A 2.5-GHz GaN power amplifier design and modeling by circuit-electromagnetic co-simulation

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Abstract—In this paper a 2.5-GHz GaN power amplifier is presented. The amplifier is designed to achieve unconditional stability in the frequency range from DC to 6 GHz. The circuit-EM co-simulation model of the complete amplifier, including transistor model, passive components, connector model and the EM model of the critical parts of the design is created. The impact of each component is addressed. The amplifier is processed and measured, the measurements are compared to simulations and a good agreement is achieved. The amplifier parameters power added efficiency (PAE), drain efficiency (DE) and IP3 are measured and compared to results published in open literature.

I. INTRODUCTION

The growing market of wireless communications operating at GHz frequencies continues to push boundaries of transistor development. Significant effort is invested in high performance microwave transistors based on Gallium Nitride. GaN-based high electron mobility transistors (HEMTs) have many advantages over other existing technologies, such as high output power density, high operating voltage, higher impedance, higher operating temperatures [1] and better noise performance (compared to MESFET’s) [1, 2] which makes it ideal for RF power amplifier applications.

RF power amplifiers are mostly processed using MMIC technology [3-5] or a printed circuit board technology [6, 7]. If a printed circuit board technology is used, external SMD passive components are typically employed for impedance matching and bias supply network. However, SMD passive components are not ideal; at RF frequencies their characteristics are significantly different from the nominal characteristics [8]. Models of passive components that capture their behavior at high frequencies are therefore needed to achieve better agreement between measurements and simulations. This in return enables optimization of a design in an early stage of design cycle, therefore reducing the time and expenses necessary for the project.

A power amplifier using the same transistor as in this paper is designed in [5]. 3D simulations and model developing for lumped elements, bond wires and coaxial connectors have been considered for the power amplifier design in [6]; however, no additional information on the modeled structures or the impact of the modeled components on the modeled amplifier characteristics has been given. The main focus of this paper is the characterization and optimization of the RF power amplifier realized in a printed circuit board technology with respect to the high frequency models of passive components. Simple circuit models for each of the modeled components are given and the impact of each modeled component on the amplifier characteristics is addressed.

The design process and simulation models are presented in Section II. The simulations are compared to measurements in Section III. Section IV concludes the paper.

II. POWER AMPLIFIER DESIGN AND SIMULATION MODEL

The schematic of the amplifier is based on [9] and is shown in Fig. 1. The substrate on which the amplifier is designed is 1.55-mm thick FR4 (εr = 4.4, tanδ = 0.02 at 1 GHz). The transmission line technology used for interconnects is a grounded coplanar waveguide. The transistor model used in simulations is the small-signal S-parameters model provided by the manufacturer [9]. The values of the passive components and transmission line lengths are optimized to achieve impedance matching and maximum gain at 2.5 GHz. The parameters of the optimized passive components and transmission lines are shown in Fig. 1. The high frequency models of passive components, connector model and T-junction EM-based model used in the simulations are discussed in the rest of this section. Four amplifier models are created and compared to measurements to assess the effect of each of the components described in this section:

a) 1st model – includes only the transistor model, transmission line models and ideal passive component models.

b) 2nd model – the same as the 1st model, but with the high frequency passive component models instead of the ideal ones.

c) 3rd model – the same as the 2nd model, but with the connector model added.

d) 4th model – the same as the 3rd model, but with the additional EM-based models of T-junctions.
High frequency passive components models

High frequency capacitor and resistor models and their corresponding parameter values of 0805-package on grounded coplanar waveguide and 1.55-mm thick FR4 substrate [10] used in simulations are shown in Fig. 2 and Fig. 3, respectively.

Connector model

The connectors at RF ports used in simulations are Southwest Microwave’s 292-04A-5 end-launch connectors and are mounted without soldering [11]. The connector model [12] used in the simulations is shown in Fig. 4. Three coplanar waveguide lines of different lengths (30 mm, 80 mm and 130 mm) are used to optimize the model.

Circuit-EM co-simulation

The segmentation technique is used to characterize the grounded coplanar waveguide T-junctions present in the design: electromagnetic simulation of the T-junction is performed and an optimization of the T-junction grounded coplanar waveguide model [13] is carried out to extract the parameters of the model. The model and the corresponding parameters used in the simulation are shown in Fig. 5.

Achieving unconditional stability

Finally, having the complete model, the stability of the amplifier is assessed. One of the most challenging problems in the design of RF amplifiers is its stability at low out-of-band frequencies [14]. In particular, simulations of this amplifier showed possible instability around 1 GHz. One of the possible solutions is adding a series gate resistance [14, 15]. The simulations showed improvement even with small values of the resistance. The final design is unconditionally stable with the 1-Ω series gate resistance. The associated simulated gain loss is only 0.1 dB.
III. MEASUREMENTS

$S$-parameters

The amplifier bias point for the measurements is $V_{DS} = 14\,V$ and $I_{DS} = 50\,mA$. The comparison of four models and the measurements is shown in Fig. 6. The 1st model does not predict the amplifier characteristics at satisfactory level (Fig. 6a). Adding high frequency passive components models improves the amplitude characteristics up to 4 GHz (Fig. 6b). Adding connector model improves the phase characteristic up to 4 GHz (Fig. 6c). Finally, the frequency of the maximum gain is matched to the measured one in the 4th model by adding the EM-based T-junction model (Fig. 6d). It should be noted that the frequency of the maximum gain is shifted from 2.5 GHz to 2.35 GHz. The measured gain at 2.35 GHz is 14.1 dB, while the simulated one is 16.7 dB. The reason for this difference is most probably the tolerance of the nominal values of passive components in the RF nets.

The comparison between the measurements and the 4th model show good agreement, similar to the comparison between the measurements and simulations presented in [6] (it should be noted that the amplifier modeled in [6] is a broadband amplifier, while the amplifier presented here is a narrowband amplifier which is expected to be easier to model). However, the agreement is not perfect. One of the reasons for that are the parameters of the passive component models whose values are taken based on the package dimensions as published in [10], although they depend not only on the package dimensions but also on the process technology and mounting scheme. Another reason is the tolerance of the nominal value of components (both passive and active). This is especially significant for the transistor and the components in the RF input and output lines. At higher frequencies the characteristics of the FR4 substrate, which is not meant to be used at RF, start to play a role as well.

$K$-factor

Rollet’s stability factor ($K$-factor) is often used to determine the stability of an amplifier. It is calculated using (1) [14].

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|}$$  \hspace{1cm} (1)

where

$$\Delta = S_{11}S_{22} - S_{12}S_{21}.$$  \hspace{1cm} (2)

The simulated and measured stability factors are shown in Fig. 7. The processed amplifier is unconditionally stable from DC to 6 GHz, as was predicted in simulations. It is interesting to note that the measured Rollet's stability factor indicates better stability than the simulated Rollet's stability factor.

$PAE$, $DE$, $IP3$

The drain efficiency ($DE$) and power-added efficiency ($PAE$) are given by (3) and (4), respectively [14].

$$DE = \frac{P_{RFout}}{P_{DC}} = \frac{P_{RFout}}{V_{DC}I_{DC}}$$  \hspace{1cm} (3)

$$PAE = \frac{P_{RFout} - P_{RFin}}{P_{DC}} = \frac{P_{RFout} - P_{RFin}}{V_{DC}I_{DC}}$$  \hspace{1cm} (4)

The measured gain, output power, $DE$ and $PAE$ as a function of the input power are shown in Fig. 8.

The input third-order intercept point ($IP3$) is a linearity measure used for weakly nonlinear systems and devices. The definition used in this paper is based on the intermodulation products [14]. The amplifier is fed with two sine tones with a 100 kHz frequency difference. The $n$-th order intermodulation products appear at $n$ times the frequency spacing of the input tones. The $IP3$ extrapolation is shown in Fig. 9.

![Figure 6. Comparison between the measurements and four models: a) 1st model, b) 2nd model, c) 3rd model and d) 4th model.](image-url)
Figure 7. The measured and simulated stability factor for the amplifier.

Figure 8. Measured output power, gain, \( PAE \) and \( DE \) as a function of input power at 2.5 GHz for a bias point \( V_{DS} = 14 \) V and \( I_{DS} = 50 \) mA.

Figure 9. Extrapolated \( IIP3 \) at 2.5 GHz for a bias point \( V_{DS} = 14 \) V and \( I_{DS} = 50 \) mA.

Table 1. The comparison of measured performance to several other papers.

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<th>( PAE ), %</th>
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Figure 10. The processed amplifier printed circuit board.

Note that only the small-signal model of the transistor is available for NPTB00004, and therefore \( PAE \), \( DE \) and \( IIP3 \) are not simulated.

The measured amplifier performance is compared to the performance presented in several other papers and is shown in Table 1.

The processed amplifier printed circuit board is shown in Fig. 10.

IV. CONCLUSION

An unconditionally stable impedance matched 2.5-GHz GaN HEMT amplifier is designed in printed circuit board technology, simulated, optimized and measured. The passive components, the connectors and the T-junctions are recognized as parts of the design that need to be carefully modeled to predict the amplifier characteristics correctly and therefore to optimize the design. The final model shows a good agreement between the simulated and measured characteristics. A clear improvement in modeling results is seen when the high frequency passive components models, the connector model and the EM-based T-junction model are included in the simulation model as opposed to the simulation model with the ideal, low-frequency models.

The measured amplifier gain at 2.5 GHz is 11.8 dB for the power consumption of 50 mA at 14 V power supply. The measured \( IIP3 \) is 20.7 dBm. The output power at 1-dB compression point \( P_{1dB} \) is 24.8 dBm with the associated \( PAE \) of 40.8% and \( DE \) of 44%.

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REFERENCES


