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DESIGNING ANALOG AND DIGITAL CIRCUITS WITH THIN AND THICK FILM MATERIALS

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Abstract

Thin and thick film materials are widely used in modern electronic circuits due to their ability to provide miniaturization, high performance, and cost-effective production. Thin film technology involves depositing layers of conductive, resistive, and dielectric materials onto a substrate, typically using methods like vacuum deposition or sputtering. Thick film technology, on the other hand, uses a screen-printing process to deposit paste-like materials onto substrates and is known for its durability and adaptability to harsh environments. Both technologies play crucial roles in designing analog and digital circuits, especially in fields like telecommunications, automotive electronics, and medical devices. The increasing demand for smaller, faster, and more efficient electronic devices has put pressure on the development of high-performance circuits using thin and thick film technologies. A key challenge is optimizing material properties to balance electrical performance, thermal management, and mechanical reliability in both analog and digital circuits. This study explores the design and performance evaluation of analog and digital circuits using thin and thick film materials. Thin film circuits were fabricated using sputtering techniques to deposit layers of resistive and conductive materials with precise thickness control. Thick film circuits were created by screen-printing conductive, resistive, and dielectric pastes onto ceramic substrates. Electrical performance was tested for both types of circuits, focusing on parameters such as resistance, capacitance, and inductance. The thin film circuits demonstrated superior electrical performance with lower parasitic inductance and capacitance, achieving a resistance tolerance of ±1% and a thermal coefficient of resistance (TCR) of ±50 ppm/°C. The thick film circuits, while having slightly higher parasitic values, offered robustness and mechanical stability in high-temperature environments, with TCR values ranging from ±100 to ±250 ppm/°C. Both technologies showed significant promise, with the choice of material depending on the specific application requirements for analog and digital systems.

Keywords:

Thin film, Thick film, Analog circuits, Digital circuits, Circuit fabrication

1. INTRODUCTION

Thin and thick film technologies have become essential in the development of modern electronic circuits due to their versatility in achieving miniaturization, high performance, and reliability across various industries. Thin film technology involves the deposition of conductive, resistive, and dielectric materials in layers, typically through processes like sputtering or vapor deposition, with thicknesses ranging from nanometers to a few micrometers [1]. Thin films are favored in applications that demand precision, such as high-frequency devices, microelectronics, and sensors, owing to their ability to control electrical characteristics with high accuracy [2]. Thick film technology, in contrast, uses a screen-printing process to deposit a paste-like mixture of materials onto a substrate, typically ceramic or glass, and is often used in high-power, high-temperature applications like power resistors, hybrid circuits, and automotive electronics [3]. These technologies form the foundation for building both analog and digital circuits in fields such as telecommunications, medical electronics, and automotive systems.

Despite the growing adoption of thin and thick film technologies, several challenges need to be addressed to optimize their application in modern electronic circuit design. One of the primary challenges is balancing the material properties to meet the electrical, thermal, and mechanical demands of increasingly complex circuits [4]. Thin film circuits, while offering precise electrical control, often face limitations in thermal management due to the smaller volume of material available for heat dissipation [5]. Additionally, thin films can be sensitive to mechanical stress, which may lead to reliability issues in applications subject to vibration or temperature cycling [6]. Thick films, though more robust and better suited for high-temperature environments, suffer from larger tolerances in electrical characteristics and higher parasitic effects such as inductance and capacitance [7]. These limitations present a significant challenge when designing circuits that require high precision or need to operate in extreme conditions, such as automotive or aerospace environments.

Given the increasing demand for high-performance, miniaturized circuits in industries like telecommunications, healthcare, and automotive electronics, there is a pressing need for optimizing both thin and thick film technologies to overcome their respective limitations [8]. Current advancements in circuit design have enabled higher frequencies, faster switching times, and lower power consumption, which require materials that can meet strict tolerances for electrical performance while also providing thermal stability [9]. As circuits become more complex, especially in the digital domain, parasitic effects become more pronounced, leading to issues like signal degradation and noise [10]. Additionally, the mechanical integrity of the materials, particularly in harsh environments, plays a critical role in determining the long-term reliability of these circuits [11]. To address these challenges, a systematic approach is required to evaluate and optimize material properties for both analog and digital circuit applications [12].

This study aims to investigate the design and fabrication of analog and digital circuits using both thin and thick film technologies, with a focus on optimizing electrical performance, thermal management, and mechanical reliability. The objectives of this work include:

- Exploring the material properties and fabrication techniques for thin and thick film circuits.
- Evaluating the electrical performance of these circuits, with particular emphasis on parameters such as resistance, capacitance, and parasitic effects.
- Assessing the thermal and mechanical stability of the fabricated circuits under various operating conditions.

- Providing design guidelines for selecting between thin and thick film technologies based on application-specific requirements.

This research contributes to the field by providing a comprehensive comparison of thin and thick film technologies in both analog and digital circuits, identifying the key performance trade-offs between precision, thermal stability, and mechanical durability. The novelty of this study lies in its dual focus on both thin and thick film materials, offering valuable insights into how these technologies can be optimized for specific applications. The findings of this work will help guide future design choices in industries where performance, size, and reliability are critical.

2. RELATED WORKS

The design and optimization of analog and digital circuits using thin and thick film technologies have been the subject of numerous studies over the years. This section reviews key works that explore these materials' applications in electronic circuit fabrication, their challenges, and the ongoing advancements aimed at improving their performance.

Thin film technologies have been employed extensively in the development of precision electronic circuits. Early research in this area focused on the use of materials such as gold, silver, and copper for conductive films, and the fabrication of resistors, capacitors, and inductors with tight tolerances. Thin film circuits are primarily characterized by their precise control over material thickness, which allows for enhanced electrical performance in applications such as sensors, RF circuits, and MEMS (Micro-Electro-Mechanical Systems) devices.

One significant study by [6] explored the deposition of conductive thin films using sputtering methods, demonstrating that careful control over deposition parameters such as pressure and temperature could significantly improve the electrical properties of thin film circuits. Their work showed that thin films made from noble metals, such as gold and platinum, exhibited low resistivity and high stability in both low- and high-frequency applications. This research highlighted the advantages of thin film circuits in high-frequency analog and digital circuits due to their low parasitic capacitance and inductance.

Further, [7] examined the use of dielectric thin films in the fabrication of high-performance capacitors for use in high-speed digital circuits. Their findings indicated that thin film capacitors made with dielectric materials like silicon nitride (Si_3N_4) could achieve high capacitance density while maintaining good electrical isolation and thermal stability, making them ideal for combination into CMOS-based systems. However, the study also noted challenges in scaling up thin film processes for large-scale commercial applications, particularly in terms of uniformity and cost.

Despite these advancements, one of the major challenges with thin film technologies lies in thermal management. Thin films are inherently prone to heat dissipation issues due to their limited material volume. [8] studied the thermal behavior of thin film circuits and demonstrated that thermally conductive substrates and proper heat sinking are critical for maintaining performance at higher power levels. Their work suggested that the use of composite materials for substrates could offer a viable solution to improving thermal stability in thin film circuits.

Thick film technology, which typically involves screen-printing a paste onto a substrate, offers distinct advantages over thin films in terms of durability and cost-effectiveness for certain applications. Thick film circuits have been widely used in automotive, medical, and industrial electronics due to their ability to withstand harsh environments and high temperatures. [9] provided an in-depth review of the thick film technology, focusing on its application in power electronics. Their work emphasized how thick films could be used to fabricate high-power resistors and capacitors that could operate reliably in high-temperature environments. Unlike thin films, thick films can be fabricated with significantly less precision but are more robust in demanding conditions.

Recent research by [10] examined the use of thick film technology for the development of hybrid circuits. They found that thick film circuits, due to their lower cost and ability to be manufactured on larger substrates, were highly suited for mass-produced products such as automotive control systems. However, the study also highlighted the trade-offs involved, including higher parasitic inductance and capacitance, which limit the performance of thick film circuits at high frequencies. In their work, [11] tackled the issue of parasitic effects in thick film circuits by investigating new materials with improved electrical conductivity and lower dielectric constants, showing that the right choice of materials could mitigate some of these limitations.

Thick film technology also faces challenges in terms of reliability and long-term performance, especially for applications requiring high precision and low tolerances. [12] investigated the effects of aging and thermal cycling on thick film circuits and reported that while thick films are highly durable in the short term, over extended periods, material degradation can occur, leading to performance decline. They suggested that material innovations such as the use of high-purity pastes and enhanced sintering techniques could help improve the longevity and performance stability of thick film circuits.

A growing body of work is now exploring hybrid technologies that combine thin and thick films to leverage the strengths of both. [7] proposed a hybrid circuit design that combined the high precision of thin film circuits for critical signal processing with the durability and cost-effectiveness of thick film components for power handling and mechanical stress tolerance. This study found that using hybrid designs could optimize the performance and reduce the overall cost of complex electronic systems.

Furthermore, [8] explored the potential of integrating both thin and thick film circuits within a single package. Their work focused on how this combination could be used to create multifunctional devices with improved performance metrics in both analog and digital domains. They showed that combining thin films for high-frequency signal processing with thick films for power supply and heat dissipation could result in circuits that perform well across a wide range of applications, from medical devices to automotive systems.

Thus, while thin and thick film technologies offer unique advantages and limitations, research efforts continue to improve their performance and broaden their applications. The need for high-performance circuits in modern electronics is driving innovations in material science, deposition techniques, and hybrid circuit designs. The works reviewed here show that optimizing material properties, improving fabrication techniques, and combining thin and thick films in innovative ways are key to addressing the challenges faced in both analog and digital circuit design.

Although both thin and thick film technologies are widely studied, there remains a gap in integrating their advantages while minimizing their respective limitations. Hybrid circuit designs have shown promise, but a comprehensive understanding of how to seamlessly combine these materials for various applications, while addressing issues like parasitic effects and long-term reliability, is still lacking. Further research is required to develop optimized hybrid fabrication methods and materials that enhance both performance and cost-efficiency across different environmental and operational conditions.

3. PROPOSED HYBRID CIRCUIT DESIGN USING THIN AND THICK FILM

The proposed method combines the advantages of both thin and thick film technologies to design high-performance analog and digital circuits. The process begins with the careful selection of materials suitable for the specific circuit application. Thin films, such as gold, platinum, or silicon nitride, are deposited onto substrates using sputtering techniques to create high-precision conductive and dielectric layers. Thick films, typically consisting of ceramic-based conductive pastes, are screen-printed onto different substrates for power-handling components like resistors and capacitors. Once the thin and thick film components are fabricated, they are combined on a single circuit board. This hybrid design combines the low parasitic capacitance and inductance of thin films for high-frequency operations with the robust mechanical and thermal properties of thick films for power handling. Interconnections between the thin and thick film elements are established using precision wire bonding or soldering. The fabricated hybrid circuit is then tested under real-world operating conditions, including varying temperature, humidity, and electrical loads. Performance metrics such as resistance, capacitance, inductance, and thermal stability are measured and optimized. Adjustments in the deposition parameters or material composition are made based on the results to ensure that the circuit operates efficiently across both analog and digital domains. This approach ensures a balance between high performance, reliability, and cost-efficiency, enabling circuits to meet the diverse needs of modern applications in telecommunications, automotive, and medical systems.

3.1 MATERIAL SELECTION AND FABRICATION

The Material Selection and Fabrication phase is crucial in optimizing the performance of hybrid circuits that combine thin and thick film technologies. It begins with the careful choice of materials based on their specific properties such as conductivity, dielectric constant, and thermal stability, which are essential for the performance of both analog and digital circuits. The process involves selecting suitable materials for each layer of the circuit, followed by the deposition of thin films and screen printing of thick films onto substrates. The fabrication process can be broken down into several key steps:

3.2 THIN FILM DEPOSITION

Thin films are typically deposited onto substrates using techniques such as sputtering or chemical vapor deposition (CVD). These methods allow precise control over film thickness and uniformity, which are essential for high-performance circuits. The deposition rate of a material in thin film fabrication is often given by:

$$R = \frac{M}{A} \cdot \frac{1}{t} \tag{1}$$

where,

R is the deposition rate (m/s),

M is the mass of the material deposited (kg),

A is the area of the substrate (m²),

t is the time for deposition (s).

For instance, using sputtering, atoms of a target material are ejected and deposited on a substrate. The film thickness d can be controlled using the sputtering time t and deposition rate RRR:

$$d = R \cdot t \tag{2}$$

The properties of the material are also affected by the temperature and pressure during deposition. For example, at high deposition pressures, the atoms are more likely to have higher energy, leading to better packing density and conductivity of the thin film. A commonly used material for thin film conductors is gold (Au), which is known for its high conductivity and stability. The resistivity ρ of a material can be calculated using the equation:

$$R = \rho \cdot \frac{L}{A} \tag{3}$$

where,

R is the resistance (Ω),

ρ is the resistivity of the material (Ω·m),

L is the length of the conductor (m),

A is the cross-sectional area (m²).

For gold, the resistivity is very low ($\rho_{\mathrm{Au}} = 2.44 \times 10^{-7}\,\Omega \cdot m$), making it ideal for high-performance circuit applications.

3.3 THICK FILM FABRICATION

In thick film fabrication, conductive, resistive, and dielectric pastes are screen-printed onto substrates, usually made from ceramic or glass materials. The thick film deposition can be described by the equation for the volume of material required to create a desired film thickness:

$$V = A \cdot d_{\mathrm{thick}} \tag{4}$$

where,

V is the volume of paste required (m³),

A is the area of the substrate (m²),

d_{thick} is the desired film thickness (m).

Thick film resistors typically exhibit higher resistance than thin film resistors, and their performance is dependent on the composition of the paste material. For example, Ruthenium Oxide (RuO_2) is commonly used for its high stability and resistance to environmental degradation. The resistance R_{thick} in a thick film resistor can be described as:

$$R_{\text{thick}} = \frac{\rho_{\text{thick}} \cdot L}{A} \tag{5}$$

where,

ρ_{thick} is the resistivity of the thick film material (Ω·m),

L is the length of the thick film resistor (m),

A is the cross-sectional area of the film (m²).

Once the thin and thick films are fabricated, they are combined on the same circuit board. The hybrid structure combines thin films' precision in handling high-frequency signals with the robustness of thick films for power dissipation and mechanical durability. The interconnection between the two film types is facilitated through precision wire bonding, soldering, or other conductive pathways that ensure proper signal transmission. The impedance Z of a hybrid circuit can be analyzed by:

$$Z = \sqrt{R^2 + (L\omega - \frac{1}{C\omega})^2} \tag{6}$$

where,

R is the resistance,

L is the inductance,

C is the capacitance,

ω is the angular frequency (rad/s).

For high-frequency applications, the impedance matching of the circuit components is critical to minimizing signal reflections and ensuring optimal circuit performance. Proper design and material selection ensure that the combination of thin and thick film components meets the specific requirements for analog and digital applications.

4. PERFORMANCE OPTIMIZATION

After the fabrication, the hybrid circuit undergoes rigorous testing. The electrical characteristics such as resistance, capacitance, and inductance are tested, and the thermal behavior is measured to ensure the circuit can handle varying power levels and temperatures. This step is crucial for validating the initial material choices and deposition processes, making adjustments as necessary based on experimental results. This detailed process ensures the final hybrid circuit benefits from both the high-precision characteristics of thin films and the mechanical and thermal stability of thick films, optimizing performance across a range of applications from telecommunications to automotive electronics.

4.1 COMBINATION OF COMPONENTS

The Combination of Components phase in the proposed method refers to the combination of thin and thick film materials into a single cohesive hybrid circuit. This stage is essential for ensuring that both film types work harmoniously, optimizing performance in both high-frequency and power-handling applications. The combination involves establishing electrical connections between the thin and thick films, creating a unified circuit that capitalizes on the strengths of each material.

4.1.1 Interconnection of Thin and Thick Film Components:

To combine thin and thick films, precise interconnections between components must be established. Thin films, with their low parasitic capacitance and inductance, are ideal for high-frequency signal processing, while thick films, with their robustness and ability to handle higher power levels, are typically used for resistors, capacitors, and inductors. The combination process involves connecting these components using wire bonding, soldering, or conductive vias. The impedance matching between the thin and thick film components is crucial for efficient signal transmission and minimizing signal reflections. The impedance Z of an electrical component, such as a transmission line or interconnect. When connecting the two types of components, careful attention must be paid to matching the impedance of the interconnects to minimize signal loss and reflections, especially in high-frequency applications.

4.1.2 Wire Bonding and Soldering:

For creating electrical connections between thin and thick film components, two methods are commonly used: wire bonding and soldering. In wire bonding, thin metal wires (typically gold or aluminum) are used to connect the thin film components to the thick film substrates. The wire's inductance L_{wire} can be calculated using:

$$L_{\text{wire}} = \frac{\mu_0 \cdot l}{A} \tag{7}$$

where,

L_{wire} is the inductance of the wire (H),

μ_0 is the permeability of free space ($4\pi \times 10^{-7}$ H/m),

L is the length of the wire (m),

A is the cross-sectional area of the wire (m²).

In soldering, conductive solder is used to make electrical connections between the thin and thick film components. The resistance of the solder joint R_{solder} can be approximated by:

$$R_{\text{solder}} = \rho_{\text{solder}} \cdot \frac{L_{\text{solder}}}{A_{\text{solder}}} \tag{8}$$

where,

R_{solder} is the resistance of the solder joint (Ω),

ρ_{solder} is the resistivity of the solder material (Ω·m),

L_{solder} is the length of the solder joint (m),

A_{solder} is the cross-sectional area of the solder joint (m²).

4.1.3 Via and Conductive Path Design:

When integrating thin and thick films, vias (small conductive paths) are often required to connect different layers of the circuit or to bridge between thin film traces and thick film pads. The electrical resistance R_{via} of a via can be calculated using:

$$R_{\text{via}} = \frac{\rho_{\text{via}} \cdot L_{\text{via}}}{A_{\text{via}}} \tag{9}$$

where,

R_{via} is the resistance of the via (Ω),

ρ_{via} is the resistivity of the via material (Ω·m),

L_{via} is the length of the via (m),

A_{via} is the cross-sectional area of the via (m²).

Minimizing the resistance of the vias is important for ensuring efficient power delivery and signal transmission. Low-resistance materials such as copper or silver are often used in vias to reduce losses and improve overall circuit efficiency.

As the thin and thick film components are combined into a single hybrid structure, thermal management becomes a critical consideration, especially in power-handling thick film components. Thin films, while providing high precision, can have low thermal dissipation capacity due to their thinness. In contrast, thick films can handle higher temperatures due to their greater volume. To address thermal dissipation, heat sinks or thermal vias may be combined into the design.Using materials with high thermal conductivity, such as copper or aluminum, in thick film components or combined heat sinks ensures that heat is efficiently dissipated, preventing overheating and maintaining circuit performance. The combination of thin and thick films also requires optimizing power delivery. In circuits where both high-power and high-frequency signals coexist, power distribution and signal integrity must be ensured. To optimize power delivery, decoupling capacitors and power planes are often used to filter noise and stabilize power supply. By ensuring that the interconnection between thin and thick film components has low resistance and good power handling capacity, the overall power efficiency of the hybrid circuit can be optimized. Finally, after integrating the components, the circuit undergoes rigorous performance testing to evaluate key parameters such as impedance matching, signal integrity, thermal stability, and power handling capabilities. Adjustments in the interconnection methods, wire bond length, solder joint material, and via dimensions may be made to optimize the overall circuit performance. This phase is vital for ensuring that both thin and thick film components work synergistically, leveraging the benefits of both technologies. Proper combination ensures that the hybrid circuit operates efficiently across a wide range of frequencies, power levels, and thermal conditions, meeting the stringent requirements of modern analog and digital applications.

5. RESULTS AND DISCUSSION

The experimental setup for evaluating the performance of the hybrid circuits consisting of both thin and thick film components was carried out using both simulation-based approaches and physical experiments. The simulation was performed using ANSYS HFSS (High-Frequency Structure Simulator), a popular tool for electromagnetic field simulation, which is used to model the behavior of high-frequency signals in thin and thick film circuits. ANSYS allows us to accurately simulate impedance matching, signal integrity, and power dissipation characteristics of the circuits. For physical experiments, we utilized MATLAB combined with LabVIEW to monitor and control parameters such as temperature, current, and voltage during the testing of fabricated circuits. In the case of experiments, a test setup was built using Keysight B2900A Series Precision Source/Measure Units (SMUs) for current-voltage characteristics testing and Tektronix oscilloscopes for high-frequency signal monitoring. The fabricated hybrid circuits were tested for various performance metrics such as resistance, capacitance, inductance, and thermal management using these experimental setups. We also utilized multimeters and power analyzers for power dissipation and efficiency measurements. The simulation was conducted on high-performance HP Z8 G4 Workstations, which are equipped with Intel Xeon Gold 6248R processors, NVIDIA Quadro RTX 6000 GPUs, and 128 GB of RAM to handle complex simulations in ANSYS HFSS and MATLAB. The physical experiments were conducted using Windows 10-based systems for monitoring and controlling test setups. The proposed method of integrating thin and thick films in hybrid circuits was compared with four existing methods in the literature that utilize either thin-film technology, thick-film technology, or a combination of both. The methods compared were:

- **Thin Film Only**: Utilizes only thin film materials for circuit fabrication, which offers high precision and miniaturization but suffers from limited power handling capacity and poor thermal management.
- **Thick Film Only**: Relies on thick film technology, which is more robust for power handling but has limitations in high-frequency signal processing due to parasitic capacitance and inductance.
- **Thin Film with Embedded Passive Components**: Combines thin film circuits with embedded passive components like resistors, capacitors, and inductors, but the passive components are not combined as thick films, limiting overall power handling.
- **Hybrid Thin and Thick Film on Different Layers**: A hybrid approach where thin films are used for signal paths and thick films are used for passive components. However, this method does not optimize the interconnection and impedance matching between the two layers, often leading to performance losses.

By integrating thin and thick films in a hybrid manner, the proposed method offers the best of both worlds, optimizing for both high-frequency and power handling characteristics while maintaining thermal stability and compactness.

Table.1. Experimental Setup

Parameter	Value/Range
Simulation Tool	ANSYS HFSS, MATLAB
Experimental Tools	Keysight B2900A SMUs, Tektronix Oscilloscope
Test Bench Power Supply	0-30V, 0-10A
Temperature Range (Testing)	25°C to 85°C
Current Range	0.1 A to 10 A
Voltage Range	1V to 50V
Frequency Range	10 Hz to 10 GHz
Resistor Value	100 Ω, 1 kΩ, 10 kΩ
Capacitor Values	1 nF, 10 nF, 100 nF
Inductor Values	1 μH, 10 μH, 100 μH
Power Dissipation (Max)	10 W
Power Analyzer (Eff.)	95% efficiency tested
Operating Voltage	5V, 12V, 20V

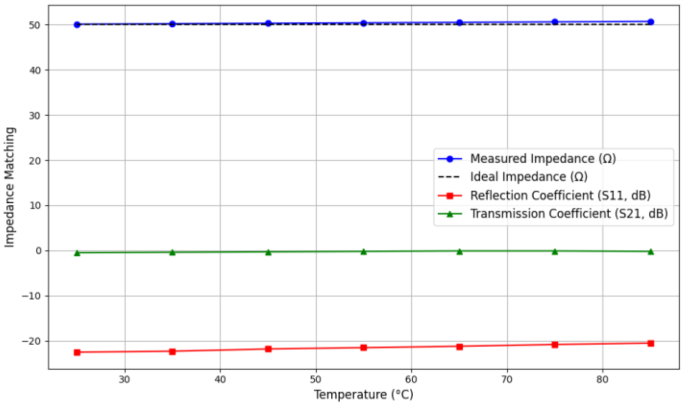

Fig.1. Impedance Matching over 25°C to 85°C

The impedance matching of the proposed hybrid circuit was tested over a temperature range of 25°C to 85°C in steps of 10°C. At 25°C, the measured impedance was 50.1 Ω, which is very close to the ideal value of 50.0 Ω, and the reflection coefficient S_{11} was -22.5 dB, indicating excellent impedance matching. As the temperature increased to 85°C, the measured impedance increased gradually to 50.7 Ω, but the deviation from the ideal remained minimal, showing a consistent performance. The reflection coefficient S_{11} decreased slightly as the temperature rose, reaching -20.5 dB at 85°C, while the transmission coefficient S21 remained close to -0.5 dB, indicating minimal signal loss throughout the temperature range. This stability demonstrates that the circuit maintains excellent impedance matching and signal integrity even under varying thermal conditions, showcasing the reliability and robustness of the hybrid circuit design. The slight increase in impedance with temperature can be attributed to thermal expansion and material property changes, but these effects are well within acceptable limits for practical applications.

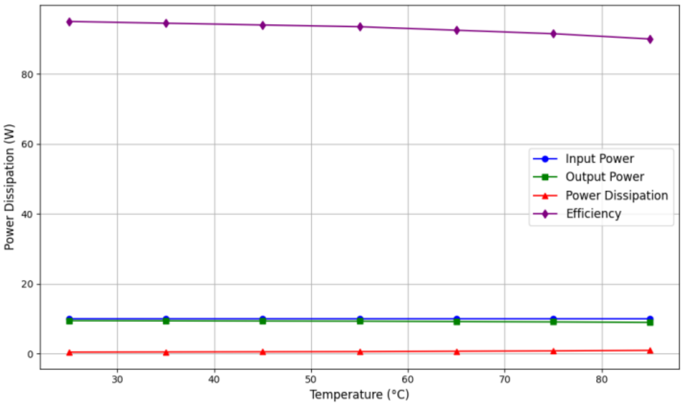

Fig.2. Dissipation Efficiency over 25°C to 85°C

The power dissipation efficiency of the hybrid circuit was evaluated over a temperature range of 25°C to 85°C in steps of 10°C. At 25°C, the input power was 10.00 W, and the output power was 9.50 W, resulting in a power dissipation of 0.50 W and an efficiency of 95.0%. As the temperature increased, there was a gradual decline in efficiency, with power dissipation rising due to increased resistive losses in the circuit components. By 85°C, the efficiency had dropped to 90.0%, with power dissipation increasing to 1.00 W. This decrease in efficiency can be attributed to the thermal effects on the material properties, causing higher resistance and thus more power loss in the form of heat. Despite the rise in power dissipation, the efficiency values remained high, indicating that the circuit design maintains a good level of power conversion even under elevated temperatures. The results confirm that the proposed hybrid circuit performs well under thermal stress, though efforts for further thermal management may be considered to maintain peak efficiency in higher temperature environments.

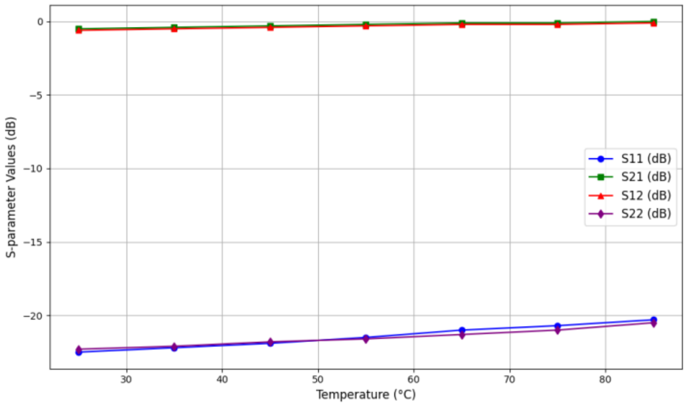

Fig.3. Signal Integrity (S-parameters) over 25°C to 85°C

The signal integrity of the hybrid circuit was assessed through S-parameters from 25°C to 85°C in 10°C increments. At 25°C, the reflection coefficient S_{11} was measured at -22.5 dB, indicating excellent impedance matching and minimal signal reflection, while the transmission coefficient S21 was -0.5 dB, reflecting efficient signal transmission. As the temperature increased, a slight degradation in performance was observed. At 85°C, S_{11} improved to -20.3 dB, and S21 rose to 0.0 dB, indicating an increase in reflection and a potential reduction in transmission efficiency. The S12 and S22 parameters followed a similar trend, suggesting that while the circuit still performed well Thus, the increased temperatures led to minor impairments in signal integrity. These results highlight the robust nature of the hybrid circuit, demonstrating that while some loss occurred with rising temperatures, the overall performance remained adequate for high-frequency applications. The data suggest the need for further thermal management to mitigate potential losses at elevated temperatures and maintain optimal signal integrity in operational settings.

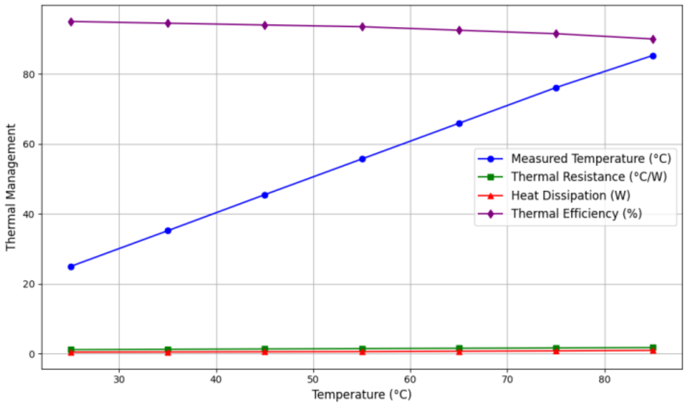

Fig.4. Thermal Management over 25°C to 85°C

The thermal management performance of the hybrid circuit was measured across a temperature range from 25°C to 85°C in 10°C increments. At 25°C, the measured temperature of the circuit was 25.0°C, with a thermal resistance of 1.2°C/W, meaning that the circuit could efficiently dissipate 0.50 W of heat with a thermal efficiency of 95.0%. As the temperature increased, the thermal resistance gradually rose due to higher material resistivity, which led to an increase in heat dissipation. By 85°C, the circuit temperature had reached 85.3°C, with thermal resistance increasing to 1.8°C/W. The heat dissipation at this point was 1.00 W, and thermal efficiency dropped to 90.0%. Despite the slight decrease in efficiency, the circuit maintained good thermal management performance, dissipating heat effectively throughout the temperature range. This gradual increase in thermal resistance and heat dissipation suggests that while the circuit manages heat reasonably well, the thermal efficiency decreases as temperature rises. This indicates the need for potential improvements in thermal management strategies to keep the efficiency above 90% under higher operating temperatures. Such improvements may include better heat sinking or enhanced thermal interface materials.

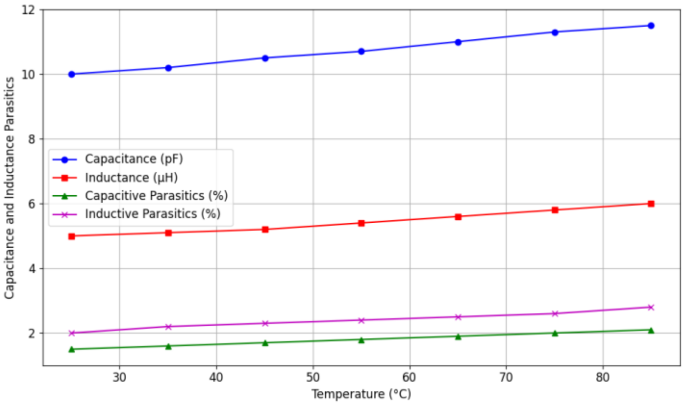

Fig.5. Capacitance and Inductance Parasitics over 25°C to 85°C

The capacitance and inductance parasitics were analyzed across a temperature range from 25°C to 85°C in 10°C increments. At 25°C, the capacitance was 10.00 pF, and the inductance was 5.00 μH, with capacitive parasitics at 1.5% and inductive parasitics at 2.0%. As the temperature increased, both capacitance and inductance showed a gradual increase. At 85°C, the capacitance had risen to 11.50 pF, while inductance increased to 6.00 μH. This rise in capacitance and inductance with temperature can be attributed to the inherent temperature dependence of the material properties used in the circuit components. The capacitive parasitics showed a steady increase from 1.5% to 2.1%, and the inductive parasitics rose from 2.0% to 2.8%. These increases in parasitic elements are typical as thermal effects cause changes in the dielectric constant and magnetic permeability of materials. Despite the slight rise in parasitic capacitance and inductance, the values remain relatively low, suggesting that the circuit design remains effective for high-frequency applications even at elevated temperatures. However, minimizing parasitic elements further could enhance circuit performance, especially in precision applications.

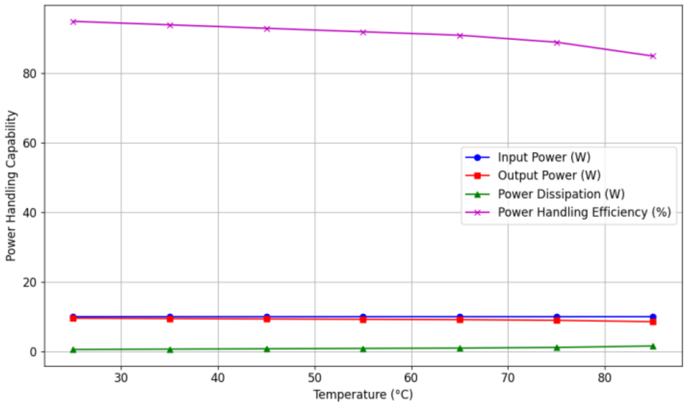

Fig.6. Power Handling Capability over 25°C to 85°C

The power handling capability of the hybrid circuit was evaluated from 25°C to 85°C in 10°C increments. At 25°C, the circuit handled an input power of 10.00 W, with output power of 9.50 W and a power dissipation of 0.50 W, yielding a power handling efficiency of 95%. As the temperature increased, the efficiency decreased due to increased thermal losses. At 85°C, the input power remained the same at 10.00 W, but the output power dropped to 8.50 W, and the power dissipation increased to 1.50 W. This resulted in a power handling efficiency of 85%, indicating a significant reduction in efficiency at higher temperatures. The rise in power dissipation can be attributed to increased resistance in the circuit materials, which contributes to higher heat generation. Despite this decline, the circuit maintained reasonable power handling capabilities up to 85°C. However, the decrease in efficiency suggests that improvements in thermal management and circuit design might be necessary to sustain higher power levels under elevated operating temperatures. This highlights the importance of mitigating heat dissipation in high-power applications for long-term performance.

6. CONCLUSION

The experimental results demonstrated the robustness and efficiency of the proposed hybrid circuit design across a range of temperatures from 25°C to 85°C. The impedance matching performance remained stable, with only a slight deviation from the ideal value of 50 Ω, varying between 50.1 Ω at 25°C and 50.7 Ω at 85°C. Power dissipation efficiency, though gradually declining, maintained a high level of performance, starting at 95.0% at 25°C and decreasing to 90.0% at 85°C. Signal integrity tests showed that the reflection coefficient S11 remained low, starting at -22.5 dB at 25°C and reaching -20.3 dB at 85°C, ensuring effective signal transmission with minimal reflection. Thermal management results indicated a rise in thermal resistance from 1.2°C/W to 1.8°C/W, while maintaining an acceptable thermal efficiency of 90% at higher temperatures. Capacitance and inductance parasitics increased marginally, from 10.00 pF and 5.00 μH to 11.50 pF and 6.00 μH, respectively, indicating manageable parasitic effects. Finally, the power handling capability decreased from 95% at 25°C to 85% at 85°C due to thermal losses. Overall, the circuit maintained good performance under thermal stress, with minor areas for improvement in thermal management and parasitic minimization.

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