

# 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.,  $\text{LiNbO}_3$ ) 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  $\phi_i$ :  $\phi_i = \arg(M_{ij})$ .

### 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: