{\left(1 - |\Gamma_{out}|^2\right)|1 - S_{11}\Gamma_S|^2} \tag{4}$$

$$\text{Transducer gain, } G_T = \frac{|S_{21}|^2\left(1 - |\Gamma_S|^2\right)\left(1 - |\Gamma_L|^2\right)}{|1 - S_{22}\Gamma_L|^2 |1 - \Gamma_{in}\Gamma_S|^2} \tag{5}$$

$$\text{Noise Figure, } F = F_{\min} + \frac{4R_n|\Gamma_s - \Gamma_{opt}|}{Z_o|1 + \Gamma_{opt}|^2\left(1 - |\Gamma_S|^2\right)} \tag{6}$$

Lumped-element matching network calculated by;

$$C = \frac{-1}{2\pi f x Z_o} \tag{7}$$

$$L = \frac{-Z_o}{2\pi f b} \tag{8}$$

Lumped element matching networks use discrete components such as inductors and capacitors to achieve impedance matching as shown in Figure 2 and Figure 3. These networks are simple and compact, making them ideal for applications where space is limited (Zhang, 2023). However, their performance is often constrained by the limited availability of discrete component values, which can make it difficult to achieve optimal matching.

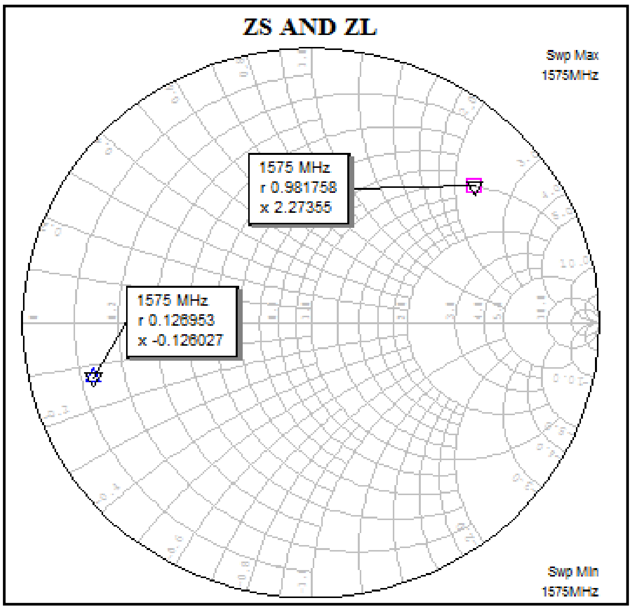

Figure 2: Smith Chart for load impedance

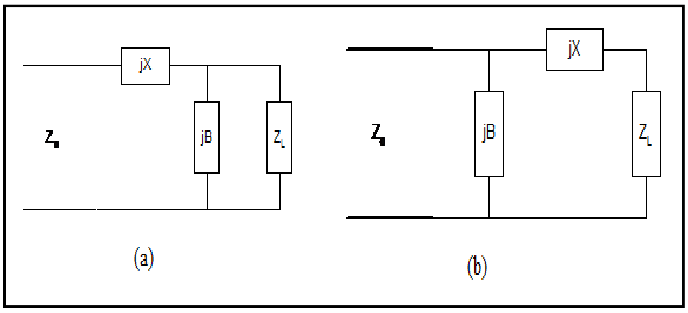

Figure 3: L-section network matching

In contrast, quarter-wave matching networks use transmission lines with a length of one-quarter of the wavelength of the operating frequency to transform impedances. Figure 4, Figure 5 and Figure 6 show the design for quarter wave matching network. While this method offers better performance in terms of gain and noise figure, it requires more space, which can be a limitation in compact GPS receivers (Sharma et al., 2020; Wang and Tang, 2020).

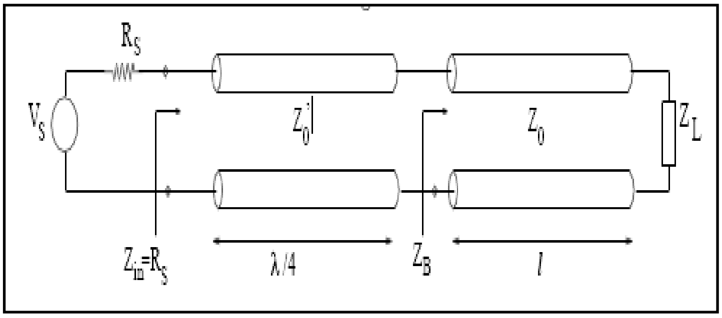

Figure 4: The quarter wave matching network

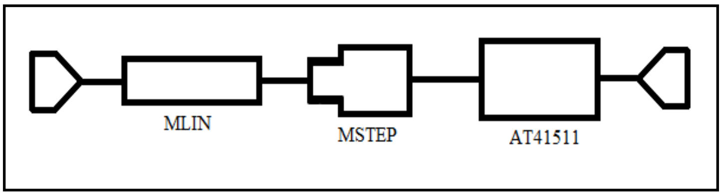

Figure 5: The Input Matching Network

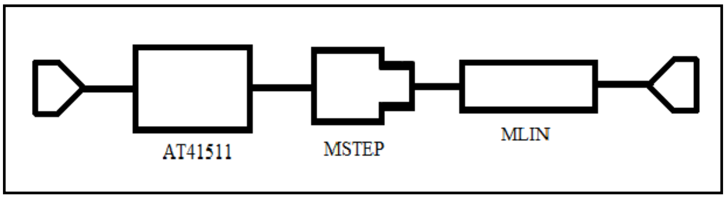

Figure 6: The Output Matching Network

Referring to Figure 7 and Figure 8, the single-stub matching network, on the other hand, is a hybrid approach that uses both transmission lines and stubs (either open or shorted) to achieve impedance matching. This technique offers a balance between performance and size, making it well-suited for GPS applications (Chen and Chen, 2021).

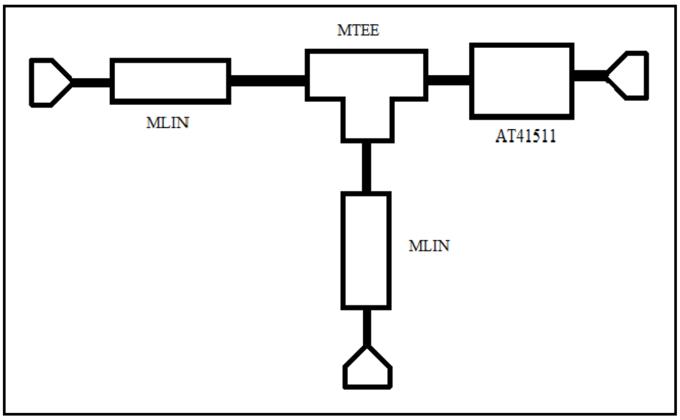

Figure 7: The Input Matching Network single-stub matching network

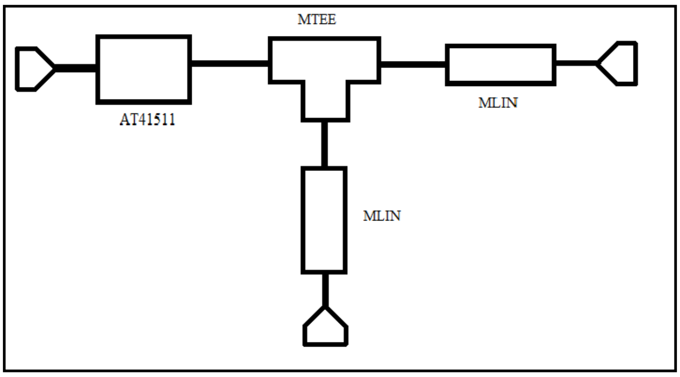

Figure 8: The Output Matching Network single-stub matching network

The design of the LNA is centered around the AT41511 transistor, which was chosen for its low noise and high gain characteristics. The primary challenge in LNA design is to achieve optimal impedance matching between the transistor and the input/output stages to minimize reflections and maximize power transfer. This is achieved through the use of matching networks, which are designed to match the impedance of the source and load to the transistor's impedance.

Result and Analysis

AT41511 was simulated to determined its characteristic. S-parameter and parameter for the transistor is shown in Table 2 and Table 3 respectively.

Table 2

AT41511 S-parameter

AT41511 S-parameter
$S_{11} = 0.439 \angle 166$
$S_{12} = 0.086 \angle 56$
$S_{21} = 3.7513 \angle 66.785$
$S_{22} = 0.37249 \angle -40745$

Table 3

AT-41511 transistor parameter

Parameter	Calculation (dB)	Simulation (dB)
K	1.07	1.0743
Δ	0.347	0.3465
Power Gain	12.42	12.417
Available Gain	12.13	12.132
Transducer Gain	11.48	11.484
Noise Figure	2.443	1.6255

K is the stability factor, where values greater than 1 indicate unconditional stability of the transistor. Both the calculated (1.07) and simulated (1.0743) values confirm that the AT-41511 is stable across the operating frequency of 1.575 GHz. Δ represents the auxiliary stability condition, with values close to the calculated (0.347) and simulated (0.3465) results indicating the transistor's ability to avoid oscillations under various loads. The gain values are divided into three types: Power gain (12.42 dB calculated, 12.417 dB simulated), Available gain (12.13 dB calculated, 12.132 dB simulated), and Transducer gain (11.48 dB calculated, 11.484 dB simulated). These values indicate the transistor's ability to amplify the signal effectively, with the small differences between calculated and simulated results confirming the accuracy of the model. The calculated Noise Figure value (2.443 dB) is slightly higher than the simulated result (1.6255 dB), showing that the AT-41511 delivers a very low noise figure, making it suitable for high-performance GPS LNAs.

Table 4

MSUB specification

Specifications	Value
Dielectic Constant, E_r	4.6
Height	1.6mm
Thickness	0.0035mm
Tand	0.0019

The specification of the MSUB substrate is shows in table 4.

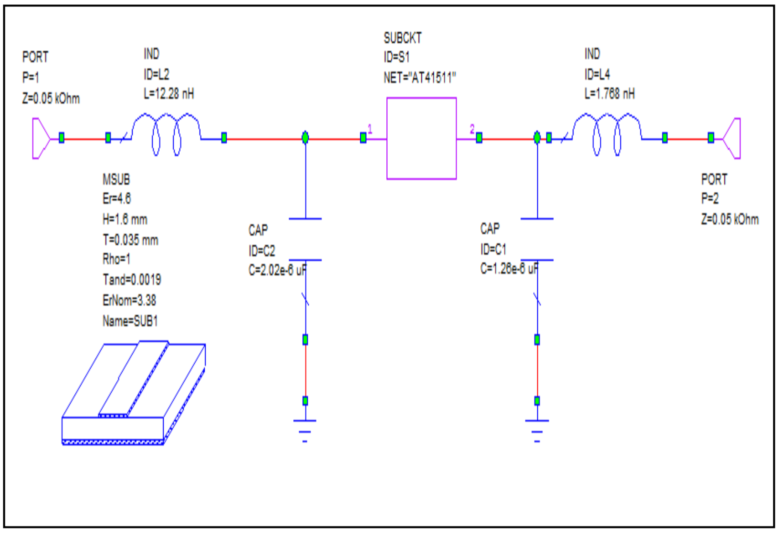

Figure 9: Lumped Element matching network configuration

Table 5

Lumped element

Components	**Value**
L2	12.28nH
C2	2.02pF
C1	1.768nH
L4	1.25pF

Figure 9 illustrates the lumped element simulation circuit used for the matching network in the LNA design, while Table 5 provides the corresponding lumped element values for the components used in this matching circuit.

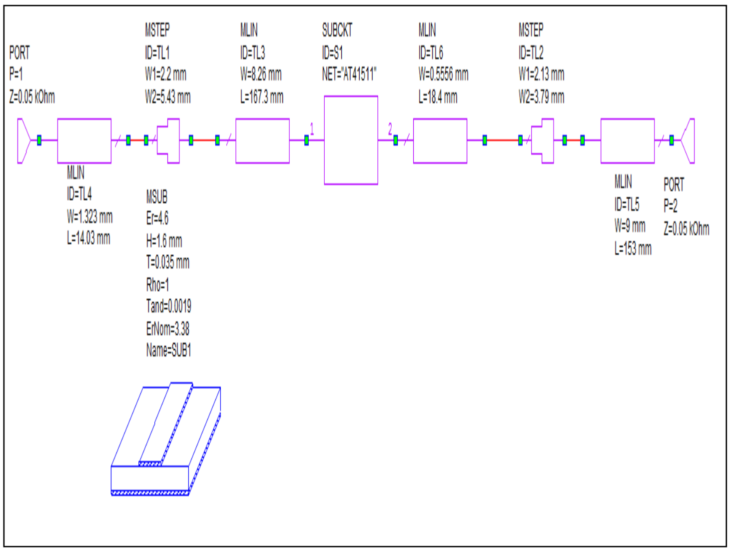

Figure 10: Quarter wave matching network configuration

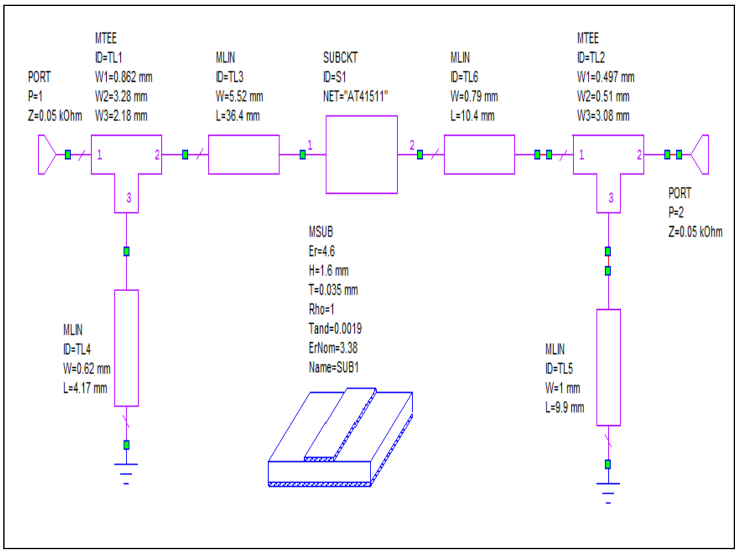

Figure 11: Single Stub matching network configuration

Figure 10 shows the quarter-wave matching network configuration, while Figure 11 depicts the single-stub matching network configuration. The Smith Chart was utilized to determine the appropriate length and distance for both the single-stub and quarter-wave networks, with the rotation on the Smith Chart playing a crucial role in optimizing these parameters. Comparing the performance of these configurations, the single-stub matching network consistently outperforms the quarter-wave design in terms of gain and noise figure, making it more suitable for LNA applications.

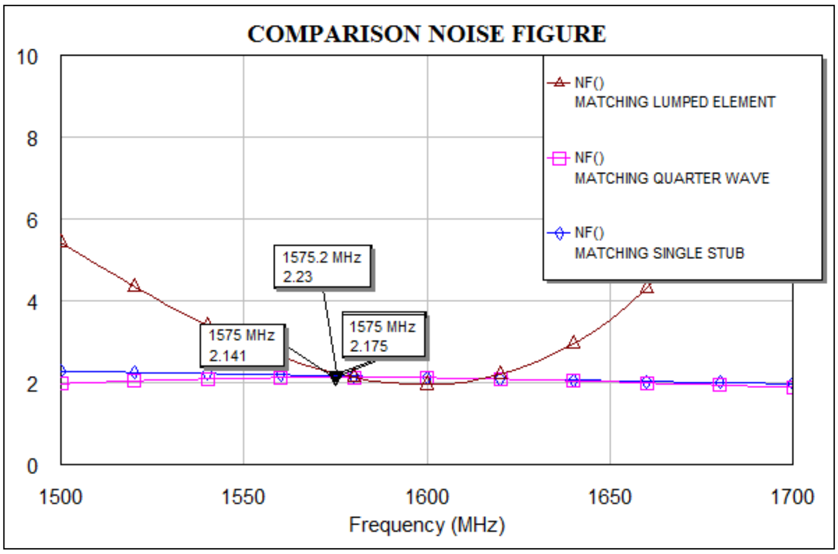

Figure 12: The comparisons of noise figure

As depicted in Figure 12, the noise figures for the three matching techniques—lumped element, quarter-wave, and single-stub—are 2.23 dB, 2.141 dB, and 2.175 dB, respectively. Since GPS applications require a noise figure below 2.5 dB, all three designs using the AT-41511 transistor meet the necessary criteria for GPS use.

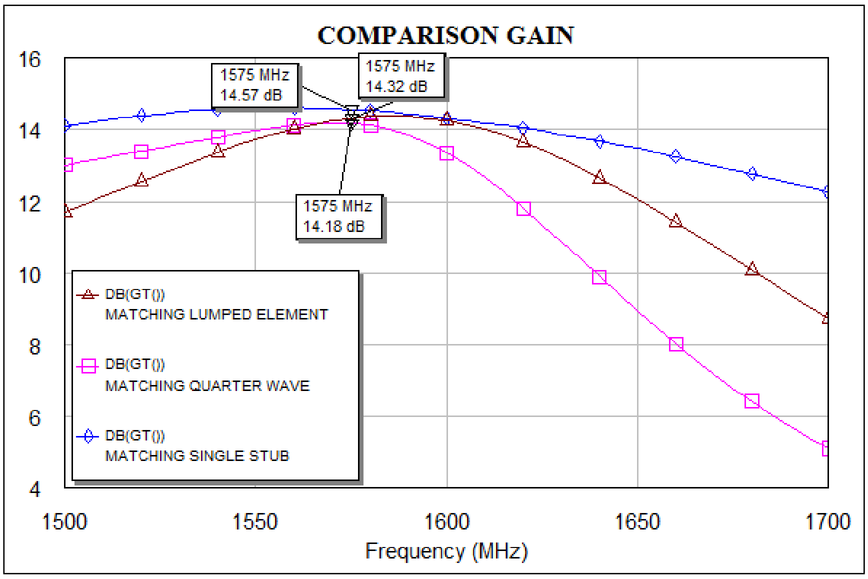

Figure 13: The comparisons of gain

In Figure 13, the gain performance of the three matching networks is compared. The lumped element matching network achieves a gain of 14.18 dB, and the quarter-wave design reaches 14.32 dB. The single-stub matching network, however, provides the highest gain at 14.57 dB. Given that GPS systems require a minimum gain of 10 dB, all designs satisfy this requirement, with the single-stub design being the most effective.

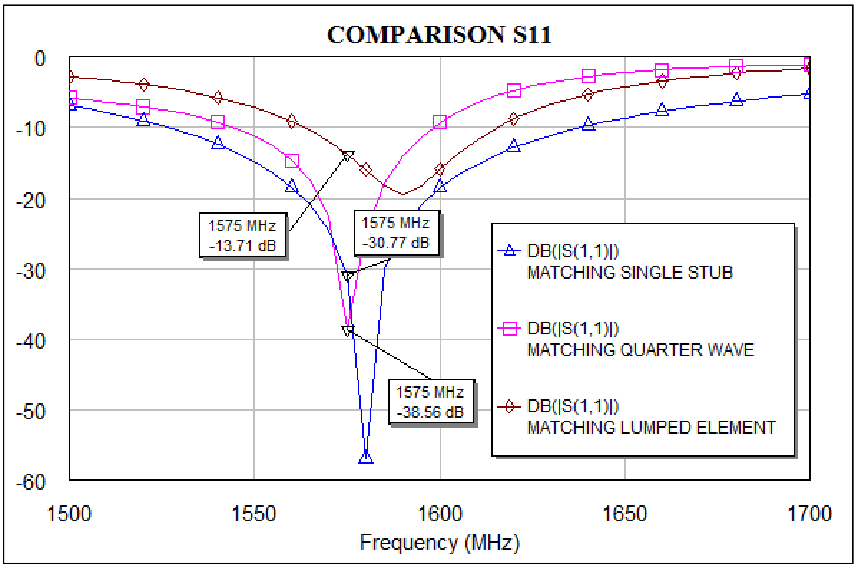

Figure 14: The comparisons of input return loss

Figure 14 highlights the input return loss (S_{11}) across the different matching networks. For the lumped element configuration, S_{11} is -13.71 dB, while the quarter-wave network shows significantly better performance at -38.56 dB. The single-stub network registers an input return loss of -30.77 dB. Both the quarter-wave and single-stub networks offer excellent return loss characteristics, indicating minimal signal reflection.

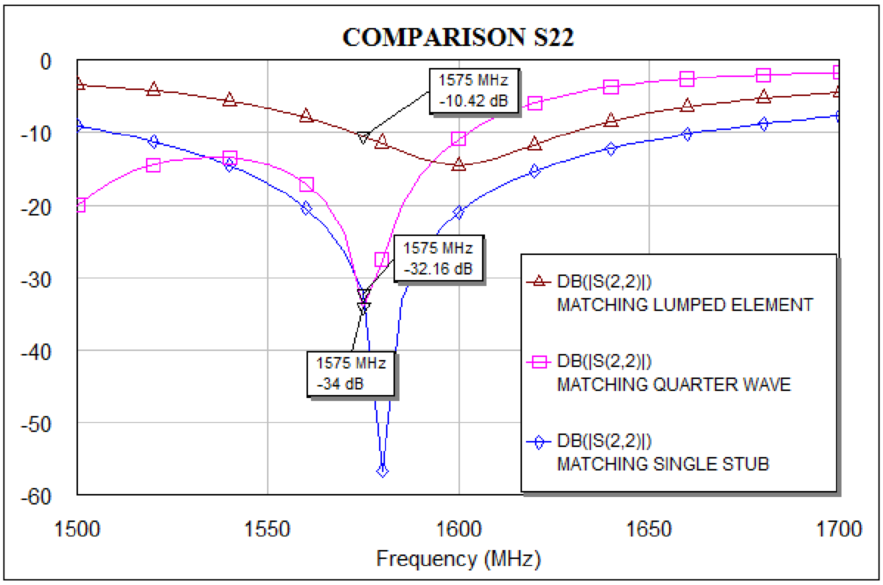

Figure 15: The comparisons of output return loss

Figure 15 presents the output return loss (S_{22}) results. For the lumped element configuration, S_{22} is -10.42 dB, while the quarter-wave network achieves a much better value of -32.16 dB. The single-stub network performs even better with an S_{22} of -34 dB. A return loss of less than -10 dB is essential, as it indicates that most of the signal is transmitted with minimal power reflection. Therefore, all three designs ensure more than 90% of the transmitted power reaches the load, with the quarter-wave and single-stub networks being superior.

Table 6

Comparison of Matching Networks

Parameter	Lumped Element	Quarter-Wave	Single-Stub
Noise Figure (dB)	2.234	2.141	2.175
Gain (dB)	14.18	14.32	14.57
Input Return Loss (dB)	-13.71	-38.56	-30.77
Output Return Loss (dB)	-10.42	-32.16	-34.00

The noise figure (NF) of the single-stub matching network was 2.175 dB, which is well below the 2.5 dB requirement for GPS applications. Additionally, the gain of 14.57 dB exceeded the minimum gain requirement of 10 dB, making this design highly suitable for GPS receivers. The input return loss S_{11} and output return loss S_{22} were also favourable, indicating that the matching network effectively minimized signal reflections and maximized power transfer.

Table 6 show the summarization of the noise figure and gain of the LNA for the three matching networks, as well as their return loss performance. As seen in the figures, the single-stub matching network consistently outperformed the other designs across the frequency band of interest.

Conclusion and Future Work

In conclusion, this paper presents the design and performance evaluation of a LNA for GPS applications operating at the L1 band (1.575 GHz). The LNA was designed using the AT41511 transistor, with three different matching networks evaluated: lumped element, quarter-wave, and single-stub. The single-stub matching network provided the best performance, achieving a noise figure of 2.175 dB and a gain of 14.57 dB, making it the most suitable for GPS receiver applications.

The lumped element matching network was the simplest to design, but it had limitations in terms of fabrication and implementation. The quarter-wave matching network provided better performance in terms of gain, but it was larger and more complex to implement. The single-stub matching network, however, offered the best overall performance, with a noise figure of 2.175 dB and a gain of 14.57 dB.

This study demonstrates that the choice of matching network plays a significant role in the overall performance of the LNA. Future work could explore the use of other matching techniques or alternative transistor technologies to further optimize LNA performance.

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