

# **Chapter 1**

## **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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## 1.1 Basics: Photonic Chips in Communication Engineering

Photonic quantum chips use light waves for highly parallel, energy-efficient processing – essential for 6G (bandwidths  $> 100$  GHz, latency  $< 1$  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 [?, ?].

## 1.2 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<sub>3</sub>) or thermal control for continuous signals.
- **Monolithic Integration:** Co-packaging on Si or TFLN platforms minimizes losses ( $< 1$  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  $\phi_i$ :  $\phi_i = \arg(M_{ij})$ .

## 1.3 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:

Not preferred: Non-linear logic (e.g., AND/OR), as photons are linear; hybrids required here.

Operation	Realization (analog)	Relevance for Communication Engineering
Matrix Multiplication (GEMM)	MZI arrays for interference-based addition/multiplication	AI training in edge networks (e.g., Transformers for 6G routing) [?]
RF Signal Filtering	Optical diffraction/FFT via waveguides	Demodulation, BSS in 5G/6G (bandwidth > 100 GHz) [?]
Recurrent Processing	Programmed photonic circuits (PPCs) for sequential transformations	Real-time monitoring in networks (e.g., RNNs for anomaly detection) [?]
Differential Operations	Meta-optics for gradients (e.g., edge detection)	Image/signal enhancement in optical networks [?]
Parallel Optimization	Correlation via coherent PICs	Gradient descent for routing optimization [?]

Table 1.1: Preferred Operations on Photonic Chips – Focus on Analog Techniques

## 1.4 Literature Review: Current Developments (2024–2025)

Based on the latest reviews (open access) and current projects:

- **Analog optical computing: principles, progress, and prospects (2025):** Overview of analog PICs; advances in reconfigurable designs for real-time signals [?].
- **Integrated Terahertz Communication:** A revolutionary optoelectronic processor (EPFL/Harvard, 2025) integrates the processing of \*\*terahertz waves\*\* and optical signals on a chip. This breakthrough is crucial for 6G, as it enables high performance without significant energy loss and is compatible with existing photonic technologies [?].
- **Integrated Photonics for 6G Research:** Projects like \*\*6G-ADLANTIK\*\* and \*\*6G-RIC\*\* (Fraunhofer HHI) develop photonic-electronic integration components to unlock the THz frequency range for 6G and improve network resilience (SUSTAINET) [?].
- **Integrated photonic recurrent processors (2025):** Recurrent operations via PPCs; applications in sequential processing (e.g., network monitoring) [?].
- **Photonics for sustainable AI (2025):** GEMM as core for AI; photonic advantages for energy-poor 6G inference [?].
- **All-optical analog differential operation... (2025):** Meta-optics for differential computing; ideal for signal enhancement [?].

- **Harnessing optical advantages in computing: a review (2024):** Parallel advantages; focus on FFT and correlation for RF [?].

These sources emphasize the shift to analog hybrids for 6G: From prototypes to scalable wafers.

## 1.5 Outlook: Photonics in 6G Networks

Photonic chips enable low-latency, scalable communication: E.g., optical BSS for multi-user MIMO in 6G. Challenges: Minimize losses (via InAs QDs). Future: Fully integrated PICs for edge computing in base stations. \*\*Fraunhofer HHI already offers application-specific PICs on the silicon nitride (SiN) platform, which are also used in biosciences and sensing [?].\*\*

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