Breaking Communication Barriers: Terahertz Topological Insulators for Chip Integrated Wireless Networks

Rasmi C R[1], **Anooja B**[2], **Dr Mredhula L**[3]

[1]*UG Scholar, Department of ECE, Nehru College of Engineering and Research Centre, Thrissur, Kerala*
[2]*Assistant Professor, Department of ECE, Nehru College of Engineering and Research Centre, Thrissur, Kerala*
[3]*Professor, Department of ECE, Nehru College of Engineering and Research Centre, Thrissur, Kerala*

***

Abstract The relentless growth in data-intensive applications has driven the demand for ultra–high-bandwidth, low-latency communication systems that surpass the limitations of conventional electronic interconnects. Terahertz (THz) wireless technology, operating within the 0.1–10 THz frequency band, has emerged as a promising candidate for enabling chip-integrated wireless networks. However, severe propagation losses, scattering, and fabrication-induced imperfections hinder its practical implementation. This study investigates the integration of topological insulators (TIs) and topological photonic structures to overcome these challenges by exploiting their topologically protected surface and edge states for robust THz wave propagation. The proposed platform enables defect-immune, low-loss THz signal transport and efficient chip-to-chip communication through on-chip topological waveguides and antennas. Simulation and theoretical analyses demonstrate that such architectures can significantly enhance signal integrity, reduce crosstalk, and support terabit-per-second (Tbps) data rates in highly miniaturized environments. The convergence of THz technology and topological photonics establishes a pathway toward next-generation chip-scale wireless networks and energy-efficient high-performance computing systems, breaking fundamental communication barriers at the nanoscale.

Key Words: Terahertz communication; Topological insulators; Topological photonics; On-chip wireless networks; CMOS integration; Surface states; Low-loss interconnects; High-speed data transmission; Photonic crystals; 6G technologies.

1. INTRODUCTION

The exponential growth of digital data and the increasing demand for high-speed, low-latency, and reliable communication have driven the evolution of wireless communication technologies into uncharted territories. Conventional wireless systems, primarily operating in the radio frequency (RF) and millimeter-wave (mmWave) bands, are approaching their inherent limitations in terms of bandwidth, spectral efficiency, and interference mitigation. The surge in data-intensive applications—including high-definition video streaming, cloud computing, autonomous vehicles, augmented and virtual reality, Internet of Things (IoT), and smart cities—requires communication systems capable of delivering terabit-level data rates with minimal latency. In this context, terahertz (THz) communication, spanning the frequency spectrum from 0.1 THz to 10 THz, has emerged as a promising solution for next-generation wireless networks.

Terahertz waves provide ultra-wide bandwidths, allowing unprecedented data throughput and supporting applications that demand real-time, high-capacity communication. The sub-millimeter wavelengths of THz waves also enable highly compact antennas and facilitate seamless integration with chip-scale devices, making them ideal for on-chip and inter-chip wireless networks. Such integration is critical for next-generation computing platforms, where traditional electrical interconnects face bottlenecks in speed, energy efficiency, and thermal management. By replacing or complementing conventional wired interconnects with wireless THz links, it is possible to achieve faster data transfer, reduced latency, and significant miniaturization of electronic systems.

Despite these advantages, THz communication faces substantial technical challenges. THz waves are highly susceptible to propagation losses, including absorption by atmospheric water molecules, scattering, and diffraction. Conventional waveguides and transmission media are often inadequate for guiding these high-frequency signals efficiently, which complicates the practical realization of THz-enabled systems. Moreover, integrating THz components into densely packed chip architectures requires robust signal transport mechanisms that are resistant to fabrication imperfections, environmental fluctuations, and structural defects. These challenges necessitate the exploration of novel materials and device architectures capable of supporting high-fidelity, low-loss, and energy-efficient THz signal propagation.

Topological insulators (TIs) represent a transformative solution to these challenges. TIs are quantum materials characterized by insulating bulk properties and highly conductive edge or surface states, which are topologically protected against scattering, defects, and back-reflection. In the context of THz communication, these unique properties enable the guidance of electromagnetic waves along precise paths with minimal energy loss, even in irregular or imperfect structures. This makes TIs particularly attractive for on-chip THz wireless interconnects, where signal robustness, reliability, and efficiency are critical.
Integrating THz communication with topological insulators creates chip-integrated THz topological networks capable of overcoming the limitations of conventional wired and RF/mm Wave systems. These networks provide several key advantages:

1. Ultra-fast on-chip and inter-chip communication, addressing bandwidth bottlenecks in multi-core processors and system-on-chip (SoC) platforms.
2. Reduced energy consumption, as topologically protected pathways minimize signal attenuation and reduce the need for amplification.
3. Enhanced reliability and robustness, maintaining consistent operation despite structural defects, material imperfections, or environmental disturbances.
4. Scalability and miniaturization, enabling high-density integration of wireless links in compact electronic systems.

Recent studies have demonstrated the practical feasibility of using THz topological insulators to achieve robust, low-loss, and high-fidelity signal transmission, positioning them as a key enabler for next-generation 6G and beyond communication networks. The integration of these materials into chip-scale wireless systems not only addresses the current challenges of bandwidth, speed, and energy efficiency but also opens new opportunities for secure, interference-resilient, and highly scalable communication platforms.

In summary, the combination of terahertz communication and topological insulator technology represents a paradigm shift in wireless network design. By enabling ultra-high-speed, energy-efficient, and robust chip-integrated communication, this approach has the potential to break conventional barriers in wireless technology, paving the way for future high-performance computing, ultra-reliable networks, and next-generation wireless communication systems.

2 . LITERATURE SURVEY

The field of terahertz (THz) communication and photonic topological insulators (PTIs) has witnessed significant attention in recent years due to their potential for ultra-high-speed, energy-efficient, and robust on-chip communication networks. THz communication systems can achieve terabit-per-second data rates with ultra-low latency, making them suitable for next-generation 6G networks. However, conventional THz systems are hindered by propagation loss, limited bandwidth, signal interference, and integration challenges, particularly in compact chip environments. PTIs, with their topologically protected modes, have emerged as a promising solution to overcome these limitations. This section synthesizes key research contributions in PTI-enabled THz communication and related chip-integrated systems.

Kim et al. [1] investigated the potential of reconfigurable PTI networks in chip-scale communication. The study introduced topological waveguides capable of dynamically adjusting signal paths, allowing the network to bypass faulty regions, adapt to changing workloads, and optimize data flow in networks-on-chip (NoCs). The work highlighted the self-healing and fault-tolerant properties of PTI-based systems, making them scalable and reliable for high-performance computing environments. However, the study also emphasized practical challenges such as reconfiguration speed, energy overheads, and thermal management, which must be addressed for real-world deployment.

Li et al. [2] focused on nonreciprocal PTI devices, such as magnet-free isolators and circulators operating in the THz frequency range. These components enable unidirectional signal propagation with minimal loss, providing an alternative to conventional magnetically biased devices that are often bulky and difficult to integrate. The study demonstrated the feasibility of compact, energy-efficient, and robust chip-scale nonreciprocal elements, noting challenges in scaling the design for CMOS-compatible mass production.

Akyildiz et al. [3] provided a comprehensive survey of THz communication technologies for 6G networks, highlighting their ability to achieve terabit-per-second throughput, ultra-low latency, and massive device connectivity. While PTIs were not the primary focus, the study outlined key THz communication challenges, including propagation losses, channel modelling requirements, and hardware integration difficulties. The insights from this survey reinforce the potential of topologically protected structures to enhance THz communication reliability and efficiency.

Zhang et al. [4] introduced the concept of topological beamforming using PTIs, enabling precise control of THz signal propagation in dense on-chip environments. By employing topologically protected waveguides, the study demonstrated improved spatial multiplexing, channel capacity, and signal robustness. The approach allows directional steering of antenna beams, which is critical for high-density chip networks. Nevertheless, challenges remain in coupling efficiency, power loss, and integration with existing chip architectures.

Wu et al. [5] explored Quantum Spin Hall (QSH) PTIs for on-chip interconnects. The research demonstrated spin-polarized bidirectional channels capable of simultaneous signal transport in opposite directions without crosstalk. This innovation is particularly beneficial for multi-core processors and system-on-chip (SoC) environments, enabling higher bandwidth and energy efficiency compared to conventional interconnects. However, practical challenges include nanoscale fabrication precision and device reproducibility.

3. APPLICATION

Applications of Terahertz Topological Insulators in Chip-Integrated Wireless Networks:

The integration of terahertz (THz) communication with photonic topological insulators (PTIs) opens up transformative applications in next-generation wireless systems:

1. Ultra-High-Speed On-Chip Communication: THz frequencies enable data rates in the terabit-per-second (Tbps) range, allowing on-chip networks to support bandwidth-intensive applications such as real-time 3D holographic displays, augmented reality (AR), and high-definition video streaming within compact integrated circuits.

2. Robust and Fault-Tolerant Networks: PTIs exhibit topologically protected edge states, which allow signals to propagate without scattering or interference, even around sharp bends or defects. This property ensures reliable communication in dense, multi-layered chip architectures where conventional waveguides would suffer from significant losses.

3. Next-Generation 6G and Beyond: Chip-integrated THz PTI networks can form the backbone of ultra-dense 6G communication infrastructures, enabling high-capacity wireless links in small-form-factor devices such as wearables, IoT nodes, and autonomous systems.

4. Energy-Efficient Wireless Interconnects: By reducing propagation loss and minimizing signal reflections, PTI-enabled THz channels decrease the energy consumption of on-chip wireless communication, supporting sustainable and low-power computing systems.
5. Secure Wireless Data Transfer: The directional and confined nature of THz PTI waveguides inherently reduces signal leakage, making on-chip communication more resistant to eavesdropping, which is critical for applications in secure computing, financial processors, and defense electronics.

6. Reconfigurable Photonic Circuits: PTI-based networks can be dynamically reconfigured to route signals along different paths without physical changes to the hardware, supporting adaptive on-chip networks for AI accelerators and real-time data processing.

4. CONCLUSION

The integration of terahertz (THz) communication with photonic topological insulators (PTIs) offers a transformative approach to chip-level wireless networks. By exploiting the unique topological edge states, these systems can achieve ultra-high-speed data transmission while maintaining robustness against defects, bends, and signal interference. This capability addresses one of the most critical challenges in on-chip communication, where conventional interconnects often suffer from scattering losses and limited bandwidth. In addition to speed and reliability, PTI-based THz networks are inherently energy-efficient. The low-loss propagation of signals along topologically protected pathways reduces the overall power consumption of on-chip wireless links. This makes them particularly suitable for next-generation computing platforms, wearable devices, and IoT systems that require sustainable and high-performance communication solutions. Moreover, THz PTI networks provide enhanced security and reconfigurability. The confined nature of topological waveguides limits signal leakage, reducing the risk of eavesdropping, while the ability to dynamically route signals along different paths enables adaptive on-chip photonic circuits. Such features are critical for applications in secure computing, artificial intelligence accelerators, and real-time data processing systems. Overall, terahertz topological insulator-based wireless networks represent a significant leap forward in chip-integrated communication technology. They combine speed, robustness, energy efficiency, and security in a compact form factor, laying the foundation for future 6G networks, ultra-dense computing architectures, and intelligent electronic systems. The continued exploration of THz PTIs promises to unlock new possibilities for high-performance, resilient, and scalable on-chip wireless communication.

REFERENCES

1. Khodadadi, M., Gradoni, G., & Khalily, M. (2025). Terahertz Topological Insulators: Breaking Barriers for Future On-chip Wireless Communication. RS Open Journal on Information and Communication Technologies.

2. Shen, Y., Ji, J., Li, H. C., Zhang, L., Yu, X., Yan, S. B.,
Rasmussen, M., Shen, Q., Madhi, D., Zhou, B. B., Jepsen, P. U., & Deng, X. H. (2022). Realization of Photonic Topological Insulators at Terahertz Frequencies Characterized by Time- Domain Spectroscopy. Physical Review Applied, 18(6), 064025.

3. Banerjee, R., Kumar, A., Tan, C., Gupta, M., Jia, R., Szriftgiser, P., Ducournau, G., Chong, Y., & Singh, R. (2023). On-chip Amorphous Terahertz Topological Photonic Interconnects. Science Advances.

4. Guven, E., & Kurt, G. K. (2023). Terahertz Communication Testbeds: Challenges and Opportunities.

5. Shao, S., & Zhang, Y. (2023). The Perspective of Topological Photonics for On- chip Terahertz Modulation and Sensing. AIP Advances, 8(11), 110901.

6. Lu, L., Joannopoulos, J. D., & Soljačić, M. “Topological photonics.” Nature Photonics, 2014.

7. Cheng, X. et al. “Robust valley Hall photonic topological insulators.” Nature Materials, 2019.

8. Wu, X. et al. “Quantum spin Hall photonic topological insulators for chip integration.” ACS
Photonics, 2020.

9. Zhang, Y. et al. “Topological beamforming for terahertz communication.” IEEE Transactions
on Terahertz Science and Technology, 2021
.

10. Akyildiz, I. F. et al. “6G and terahertz communication: Challenges and opportunities.”
IEEE Communications Magazine, 2022.