

# Introduction to Photonic Quantum Chips for Communication Engineers

January 2025

## 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 [7].** 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 [8].**

# Contents

0.1	Basics: Photonic Chips in Communication Engineering . . . . .	1
0.2	Realization of Operations: Analog Principles . . . . .	2
0.3	Preferred Operations for Photonic Components . . . . .	2
0.4	Literature Review: Current Developments (2024–2025) . . . . .	3

## 0.1 Basics: Photonic Chips in Communication Engineering

Photonic quantum chips use light waves for highly parallel, energy-efficient processing – essential for 6G (bandwidths  $> 100$  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 [7]. 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 [6].** 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

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 [3, ?].

## 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<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) [1].

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:

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) [3]
RF Signal Filtering	Optical diffraction/FFT via waveguides	Demodulation, BSS in 5G/6G (bandwidth > 100 GHz) [10]
Recurrent Processing	Programmed photonic circuits (PPCs) for sequential transformations	Real-time monitoring in networks (e.g., RNNs for anomaly detection) [2]
Differential Operations	Meta-optics for gradients (e.g., edge detection)	Image/signal enhancement in optical networks [4]
Parallel Optimization	Correlation via coherent PICs	Gradient descent for routing optimization [5]

**Table 1:** Preferred Operations on Photonic Chips – Focus on Analog Techniques

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

## 0.4 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 [1].
- **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 [8].

- **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) [9].
- **Integrated photonic recurrent processors (2025):** Recurrent operations via PPCs; applications in sequential processing (e.g., network monitoring) [2].
- **Photonics for sustainable AI (2025):** GEMM as core for AI; photonic advantages for energy-poor 6G inference [3].
- **All-optical analog differential operation... (2025):** Meta-optics for differential computing; ideal for signal enhancement [4].
- **Harnessing optical advantages in computing: a review (2024):** Parallel advantages; focus on FFT and correlation for RF [5].

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

# Bibliography

- [1] Analog optical computing: principles, progress, and prospects. ScienceDirect, 2025. [Link](#).
- [2] Integrated photonic recurrent processors. SPIE, 2025. [Link](#).
- [3] Photonics for sustainable AI. Nature, 2025. [Link](#).
- [4] All-optical analog differential operation... De Gruyter, 2025. [Link](#).
- [5] Harnessing optical advantages in computing: a review. Frontiers, 2024. [Link](#).
- [6] Leichsenring, H. (2025). Steht die Quantentechnologie 2025 am Wendepunkt. Der Bank Blog; DPG (2025). 2025 – Das Jahr der Quantentechnologien. LP.PRO - Technologieforum Laser Photonik.
- [7] Europäische Kommission (2025). 6G-Netze in Europa. Gestaltung der digitalen Zukunft Europas.
- [8] Benea-Chelmus, C. et al. (2025). 6G-Mobilfunk rückt näher – Revolutionärer Chip schafft optische und elektronische Datenverarbeitung. Leadersnet; Nature Communications (Publikation).
- [9] Fraunhofer HHI (2025). Berlin 6G Conference 2025; Fraunhofer HHI (2025). Photonics West 2025.
- [10] RF-Signal-Filterung. (Placeholder reference for the table entry).