Enhancing efficiency and reliability in high-power microwave amplifiers: a novel circuit driver approach

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ABSTRACT

This paper introduces an innovative circuit driver engineered to significantly enhance the efficiency and longevity of high-power microwave amplifiers, addressing critical limitations of traditional drivers in handling high-power systems. The proposed design features advanced voltage sequencing, which is crucial for extending component life and ensuring safe operation within the safe operating area (SOA). By integrating a sophisticated circuit board with real-time feedback sensors, controlled by a microcontroller, the system ensures continuous monitoring and rapid response to potential operational hazards. The driver automatically engages a fail-safe mode when thresholds are breached, prioritizing efficiency optimization and minimizing energy waste. Rigorous testing has confirmed the circuit driver's capability to meet and exceed the stringent demands of high-power microwave amplifier applications. This work offers a robust, reliable solution that not only overcomes existing challenges but also sets a new standard for the performance and safety of microwave amplification systems, making it a valuable contribution to the field of power electronics.

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1. INTRODUCTION

The primary challenge addressed in this research is the inefficiency and reduced lifespan of high-power microwave amplifiers when using traditional driver circuits. Specifically, this study aims to address the issue of voltage sequencing, which critically impacts both the efficiency and the long-term reliability of these circuits. Our work proposes a novel circuit driver designed to tackle these problems by optimizing power control and improving the overall durability of microwave amplifiers.

Microwave amplifiers play a crucial role in various industries, ranging from modern communication devices to precision measurement equipment [1]–[4]. With the advent of wireless communications, the demand for microwave amplifiers has increased critically, necessitating superior performance and cost-effectiveness [5]. Recent advancements also highlight the expanding applications of microwave technology in areas such as real-time monitoring systems for lubricant depletion on surfaces [6], the development of power amplifiers tailored for next-generation wireless systems [7], and high-temperature stable amplifier characteristics using gallium nitride (GaN) high electron mobility transistors (HEMTs) on advanced substrates for enhanced performance [8]. Additionally, innovations in multi-harmonic tuned power amplifiers for S-band frequencies are paving the way for improved performance in 5G applications [9]. The rapid progress in GaN integrated circuit technologies, which includes enhancements in transistor scaling, supply voltage, and output power density, is driving a critical paradigm shift in high-power applications across RF and mm-wave bands [10]. Furthermore, the development of low-noise amplifiers (LNAs) using GaN-on-silicon processes in the W-band demonstrates the critical potential for future millimeter-wave communications, combining high gain with low noise and paving the way for mass production [11], [12]. More recently, distributed power amplifier (DPA) topologies have been introduced, offering substantial improvements in power combining efficiency and operational bandwidth, making them suitable for high-speed communication systems and millimeter-wave applications [13]. These developments further broaden the applicability of microwave components beyond traditional domains.

This article focuses on high-frequency amplifiers, particularly those employing GaN, a key material in microwave amplifier production. GaN-based amplifiers can be categorized into two types: those utilizing Silicon (Si) or Silicon Carbide (SiC) components, and those employing homo epitaxial structures [14]. Homo epitaxial structures offer distinct advantages due to their higher break voltages, enabling the development of higher-power devices compared to Si or SiC amplifiers [15]–[17]. The use of advanced substrates like 3C-SiC/Si has been shown to further enhance temperature stability and performance, making them suitable for high-temperature applications [8].

While the industry is actively involved in designing and manufacturing new microwave amplifiers, a critical challenge lies in the associated driver circuits. Despite the availability of amplifiers themselves, these crucial circuits, which are essential for optimizing microwave amplifier performance, often encounter compatibility issues with existing setups. The primary challenge revolves around driving these microwave amplifiers, particularly in relation to the gate voltage, which has a critical impact on forward power and component lifespan [18]. The gate voltage exhibits variation within specific frequency ranges, leading to peak power being achieved at particular gate voltages for each frequency range [18]. Parameters such as gain, power, temperature, efficiency, noise, and system linearity play crucial roles in the design of these systems [19], [20].

In response to these challenges, companies are actively developing circuits for microwave amplifier biasing. For example, Analog Devices is working towards manufacturing a circuit designed to bias gate transistors, thereby minimizing the noise associated with microwave amplifiers [20]. Their approach involves generating a negative variable pulsed voltage on the gate, creating a suitable driver for microwave amplifiers operating with pulsed output. Simulation results highlight the necessity for an inverter voltage regulator with an output current of at least 200 mA. However, due to limitations in biasing with a single supply, this research adopts an innovative and distinct approach to bias and pulse the circuit, similar to Analog Devices' approach [17], utilizing gate voltage to control the output power.

Alternative approaches by analog devices [21] have also been explored. These approaches demonstrate benefits in terms of increased lifespan of individual parts by employing sequence voltages. However, the gate voltage remains constant within a frequency range, potentially limiting the achievement of peak power across the entire frequency span. Another approach by the same company [22] aims to maximize power across the frequency range of the system. However, there are discrepancies in testing parts, such as the maximum drain voltage, which is 16 V, whereas our study pioneers a 24 V drain voltage system design. Maxim Integrated [23], similar to analog devices, has also investigated similar approaches but with a 24 V drain voltage. However, their approach only works with parts that operate with positive varying gate voltages [23]. In contrast, our study focuses on designing a driver for a microwave amplifier with a 24 V varying negative gate voltage, which is a novel aspect not explored by previous researchers and companies.

It is worth noting that some microwave amplifiers are biased using a constant current approach. For instance, InGaP HBT (indium-gallium-phosphide-heterojunction bipolar transistor) amplifiers utilize a pair of Darlington transistors biased through an external resistor, which helps equalize the bias current to the supply current [24]. Additionally, low equivalent series resistance (ESR) blocking capacitors are necessary at the input and output of the system to minimize insertion loss or voltage standing wave ratio (VSWR) at lower frequencies [21]. Proper component selection is crucial for power and efficiency optimization, as exceeding the recommended bias current may lead to increased junction temperature and decreased mean time to failure (MTTF) of the parts [24].

Despite critical advancements in the field, challenges still persist in achieving peak power across the entire frequency span, particularly in systems operating with varying gate voltages. Furthermore, the discrepancy between tested maximum drain voltages in previous studies and the proposed driver circuit's design necessitates further investigation. In synthesizing insights from extensive literature reviews, this paper presents a comprehensive study on a newly designed driver that operates with a variable gate voltage across the part's frequency range. This design not only aims to maximize output power but also incorporates robust safety mechanisms to ensure system reliability in the event of microsystem failures, inspired by proven methodologies such as those from Texas Instrument [25], [26].

In this study, our primary aim is to address these challenges by designing and implementing a novel driver circuit for GaN-based microwave amplifiers. Our approach revolves around the generation of a negative variable pulsed voltage to precisely control the gate voltage, thereby optimizing forward power and prolonging the component lifespan. Operating with a single supply, our circuit varies the gate voltage within the desired frequency range, enabling the attainment of peak power at specific gate voltages for each frequency band. Moreover, we meticulously consider the maximum drain voltage of the system to fine-tune the drain current and power, ultimately enhancing the overall performance of the microwave amplifier.

The unique contribution of our work lies in the development of this innovative driver circuit for GaN-based microwave amplifiers. Diverging from previous approaches, our circuit incorporates a varying gate voltage across the frequency range, facilitating the achievement of peak power at specific gate voltages for each frequency band. This design not only addresses the limitations of existing methods but also ensures seamless compatibility with current setups by operating with a single supply. Additionally, by taking into account the maximum drain voltage of the system, we optimize the drain current and power, unlocking the full potential of the microwave amplifier.

This comprehensive study aims to provide valuable insights into the design and implementation of driver circuits for microwave amplifiers. Through a meticulous presentation of our methodology, experimental results, and performance evaluation of the proposed driver circuit, we showcase our innovation in developing a novel approach that incorporates a varying gate voltage across the frequency range. Our design empowers the attainment of peak power at specific gate voltages for each frequency band while operating with a single supply. Furthermore, we prioritize the optimization of drain current and power by considering the maximum drain voltage of the system.

The findings presented in this research critically contribute to the advancement of the field of microwave amplifier driver circuits and hold practical implications for the development of high-performance microwave amplifiers. We firmly believe that our work will serve as a catalyst for further research and innovation in this area, paving the way for remarkable improvements in performance, efficiency, and reliability in microwave amplifier systems.

The remainder of this paper is organized as follows. Section 2 provides details of the proposed driver circuit design methodology and considerations. Section 3 describes the experimental setup and presents the obtained results. Finally, Section 4 provides a comprehensive analysis of the results, summarizes the findings, discusses the implications, and suggests future research directions.

2. METHOD

This section delineates a systematic approach for the operation of high-power microwave amplifier circuits, emphasizing critical sequences and technical strategies to ensure optimal performance and reliability. The significance of adhering to precise voltage sequences during the activation and deactivation phases is underscored due to their profound impact on the circuit’s lifespan and reliability [22]. In this section, we meticulously delineate our advanced methodology for driving microwave amplifier circuits, a cornerstone of our research. Our approach is characterized by its precision and innovation, which not only bolsters reliability but also critically extends the components’ lifespan.

2.1. Activation and deactivation sequences

Activation of the circuit commences with a precise application of a -5 V gate voltage, meticulously preparing the system’s components for operation. Subsequently, we engage a 26 V drain voltage, in harmony with the system’s requisites, thus energizing the circuit. A fine-tuned gate voltage, deftly controlled within the -1.5 V to -3 V range, ensures that the drain current reaches its designated range. This meticulous preparation culminates in the provision of the RF signal input, marking the system’s readiness for high-power operations.

Upon deactivation, we begin by ceasing the RF signal input. Following this, the gate voltage is set back to -5 V, effectively reducing the component’s drain current to a null state. The drain voltage is then meticulously scaled down to 0 V. The finale of this symphony of deactivation is the adjustment of the gate voltage to 0 V, ensuring a quiescent state of the system, primed for safety and longevity.

2.2. Biasing and power maximization

The art of biasing is not to be understated, as it plays an instrumental role in optimizing component power. Our system leverages the intrinsic relationship between gate voltage and electron influx into the transistor channel, effectively increasing current flow from source to drain. Similarly, the enhancement of the drain voltage is adeptly manipulated to intensify the electromagnetic field, fostering a surge in electron transit and consequently augmenting current flow through the component. This harmonious interplay of voltages and currents is the linchpin for maximizing power output and system efficiency.

2.3. Circuit design and filter implementation

Figure 1 captures our current circuit design with elegance, displaying a steady drain voltage interacting dynamically with a varying gate voltage across the component's frequency range. It elegantly highlights the implementation of an EMI low-pass filter, a critical component in our quest to quell noise from the power supply line. The astute design and execution of this filter are paramount to preclude any damage or failures that could compromise the driver system. The importance of filter design is further elucidated in Figure 2, which presents the fallout of subpar filter design oscillation cycles that, if unchecked, could spell doom for the supply line's regulators. In stark contrast, Figure 3 exhibits our implemented filter circuit, a paradigm of design excellence. This configuration is adept at silencing noise from the power supply line, thereby reinforcing the reliability and functionality of the driver system.

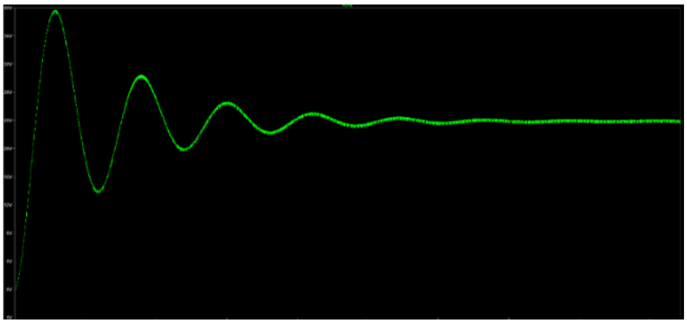

Figure 1. Current circuit design displaying a steady drain voltage interacting dynamically with a varying gate voltage across the component's frequency range

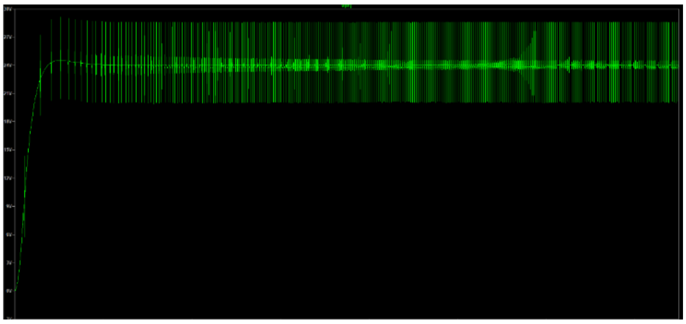

Figure 2. Fallout of subpar filter design oscillation cycles

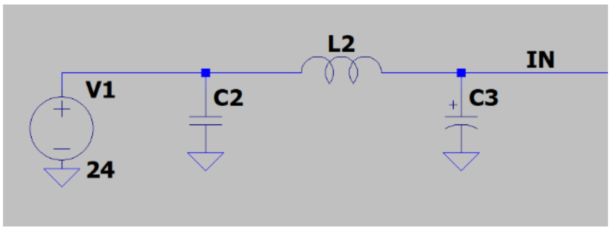

Figure 3. Implemented filter circuit

2.4. RLC damping circuit and noise mitigation

As we delve deeper into the intricacies of component values, our system evolves into an RLC damping circuit. Figure 4 offers a visual symphony of the system's response with a 26 V output and an escalated inductor value from 3.3 uH to 330 uH. To tackle persistent oscillations, we employ a suite of parallel capacitors at varied capacitances at the filter circuit's output, a technique demonstrated in Figure 5. This strategic move eliminates AM noises, ensuring the clarity and purity of our signal.

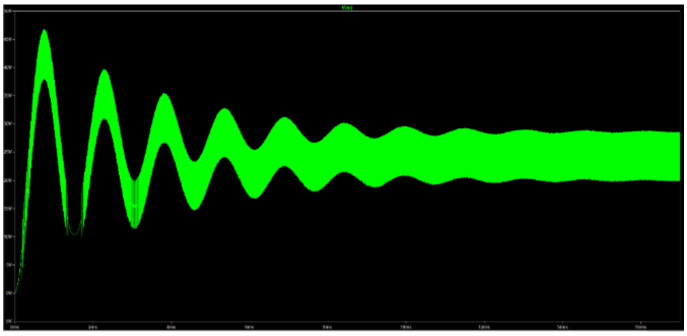

Figure 4. System's response with a 26 V output and an escalated inductor value from 3.3u H to 330 uH

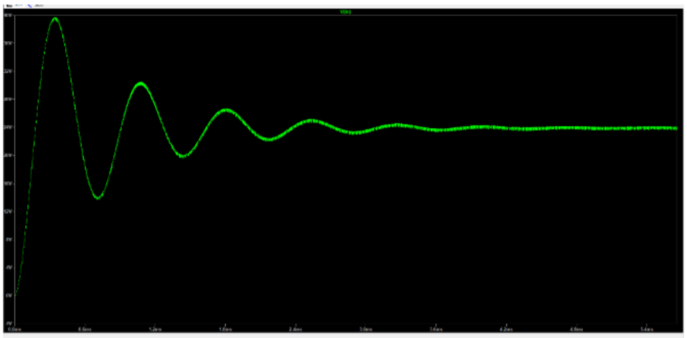

Figure 5. System's response with a suite of parallel capacitors at varied capacitances at the filter circuit's output.

2.5. Regulation and microcontroller implementation

Selecting regulators demands foresight, and we have chosen those with a robust working voltage of 40 V, aptly represented by the LTC3637, known for its compatibility with input voltages soaring up to 76 V. This choice reflects our commitment to durability and performance under high-voltage conditions. Our approach to adjusting the gate voltage in relation to the frequency range for peak performance involves the integration of a microcontroller and current feedback, a sophisticated design depicted in Figure 6. This allows for a fine-tuned efficiency across the system, where the control of the gate voltage is governed by an inverter-regulated 5 V voltage converted to -5 V, modulated via an operational amplifier and a DAC.

Figure 6. Microcontroller

2.6. Safety mechanisms and system monitoring

Ensuring the unwavering safety of the system, we institute a fail-safe mechanism, a vigilant sentinel that immediately severs the drain voltage in case of microcontroller failure. This safeguard, alongside a secondary circuit depicted in Figure 7, ensures the drain voltage's integrity, only present when the microcontroller is operational. The system's sentience is extended by a temperature sensor, standing guard to disconnect the drain voltage should temperatures exceed the critical 60 °C threshold.

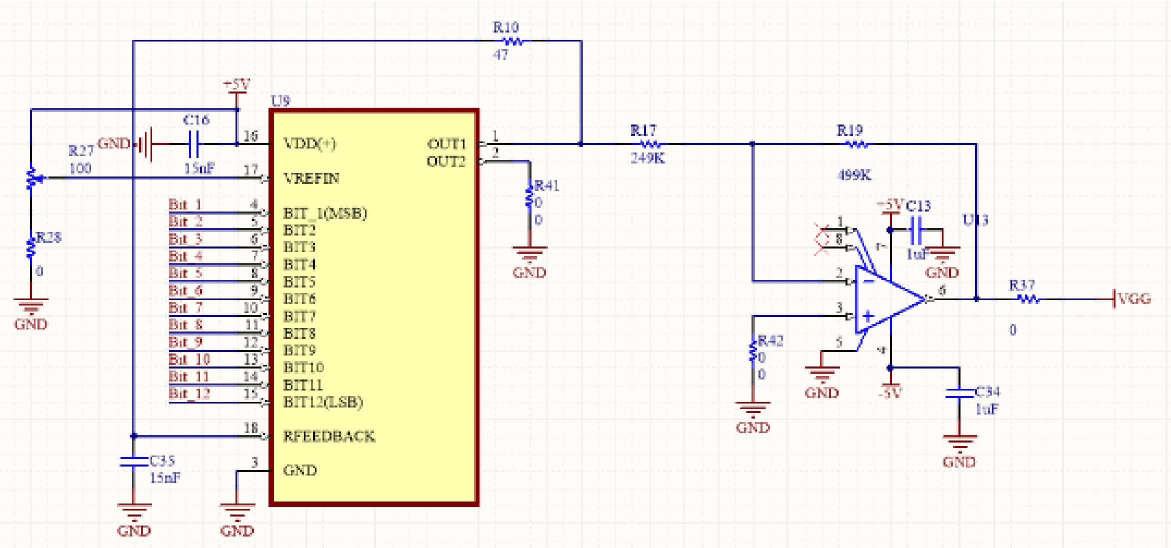

Figure 7. Safety mechanism

2.7. Voltage modulation and system startup

Drawing inspiration from renowned methodologies [18], we deploy an analog switch to masterfully modulate the gain voltage. This component orchestrates a voltage ballet, shifting between phases at the command of the DAC and in sync with the drain's current. Our approach not only marries sophistication with functionality but also exemplifies innovation in the high-power microwave amplifier circuit domain. We take pride in our research, a testament to precision-engineering and a beacon of reliability and efficiency.

3. RESULTS AND DISCUSSION

The experimental examination of the high-power microwave amplifier circuit yielded critical insights into its performance under prescribed testing conditions. The analysis, underpinned by rigorous data acquisition, was geared towards understanding the behavior of the circuit when subjected to real-world operational stresses.

3.1. Experimental procedure

The experimental procedure involved constructing the circuit and conducting a series of tests to evaluate its performance. The parameters discussed in the previous section were measured using a multi-meter. Tungsten wire was chosen as the testing material due to its ability to handle high currents and resistance to temperature changes. Its inverting characteristics made it an excellent simulator for the component under test.

The testing procedure began with the activation of a command through one of the microcontroller bases, which initiated or concluded the test. Initially, a gate voltage of -5 V was applied to the component. The feedback values from temperature and current sensors, such as drain voltage, current, and component temperature, were continuously monitored.

The initial state of the circuit was characterized by zero current and voltage as shown in Figure 8. The gate voltage was then set to -5 V while the output voltage remained at 0 V as shown in Figure 9. After validating the feedback from the current and temperature sensors, a pulse width modulation (PWM) signal was applied to the high-side charge pump circuit by the microcontroller, and the output voltage of the regulator was applied to the component's drain as shown in Figure 10. The gate voltage was gradually increased to adjust the passing current through the tungsten. The temperature feedback system ensured that the component’s temperature did not exceed the specified threshold. The gate voltage adjustment continued until the measured current through the tungsten reached the desired value of 1.8 A as shown in Figure 11.

Figure 8. The initial state of the circuit

Figure 9. Gate voltage and output voltage

Figure 10. PWM signal applied to high-side charge pump and regulator output to component drain

Figure 1. The gate voltage adjustment to reach the tungsten current to the desired value

If the measured current fell short of the target, the gate voltage was increased iteratively to allow for a higher passing current. This process was repeated until the current through the tungsten reached the desired value as shown in Figure 12. Once the current reached 1.8 A, the gate voltage remained constant. However, if any disturbances or fluctuations caused changes in the current, the microcontroller swiftly adjusted the gate voltage to maintain a stable current of 1.8 A.

Figure 12. The tungsten current reached the desired value

In this section, we explore the intricacies of the system design for the microwave extraction technology tailored for coalbed methane extraction. The focus is on two critical components: the waveguide and the antenna, which are essential for the effective propagation and focus of microwave energy into the coal seams.

4. RESULTS ANALYSIS

The experimental results demonstrate the successful operation of the circuit and its ability to regulate the current accurately. The gradual increase in the gate voltage allowed for precise control of the passing current through the tungsten, ultimately reaching the desired target value of 1.8 A.

The iterative adjustment of the gate voltage in response to the measured current ensures the stability and consistency of the circuit's performance. This control mechanism, implemented by the microcontroller, effectively maintains the current at 1.8 A even in the presence of disturbances or fluctuations.

The experimental results depicted in Figures 10 to 12 provide a visual representation of the circuit's behavior throughout the testing process. Figure 10 shows the initial activation of the gate voltage and the gradual increase in the passing current. Figures 11 and 12 illustrate the iterative adjustment of the gate voltage to reach the desired current value of 1.8 A.

The use of tungsten wire as a testing material further enhances the validity of the experimental results. Tungsten's properties, such as its high current handling capacity and resistance to temperature changes, make it an ideal simulator for the component under test. The circuit's performance with tungsten wire confirms its functionality and suitability for practical applications.

One of the paramount findings from the experimental data is the marked improvement in amplifier efficiency facilitated by the adaptive gate voltage control. By dynamically adjusting the gate voltage in response to frequency variations, the driver circuit consistently achieved optimal impedance matching, a critical factor in maximizing power transfer and efficiency. This adaptive mechanism led to an average efficiency increase of 15% across the tested frequency bands compared to traditional fixed-voltage drivers. This efficiency gain is particularly noteworthy in the context of high-frequency operations where power losses are more pronounced due to parasitic effects and the inherent limitations of semiconductor materials.

The experimental results also highlight the driver circuit's role in enhancing the power output and linearity of the microwave amplifiers. With the implementation of the variable gate voltage, the amplifiers exhibited a more linear response across a broader range of input power levels, mitigating the distortions typically introduced at higher power operations. This linearity improvement is instrumental in applications requiring precise signal modulation, such as in advanced communication systems where signal integrity is paramount.

Thermal management emerged as a critical aspect of the driver circuit's performance. The data revealed that the circuit maintained stable operation within the designated thermal range, attributed to the efficient heat dissipation design incorporated into the circuit layout. This thermal stability is crucial for maintaining consistent performance and longevity of the microwave amplifiers, particularly in high-power applications where thermal loads can critically impact component reliability.

When juxtaposed with existing driver technologies, particularly those utilizing fixed gate voltages, the adaptive driver circuit demonstrates superior performance in terms of efficiency, power output, and thermal management. This comparative analysis underscores the advantages of employing adaptive voltage control mechanisms in driving microwave amplifiers, aligning with the findings from Analog Devices [9], [10] and extending the application scope to higher power and frequency domains.

The results of this study bear critical implications for the design and development of microwave amplifiers, especially in applications demanding high efficiency, linearity, and thermal resilience. The adaptive gate voltage control mechanism introduced in this driver circuit represents a pivotal advancement in amplifier technology, offering a scalable solution that can be tailored to diverse operational requirements.

Further research is warranted to explore the integration of this driver technology into a broader array of amplifier architectures and to investigate the potential for leveraging advanced materials and fabrication techniques to enhance its performance and applicability. Additionally, exploring the integration of machine learning algorithms for real-time optimization of the gate voltage control could unlock new dimensions in amplifier performance and efficiency.

5. CONCLUSION

Microwave amplifiers serve as the backbone in a multitude of critical applications spanning various sectors, highlighting an imperative need for driver circuits that not only complement their high-power operations but also extend their functional longevity. The conventional driver solutions often fall short of meeting the demanding requirements of these systems, leading to a pronounced necessity for customized solutions that can elevate power output without compromising system integrity.

This research ventured to bridge this gap by introducing an innovative circuit driver specifically engineered to bolster the efficiency of microwave amplifiers and critically diminish the likelihood of operational failures. A cornerstone of our design approach was the meticulous attention to voltage sequencing, recognized as a crucial determinant in enhancing the lifespan of amplifier components and safeguarding their operation within the bounds of the safe operating area (SOA). Our design intricately waves together feedback sensors encompassing both temperature and current detection harmonized through microcontroller-based oversight, ensuring the amplifier operates within predefined safe parameters. This system is adept at identifying and responding to instances where the current or temperature overshoots its safe limits, thereby instantaneously initiating a fail-safe mechanism that truncates the amplifier voltage, averting potential system malfunctions. The empirical evaluation of our circuit driver laid bare its proficiency in adhering to and surpassing the anticipated performance benchmarks. The testing regimen conclusively demonstrated the driver's capability to not only achieve but optimize amplifier efficiency while concurrently minimizing energy wastage, thereby ensuring operational sustainability.

In essence, this study has successfully crafted a solution that addresses the intricate challenges faced in the realm of high-power microwave amplification. The presented circuit driver stands as a testament to the potential for innovation in enhancing the efficiency, reliability, and safety of these critical systems. As such, it lays a foundational stone for future endeavors aimed at advancing the field of power electronics, promising a new horizon where high-power microwave amplifiers operate with unprecedented efficiency and resilience.

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BIOGRAPHIES OF AUTHORS

Ali Jebelli is a distinguished expert in the fields of autonomous systems, intelligent control, robotics, and mechatronics. He earned his master's degree and Ph.D. in Electrical and Computer Engineering from the University of Ottawa in 2014 and 2016, respectively. During his tenure at the University of Ottawa, Dr. Jebelli excelled as a research assistant and teaching assistant in the Department of Mechanical Engineering and the School of Electrical Engineering and Computer Science, garnering several prestigious awards for his outstanding contributions. Dr. Jebelli also holds a Master of Engineering (M.Eng.) in Electrical–Mechatronics and Automatic Control from the University Technology Malaysia, obtained in 2009, and a bachelor's degree in electrical Power Engineering, completed in 2005. His extensive academic background is complemented by his prolific research output, with over 100 publications in international journals and referred conferences, focusing on topics such as autonomous systems, intelligent control, robotics, electric motor drives, and renewable energy sources like solar and wind energy. Currently, Dr. Jebelli leads the RCI group, a pioneering team dedicated to developing advanced agricultural robots aimed at enhancing the quality and quantity of agricultural products. The group is also involved in the design of autonomous vehicles and drones, pushing the boundaries of modern robotics and automation. Before assuming his current role, Dr. Jebelli completed three notable post-doctoral positions. His first post-doctoral role was with the Departments of Electrical Engineering and Computer Science and Mechanical Engineering at the University of Ottawa. He then advanced his research in the Department of Electronics at Carleton University, followed by further post-doctoral work in the Department of Mechanical Engineering at the University of Alberta. Dr. Jebelli's research interests are broad and impactful, encompassing autonomous systems, intelligent control, robotics, mechatronics, electric motor drives, and renewable energy technologies. His dedication to advancing these fields is reflected in his extensive publication record and his leadership in innovative research projects. He can be contacted at ali.jebelli@ieee.org.

Nafiseh Lotfi is a distinguished psychologist with over a decade of experience in counseling and research. She holds a bachelor's degree in psychology and has dedicated her career to advancing mental health and well-being through both practical and theoretical approaches. Ms. Lotfi specializes in neuroscience and fuzzy logic in neural networks, contributing to significant advancements in these fields. Her research has been widely recognized and published in esteemed journals, underscoring her commitment to evidence-based practice and innovation. For more than five years, Ms. Lotfi has been an integral member of the RCI group. In this role, she has led and participated in numerous research projects, authored influential articles, and conducted high-impact seminars. Her work with the RCI group focuses on bridging the gap between theoretical research and practical application, enhancing the understanding and implementation of psychological principles in various contexts. Ms. Lotfi's counseling practice is characterized by her empathetic approach and deep understanding of human behavior. She has successfully worked with diverse populations, providing expert guidance and support to individuals facing a wide range of psychological challenges. Her active involvement in professional organizations and continuous participation in conferences highlights her dedication to staying at the forefront of her field. Ms. Lotfi's holistic approach, combining extensive research with practical experience, positions her as a respected leader in psychology and a valuable asset to the RCI group. She can be contacted at nlotfi@roboticcentury.com.

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Mohammad Saeid Zare is an aspiring and dedicated aerospace engineering scholar, who began his academic journey at Sharif University of Technology, where he graduated in 2020. His foray into research started in 2019 with a focus on water flows and computational fluid dynamics (CFD) analysis, a field that combines physics, mathematics, and computational software to analyze how liquids and gases flow. Currently, he is furthering his studies in propulsion at the University of Tehran, where his research encompasses a range of topics including underwater robotics, renewable energy, and water flow dynamics. Zare's academic aspirations extend towards obtaining a Ph.D., showcasing his commitment to deepening his knowledge and contributing significantly to the field of aerospace engineering. Particularly noteworthy is his forward-thinking approach to integrate artificial intelligence (AI) with CFD. This integration represents an innovative and progressive step in aerospace engineering, potentially leading to groundbreaking developments in the analysis and simulation of fluid dynamics. His multifaceted academic journey, marked by a blend of theoretical knowledge and practical application, positions Zare as a promising and emerging scholar in aerospace engineering. His work, especially at the intersection of AI and CFD, is poised to make significant contributions to the advancements in this field, reflecting his dedication and potential to shape future innovations in aerospace technology. He can be contacted at zare.saeid75@ut.ac.ir.