An Impedance Matching Network towards Amplifier Design from Conceptual to Practical: Simulation Study

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Abstract. In many systems, the impedance matching networks are vital to ensure their having good performances, especially in such systems performances that related to the gain, linearity, and quality factors. This article mainly focuses on the simulation study of the impedance matching network from conceptual to practical on amplifier design. This simulation study from the conceptual of the ideal transmission-line based design to the practical of the microstrip-line based circuit implemented by using LineCalc of the ADS tool. The gallium nitride high electron mobility (GaN-HEMT) transistor by Cree is being one of the key components in understanding the importance of the impedance matching networks on the amplifier design at the operating frequency of 5 GHz. The Agilent’s Advance Design Systems (ADS) is used to perform this research. The obtained voltage standing wave ratio (VSWR) are approximately to 1 for both conceptual and practical of the impedance matching towards the amplifier design at 5 GHz. Thus, it is showing the maximum power transfer was occurring from the power stages to the load.

1. Introduction

The impedance matching network are widely implemented in active microwave measurement circuits purposely to improve their performances of the systems. The performances of the systems which influence by the impedance matching networks are power gain, output power level, efficiency [2]-[8], [12], quality factor, linearity, and losses [4], [9]-[11]. Therefore, the impedance matching network is a crucial part in such systems. The main function of the impedance matching network is to deliver the maximum power and to provide the desired impedance to the circuit to achieve other desired characteristics. Usually, the impedance matching networks in the microwave amplifier design employs at its input and output, which known as impedance matching and output matching, respectively. The input impedance matching can boost the power gain and have the lower influence on the efficiency performance of the systems. Subsequently, the output impedance promotes the optimum output power [5], maximum linearity and has the highest influence on the efficiency of the system [2]-[8]. The general impedance matching networks on the transistor amplifier design block diagrams will be modelled as presented in Figure 1.

![Figure 1](image-url)  

**Figure 1.** Block diagram of the impedance networks towards the transistor amplifier design [9]-[10].
In this article mainly focuses on the simulation study of the impedance matching networks towards gallium nitride high electron mobility (GaN-HEMT) transistor at an operating frequency of 5 GHz. GaN-HEMT transistor by Cree of CGH4006P offers a general purpose, broadband solution to a variety of RF and microwave application. Their high efficiency, immense gain and wide bandwidth capabilities was makes it are ideally for linear and compressed amplifier circuits [10]. The investigation and understanding on the importance of the impedance matching network towards amplifier design are evaluated by reflection coefficients and voltage standing wave ratio (VSWR). VSWR is a way to measure transmission line inaccuracy and the efficiency of the radio frequency (RF) power transmission from the power source, through the transmission line and into the load. It also performs the ratio between the transmitted and reflected wave, where it is related to system efficiency. Meanwhile, the amplifier is an integral part of any communication system that promotes the signal to the desired level [1].

The simulation study of the impedance matching network highlighted in this article is based on the manufacturer impedance values of the GaN-HEMT transistor of CGH40006P given in the technical datasheet at an operating frequency of 5 GHz [10]. Furthermore, the simulation study of the implementation of the impedance matching towards amplifier design mainly focuses on the operational mechanism and design arts of the ADS simulation software which also referred as ADS tool. The ADS tool is chosen due to it is characterized as reliable, efficient, and controlled functioning compared to the conventional approaches. This simulation tool also allows microwave engineers to analyze, design and simulate the active and passive microwave components and systems. The layout and powerful optimization cockpit in ADS simulation software will be helped to increase the productivity and efficiency, validating high-yield design prior to practical manufacturing [1]. The block diagram as represents in Figure 2 shown their scattering parameters (S-parameters) behaviors to model the general concept of the transistor [9]. The reflection coefficient at Port 1 when Port 2 is matched, and at Port 2 when Port 1 is matched was represented by S11 and S12, respectively. Meanwhile, the transmission coefficient at Port 1 when Port 2 is matched was represented by S21 and S22, respectively.

This article is organized as follows. Section 2 discusses on the overview of the amplifier characteristics. Then, followed by the impedance matching network towards the amplifier design mechanism at 5 GHz. In the subsection 3.1, the input matching network is presented. Then, followed by the output matching network discussed in subsection 3.2. The input and output matching network are started by conceptual ideal transmission-line based design.

Next, proceed to practical microstrip-line based circuit by LineCalc in ADS simulation software. Section 4 explained about the simulation results of input and output matching networks of conceptual ideal transmission-line and practical microstrip-line which includes the obtained reflection coefficients and VSWR performances of GaN-HEMT transistor (CGH400006P) towards amplifier design. Finally, our work examined in this article is summarized in the last section.

2. Amplifier design characteristics

An amplifier is a most paramount block of the communication systems which amplify the signal by increases the strength of the input signal, where it will amplify the weak signal to a reasonable working level [9]. In conventional approaches, there are many references available to design the basic amplifier concepts and design. The vital design characteristic is needs accountable to obtain good performances depends on the purpose of the amplifier design, such as gain performance, stability conditions, noise figure, losses and others depends on their applications.
As example, there are several power gain equations used to design an amplifier like transducer power gain (GT), the operating power gain (GP) and the available power gain (GA). Besides that, the maximum available gain (MAG) of a device is only defined when Rollet’s stability factor (K) is greater than 1. This is because the term under the square-root becomes negative for the value of K less than 1, thus the gain is infinite. When the gain is infinite, it is means that the oscillation was occurred, thus the device is failed to perform as amplifier. In addition, the maximum stable gain (MSG) of the device is defined when the MAG is undefined, where the value of K is less than 1. This is merely the ratio of the magnitude S21 divided to magnitude S12 as represents in (1) [1], [13], [15].

\[
MAG = \left| \frac{S_{12}}{S_{21}} \left( k \pm \sqrt{k^2 - 1} \right) \right|
\]  

Besides that, the Rollet’s stability factor (K) can be used to determine whether the device is in stable or unstable condition. The stability of the amplifiers is referring to it immunity to causing spurious oscillations. There are two possibility condition either the value of K greater than 1 or K less than 1. When K >1, the device is in unconditionally stable condition, while the device is conditionally stable and potentially unstable condition when K < 1. Thus, the absolute stability condition of the amplifier which defined by K is given by (2). The unconditional stability of the amplifier circuit is one of the goals of the amplifier designer [1], [9], [13]-[15].

\[
K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2}{2|S_{12}||S_{21}|}, |\Delta| = |S_{11}S_{22} - S_{12}S_{21}| < 1
\]  

Concurrently, a Smith chart as graphical technique to visual illustration of radio frequency (RF) stability will be executed through the stability circles, where the circumference of the circles is represented the locus of all borderline terminations [1]. The stability circles are a determination of load or source value that must be avoided to achieve non-oscillation behavior of the device. It also knew as the area of instability for the input and output. The region inside the circle is considered as the instability area, while the region outside the circle represents the stable region [13]. The centre and radius of the stability circle can be determined by (3) and (4) for the input and output, respectively [15].

\[
C_s = \frac{S_{11} - \Delta S_{22}^*}{|S_{11}|^2 - |\Delta|^2}, R_s = \frac{|S_{12}S_{21}|}{|S_{11}|^2 - |\Delta|^2}
\]

\[
C_l = \frac{S_{22} - \Delta S_{11}^*}{|S_{22}|^2 - |\Delta|^2}, R_l = \frac{|S_{12}S_{21}|}{|S_{22}|^2 - |\Delta|^2}
\]

Another important characteristic for an amplifier is a matching network. The input matching network can be generated by the input impedance of the transistor with source impedance, while the output impedance matching with load impedance will be generated an output matching network. Generally, the input and output impedance of the transistor can be calculated from input and output reflection coefficient as represent by (5) and (6), respectively [15].

\[
\Gamma_{in} = S_{11} + \left( \frac{S_{12}S_{21}I_L}{1 - S_{22}I_L} \right) = \frac{S_{11} - \Delta \Gamma_s}{1 - \Delta \Gamma_s}
\]

\[
\Gamma_{out} = S_{22} + \left( \frac{S_{12}S_{21}I_L}{1 - S_{11}I_L} \right) = \frac{S_{22} - \Delta \Gamma_s}{1 - \Delta \Gamma_s}
\]
The matching networks either input or output matching must provide DC paths for biasing and some active elements. The input and output matching networks follow the different design principle based on the specific matching function. In purpose to easily understand and overview towards amplifier design, the implementation of the matching networks is performed by using ADS tool in this article. The details about that are discussed in the next following section 3.

3. Impedance matching network towards amplifier design

The impedance matching network towards amplifier design are divided into two main parts, which is input and output matching where it started with the conceptual ideal transmission-line based design before proceeding to the practical microstrip-line based circuit by using LineCalc. The LineCalc is one of an interactive tool that available in ADS simulation software. The details of these parts are discussed in subsection 2.1 and 2.2, respectively.

The flows of the experimental and understanding of this simulation study is illustrated in Figure 3, while the impedance values of S-parameters for GaN-HEMT transistor (CGH40006P) [16] are stated in Table 1. As mentioned earlier, this simulation study is performed in ADS simulation software.

![Flow chart simulation study of the impedance matching networks towards amplifier design.](image)

**Table 1.** Impedance values of S-parameters of the GaN-HEMT transistor by Cree (CGH40006P) at 5 GHz.

| Operating Frequency | $Z_{\text{source}}$ | $Z_{\text{load}}$ |
|---------------------|---------------------|-------------------|
| 5 GHz               | 4.42-j25.8          | 9.78+j4.85        |
By using these impedance values, the input and output impedance matching network are easily designed by using Smith Chart. The Smith Chart Utility is an iterative tool in ADS simulation software as illustrated in Figure 4. It provides full Smith Chart capabilities, enabling impedance matching, synthesis of matching networks and plotting of gain or quality factors (Q) or VSWR and noise circles. Mainly, the choosing of the matching network’s topology depends on the bandwidth of the amplifier design [1].

Through these available tools in ADS software, the conceptual ideal transmission-line based design can be obtained. Then, the obtained matching networks topology is used as references to obtain the width and length of the practical microstrip-line based circuit. The LineCalc as shown in Figure 5 will be used for this purpose, while Rogers 4003C by Rogers Corporation is used as substrate. This substrate has low dielectric tolerance, low loss and its excellent electrical performances makes it a good choice for applications at high operating frequency range [17].

![Smith Chart Utility in ADS tool software.](image1)

**Figure 4.** Smith Chart Utility in ADS tool software.

![LineCalc in ADS software.](image2)

**Figure 5.** LineCalc in ADS software.
Besides that, Figure 6 represent the impedance matching networks in ADS schematic for input and output impedance matching with transistor.

![Figure 6](image)

**Figure 6.** Impedance matching network in ADS schematic.

### 3.1. Input matching network

The simulation study of the input matching network for GaN-HEMT transistor in amplifier design at the operating frequency of 5 GHz is investigated from the conceptual ideal transmission-line based design to the practical microstrip-line based circuit. The Smith Chart Utility in ADS tool software is used to obtain the ideal transmission-line based design is illustrated as Figure 7. Then, the width and length of microstrip-line are obtained by using LineCalc. The ADS schematic for input matching network of conceptual ideal transmission-line based design and practical microstrip-line based circuit are shown in Figure 8. Thus, the obtained results of input matching network are discussed in Section 3 which included the VSWR performances of GaN-HEMT transistor (CGH40006P) towards amplifier design.

![Figure 7](image)

**Figure 7.** Input impedance matching network obtained by using Smith Chart Utility in ADS tool software.
3.2. Output matching network

A similar procedure as for input impedance matching is reciprocated for the output impedance matching for GaN-HEMT transistor in amplifier design at the operating frequency of 5 GHz. The ideal transmission-line based design that obtained by using Smith Chart Utility in ADS tool software is shown in Figure 9, whilst Figure 10 illustrates ADS schematic for output matching network of conceptual ideal transmission-line and practical microstrip-line.

Figure 8. ADS schematic for input matching network of the conceptual ideal transmission line and the practical microstrip-line.

Figure 9. Output impedance matching network obtained by using Smith Chart Utility in ADS tool software.
Figure 10. ADS schematic for output matching network of the conceptual ideal transmission line and the practical microstrip-line.

The acquired results of the output matching network are also discussed in the next following Section 4, which includes the reflection coefficients and VSWR performances of GaN-HEMT transistor (CGH40006P) towards the amplifier design.

4. Simulation results and discussion

The obtained simulation results of the conceptual ideal transmission-line based design are represented in Figure 11 and 12. Figure 11 illustrates the S-parameters of the input and output matching networks that analyzed by using Smith Chart Utility in ADS tool software. As can be seen in Figure 11, the $S_{11}$ and $S_{22}$ response of the impedance matching networks for conceptual ideal transmission-line based design are shown good performance at required operating frequency of 5 GHz.

Meanwhile, Figure 12 and Figure 13 shows the reflection coefficients and VSWR, respectively for the amplifier design at the operating frequency of 5 GHz.
Figure 12. Reflection coefficients for the impedance matching network of the conceptual ideal transmission-line based design.

Figure 13. VSWR for the impedance matching network of the conceptual ideal transmission-line based design.

The obtained magnitude of $S_{11}$ (reflection coefficient) response in Figure 12 is approximately 0 at their operating frequency of 5 GHz. It means, this amplifier design has properly matched between the source and load. While the obtained VSWR at operating frequency of 5 GHz in Figure 13 is around 1 signify that the maximum power transfer was occurred from the power stages to the load.

Next, the optimization and tunable of the lengths of all lines is required for the practical microstrip-line based circuit. The optimization is performing by using Optimization Cockpit tool as illustrated in Figure 14.

Figure 14. Optimization cockpit in ADS simulation software.

The obtained results for practical microstrip-line based circuit after prosecuted optimization and tunable by ADS tool in Figure 14 are represents in Figure 15 until Figure 17.
S-parameter responses for the impedance matching network of the practical microstrip-line based circuit.

Figure 15. $S_{11}$ and $S_{22}$ responses for the impedance matching network of the practical microstrip-line based circuit.

$S_{11}$ and $S_{22}$ responses of impedance matching networks for practical microstrip-line based circuit that executed using LineCalc from ideal transmission-line based design are illustrated in Figure 15. These acquired results still shown good performance at required operating frequency of 5 GHz even it was a little shifted.

Reflection coefficients $(S_{11})$  

Voltage standing wave ratio (VSWR)

Figure 16. Reflection coefficients for the impedance matching network of the practical microstrip-line based circuit.

Figure 17. VSWR for the impedance matching network of the practical microstrip-line based circuit.

Besides that, Figure 16 and Figure 17 shows the reflection coefficients and VSWR, respectively for practical microstrip-line based circuit. The obtained reflection coefficient (magnitude of $S_{11}$) in Figure 16 is 0.057 which approximately around 0 at operating frequency of 5 GHz. This amplifier design can clarify has properly matched between source and load. Meanwhile, the acquired VSWR in Figure 17 at operating frequency of 5 GHz is around 1 indicates the maximum power has been transfer from the power stages to the load.

5. Conclusion

As conclusion, this article describes about the simulation study of the impedance matching network from the conceptual transmission-line based design to the practical microstrip-line based circuits. The interactive procedure is represented by ADS tools software which provides easier understanding and references of the overview to implement matching network towards amplifier design. For both conditions, the impedance matching network focused on input and output matching network. To investigate and understand the ways of an importance of the impedance matching network towards amplifier design, the manufacturer S-parameters of the GaN-HEMT transistor (CGH40006P) by Cree, which given in the technical datasheet at operating frequency of 5 GHz are used. The obtained results...
for the reflection coefficients of both conditions shows that, the amplifier design has properly matched between source and load. Meanwhile, the acquired VSWR represents the maximum power transfer has occurred for both condition when it is approximately to 1.

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