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Integrating Research into Undergraduate EE Education: An MMIC RF Power Amplifier Design

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Abstract—**This paper presents an approach to enhancing undergraduate Electrical Engineering (EE) education through research collaboration and hands-on project-based learning. The study focuses on the design, simulation, and optimization of an $8 - 12$ GHz MMIC RF power amplifier, reinforcing foundational EE concepts while introducing students to advanced industry-standard tools. Through the use of Candence AWR Microwave Office™ and Smith chart analysis for impedance matching, students gain practical experience that extends beyond traditional coursework. By integrating simulation, optimization, and fabrication preparation, this project bridges the gap between theoretical instruction and real-world RF engineering practices.**

Keywords—**RF power amplifiers, MMIC, undergraduate research, electrical engineering education**

I. INTRODUCTION

RF and microwave engineering curricula often fall short in providing sufficient hands-on experience with essential tools used in the industry. While classroom lectures could cover topics such as Smith chart analysis, they often do not explore them in depth. Even when these topics are included, they fail to fully capture the complexity encountered in real-world applications. Similarly, various simulation techniques crucial for RF chip development as well as for non-linear RF amplifier design are frequently overlooked in coursework. This gap between theory and applications can leave graduates unprepared for real world engineering challenges.

RF and microwave engineering is a highly complex yet essential field, requiring a strong foundation in electromagnetism, circuit theory and signal processing. Due to its steep learning curve, it is often considered too advanced for undergraduate curricula, limiting exposure at the bachelor level. However, the demand for engineers in this field remains high. Without the proper exposure, many students are unaware of the career opportunities in RF engineering or lack the confidence and technical background to pursue them. This project, developed from an internship study and now serving as an undergraduate thesis foundation, employs industry-standard simulation tools to provide an immersive educational experience. It offers a case study that bridges the gap between theoretical models and practical design challenges.

II. PROJECT OVERVIEW AND METHODOLOGY

As part of undergraduate EE education, students develop a foundational understanding of key concepts, including circuit analysis, amplifier design, electromagnetic fields and signal processing. This project requires extending beyond these fundamentals and rapidly acquiring knowledge of high frequency (non-linear) circuit behavior. This includes concepts such as transmission line effects, impedance transformations and power efficiency optimization. While these topics are typically introduced in master's level, this project necessitates understanding and applying them in real-time alongside the design process. This research illustrates how undergraduate research projects can effectively bridge the gap between core courses and advanced engineering challenges by enriching students' learning experience.

The project employs AWR software to design and simulate an RF power amplifier IC, a so-called Monolithic Microwave Integrated Circuit (MMIC), operating in the 8–12 GHz X-band, presenting a significant challenge that extends well beyond the typical undergraduate knowledge base. This pursuit requires not only an understanding of advance RF circuit design principles, but also the ability to apply them in real time while navigating the complexities of high frequency performance. The simultaneous learning and design process pushes the development of critical problem solving skills, adaptation to new theoretical and practical concepts and the gain of hands-on experience with industry standard simulation tools.

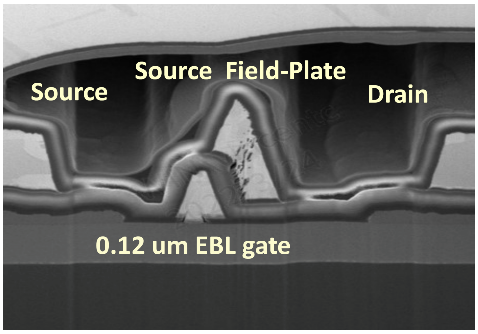

Fig. 1. Overview of EBL gate fabrication and GaN HEMT structure used in the RF power amplifier design.

In order to implement the RF power amplifier design, we use Gallium Nitride (GaN) High Electron Mobility Transistors (HEMTs) with Electron Beam Lithography (EBL) gates. This is a technology that forms the current State-of-Art for microwave high-power high-efficiency MMICs: The circuit is fabricated using the WIN Semiconductors

NP12-01 GaN-on-SiC technology with 0.12 um gates and source-coupled field plates for high breakdown and 28 V operation. The process offers two interconnect metals, MIM capacitors, TaN resistors and through wafer vias. Process details can be found in [1].

Before starting with a design a solid understanding of Smith chart analysis, impedance matching, $S-$parameters, network theory, stability analysis and nonlinear device modeling is essential. These fundamental concepts provide the necessary framework for developing a high frequency circuit that meets performance requirements and operates reliably within real world constraints. Mastering these topics ensures that design choices are based on sound theoretical principles and helps reduce the likelihood of unexpected performance issues when transitioning from simulation to fabrication. These topics are often not covered in detail at the undergraduate stage, but they can be effectively introduced through supervised measurements. Measuring the $S-$parameters of a chip, analyzing the K-factor, conducting load-pull simulations and measurements on transistors while discussing the results and methods with a supervisor provides hands-on experience that reinforces theoretical learning. Engaging with professionals who work in a lab also offers a different perspective than that of a chip designer, highlighting practical considerations that influence both the design and measurement. This gives valuable insights into optimizing the design process: to design with measurement requirements in mind. Additionally, these discussions and measurements offer an opportunity to become familiar with the terminology used in the field, ensuring greater confidence and competence when starting a design in advanced RF or microwave technology.

We utilize standard circuit theory and RF-theory foundations through the applied research presented here by focusing on high-frequency circuit design. Below we outline the design objectives structured to demonstrate how key RF concepts are integrated into the design process. The key design objectives include:

- **Impedance Matching:** Using Smith charts to determine appropriate load impedances, thus enabling students to visualize and understand impedance transformations.
- **Stability, Power and Efficiency Trade-offs:** Maintaining circuit stability by ensuring that key parameters such as S_{11}, S_{22}, and the K-factor remain within acceptable limits while optimizing output power and Power-Added Efficiency (PAE).
- **Simulation Documentation:** Encouraging meticulous documentation of simulation parameters, design assumptions, and iterative adjustments to foster a reflective and analytical design process.

Prior to the design process, it is essential to first establish the intended function of the power amplifier. This includes defining the desired results for the bandwidth and center frequency, output power, gain and power-added efficiency. These specifications determine the overall architecture of the amplifier, including the number of amplification stages required. The transistor choices are further guided by a load-pull analysis of a single transistor, which helps identify the maximum achievable power and efficiency while determining the area where the output impedance is optimal [2]. The load-pull analysis can be conducted using the AWR software, utilizing the template provided. An even more effective approach would be to perform the load-pull analysis both in AWR and experimentally during the lab session, allowing for a direct comparison between simulated and measured results. This would provide greater confidence in the accuracy of the simulated data and ensure that the real-world performance aligns with expectations. For this project, a two-stage power amplifier was selected based on the desired gain (20dB), PAE and output power.

Once the key specifications are defined, the design process begins. In RF power amplifier design, the workflow proceeds from the output to the input, unlike in low-noise-amplifiers (LNAs) [3], where the sequence is reversed and the noise figure minimization at the input is prioritized. The design begins with the output matching network, which combines the output power of the second-stage transistors and transforms their output impedance to the 50Ω output. This stage has the greatest impact on the output power and must be carefully tuned. Next, the interstage matching network is designed and tuned such that the gain achieves the desired frequency response. Finally, the input matching network is designed to minimizes the input reflections, ensuring maximum gain. At all these steps, the stability is carefully analyzed. By following this structured approach the amplifier achieves high efficiency, sufficient gain, unconditional stability and optimal power performance. Using the provided components of WIN Semiconductors is recommended. However, for inductors and capacitors it is challenging to model this accurately with equation-based models, which is why EM tools are commonly used; this approach is also recommended by WIN themselves.

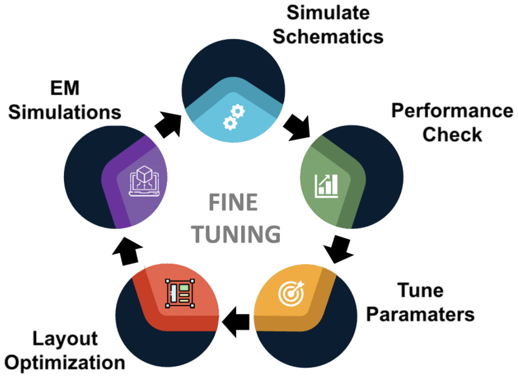

Fig. 2. Iterative fine-tuning process of the amplifier design.

Once the schematic design is complete, the next step is to transition to the physical layout, ensuring that all components are properly connected while avoiding overlaps or tight spacing that could impact performance. During this process, some schematic values may change due to physical constraints, necessitating a retuning of the matching networks to achieve optimal performance. Once the layout is finalized, the design undergoes Electromagnetic (EM) Simulations using the software Axiem to refine its behavior. Initially, small-scale EM simulations help analyze localized effects, followed by a more detailed segmentation of each matching network for separate EM analysis before progressing to a full-network simulation. In the final stage, an EM simulation is performed for the entire amplifier, excluding the transistors, which are incorporated later through circuit simulation.

As shown in Fig. 2, the iterative fine-tuning process begins only after the basic model is completed. The cycle starts with Simulating Schematics, where circuit behavior is analyzed to ensure it meets the design objectives. A Performance Check follows, evaluating key metrics such as stability and efficiency. If adjustments are necessary, the process moves to Tuning Parameters, refining component values to enhance performance. Once tuning is complete, Layout Optimization ensures the physical design is correctly implemented, maintaining proper connectivity and minimizing interference. Finally, EM Simulations validate the design by analyzing electromagnetic effects and refining the layout as needed. Each modification in component placement or values requires repeating this cycle until the amplifier meets all specifications. This process is time-intensive but essential for achieving a stable and high-performing design. Stability checks must be performed under various nonlinear conditions to ensure robustness in real-world applications.

III. SIMULATION AND PRELIMINARY RESULTS

Prior to the fabrication of the RF amplifier, extensive simulations are needed to verify the design's performance and stability. The simulations help ensure that the amplifier meets the predefined specifications for stability, power output, and efficiency. The first step in the process is to create the Smith charts which provide a visual representation of the impedance matching across a frequency range. This impedance matching is important to minimize reflections between adjacent components and maximize power transfer.

Next, we analyze the $S-$parameters and stability metrics to confirm that the design is stable under small-signal conditions. Specifically, the input and output reflection coefficients S_{11} and S_{22} should be below 0dB, while the $K-$factor must be larger than 1 (0dB) to ensure the required stability. In addition, the small-signal gain, PAE and ouput power, P_{out}, need to meet the amplifier's performance goals.

Our initial simulation results support the viability of the design methodology we employed:

- **Impedance Matching:** Smith chart analysis shown in Fig. 3 has enabled the selection of load impedances that result in acceptable return loss levels, ensuring minimal reflection and maximum power transfer.
- **Stability Metrics:** Key parameters such as S_{11}, S_{22}, and the K-factor remain within target thresholds under various simulation conditions. Fig. 4 confirms the unconditional stability.
- **Efficiency Trade-offs:** The power efficiency analysis shown in Fig. 5 illustrates the trade-offs between the output power P_{out}, gain, and, PAE. These are the critical design parameters in industry applications. Our results ensure that the amplifier meets the expected performance requirements. Early findings illustrate the

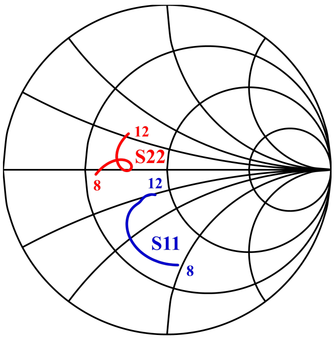

Fig. 3. Smith Chart S_{11} and S_{22} from 8 to 12 GHz

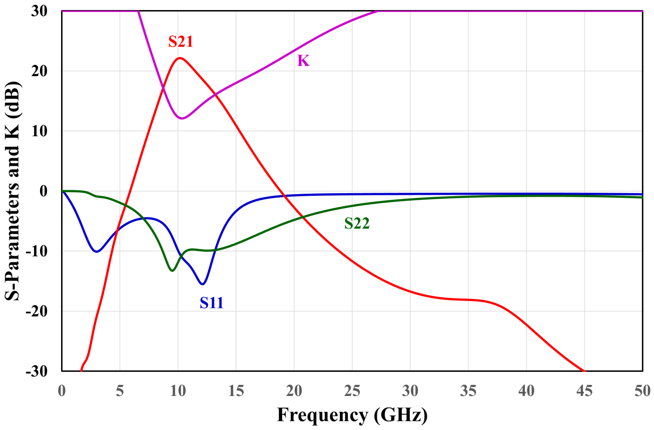

Fig. 4. The $S-$parameters and K-factor of the whole amplifier

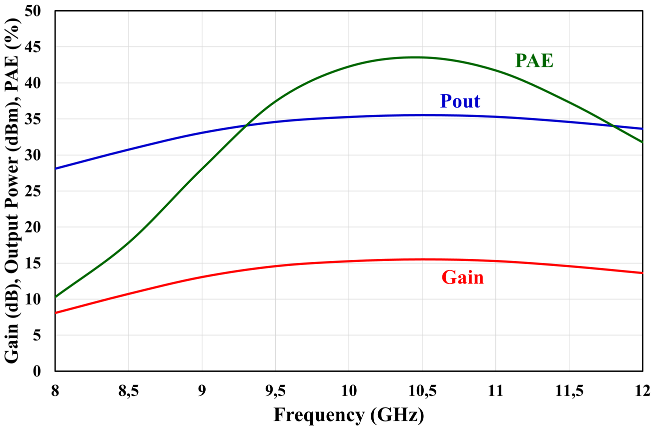

Fig. 5. The gain, output power and PAE at the output

inherent trade-offs between achieving high output power and maintaining optimal efficiency.

These simulation results validate the amplifier design by confirming its impedance matching, stability, and efficiency performance. This process is crucial prior to fabrication as it allows for iterative improvements and enhance overall performance. It also enables us to mitigate any potential risks.

IV. EDUCATIONAL IMPACT

This project integrates research into undergraduate education through an independent BSc minor.[1] The scheme we present allows students to engage in the complete RF design process beyond traditional coursework. Research-based learning has been shown to enhance student engagement, enhance critical- and research-based-thinking, and improve problem-solving skills by bridging theory and practice as illustrate in other examples from the literature [4], [5], [6].

The project also illustrates an international collaboration between two universities, exposing students to both theoretical modeling and practical circuit design in different educational settings. A key strength of the project is that it has has modular structure which enables students to engage with different aspects of RF amplifier development at various stages:

- **Design and Simulation:** Students can apply core EE concepts (e.g. impedance matching and circuit analysis) using industry-standard tools like AWR software.
- **Fabrication Process:** Transitioning from schematic design to physical layout introduces real-world constraints such as layout optimization and electromagnetic simulations.
- **Experimental Characterization:** After fabrication, students can analyze discrepancies between simulation and real-world performance to reinforce practical RF knowledge.

All of these steps can be integrated into different parts of the undergraduate curriculum through independent minor, internship, and/or bachelor end projects, and can be studied in continuation throughout students' degree.

Beyond technical skills, the project also provides first hand experience in the unpredictable challenges of the research world which requires students to assess trade-offs, analyze performance data, and iteratively refine their approach. The hands-on experience builds confidence in applying theoretical concepts to practical engineering challenges. By integrating simulation, fabrication, and experimental validation, this research-based approach prepares students for careers in industry and academia, demonstrating how research can become an integral part of undergraduate education. These experiences significantly contribute to students' ability to make informed decisions about their next steps be it in terms of graduate education or pursuing industry experience. This approach also allows development of future-proof education as it allows students to engage in state-of-the-art research experience as part of their undergraduate training.

V. CONCLUSIONS AND FUTURE WORK

This paper presents a research-driven approach to undergraduate learning through the design, simulation, and optimization of an RF power amplifier. By engaging students in a structured design process, the project bridges the gap between coursework and practical engineering, fostering problem-solving and critical thinking through simulation tools, stability analysis, and iterative refinement.

The next phase involves the fabrication and experimental validation of the designed amplifier, offering insight into simulation accuracy and fabrication constraints. The iterative tuning process will continue post-measurement to refine efficiency and stability. If the designed MMIC meets expectations, the results could be presented at a future microwave conference, showcasing the potential of undergraduate RF/microwave IC design.

Future work will focus on expanding similar research-oriented educational initiatives through collaborations with other institutions and industry partners. These partnerships will help integrate research into undergraduate curricula, ensuring students gain practical, industry-relevant experience. By fostering these collaborations, this approach serves as a scalable model for incorporating research into undergraduate learning, equipping students with both technical knowledge and hands-on skills for careers in RF engineering.

ACKNOWLEDGMENT

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[1] At TU Delft this work load is equivalent to one semester (two quarters) of academic work, totaling 30 ECTS credits. Given that one ECTS represents approximately 28 hours of student effort, this translates to a total workload of about 840 hours per student for the project and its related activities.