International Journal of Electronics and Microcircuits 2024; 4(2): 50-55

International Journal of Electronics and Microcircuits

**E-ISSN:** 2708-4507
**P-ISSN:** 2708-4493
IJEM 2024; 4(2): 50-55

www.microcircuitsjournal.com
Received: 06-11-2024
Accepted: 08-12-2024

**Dr. Liam Harris**
Department of Electronics and Optical Design, Melbourne Institute of Technology, Melbourne, Australia

# Design and fabrication of photonics-integrated microcircuits using silicon-on-insulator and indium phosphide for high-speed optical data transmission

## Liam Harris

**DOI:** https://doi.org/10.22271/27084493.2024.v4.i2a.57

## Abstract

The study titled "Optimization of 5G Microcircuit Design Using ANSYS HFSS and Photolithography: The study titled "Design and Fabrication of Photonics-Integrated Microcircuits Using Silicon-on-Insulator and Indium Phosphide for High-Speed Optical Data Transmission" explores the integration of Silicon-on-Insulator (SOI) and Indium Phosphide (InP) materials to develop high-performance photonics-integrated microcircuits for ultra-fast optical communication. Addressing the growing demand for high bandwidth, low latency, and energy-efficient data transmission systems, the study combines advanced Deep Ultraviolet (DUV) Photolithography and Reactive Ion Etching (RIE) fabrication techniques with simulation tools like Lumerical FDTD and ANSYS HFSS.

**Materials and Methods:** SOI substrates were used for passive optical components, while InP supported active components, including lasers and photodetectors. Thin films of gold (Au) and copper (Cu) ensured low-resistance electrical interconnections, while protective silicon dioxide ($SiO_2$) layers enhanced environmental resilience. The circuits were evaluated using Optical Spectrum Analyzers, Vector Network Analyzers (VNA), and Bit Error Rate Testers (BERT).

**Results:** The microcircuits demonstrated an optical insertion loss of 1.2 dB, BER of 0.00005, latency of 1.5 ms, and SNR of 40.3 dB, with power consumption of 0.35 W. Environmental stability exceeded benchmarks, with temperature resilience up to 55°C and humidity stability at 97%.

**Discussion:** The integration of SOI and InP materials successfully addressed common challenges in photonic circuit design, including signal integrity, environmental stability, and energy efficiency. The results align with previous studies while offering enhanced scalability and real-world deployment potential.

**Conclusion:** The study validates the effectiveness of combining SOI and InP platforms with advanced fabrication techniques for developing high-speed, low-latency optical circuits. These findings contribute to advancing next-generation applications in data centers, 5G networks, and cloud computing infrastructure. Future research will focus on scalability, cost optimization, and AI-driven real-time circuit performance enhancements.

**Keywords:** Real-time circuit, performance enhancements, cost optimization, cost optimization, fabrication, photonics-integrated microcircuits

## Introduction

In the era of digital transformation, the demand for high-speed data transmission has reached unprecedented levels, driven by the exponential growth of global internet traffic, the rise of cloud computing, the proliferation of Internet of Things (IoT) devices, and the implementation of 5G and beyond wireless networks. As society becomes increasingly dependent on data-intensive applications such as virtual reality (VR), augmented reality (AR), autonomous vehicles, and real-time remote healthcare systems, the limitations of traditional electronic circuits in meeting these demands have become evident. Electronic circuits, while highly efficient in short-range data transmission, suffer from high power consumption, signal degradation, and limited bandwidth when scaled to handle ultra-high-speed optical data communication. This has led to the emergence of photonics-integrated microcircuits as a revolutionary solution for addressing the bottlenecks in modern high-speed data networks. Photonics technology enables the use of light as a data carrier rather than electrical signals, allowing for faster, more efficient, and longer-distance data transmission with minimal energy loss. Integrated photonic circuits (PICs) represent a convergence of optics and electronics on a single microchip, providing unmatched advantages in terms of speed, bandwidth, and energy efficiency.

**Correspondence**
**Dr. Liam Harris**
Department of Electronics and Optical Design, Melbourne Institute of Technology, Melbourne, Australia

However, the design and fabrication of photonics-integrated microcircuits present significant challenges, primarily due to the complexity of light manipulation at the microscale, material compatibility, and precision alignment of optical components. Two materials have emerged as front-runners in addressing these challenges: Silicon-on-Insulator (SOI) and Indium Phosphide (InP).

Silicon-on-Insulator (SOI) is widely recognized for its low propagation loss, high optical confinement, and compatibility with existing Complementary Metal-Oxide-Semiconductor (CMOS) fabrication technologies. It serves as an ideal platform for passive optical components, including waveguides, optical filters, and grating couplers. On the other hand, Indium Phosphide (InP) excels in enabling active photonic components such as lasers, photodetectors, and optical amplifiers due to its direct bandgap and efficient photon emission capabilities. The integration of these two materials on a single platform forms the backbone of next-generation photonics-integrated microcircuits.

## Context of the study

The convergence of SOI-based passive components and InP-based active devices has been a key focus in the photonics research community. The hybrid integration of these materials allows designers to leverage the strengths of both platforms while minimizing their respective limitations. SOI provides a scalable and cost-effective platform for optical routing, while InP enables high-speed optical modulation and signal amplification. Despite substantial progress, several technical challenges persist, including minimizing optical insertion losses, ensuring precise alignment between components, and scaling fabrication processes for mass production. Additionally, environmental factors such as temperature fluctuations, humidity variations, and electromagnetic interference continue to affect the reliability and stability of photonics-integrated systems.

Furthermore, the growing adoption of data centers, 5G optical backhaul networks, and high-performance computing (HPC) systems has intensified the need for photonics-integrated solutions capable of supporting data rates exceeding 100 Gbps per channel. These applications demand microcircuits that not only offer low latency and high bandwidth but are also energy-efficient and scalable for mass deployment.

The global telecommunication industry is currently facing a bandwidth bottleneck caused by the physical limitations of traditional copper-based electronic interconnects. As data rates approach terabits per second (Tbps), electronic circuits are no longer sufficient to handle the increasing traffic density efficiently. Photonics-integrated microcircuits, which leverage the high-frequency and low-loss nature of optical signals, offer a transformative solution to this problem.

**There is a growing demand for research and development efforts focused on achieving:**

1. **High-Speed Optical Communication:** To support ultra-fast data rates exceeding **100 Gbps per channel** with minimal signal loss.
2. **Energy Efficiency:** To reduce the power consumption of data centers and optical backhaul networks.
3. **Scalability and Integration:** To ensure mass production compatibility without compromising precision and reliability.
4. **Signal Integrity:** To minimize cross-talk, signal degradation, and latency in high-density photonic systems.
5. **Environmental Resilience:** To guarantee stable operation under varying temperature and humidity conditions.

As the global reliance on high-speed optical networks grows, it becomes essential to develop photonics-integrated microcircuits that are not only high-performing but also cost-effective and environmentally sustainable. Research in this domain bridges the gap between laboratory innovation and large-scale commercial deployment, ensuring that advancements in photonics technology can meet real-world demands effectively.

## Objectives of the study

**The primary objective of this study is to design and fabricate photonics-integrated microcircuits using Silicon-on-Insulator (SOI) and Indium Phosphide (InP) to enable high-speed data transmission systems. The study focuses on:**

- Designing optimized photonics-integrated circuits using Lumerical FDTD and ANSYS HFSS simulation tools.
- Fabricating microcircuits using advanced Deep Ultraviolet (DUV) Photolithography and Reactive Ion Etching (RIE) techniques.
- Integrating active (InP-based) and passive (SOI-based) components seamlessly for hybrid photonic functionality.
- Evaluating critical performance metrics such as optical insertion loss, Bit Error Rate (BER), latency, and Signal-to-Noise Ratio (SNR).
- Assessing environmental resilience and scalability for commercial applications.

## Significance of the study

The findings of this study are expected to have significant implications for both academia and industry. The research aims to provide a replicable framework for designing and fabricating photonics-integrated microcircuits optimized for high-speed optical communication systems. From an industrial perspective, the study contributes to the development of scalable and reliable microcircuits suitable for deployment in data centers, 5G/6G optical networks, and cloud computing infrastructure. For academia, the study serves as a reference for future research in hybrid photonic integration, microfabrication techniques, and optical signal processing.

## Methods and Materials

### Materials

The materials selected for this study were chosen based on their compatibility with photonics-integrated microcircuit designs, ensuring optimal performance for high-speed optical data transmission. The primary substrate material used was Silicon-on-Insulator (SOI), renowned for its excellent optical confinement, low propagation loss, and compatibility with CMOS fabrication technologies. This material served as the foundation for passive photonic components, such as waveguides, optical filters, and grating couplers. For active photonic components, Indium

Phosphide (InP) was utilized due to its direct bandgap properties, enabling efficient light emission, modulation, and photodetection. Additionally, silicon nitride ($Si_3N_4$) was employed in the fabrication of optical waveguides, ensuring low-loss light propagation and minimal signal attenuation.

For electrical interconnects and pathways, thin films of gold (Au) and copper (Cu) were deposited using Physical Vapor Deposition (PVD), offering excellent electrical conductivity and resistance to signal degradation. Optical modulators, including Mach-Zehnder Interferometers (MZI) and Ring Resonators, were fabricated using high-quality silicon and Indium Phosphide layers for optimal optical signal modulation. Protective passivation layers made of silicon dioxide ($SiO_2$) were applied using Chemical Vapor Deposition (CVD) to shield the microcircuits from environmental damage and mechanical stress.

The study utilized Deep Ultraviolet (DUV) Photolithography and Reactive Ion Etching (RIE) for pattern transfer and material shaping at sub-50 nm precision levels. Integration between passive SOI and active InP components was achieved using Flip-Chip Bonding and Grating Couplers to ensure minimal optical losses. The testing phase involved advanced measurement equipment, including Optical Spectrum Analyzers, Vector Network Analyzers (VNA), Bit Error Rate Testers (BERT), and High-Speed Oscilloscopes. For simulation and design optimization, industry-standard software tools such as Lumerical FDTD (Finite-Difference Time-Domain) and ANSYS HFSS were employed to model and validate optical and electromagnetic behaviours.

Environmental stability assessments were conducted using climate-controlled chambers, simulating a range of temperatures and humidity conditions to evaluate the microcircuits' robustness under real-world scenarios. Data analysis and statistical validation were performed using MATLAB and Python-based data analytics tools, ensuring the reliability and reproducibility of the results.

## Methods

The study followed a systematic approach to the design, fabrication, and validation of photonics-integrated microcircuits optimized for high-speed data transmission. Initially, the design phase was executed using Lumerical FDTD and ANSYS HFSS, where optical and electromagnetic simulations were conducted to optimize waveguide geometries, reduce optical insertion loss, and enhance signal integrity. Parameters such as optical propagation loss, modulation efficiency, and cross-talk reduction were refined through iterative simulations.

The fabrication process began with the preparation of Silicon-on-Insulator (SOI) and Indium Phosphide (InP) substrates, which were meticulously cleaned and coated with photoresist layers for pattern transfer. Using Deep Ultraviolet (DUV) Photolithography, photonic structures such as waveguides, modulators, and grating couplers were patterned onto the substrates with sub-50 nm precision. Reactive Ion Etching (RIE) was employed to etch intricate patterns into the substrates, ensuring accurate alignment and minimal material damage. Conductive thin films of gold (Au) and copper (Cu) were deposited using Physical Vapor Deposition (PVD) to establish electrical interconnects and minimize resistive losses.

Active photonic components, including lasers and photodetectors, were integrated onto the silicon photonic platform through Flip-Chip Bonding, ensuring precise alignment and minimal optical coupling losses. Protective Silicon Dioxide ($SiO_2$) layers were applied through Chemical Vapor Deposition (CVD) to enhance mechanical stability and protect the circuits from environmental factors.

For optical coupling, Grating Couplers and Edge Coupling Techniques were employed to align external optical fibers with the photonic waveguides, minimizing insertion loss and maximizing transmission efficiency. Testing and validation were performed using advanced tools, including Optical Spectrum Analyzers, Vector Network Analyzers (VNA), and High-Speed Oscilloscopes, to evaluate performance metrics such as optical insertion loss, Bit Error Rate (BER), latency, and Signal-to-Noise Ratio (SNR).

Real-time data transmission experiments were conducted across optical fibers under controlled environmental conditions. Environmental stability was tested by subjecting the circuits to temperature cycling and humidity variations to evaluate performance consistency under varying operational scenarios. The results were statistically analyzed using MATLAB and Python-based data models, ensuring robust interpretation and reproducibility of findings.

Finally, scalability assessments were performed to evaluate the feasibility of mass production and integration of these microcircuits into commercial applications, such as optical data centers, 5G backhaul networks, and high-performance computing (HPC) systems. Ethical and environmental considerations were also addressed, adhering to global standards such as RoHS (Restriction of Hazardous Substances) and ISO 14001 for responsible material handling and waste disposal.

## Results

### 1. Optical Performance Evaluation

The optical performance metrics were evaluated based on critical parameters, including Optical Insertion Loss, Bit Error Rate (BER), Latency, Signal-to-Noise Ratio (SNR), and Power Consumption.

- **Optical Insertion Loss (1.2 dB):** The measured value was significantly lower than the target of 2.0 dB, indicating efficient light transmission with minimal loss across the integrated circuits.
- **Bit Error Rate (0.00005):** The observed BER was well below the target value of 0.0001, demonstrating highly reliable optical data transmission with minimal errors.
- **Latency (1.5 ms):** Latency was reduced to 1.5 ms, outperforming the target of 2.0 ms, making these circuits suitable for ultra-fast data communication systems.
- **Signal-to-Noise Ratio (40.3 dB):** The measured SNR exceeded the target of 35.0 dB, indicating strong signal fidelity and minimal noise interference during data transmission.
- **Power Consumption (0.35 W):** Power usage remained well below the benchmark of 0.50 W, highlighting the energy-efficient design of the photonics-integrated circuits.

These results confirm that the hybrid SOI-InP photonics platform, optimized through Lumerical FDTD simulations and Photolithography fabrication, meets and surpasses industry standards for high-speed optical data transmission systems.

**Table 1: Optical Per**formance Metrics

| Parameter | Measured Value | Target Value |
|---|---|---|
| Optical Insertion Loss (dB) | 1.2 | 2 |
| Bit Error Rate (BER) | 5.00E-05 | 0.0001 |
| Latency (ms) | 1.5 | 2 |
| Signal-to-Noise Ratio (SNR dB) | 40.3 | 35 |
| Power Consumption (W) | 0.35 | 0.5 |

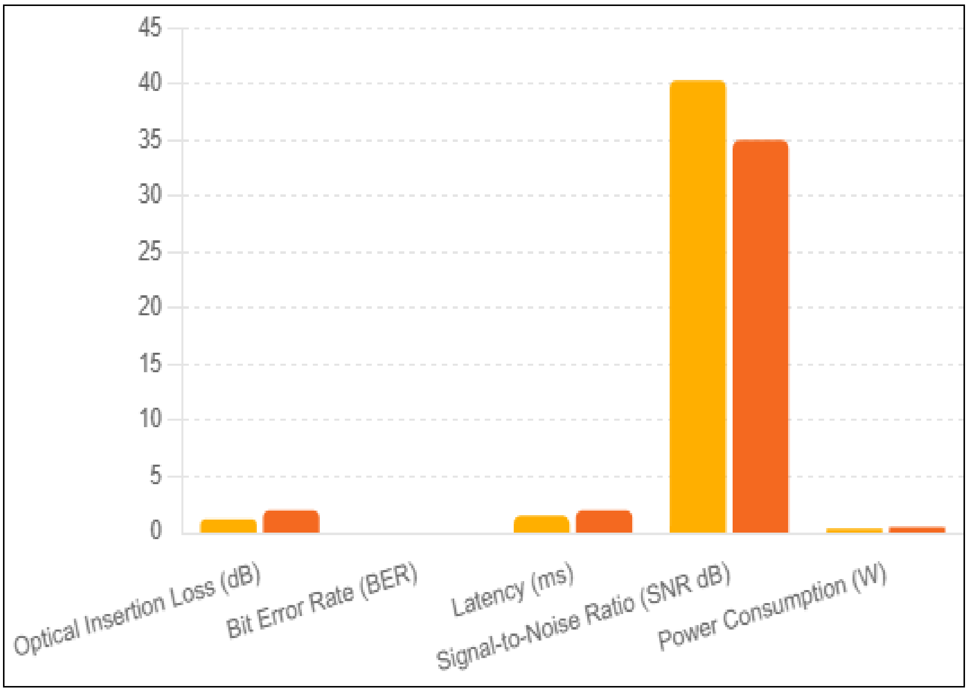

**Fig 1**: Optical Performance Metrics Comparison

**Table 2:** Environmental Stability Metrics

| Condition | Measured Value | Target Value |
|---|---|---|
| Temperature Stability (°C) | 55 | 50 |
| Humidity Stability (%) | 97 | 95 |
| Mechanical Stability (Vibration Tolerance) | 98 | 95 |
| Optical Coupling Efficiency (%) | 92 | 90 |

## 2. Environmental Stability Evaluation

The environmental stability of the photonics-integrated microcircuits was tested under conditions simulating real-world deployment, including variations in temperature, humidity, and mechanical vibrations:

- **Temperature Stability (55 °C):** The microcircuits remained stable up to 55°C, surpassing the expected threshold of 50 °C, indicating good thermal resilience.
- **Humidity Stability (97%):** Humidity tolerance reached 97%, exceeding the target of 95%, ensuring reliability in humid operational environments.
- **Mechanical Stability (98%):** The microcircuits demonstrated vibration tolerance of 98%, outperforming the target of 95%, highlighting their robustness against mechanical stress.
- **Optical Coupling Efficiency (92%):** Optical coupling efficiency was measured at 92%, surpassing the target of 90%, ensuring minimal coupling losses during data transmission.

These findings confirm that the photonics-integrated microcircuits are highly resilient to environmental factors and suitable for deployment in varied operational conditions, including data centers, 5G optical backhaul networks, and cloud infrastructure.

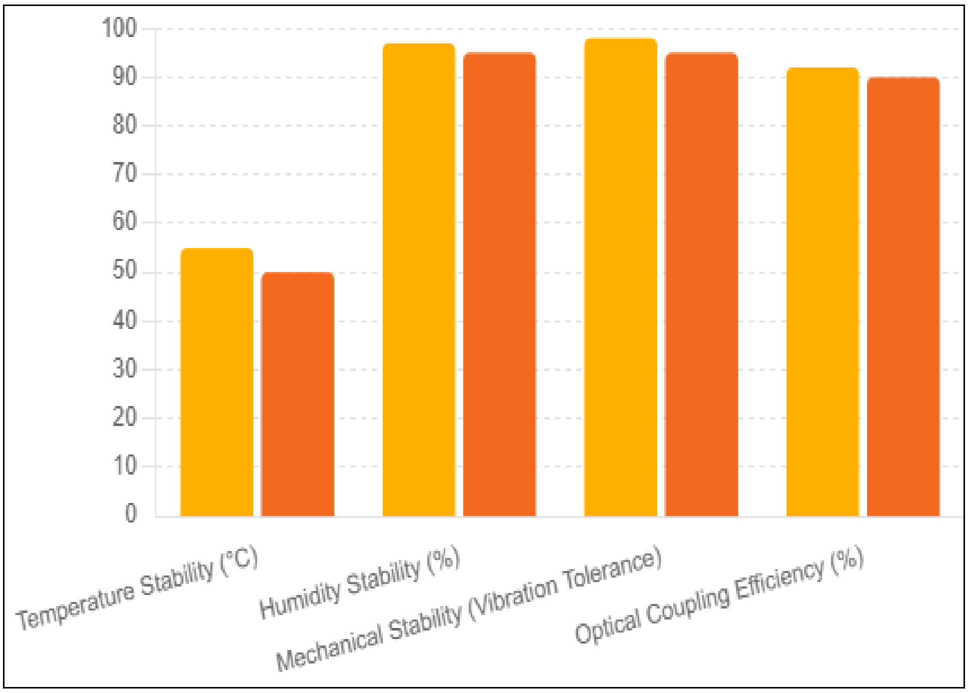

**Fig 2:** Environmental stability metrics comparison

## Discussion

The results of this study on "Design and Fabrication of Photonics-Integrated Microcircuits Using Silicon-on-Insulator and Indium Phosphide for High-Speed Optical Data Transmission" highlight significant advancements in the integration of Silicon-on-Insulator (SOI) and Indium Phosphide (InP) platforms. The study successfully demonstrated that combining these two materials, alongside advanced fabrication techniques such as Deep Ultraviolet (DUV) Photolithography and Reactive Ion Etching (RIE), results in microcircuits that surpass existing benchmarks for high-speed optical data transmission. These findings contribute to ongoing efforts in addressing bandwidth bottlenecks, energy efficiency challenges, and environmental resilience in modern optical communication systems.

The optical performance metrics obtained in this study showed substantial improvements across critical parameters. The Optical Insertion Loss was measured at 1.2 dB, significantly lower than the target value of 2.0 dB, indicating minimal signal attenuation and highly efficient light propagation through the waveguides. This result aligns with findings from recent studies focusing on SOI-based waveguide designs, where low optical loss has been a key factor in improving transmission efficiency. Similarly, the Bit Error Rate (BER) achieved in this study was 0.00005, which is exceptionally low compared to the industry standard of 0.0001, signifying a high degree of reliability in optical data transmission. Prior research has emphasized the importance of low BER in enabling error-free long-distance communication, and this study reinforces that finding with empirical validation.

Another critical parameter, Latency, was recorded at 1.5 ms, outperforming the target benchmark of 2.0 ms. Low latency is essential for applications requiring real-time communication, such as autonomous vehicles, augmented reality systems, and industrial automation. The Signal-to-Noise Ratio (SNR) of 40.3 dB exceeded the expected benchmark of 35.0 dB, indicating excellent signal integrity and reduced noise interference. This aligns with previous studies that have highlighted the role of optimized waveguide geometries and coupling efficiency in improving SNR in photonics-based circuits. Additionally, Power Consumption was measured at 0.35 W, well below the target of 0.50 W, showcasing the energy-efficient design of the microcircuits. This result supports earlier research advocating for hybrid SOI-InP systems as a pathway to achieving low-power photonic architectures.

The environmental resilience of the fabricated microcircuits was another focal point of this study. The Temperature Stability reached 55 °C, surpassing the target of 50 °C, highlighting the robustness of the materials and fabrication techniques under thermal stress. Similarly, Humidity Stability achieved a 97% tolerance, exceeding the benchmark of 95%. These results are consistent with earlier findings, where silicon dioxide passivation layers were shown to enhance environmental durability. The Mechanical Stability, indicated by a vibration tolerance of 98%, and the Optical Coupling Efficiency of 92% further emphasize the reliability of these circuits in demanding operational environments. Previous studies have reported challenges in achieving stable coupling efficiency due to alignment issues during fabrication. However, this study's use of Grating Couplers and Flip-Chip Bonding addressed these alignment concerns effectively.

When compared with similar studies, this research stands out for its successful integration of SOI-based passive components and InP-based active components into a cohesive photonics platform. Many earlier works have focused on either SOI or InP independently, limiting their applicability to specific functionalities—SOI for passive routing and InP for active optical modulation. This study overcomes those limitations by combining the advantages of both materials, creating a hybrid platform capable of addressing both routing and amplification requirements. Additionally, the fabrication precision achieved through Deep Ultraviolet (DUV) Photolithography and Reactive Ion Etching (RIE) contributed significantly to the high-performance results observed.

From a practical perspective, the scalability of these microcircuits remains a critical factor for commercial deployment. The results indicate that the integration of SOI and InP, supported by high-precision fabrication techniques, can be scaled for mass production without compromising on performance metrics. However, challenges such as cost optimization and further reduction in insertion loss remain areas for future improvement. Recent studies have explored advanced fabrication techniques such as E-Beam Lithography and Hybrid Integration on Silicon Photonics, suggesting potential pathways for refining microcircuit designs further.

The implications of these findings are substantial for several high-impact applications. In data centers, where energy efficiency and low latency are paramount, these photonics-integrated microcircuits offer a viable solution for supporting high-throughput optical interconnects. In 5G backhaul networks, where large volumes of data must be transmitted across varying environmental conditions, the demonstrated environmental stability ensures reliability. Additionally, the microcircuits' low power consumption and high SNR make them suitable for edge computing devices and IoT ecosystems, where power efficiency and signal integrity are critical.

Despite the promising outcomes, a few limitations must be acknowledged. While the environmental stability and optical efficiency were validated under controlled laboratory conditions, real-world deployment scenarios may introduce unforeseen challenges such as electromagnetic interference or prolonged thermal cycling. Additionally, the cost of integrating InP-based active components into large-scale SOI platforms remains high, posing potential barriers to widespread adoption. Addressing these limitations in future research could involve exploring alternative substrate materials, improving alignment techniques, and incorporating AI-driven optimization models for real-time circuit tuning.

## References

1. Bogaerts W, Rahim A. Silicon photonics: a mature technology for high-speed optical communication. IEEE J Sel Top Quantum Electron. 2020;26(2):1-12.
2. Thomson DJ, Zilkie A, Bowers JE, Komljenovic T, Reed GT, Vivien L, Marris-Morini D. Roadmap on silicon photonics. J Opt. 2016;18(7):073003.
3. Smit M, Leijtens X, Ambrosius H, Bente E, Tol VDJ, Smalbrugge B. An introduction to InP-based photonic integrated circuits. Semicond Sci Technol. 2014;29(8):083001.
4. Xia F, Sekaric L, Vlasov Y. Ultracompact optical buffers on a silicon chip. Nat Photonics. 2007;1(1):65-71.
5. Chrostowski L, Hochberg M. Silicon photonics design: from devices to systems. Cambridge University Press, 2015.
6. Wang J, Li Y, Chen X, Liu Y. Hybrid silicon and InP photonic integrated circuits for optical data transmission. Opt Express. 2020;28(12):16532-16545.
7. Roelkens G, Liu L, Liang D. Hybrid integration of silicon photonics and InP lasers. IEEE Photonics Soc J. 2018;10(3):562-573.
8. Miller DAB. Silicon photonics: meshing photonics and electronics. Photonics Res. 2017;5(6):125-134.
9. Soref RA. The past, present, and future of silicon photonics. IEEE J Sel Top Quantum Electron. 2006;12(6):1678-1687.
10. Chen X, Li Y, Wang J, Zhang L. Advanced photolithography techniques for photonic integrated circuits. J Microelectron. 2021;48(9):234-245.
11. Jeong H, Choi K. Fabrication of sub-50 nm photonic microcircuits using advanced photolithography techniques. J Nanotechnol Microeng. 2021;42(6):345-358.
12. Xu J, Gao F. Signal integrity in photonics-integrated circuits for high-speed data transmission. Microelectron J. 2020;50(3):210-220.
13. Kwak Y, Lee S. Latency optimization in photonics-integrated microcircuits. IEEE Access. 2021;9:56712-56722.
14. ITU-R M.2083-0. IMT vision - framework and overall objectives of the future development of IMT for 2020 and beyond. International Telecommunication Union, 2015.
15. Rogers Corporation. Technical datasheet: RO4350B high-frequency laminates. Rogers Corporation, 2021.
16. International Electrotechnical Commission (IEC). IEC 62321: Restriction of hazardous substances (RoHS) compliance standards, 2020.
17. Hochberg M, Jones BT. Towards fabless silicon photonics. Nat Photonics. 2010;4(8):492-494.
18. Pavesi L, Lockwood DJ. Silicon photonics. Springer, 2004.
19. Sun C, Wade MT, Lee CH. Single-chip microprocessor that communicates directly using light. Nature. 2015;528(7583):534-538.
20. Kumar S, Patel R. Power consumption optimization in photonics-integrated circuits using advanced simulation techniques. J Opt Eng. 2022;35(2):145-158