Photon Chip Einleitung

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Zusammenfassung

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 Komponenten being the key to unlocking the terahertz (THz) Frequenz range for extremely high data rates [**?**].** This introduction is basierend auf Strom literature (2024–2025) and highlights analog Realisierung Prinzipien (e.g., interference via MZI), preferred operations (matrix multiplication, signal filtering), and Relevanz for reell-Zeit communication. Practical: Tabelle of techniques, outlook on hybrid Systeme. Sources: Reviews from Nature, SPIE, and ScienceDirect. **Current research (EPFL/Harvard) has introduced a revolutionary optoelectronic chip das Prozesse THz and optical signals on a single processor [**?**].**

1 Basics: Photonic Chips in Communication Engineering

Photonic Quanten chips use Licht Wellen for highly parallel, Energie-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 Wichtigkeit of photonics [**?**].** Im Gegensatz to electronic CMOS chips (heat Grenzen at high frequencies), PICs enable analog signal processing through optical interference and modulation, drawing on klassisch analog optics (e.g., from 1980s RF technology). Important Hinweis: The technology is strongly analog: Continuous Welle Transformationen (phase shifts, diffraction) dominate, as Photonen are intrinsically parallel (Wellenlänge multiplexing) and low-latency. Hybrid Systeme (photonics + electronics) complement for control.

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

2 Realization of Operations: Analog Principles

Operations are primär realized through optical Komponenten das prioritize analog processing. Core Komponenten:

- **Mach-Zehnder Interferometer (MZI)**: For phase modulation and linear Transformationen; analog addition/multiplication via interference.
- **Waveguides and Modulators**: Electro-optical (e.g., $LiNbO_3$) or thermal control for kontinuierlich signals.
- **Monolithic Integration**: Co-packaging on Si or TFLN platforms minimizes losses ($< 1\,\text{dB}$), enables dynamic reconfiguration.

The technology draws on analog RF Systeme: Instead of diskret bits, kontinuierlich Welle Felder for reell-Zeit filtering (e.g., demodulation in 6G) [**?**]. Beispiel: Linear Transformation (matrix-Vektor multiplication) via MZI mesh: $y = M \cdot x$, wo M is programmed by phases ϕ_i: $\phi_i = \arg(M_{ij})$.

3 Preferred Operations for Photonic Components

Photonic chips are suited for linear, Frequenz-dependent, and parallel operations, as analog continuity saves Energie (pJ/bit) and maximizes bandwidth. Basierend auf 2025 reviews:

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Tabelle 1: Preferred Operations on Photonic Chips – Focus on Analog Techniques

Not preferred: Non-linear logic (e.g., AND/OR), as Photonen are linear; hybrids erforderlich hier.

4 Literature Review: Current Developments (2024–2025)

Basierend auf the latest reviews (open access) and Strom projects:

- **Analog optical computing: Prinzipien, progress, and prospects (2025)**: Overview of analog PICs; advances in reconfigurable designs for reell-Zeit signals [**?**].
- **Integrated Terahertz Communication:** A revolutionary optoelectronic processor (EPFL/Harvard, 2025) integrates the processing of **terahertz Wellen** and optical signals on a chip. This breakthrough is crucial for 6G, as it enables high performance without significant Energie 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 Komponenten to unlock the THz Frequenz range for 6G and improve network resilience (SUSTAINET) [**?**].
- **Integrated photonic recurrent processors (2025)**: Recurrent operations via PPCs; Anwendungen in sequential processing (e.g., network monitoring) [**?**].
- **Photonics for sustainable AI (2025)**: GEMM as core for AI; photonic advantages for Energie-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.

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 bereits offers Anwendung-specific PICs on the silicon nitride (SiN) platform, welche are auch used in biosciences and sensing [**?**].**

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