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Conclusions

The development of Substrate Integrated Coaxial Line (SICL)-based microwave and millimeter-wave active circuits represents a significant milestone in the field of high-frequency electronics. These circuits offer numerous advantages, including enhanced performance, cost-effectiveness, and the potential for integration into a variety of applications. This document synthesizes the key findings from the research on SICL-based circuits, highlighting the innovations introduced and outlining potential future research directions.

7.1 SUMMARY OF KEY FINDINGS

- **Design and Performance:** The design of the SICL-based millimeter-wave bias tee network has demonstrated significant advancements in terms of performance and integration for 5G FR2 applications. By utilizing a butterfly stub for RF isolation and a single-layer ceramic capacitor for DC isolation, the proposed network effectively operates within the 20-29 GHz range. The design achieves low insertion losses, strong RF-DC isolation, and excellent impedance matching, making it well-suited for integration with active circuits at millimeter-wave frequencies. The innovative use of SICL technology in this design not only simplifies the fabrication process but also ensures cost-effectiveness, while maintaining robust performance. The proposed bias tee network stands out as a valuable contribution to the field, addressing the challenges of high-frequency circuit design and paving the way for future advancements in microwave and millimeter-wave technologies. Complementing this, the design and performance of the SPDT switch for millimeter-wave applications demonstrate its suitability for high-frequency operations within the 27-28.5 GHz range. The switch has been carefully optimized to achieve low insertion loss, high isolation, and favorable return loss, making it an efficient component in RF transceiver systems. The results indicate that the switch meets the necessary requirements for millimeter-wave communication systems, offering reliable performance for applications such as 5G networks and radar systems. The successful implementation of the switch reflects the effectiveness of the design approach and the potential for its use in various high-frequency applications. Building on these advancements, the research also presented a SICL-based amplifier circuit that demonstrated outstanding performance metrics. Notably, the amplifier achieved a peak small-signal gain of 9.2 dB, with a minimal gain ripple less than 1 dB across the 23.35–24.05 GHz frequency range. This indicates the circuit's capability to maintain consistent performance over its operating range, a critical requirement for high-frequency applications. Additionally, the amplifier exhibited impressive input and output return losses, both exceeding 10 dB, which suggests efficient signal reflection handling at the circuit's ports. The low power dissipation further emphasizes the circuit's suitability for applications where energy efficiency is paramount. Collectively, these performance characteristics demonstrate the potential of SICL-based circuits to serve as highly efficient solutions in microwave and millimeter-wave systems. Further advancing the scope of SICL technology, a reflection oscillator was designed utilizing Substrate Integrated Coaxial Line (SICL) resonator technology. The high-quality

factor of the SICL resonator contributed to improved phase noise performance in the oscillator circuit. The experimental results demonstrated that the proposed reflection oscillator achieved sufficient output power and exhibited low phase noise, making it well-suited for applications in Ku-band circuits. In addition, a downconverter mixer was designed using a SICL-based rat-race coupler. The SICL-based circuit leverages a five-port hybrid ring to implement the mixer, effectively avoiding the use of air bridges and crossing transmission lines, which could otherwise degrade the circuit's performance. The mixer achieves a conversion loss below 13.5 dB when transmitting signals within the 24 GHz to 32 GHz range. Its advantages include cost-effectiveness, compactness, and a low-profile PCB technique. This proposed mixer is well-suited for modern communication systems operating in the millimeter-wave frequency range, particularly within the FR2, n257, and n258 bands, making it an excellent choice for designing high-performance millimeter-wave integrated circuits.

- **Simulation and Measurement Correlation:** The reliability and accuracy of the SICL-based designs were rigorously tested through extensive simulations and practical measurements. The correlation between simulated and measured results was strong, indicating the robustness of the proposed designs. While there were slight deviations due to fabrication tolerances and connector losses, the overall agreement between the simulation and measurement data validated the effectiveness of the simulated models. This strong correlation underscores the predictability and reliability of the design process for SICL-based circuits, making them promising candidates for real-world applications.

- **Cost-Effective Fabrication:** The proposed SICL-based designs were realized using low-cost printed circuit board (PCB) fabrication techniques. This approach not only made the circuits economically viable for commercial production but also opened new possibilities for their widespread adoption in various high-frequency applications. The use of PCB technology, which is well-established and widely available, ensures that the benefits of SICL-based circuits can be leveraged without the need for expensive or specialized manufacturing processes. This cost-effective fabrication method aligns well with the increasing demand for affordable high-frequency components in emerging technologies.

- **Justification for Frequency Band Selection:** The selection of different frequency bands across various designs presented in this research is guided by application-specific requirements, feasibility considerations, and the inherent advantages of Substrate Integrated Coaxial Line (SICL) technology. Given the diversity of circuit implementations—such as mixers, amplifiers, and oscillators—each frequency range is chosen to optimize performance in its intended function while leveraging the unique benefits of SICL-based integration. For instance, the amplifier operates in the 23.35–24.05 GHz band, aligning with emerging 5G and satellite communication applications. This frequency range is well-suited for high-gain amplification while ensuring compatibility with SICL's shielding properties, which reduce spurious radiation and minimize losses. In contrast, the mixer circuit is designed for 24–32 GHz operation, where SICL's low-loss transmission characteristics and compact hybrid ring implementation provide a distinct advantage for frequency conversion applications in millimeter-wave radar and communication systems. Additionally, the oscillator design in this work operates in the Ku-band, specifically chosen to exploit the high-Q resonator characteristics of SICL. This ensures phase noise reduction, which is critical for stable signal generation in radar and frequency synthesis applications. The feasibility of implementing each circuit at its respective frequency band is thoroughly evaluated based on SICL's manufacturing constraints, dispersion characteristics, and practical realization aspects.

- **Potential Application:** The unique characteristics of SICL-based circuits make them suitable for a wide range of applications. In wireless communication systems, the high gain and

excellent return loss characteristics of these circuits can significantly enhance signal strength and reliability, particularly in the millimeter-wave spectrum. This is crucial for improving the performance of communication systems, especially as the demand for higher data rates continues to grow. In modern communications, the robust performance of SICL-based circuits in mmWave frequencies is particularly advantageous. These applications require high precision and reliability, which are well-supported by the low-loss and high-gain properties of the proposed circuits. The ability to operate effectively in this frequency range makes SICL-based circuits ideal for use in advanced radar systems and high-resolution sensing technologies. The lightweight and compact nature of SICL-based designs, combined with their high-frequency capabilities, also make them well-suited for satellite and aerospace applications. In these environments, where size, weight, and performance are critical factors, SICL-based circuits can be employed in communication systems, navigation systems, and other essential applications, offering a balance of efficiency and functionality.

7.2 FUTURE RESEARCH DIRECTIONS

The future of SICL-based microwave and millimeter-wave circuits holds exciting possibilities. One potential area of research is the optimization of these circuits for broader frequency ranges. By extending their applicability to various emerging high-frequency technologies, SICL-based circuits could play a pivotal role in the development of next-generation communication systems and other advanced applications. Enhancements in design techniques and materials could further improve the bandwidth and overall performance of these circuits, making them even more versatile. Another promising direction is the integration of SICL-based designs with advanced materials. The use of high-conductivity metals and low-loss substrates could further reduce insertion losses and enhance overall circuit performance. Exploring novel materials and their integration into SICL-based circuits could lead to significant advancements in their efficiency and effectiveness, opening new possibilities for their application in cutting-edge technologies. Another key aspect is the exploration of miniaturization techniques to develop more compact and lightweight SICL-based components. Given SICL's potential for high-density integration, research can be directed toward reducing the overall footprint of SICL-based circuits while maintaining performance integrity. Advanced fabrication methods, such as multilayer integration and embedded passive components, can further contribute to achieving size reduction and improved circuit efficiency. Furthermore, investigating higher-frequency applications of SICL technology, particularly in the millimeter-wave (mmWave) regime, presents a promising area for future research. As communication and radar systems continue to evolve toward higher frequency bands (e.g., 60 GHz, 77 GHz, and beyond), SICL technology can be leveraged for designing low-loss, high-performance components that are well-suited for these demanding applications. Enhancing the design methodology to account for frequency-dependent effects, dispersion characteristics, and substrate losses will be essential for realizing SICL circuits that operate efficiently at mmWave frequencies. In summary, the expansion of SICL-based active circuit research holds significant potential for advancing next-generation high-frequency, low-loss, and compact RF systems. By addressing these key areas—amplifier optimization, circuit miniaturization, and higher-frequency applications—future research can contribute to the development of more efficient, scalable, and high-performance SICL-based technologies for modern communication and radar systems.

7.3 CONCLUDING REMARKS

The research and development of SICL-based microwave and millimeter-wave active circuits presented in this work highlight significant advancements in the field of high-frequency electronics. The innovative design techniques, cost-effective fabrication methods, and robust performance characteristics of these circuits make them promising candidates for a wide range of applications. As technology continues to evolve, further research and development in SICL-based designs hold the potential to drive significant progress in high-frequency systems, paving the way for new technological innovations and applications.