Integrated Silicon Photonics Switches for Transparent Optical Networks

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Abstract

The modern communication landscape is undergoing a profound transformation, marked by a steady increase in bandwidth consumption, an expanding user base, and the proliferation of latency-sensitive applications. To meet these evolving demands, network infrastructures must be upgraded not only by optimizing current capacities but also by deploying new, high-performance hardware.

Optical fibre networks remain the foundational backbone of today's communication systems, owing to their exceptionally high bandwidth and minimal latency—features that set them apart from alternative technologies such as satellite or radio-based links. In this context, transparent optical switching and routing elements have become key enablers in achieving the performance levels required by modern applications, shaping the design of transmission protocols and network standards.

Transparent photonic devices—i.e., components that do not require electro-optical conversion—are essential to fully realize the potential of fibre-optic communication. Although this area is still technologically maturing, transparent optics are already proving critical for future-ready network design.

Photonic Integrated Circuits (PICs) have emerged as a core technology in the development of transparent optical systems. These devices provide a platform capable of delivering the benefits of integration—namely reduced power consumption, compact size, high functional density, and the potential for scalable mass production—mirroring the revolutionary impact of integrated electronics in the digital domain.

PICs are a rapidly growing research field not only due to their applicability in telecommunications, but also as a foundational technology for adjacent domains such as data centers, quantum computing, biomedical diagnostics, and

environmental sensing. Despite the promise, industrial adoption remains limited by several challenges, including the lack of technological maturity, scarcity of large-scale photonic foundries, and long prototyping cycles.

A promising subfield addressing many of these challenges is Silicon Photonics (SiPh), which is the primary focus of this thesis. SiPh employs silicon as the guiding medium for optical signals and benefits from compatibility with well-established CMOS fabrication processes. This enables seamless integration of electronic and photonic components on a single chip, significantly reducing cost and fabrication complexity.

Moreover, the compatibility with CMOS technology has led to the emergence of standardized design platforms and foundry processes, fostering faster development, increased reproducibility, and more robust implementations. These advantages position SiPh as a strong candidate for scalable deployment in future optical networks.

With the technological context established, this work proposes a comprehensive bottom-up design and analysis of photonic components and architectures targeted at transparent optical telecommunications. The focus is primarily on Wavelength Division Multiplexing (WDM) and other frequency-dependent transmission techniques.

Using both established simulation tools and novel modeling techniques, various PICs are designed and characterized from the physical and material layers up to the system level, including transmission penalty analysis in deployment scenarios.

The multidisciplinary approach adopted in this research has led to multiple novel contributions across different levels of abstraction. At the device level, several optimized waveguide designs are presented, including a novel grating-assisted coupler incorporating Phase Change Materials (PCMs), which enables non-volatile, power-efficient, and reconfigurable optical switching.

At the circuit level, a modular multi-band switching architecture is introduced, designed to enhance network resource management by utilizing residual bandwidth more effectively.

At the system and network level, an automated transmission penalty abstraction model is developed for reconfigurable multi-stage switching structures. This model supports system-level optimization strategies aligned with Software-Defined Networking (SDN) principles and demonstrates the potential of multi-layer-aware design in the development of next-generation optical networks.