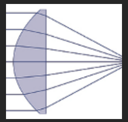
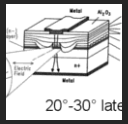
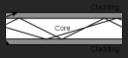
Lectures & Labs
by Donn Silberman



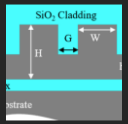
Introduction to Optics (1st lecture was today)



Photonics Industry & Technologies (2nd lecture)



Fiber Based Photonics (3rd lecture)



Integrated Photonics (4th lecture now)

Labs – IPEK Demo Wed. 29th & Quantum Demos Fri. 31st

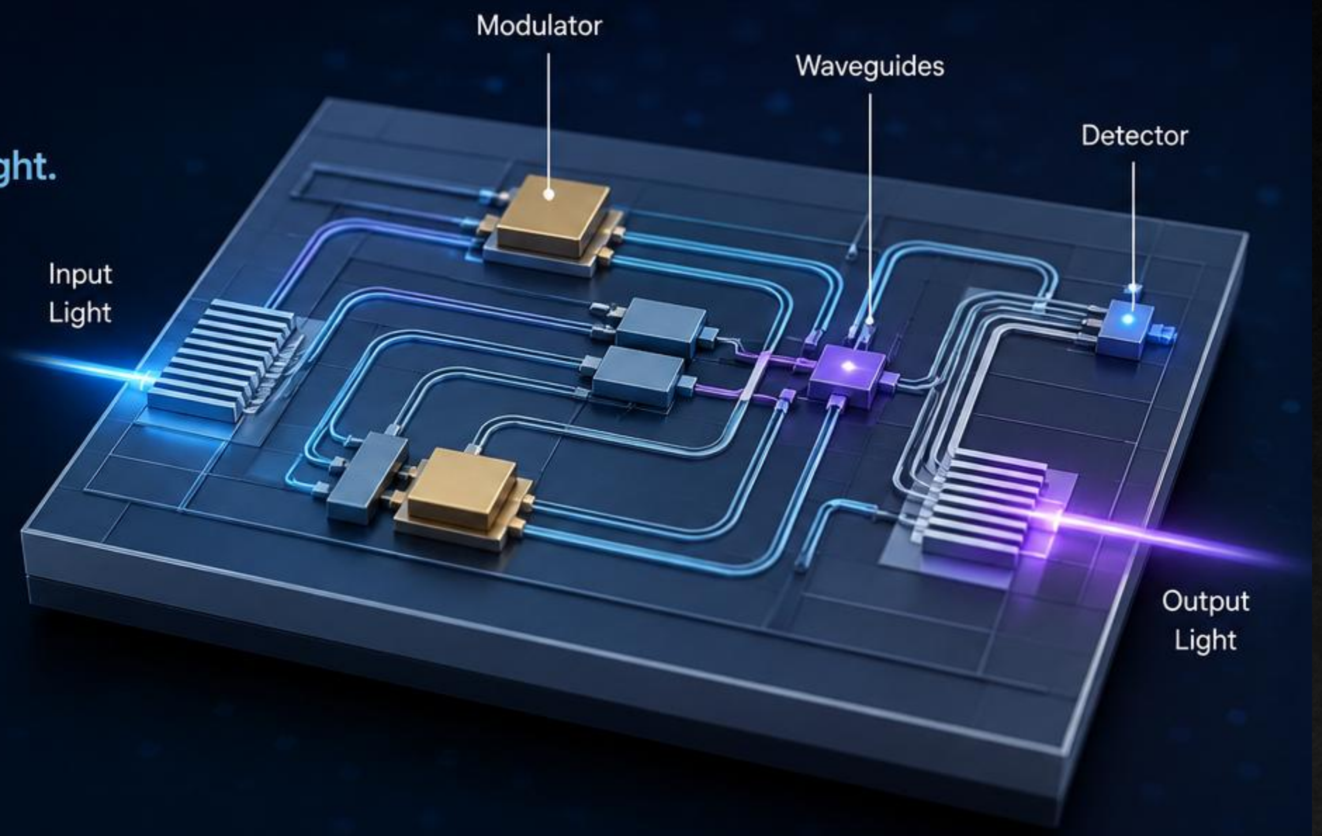
Start stopwatch on phone to monitor pace

QOISC
QUANTUM OPTICS INSTITUTE OF SOUTHERN CALIFORNIA

Instructor: Donn Silberman
Founder QOISC
www.qoisc.org

What Is Integrated Photonics?

Integrated photonics is the integration of optical components onto a common chip to generate, guide, manipulate, and detect light.



Integration of optical components onto a common chip
Waveguides, modulators, detectors, filters, couplers, and more—fabricated together on a single substrate.

Enables compact control of light on a semiconductor platform
Offers high performance with low power, small footprint, and high scalability.

Combines optics, electronics, and materials engineering
Leverages advances in device design, material platforms, and semiconductor manufacturing.

THE POWER OF INTEGRATION

OPTICS
Light generation, manipulation, and detection

+

ELECTRONICS
Control, modulation, processing, and interfacing

+

MATERIALS ENGINEERING
Enabling high performance through advanced materials and processes

=

INTEGRATED PHOTONICS
Smarter. Smaller. Faster. More efficient.

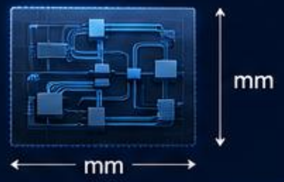
Integrated photonics is a key enabler of the next generation of communication, sensing, computing, and quantum technologies.

Why Integrated Photonics?

Integrating optical components on a chip delivers transformative advantages over bulky, discrete optical systems.

SMALL SIZE

Dramatically reduced footprint by integrating multiple optical functions on a single chip.



LOWER POWER

Shorter optical paths, lower driving voltages, and efficient components reduce overall power consumption.

Discrete Optics

Integrated Photonics

UP TO **10x** LOWER POWER

HIGH SPEED

Ultra-fast performance with low latency, high bandwidth, and minimal signal distortion—ideal for next-generation communication and computing.

MASS-PRODUCIBLE
WITH SEMICONDUCTOR PROCESSES

Leverages mature CMOS-compatible manufacturing for high yield, reliability, and low cost at scale.

FROM BULKY SYSTEMS TO COMPACT INTEGRATION

DISCRETE OPTICAL SYSTEM

- ✗ Large footprint
- ✗ High power consumption
- ✗ Complex assembly
- ✗ Sensitive to alignment
- ✗ High cost

INTEGRATED PHOTONIC CHIP

- ✓ Ultra-compact
- ✓ Low power
- ✓ Monolithic & robust
- ✓ Alignment-free
- ✓ Low cost at scale

Integrated photonics enables smaller, faster, more efficient, and scalable solutions—powering the future of communication, sensing, computing, and beyond.

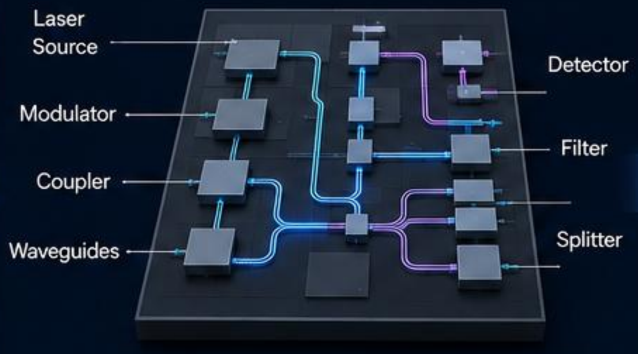
From Bulk Optics to Semiconductor Chips

Integrated photonics transforms light manipulation from complex setups to compact, efficient, and scalable chip-scale solutions.

BULK OPTICAL SYSTEMS

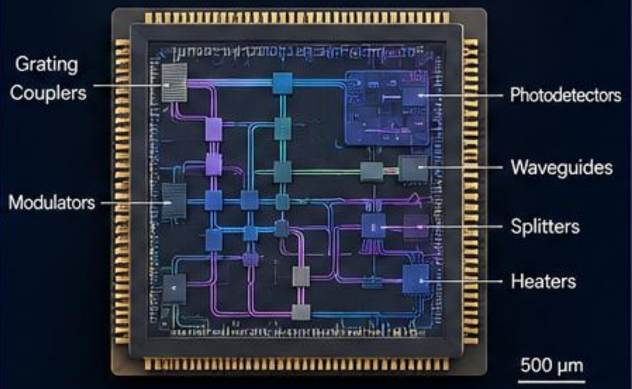
- Bulk optical systems are large and alignment-sensitive
- Require manual alignment and frequent recalibration
- Bigger, heavier, higher power and cost

INTEGRATED PHOTONICS



- Integrated photonics reduces footprint and improves stability
- Passive alignment and robust operation
- Lower power, higher performance and reliability

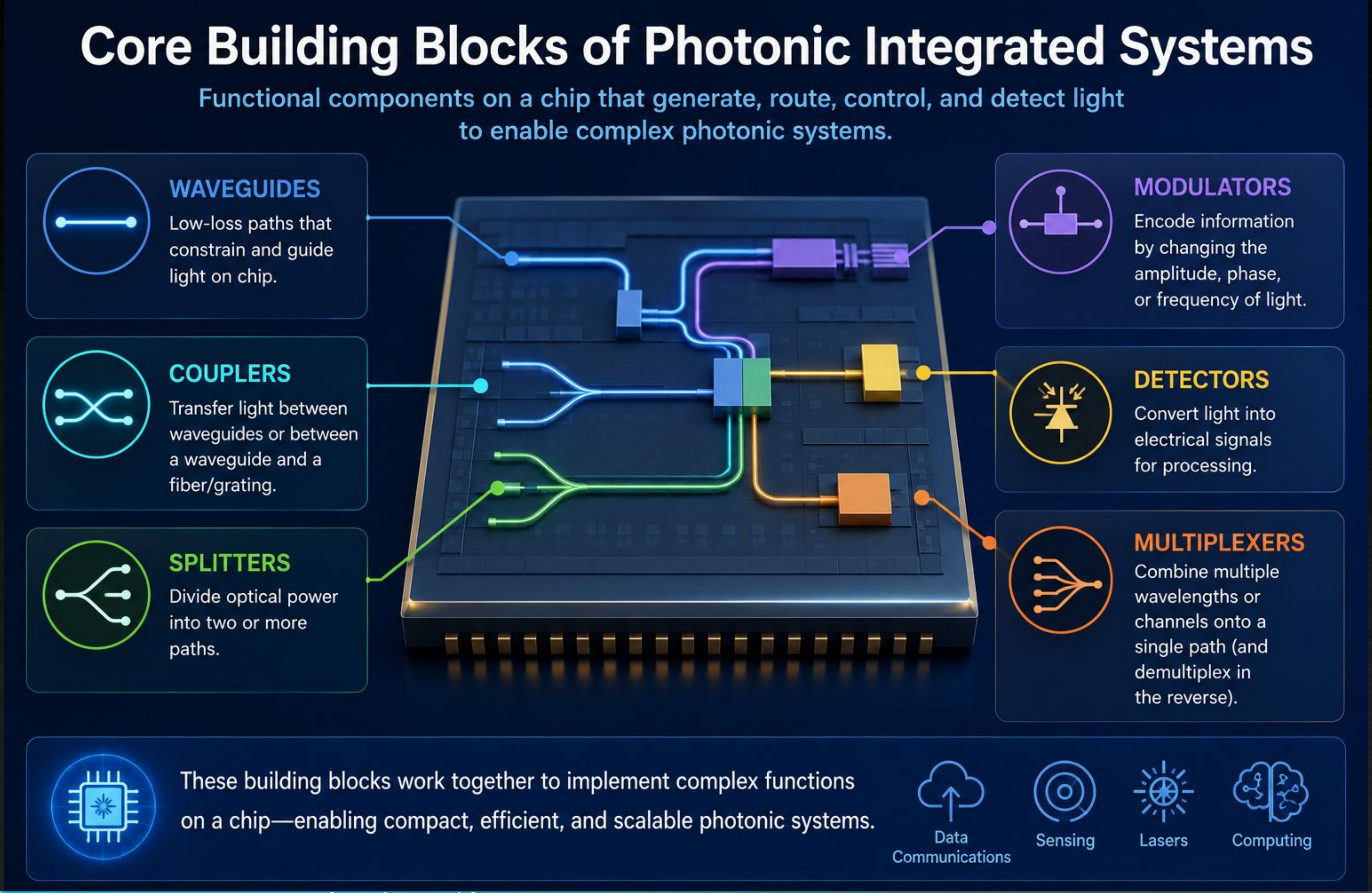
CHIP-SCALE PHOTONIC SYSTEMS



- Chip-scale devices enable scalable photonic systems
- Mass-producible with semiconductor manufacturing
- Enables complex functions in compact, cost-effective solutions

Bulk optical systems are large and alignment-sensitive → Integrated photonics reduces footprint and improves stability → Chip-scale devices enable scalable photonic systems

Smaller. Smarter. Faster. The power of light—integrated.


Core Building Blocks of Photonic Integrated Systems
Functional components on a chip that generate, route, control, and detect light to enable complex photonic systems.
WAVEGUIDES
Low-loss paths that constrain and guide light on chip.
COUPLERS
Transfer light between waveguides or between a waveguide and a fiber/grating.
SPLITTERS
Divide optical power into two or more paths.
MODULATORS
Encode information by changing the amplitude, phase, or frequency of light.
DETECTORS
Convert light into electrical signals for processing.
MULTIPLEXERS
Combine multiple wavelengths or channels onto a single path (and demultiplex in the reverse).
These building blocks work together to implement complex functions on a chip—enabling compact, efficient, and scalable photonic systems.
Data Communications
Sensing
Lasers
Computing

PHOTONIC INTEGRATED CIRCUITS

Waveguides

The Optical analog of electrical wires

Confine and route light on chip

Waveguides guide light along defined paths within the substrate with high precision and minimal loss.

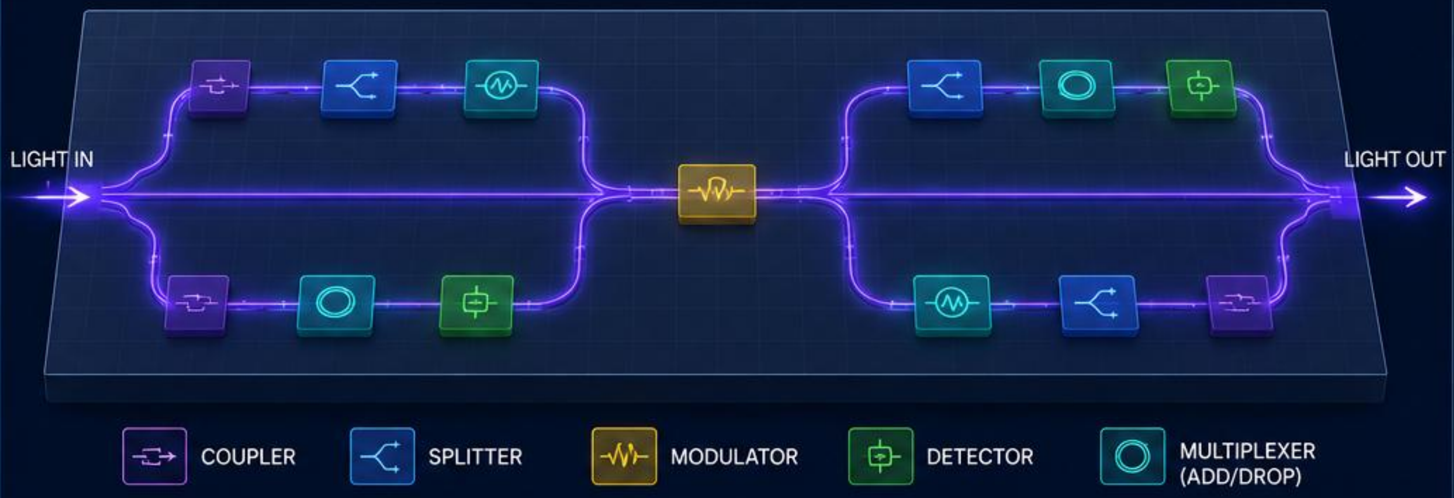
Designed for low loss

Engineered geometry and materials minimize scattering, bending, and propagation loss.

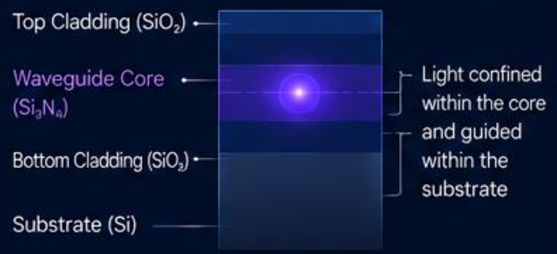
Controlled mode propagation

Waveguides support specific optical modes for efficient coupling and system performance.

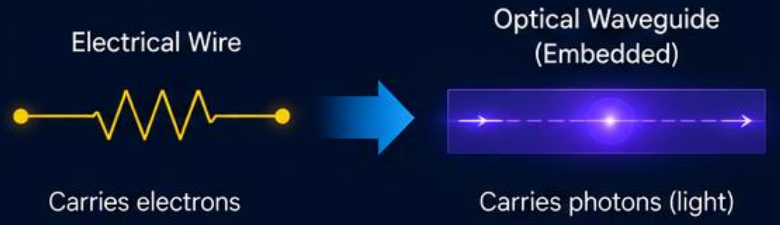
WAVEGUIDES EMBEDDED WITHIN THE SUBSTRATE



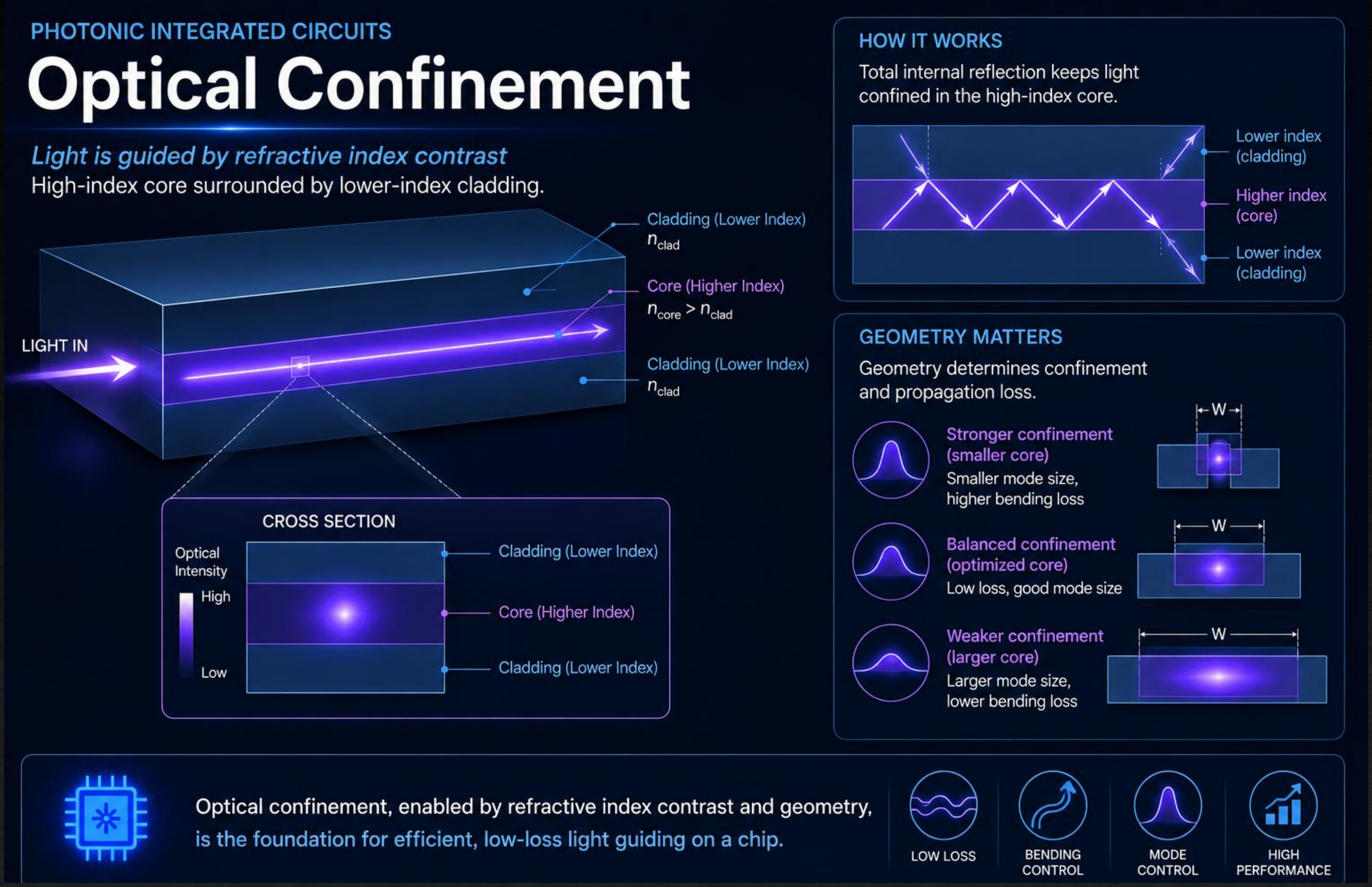
CROSS SECTION (TYPICAL)



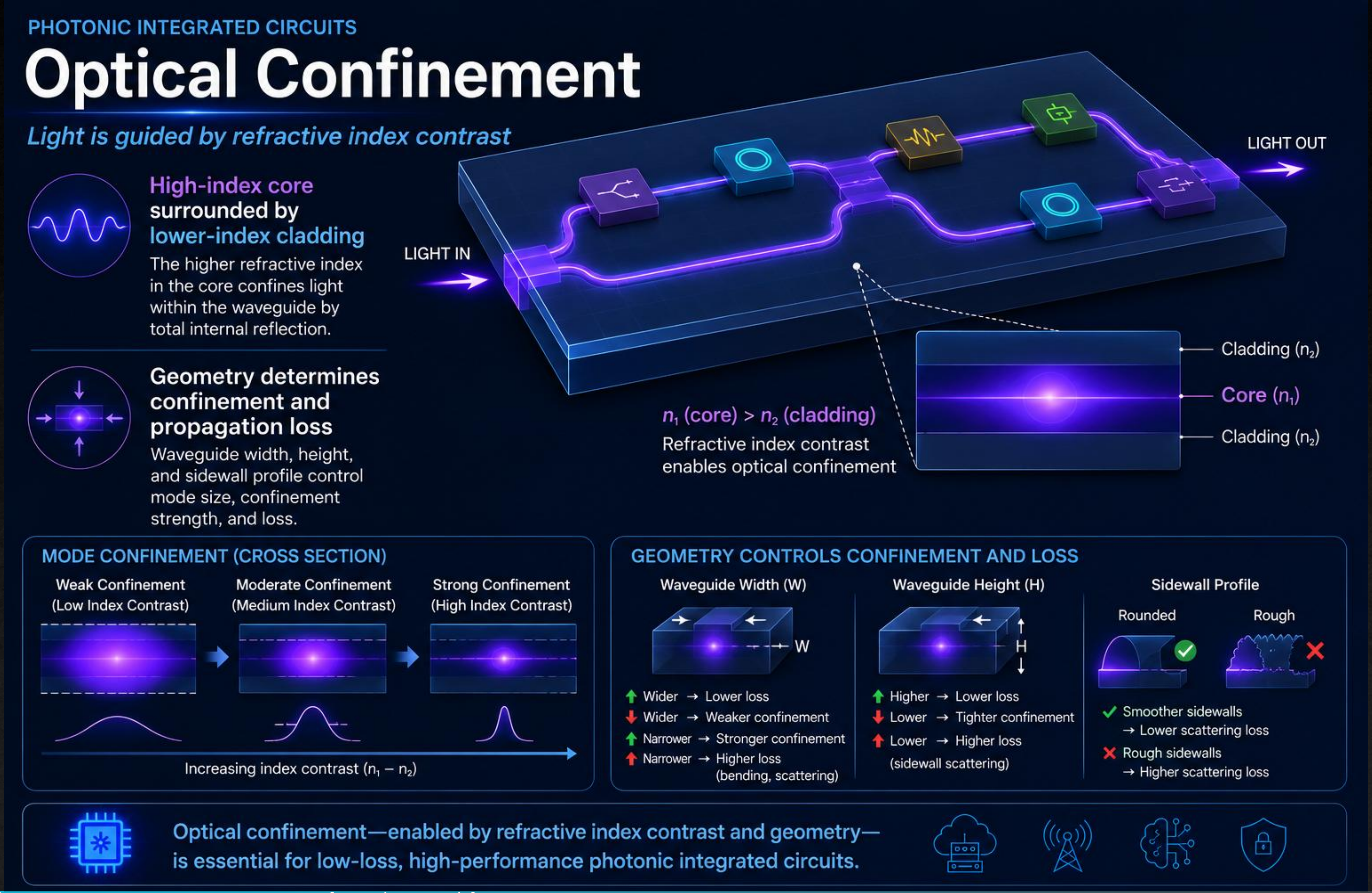
OPTICAL WIRE ON A CHIP



Waveguides are the foundation of photonic integrated circuits, enabling compact, efficient, and scalable manipulation of light.



PHOTONIC INTEGRATED CIRCUITS
Optical Confinement
Light is guided by refractive index contrast
High-index core surrounded by lower-index cladding.
LIGHT IN
Cladding (Lower Index)
n_{clad}
Core (Higher Index)
$n_{core} > n_{clad}$
Cladding (Lower Index)
n_{clad}
CROSS SECTION
Optical Intensity
High
Low
Cladding (Lower Index)
Core (Higher Index)
Cladding (Lower Index)
HOW IT WORKS
Total internal reflection keeps light confined in the high-index core.
Lower index (cladding)
Higher index (core)
Lower index (cladding)
GEOMETRY MATTERS
Geometry determines confinement and propagation loss.
Stronger confinement (smaller core)
Smaller mode size, higher bending loss
W
Balanced confinement (optimized core)
Low loss, good mode size
W
Weaker confinement (larger core)
Larger mode size, lower bending loss
W
Optical confinement, enabled by refractive index contrast and geometry,
is the foundation for efficient, low-loss light guiding on a chip.
LOW LOSS
BENDING CONTROL
MODE CONTROL
HIGH PERFORMANCE


PHOTONIC INTEGRATED CIRCUITS
Optical Confinement
Light is guided by refractive index contrast
High-index core surrounded by lower-index cladding
The higher refractive index in the core confines light within the waveguide by total internal reflection.
Geometry determines confinement and propagation loss
Waveguide width, height, and sidewall profile control mode size, confinement strength, and loss.
LIGHT IN
LIGHT OUT
Cladding (n_2)
Core (n_1)
Cladding (n_2)
n_1 (core) > n_2 (cladding)
Refractive index contrast enables optical confinement
MODE CONFINEMENT (CROSS SECTION)
Weak Confinement (Low Index Contrast)
Moderate Confinement (Medium Index Contrast)
Strong Confinement (High Index Contrast)
Increasing index contrast ($n_1 - n_2$)
GEOMETRY CONTROLS CONFINEMENT AND LOSS
Waveguide Width (W)
W
Wider → Lower loss
Wider → Weaker confinement
Narrower → Stronger confinement
Narrower → Higher loss (bending, scattering)
Waveguide Height (H)
H
Higher → Lower loss
Lower → Tighter confinement
Lower → Higher loss (sidewall scattering)
Sidewall Profile
Rounded
Rough
Smoother sidewalls → Lower scattering loss
Rough sidewalls → Higher scattering loss
Optical confinement—enabled by refractive index contrast and geometry—is essential for low-loss, high-performance photonic integrated circuits.

PHOTONIC INTEGRATED CIRCUITS

Common Material Platforms

Diverse materials enable a wide range of performance, functionality, and integration capabilities.

Silicon photonics

Mature, high-index contrast platform on silicon

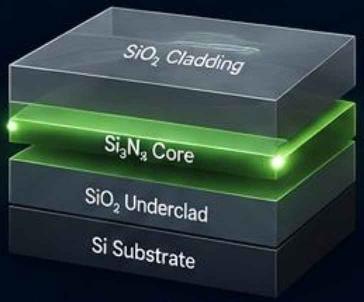
- High index contrast (Si/SiO_2)
- Strong confinement, compact devices
- CMOS compatible
- Wavelength: 1.3 – 1.55 µm

Applications

Data centers · High-density interconnects · On-chip sensing

Silicon nitride

Low loss, wide bandwidth, versatile platform



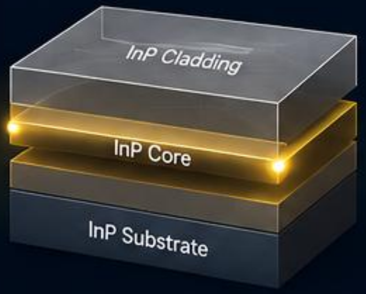
- Low propagation loss
- Wide transparency window (visible to mid-IR)
- High power handling
- Wavelength: 400 nm – 2.3 µm+

Applications

Frequency combs · Bio-sensing · LIDAR & sensing

Indium phosphide

High speed and active optoelectronic integration



- Direct bandgap material
- High-speed modulators, lasers, detectors
- Heterogeneous integration capable
- Wavelength: 1.2 – 1.65 µm

Applications

High-speed comms · Optical transceivers · Integrated lasers

Lithium niobate

Electro-optic performance and low loss

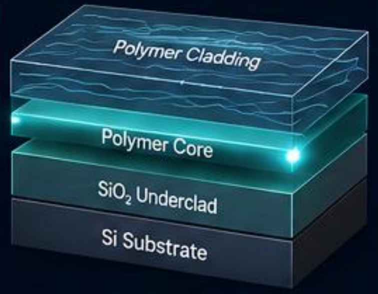
- Strong electro-optic effect
- High bandwidth modulators
- Low loss waveguides
- Wavelength: 400 nm – 5 µm

Applications

Modulators · RF photonics · Quantum photonic circuits

Polymer and hybrid platforms

Flexible, scalable, application-specific solutions



- Low-cost, scalable fabrication
- Tailorable refractive index and functionality
- Heterogeneous integration with other materials
- Wavelength: Visible – NIR

Applications

Lab-on-chip · Wearable sensors · Flexible photonics

The right material platform enables the right performance.

Each offers unique advantages for photonic integrated circuits across applications and wavelength ranges.

PERFORMANCE · INTEGRATION · SCALABILITY · WAVELENGTH FLEXIBILITY · COST EFFECTIVENESS

PHOTONIC INTEGRATED CIRCUITS

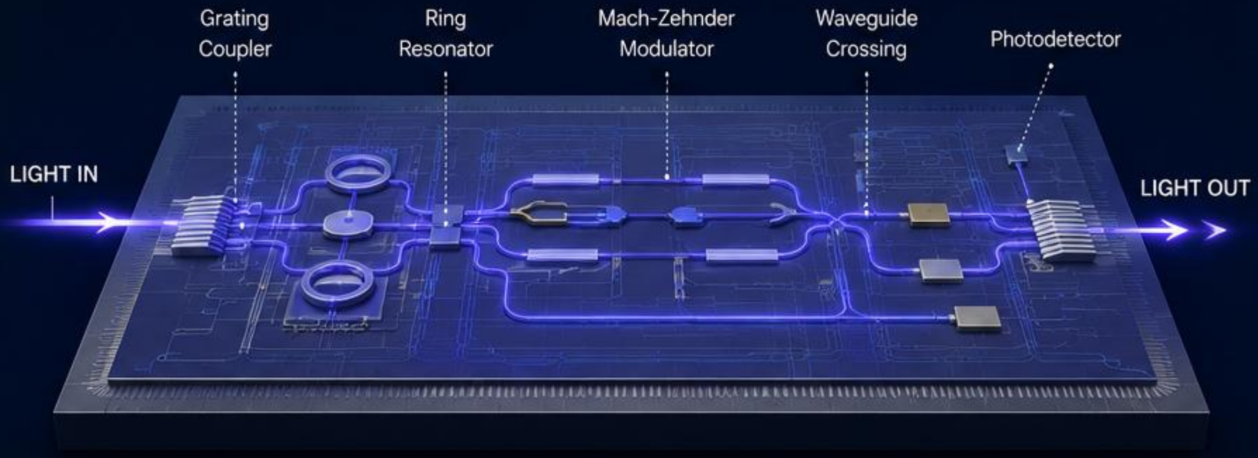
Silicon Photonics

Mature technology. Scalable production.
Built for data-driven applications.

SILICON PHOTONIC PLATFORM

- High refractive index contrast (Si ~3.48, SiO_2 ~1.44) enables strong confinement and compact devices
- Wavelength range: 1.3 µm and 1.55 µm (telecom bands)

DENSE INTEGRATION ON SILICON

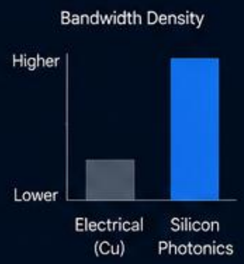


- Thousands to millions of components on a single chip
- CMOS compatible process on 200 mm and 300 mm wafers
- Low cost per chip enables mass scaling

STRONGLY SUPPORTED BY CMOS MANUFACTURING

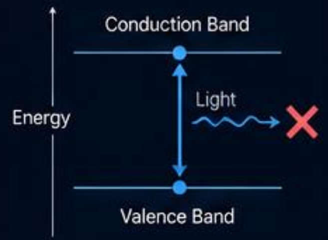
- Leverages mature silicon foundry infrastructure
- High yield, reproducibility, and scalability
- Enables large-scale, cost-effective production

EXCELLENT FOR DENSE INTEGRATION AND DATA COMMUNICATION



- High-speed modulators and detectors
- Low loss waveguides for long reach
- Ideal for data centers, AI/ML, HPC, and optical interconnects

LIMITED IN NATIVE LIGHT EMISSION



- Silicon is an indirect bandgap material
- Cannot efficiently emit light
- Requires hybrid integration with III–V materials or external lasers

Silicon photonics combines the power of CMOS manufacturing with the performance needed for next-generation data communication and computing.

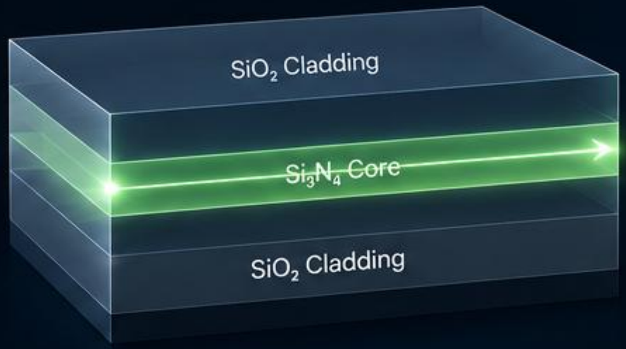
MATURE TECHNOLOGY | DENSE INTEGRATION | HIGH SPEED | CMOS COMPATIBLE | COST EFFECTIVE

PHOTONIC INTEGRATED CIRCUITS

Silicon Nitride (Si_3N_4) Photonics

Low loss. Wide transparency. Versatile platform.

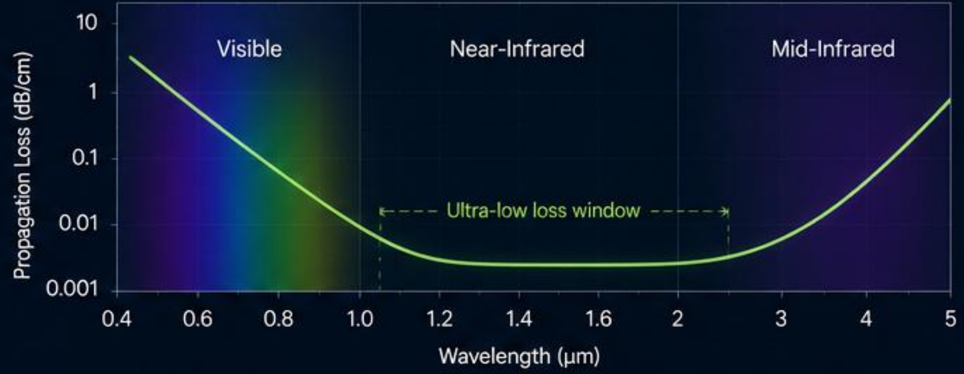
SILICON NITRIDE WAVEGUIDE



- High-index Si_3N_4 core (n ≈ 1.98 at 1550 nm)
- Lower-index SiO_2 cladding (n ≈ 1.44)
- → Refractive index contrast confines light in the core
- Low propagation loss enables efficient routing over long distances

WIDE TRANSPARENCY RANGE

Low loss from visible to mid-infrared



- Typical loss: < 0.1 dB/m (at 1550 nm)
- Transparent from ~400 nm to > 5 μm
- Thermally stable and chemically robust
- CMOS-compatible manufacturing (via PECVD)

USEFUL FOR A BROAD RANGE OF APPLICATIONS

FILTERS

High-Q resonant filters with sharp roll-off and low loss

- Wavelength-selective routing
- Low insertion loss
- Compact footprint
- High spectral purity

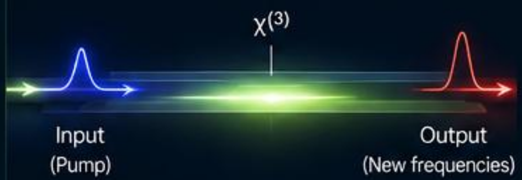
RESONATORS

High-Q resonators for sensing, lasing, and signal processing

- Ultra-high Q factors ($>10^6$)
- Small mode volume
- Stable performance
- Temperature insensitive designs

NONLINEAR OPTICS

Strong nonlinear response enables advanced functions on a chip



- Four-wave mixing
- Supercontinuum generation
- Frequency combs
- Quantum photonics

Silicon nitride photonics offers **low loss, broad bandwidth,** and **exceptional versatility** for next-generation integrated photonic systems.

LOW LOSS | WIDE TRANSPARENCY | HIGH-Q RESONATORS | PRECISE FILTERS | NONLINEAR OPTICS | CMOS COMPATIBLE

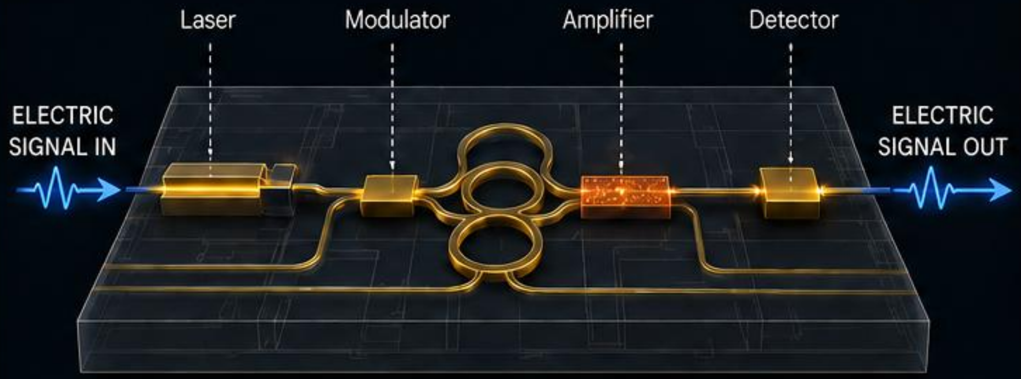
PHOTONIC INTEGRATED CIRCUITS

Indium Phosphide (InP) Photonics

Active by nature. Built for performance.

Indium phosphide is a III–V semiconductor with a direct bandgap, enabling efficient light emission, amplification, and detection.

INDIUM PHOSPHIDE PIC PLATFORM



InP Cladding (n-InP)
Active Layer (InGaAsP)
InP Waveguide (InP)
InP Substrate

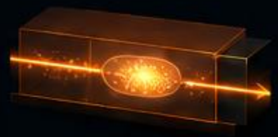
- Direct bandgap enables efficient light emission and amplification
- High refractive index contrast for strong confinement
- Heterogeneous integration with passive platforms (e.g., SiN, Si)

SUPPORTS LASERS, AMPLIFIERS, AND DETECTORS

Lasers

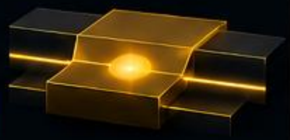
- High output power
- Narrow linewidth
- Wavelength agility

Amplifiers



- Semiconductor optical amplifiers (SOAs)
- On-chip gain
- Low noise

Detectors



- High responsivity
- High speed
- Low dark current

GOOD FOR FULLY INTEGRATED ACTIVE PHOTONIC SYSTEMS

- On-chip lasers
- Integrated amplifiers
- High-speed detectors
- Modulators and switches
- High-density interconnects

COMMON IN TELECOM AND SENSING APPLICATIONS

TELECOM

- Coherent transceivers
- Wavelength tunable lasers
- Optical amplifiers
- High-speed modulators

SENSING

- LIDAR
- Gas sensing
- Spectroscopy
- Biosensing

Indium phosphide enables monolithic integration of active and passive functions for high-performance photonic systems.

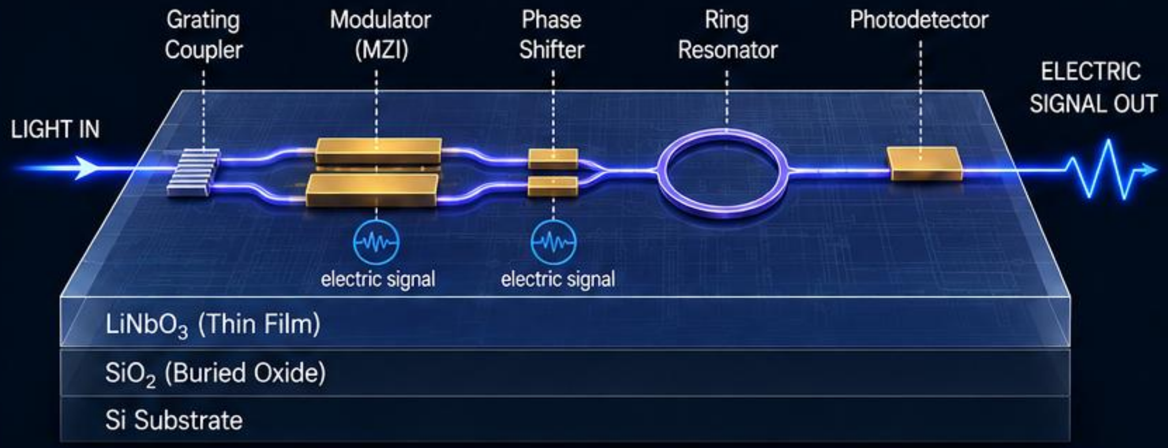
HIGH PERFORMANCE | INTEGRATED ACTIVE DEVICES | HIGH SPEED | TELECOM OPTIMIZED | IDEAL FOR SENSING | HETEROGENEOUS INTEGRATION

PHOTONIC INTEGRATED CIRCUITS

Lithium Niobate on Chip (LNOI)

Strong electro-optic response. Fast, efficient modulation.
Valuable for high-performance communications.

LITHIUM NIOBATE ON INSULATOR (LNOI) PLATFORM

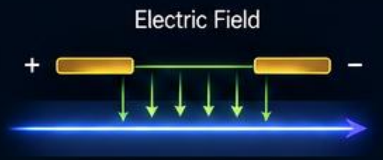


- High electro-optic coefficient (r_{33})
- Low optical loss
- Broad transparency (visible to IR)
- CMOS-compatible processing

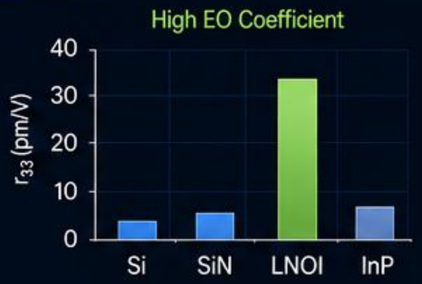
KEY APPLICATIONS

- Coherent Optical Transceivers
- Data Center Interconnects
- 5G / 6G Fronthaul
- Satellite Communications
- Quantum Photonic Systems
- RF Photonics and Sensing

STRONG ELECTRO-OPTIC RESPONSE

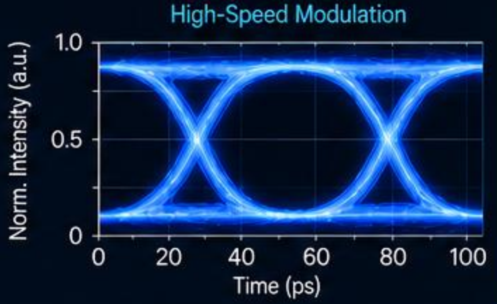


Applied voltage changes the refractive index via the Pockels effect, modulating the light.



ENABLES FAST, EFFICIENT MODULATION

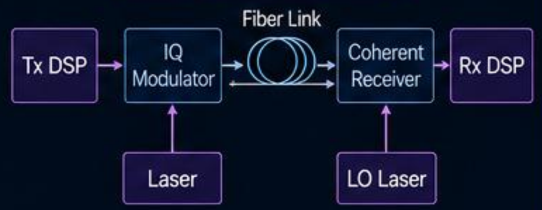
- Ultra-high bandwidth (> 50 GHz)
- Low driving voltage (↓ power consumption)
- High linearity and signal fidelity



VALUABLE FOR HIGH-PERFORMANCE COMMUNICATIONS

- Supports next-generation coherent and modulation formats
- Ideal for data centers, telecom networks, and 5G/6G fronthaul
- Enables long reach, high capacity, and energy efficiency

Coherent Transceiver Example



Lithium niobate on chip combines unparalleled electro-optic performance with low loss and high speed—enabling the future of high-capacity, energy-efficient photonic communication systems.

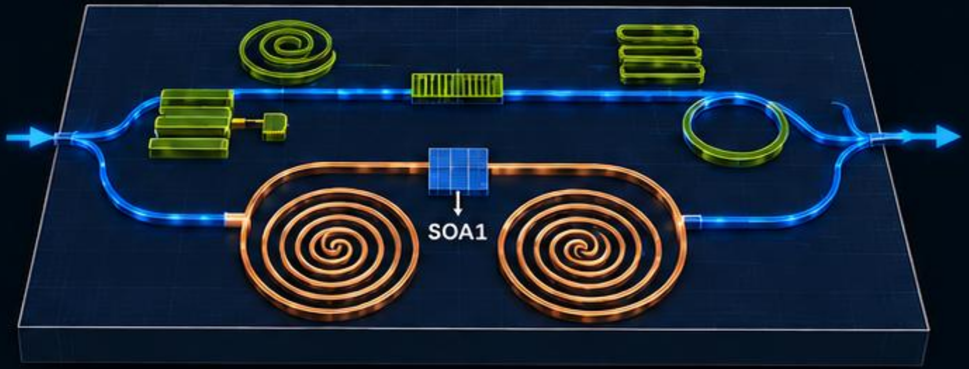
- STRONG EO RESPONSE
- FAST, EFFICIENT MODULATION
- HIGH PERFORMANCE
- COMMUNICATIONS READY
- ENERGY EFFICIENT

PHOTONIC INTEGRATED CIRCUITS

Passive Photonic Devices

Passive devices manipulate light without requiring optical gain.

Passive components are the building blocks of photonic integrated circuits. They route, split, combine, filter, store, and control light efficiently and reliably.



1. SPLITTERS

Divide optical power into multiple outputs.

Example: 1×3 Splitter

- Evenly or unequally splits light
- Low loss and broadband
- Common: Y-branch, MMI splitter

Typical Use: Power distribution, interferometers

2. COUPLERS

Combine or transfer light between waveguides.

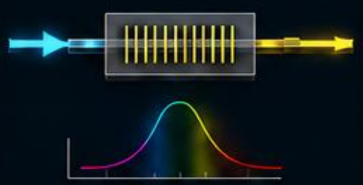
Example: Directional Coupler

- Evanescent coupling of light
- Can split, combine, or tap
- Compact and low loss

Typical Use: Power combining, switching, sampling

3. FILTERS

Select desired wavelengths and block others.



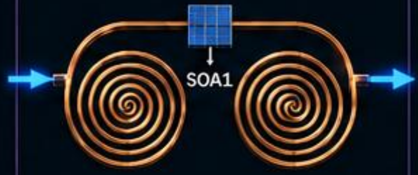
Example: Ring Resonator Filter

- Wavelength-selective routing
- High rejection and low loss
- Types: Ring, Bragg, AWG, MZI

Typical Use: Wavelength multiplexing, channel selection

4. DELAY LINES

Introduce controlled time delays to optical signals.



Example: Spiral Delay Line

- Adjust optical path length
- Compact footprint
- Low loss, precise delay

Typical Use: Interferometry, signal synchronization

5. RESONATORS

Trap light at specific wavelengths using resonance.

Example: Ring Resonator

- High Q (quality factor)
- Small footprint
- Sensitive to wavelength changes

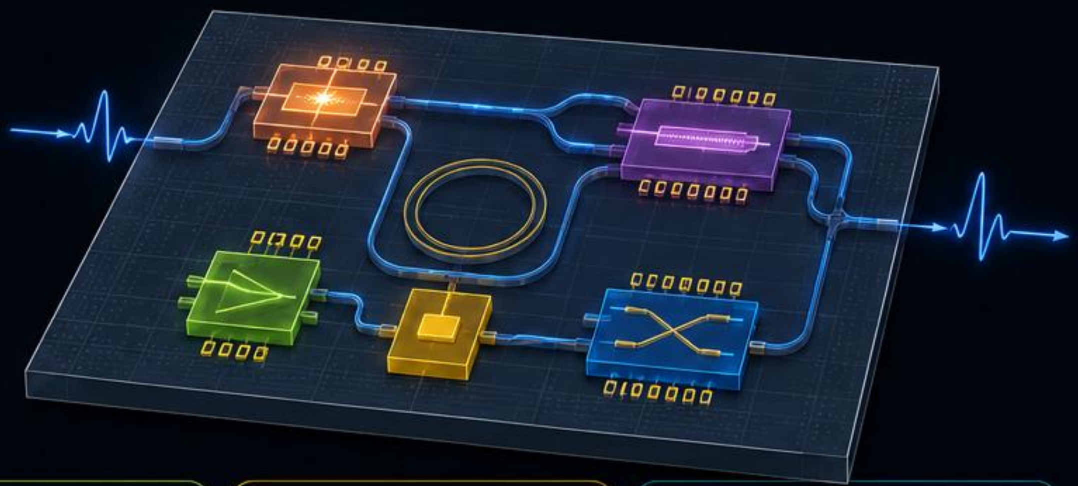
Typical Use: Filtering, sensing, modulation, lasers

Passive photonic devices enable efficient, compact, and scalable manipulation of light—forming the essential infrastructure of photonic integrated circuits.

PHOTONIC INTEGRATED CIRCUITS

Active Photonic Devices

Active devices control light by adding, removing, or converting energy.



Active devices provide gain, modulation, detection, and reconfiguration—enabling functionality and intelligence in photonic integrated circuits.

1. LASERS

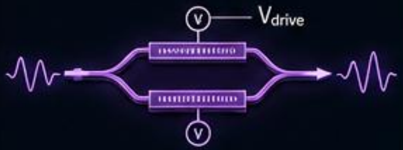
Generate coherent light.

- On-chip light source
- Narrow linewidth
- High efficiency
- Types: DFB, DBR, VCSEL

Typical Use: Light generation for communication, sensing, and computation

2. MODULATORS

Imprint information onto light.



- Convert electrical signals to optical modulation
- High speed
- Types: MZM, ring, EAM

Typical Use: Data encoding, signal processing, and telecommunications

3. AMPLIFIERS

Increase optical power.

- Compensate for losses
- Boost signal power
- Types: SOA, EDFA, Raman

Typical Use: Signal amplification in long-distance links and photonic circuits

4. DETECTORS

Convert light into electrical signals.

- High responsivity
- Low dark current
- Types: PIN, APD, Ge PD

Typical Use: Signal reception, sensing, and monitoring

5. SWITCHES

Dynamically route or select optical paths.

- Reconfigure optical circuits
- Low insertion loss
- Types: MZI switch, MEMS, thermal, carrier-depletion

Typical Use: Routing, reconfiguration, and optical networking

Active photonic devices add control, intelligence, and functionality, enabling high-performance, scalable photonic systems.

PHOTONIC INTEGRATED CIRCUITS

Photonic **Modulators**

Convert electrical signals into optical changes, control amplitude, phase, or frequency of light, and are critical for data transmission.

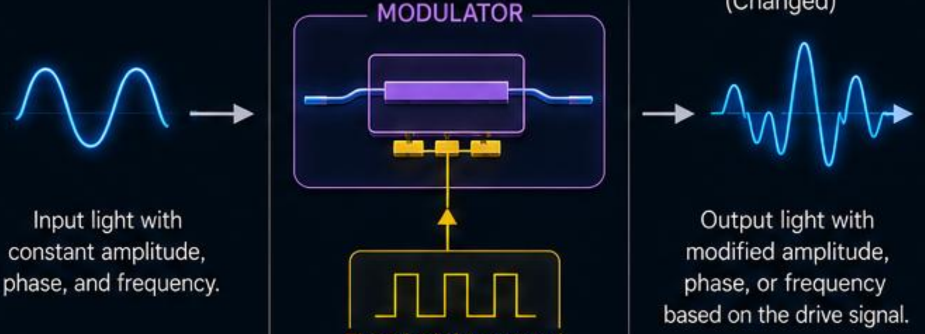
Convert electrical signals into optical changes
Electrical drive signals modify the properties of light using effects such as the electro-optic effect.

Control amplitude, phase, or frequency of light
Enable precise modulation of light's intensity, phase, or frequency to encode information.

Critical for data transmission
Fundamental building blocks for high-speed, high-capacity optical communication systems.

HOW IT WORKS

1. Optical signal in (Continuous wave)
2. Modulation by electric drive signal
3. Modulated optical signal out (Changed)



Input light with constant amplitude, phase, and frequency.

Electrical drive signal (Data / Control)

Output light with modified amplitude, phase, or frequency based on the drive signal.

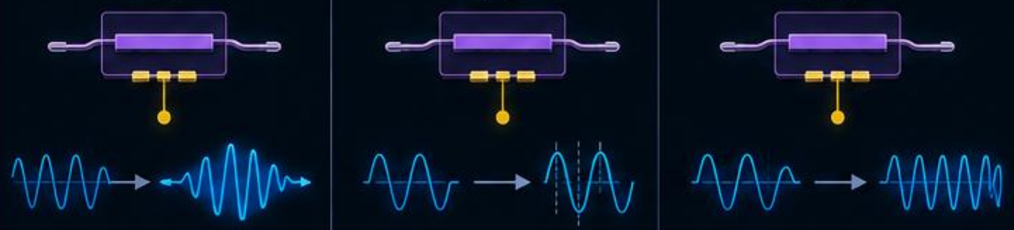
The electric signal changes the refractive index, absorption, or geometry of the modulator, altering the light that passes through it.

Optical changes


- Amplitude modulation
- Phase modulation
- Frequency modulation

The electric drive signal is what **creates the difference** between the input optical signal and the modulated output.

TYPES OF MODULATORS

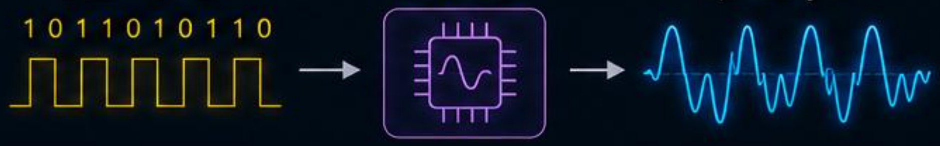


AMPLITUDE MODULATOR (AM)	PHASE MODULATOR (PM)	FREQUENCY MODULATOR (FM)
Vary the intensity (power) of the light.	Vary the phase of the light.	Vary the frequency (or wavelength) of the light.

Implemented using electro-optic, carrier-depletion, thermal, or piezoelectric effects in integrated photonic platforms.

CRITICAL FOR DATA TRANSMISSION

Electrical data → Modulator → Optical signal



- Optical Communications
- Data Centers & Interconnects
- 5G / 6G Networks
- Satellite Links
- AI / HPC Systems

Enable high speed, high bandwidth, and energy-efficient transmission of information over long distances.

PHOTONIC INTEGRATED CIRCUITS

Photodetector

Convert optical signals to electrical output, enable readout and signal recovery, and are often integrated with communication circuits.

Convert optical signals to electrical output
Absorb photons and generate an electrical current proportional to the light intensity.

Enable readout and signal recovery
Recover amplitude and data from optical signals for further processing.

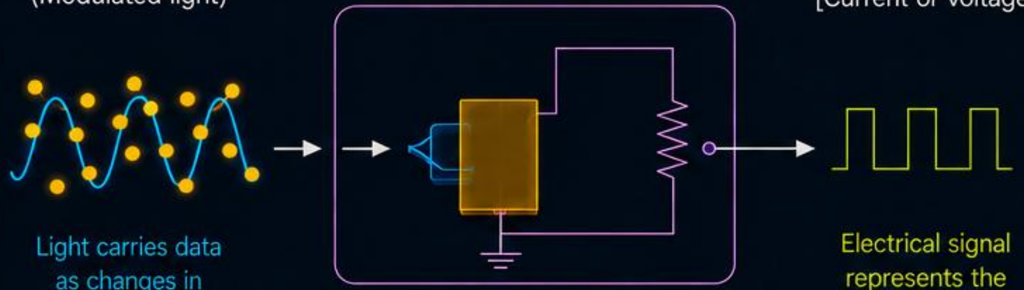
Often integrated with communication circuits
Monolithically integrated with modulators, amplifiers, and other components for compact, high-performance photonic systems.

HOW IT WORKS

1. Optical signal in (Modulated light)

PHOTODETECTOR

2. Electrical output [Current or voltage]



Light carries data as changes in intensity.

Electrical signal represents the optical data.

Photons are absorbed in the active material, generating electron–hole pairs that produce a photocurrent.

Key Characteristics

- High responsivity
- Low dark current
- High bandwidth
- Low noise
- High linearity
- Wavelength selectivity

Photodetectors are essential for converting light to electrical signals, enabling the interface between photonic systems and electronic circuits.

TYPES OF PHOTODETECTOR

PIN Photodetector	Avalanche Photodiode (APD)	Ge-on-Si Photodetector	III–V on Si Photodetector	Waveguide Integrated Photodetector

PIN Photodetector	Avalanche Photodiode (APD)	Ge-on-Si Photodetector	III–V on Si Photodetector	Waveguide Integrated Photodetector
Wide bandwidth, low noise, high sensitivity	Internal gain through impact ionization for high sensitivity	High responsivity in telecom wavelengths (1.3–1.6 μm)	High speed and high efficiency detection	Evanescent coupling enables compact integration

OFTEN INTEGRATED WITH COMMUNICATION CIRCUITS

- Receives optical signal
- Converts to electrical signal
- Amplifies and conditions signal
- Digitized for further processing

Photodetectors bridge the photonic and electronic worlds—enabling accurate readout, low-noise detection, and compact integration in high-speed communication systems.

- Essential for data recovery in optical links
- Key enabler of high-performance PICs
- Supports high bandwidths and energy-efficient operation

PHOTONIC RESONATORS

Trap light to enhance interaction
Light circulates or bounces within a resonator, building up intensity.

Used in filtering, sensing, and nonlinear optics
Resonance enhances selectivity, sensitivity, and nonlinear effects.

Include ring resonators and cavities
Common resonator geometries used in integrated photonic circuits.

HOW IT WORKS

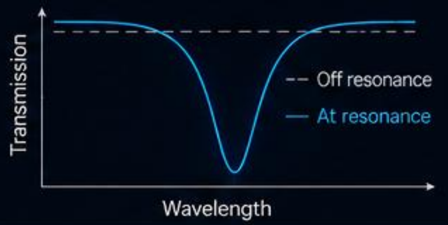
At resonance, light constructively interferes with itself on each round trip, building up intensity inside the resonator.

RESONANCE CONDITION

$$m \cdot \lambda_{res} = n_{eff} \cdot L$$

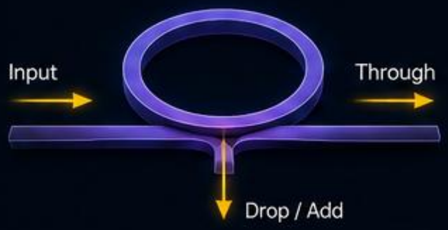
m: integer (mode number)
λ_{res}: resonant wavelength
n_{eff}: effective refractive index
L: round-trip optical path length

EFFECT OF RESONANCE



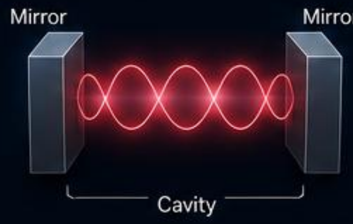
TYPES OF PHOTONIC RESONATORS

RING RESONATORS



- Light circulates in a closed loop
- Compact footprint
- High Q with low loss

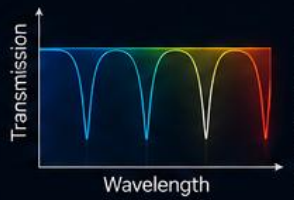
CAVITY RESONATORS



- Light bounces back and forth
- Very high quality factor (Q)
- Small mode volume for strong light–matter interaction

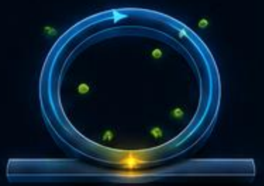
APPLICATIONS

FILTERING



Select specific wavelengths while rejecting others.

SENSING

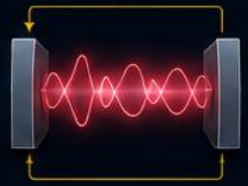


Environmental changes shift resonance, enabling ultra-sensitive detection.

NONLINEAR OPTICS

Enhanced intensity inside the resonator boosts nonlinear interactions.

LASERS



Resonators provide optical feedback to support coherent light generation.

KEY ADVANTAGES

- **High Quality Factor (Q)** — High field enhancement and narrow linewidth
- **Compact & Integrable** — Small footprint, CMOS compatible
- **Efficient** — Low power operation with strong interaction

WHERE THEY ARE USED

- Telecom filters & mux/demux
- Biosensing & chemical sensing
- Quantum photonics & frequency combs
- On-chip lasers & light sources

PHOTONIC MULTIPLEXING AND ROUTING

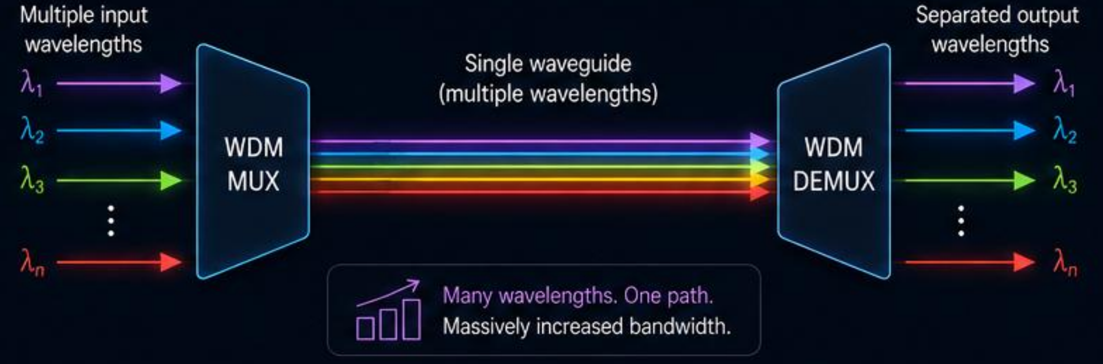
Enabling higher capacity and intelligent signal delivery in photonic systems.

Increase capacity with wavelength-division multiplexing
Transmit multiple wavelengths of light simultaneously over the same waveguide to dramatically boost bandwidth.

Use optical switches and routers to direct signals on chip
Reconfigure paths dynamically to connect sources to destinations with low loss and high speed.

Important for large-scale photonic networks
Essential for data centers, AI systems, and future optical interconnects that demand scalability and efficiency.

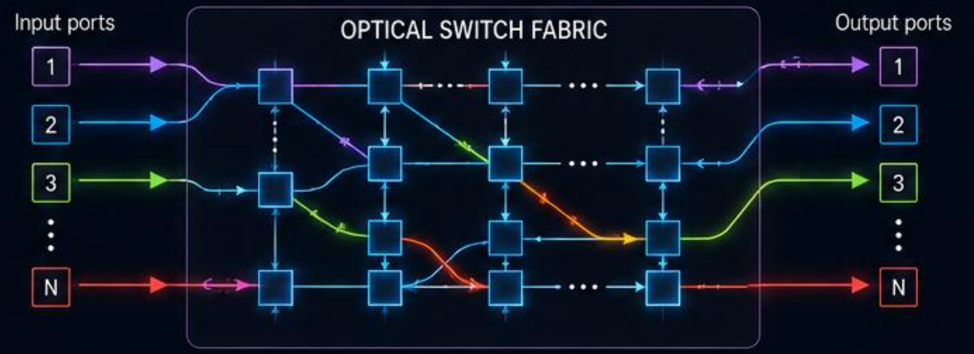
1. INCREASING CAPACITY WITH WAVELENGTH-DIVISION MULTIPLEXING (WDM)



WDM BENEFITS

- Much higher data capacity
- Efficient use of waveguide infrastructure
- Lower power per bit vs. parallel electrical links

2. OPTICAL SWITCHES AND ROUTERS TO DIRECT SIGNALS ON CHIP



TYPES OF OPTICAL ROUTING

Non-blocking switch
Any input can connect to any output.

Reconfigurable router
Dynamically select paths based on demand and policy.

3. IMPORTANT FOR LARGE-SCALE PHOTONIC NETWORKS

KEY TAKEAWAYS

- WDM multiplies capacity by sending many wavelengths on one waveguide.
- Optical switches and routers steer signals to where they are needed.
- Together, they are essential for building scalable, efficient photonic networks.

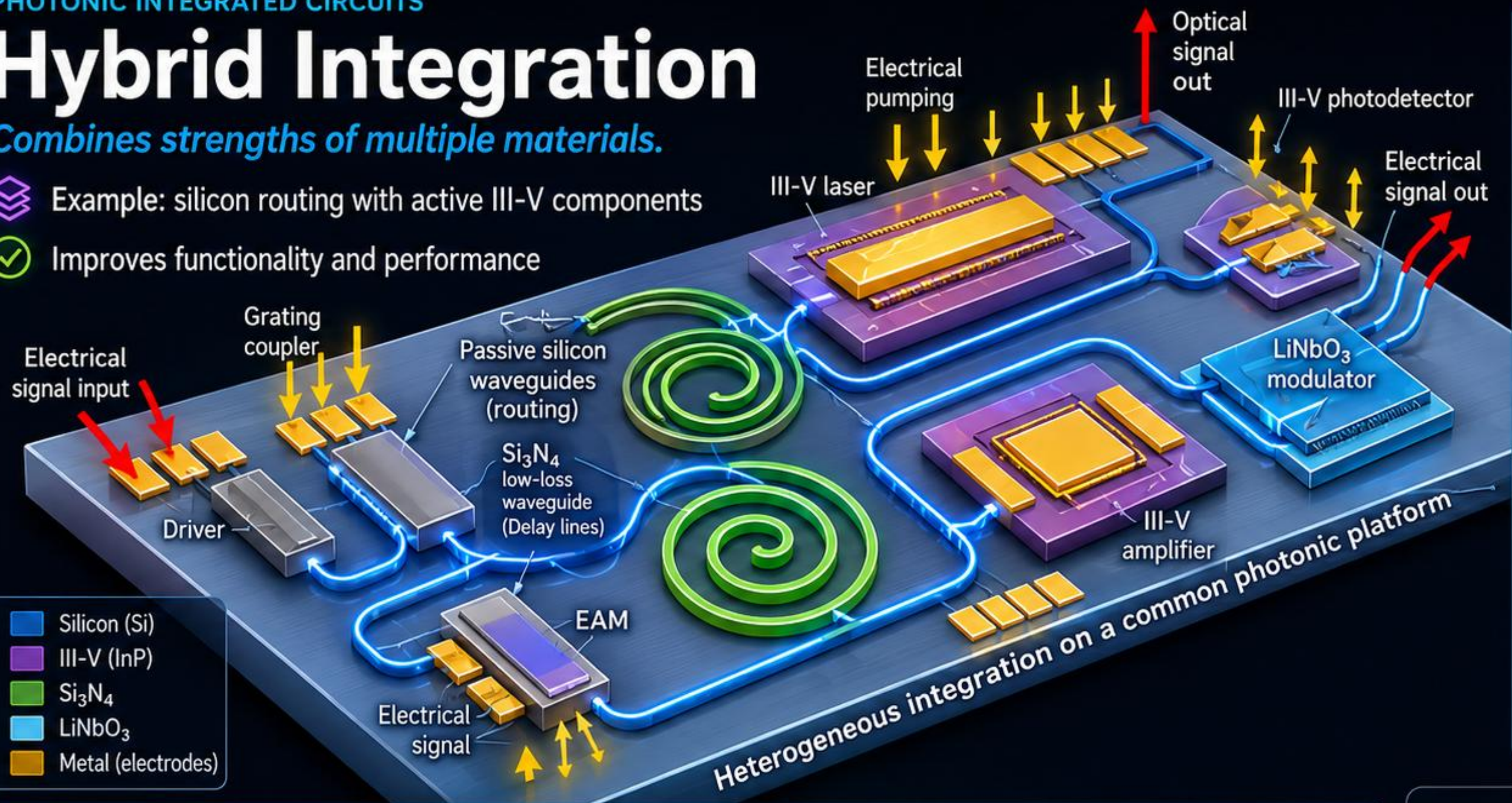
Multiplex. Route. Scale. The foundation of tomorrow's photonic infrastructure. | Higher Capacity • Dynamic Connectivity • Scalable Networks • Lower Power

PHOTONIC INTEGRATED CIRCUITS

Hybrid Integration

Combines strengths of multiple materials.

- Example: silicon routing with active III-V components
- Improves functionality and performance



WHY HYBRID INTEGRATION?

COMBINES STRENGTHS
Leverages the best properties of multiple materials in a single platform.

IMPROVES PERFORMANCE
Enables active functionality with low loss, high speed, and high efficiency.

EXPANDS CAPABILITIES
Supports complex systems that are difficult or impossible with a single material alone.

BENEFITS OF HYBRID INTEGRATION

HIGHER PERFORMANCE
Gain, modulation, and detection with low driving power.

DENSE INTEGRATION
Silicon enables compact, complex routing.

DESIGN FLEXIBILITY
Use the right material for each function.

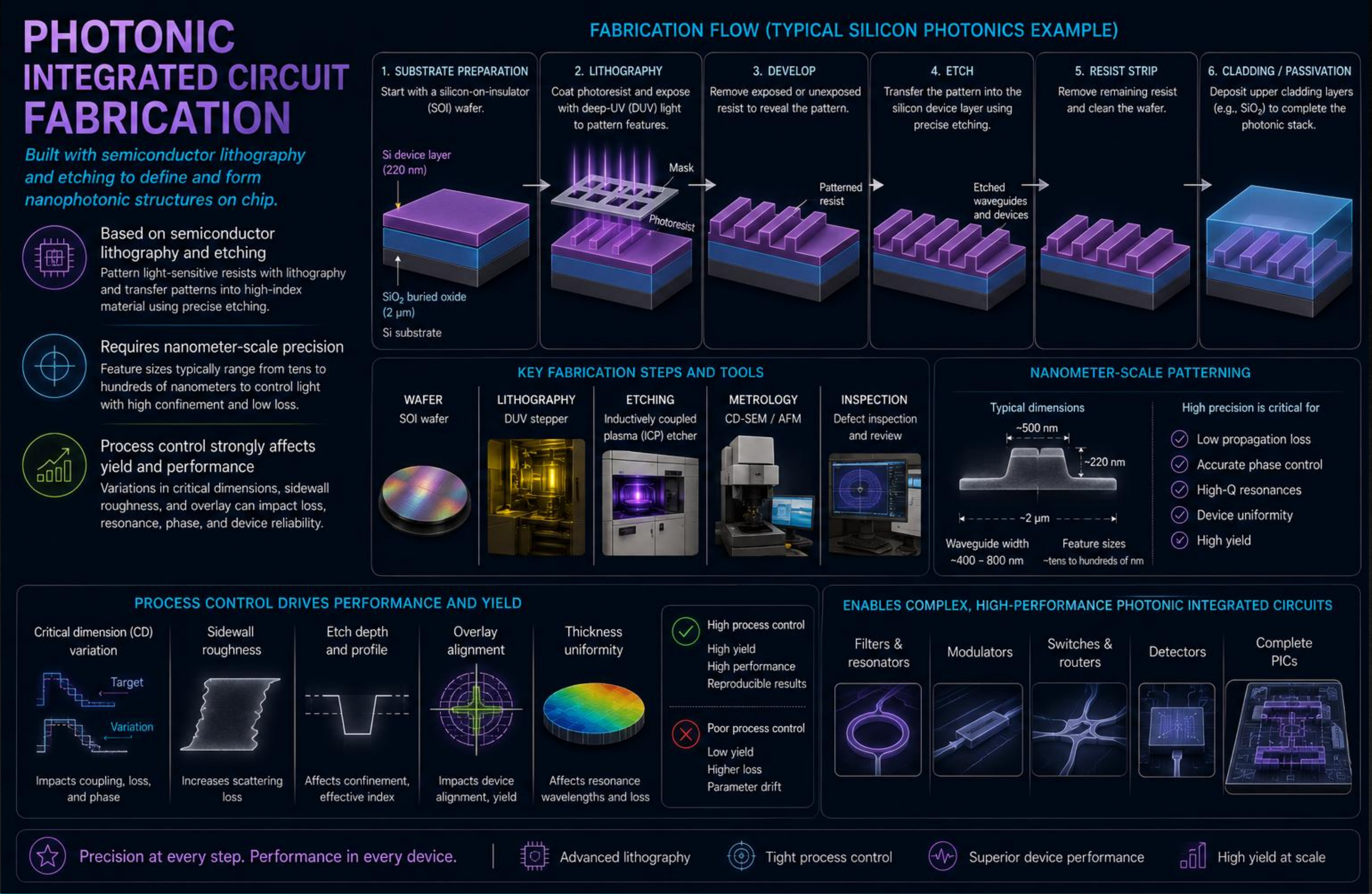
COST & SCALABILITY
Leverages mature CMOS platforms.

ENABLED APPLICATIONS
Telecom, datacom, sensing, and beyond.

EXAMPLE APPLICATIONS

- Telecom Networks
- Data Centers
- Sensing (LiDAR)
- AI & HPC Interconnects

Hybrid integration unlocks the full potential of photonic integrated circuits by combining the best of different materials—delivering **superior functionality, performance, and scalability** for next-generation applications.


PHOTONIC INTEGRATED CIRCUIT FABRICATION
Built with semiconductor lithography and etching to define and form nanophotonic structures on chip.
Based on semiconductor lithography and etching
Pattern light-sensitive resists with lithography and transfer patterns into high-index material using precise etching.
Requires nanometer-scale precision
Feature sizes typically range from tens to hundreds of nanometers to control light with high confinement and low loss.
Process control strongly affects yield and performance
Variations in critical dimensions, sidewall roughness, and overlay can impact loss, resonance, phase, and device reliability.
FABRICATION FLOW (TYPICAL SILICON PHOTONICS EXAMPLE)
1. SUBSTRATE PREPARATION
Start with a silicon-on-insulator (SOI) wafer.
Si device layer (220 nm)
SiO2 buried oxide (2 μm)
Si substrate
2. LITHOGRAPHY
Coat photoresist and expose with deep-UV (DUV) light to pattern features.
Mask
Photoresist
3. DEVELOP
Remove exposed or unexposed resist to reveal the pattern.
Patterned resist
4. ETCH
Transfer the pattern into the silicon device layer using precise etching.
Etched waveguides and devices
5. RESIST STRIP
Remove remaining resist and clean the wafer.
6. CLADDING / PASSIVATION
Deposit upper cladding layers (e.g., SiO2) to complete the photonic stack.
KEY FABRICATION STEPS AND TOOLS
WAFER
SOI wafer
LITHOGRAPHY
DUV stepper
ETCHING
Inductively coupled plasma (ICP) etcher
METROLOGY
CD-SEM / AFM
INSPECTION
Defect inspection and review
NANOMETER-SCALE PATTERNING
Typical dimensions
~500 nm
~220 nm
~2 μm
Waveguide width ~400 – 800 nm
Feature sizes ~tens to hundreds of nm
High precision is critical for
Low propagation loss
Accurate phase control
High-Q resonances
Device uniformity
High yield
PROCESS CONTROL DRIVES PERFORMANCE AND YIELD
Critical dimension (CD) variation
Target
Variation
Impacts coupling, loss, and phase
Sidewall roughness
Increases scattering loss
Etch depth and profile
Affects confinement, effective index
Overlay alignment
Impacts device alignment, yield
Thickness uniformity
Affects resonance wavelengths and loss
High process control
High yield
High performance
Reproducible results
Poor process control
Low yield
Higher loss
Parameter drift
ENABLES COMPLEX, HIGH-PERFORMANCE PHOTONIC INTEGRATED CIRCUITS
Filters & resonators
Modulators
Switches & routers
Detectors
Complete PICs
Precision at every step. Performance in every device.
Advanced lithography
Tight process control
Superior device performance
High yield at scale

PHOTONIC INTEGRATED CIRCUIT PACKAGING

Bridging photonic chips to the outside world with precision, reliability, and efficiency.

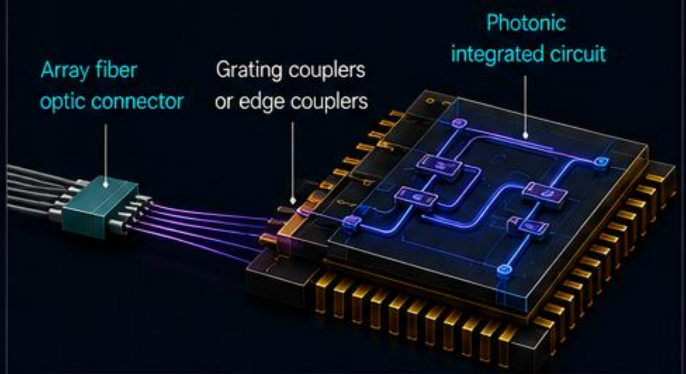
Fiber-to-chip coupling
Efficiently couple light between optical fibers and on-chip waveguides with low loss and high alignment precision.

Thermal management
Remove heat effectively to ensure stable operation, maintain performance, and improve reliability.

Electrical interconnects
Provide power, control, and high-speed signals to and from the chip.
One of the biggest practical challenges.

1. FIBER-TO-CHIP COUPLING

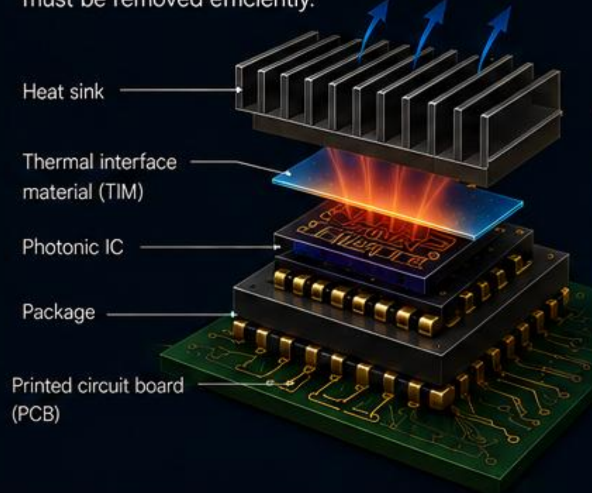
Efficient, low-loss coupling is critical for system performance.



- High alignment precision
- Low coupling loss
- Broadband operation

2. THERMAL MANAGEMENT

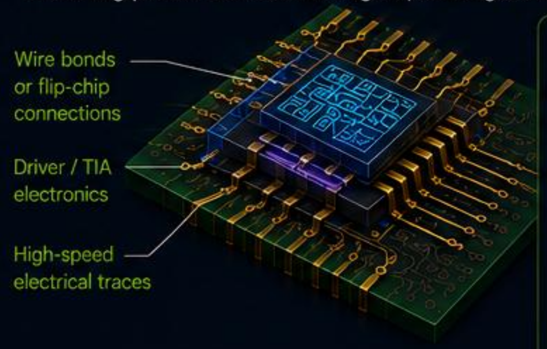
Heat generated by lasers, modulators, and electronics must be removed efficiently.



- Maintain stable temperature
- Prevent thermal crosstalk
- Ensure long-term reliability

3. ELECTRICAL INTERCONNECTS – ONE OF THE BIGGEST PRACTICAL CHALLENGES

Delivering power, control, and high-speed signals with low loss, low noise, and high density is extremely challenging.



KEY CHALLENGES

- **High bandwidth** – Supporting multi-Gbps to 100+ Gbps per channel
- **High density** – Large number of I/O in a small footprint
- **Low power & noise** – Minimize parasitics, crosstalk, and signal integrity issues
- **Reliability** – Ensure robust performance over temperature and time

APPROACHES

- Advanced packaging (flip-chip, 2.5D/3D)
- High-speed electrical design & simulation
- Impedance control & signal integrity techniques
- Low-loss materials and short interconnects
- Co-design of photonic and electronic interfaces

Electrical interconnects are often the bottleneck that limits overall system performance, scalability, and yield.

INTEGRATED PACKAGING CONSIDERATIONS

- **MECHANICAL PROTECTION** – Protects the fragile photonic chip from stress, vibration, and environmental factors.
- **ENVIRONMENTAL SEALING** – Prevents moisture, dust, and contaminants from degrading performance.
- **TEST & RELIABILITY** – Enables testing, monitoring, and long-term reliability validation.
- **SCALABILITY** – Packaging solutions must scale with chip complexity and system requirements.

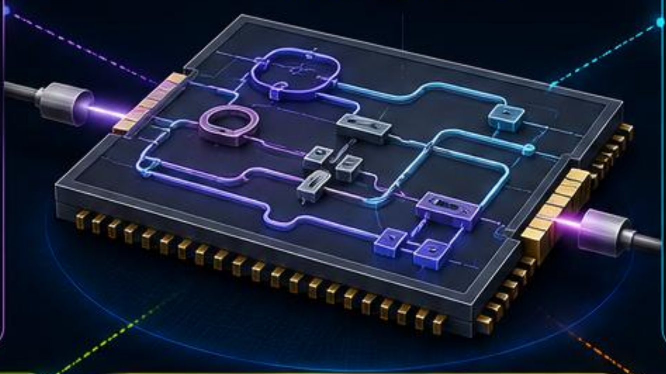
THE BIG PICTURE

Effective packaging is essential to unlock the full potential of photonic integrated circuits.

PERFORMANCE METRICS
FOR PHOTONIC INTEGRATED CIRCUITS

Performance metrics quantify how well a photonic integrated circuit (PIC) performs for a given application and guide design trade-offs.

PIC PERFORMANCE IS A BALANCE OF MULTIPLE METRICS



1. INSERTION LOSS

Total optical loss through the circuit, including coupling, propagation, and component losses.

Lower is better

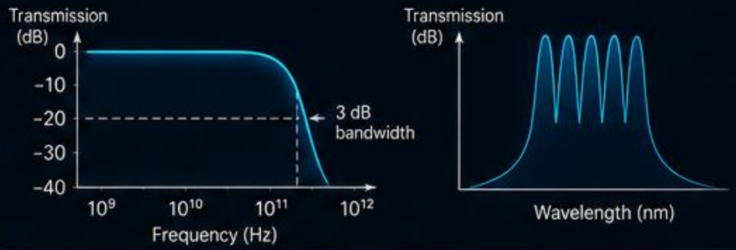
P_{in} → PIC → P_{out}

Insertion Loss (dB) = $10 \log_{10} (P_{in} / P_{out})$

2. BANDWIDTH

Range of frequencies (or wavelengths) over which the PIC operates effectively.

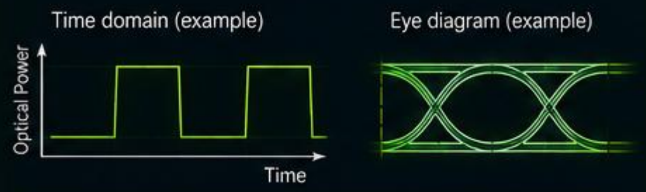
Wider bandwidth = higher capacity



3. MODULATION SPEED

How fast the PIC can modulate light to encode information.

Higher speed = higher data rate

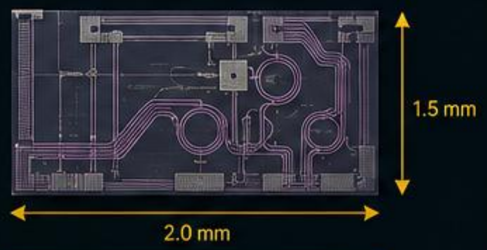


Key metric: 3 dB electro-optic bandwidth (f_{3dB}) or data rate (Gb/s)

4. FOOTPRINT

Physical area of the PIC.

Smaller footprint = higher integration density and lower cost



Metric: Area (mm²)

5. POWER CONSUMPTION

Total electrical power required to operate the PIC (heaters, modulators, drivers, etc.).

Lower power = better efficiency and scalability

Metric: Total power (mW) or energy per bit (fJ/bit)

OPTIMIZING THESE METRICS is key to achieving high-performance, scalable, and energy-efficient PICs.

- High speed communications
- Data centers & AI
- Sensing & metrology
- Quantum technologies
- Biophotonics & healthcare

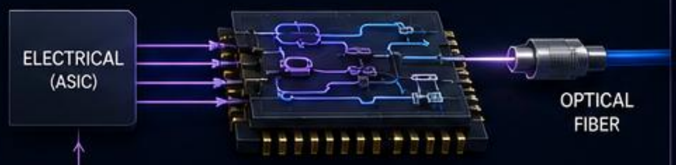
DATA COMMUNICATIONS

THE PRIMARY COMMERCIAL DRIVER FOR PHOTONIC INTEGRATED CIRCUITS

Explosive growth in data traffic demands higher bandwidth, lower latency, and lower power. Photonic integrated circuits (PICs) enable the infrastructure that makes it possible.

USED IN TRANSCEIVERS

PICs integrate high-speed optical functions to convert data between electrical and optical domains with high efficiency.



- Laser sources → Modulators
- Photodetectors
- Filters & multiplexers

USED IN SWITCHES

PICs enable high-density, low-latency optical switching for data centers and networks.

- High port count
- Low latency switching
- Low power operation
- Scalable integration

USED IN INTERCONNECTS

PICs provide high-bandwidth, low-loss links within and between systems.

- Higher bandwidth
- Lower latency
- Lower power
- Smaller, lighter systems

WHY IT MATTERS

- Meets ever-growing bandwidth demands
- Reduces power and footprint vs. traditional solutions
- Enables next-generation data centers, AI/ML clusters, and cloud infrastructure
- Drives the commercialization and rapid adoption of photonic integrated circuits

SUPPORTS FASTER AND MORE EFFICIENT DATA MOVEMENT

Data Generated → PICs Move Data Optically → Higher Throughput Lower Latency → Lower Power Consumption → Better Performance at Scale

Data communications is the #1 commercial driver for PICs—powering the connected world.

DATACENTERS AND AI SYSTEMS
NEED PHOTONIC INTEGRATED CIRCUITS

AI workloads generate massive data flows that traditional electrical links struggle to handle. Photonic integrated circuits (PICs) provide the bandwidth, efficiency, and scalability modern AI infrastructure demands.

PICs are a **GROWING IMPORTANCE** in AI infrastructure

AI WORKLOADS DRIVE EXPLOSIVE DATA GROWTH

- Larger models
- More GPUs / accelerators
- More data
- Higher performance demands

ELECTRICAL INTERCONNECTS BECOME A BOTTLENECK
Limited bandwidth, higher power, and short reach

HIGH-SPEED OPTICAL INTERCONNECTS REDUCE BOTTLENECKS

- Massive bandwidth
- Low latency
- Lower power
- Scalable reach

INTEGRATED PHOTONICS MOVES DATA EFFICIENTLY BETWEEN CHIPS AND RACKS

- CHIPS: On-package / on-board optical I/O
- PIC: High-speed optical interconnect (PIC)
- RACK / SWITCH: Optical links within rack or across racks
- RACKS: Data center scale connectivity

END-TO-END OPTICAL DATA PATH

WHERE PICS MAKE AN IMPACT IN AI INFRASTRUCTURE

- **GPU / ACCELERATOR CONNECTIVITY**: High-bandwidth links between GPUs/accelerators
- **SCALE-UP NETWORKS (WITHIN SERVER)**: Replace electrical traces with optical links for higher density and lower power
- **SCALE-OUT NETWORKS (BETWEEN SERVERS)**: Optical interconnects for high-throughput, low-latency communication
- **RACK-TO-RACK AND DATA CENTER FABRIC**: Longer reach, higher bandwidth links across racks and pods

THE RESULT: BETTER AI INFRASTRUCTURE

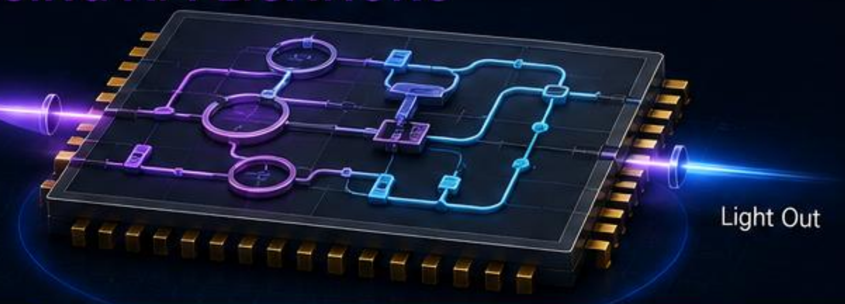
- Higher performance
- Lower power consumption
- Greater scalability
- Lower cost per bit

Photonic integrated circuits are a key enabler for the next generation of **AI systems.**

As AI continues to scale, PICs will be essential to move data faster, farther, and more efficiently.

PHOTONIC INTEGRATED CIRCUITS
DESIGNED INTO MANY SENSING APPLICATIONS

Photonic integrated circuits (PICs) enable compact, high-performance sensors for a wide range of applications.

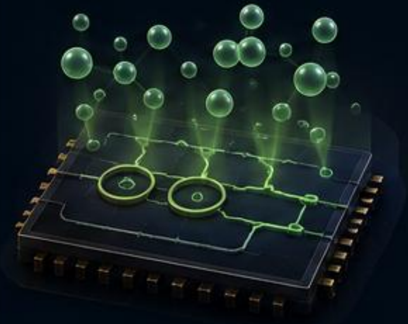


PICs BRING UNIQUE ADVANTAGES TO SENSING

- High sensitivity
- Multiplexing capability
- Compact footprint
- Low power consumption
- CMOS-compatible fabrication
- Immune to electromagnetic interference

1. CHEMICAL SENSING

Detect and identify chemicals and gases with high selectivity and sensitivity.

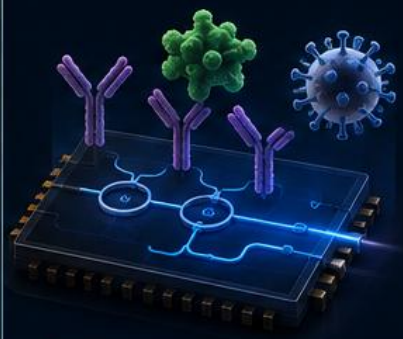


- Gas detection
- Environmental monitoring
- Industrial process control
- Hazardous chemical detection

Surface functionalization of PIC waveguides interacts with target molecules, causing measurable optical changes.

2. BIOSENSING

Label-free detection of biomolecules and pathogens with remarkable sensitivity.



- Disease diagnostics
- Health monitoring
- Genomics & proteomics
- Drug discovery & screening

Biorecognition events on the PIC surface alter the optical signal, enabling ultra-sensitive detection in real time.

3. TEMPERATURE AND STRAIN MEASUREMENT

Monitor physical changes with precision for harsh and demanding environments.

- Temperature monitoring
- Structural health monitoring
- Aerospace & automotive
- Industrial automation

Changes in temperature or strain alter the optical properties of the PIC, enabling accurate, real-time measurements.

COMPACT AND HIGHLY SENSITIVE PLATFORMS

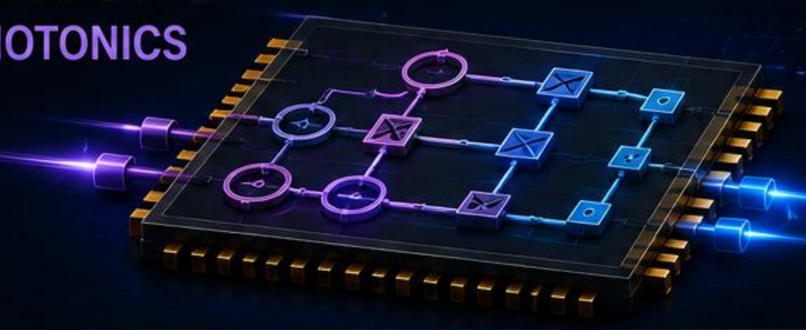
PIC sensors combine small size with exceptional performance—enabling smarter systems in more places.

- Small footprint
- Ultra-high sensitivity
- Real-time measurement
- Low power consumption
- Multiplexed sensing
- Robust and reliable

PHOTONIC INTEGRATED CIRCUITS

DESIGNED INTO MANY QUANTUM PHOTONICS APPLICATIONS

PICs provide the precision, stability, and scalability needed to advance quantum technologies.



PICs ENABLE QUANTUM ADVANTAGE

- High stability and phase control
- Low loss, low crosstalk
- Compact and scalable
- CMOS-compatible fabrication
- Path to large-scale integration

KEY BUILDING BLOCKS INTEGRATED ON A CHIP

1. INTEGRATED SOURCES

Generate non-classical light such as single photons and entangled photon pairs.

- Spontaneous parametric down-conversion (SPDC)
- Quantum dots
- On-chip lasers

2. INTERFEROMETERS

Manipulate quantum states using precise control of phase and interference.

- Mach-Zehnder interferometers
- Multiport interferometers
- Programmable photonic circuits

3. DETECTORS

Detect single photons with high efficiency and low noise.

- Superconducting nanowire single-photon detectors (SNSPDs)
- Geiger-mode APDs
- On-chip integrated detectors

POWERING QUANTUM COMMUNICATION AND COMPUTING RESEARCH

QUANTUM COMMUNICATION

Secure information transfer using quantum states.

Transmitter → Quantum channel → Receiver

QUANTUM COMPUTING

Perform calculations using qubits and photonic quantum states.

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QUANTUM SIMULATION & SENSING

Simulate complex systems and measure with extreme precision.

WHY PICs FOR QUANTUM PHOTONICS?

- Stable and robust operation
- High-precision control
- Massively parallel integration
- Lower power and footprint
- Path to large-scale, manufacturable systems

PROMISING FOR SCALABLE QUANTUM HARDWARE AT THE COMMERCIAL AND INDUSTRIAL SCALES

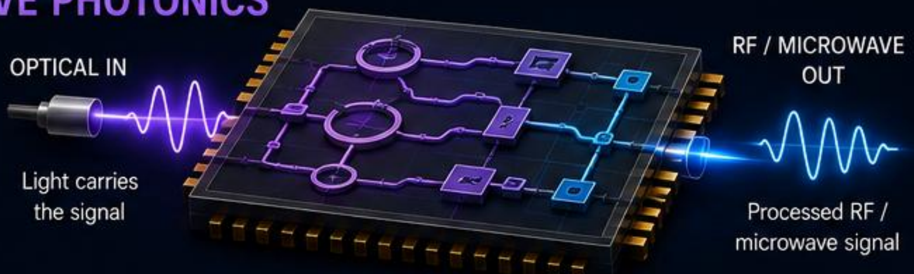
- Scalable integration
- Lower cost per function
- CMOS-compatible manufacturing
- Enables real-world quantum technologies

→

- From lab to fab
- From research to real-world impact

PHOTONIC INTEGRATED CIRCUITS
DESIGNED INTO MANY MICROWAVE PHOTONICS APPLICATIONS

Microwave photonics uses light to generate, process, and transmit RF and microwave signals with unmatched bandwidth, linearity, and stability.



MICROWAVE PHOTONICS AT A GLANCE

- Use light to process RF and microwave signals
- Low loss, wide bandwidth
- High linearity and dynamic range
- Immunity to EMI
- Reconfigurable and scalable

HOW MICROWAVE PHOTONIC PICS WORK

1. RF INPUT
Electrical RF/microwave signal enters the system.

2. OPTICAL TRANSMISSION
The signal is converted to light and transmitted with ultra-low loss and wide bandwidth.

3. PHOTONIC PROCESSING
PICs perform filtering, true time delay, beamforming, frequency conversion, and more.

4. OPTICAL-TO-RF CONVERSION
The processed signal is converted back to RF/microwave.

KEY MICROWAVE PHOTONIC FUNCTIONS

- **Wideband Signal Generation** — Generate high-purity, low-phase-noise RF signals.
- **Filtering & Channel Selection** — Reconfigurable filters with ultra-wide bandwidth.
- **True Time Delay** — Precise, broadband time delays for beamforming.
- **Frequency Conversion** — Up/down conversion with high linearity.
- **Signal Distribution** — Fan-out and routing with minimal loss.

WHY MICROWAVE PHOTONIC PICS?

- **ULTRA-WIDEBAND** — Supports tens to hundreds of GHz.
- **LOW LOSS** — Optical links reduce loss and degradation.
- **HIGH LINEARITY** — Excellent performance with complex signals.
- **EMI IMMUNITY** — Optical domain is immune to electromagnetic interference.
- **RECONFIGURABLE & SCALABLE** — Easily reprogrammed and integrated.

USED IN DEFENSE, RADAR, AND COMMUNICATIONS

- **RADAR SYSTEMS** — High-resolution imaging and target detection
- **ELECTRONIC WARFARE** — Wideband signal capture and processing
- **TACTICAL COMMUNICATIONS** — Secure, resilient, high-capacity links
- **SATELLITE & 5G / 6G NETWORKS** — High-throughput, low-latency backhaul and fronthaul

THE POWER OF LIGHT FOR RF AND MICROWAVES

Photonic integrated circuits bring the speed of light to the world of RF—enabling the performance needed for today's and tomorrow's systems.

- Higher performance
- Lower loss and power
- Smaller, lighter systems
- Scalable for commercial and industrial markets

- From RF to light
- From lab to field
- From innovation to impact

PHOTONIC INTEGRATED CIRCUITS

POWERING MANY HIGH-TECH EMERGING APPLICATIONS

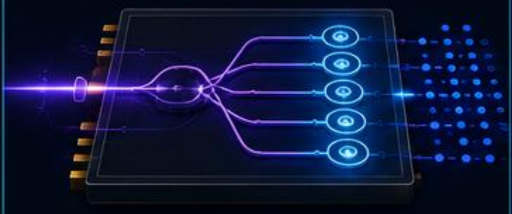
PICs are enabling a new wave of transformational technologies that go beyond traditional communications, opening the door to intelligent, efficient, and highly integrated photonic systems.

PICS DRIVE INNOVATION AT THE FRONTIERS

- Breakthrough performance
- Miniaturization and scalability
- Energy efficiency
- Enabling entirely new capabilities

1. OPTICAL COMPUTING

Use light to perform computing operations at unprecedented speed.



- Massive parallelism for ultra-fast processing
- Ideal for matrix operations and linear algebra
- Potential for orders of magnitude higher throughput
- Lower latency and energy compared to electronics

2. NEUROMORPHIC PHOTONICS

Mimic the brain's architecture using light for efficient, adaptive computation.

- Implements spiking neural networks with light
- Adaptive learning with low power consumption
- Great for AI at the edge
- Scalable and highly parallel architectures

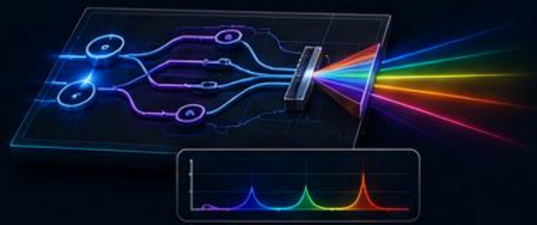
3. LiDAR

Enable high-performance, compact, and solid-state 3D sensing.

- High resolution 3D imaging
- Solid-state, no moving parts
- Compact, rugged, and reliable
- Ideal for autonomous vehicles, drones, and robotics

4. ON-CHIP SPECTROSCOPY

Perform precise spectral analysis in a compact, integrated platform.



- Broadband spectral measurement
- High sensitivity and resolution
- Fully integrated and miniaturized
- Applications in chemistry, biology, and material analysis

PICs are unlocking the next generation of intelligent, sensing, and computing technologies.
The future is photonic—and it's just beginning.

WHY IT MATTERS

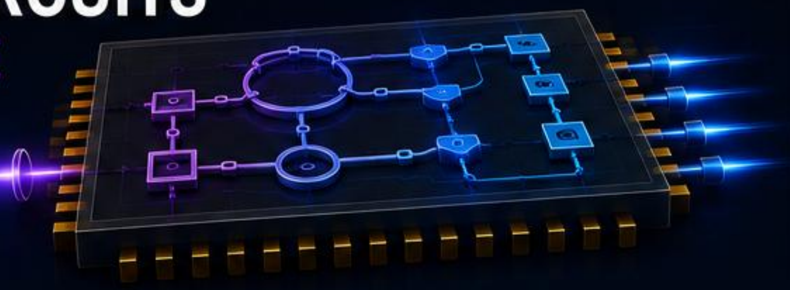
- Extreme speed and bandwidth
- Low power and high efficiency
- Small size and high integration
- Robust and reliable
- Disruptive potential across industries

EMERGING TODAY. ESSENTIAL TOMORROW.

PHOTONIC INTEGRATED CIRCUITS

MANY CHALLENGES TO OVERCOME

While PICs offer tremendous potential, several technical and economic challenges must be addressed to realize their full impact.



KEY TAKEAWAY

Overcoming these challenges requires progress in materials, design tools, fabrication, packaging, and ecosystem development.

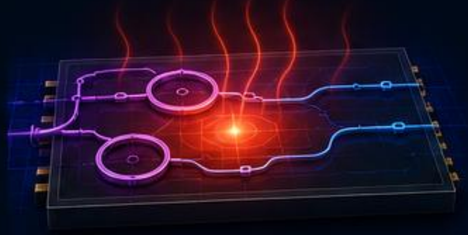
1. EFFICIENT LIGHT SOURCES ON CHIP

Integrating high-performance, stable, and efficient light sources remains a major hurdle.

- Lasers often require heterogeneous integration (e.g., III-V on Si)
- Power consumption and heat dissipation are critical
- Achieving reliability and long lifetimes at scale is still difficult

2. THERMAL EFFECTS

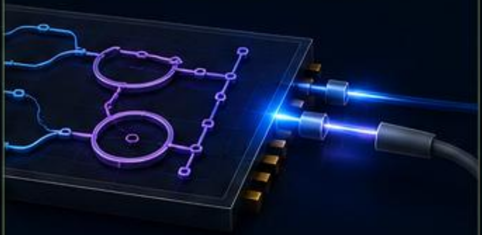
Heat generated on chip can degrade performance and limit device density and stability.



- Temperature changes shift wavelengths and affect phase stability
- Thermal crosstalk impacts neighboring components
- Effective thermal management is essential

3. PACKAGING AND COUPLING LOSS

Getting light on and off the chip efficiently is complex and lossy.



- Fiber-to-chip and chip-to-chip coupling introduce loss and alignment challenges
- Packaging adds cost, size, and performance penalties
- Advanced coupling and co-packaging solutions are still evolving

4. COST, TESTING, AND SCALABILITY

Scaling PICs to high volumes with consistent quality and reasonable cost is a major industry challenge.

- Fabrication processes must be high-yield and cost-effective
- Testing PICs at scale is complex and time-consuming
- Ecosystem maturity and standardization are still in progress

THE PATH FORWARD

Solving these challenges will unlock the full potential of PICs and enable widespread adoption across industries.

- Advanced materials and sources
- Better thermal management
- Innovative packaging and integration
- Smarter test and design tools
- Industry collaboration and standards

Overcoming today's challenges will define tomorrow's photonic breakthroughs.

SUMMARY

THE POWER OF INTEGRATED PHOTONICS

Integrated photonics brings optical functions onto compact chips.

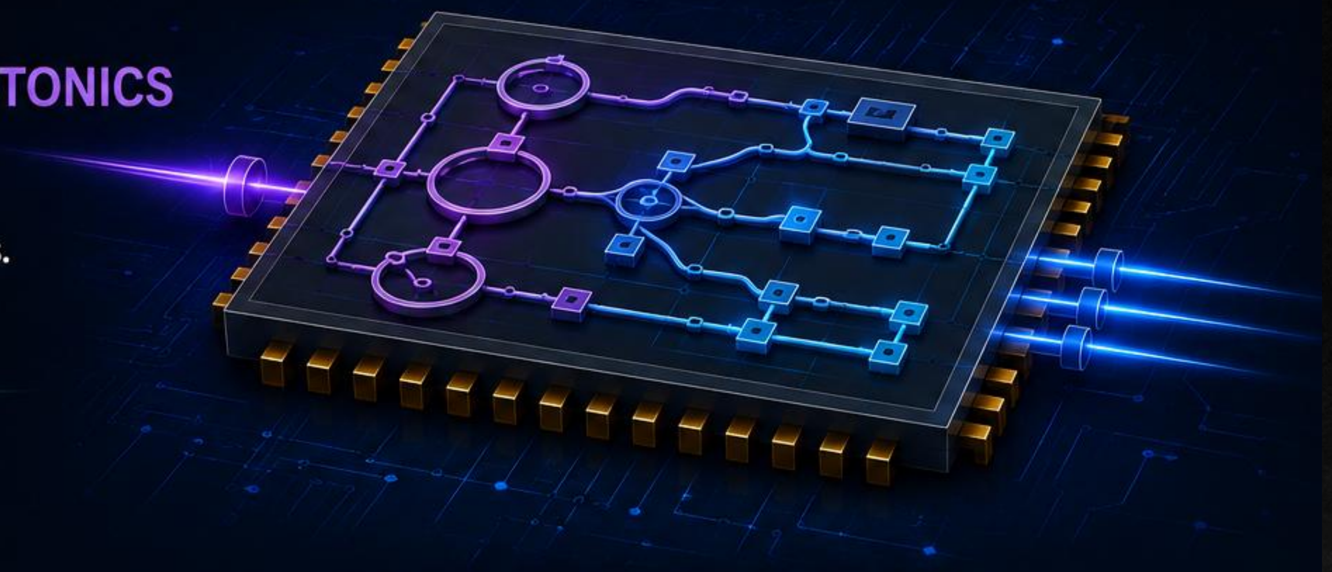
It replaces bulky and power-hungry optical systems with high-performance, energy-efficient solutions.

It enables scalable systems for communications, sensing, and emerging computing.

PICs are at the heart of technologies powering our connected and intelligent world.

Ongoing advances in materials and fabrication are expanding what photonic chips can do.

Innovation continues to unlock new capabilities and open doors to future applications.

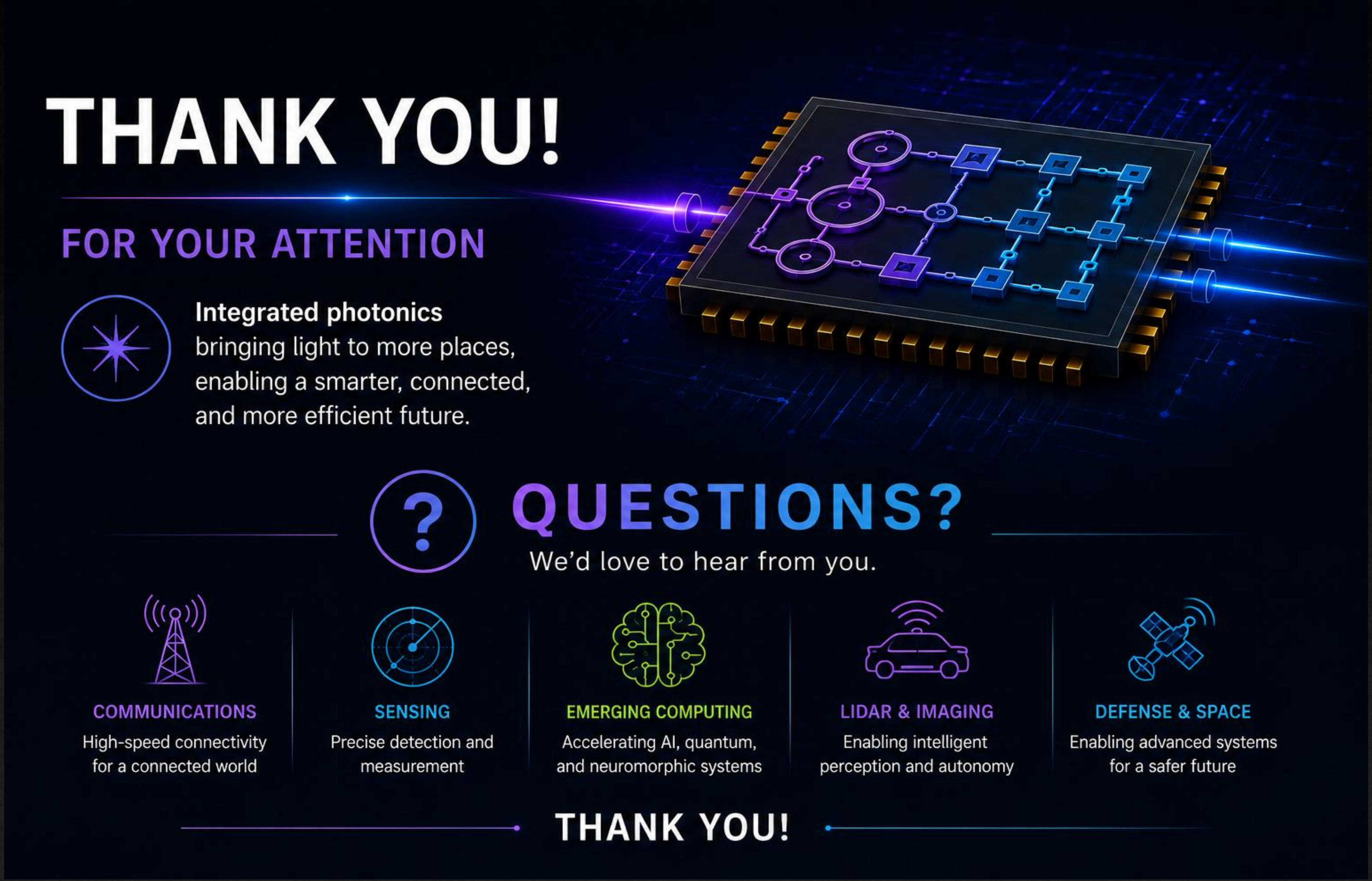


ENABLING A WIDE RANGE OF IMPACTFUL APPLICATIONS

COMMUNICATIONS	SENSING	EMERGING COMPUTING	LIDAR & IMAGING	DEFENSE & SPACE
High-speed data transmission and networking	Precision sensing for health, environment and industry	Accelerating AI, quantum, and neuromorphic systems	3D sensing and imaging for autonomous systems and beyond	Advanced radar, EW, and secure communications

Integrated photonics is transforming how we transmit, sense, and process information.

Small chips. Big impact. Limitless potential.


THANK YOU!
FOR YOUR ATTENTION
Integrated photonics
bringing light to more places,
enabling a smarter, connected,
and more efficient future.
QUESTIONS?
We’d love to hear from you.
COMMUNICATIONS
High-speed connectivity
for a connected world
SENSING
Precise detection and
measurement
EMERGING COMPUTING
Accelerating AI, quantum,
and neuromorphic systems
LIDAR & IMAGING
Enabling intelligent
perception and autonomy
DEFENSE & SPACE
Enabling advanced systems
for a safer future
THANK YOU!