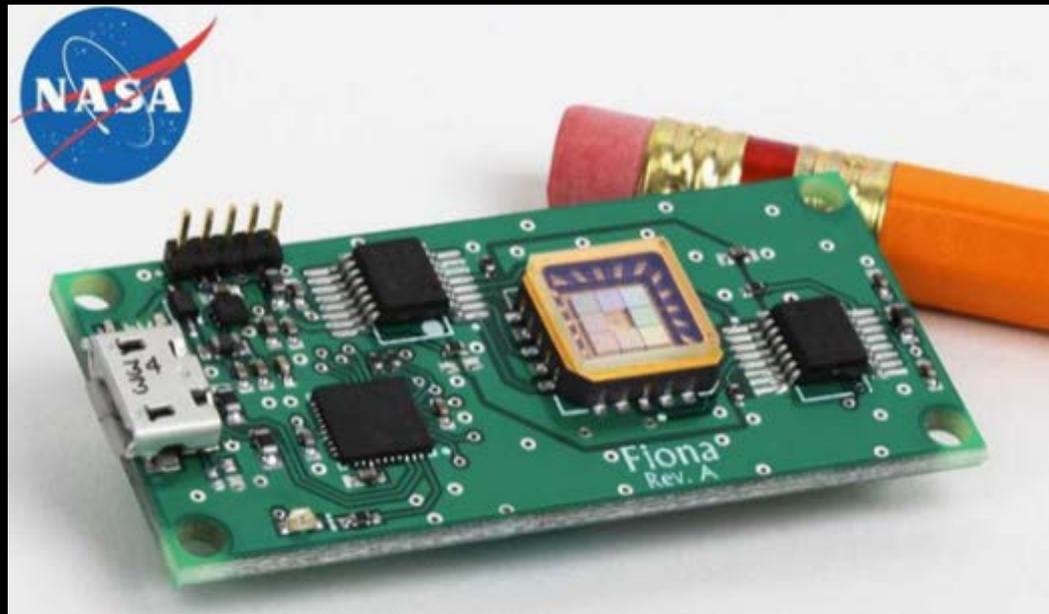




Photonic Integrated Circuits (PICs) for Next Generation Space Applications

NASA Electronics Parts and Packaging (NEPP)



Amanda N. Bozovich

2020 Electronics Technology Workshop (ETW)

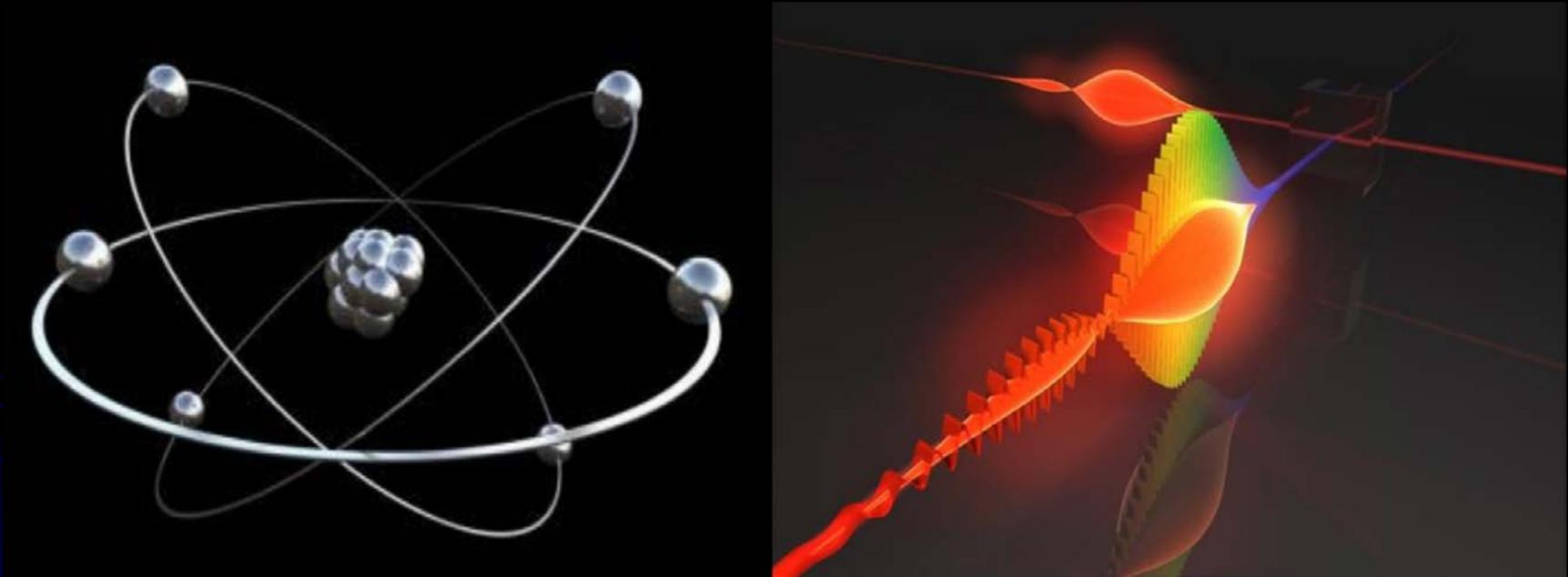
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AGENDA:

The Evolution of Photonic Integrated Circuits: **Past**, **Present**, and **Future** of Communications



Will Electrons or Photons Rule Tomorrow's Applications?

THE PAST: Discrete Optics for Communication Systems

Since invention of transistor, integrated circuits for communication systems have relied heavily on electrons to transmit/receive data. Next generation electronic ICs contain more transistors in smaller areas, operating at faster speeds. Today, communications market >\$300B per year, dominated by CMOS chips containing billions of transistors (mainly electrical).

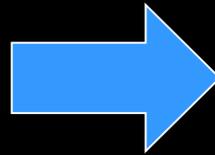


Optical assembly process with discrete components far more complex than electronics!

- Electronics increasingly supplemented by optics with the introduction of optical communication systems (1980s) for long distance telecommunication (lasers, photodetectors, optical fiber, waveguides, optical amplifiers, etc. – photonic building blocks complement electronics).
- Optical transmitters and receivers hand-assembled from several “bulk” commercial-off-the-shelf piece parts (over 20 discrete passive and active devices).
- **Internal interconnects and packaging have always posed significant reliability challenges for traditional “discrete” optical designs.**
 - Discrete optics require hermetic packaging (metal) and mechanical stability to mitigate component misalignment over time due to environmental stresses like vibration and temperature variations (reduces yield and increases cost).

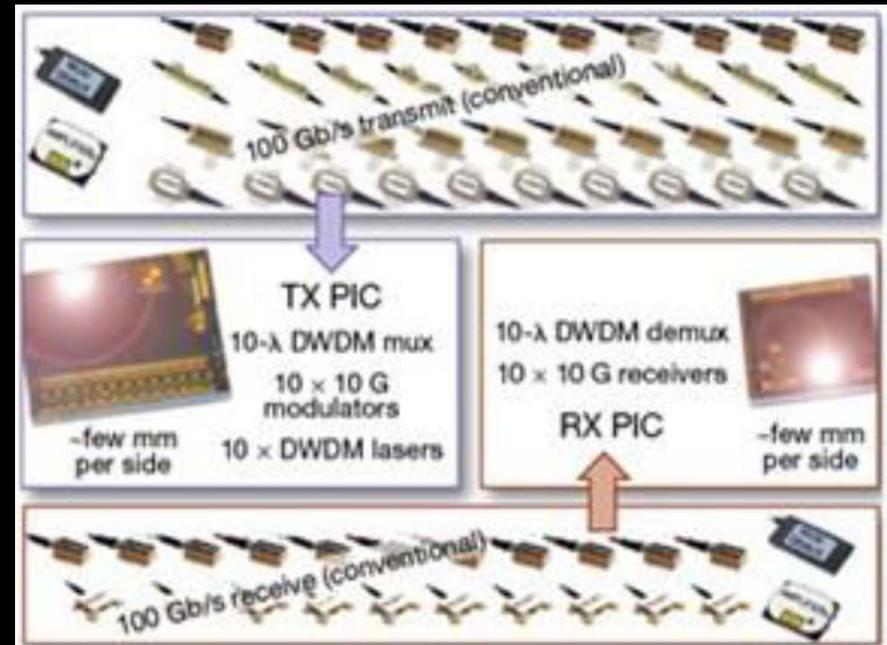
THE PRESENT: Integrated Photonics

Discrete optical components not easily scaled and integrated into complex systems. Growth of network interconnects to meet data demand slowed by implementation of complex discrete optical designs.



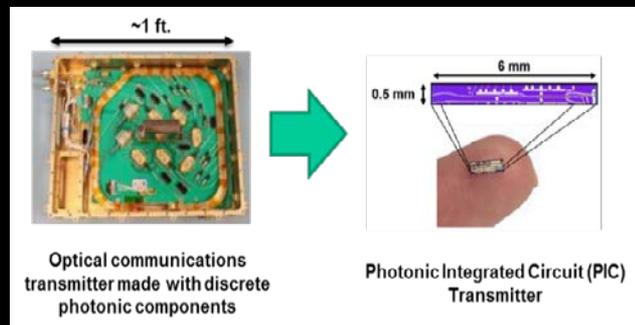
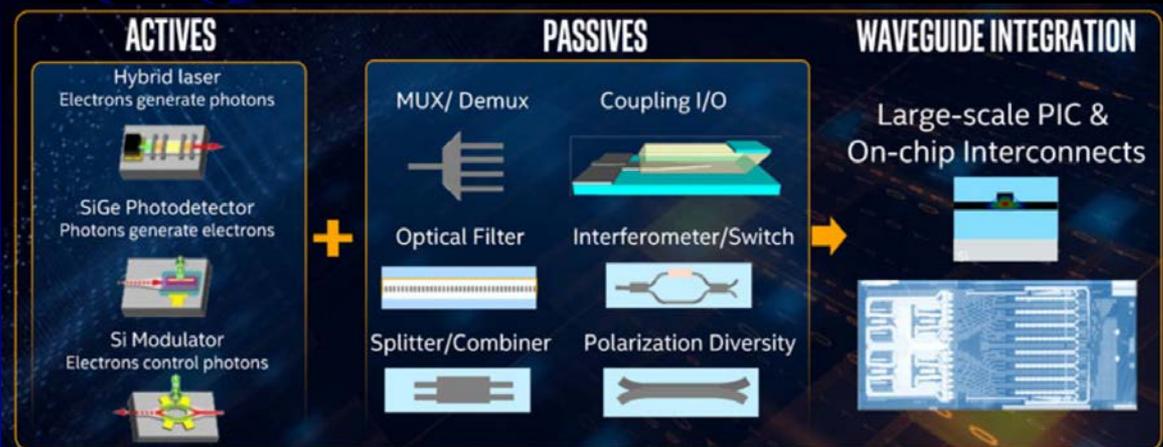
Containing over 100s of optical components on a single Tx or Rx chip, photonic integrated circuits (PICs) offer more functionality, reliability, and scalability than discrete systems.

- Monolithic InP-based PICs (first introduced in 2004) established commercial viability for large-scale production of integrated photonics for telecom networks.
- PICs are technology of present and future for data centers and cloud computing, enabling simpler, more reliable, and cost effective higher bandwidth communications (overcoming limitations of discrete optical designs and electronic comm systems).



What is a Photonic Integrated Circuit (PIC)?

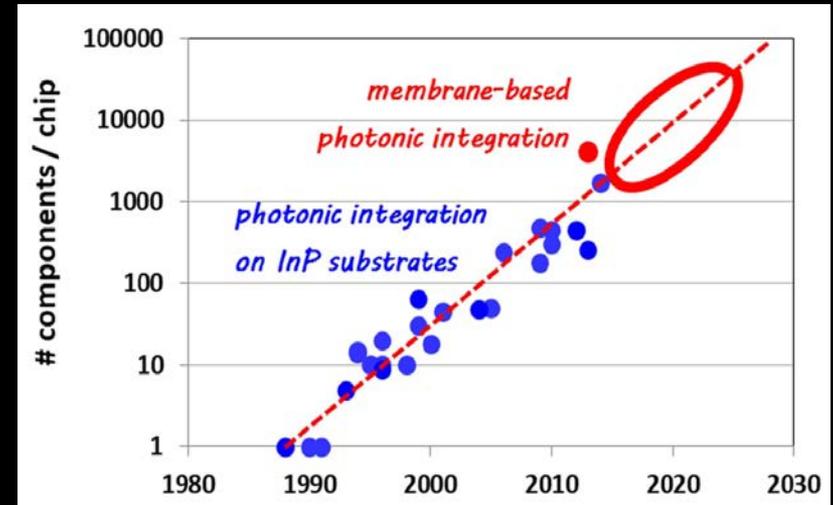
- PICs are advanced systems-on-a-chip, enabling transmission of data at high speeds, using optical carriers. Operate in visible and near infrared of EM spectrum (350–1650 nm).
- Feature highly-scaled integration of multiple optical components on single compact chip (micron to mm-size), enabling complex functions analogous to electronic ICs. Future integration with electronic circuits (drivers, logic) will further extend PIC functionality for wider market applications.
- Common PIC components: optical amplifiers, MUX/DEMUX, lasers, modulators, LEDs, photodetectors, planar optical waveguides, optical fiber, lenses, attenuators, filters, switches.
- Available PIC platform materials: **Si (SOI)**, LiNbO₂, GaAs, InGaAsP, **SiN**, **InP**, SiO₂.
- Integrated photonics is next generation disruptive technology critical to meeting size, weight, power (SWaP) as well as performance goals for many diverse applications.
- *Key benefits of PICs: >50% less mass and power, 100X size reduction, higher bandwidth and data rate, no-cost redundancy, aperture-independent (fiber-coupled), transparent to modulation format, versatile, and scalable. Offering improvements in performance and reliability.*



Current State-of-the-Art PIC Designs

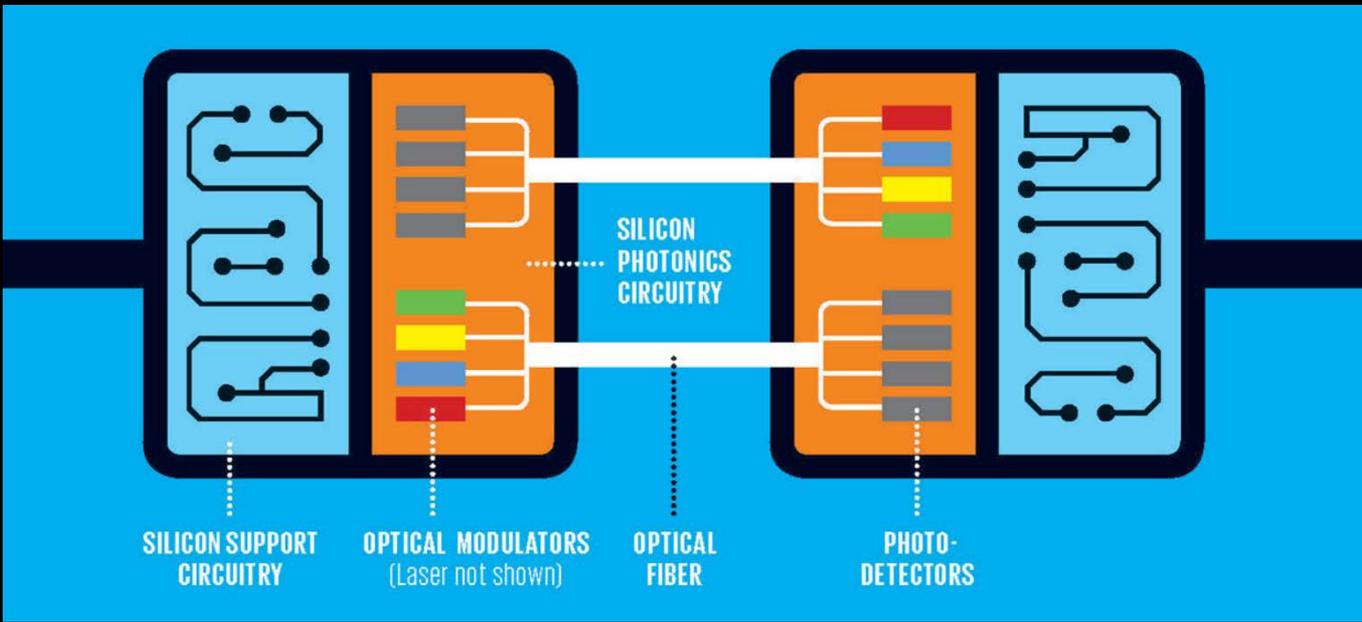
- Most sophisticated PICs to date contain over 1000 optical components on single, monolithic, InP-based chip.
- Application of membrane-based photonic technologies creates roadmap for integration of >10,000 components per chip. Offers size and energy reductions required for higher density integration, and for close integration with electronics.
- Highest number of components per chip reported: 4096 (for 64 × 64 phased array realized in Silicon Photonics) (Sun et al., 2013) (red dot)

Moore's Law of Photonics



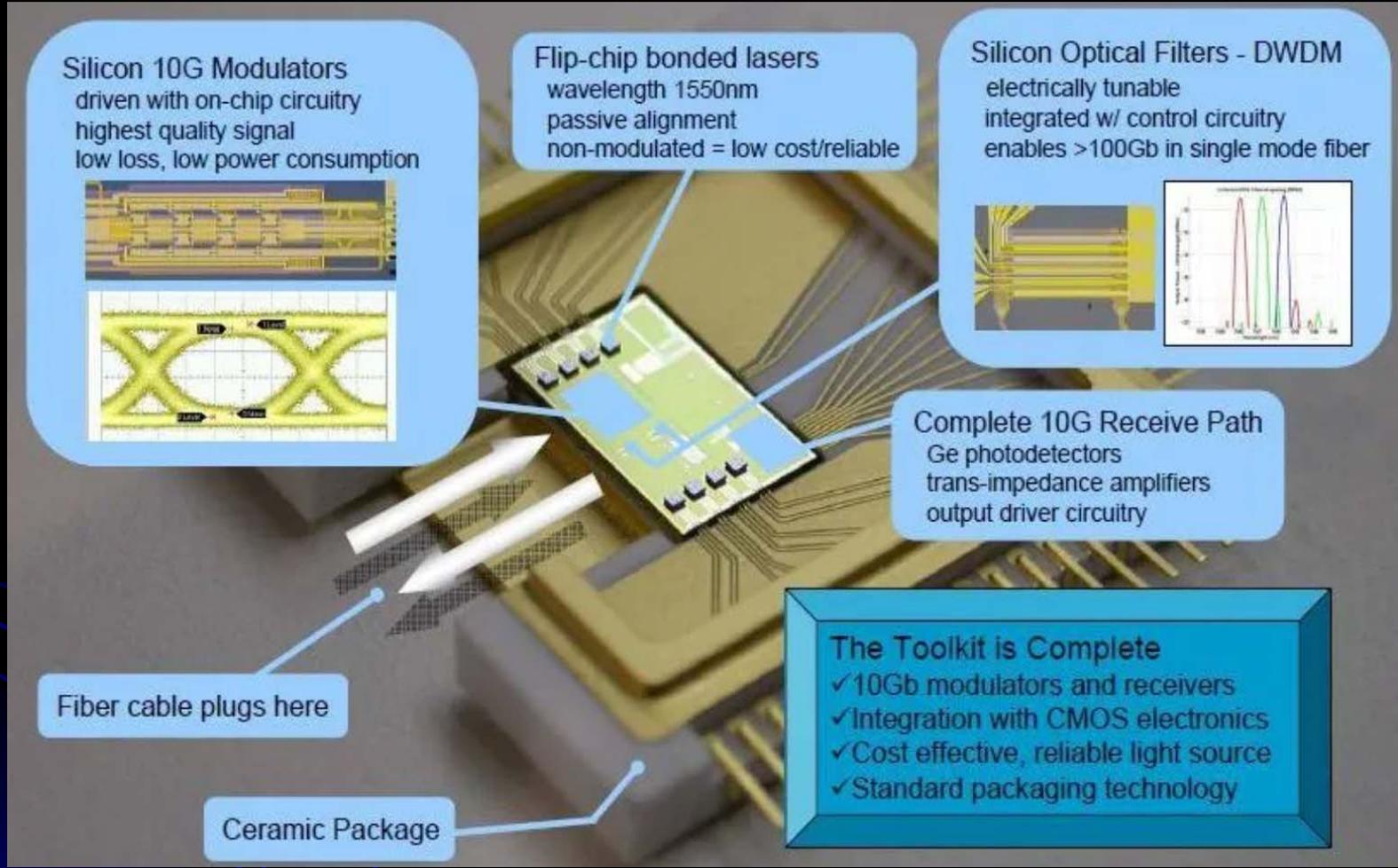
Integrated photonics not expected to scale to same component densities seen in CMOS electronics (components per chip constrained by size of optics, electrical connectivity, and thermal management challenges)

Basic Concept of Silicon Integrated Photonics



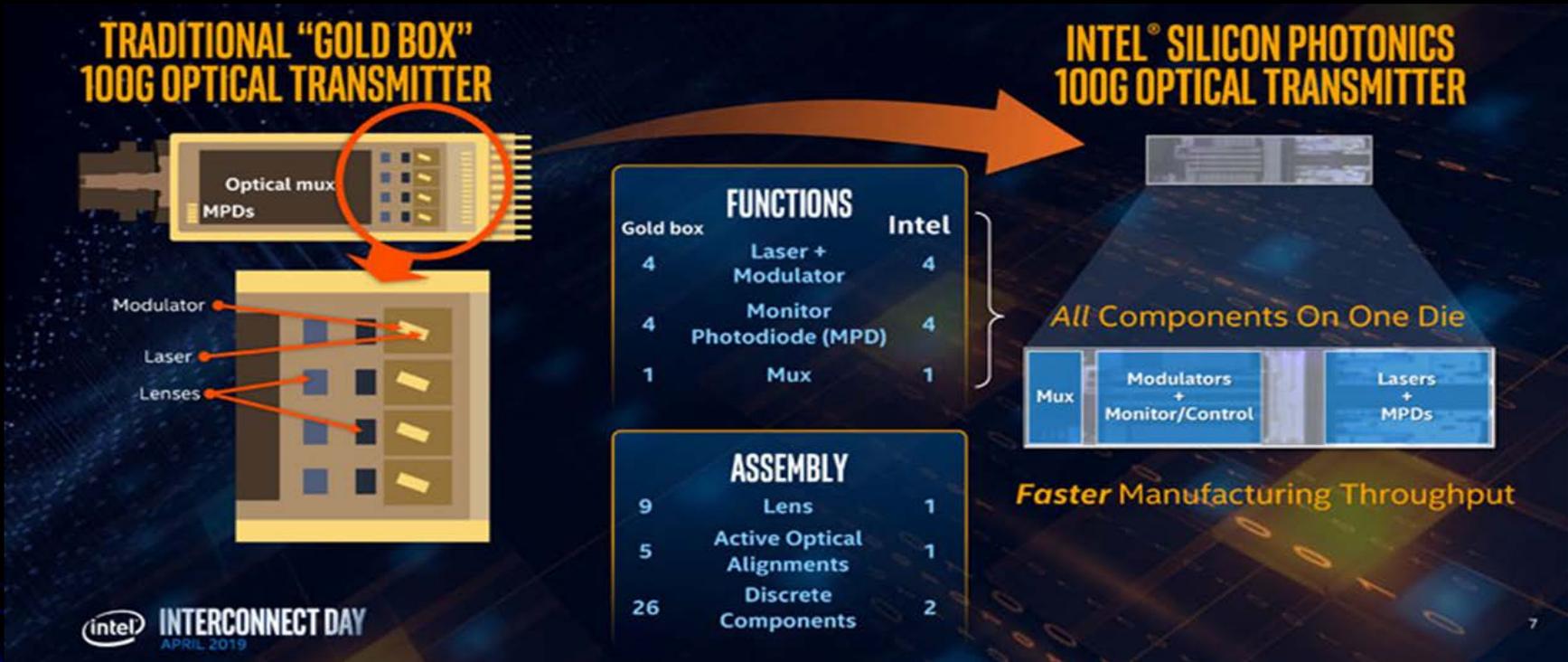
Plug-and-Play: silicon photonics module converts electronic data to photons and back again. Silicon circuitry helps optical modulators encode electronic data into pulses of several colors of light. The light travels through optical fiber to another module, where photodetectors turn light back into electronic bits. The electronic data is processed again by silicon circuits and sent on to the appropriate servers.

Optical Transceiver with Silicon Integrated Photonics



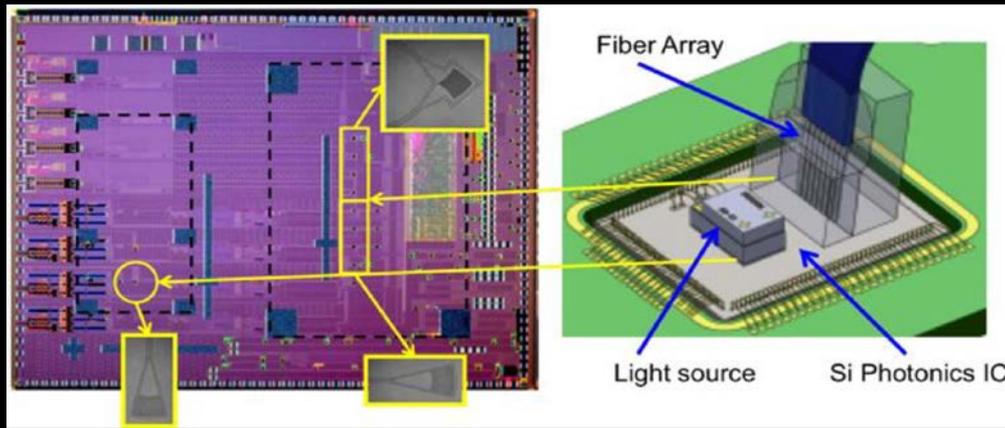
This commercial optical transceiver, using silicon integrated photonics, is an example of a typical PIC that can be purchased off-the-shelf today.

Today's Advantage of Silicon Photonic Integration

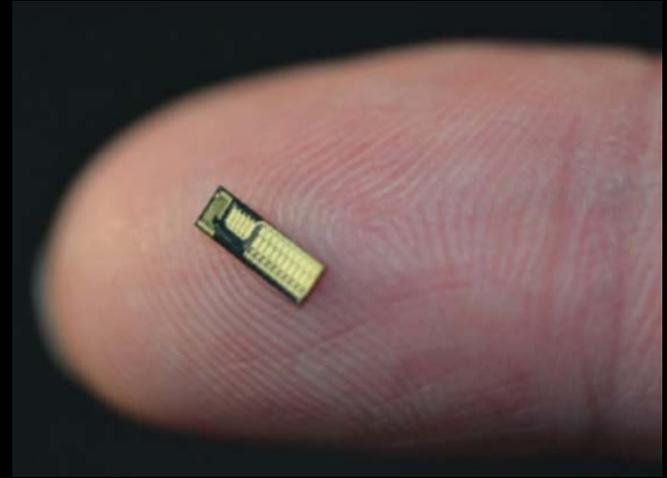


- Optical transceivers based on silicon photonics first hit market in 2016 (major players: Intel, Acacia, Luxtera).
- PICs are much more compact and efficient than the discrete optical sub-assemblies they replace, eliminating need for hand assembly of numerous discrete components.
- Incorporated in small, pluggable transceivers, silicon photonics (Si-Ph) can enable high speed routers and switches in data centers to communicate with pipes >100 Gb/s, over distances >10 km (dense wavelength division multiplexing or DWDM is key).

State-of-Art Commercial PIC Examples

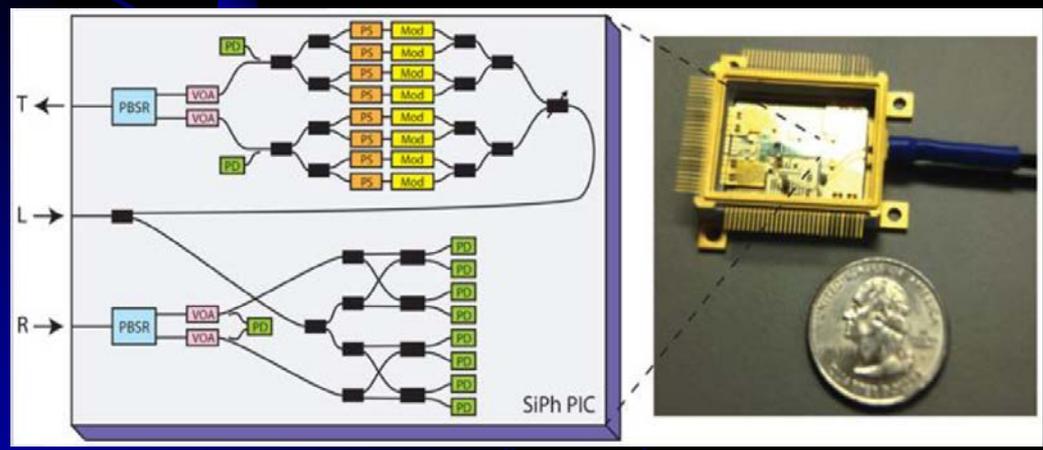


EFFECT Photonics 100 Gb/s Transceiver Chip (powerful DWDM optical system on monolithically integrated InP PIC)



Luxtera-8-PSM transceiver (Si-Ph)

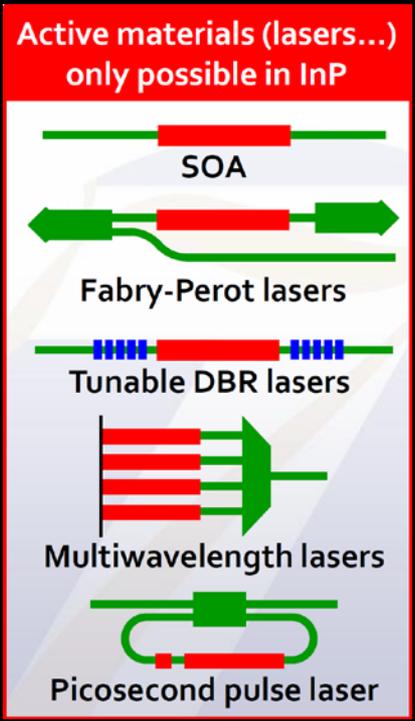
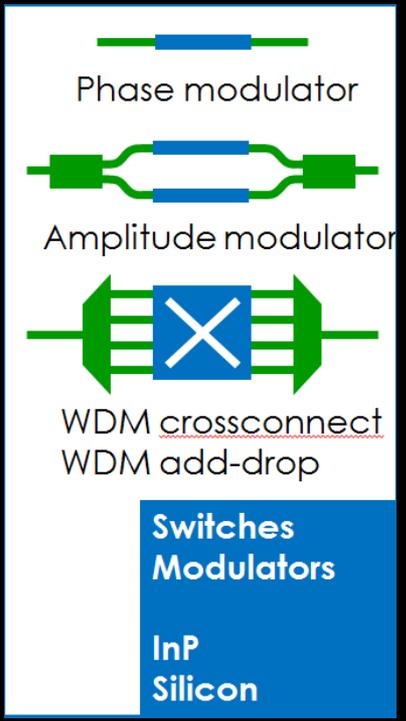
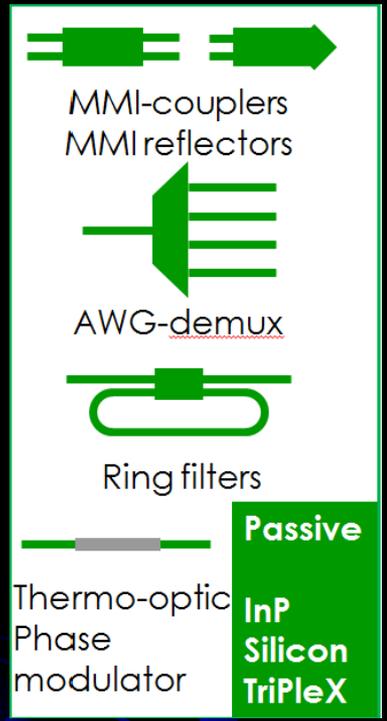
- 8-fiber PSM solution (4 fibers out and 4 fibers in)
- 1.4- μm laser in small hermetic assembly on top of PIC (Luxtera)
- Split four ways to four 10-Gb/s OOK distributed-driven MZMs
- CMOS drive electronics monolithically integrated with photonics



Acacia Coherent 100 Gb/s Transceiver

- Three fibers connected to module: laser input (split between Tx and Rx); transmitter output; and receiver input
- Co-packaged in hermetic gold box with four drivers and four TIAs
- No temp control, power consumption <5W, operation range: -5 to 80°C

Choosing the Right PIC Platform



- PIC structures & material systems are complex
- Main PIC platforms: **Silicon (SOI), SiN, and InP (III-V)**
- Pros and cons in terms of available functionalities and performance
- Silicon photonics (Si-Ph) is CMOS-compatible (high volume production)
- Only InP has direct integration of lasers (Si-Ph does not)

- Platform choice matter of desired functionality than area cost
- Cost of substrate has minor impact on volume production
 - InP MPWs (multi-project wafers): 2"-3" wafers, 50 –200 chips per wafer
 - Silicon Photonics MPWs: 6"-8" wafers, 300 –5000 chips per wafer
- Perception is Silicon Photonics more cost effective with higher manufacturing volume, but when considering cost of laser integration, InP often wins
- PIC packaging always dominates final cost (>60% of total)!!

Comparison of Integrated Photonics Technology Platforms

Material	Optical Components	Refractive Index Contrast	Propagation Loss	Thermo-optic coefficient	Compatibility with CMOS electronics	Reliability
III-V Semiconductors (InP, GaAs)	Lasers, optical amplifiers, modulators, detectors	Low	Relatively high	High	No	High
Silicon	Filters, modulators, switches	High	Relatively high	High	Yes	High
Silica on silicon	Filters, modulators, switches, splitters	Low	Very low	Low	Yes	High
Polymer	Modulators, attenuators	Low	Low	High	Yes	Low

Comparison of material and waveguide characteristics for popular PIC technology platforms.

InP vs Si Photonics (Si-Ph)

- Silicon photonics (SOI) is CMOS-compatible. CMOS infrastructure provides well controlled and rapidly scalable fab environment (higher yield than InP). **Enables 3D-integration with driving CMOS electronics, offering optical interconnect solution with high-performance, low-cost, high volume, and small form-factor transceiver modules.** Mostly single-mode (SM) components/systems.
- Silicon WG high index contrast laterally &vertically allows for smaller bend radii, more compact PICs.
- InP modulators temperature sensitive; Silicon modulators minimal temperature dependence.
- Silicon cannot be used to build lasers (indirect band-gap). Laser source separate from chip, leading to high-cost, packaging complexity and unavoidable coupling losses, limiting power savings. InP is direct band gap for all telecom wavelengths; laser integration enables scalability.
 - **Packaging solution for Si-Ph: mount laser as a flip-chip, but alignment issues remain.**
- Hybrid III-V-on-silicon laser is solution – challenge is to efficiently couple light from III-V to silicon.
 - **Wafer-level integration by bonding or deploying epitaxial re-growth of InP to silicon chip, and then processing it with traditional lithographic techniques.**

Integrated Photonics platform technologies			
Technique	InP	Si Photonics	Hybrid Si.
Schematic view ■ Silicon element ■ InP element	 Integrated full InP based chip	 Silicon based chip with connected InP laser	 Silicon based chip with InP based lasers bonded
Maximum bandwidth ¹	> 1,000 Gb/s	100 Gb/s	400 Gb/s
Integration level	Full	-	Limited

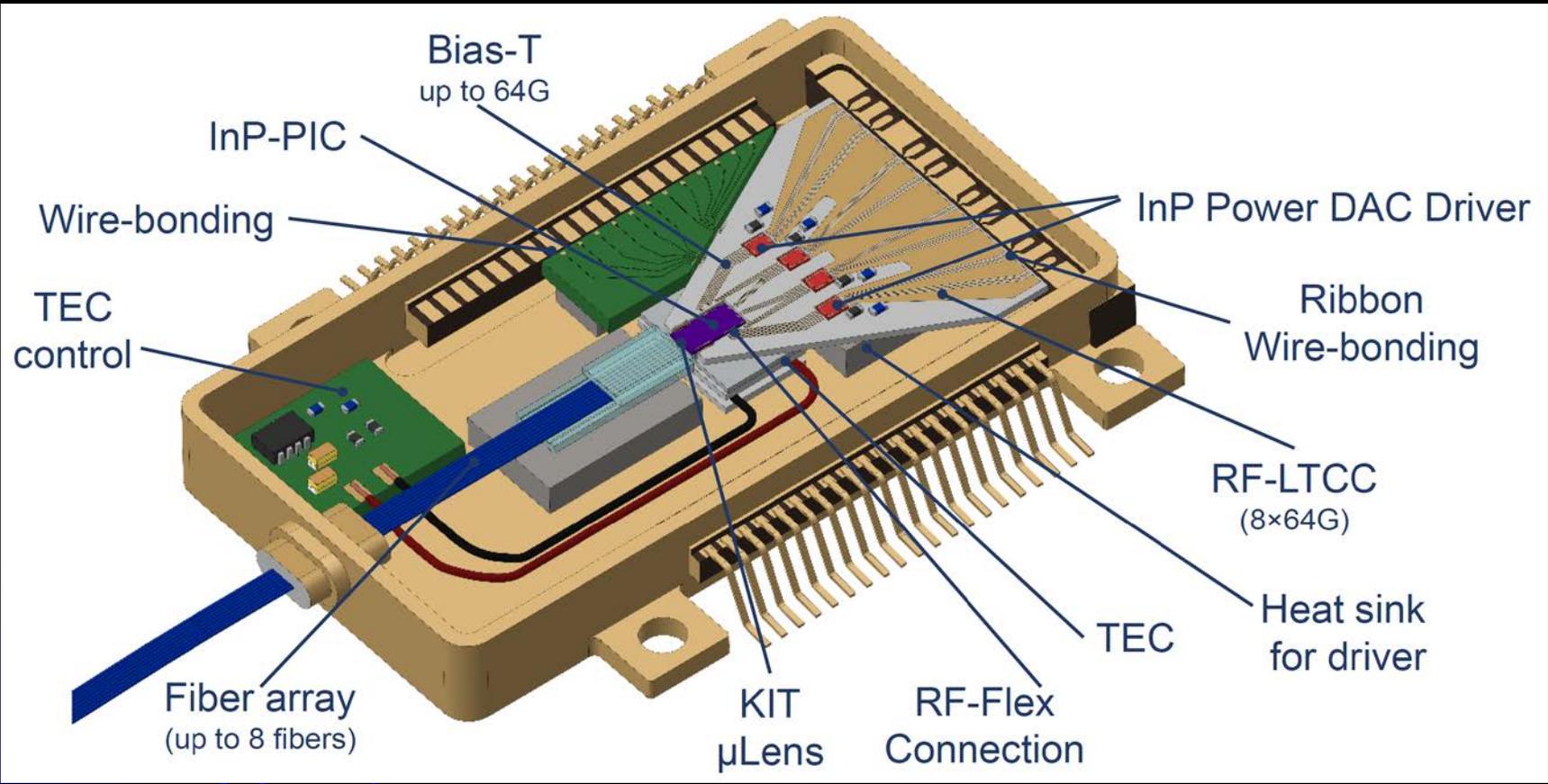
Integration of InP lasers and amplifiers on silicon substrates is key to reducing power consumption and cost as well as maximizing full scalability potential of silicon photonics PICs. Development is underway but formidable manufacturing challenges still remain.

Current PIC Challenges

- **Electrical connectivity and thermal management (heat dissipation of photonic circuits orders of magnitude larger than transistors).**
 - Resistive heaters necessary for photonics (optics can drift fast).
- **Without open-access foundries, very high costs for developing PICs – impacts companies & universities (dedicated runs versus multi-project wafer runs).**
 - Cost barrier for newcomers exploring PIC potential without major upfront investments.
 - Component test and packaging can add up to >60% of total cost!!
- **Packaging – no standards exist for these custom devices.**
 - Demand for high level of electronic-photonic integration results in complex packaging with control circuitry, amplifiers, and electronic drivers. Lack of digitalization and awareness of advanced packaging techniques.
 - Die processing varies (dicing, coating, etc.), assembly varies.
- **Light source integration (heterogeneous), fiber coupling (hybrid, heterogeneous, monolithic), alignment – all approaches are complex and must work at wafer scale.**
 - Wafer-level packaging and photonics-electronics integration – problem with overall yield and cost of the process.
- **Other issues depending on integration platform: high propagation losses, low optical power handling, and narrow transparency window.**

No single platform or technology exists to integrate, on a single chip, the entire array of photonic devices needed in various applications and fields.

Complexity of PIC Packaging (future NEPP research)



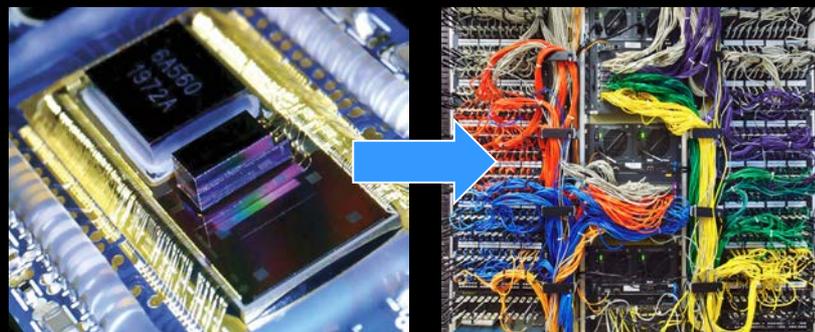
Understanding PIC packaging challenges is the next step for future NEPP FY21 work in this area – especially for the advancement of PIC technology for space applications.

Future Market Demand for Integrated Photonics

- Integrated photonics dominant technology for high speed communications driven by today's 100-400 Gb/s optical transceivers for telecommunications and datacenters.
- PICs offer scalable platform to meet BW challenges for next-gen telecom and datacom interconnects.
 - Cisco forecasts tripling of data center traffic by 2021 to >several billion terabytes/yr (Google, Amazon, Facebook, Apple, Microsoft using hyperscale data centers). By 2021, US data center energy consumption will triple (~2.5% of electricity in US, costing ~\$4.5B).
 - PIC market rapidly growing in parallel with data demand (>40% per year) (billions \$ by 2024).
 - Advanced coherent modulation formats enable higher data rates and more bandwidth. Silicon photonics-based coherent transceivers already commercialized.
 - Assembly process simpler, cheaper, more reliable than designs combining discrete optics.
 - PICs enable data centers to handle Tb-scale data rates with nanosecond switching speeds (using DWDM), consuming only half as much power, lowering costs. Supports 100 m to 10 km.

Current data centers can use up to 32 optical transceivers at 100 Gb/s for traffic between servers. Next-generation interconnects will need same number of 400 Gb/s chips to achieve quadrupling of capacity.

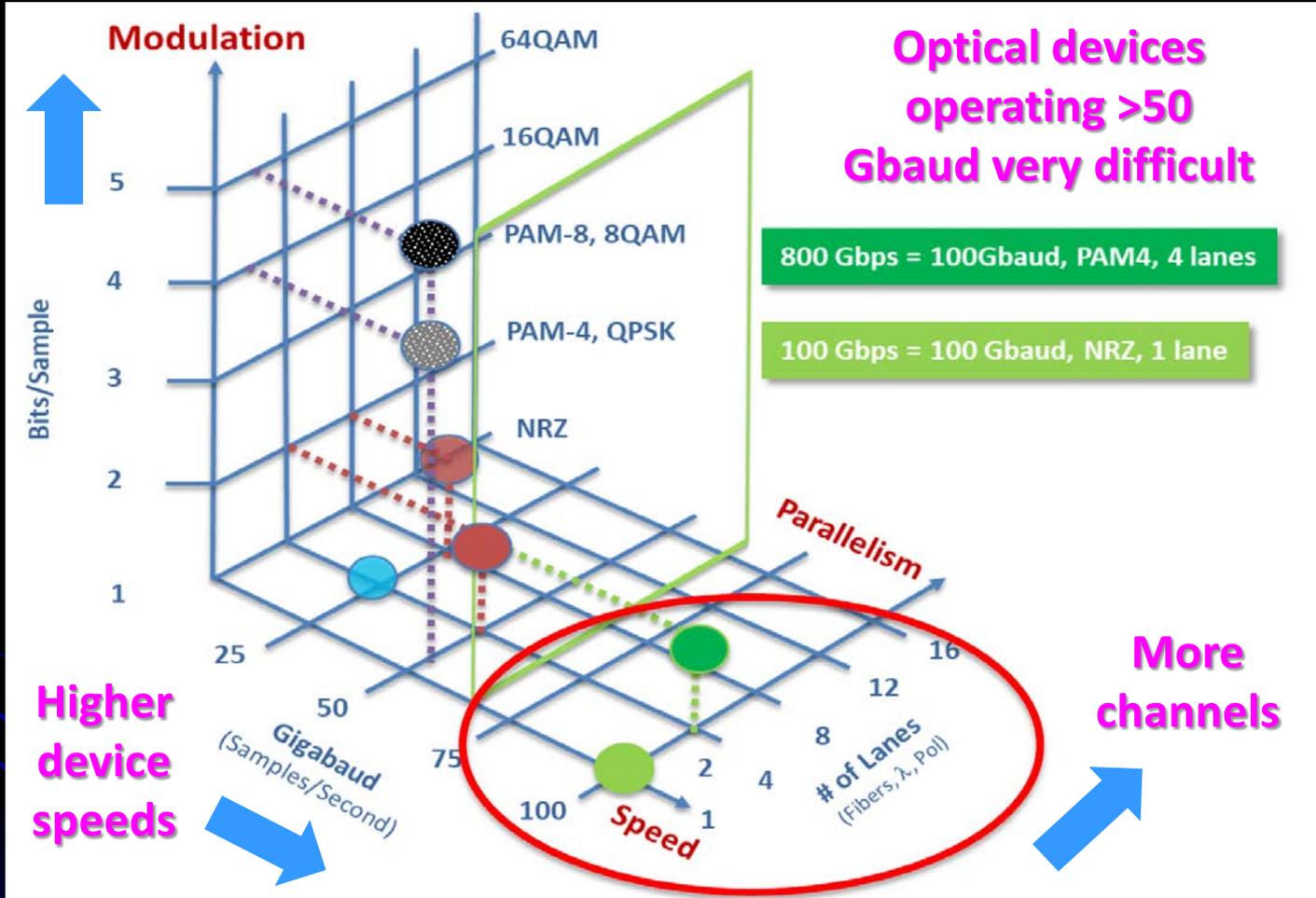
- If data demand increases fourfold, today's approach of using individual pluggable optical transceivers, with separate microelectronic switches, will not work.
- Traditional optics requires too much space and too many discrete components to achieve desired capacity.
- Solution: co-package integrated photonics & electronics.



Optical transceiver built using silicon photonics. Today, these PICs link servers together in data centers. In the future, the technology could connect chips or even sections of chips.

Limitation of Optics to Meet Future Need for Speed Demands

More info per bit



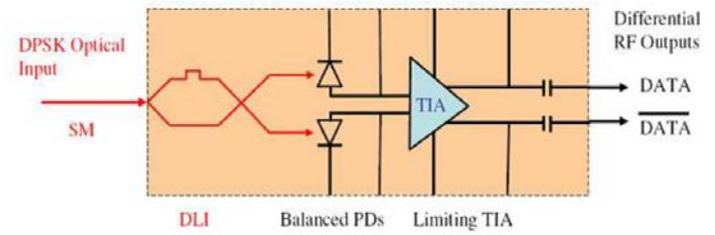
100 Gbaud devices break through green wall (representing speed limitation of optical devices)

Advanced Modulation Formats Driving Need for Integration

NRZ links only had a laser + a detector

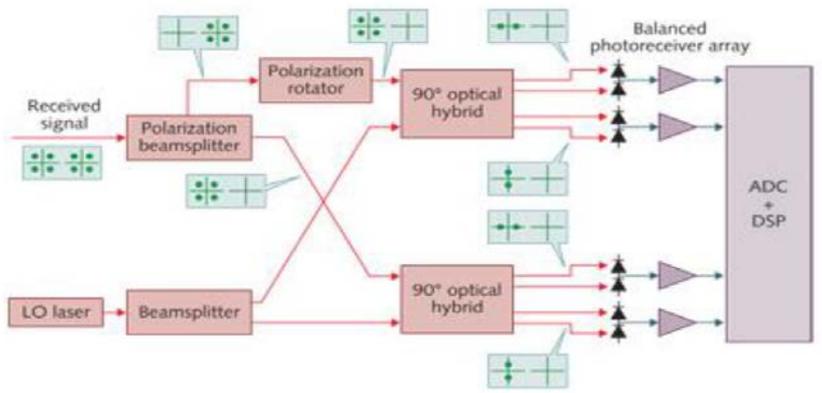


With 40G came DPSK, DQPSK, and ODB

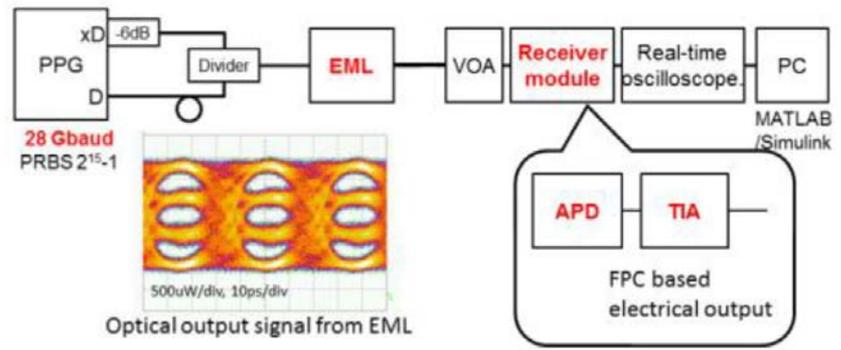


It all adds cost to the solution...

With 100G came DP-QPSK



And with 400GbE comes PAM 4

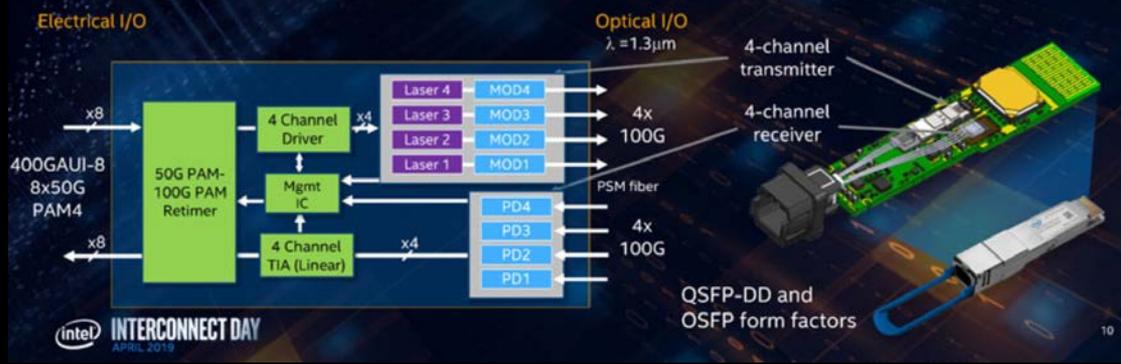


- Advanced modulation requires a lot of additional electronics for digital signal processing (DSP)
- Dramatic increase in transceiver electronics needed for PAM4
- Coherent modulation requires even more DSP

The Future of Integrated Photonics

400G DR4 SILICON PHOTONICS OPTICAL TRANSCEIVER

- 400G Ethernet connectivity for next-generation cloud data centers based on 12.8T Ethernet switches
- Standards-compliant optical interface with extended 2km reach for 400G or 4x100G breakout



Intel's PIC transceivers ("photonic engines") to be previewed in 2021: silicon chips with integrated lasers, modulators, photodetectors, drivers, and optics **co-packaged** with electronic switch ASICs. Demonstrated processing power of sixteen 100 Gb transceivers, or 4 of latest 12.8 Tb/s generation. Key to future switches at 51.2 Tbps.

Result is a compact, integrated, system with lower losses and better thermal management. Microsoft and Facebook also working on prototypes.

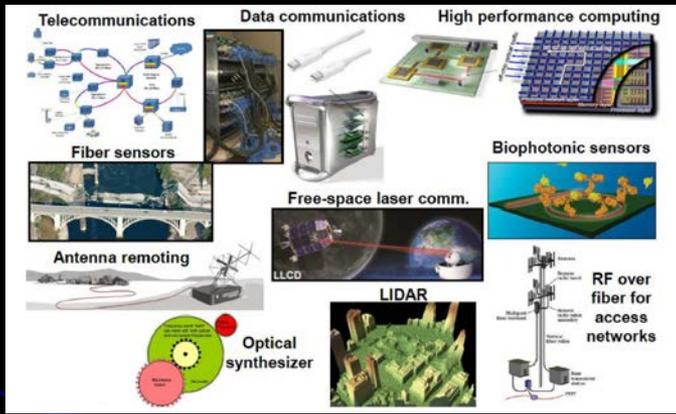
INTEGRATION DRIVES FORM FACTOR AND BANDWIDTH EVOLUTION

SHIPPING: 100G	NEW: 400G	FUTURE: OPTICAL INTEGRATION
100G PSM4 & CWDM4 MSA Pluggable	400G DR4 MSA Pluggable	High density integrated
First generation 100G Silicon Photonics	Next generation 400G Silicon Photonics	Silicon Photonics integrated for improved power, cost and bandwidth density

Technology development for miniaturization, high-temp operation, low power process

Evolution of Market – Growing PIC Application Areas

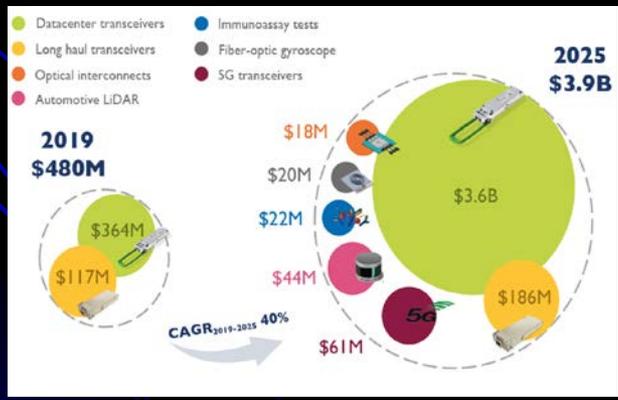
- Optical transceiver market (using integrated photonics) projected to grow 20X over next five years to accommodate needs of large data centers and 5G technology. Growth potential in need for faster communications and more computing power.
- Embedded computing capabilities, high level of integrated functionalities, low weight, power efficiency and hyper-scale performance expected to fuel future demand for PICs.



Communication applications key trends:

- Ongoing transition to higher network speeds
- Access networks migrating from DSL to Fiber
- 5G networks
- Ongoing rise in data traffic
- Increasing cloud based storage capacity (datacenters) required
- Transition to advanced coherent optical modulation formats
- Microwave/RF Photonics

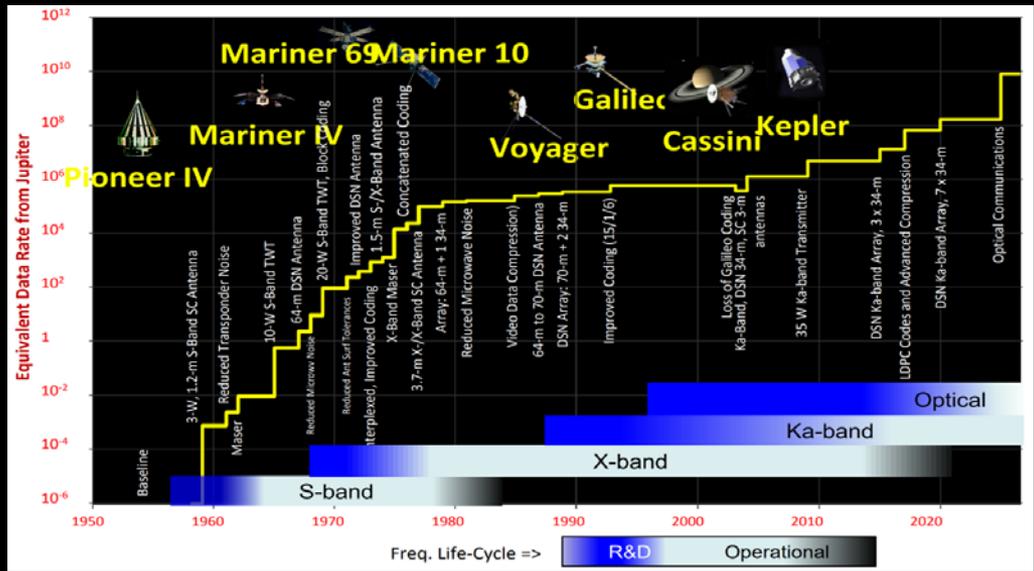
Large market demand for PICs beyond optical communications and data centers!



PICs also offer disruptive technology for wide range of markets: sensing, optical communications, and computing/optical signal processing solutions for healthcare, automotive, aerospace, machinery, energy, consumer electronics.

Optical Communications is Future of Space Communications

- NASA has moved space communications from S-band to X-band and Ka-band (100X faster) to meet growing demand for high volume data returns from science missions.
- Future demand for space applications will exceed capacity available in RF Ka-band (GHz) driving move to higher BW, unregulated/unconstrained optical comm spectrum (THz).
- With free-space optical (laser) communications NASA can realize data rates 10-100X better than RF (for same SWaP allocation) over both interplanetary and shorter near-Earth distances.
- With continued pressure on high data rates, performance, SWaP savings – move to optical regime is evident.



Integrated photonics is the disruptive, enabling technology to facilitate power efficient, high bandwidth optical communications for space, without increasing footprints and SWaP allocations to unsustainable levels.

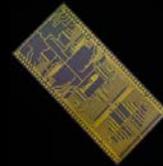
Real World Example – Integrated Photonics for Free-Space Laser Communications

- Free-space laser links used for satellite optical communications currently limited in modulation speeds due to high power-per-bit consumption of COTS optical transceivers.
- NASA project used 3D-monolithic integration of photonic structures (high-speed graphene-silicon PICs on CMOS electronics) to develop CMOS-compatible high-bandwidth transceivers for ultra-low power terabit-scale optical communications.
 - Demonstrated integrated graphene electro-optic modulator with 30 GHz BW.
 - Graphene microring modulators attractive solution for dense wavelength division multiplexed (DWDM) systems in future space applications.

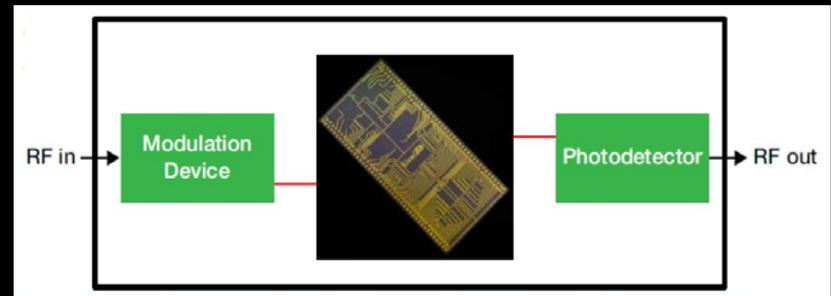


Real World Example – Integrated Photonics in 5G Networks and RF (Ka-Band) Satellite Communications

- Telecommunications industry experiencing 30% yearly growth rate, with parallel demand for faster and higher bandwidth data transfer.
 - For 5G networks, integrated photonics can satisfy data demand and minimize loss.
 - Loss during data transfer using an optical medium is only 0.2 dB per km – far less than conventional electrical cables.
- PICs enable GHz-precision RF signal processing capability. RF signals can be manipulated with high fidelity to add/drop multiple channels of radio across ultra-broadband frequency range.
- PICs can remove background noise from RF signals with unprecedented precision to increase SNR performance and lower power consumption. This high precision signal processing enables us to pack large amounts of info into small form factors for transmission of ultra-long distance radio communications.

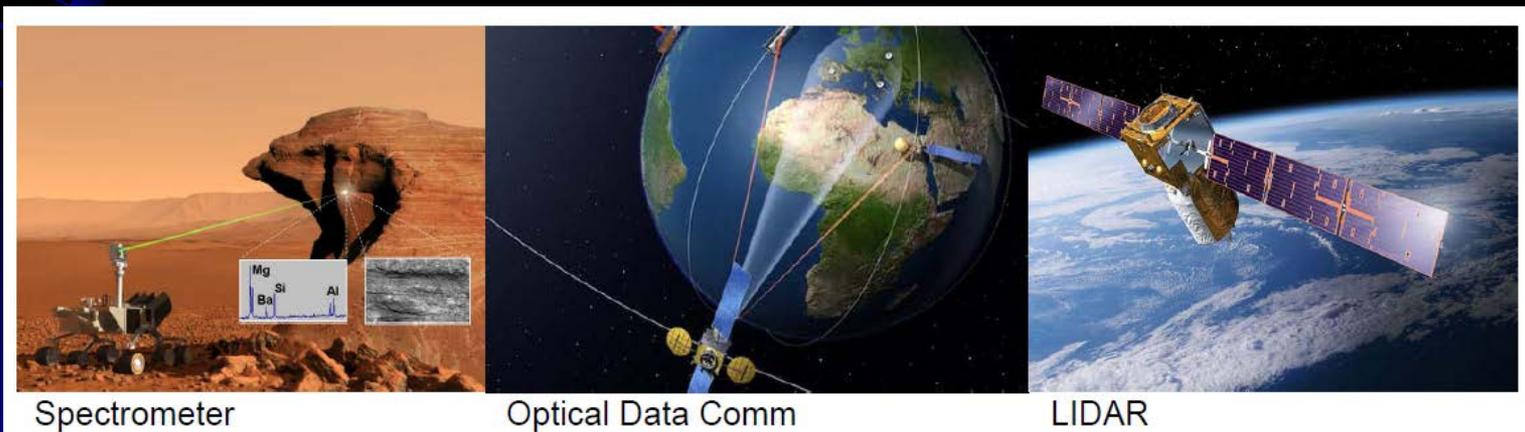


Microwave photonics: first fully integrated optical beamforming network (5G)



Future Space Applications for Integrated Photonics

- Next generation computing and free-space optical communications systems (inter-satellite or satellite-to-ground) enabling...
 - Spacecraft microprocessors, communication buses, processor buses, advanced data processing,
 - Broadband internet satellite connectivity, high bit-rate/spectrally efficient satellite links, high speed comm between deep space probes
- Scientific optical instruments on satellites or rovers (cameras, LIDAR, spectrometers)
- Signal distributions (MOEM-based switches, mixers, analog or digital optocouplers, intra-satellite communications)
- Sensing (i.e. star-trackers, gyroscopes, temperature, strain, metrology)



Current PIC Research Areas for NASA

Integrated photonics for space communications:

- “Ultra-Low Power CMOS-Compatible Integrated-Photonic Platform for Terabit-Scale Communications”
- “PICULS: Photonic Integrated Circuits for Ultra-Low size, Weight, and Power” – focused on high-performance InP PICs and hybrid integration of InP lasers/PICs with silicon photonics
- “Integrated Photonics for Adaptive Discrete Multi-Carrier Space-Based Optical Communication and Ranging”
- “Integrated Optical Transmitter for Space Based Applications” – based on InP platform and includes a tunable laser, Semiconductor Optical Amplifier (SOA), high-speed Mach-Zehnder Modulator (MZM), and electro-absorption (EAM) modulator

Integrated photonics for space sensors:

- “Multifunctional Integrated Photonic Lab-on-a-Chip for Astronaut Health Monitoring” – consists of miniaturized lab-on-a-chip device to directly monitor astronaut health during missions using ~3 drops of body fluid sample like blood, urine, and potentially other body fluids like saliva, sweat or tears. First-generation system comprises of miniaturized biosensor based on PICs (including Vertical Cavity Surface Emitting Laser, photodetector and optical filters).
- “PIC Spectrometer-on-a-Chip”.

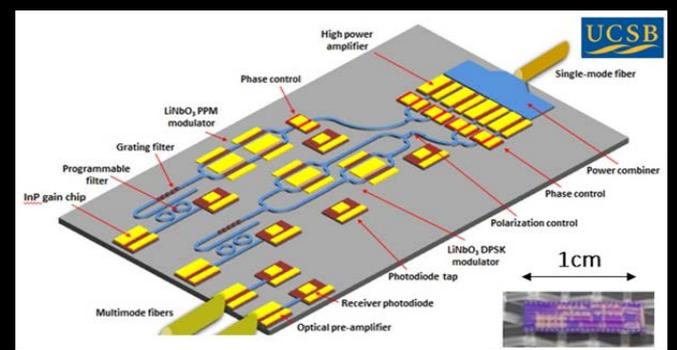
Integrated photonics for analog RF applications:

- SiN PIC suitable for a spectrally pure chip-scale tunable opto-electronic RF oscillator (OEO) that can operate as a flywheel in high precision optical clock modules, as well as radio astronomy, spectroscopy, and local oscillator in radar and communications systems is needed.

Overview of NEPP FY20 Work

- **Problem Statement:** Space requirements are demanding in terms of high peak-to-average power, high extinction ratio, radiation, lifetime reliability (including temperature) and stability. Current state-of-the-art integrated photonic chips are only designed and qualified for terrestrial communication systems in commercial applications as well as academia. As a result, risks associated with reliability of PICs in space environment not well understood.
- **Solution:** Develop, test and validate novel mission assurance methodologies for screening and qualifying a commercial photonic-integrated laser transmitter (PILT) for reliable operation in space applications.
- **Importance to NEPP:**
 - Position NEPP as leader in development and qualification of advanced integrated photonics for space.
 - Fill knowledge gap on methods for reliability screening and qualification of integrated photonics for space not addressed by Telcordia standards.
 - Reduce risk of flight insertion of integrated photonics into NASA space applications, enabling order of magnitude improvements in SWaP-C and performance.

Overall Objective: bridge technology gap between academic research and flight prototype development of integrated photonics. Seek to combine radiation and reliability screening of PIC research pathfinders with performance characterization in optical links to distill a prototype solution with path to flight. Finally, we seek to establish guidelines for the qualification of PICs for future space applications.

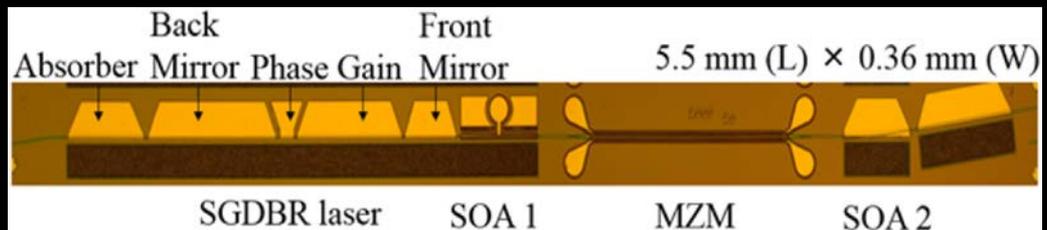


Technical Approach

The team: Amanda Bozovich (JPL), Dr. Alireza Azizi (JPL), Chuck Barnes (JPL), Cheryl Asbury (JPL), Greg Allen (JPL), Sergeh Vartanian (JPL), Professor Jonathan Klamkin (UCSB), Sergio Pina (UCSB)

- 1) UCSB has fabricated and designed custom PIC pathfinder and testbed. Professor Klamkin's group is NASA-funded to produce low-SWaP integrated micro-photonic circuits for space-based applications.
- 2) Evaluate radiation hardness of baseline (generation 1), InP PIC laser transmitter. Will examine radiation-induced damage as a result of Total Ionizing Dose (TID), Displacement Damage (DD), and Single Event Effects (SEE).
- 3) Sample test structures provided by UCSB and evaluated at discrete and integrated levels.
- 4) Objective is to quantify amount of expected radiation degradation (for a typical NASA mission), identify potential failure modes/sensitive regions/materials within the integrated chip, and determine root cause. This will include quantification of key performance parameters impacted by radiation.
- 5) From there, we will work to standardize analytical tools and test protocols for defining failure mechanisms in commercial PIC technologies as well as define risk mitigation strategies for use of advanced PICs in space applications.
- 6) Based on results of simulations, testing, and analysis, we will establish PIC qualification guidelines. We will leverage existing Telcordia standards for discrete photonic components and the body of knowledge for individual chip materials.
- 7) Future work: perform design iterations based on findings and provide feedback to UCSB for development of a highly reliable, flight-qualifiable custom PILT.

FY20 focus: radiation characterization of indium phosphide (InP)- based photonic integrated laser transmitter from UCSB



Planned NEPP PIC Radiation Testing FY20

1) Total Ionizing Dose

- Performed at integrated level (discrete testing if one or more monitored parameters observed to degrade and/or fail)
- Measure emitted optical power, laser emission spectrum, current-voltage characteristics
- Will analyze shift in emitted wavelength peak for different laser operating conditions (i.e. vary injected current). Expect generation of e-h pairs to vary refractive index of gratings in DBR laser structure, resulting in wavelength shift.

2) Displacement Damage (DD)

- Most proton/electron DD testing for semiconductor lasers has been focused on Fabry-Perot, Distributed Feedback (DFB), and Vertical Cavity Surface Emitting lasers (VCSEL).
- For tunable DBR lasers, most sensitive parameter to lattice displacement damage is carrier lifetime, which can increase the lasing threshold (including slope efficiency). Carrier removal and change in doping concentration can result in loss of output power. Internal absorption less likely in short cavity lasers.
- Will conduct room temperature irradiation, and measure lasing threshold in-situ as function of proton fluence. Will monitor received power as function of phase and Bragg current (power plane) to record changes in lasing mode structure/position of mode boundaries. If mode pattern remains unchanged, we can assume, despite change in laser efficiency, DD effects do not impair tunability of the laser.
- Electron testing and temperature dependence studies to be performed in future.

Planned NEPP PIC Radiation Testing FY20 Cont...

3) Single Event Effects (single event transients or SET)

- Heavy ion-induced SET effects can potentially change optical properties of photonic waveguide portion of the PIC (electron-hole pair density, refractive index, and absorption coefficient can change affecting polarizability of waveguide material and result in free carrier absorption).
- Objective is to measure optical signal power loss (with dominant power loss mechanism being free-carrier absorption) and phase shifts (which can occur as excess carriers recombine) at output of waveguide as a function of linear energy transfer (LET).
- Will consider displacement damage as a result of heavy ion exposure, which can potentially result in more permanent degradation in the optical power transmission.
- Aside from optical transmission loss, we will examine heavy-ion induced transient phase shifts, which can compromise information stored in the phase of the electric field (resulting from free-carrier dispersion changes in the refractive index of the waveguide material). When the phase modulation is converted into intensity modulation by MZM, phase change in one arm with respect to other can lead to transient change in modulator output power.
- This will allow us to examine changes in the transmissive properties of the waveguide over time during a heavy ion strike event (at various energies). We will be able to plot peak transmission loss and peak phase shift as a function of LET upon completion of the test.
- Future work, will include circuit level testing to study aggregate effect integrated photonic and electronic devices connected together (i.e. MZM modulator with integrated electronic drivers).

NEPP PIC Qualification Challenges

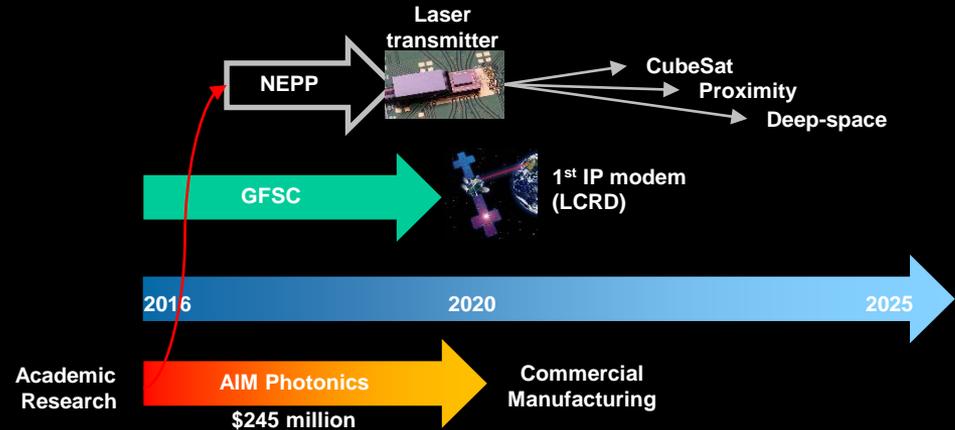
- **Many unknowns – materials, process, performance (complexity):**
 - Unlike bulk CMOS, used for silicon electronics, there is no single material suitable for all integrated photonics applications (we discussed several integrated material platforms)
 - Lack of statistically significant radiation, reliability and lifetime data for COTS-based photonics
 - Radiation tolerance
 - Failure modes and mechanisms
 - Environmental temperature limits for operation and storage
 - Lack of physics models on which to base design of reliability tests/accelerated life tests
 - Lack of standards in component selection, design, fabrication of highly reliable integrated photonics for space
 - PIC design challenges in generating Watt-level outputs needed for optical communications in space applications
- **Packaging unknowns:**
 - Effect of packaging design on functional performance, radiation effects and reliability
 - Sensitivity to launch environments (e.g. shock, vibration, thermal cycling)
 - Sensitivity to outgassed materials
- **Other issues:**
 - Difficulty diagnosing optical train problems in PICs due to small physical size
 - Potential CTE mismatch problems with higher levels of integration
 - Integrated platform must be designed to operate at high optical power levels while maintaining performance uncooled over wide temp range (<-40°C to +100°C) for DSOC

NEPP Integrated Photonics : Impact and Summary

Impact of NEPP PIC work...

- Demonstrate feasibility of commercial PIC technology with path to flight from tech demo to high reliability mission (i.e. Mars2028 will require high optical power output and long lifetime).
- Define challenges impacting development and integration of PICs for space applications – understand risks associated with mission specific environments (radiation, reliability).
- Demonstrate scalability of photonic building blocks to enable complex on-chip optical signal processing for various purposes (e.g. laser altimeters, interferometers, LIDAR). Spin-offs will directly benefit other optical instruments and NASA mission science applications.
- Address NASA needs for space communications applications. Potential to augment other optical science capabilities.

Trends in optical communications



PICs are brand new technology with imminent commercialization

Summary of NEPP Goals:

Establish library of figures of merit for selecting and qualifying commercial PICs for future space applications. Document screening and space qual methods in the form of guidelines.

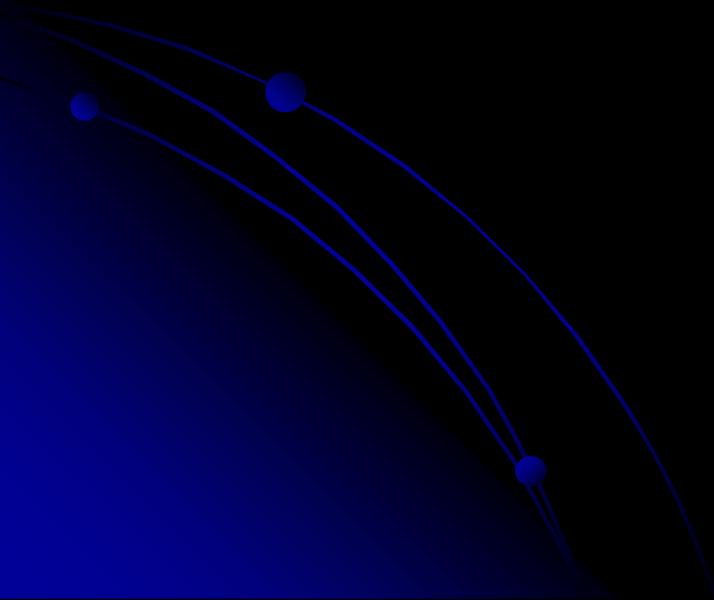
- Identify/execute diagnostic reliability and radiation tests
- Compare results to state-of-art commercial (discrete and integrated photonics)
- Identify potential radiation and reliability risks based on industry survey, test, and analytical modeling of commercial PICs (packaging)
- Study impact on link performance
- Expand collaboration in FY21 (many interested parties)



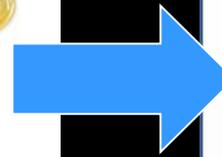
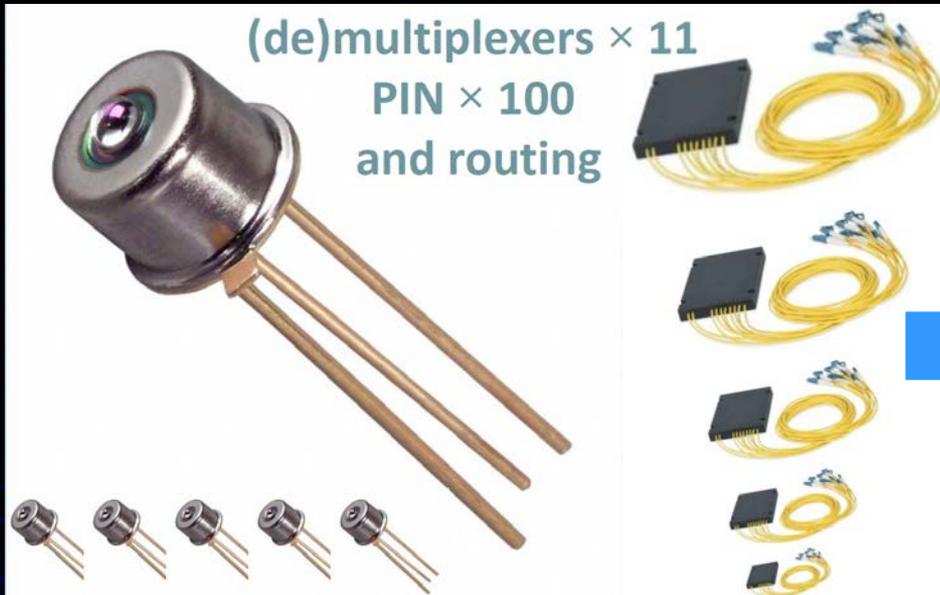
Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov

BACKUP



Example Photonic Integrated Circuit (PIC)



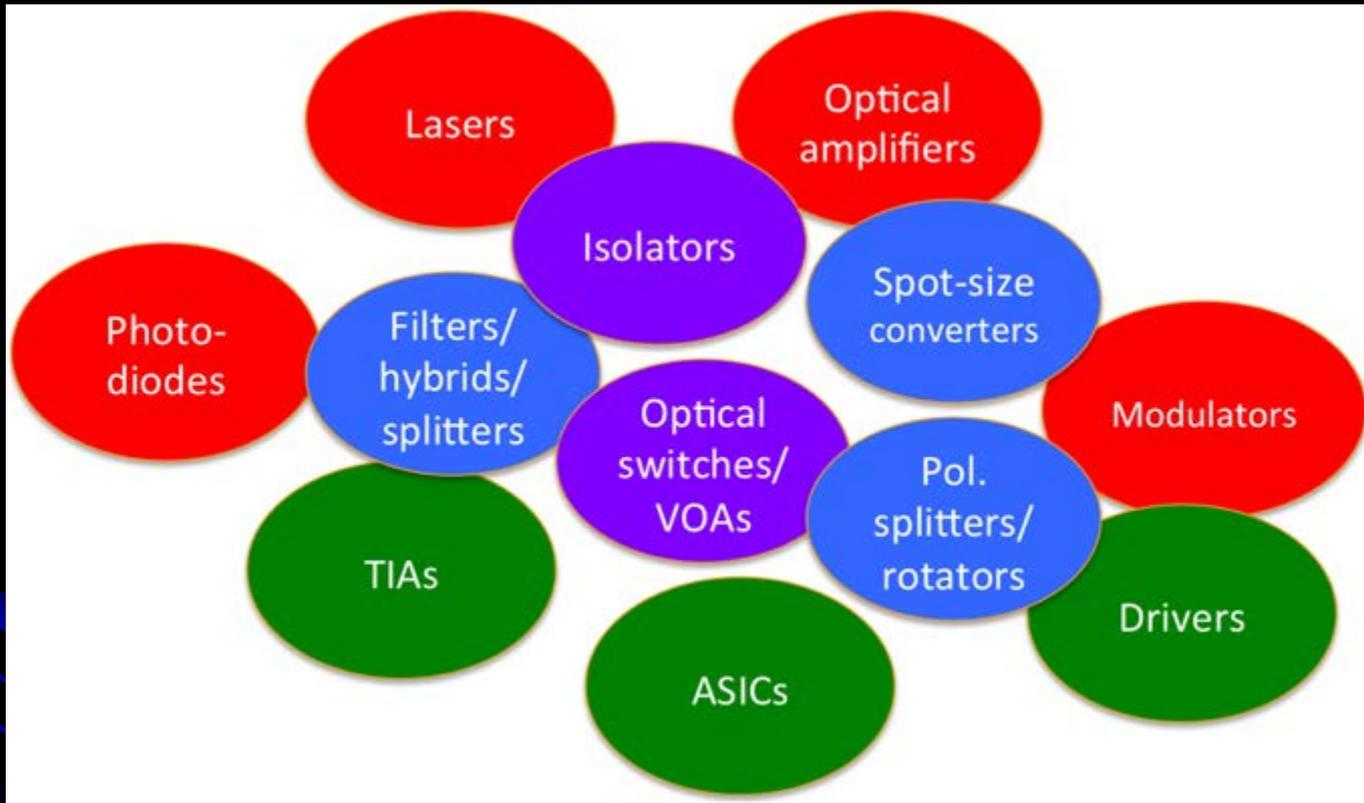
Single Photonic Integrated Circuit

6 mm × 8 mm
FBG sensor unit

BRIGHT Integrated PHOTONICS
Fraunhofer Heinrich Hertz Institute

This block contains a photograph of a single photonic integrated circuit (PIC) unit. The unit is a small, rectangular device with a complex, multi-layered internal structure visible through a transparent window. It is mounted on a printed circuit board. To the right of the image are the logos for BRIGHT Integrated Photonics and Fraunhofer Heinrich Hertz Institute.

Integrated Photonics Components

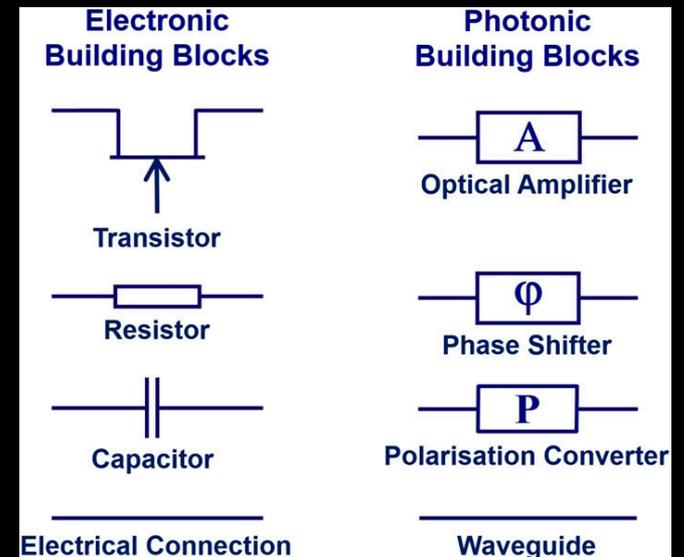


Photonic Integrated Circuits vs Electronic Integrated Circuits

- Development of photonic and microelectronic integration follows similar path, with 25-30 year delay for photonics.
- Photonic active building blocks (i.e. optical amplifiers, modulators) larger than microelectronics and operate at much higher power levels than transistors.
- Footprint of active components comparable (considering waveguide area vs transistor circuits). Electronic driver areas dominated by passives (i.e. resistors, capacitors, I/O connections). Photonic circuits include redundant chip area for cross-talk mitigation, waveguide bends, electrical connections.
- Comparisons for high performance active photonic devices closer to RF/analog electronics, considering design flow and numbers of integrated components.
- Important difference in operational capacity and technology maturity: higher wafer throughputs for electronic circuit manufacturing enables faster learning curve when introducing new technology nodes.
- Nanophotonics offers order of magnitude power level and footprint reduction. Both critical as designs become thermally constrained.

	Electronics	Photonics
Invention of key component (transistor/semiconductor laser)	1947	1969
Semiconductor integration technology	1958	1987
Generic integration technology (MPWs)	1979	2008
Killer random defect densities reported $<1 \text{ cm}^{-2}$	1987	2010

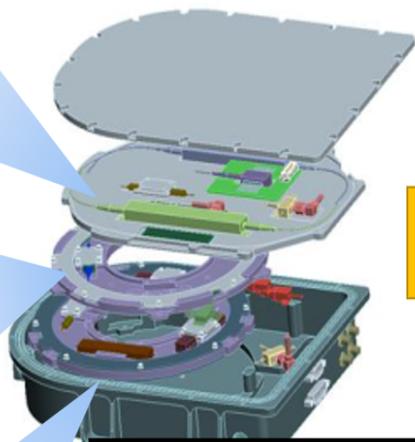
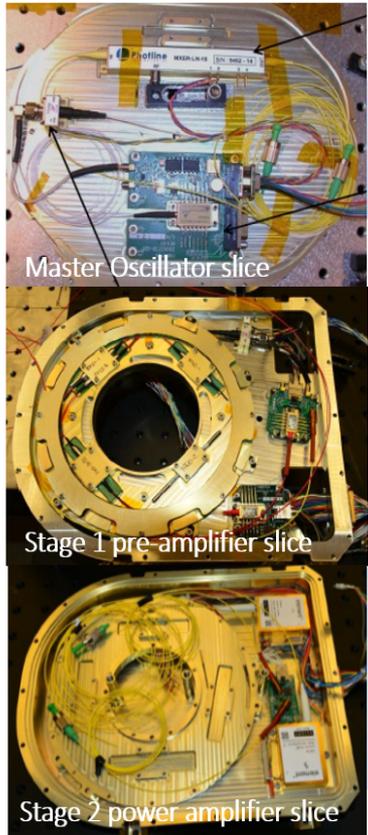
Same evolution path as electronics: aggregate multiple components of a system into a single monolithic chip.



Integrated Photonics Advantages

Fiber-based Transmitter

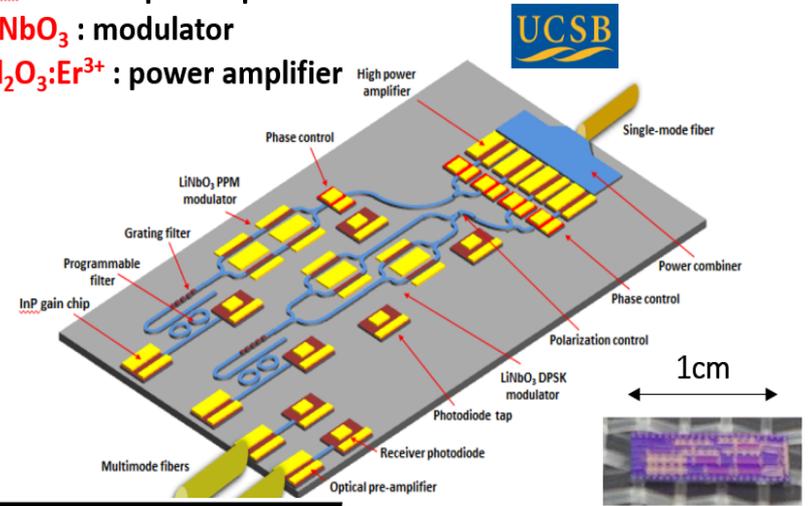
DSOC Laser Transmitter assembly



Photonic Integrated Transmitter

Integration platforms chosen for best device performances

- **InP** : laser & pre-amplifiers
- **LiNbO₃** : modulator
- **Al₂O₃:Er³⁺** : power amplifier



	Discrete	Integrated
Size and Weight	8" x 10" x 2.12", 3.4kg	2" x 0.5" x 0.25", 0.2kg
Robustness/Stability	Large footprint, fibers	Small footprint
Redundancy	Possible (SWaP limited)	"Unlimited" (at no cost)
Functionality (Modulation)	Single (PPM)	Multi (PPM, DPSK)
Output Average Power	6W	1W (in progress)
Performance	Mature	Under development
Environmental Testing	Mature	Unknown yet

Miniaturization, integration and scalability designed to optimize performance and emphasize SWaP savings.

High Level Functionality Overview

property	A InP	B Sol	C Si3N4	D SiO2	E LiNbO3	F Polymer
1 Loss	medium	medium	good	good	medium	medium
2 Optical amplification	good	challenging/no	challenging/no	challenging/no	challenging/no	challenging/no
3 Photodiodes	good	good	challenging/no	challenging/no	challenging/no	challenging/no
4 Fiber coupling	medium	medium	good	good	good	good
5 Spectral range	medium	medium	good	good	good	good
6 Polarization indep.	medium	challenging/no	medium	good	challenging/no	good
7 RF modulation	good	good	challenging/no	challenging/no	good	good
8 CMOS compatible	challenging/no	good	good	good	challenging/no	challenging/no
9 Durability	good	good	good	good	good	challenging/no
10 Footprint	good	good	good	medium	medium	medium
11 All-in-one	good	medium	medium	challenging/no	challenging/no	challenging/no
12 MPW	good	good	good	challenging/no	challenging/no	challenging/no



Tx, RX
All-in-one

True time delay
Microwave
photonics

Telecom Tx
RF modulators

Data centers
4x25 Gb
High volume

High quality
passives
De-MUX
splitters

Modulators
Cheap hybrids

Comparison of Integrated Photonics Technology Platforms

Most Versatile Platforms

Building Block	InP	SiPh	SiN	Glass	Polymer	Silica	LiNbO3
Passive components	++	++	+++	+++	+++	+++	Hybrid
Polarization components	++	++	++	+	+	Hybrid	Hybrid
Lasers	+++	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid
Modulators	+++	++	+	Thermal	+++	Hybrid	++++
Switches	++	++	+	+	+	+	Hybrid
Optical amplifiers	+++	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid
Detectors	+++	++	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid
PROs	<ul style="list-style-type: none"> Best for laser/active integration 	<ul style="list-style-type: none"> Best for electronic/optical integration Smallest size 	<ul style="list-style-type: none"> Low cost Small size 	<ul style="list-style-type: none"> Simple process, low cost 	<ul style="list-style-type: none"> Compatible with Si/InP platform 	<ul style="list-style-type: none"> Low losses Low cost 	<ul style="list-style-type: none"> Very good modulation function
CONs	<ul style="list-style-type: none"> Wavelength limited to 1.3 μm to 1.7 μm Higher cost in large volume production Complex Epi 	<ul style="list-style-type: none"> Difficult to get light in and out 	<ul style="list-style-type: none"> Material properties are process dependent 	<ul style="list-style-type: none"> Few functions are possible 	<ul style="list-style-type: none"> Reliability / thermal management issues 	<ul style="list-style-type: none"> No active functionalities 	<ul style="list-style-type: none"> Low damage threshold
INDUSTRY STATUS	RAMPING UP	HIGH VOLUME	LOW VOLUME PRODUCTION	PRE-SERIES	R&D/ QUALIFICATION	HIGH VOLUME	HIGH VOLUME

Enabling Future Disruptive Technologies

Applications		Long haul telecom	DATA CENTER INTERCON-DCI (intra, metro, submarine, long haul)	5G WIRELESS ACCESS NETWORK	Automotive interconnects	Sensors	Medical
Examples of products		Coherent optical transceivers AWG Modulators	Optical transceivers (100G/400G) Embedded optics (200G) Switches Splitters	Optical transceivers (28G)	Optical transceivers for intra car interconnects (antennas to compute / entertainment system)	Lidars Gas sensors	OCT Blood analysis
Typ. wavelength		1310 – 1550 nm	1310 – 1550 nm	1310 – 1550 nm	700nm+	900 – 7000+nm	400 – 1500 nm
Main PIC platforms	SiPh						
	InP						
	SiN						
	Polymer						
	Glass						
	Silica						
	LiNbO3						

PICs offer capabilities to advance numerous revolutionary applications ranging from immersive consumer technologies (virtual reality), LIDAR for autonomous driving (low latency), and medical imaging devices/biophotonics (i.e. medical instrumentation, analytics & diagnostics, optical biosensors, medical photonic lab-on-a-chip) while continuing to meet growing demand for energy-efficient optical links for datacenters and quantum computers.

Comparison of InP vs Silicon Materials for PIC Design

InP	Si
<p>Expensive material</p> <ul style="list-style-type: none"> • In is scarce 	<p>Cheap material</p> <ul style="list-style-type: none"> • 27% mass Earth's crust is Si
<p>Medium yield</p> <ul style="list-style-type: none"> • W.g. material from epitaxy 	<p>High yield</p> <ul style="list-style-type: none"> • W.g. material from original boules
<p>Small footprint</p> <ul style="list-style-type: none"> • High index contrast in 1D 	<p>Extremely small footprint</p> <ul style="list-style-type: none"> • High index contrast in 2D
<p>Native laser</p>	<p>No native laser</p>
<p>Poor native oxide</p>	<p>Excellent native oxide</p>
<p>Low dark current</p>	<p>Medium dark current</p>
<p>Small wafers (75 mm typ.)</p> <ul style="list-style-type: none"> • 75 mm typical • Brittle material 	<p>Large wafers (300 mm typ.)</p> <ul style="list-style-type: none"> • 300 mm typical • Strong material
<p>Modulator temperature sensitive</p> <ul style="list-style-type: none"> • Band edge moves with temperature 	<p>Modulator temperature insensitive</p> <ul style="list-style-type: none"> • Carrier density not v. temp. dep.

Comparison of SiN vs Silicon PICs

	SOI	SiN	
Spectral transparency: shortest λ	1.1 μm	0.4 μm	Silicon bandgap
Spectral transparency: longest λ	4 μm	4 μm	SiO ₂ absorption
Optical power limitation (1.3/1.5 μm)	10's of mW	W (thick film)	Two-photon absorption
Distributed backscatter	%'s per cm	$\div 10$	nm-level sidewall roughness + HIC
Optical path length error	0.1% - level	$\div 10$	nm-level width inaccuracy + HIC
T-sensitivity of path length	0.01%/K	$\div 10$	Thermo-optic coeff. silicon
Layer stack flexibility	Limited	Excellent	SOI-wafers made by bonding

SiN Benefits:

- ✓ High mode confinement (90% light confined in SiN waveguide)
- ✓ Low loss (<0.1 dB/cm)
- ✓ Small chip size
- ✓ VIS to IR
- ✓ High yield
- ✓ High optical power (Watts)

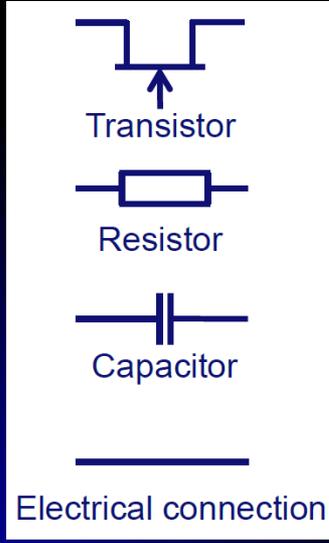
Materials for Integrated Photonic Platforms

Material	Maturity	Density	Complexity	Chips per wafer	Foundries	MPW	Laser
SiO ₂ (PLC)	High	Low	Low	Low/Medium	Few	No	Hybrid
SiO _x N _y	High	Medium	Low	Medium	None	No	Hybrid
Si ₃ N ₄	High	M/H	Medium	Medium/High	Few	Yes	Hybrid
Silicon	High	High	High	High	Several	Yes	Hyb./Heter./Monol.
InP	High	Medium	High	Medium	Several	Yes	Yes
GaAs	High	Medium	Low	Medium/High	Few	No	Yes
LiNbO ₃	High	Low	Low	Low	None	No	No
Polymers	High	Low	Low	High (roll-to-roll)	Few	No	Hybrid
Chalcogenides	Low	Medium	Low	N/A	None	N/A	No
Germanium	Low	M/L	Low	N/A	None	N/A	No
SiC	Low	High	Low	N/A	None	N/A	No
Diamond	Low	High	Low	N/A	None	N/A	No

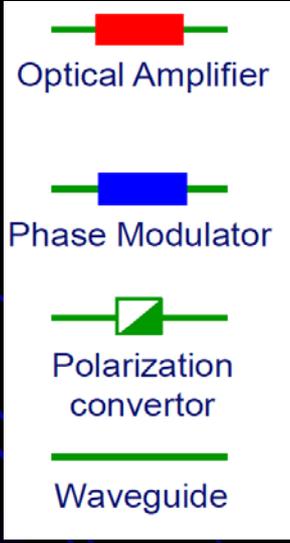
- Major waveguide platform technologies today: Indium Phosphide (InP)-based monolithic integration and Silicon Photonics (silicon-on-insulator or SOI wafers).
- Silicon and InP platforms highest complexity and integration level.
- Both processes have high propagation and fiber coupling losses, but silicon devices typically much shorter, with smaller footprint.

Generic Integration Platform for PICs

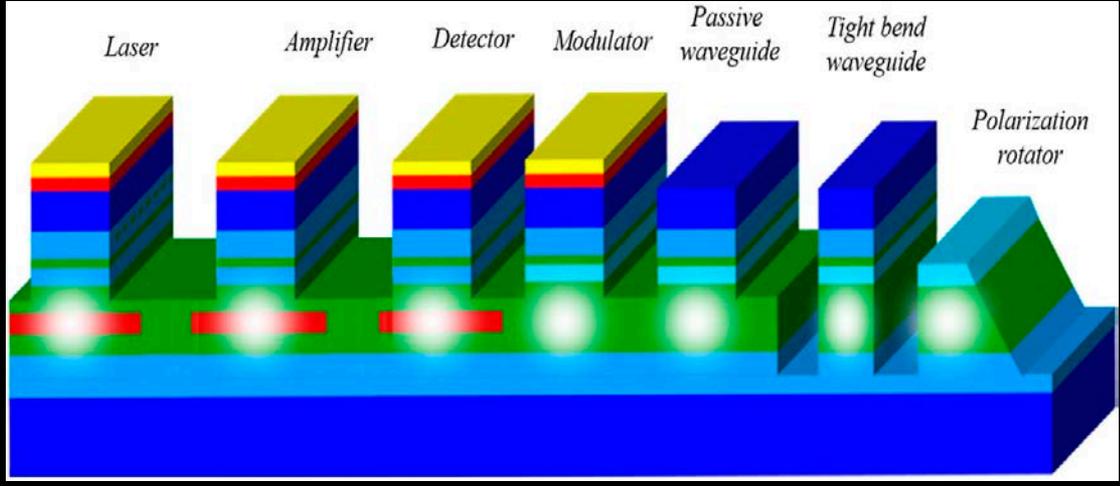
- Continued advancement of PICs into new sectors depends on development of highly standardized (generic) photonic integration platforms.
 - Offer designers small set of well-defined standardized/generic building blocks to design broad range of application-specific PICs (lowers risk).
 - **Multi-Project Wafer (MPW)**: multiple projects on single wafer to share fab costs and improve technology independent of design (not suitable for production – cannot tailor process or building blocks).
 - **Dedicated Runs**: higher cost, customize process and performance, quicker fab and cycle times, design and fab more complex – higher risk.



Electronic Blocks



Photonic Blocks



Like electronics: use photonic building blocks, separate design from process. Open-access InP platforms enable monolithic integration of many optical functions.

Integrated Photonics Fabrication Options

Generic process

- Low cost
- Shorter fab time
- Average performance



Custom process

- Expensive
- Longer fab time
- Optimal performance

MPW run

- Low cost
- Longer fab time
- Restricted options
- Few dies

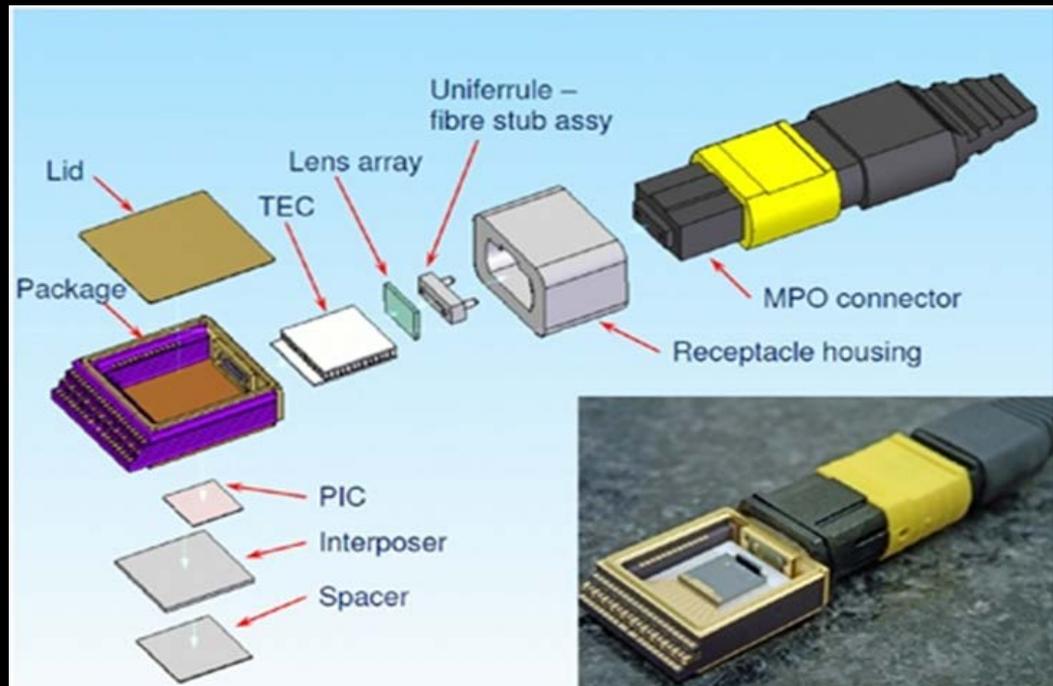


Dedicated run

- High cost
- Shorter fab time
- More options
- Many dies



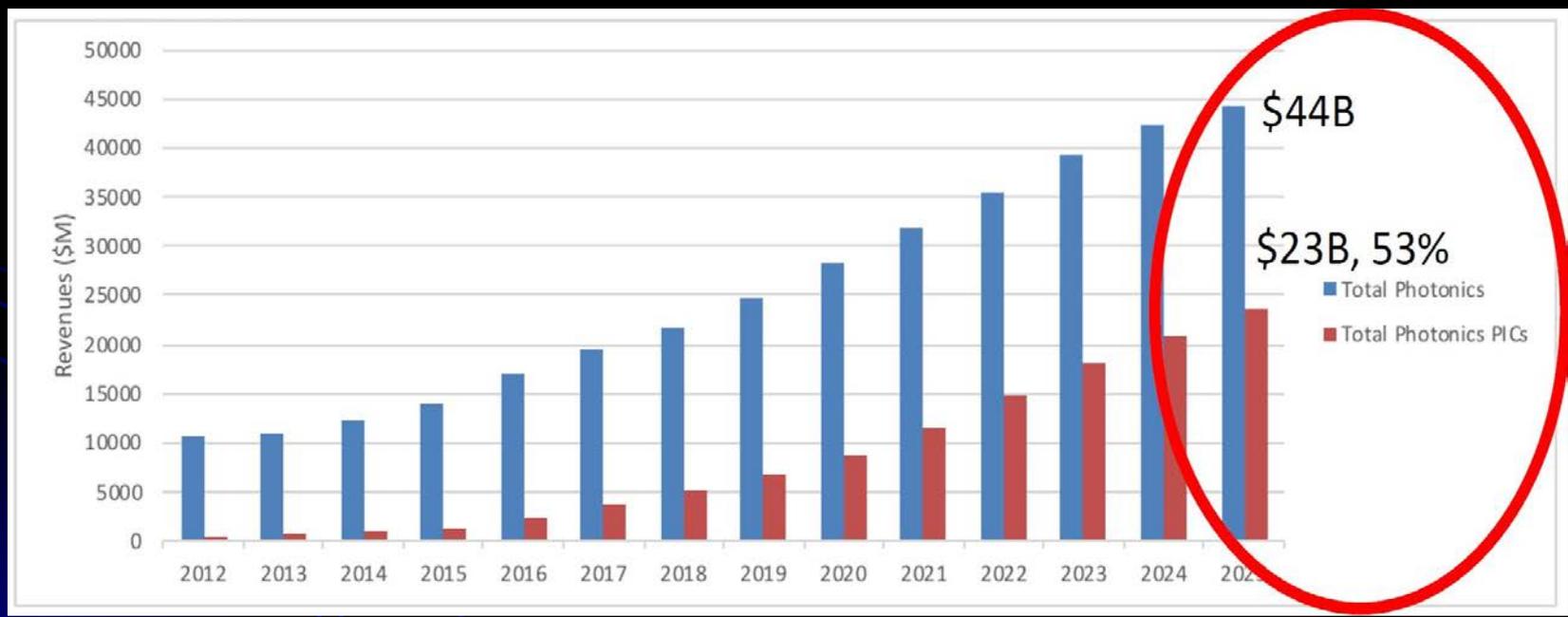
Generic PIC Packaging



- Micro lenses used for optical coupling; electrical coupling with wire bonding.
- Hybrid integration approach: light coupled from chip-to-chip to combine active structures (i.e. for Si-Ph and Silicon Nitride PICs).
- Alternative to wire bonding is flip-chip bonding (flipped electrical circuit bonded to top-side of PIC). Allows for higher integration density since the vertical electrical contacting does not suffer from limitations of wire bonding, where the wires are typically connected to a printed circuit boards at the side of the chip.

Future Growth of PIC Market

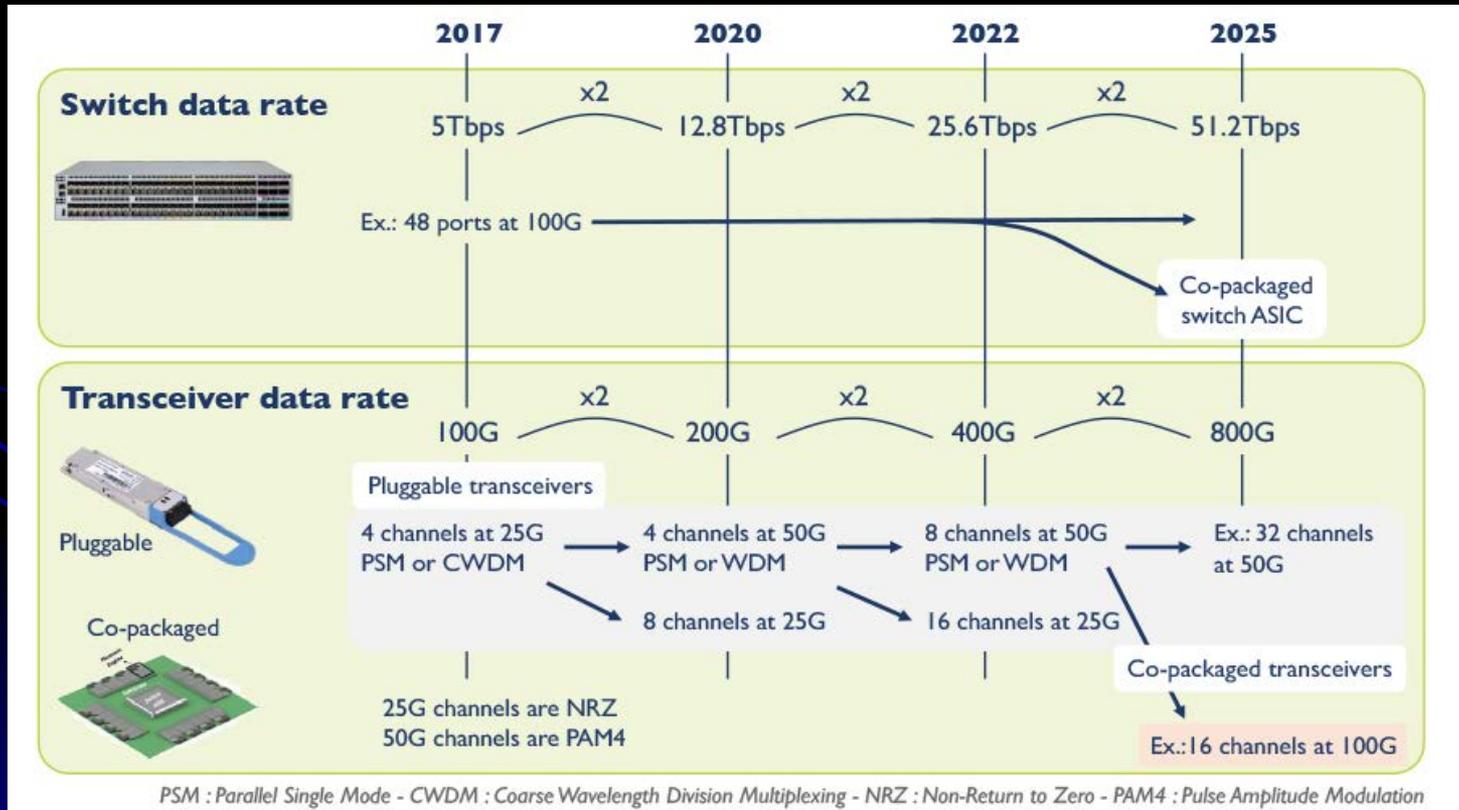
- PIC market rapidly growing: ~\$190M in 2013, ~\$539M in 2017, several billion dollars by 2024.
- Last year, shipments of silicon photonic transceivers for datacenters reached 3.5 million units (revenue ~\$364M) – impressive growth since introduction into market was only mid 2010’s.



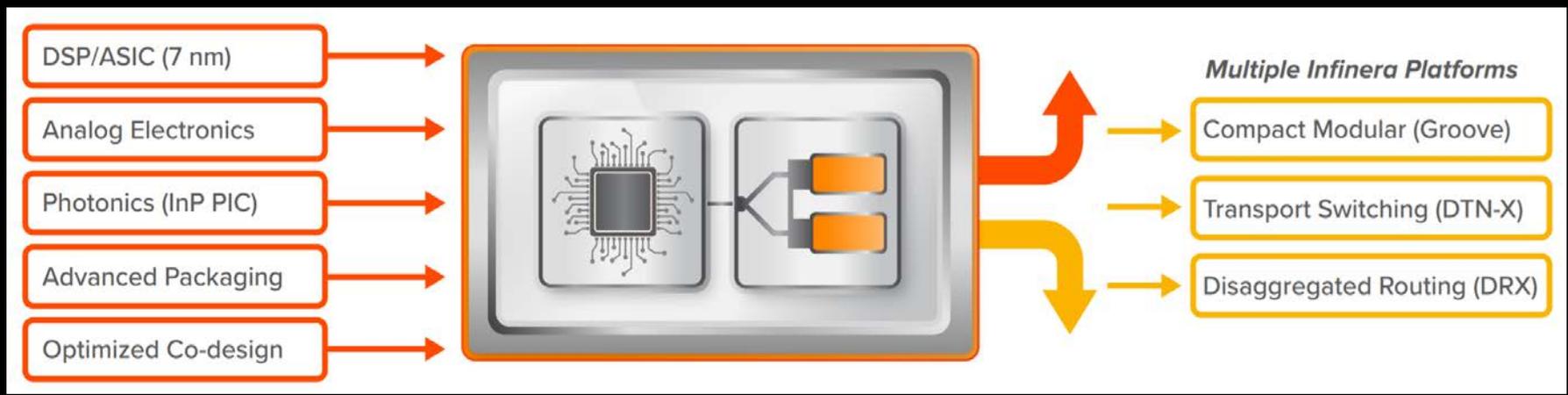
PIC technologies ~\$24B by 2025 with 18% CAGR (20-25)

Trends in Data Center Switches and Transceivers – Demand for Higher Data Rates

- Data rate of network switches and transceivers doubling every 18 months.
 - Today switch data rate 5 Tbps and will reach 51.2 Tbps in 2025.
 - Transceivers data rate will increase from 100 Gbps to 800 Gbps.
 - Number of transceivers per switch will grow from 4 to 16 or 32.
- Density of data transfer in switches increasing exponentially – integration and thermal challenges.



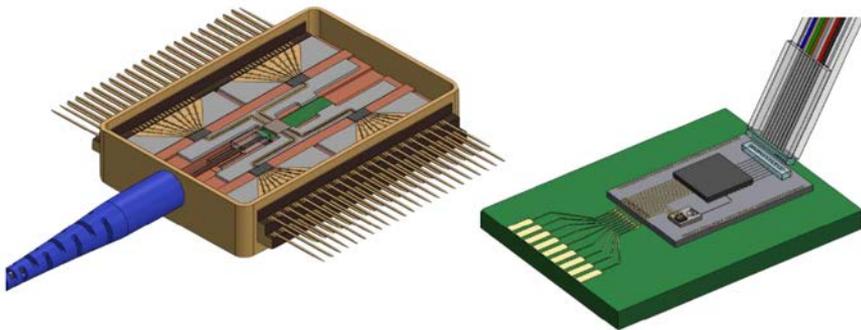
Infinera 800 Gb/s Optical Engine – Leveraging Advanced DSP and PIC Technology



- 6th Generation Infinite Capacity Engine (ICE6) is single 1.6 Tb/s optical engine that delivers two wavelengths up to 800 Gb/s each.
- Fabricated with 7 nm process node DSP/ASIC, highly integrated InP PIC, high-performance analog electronics, and advanced packaging to enable integration into multiple platforms.
- Higher baud rates enable significantly increased wavelength capacity-reach, and are the key to reducing cost per bit, power, and footprint of coherent optical transport. ICE6 offers state-of-the-art flexible baud rate of 32-96 Gbaud, enabling 800 Gb/s wavelengths to 950+ km, 600 Gb/s wavelengths to 2,500+ km, and 400 Gb/s wavelengths to 6,500+ km.
- Maximizes spectral efficiency and fiber capacity with innovative features including Nyquist subcarriers, enabling 42.4 Tb/s in the C-band and more than 80 Tb/s C+L.

Sample PIC Application Lifetimes

Communication Demonstrators



TeleComs

InP-PIC

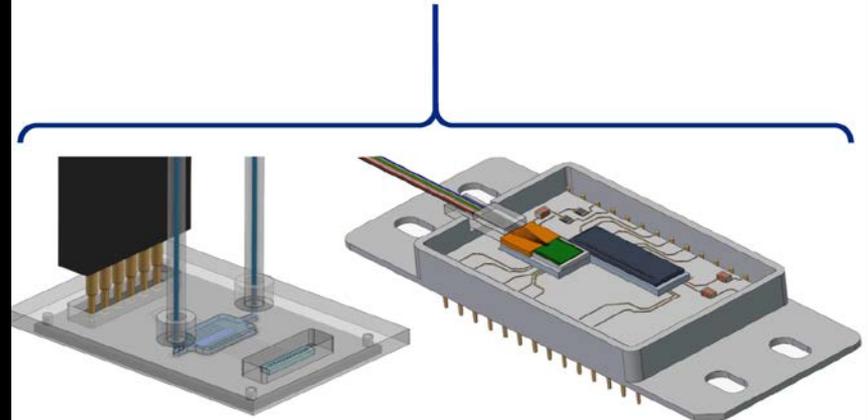
>10 Years

DataComs

Si-PIC

3-5 Years

Sensor Application Demo



BioSensor

Si_3N_4 -PIC

Single Use

Fiber Interrogator

InP-PIC & Si_3N_4

>25 Years

Delivering Integrated Photonics at Silicon Scale

LASER FABRICATION



Plasma activation and bonding:
InP die are bonded & transferred
in parallel to device wafer

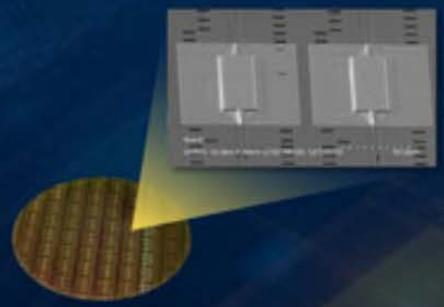


InP substrate removal: only active
epi layers remain on device wafer



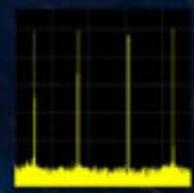
Hybrid laser >90% coupling efficiency

SILICON INTEGRATION



Advanced CMOS manufacturing
at Intel fabs on 300mm wafers

Capable of multiple
optical wavelengths
and integration of
multiple optical
components



SILICON SCALE

Optical



Electrical



RF



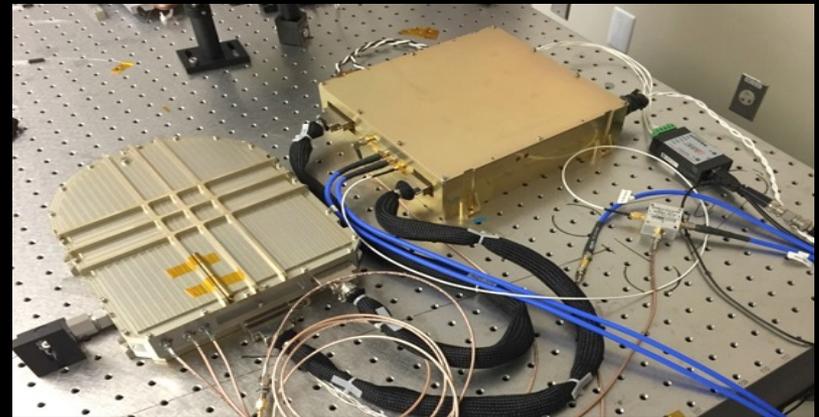
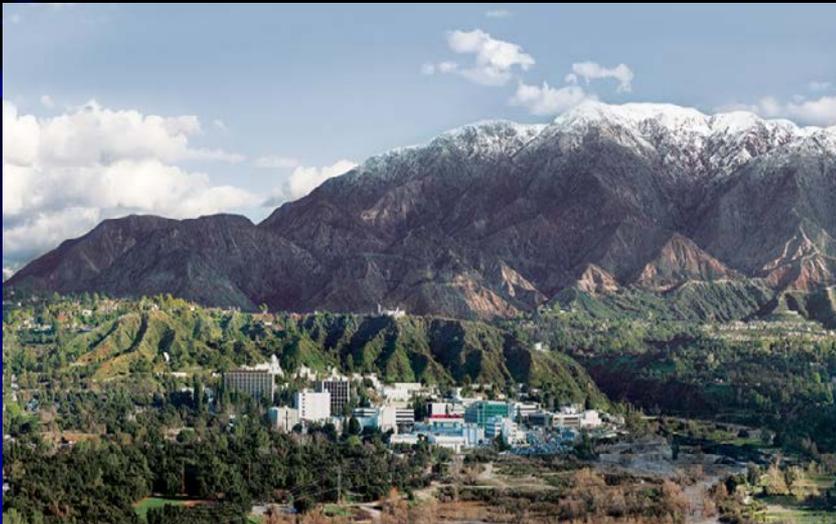
Comprehensive, automated on-wafer optical, electrical, and high-speed test capabilities

Many Open Access Silicon Photonics Platforms

<p>imec</p> <p>PSV WaveGuide FiberCoupler</p> <p>ISIPP50G</p> <p>220 nm SOI</p>	<p>leti</p> <p>Passive + heaters</p> <p>SI310-PH</p> <p>310 nm SOI</p>	<p>ihp</p> <p>IHP SG25 PIC</p> <p>IHP SG25H4 EPIC</p> <p>Photonic BiCMOS</p> <p>220 nm SOI</p>	<p>VTT</p> <p>Passives + Heaters + Implanted PIN + Flip-chip</p> <p>SOA array CAM array</p> <p>1 mm</p> <p>3 μm SOI</p>	<p>UNIVERSITY OF SOUTHAMPTON</p> <p>Passive + heaters</p> <p>Actives</p> <p>220-500 nm SOI</p>	<p>AMO</p> <p>Customized actives & Passives with EBL</p> <p>220/340 nm SOI</p>
<p>Institute of Microelectronics A*STAR</p> <p>220 nm SOI</p>	<p>AIM photonics</p> <p>220 nm SOI</p>	<p>ANT APPLIED NANOTOOLS INC.</p> <p>220/300 nm SOI</p>	<p>TOWERJ&Z The Global Specialty Foundry Leader</p> <p>220 nm SOI</p>		

Areas of Emphasis at JPL

- Key areas of emphasis in **optical** communications research and development at JPL include:
 - long-haul optical communications (DSOC)
 - optical proximity link system development
 - in-situ optical transceivers
- DSOC is developing technologies to enable streaming high definition imagery and data communications over interplanetary distances.
- Also advances in JPL's optical proximity link systems with low complexity and burden can boost surface asset-to-orbiter performance by a factor of 100 (20 dB) over current state-of-the-art. This improvement would benefit planetary and lunar orbiters to communicate with landers or rovers.



Laser transmitter assembly with module on the left in the laser optical module; the laser electronics module is shown on the right. Peak power 1 kW. (Credit: NASA)

Innovation of NEPP Integrated Photonics Task

We propose to develop screening and qualification guidelines for PICs using a custom photonic-integrated laser transmitter (PILT) built by UCSB as a technology pathfinder/baseline.

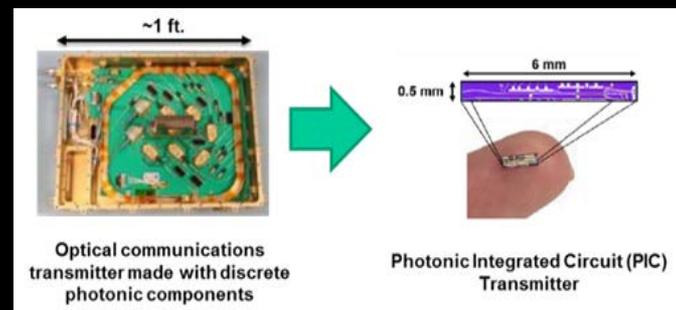
- Using versatile, reconfigurable PIC technology, we seek to demonstrate the feasibility, radiation hardness and reliability of an optical subsystem miniaturized onto single, scalable chip with a “USB drive” form factor and designed to meet end-of-life requirements for space-based missions.
- Development of these space qualification methodologies will leverage established industry standards for commercial photonic components (Telcordia) as well as military standards for semiconductor devices to address current unknown reliability weaknesses of PICs for use in space.

How does it compare to state-of-the-art (SoA)?

- Presently, industry standards do not exist for component selection, design, and fabrication of highly reliable commercial PIC for space.
- From a performance perspective:
 - Discrete designs using SoA space lasercom transmitters have high average power (>1W) and peak power (~kW) to support deep-space links but require fiber-based lasers and amplifier with external modulation. Issues: Large SWaP footprint due to fiber packaging constraints.
 - Terrestrial datacom transceivers: 10/40/100 Gpbs PIC transceivers exist in Datacom (Cisco). Issues: Incompatible with space applications; low output power (<10mW) and coherent modulation formats suitable only for short-reach, low-noise fiber networks.

Overall Objective:

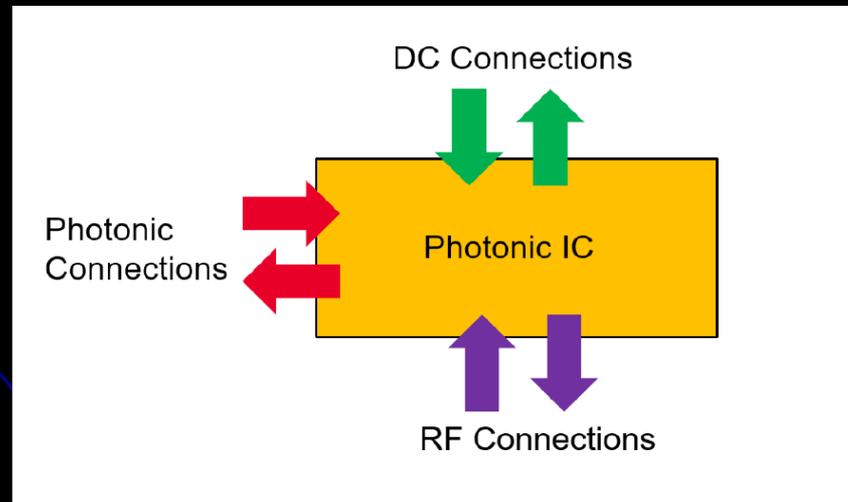
Bridge technology gap between academic research and flight prototype development of integrated photonics. This work seeks to combine radiation and reliability screening of PILT research pathfinders with performance characterization in deep-space optical links to distill a novel, final prototype solution with path to flight.



Challenges of Optical and Optical-Electrical Testing of Integrated Photonics

A new level of complexity:

- Photonic ICs are highly polarization dependent
- PICs can have a lot of electronic connections in addition to optics
- Probing can get busy, fast, and complex/error prone especially when RF comes into play



Typical WDM Optical Transceiver

