Jet Propulsion Laboratory
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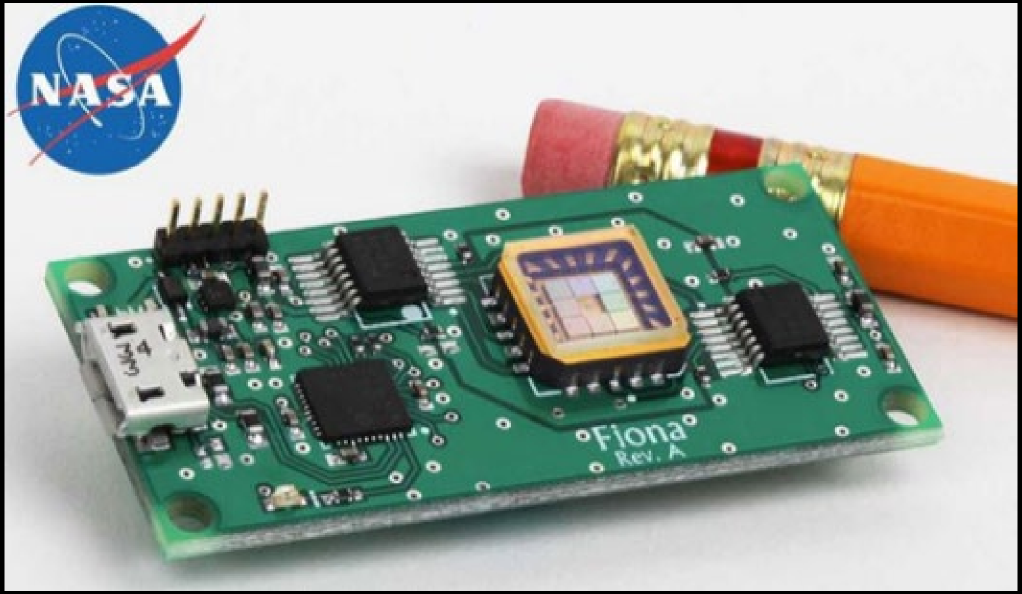
NEPP Space Qualification Efforts for Photonic Integrated Circuits (PICs)

Sponsored by: NASA Electronics Parts and Packaging (NEPP)



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NEPP 2021 Electronics Technology Workshop (ETW)
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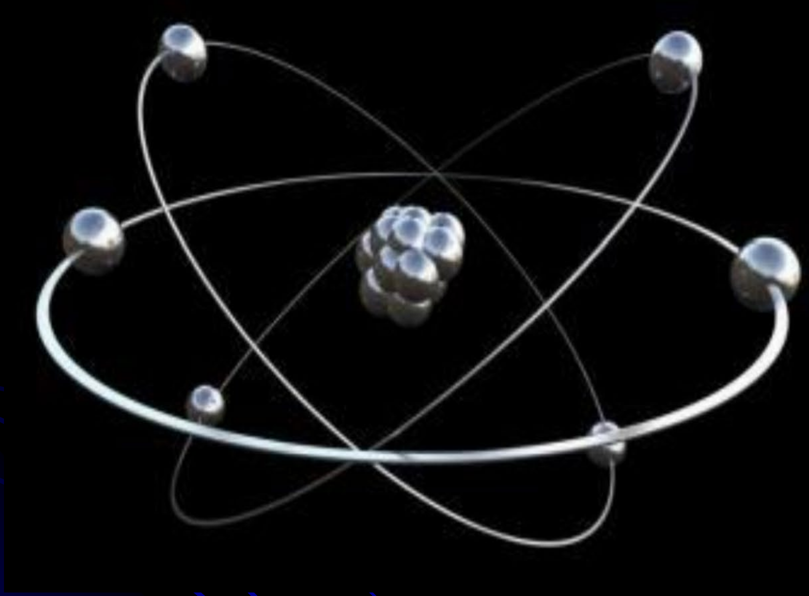
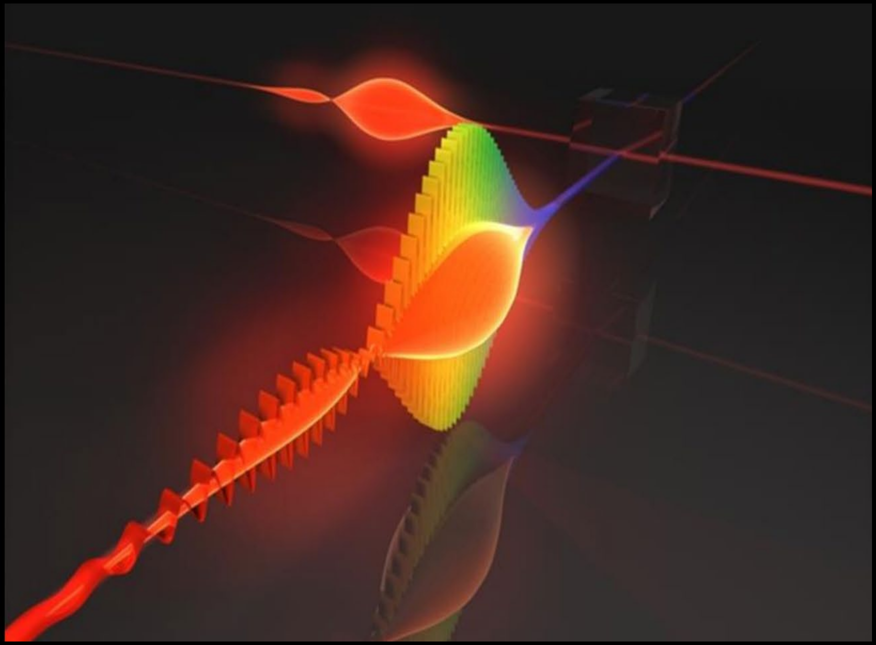
AGENDA

Photonic Integrated Circuits for Space Communications: Past, Present (focus of this talk), and Future



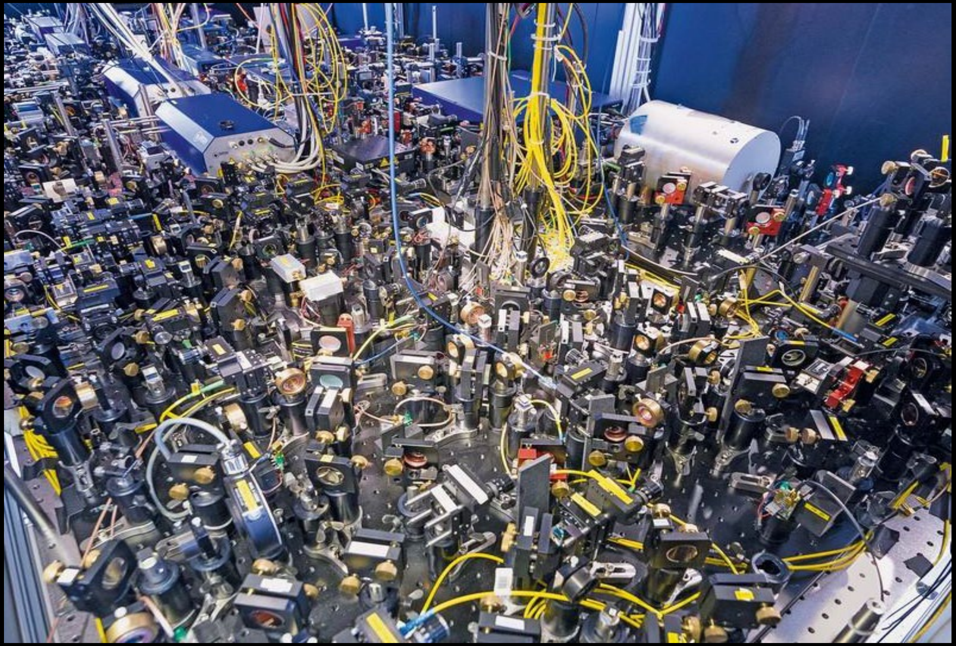


Will Electrons or Photons Rule Today and Tomorrow's Space Communications Applications?

Photo Credit: Dr. Eric Mounier and Jean-Louis Malinge, Yole Développement, "Silicon Photonics and Photonic Integrated Circuits 2019", http://www.yole.fr/PhotonicIC_SiPhotonics_MarketUpdate_Intel.aspx#.Xttu8DpKhPY

THE PAST: Discrete Optics for Communication Systems

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



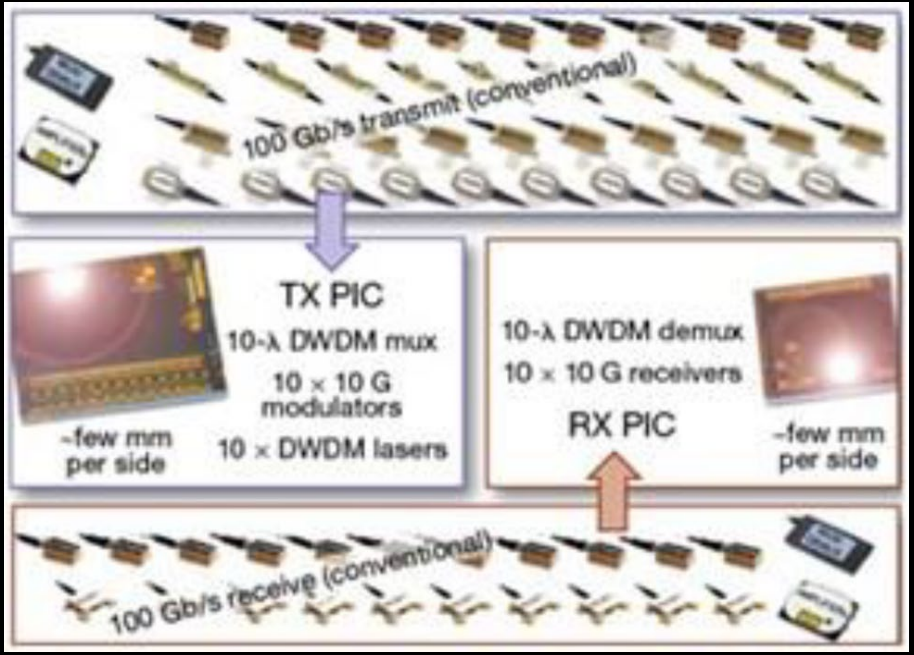
- 1980s: optical communication systems were introduced for long distance telecommunication using discrete optics (i.e. lasers, photodetectors, optical fiber).
- Optical transmitters and receivers are traditionally hand-assembled from “bulk” commercial-off-the-shelf piece parts (discrete passive and active devices).
- Internal interconnects and packaging have always posed significant reliability challenges for traditional optical communication systems consisting of discrete optics.
  - Discrete optics require hermetic packaging and mechanical stability to mitigate component misalignment over time from environmental stresses. This reduces yield and increases cost.

Photo credit: Hank Hogan, “Data Centers and More for Silicon Photonics”, https://www.photonics.com/Articles/Data_Centers_and_More_for_Silicon_Photonics/a64879#Comments

THE PRESENT: Photonic Integrated Circuits (PICs)

Growth of network interconnects to meet high data rate demands is slowed by implementation of complex discrete optical designs.

As a solution, monolithic InP-based PICs (first introduced in 2004) established commercial viability for large-scale production of integrated photonics for telecom networks.



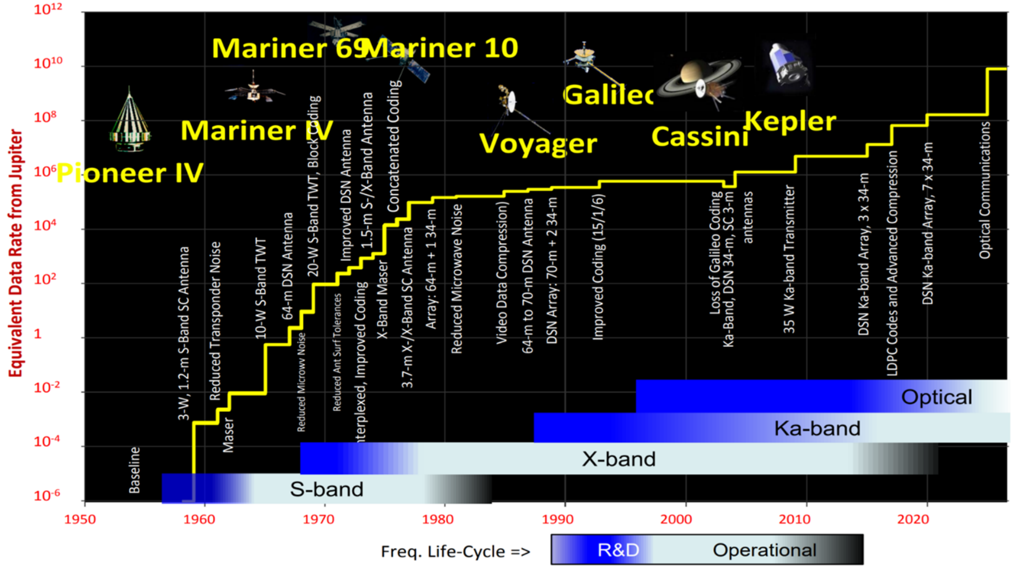
PICs are the enabling technology of the present and future for data centers, cloud, and high bandwidth optical communications systems.

Integrating up to 100s of optical components and functions on a single Tx/Rx chip, PICs can offer more speed, reliability, efficiency (power consumption), and scalability than discrete optical systems. All packaged in a chip the size of a postage stamp (unrivaled SWaP savings).

Photo Credit: Erik Pennings, "PIC Component Tutorial", 7Pennies PIC training, Dec 2019

THE FUTURE: Optical 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 data rate demands for space applications will exceed capacity available in RF Ka-band (GHz), driving necessary move to higher BW, unregulated/unconstrained optical 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.



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

Photo credit: John Rush, “NASA Advisory Council ITIC Committee Space Communications and Navigation Optical Communications Update”

Real World Example – Integrated Photonics for Space Communication

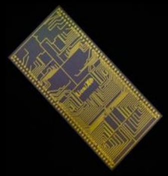
- Free-space laser links used for satellite communications currently limited in modulation speeds due to high power-per-bit consumption of commercial optical transceivers.

- NASA used 3D-monolithic integration of photonic structures (high-speed graphene-silicon PICs on CMOS electronics) to design CMOS-compatible high-bandwidth transceivers for ultra-low power terabit-scale optical comm system.
  - Demonstrated integrated graphene electro-optic modulator with 30 GHz BW.
  - Graphene microring modulators attractive solution for dense wavelength division multiplexed (DWDM) systems.

Photo Credit: Doug Messier, “Laser Demonstration Mission Proves Space Broadband Communications Feasible”,
http://www.parabolicarc.com/2013/12/27/laser-demonstration-mission-proves-space-broadband-communications-feasible/

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

- Telecom 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. 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)

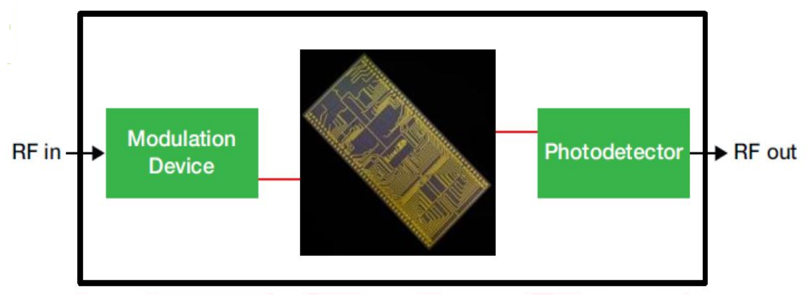
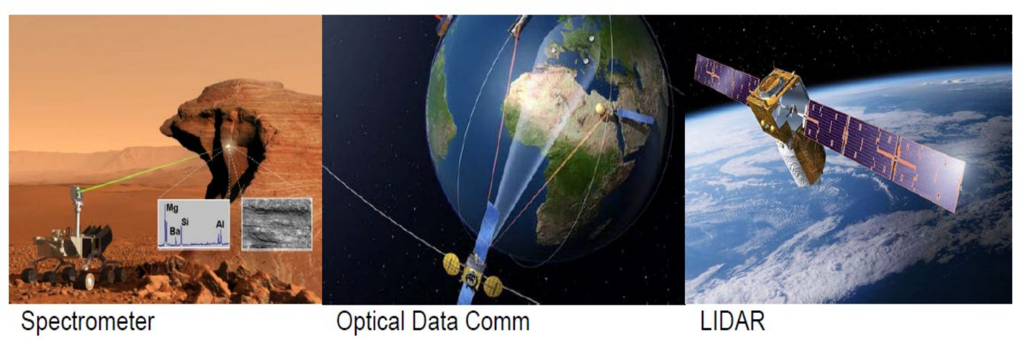


Photo Credit: Douwe Geuzebroek, Lionix International, "TriPleX: the low loss silicon nitride photonic platform ", 7Pennies PIC training, Dec 2019

Present (and Future) Areas of Emphasis at JPL

- Key areas of emphasis in JPL optical communications include:
  - long-haul optical communications (Deep Space Optical Communications)
  - 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.
- 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.



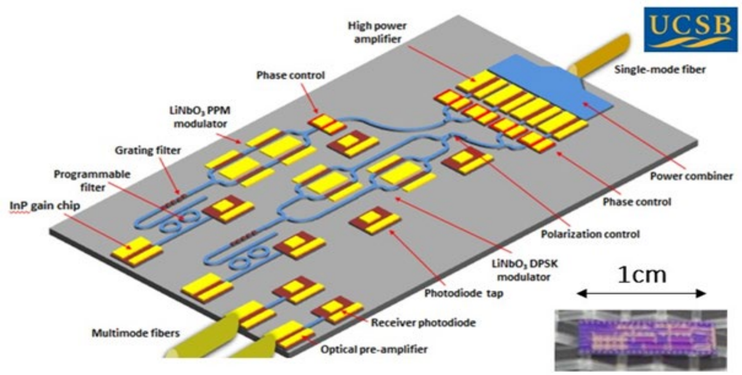
Spectrometer   Optical Data Comm   LIDAR

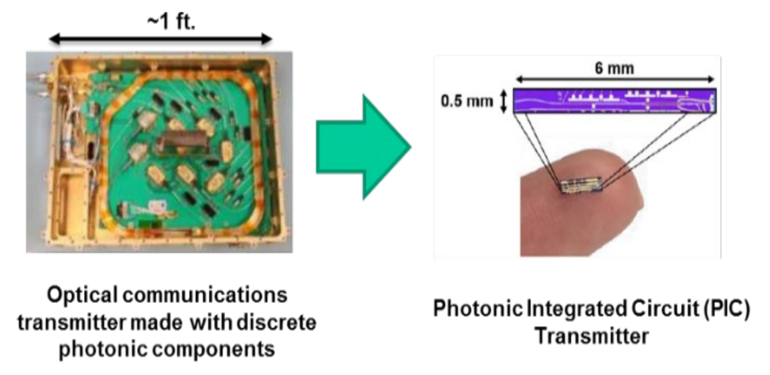
Integrated photonics can enable…

- Next gen computing and free-space optical comm systems (inter-satellite or satellite-to-ground)
- Scientific optical instruments on satellites or rovers (cameras, LIDAR, spectrometers)
- Signal distributions (MOEM-based switches, mixers, analog or digital optocouplers, intra-satellite comm)
- Sensing (i.e. star-trackers, gyroscopes, temperature, strain, metrology)

Overview of Current NEPP FY21 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 PICs 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 and validate novel mission assurance methodologies for screening and qualifying state-of-the-art commercial integrated photonics technologies 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 commercial Telcordia standards.
  - Reduce risk of flight insertion of integrated photonics into NASA space applications, while enabling order of magnitude improvements in SWaP-C and performance.





Optical communications transmitter made with discrete photonic components

Photonic Integrated Circuit (PIC) Transmitter

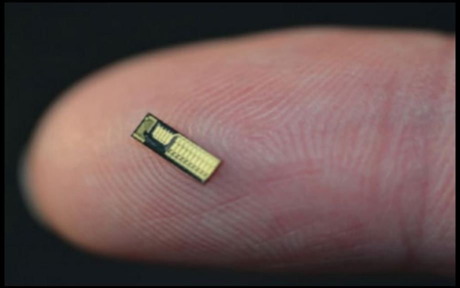
NEPP Space Qualification of Integrated Photonics: Goals

- Bridge technology and knowledge gap between academic research/commercial development of prototype designs and actual flight qualification of integrated photonics.
- PIC technology characterization and establishment of partnerships across industry.
  - Comparison of radiation hardness (TID, DD, SEE) across various PIC material platforms, foundry runs, and chip designs. Target is InP (monolithic integration), SiPh (hybrid integration, monolithic coming), SiN (hybrid integration of lasers and amplifiers).
  - Building library of radiation test data with key performance parameters for various integrated versus discrete structures.
  - Comparison of packaging types and subsequent result on radiation hardness and reliability (follow-on work).
  - Established partnerships for PIC radiation (and eventually reliability) testing: University of California Santa Barbara (UCSB), Georgia Tech, Freedom Photonics, Acacia, Infinera.

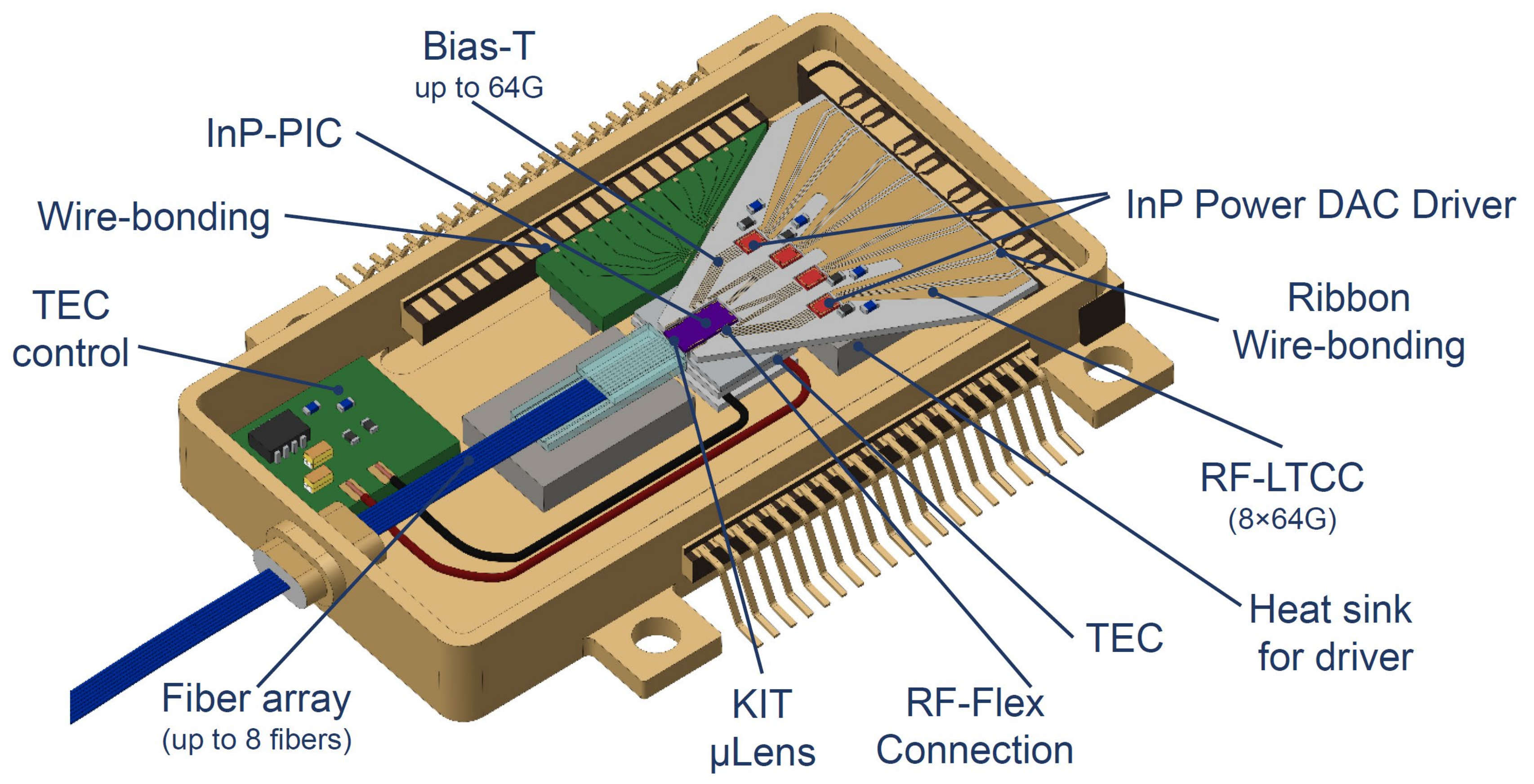
Top level goals:

- ***Development of integrated photonics radiation data library and guidelines for space qualification.***
- ***Technology roadmap for database of integrated photonic components (developed as a function of process technology and capability, will also extend into advances in packaging 2D/3D).***

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



Understanding PIC Packaging (future NEPP research)



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

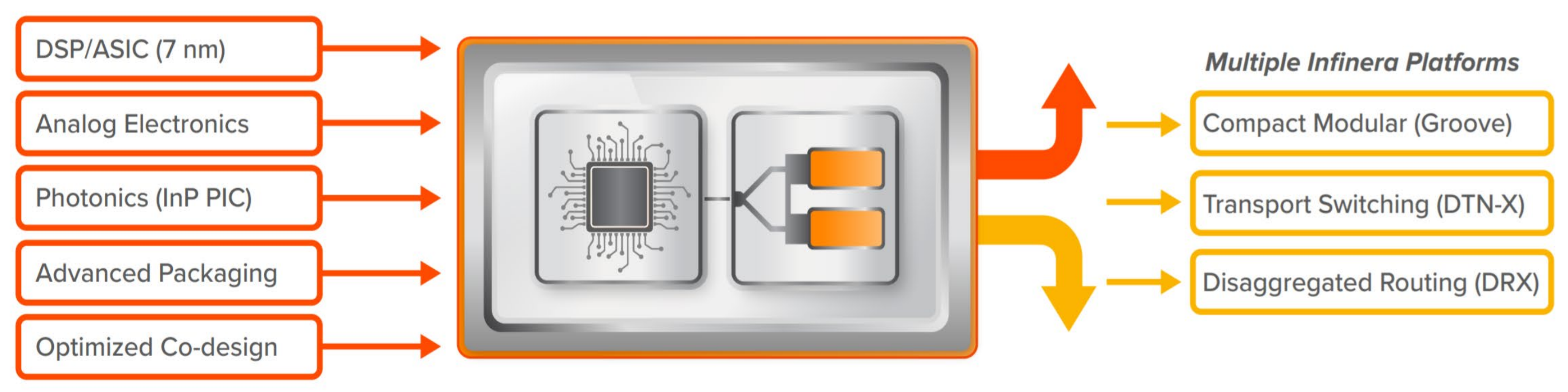
Photo Credit: PIXAPP, “Packagingtechnologiestoscale-upproductionforPIC-basedproducts”, 7Pennies PIC training, Dec 2019

NEPP Space Qualification of Integrated Photonics: Accomplishments

- **Started process for characterizing critical building block of photonic integrated circuits for use in the space environment:**
  - Completed heavy ion testing at Texas A&M on 1310 nm silicon waveguides with integrated Ge photodiodes. This collaboration is led by Georgia Tech.
  - Tested for optical single event transients with high energy heavy-ions to achieve LETs >80 MeV-cm^2/mg. Mapped out cross-section for photodiode single event transients. Results to be presented by George Tzintzarov at NSREC 2021.
  - This was the first heavy ion SEE test completed and reported on integrated photonics technology and was the first step in silicon photonics is rad hard for space applications.
  - Focus was on 1310 nm waveguides. GT also considering testing 1550 nm silicon and SiN test structures, as well as Mach Zehnder Modulators (weak point during TID studies).

- **Acquiring commercially available PIC test structures for TID, SEE, and proton DD (candy bag) survey to build integrated and discrete photonics database:**
  - Collaborators, test structures, and test plans established for full gamut of radiation characterization.
  - Freedom Photonics collaboration will involve characterization of mature technology now, with opportunity for future testing on hybrid multi-PIC structures.

Infinera Collaboration: 1.6 Tb/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.
- Features 7 nm CMOS 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 increased wavelength capacity-reach, and are key to reducing cost per bit, power, and footprint of coherent optical transport. Flexible baud rate of 32-96 Gbaud, enables 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 >80 Tb/s C+L.
- Also planning to test discrete MZM and SOAs from Infinera.

Photo Credit: https://www.infinera.com/wp-content/uploads/Infinera-ICE6-Optical-Engine-0228-PO-RevA-0320.pdf

Freedom Photonics and Acacia Communications Collaboration

Freedom Photonics:

- Freedom Photonics providing various test samples: 1550 nm integrated tunable lasers, single mode Fabry Perot lasers at various wavelengths, and InP laser transmitter with integrated SOA, as well as other components.
- Performing in-situ and pre- & post-radiation measurements with focus on key operating parameters critical to space applications.

Acacia Communications (now Cisco):

- 400G CFP2-DCO Pluggable Coherent Optical Module using a bi-directional laser designed for use in the LEO space market. Enables 16-QAM and QPSK advanced modulation formats.
- Incorporates Acacia's Greylock DSP ASIC, based on 7 nm CMOS technology, and Acacia's silicon PIC for an optimized co-packaged design (smaller than cell phone).
- Leveraging mature CMOS processes, Acacia's silicon PICs eliminate need for temperature control circuitry or costly hermetic packaging.

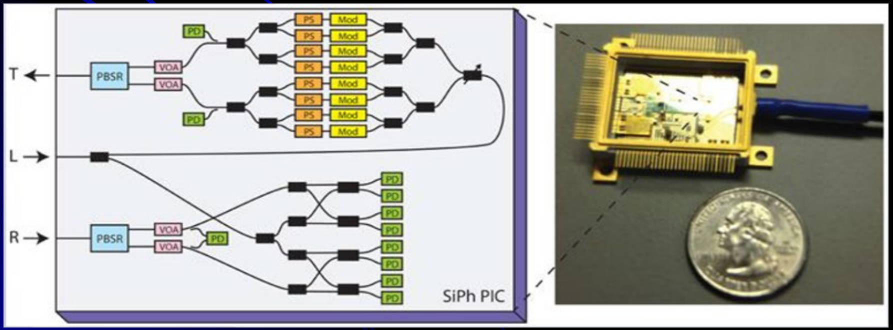


Photo Credit: https://freedomphotonics.com/

UC Santa Barbara (UCSB) Collaboration

1) Evaluate radiation hardness of baseline (generation 1) indium phosphide (InP)-based photonic integrated laser transmitter (PILT) developed by Klamkin's group at UCSB.

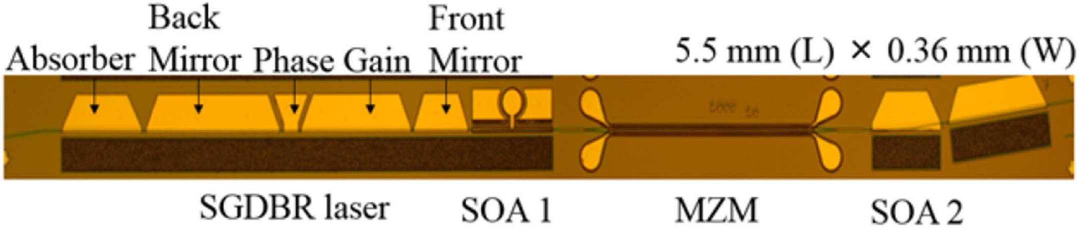
2) Examine radiation-induced damage from Total Ionizing Dose (TID), Displacement Damage (DD), and Single Event Effects (SEE) on discrete and integrated test structures.

3) Quantify radiation degradation (for typical NASA mission), identify potential failure modes/sensitive regions/materials within integrated chip, and determine root cause. Includes quantification of key performance parameters impacted by radiation.

4) Standardize 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.

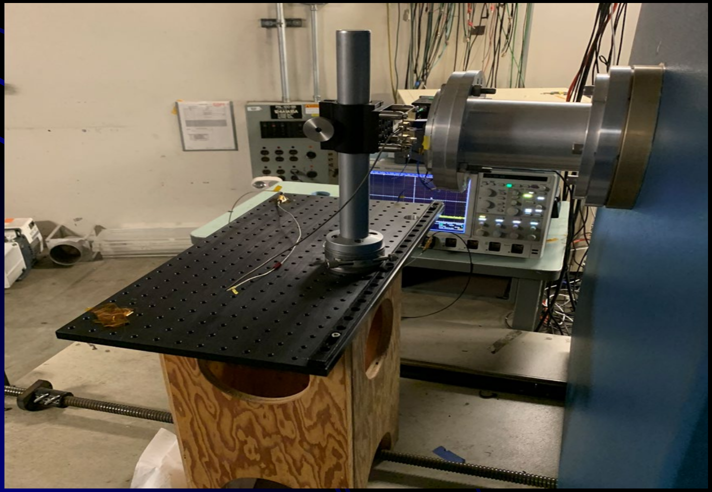
5) Roll up results into PIC space qualification guidelines. Leverage existing Telcordia standards for discrete photonics and the body of knowledge for individual chip materials.

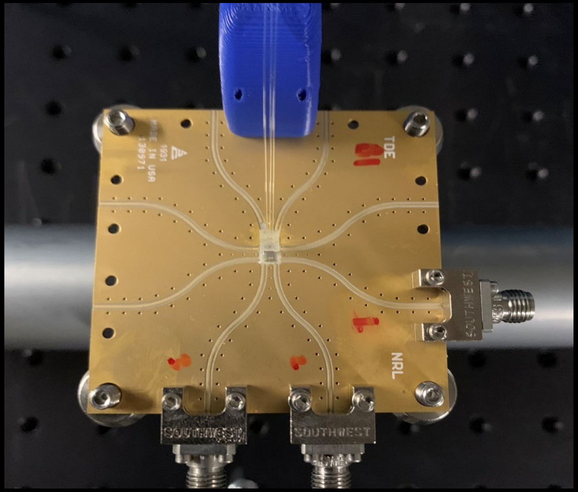
6) Future work: perform design iterations based on findings and provide feedback to UCSB for development of a highly reliable, flight-qualifiable custom PILT.



Georgia Tech Collaboration: Heavy-Ion Induced Optical Single Event Transients in Integrated Silicon Photonic Waveguides

- Georgia Tech led collaboration with George Tzintzarov and team from Professor John Cressler's group.
- Optical Single Event Transient (OSET) heavy-ion test structures:
  - Commercial silicon photonic platform fabricated by Global Foundries
  - Features integrated silicon photonics on 90-nm CMOS process node
  - Supports optical wavelengths at 1310-nm and 1550-nm
  - Includes 1-mm-long silicon waveguide and lateral p-i-n bulk germanium photodiode (60 GHz BW)





NEPP Integrated Photonics Plan: Integrated Test Structures and Key Active Discrete Building Blocks

Component	Vendor	Integrated vs discrete	TID (Co-60 gamma)	DD (proton)	SEE (heavy-ion and possibly proton)
Optical waveguide (Si and SiN) integrated photodetector (Ge) (1310 nm, 1550 nm)	Global Foundries/ Georgia Tech (GT)	Integrated (building block)	Complete (with X-ray)	Not informative	Complete (March/May 2021)
InP PIC includes tunable laser, SOA, high-speed MZM, electro-absorption modulator	Freedom Photonics	Integrated	July 2021	July 2021	August 2021
InP PIC – Integrated Laser Transmitter (ILT) (1550 nm) (telecom C band)	UCSB	Integrated	May/June 2021	May/June 2021	August 2021
Tunable Sampled Grating Distributed Bragg Reflector (SGDBR) CW laser (incl SOA and EA mod – InP) (20 mW)	Acronymeo	Integrated	July 2021	July 2021	
SiN PIC	OEwaves Inc., UC Davis team (NASA STTR program)	Integrated	July 2021	July 2021	
Silicon PIC (co-packaged with analog electronics/DSP ASIC)	Acacia Infinera (has InP)	Integrated	July 2021	July 2021	August 2021
Semiconductor Optical Amplifiers (SOA) (1310 nm and 1550 nm)	InPhenix Anritsu	Discrete	July 2021	July 2021	
Mach–Zehnder Modulator (MZM) (800 nm and 1550 nm) (w/ photonic RF driver)	GT (Si and SiN) IxBlue Photonics (LiNbO3), Freedom	Discrete	August 2021	August 2021	August 2021
Integrated graphene electro-optic (micro-ring) modulator (30 GHz BW) (tested at cryogenic temps)	Cornell University	Integrated	TBD	TBD	
Other components if time permits: Erbium-doped fiber amplifier, WDM coupler and isolator, laser sources (Fabry Perot, Multi-wavelength, Picosec pulse)	Freedom Photonics	Discrete	August 2021	August 2021	August 2021

Summary of NEPP FY21 Integrated Photonics Work

- Key accomplishments and immediate near-term plans:
    - Developed white paper and test plans for defining potential radiation-induced failure mechanisms in various PIC technologies/structures (TID, DD, SEE).
    - Completed heavy ion testing with Georgia Tech on their integrated silicon waveguides (1310 nm structures) at Texas A&M.
    - Will test silicon waveguides and discrete silicon photonic devices (MZM) as well as SiN devices at later date.
    - TID and DD proton testing on survey of commercial discrete and integrated photonic devices.

- Overall project goals for FY21:
    - Generate NEPP reports with radiation test results (TID, DD, SEE).
    - Define/standardize PIC radiation test protocols which will flow into space qualification guidelines.
    - Isolate failures at component level using discrete test chips for comparison to integrated structures.
    - Survey of various materials and components to fold into integrated photonics data library.

- Based on findings, define design risk mitigation strategies for use of advanced PICs in space as well as guidelines for PIC selection (performance/materials/component trades).

- Document guidelines for optimized PIC component/material selection (high reliability and radiation tolerant) as well as screening/space qual methods in final NEPP report.

- Provide benchmark comparison study of PILT against SoA space and terrestrial transmitters.

- Identify mission platform for flight insertion for radiation test/space qualified PIC.

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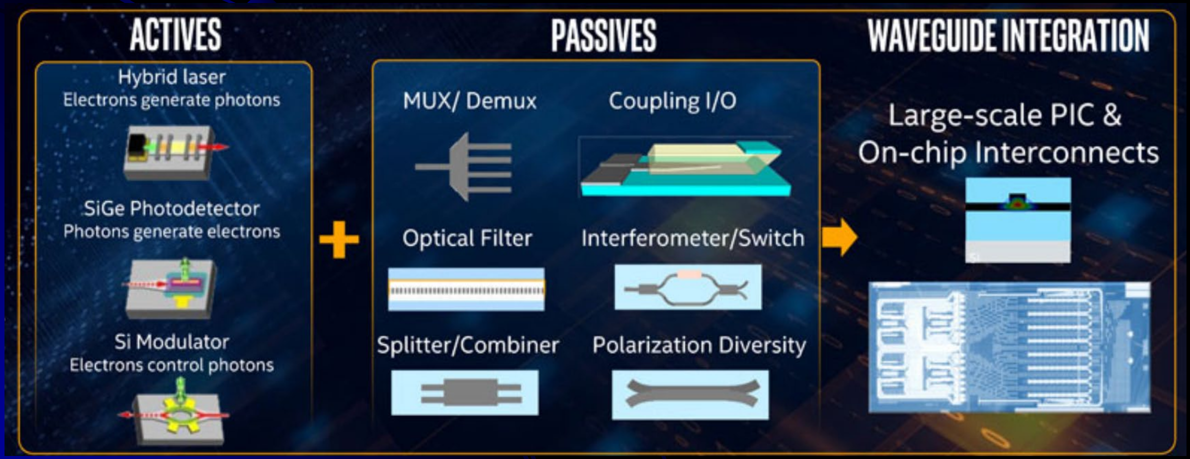
BACKUP

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).
- Integrated photonics is next generation disruptive technology critical to meeting size, weight, power (SWaP) as well as performance goals for many diverse applications.
- 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)**, $LiNbO_2$, GaAs, InGaAsP, **SiN**, **InP**, SiO_2.
- *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.*



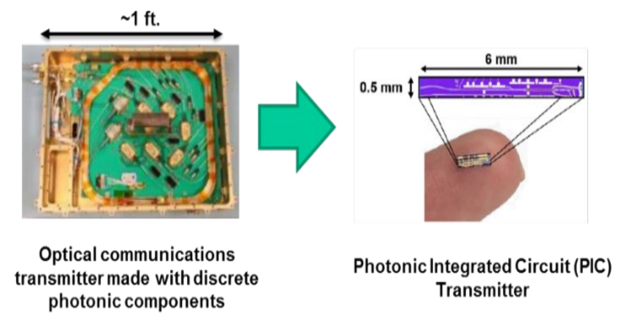


Photo Credit: Patrick Kennedy, “Intel Silicon Photonics Update at Interconnect Day 2019”, https://www.servethehome.com/intel-silicon-photonics-update-at-interconnect-day-2019/

Integrated Photonics Components

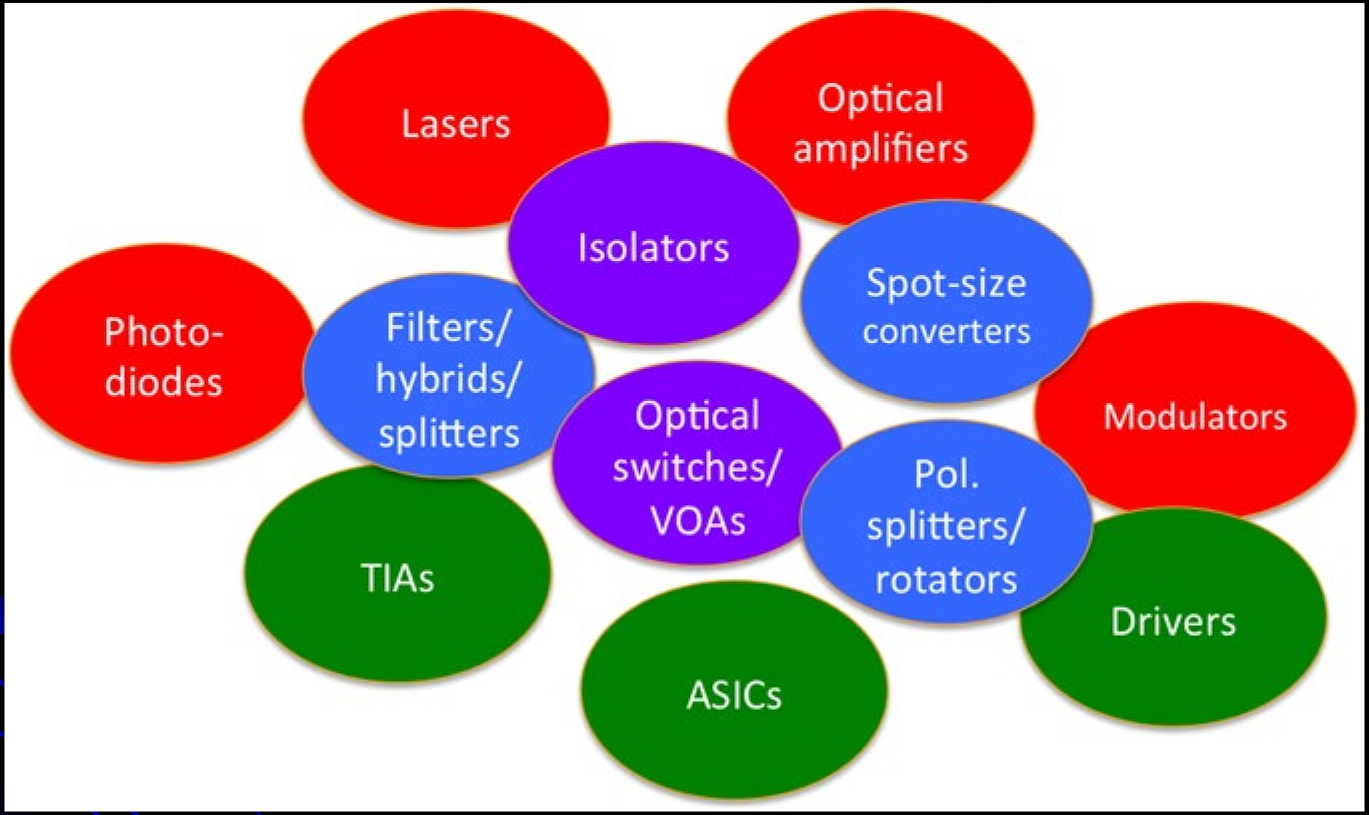
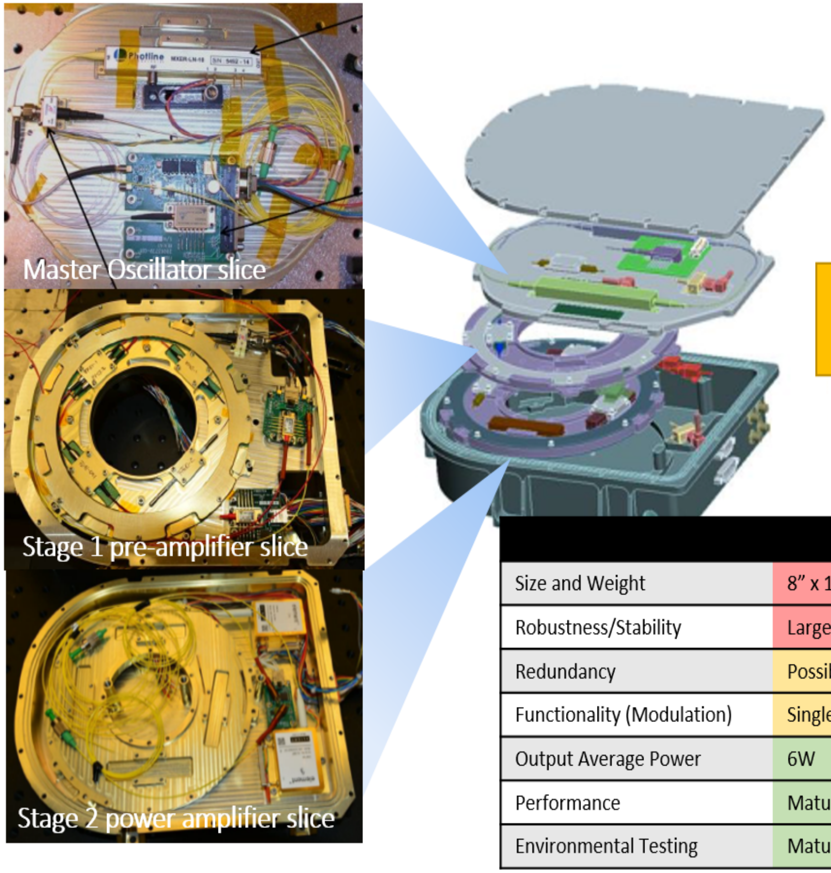


Photo Credit: Christopher R. Doerr, Acacia Communication, “Highly Integrated Monolithic Photonic Integrated Circuits”, https://acacia-inc.com/acacia-resources/highly-integrated-monolithic-photonic-integrated-circuits/

Integrated Photonics Advantages

Fiber-based Transmitter

DSOC Laser Transmitter assembly

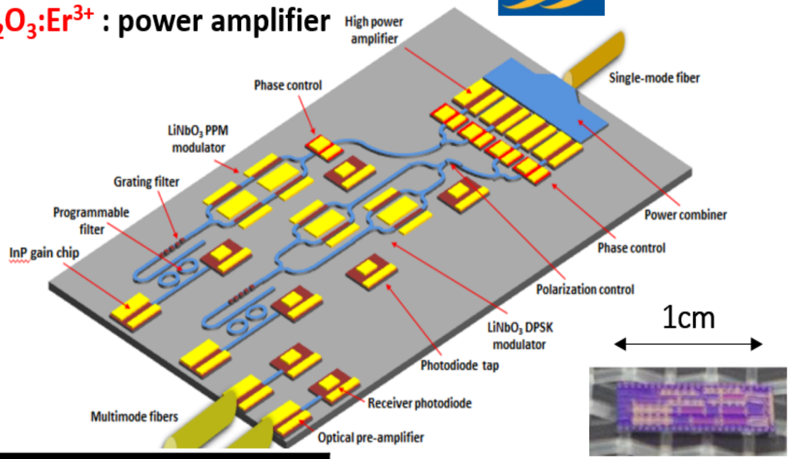


Future

Photonic Integrated Transmitter

Integration platforms chosen for best device performances

- InP : laser & pre-amplifiers
- $LiNbO_3$: modulator
- $Al_2O_3:Er^{3+}$: 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.

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.
    1. Packaging solution for Si-Ph: mount laser as a flip-chip, but alignment issues remain
    2. Wafer-level integration by bonding or deploying epitaxial regrowth of InP to silicon chip, and then processing it with traditional lithographic techniques.
- Hybrid III-V-on-silicon laser is solution – challenge is to efficiently couple light from III-V to silicon.

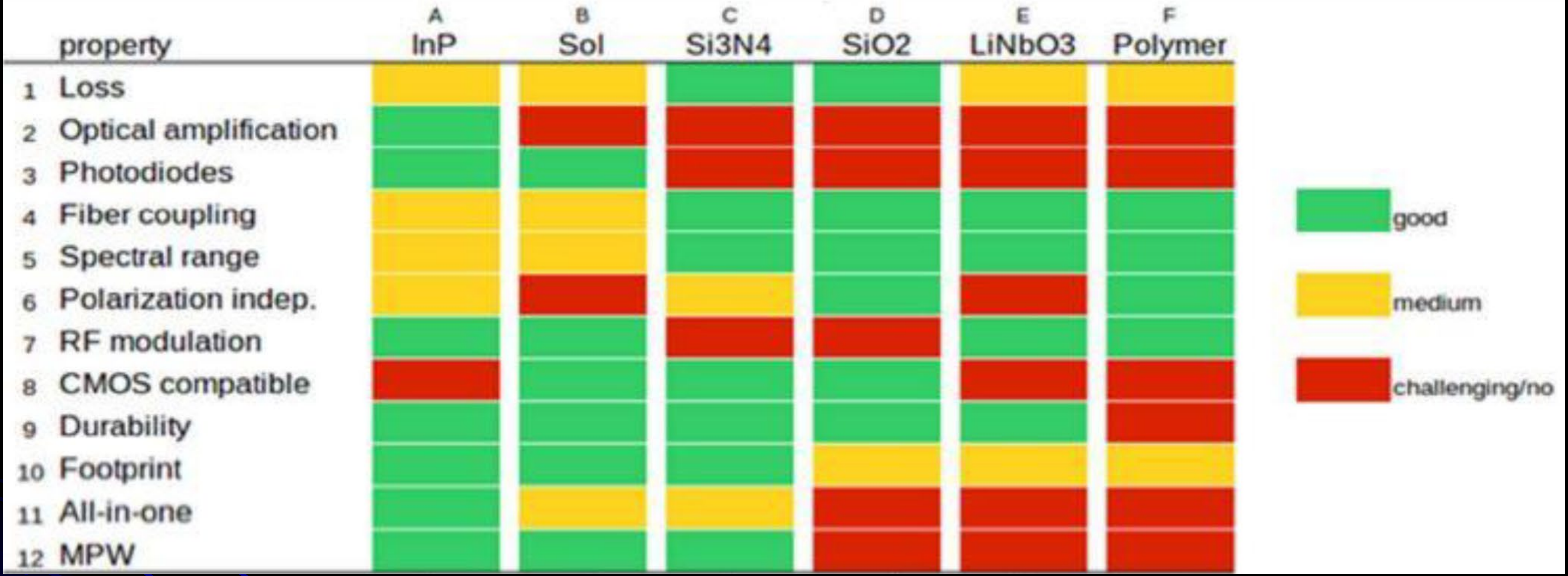
Integrated Photonics platform technologies

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.

Photo Credit: SMART Photonics, "Foundry services for Indium Phosphide based Photonic Integrated Circuits", 7Pennies PIC training, Dec 2019

High Level Functionality Overview



		A	B	C	D	E	F
	property	InP	SoI	Si3N4	SiO2	LiNbO3	Polymer
1	Loss	🟨	🟨	🟩	🟩	🟨	🟨
2	Optical amplification	🟩	🟥	🟥	🟥	🟥	🟥
3	Photodiodes	🟩	🟩	🟥	🟥	🟥	🟥
4	Fiber coupling	🟨	🟨	🟩	🟩	🟩	🟩
5	Spectral range	🟨	🟨	🟩	🟩	🟩	🟩
6	Polarization indep.	🟨	🟥	🟨	🟩	🟥	🟩
7	RF modulation	🟩	🟩	🟥	🟥	🟩	🟩
8	CMOS compatible	🟥	🟩	🟩	🟩	🟥	🟥
9	Durability	🟩	🟩	🟩	🟩	🟩	🟥
10	Footprint	🟩	🟩	🟩	🟨	🟨	🟨
11	All-in-one	🟩	🟨	🟨	🟥	🟥	🟥
12	MPW	🟩	🟩	🟩	🟥	🟥	🟥

🟩 good

🟨 medium

🟥 challenging/no

Tx, RX
All-in-one

Data centers
4x25 Gb
High volume

True time delay
Microwave
photonics

High quality
passives
De-MUX
splitters

Telecom Tx
RF modulators

Modulators
Cheap hybrids

Photo Credit: Erik Pennings, “PIC Component Tutorial”, 7Pennies PIC training, Dec 2019

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	• Best for laser/active integration	• Best for electronic/optical integration • Smallest size	• Low cost • Small size	• Simple process, low cost	• Compatible with Si/InP platform	• Low losses • Low cost	• Very good modulation function
CONs	• Wavelength limited to 1.3 µm to 1.7 µm • Higher cost in large volume production • Complex Epi	• Difficult to get light in and out	• Material properties are process dependent	• Few functions are possible	• Reliability / thermal management issues	• No active functionalities	• Low damage threshold
INDUSTRY STATUS	RAMPING UP	HIGH VOLUME	LOW VOLUME PRODUCTION	PRE-SERIES	R&D/ QUALIFICATION	HIGH VOLUME	HIGH VOLUME

Photo Credit: Dr. Eric Mounier and Jean-Louis Malinge, Yole Développement, “Silicon Photonics and Photonic Integrated Circuits 2019”, http://www.yole.fr/PhotonicIC_SiPhotonics_MarketUpdate_Intel.aspx#.Xttu8DpKhPY

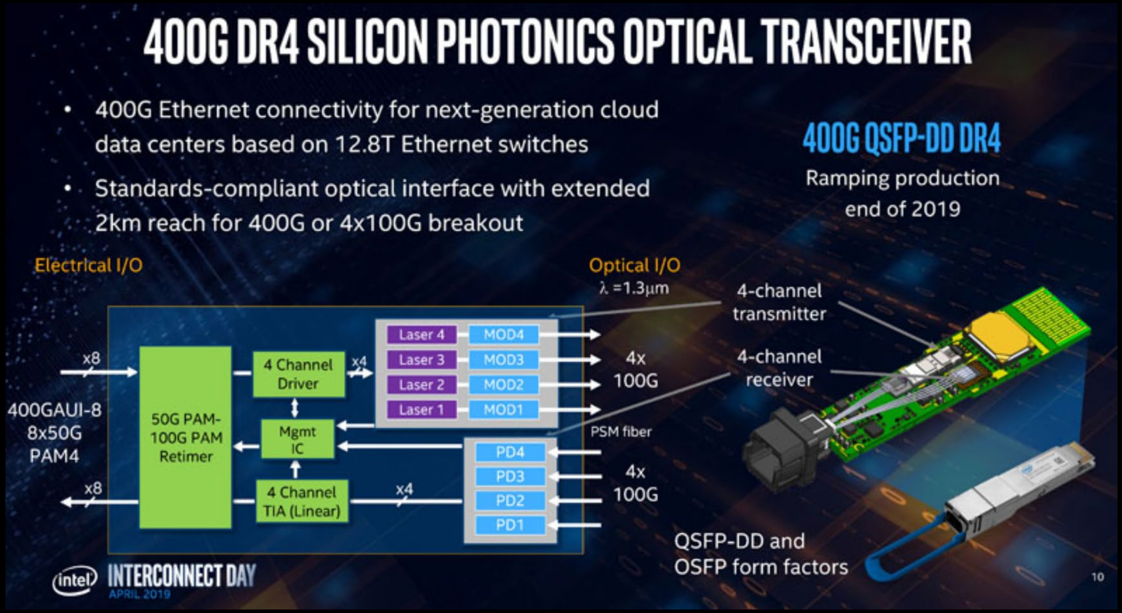
Enabling Future Disruptive Technologies

	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.

Photo Credit: Dr. Eric Mounier and Jean-Louis Malinge, Yole Développement, “Silicon Photonics and Photonic Integrated Circuits 2019”, http://www.yole.fr/PhotonicIC_SiPhotonics_MarketUpdate_Intel.aspx#.Xttu8DpKhPY

State-of-the-Art Integrated Photonics



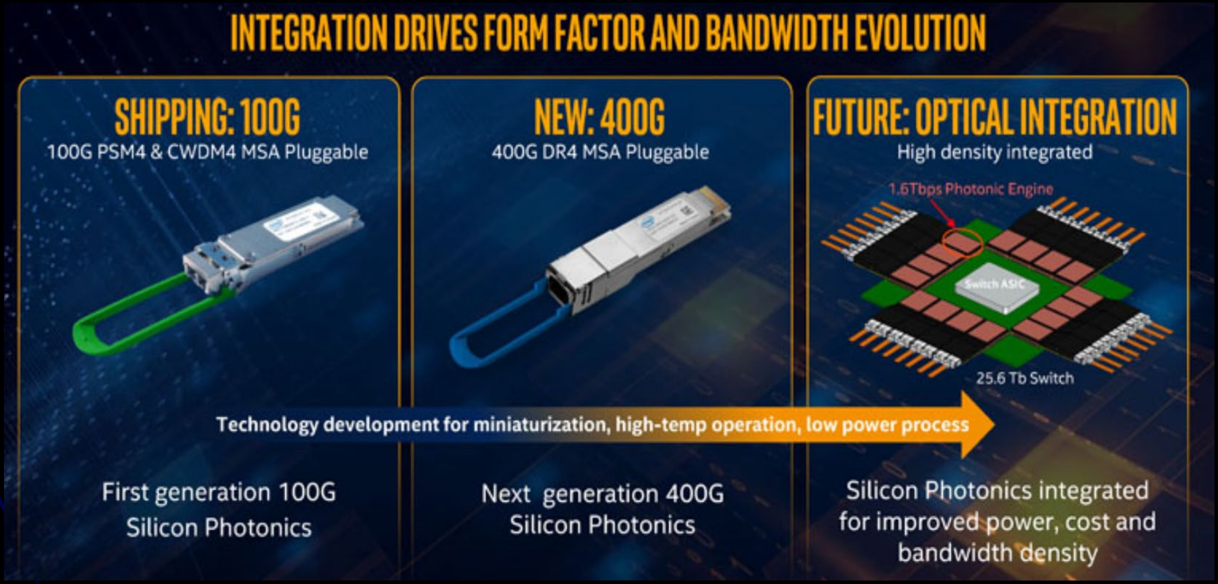
400G DR4 SILICON PHOTONICS OPTICAL TRANSCEIVER

- 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

400G QSFP-DD DR4

Ramping production end of 2019

Intel's PIC transceivers ("photonic engines") to be previewed in 2021: silicon chips with integrated lasers, modulators, photodetectors, drivers, and optics co-packaged with 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.



INTEGRATION DRIVES FORM FACTOR AND BANDWIDTH EVOLUTION

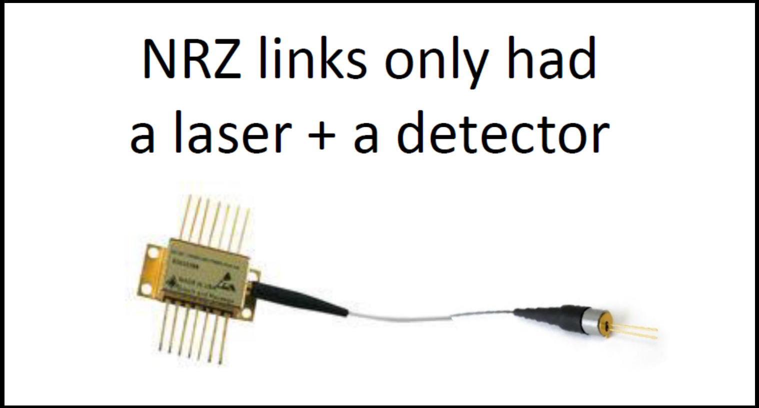
SHIPPING: 100G	NEW: 400G	FUTURE: OPTICAL INTEGRATION
100G PSM4 & CWDM4 MSA Pluggable	400G DR4 MSA Pluggable	High density integrated
First generation 100G Silicon Photonics	Next generation 400G Silicon Photonics	Silicon Photonics integrated for improved power, cost and bandwidth density

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

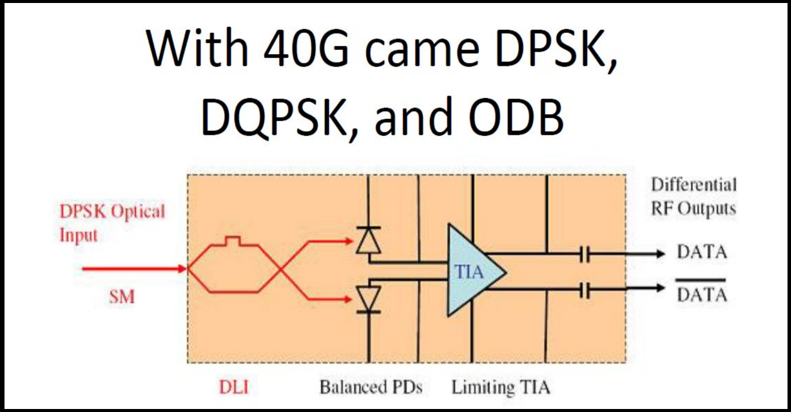
Result is a compact, integrated, system with lower losses and better thermal management. Microsoft and Facebook also working on prototypes.

Photo Credit: Patrick Kennedy, "Intel Silicon Photonics Update at Interconnect Day 2019", https://www.servethehome.com/intel-silicon-photonics-update-at-interconnect-day-2019/

Advanced Modulation Formats Driving Need for Integration

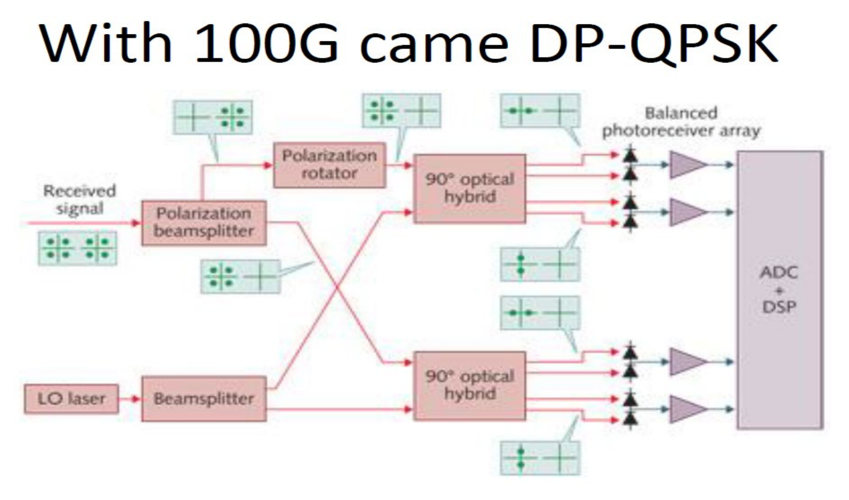


NRZ links only had a laser + a detector

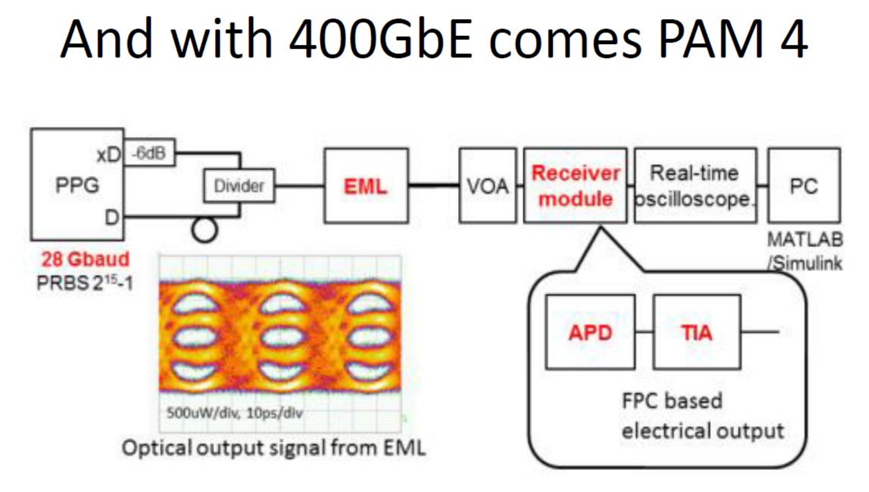


With 40G came DPSK, DQPSK, and ODB

It all adds cost to the solution…



With 100G came DP-QPSK



And with 400GbE comes PAM 4

Optical output signal from EML

- **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**

Photo Credit: Erik Pennings, "PIC Component Tutorial", 7Pennies PIC training, Dec 2019

PIC Space 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 (there are 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

Other PIC Space Qualification Challenges

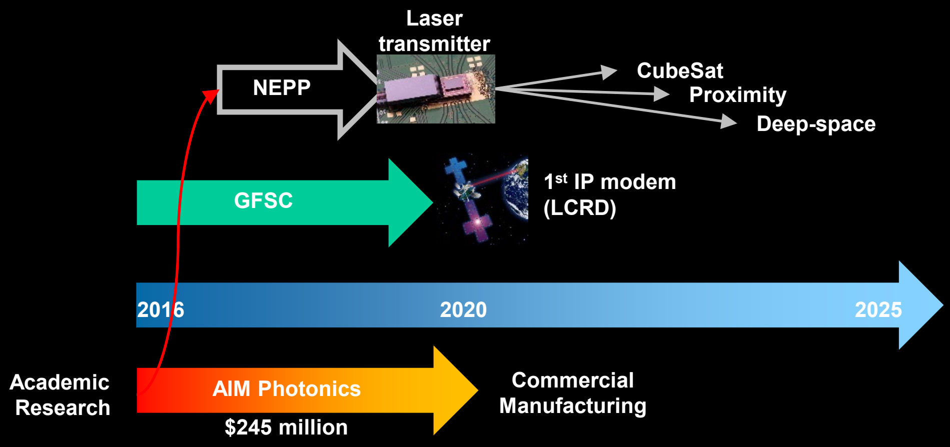
- **Electrical connectivity and thermal management (heat dissipation of photonic circuits orders of magnitude larger than transistors).**
  - Resistive heaters necessary for photonics (optics can drift fast).
- **Without open-access foundries, very high costs for developing PICs – impacts companies & 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), 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.**

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)