Introduction to Photonic Quantum Chips for Communication Engineers

Abstract

Photonic integrated circuits (PICs) are revolutionizing communication engineering: From low-latency RF filters for 6G networks to parallel AI operations in data centers. **6G standardization begins in 2025, with photonic components being the key to unlocking the terahertz (THz) frequency range for extremely high data rates [**?**].** This introduction is based on current literature (2024–2025) and highlights analog realization principles (e.g., interference via MZI), preferred operations (matrix multiplication, signal filtering), and relevance for real-time communication. Practical: Table of techniques, outlook on hybrid systems. Sources: Reviews from Nature, SPIE, and ScienceDirect. **Current research (EPFL/Harvard) has introduced a revolutionary optoelectronic chip that processes THz and optical signals on a single processor [**?**].**

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0.1 Basics: Photonic Chips in Communication Engineering

Photonic quantum chips use light waves for highly parallel, energy-efficient processing – essential for 6G (bandwidths $> 100\,\text{GHz}$, latency $< 1\,\text{ms}$). **The European Commission has announced the start of 6G standardization for 2025, with a focus on sovereignty and a leading technology position [**?**]. Additionally, 2025 has been declared by the United Nations as the International Year of Quantum Science and Technology (IYQ), underscoring the strategic importance of photonics [**?**].** In contrast to electronic CMOS chips (heat limits at high frequencies), PICs enable analog signal processing through optical interference and modulation, drawing on classical analog optics (e.g., from 1980s RF technology).

> Important Note: The technology is strongly analog: Continuous wave transformations (phase shifts, diffraction) dominate, as photons are intrinsically parallel (wavelength multiplexing) and low-latency. Hybrid systems (photonics + electronics) complement for control.

Current trends (2025): Scalable wafers (e.g., 6-inch TFLN) for industrial deployments in data centers, with $1000\times$ speedup for AI workloads [**?**, **?**].

0.2 Realization of Operations: Analog Principles

Operations are primarily realized through optical components that prioritize analog processing. Core components:

- **Mach-Zehnder Interferometer (MZI)**: For phase modulation and linear transformations; analog addition/multiplication via interference.

- **Waveguides and Modulators**: Electro-optical (e.g., LiNbO_3) or thermal control for continuous signals.

- **Monolithic Integration**: Co-packaging on Si or TFLN platforms minimizes losses ($< 1\,\text{dB}$), enables dynamic reconfiguration.

The technology draws on analog RF systems: Instead of discrete bits, continuous wave fields for real-time filtering (e.g., demodulation in 6G) [**?**].

Example: Linear transformation (matrix-vector multiplication) via MZI mesh: $y = M \cdot x$, where M is programmed by phases ϕ_i: $\phi_i = \arg(M_{ij})$.

0.3 Preferred Operations for Photonic Components

Photonic chips are suited for linear, frequency-dependent, and parallel operations, as analog continuity saves energy (pJ/bit) and maximizes bandwidth. Based on 2025 reviews: