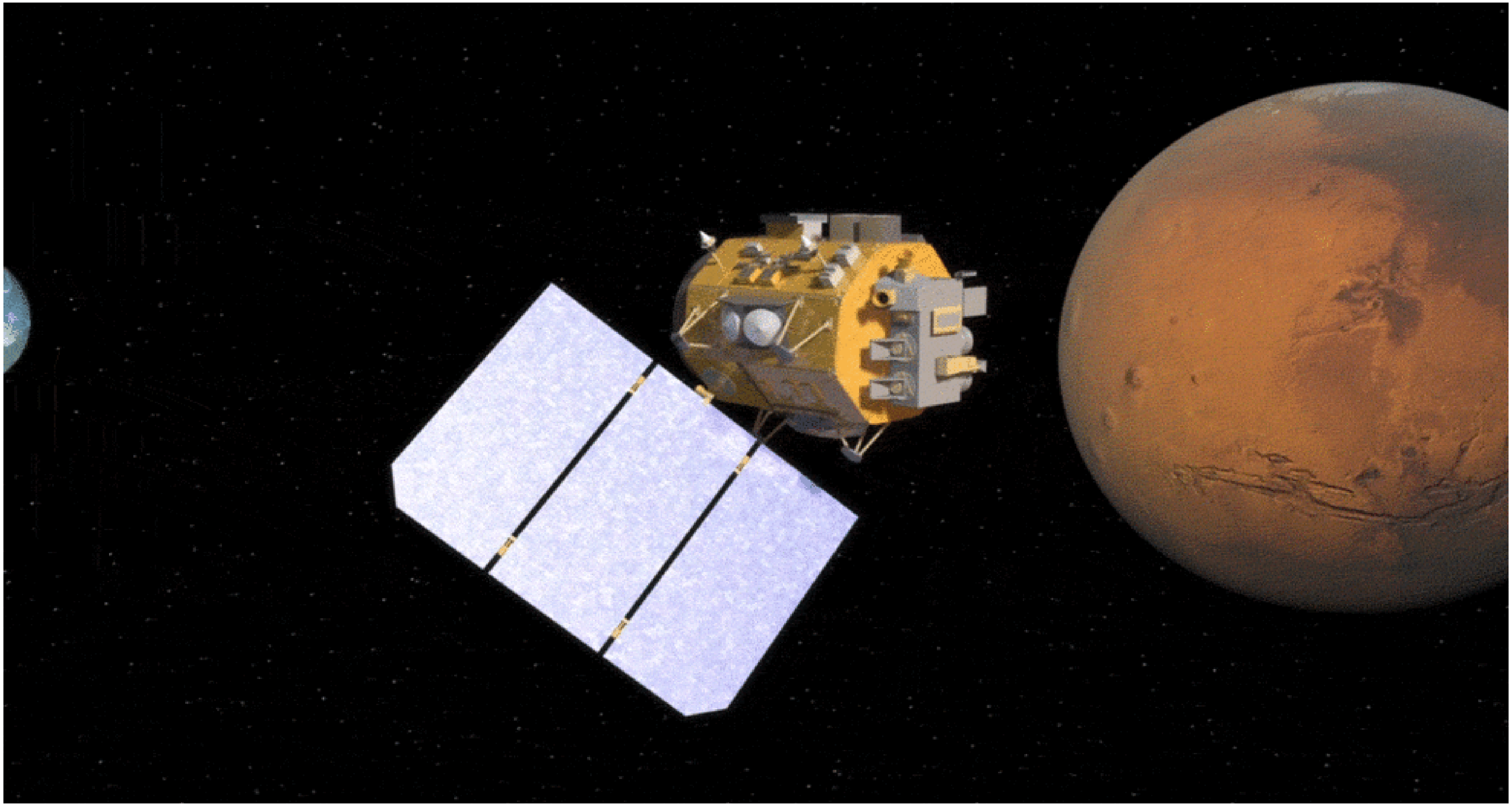

Photonic Integrated Circuits (PICs) for Next Generation Space Applications

Amanda N. Bozovich
amanda.n.bozovich@jpl.nasa.gov
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Jet Propulsion Laboratory
California Institute of Technology

Motivation

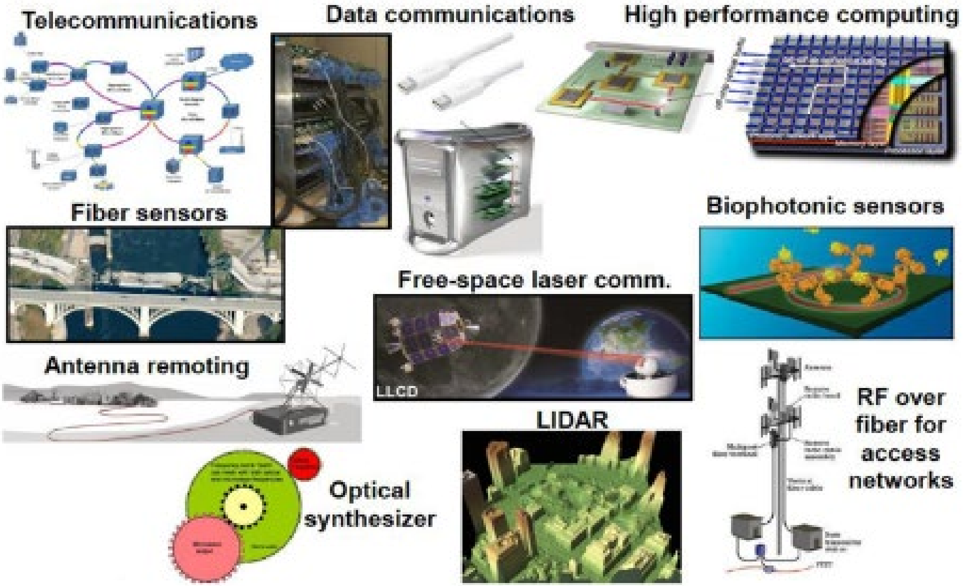
- Integrated photonics is expected to disrupt satellite technology in the same way discrete fiber optic systems revolutionized commercial terrestrial networks.
- Currently no defined path to space qualification for PICs. Industry standards for optics and photonics (Telcordia) are only suitable for commercial applications.
- JPL and industry partners are at the forefront of raising the TRL of emerging photonic technologies as well as developing novel space qualification methods (***includes development of integrated photonics radiation and reliability database***).

```
# endregion I/O ports

nline = n_vcsel_in.offset(0,0,-90).trim_to(nw).flip()
straight(dev, "WG_RIBS_ADD", nline, nline.trim_to(ne), 25.0)

# region mode-strippers
n_fiber_ins = [taper_wg(dev, INPUT_WG, node, RWG_2000) for node in n_fiber_ins]
n_fiber_ins = [straight_wg(dev, node.wg_def, node, node.trim_to(nw).offset(-850.0)) for no
n_fiber_ins = [taper_wg(dev, node.wg_def, node, RWG_2500) for node in n_fiber_ins]
n_fiber_ins = [rib_strip_wg(dev, node.wg_def, WG_2500, node) for node in n_fiber_ins]
# endregion mode-strippers

# region alignment waveguides
nar = n_fiber_ins[0]
nal = n_fiber_ins[3]

nar = line_wg(dev, nar.wg_def, nar, 200.0)
 l = line_wg(dev, nal.wg_def, nal, 200.0)
  nal] = [taper_wg(dev, node.wg_def, node, WG_1875) for node in [nar, nal]]

  er_wg(dev, nal.wg_def, nal, R_EULER_1310_L, 90)
  uler_wg(dev, nar.wg_def, nar, R_EULER_1310_L, -90)

  id = nal.offset(abs(nal - nal.trim_to(nar)) / 2.0

nodes = mmi_2x2_wg(dev, WG_3000, config.strip

node = taper_wg(dev, WG_3000, nodes[0], WG_18
straight_wg(dev, WG_1875, nal, node.flip())

node = taper_wg(dev, WG_3000, nodes[2], WG_1875)
straight_wg(dev, WG_1875, nar, node.flip())

nal = taper_wg(dev, WG_3000, nodes[1], WG_1875)
nar = taper_wg(dev, WG_3000, nodes[3], WG_1875)

nal = euler_wg(dev, nar.wg_def, nal, R_EULER_1310_L, 90)
nar = euler_wg(dev, nal.wg_def, nar, R_EULER_1310_L, -90)
[nar, nal] = [taper_wg(dev, node.wg_def, node, WG_2500) fo
[nar, nal] = [strip_rib_wg(dev, node.wg_def, RWG_2500, node)            nar, nal]]
```

Photonic ICs (PICs) are scalable, advanced systems-on-chip that are the next generation disruptive technology critical to meeting size, weight, power (SWaP) goals for a diverse range of next generation space applications.

Evolution of Commercial PIC Market

- Telecom and datacom applications main drivers for development of commercial PICs.
- PIC market rapidly growing: ~\$190M in 2013, ~\$539M in 2017, ~\$3.5B by 2024.
- PIC optical transceiver market to grow 20X over next five years to accommodate needs of large data centers and 5G.
- Embedded computing capabilities, high level of integrated functionalities, low weight, power efficiency, and hyper-scale performance expected to fuel future PIC demand.



PICs offer capabilities to advance many revolutionary technology markets, while continuing to meet growing demand for energy-efficient optical links for datacenters and quantum computers.

Large market beyond optical communications and commercial data centers!

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

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	🟨					

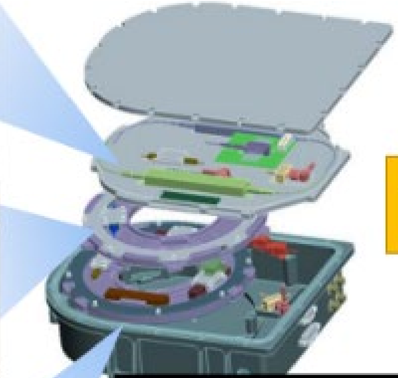
Photo Credit: Dr. Eric Mounier and Jean-Louis Malinge, Yole Développement, “Silicon Photonics and Photonic Integrated Circuits 2019”, http://www.yole.fr/PhotonicIC_SiPhotonics_MarketUpdate_Intel.aspx#.Xttu8DpKhPY

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.

Integrated Photonics Advantages

Fiber-based Transmitter

DSOC Laser Transmitter assembly

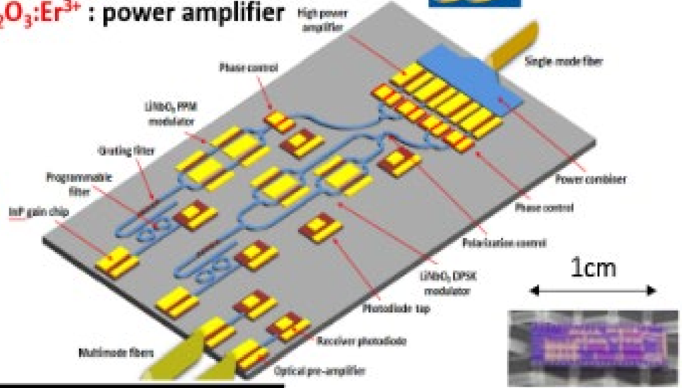


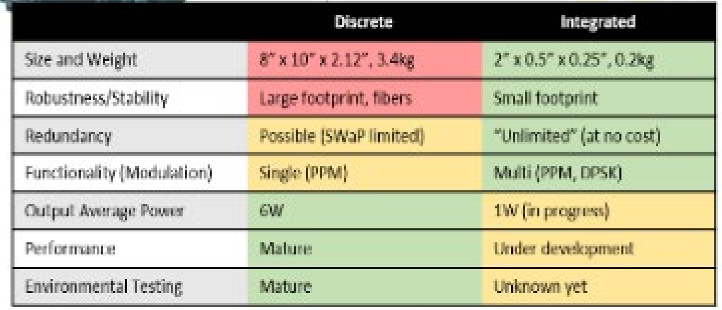
Future

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

PIC can replace oscillator and pre-amplifier slices.

- **Power amplifier is under development**

- Key PIC benefits: considerable SWaP savings, higher bandwidth and data rate, low cost redundancy, aperture-independent (fiber-coupled), transparent to modulation format, versatile, and scalable, while offering potentially significant improvements in reliability and radiation hardness.
- Due to lower average output power, PICs currently more suitable for LEO cube sat/small sat missions until TRL is advanced.

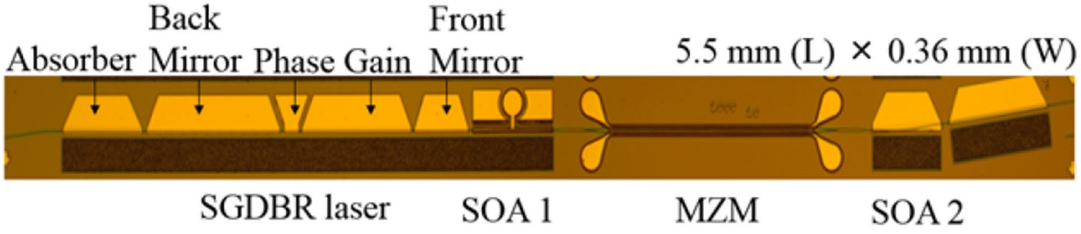
Overview of JPL Integrated Photonics Work

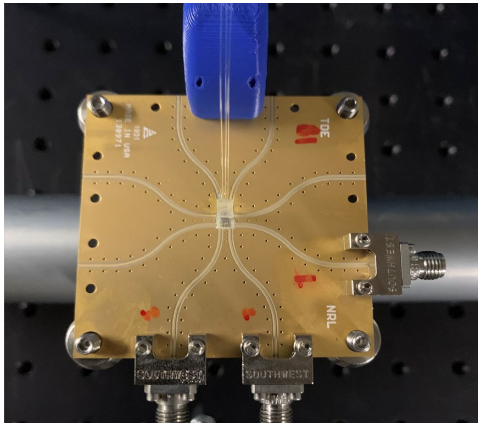
Problem Statement:

- Demanding space requirements (i.e. high peak-to-average power, high extinction ratio, radiation, lifetime reliability, stability).
- Current state-of-the-art PICs designed and qualified for terrestrial communication systems in commercial applications as well as academia. 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.





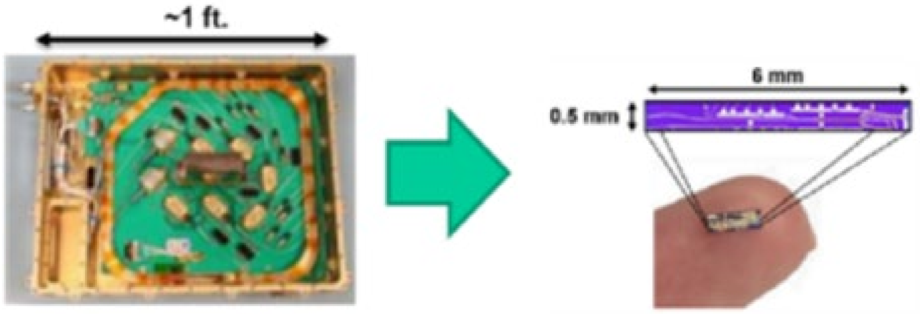
Example integrated photonic test structures characterized by JPL (1550 nm InP PIC - top and silicon waveguide with integrated germanium photodiode - right)

Importance of JPL Integrated Photonics Work

- Position NASA as a leader in development and flight qualification of advanced integrated photonics for space, while establishing partnerships across industry.

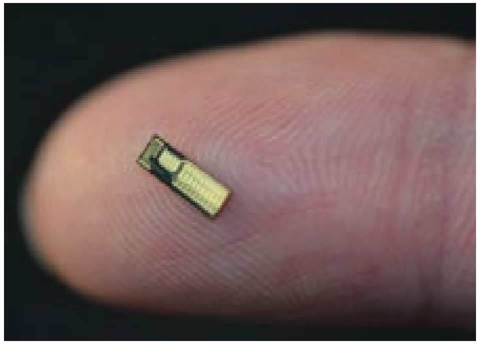
- Fill knowledge gap on methods for reliability and radiation screening and qualification of integrated photonics for space not addressed by commercial Telcordia standards.

- Reduce risk of flight insertion of integrated photonics into NASA space applications, while enabling order of magnitude improvements in SWaP.



Optical communications transmitter made with discrete photonic components

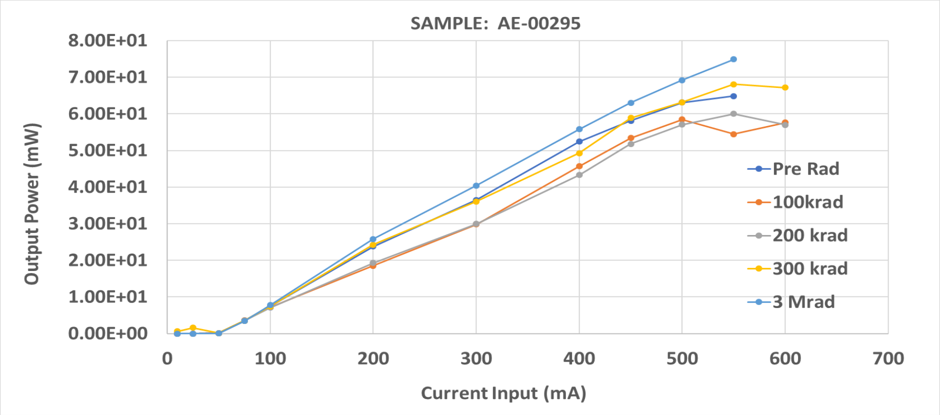
Photonic Integrated Circuit (PIC) Transmitter



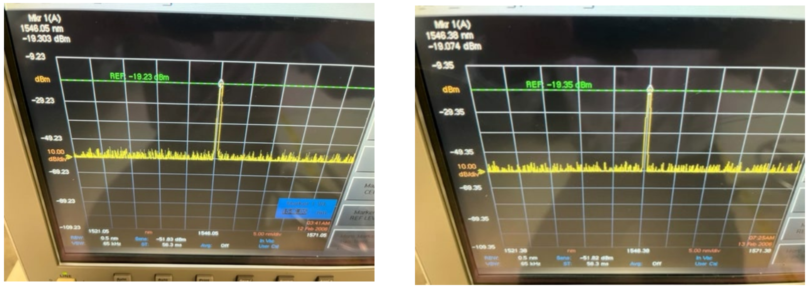
100 Gb/s Transceiver (powerful DWDM optical system on monolithically integrated InP PIC)

NEPP PIC Qualification Goals and Initial Radiation Data

- Development of photonics radiation data library and guidelines for space qualification.
  - Comparison of radiation hardness (TID, DD, SEE) across PIC material platforms.
  - Characterization data for key performance parameters (integrated vs discrete).
  - Lumerical physics modeling and Bayesian analysis to analyze trends in PIC rad data.
- PIC technology space qual roadmap developed as a function of platform, foundry/process technology, packaging, performance capability.

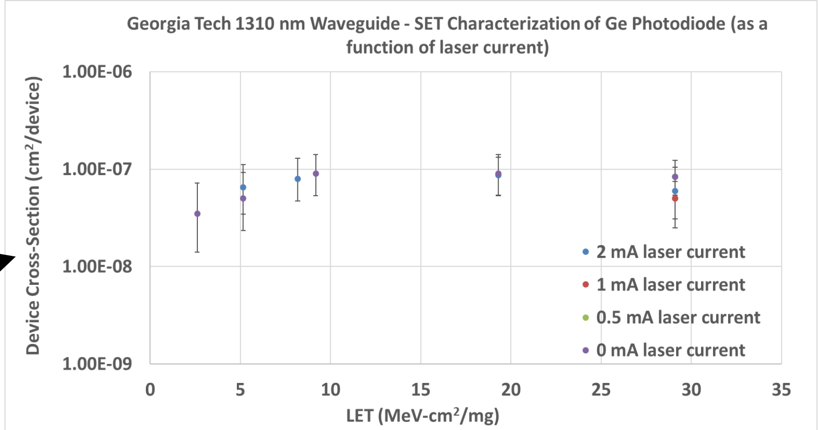


Total dose test results for Freedom Photonics 980 nm DBR lasers and 1550 nm InP PICs (integrated laser transmitter + SOA). Minimal change to 3 Mrad(Si) in LIV curves (optical power/voltage vs current).



Pre-rad (1546.05 nm) and post 3.5 Mrad(Si) (1546.38 nm) laser spectra for 1550 nm InP PICs. No shift in center wavelength observed post rad.

Heavy ion single event effects results for Georgia Tech 1 mm integrated silicon waveguides with p-i-n bulk germanium photodiode (60 GHz BW). No optical transmission loss or transient induced phase shifts to LET >120 MeV-cm^2/mg.



Initial results indicate potential robust radiation hardness of integrated photonics.

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

Integrated Photonics Data Library: Integrated Test Structures and Key Active Discrete Building Blocks

Component	Vendor(s)	Integrated vs discrete	TID	DD	SEE
Optical waveguide (Si and SiN) integrated photodetector (Ge) (1310 nm, 1550 nm)	Global Foundries/ Georgia Tech (GT)	Integrated (building block)	✓	✓	✓
InP PIC includes tunable laser, SOA, high-speed MZM, electro-absorption modulator	Freedom Photonics	Integrated	✓	✓	August 2022
InP PIC – Integrated Laser Transmitter (ILT) (1550 nm) (telecom C band)	UCSB	Integrated	August 2022	August 2022	August 2022
Tunable Sampled Grating Distributed Bragg Reflector (SGDBR) CW laser (incl SOA and EA mod – InP) (20 mW)	Acronymeo	Integrated	✓	✓	
SiN PIC	OEwaves Inc., UC Davis (NASA STTR program)	Integrated	August 2022	August 2022	
Silicon e-PIC (co-packaged with analog electronics/DSP ASIC)	Acacia Infinera (has InP)	Integrated	TBD	TBD	TBD
Semiconductor Optical Amplifiers (SOA) (1310 nm and 1550 nm)	InPhenix Anritsu	Discrete	✓	✓	
Mach–Zehnder Modulator (MZM) (800 nm and 1550 nm) (w/ photonic RF driver)	Georgia Tech (Si and SiN)	Discrete	August 2022	August 2022	August 2022
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	TBD	TBD	TBD

Summary of NEPP Integrated Photonics Work

- <u>Key Accomplishments</u> and immediate near-term <u>Plans</u>:
  - Developed white papers and test plan for defining potential radiation-induced failure mechanisms in PIC technologies (TID, DD, SEE)
  - Completed Freedom Photonics PIC TID and DD testing (to high fluence using 50 MeV protons)
  - Completed heavy ion testing with Georgia Tech on integrated silicon waveguides. Plan to test GT SiN waveguides and discrete silicon photonic devices (MZM)
  - Planned additional TID and DD proton testing on survey of commercial discrete and integrated photonic devices (UCSB, NeoPhotonics, etc)
  - Lumerical physics modeling and Bayesian analysis to analyze trends in PIC rad data.

- Long term project goals for FY22 and beyond:
  - Generate NEPP reports/summaries 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 will fold into 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.

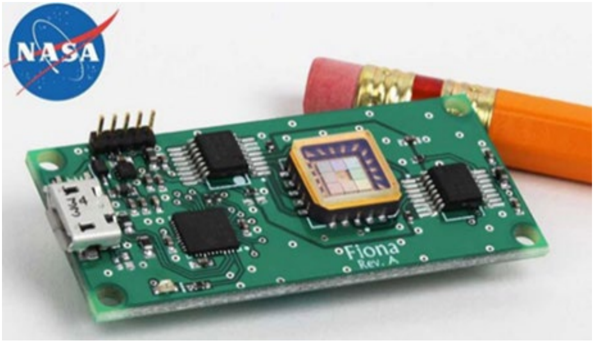
- Identify mission platform for flight insertion for radiation test/space qualified PIC.

JPL Photonics Qual Program Impact

- **Summary of goals:**
  - demonstrate feasibility of commercial PIC technology with path to flight from tech demo to high reliability mission
  - define challenges impacting development and integration of PICs for space applications

- With its highly collaborative, cross-project and cross-division information exchange, the program will enable proactive identification of limitations and failure modes of new devices.

- Other focus areas:
  - Raise TRL of technologies developed by MDL (i.e. MWIR/LWIR infrared detector focal plane array, Superconducting Nanowire Single Photon Detectors)
  - Space qualifying quantum sensing components for gravity gradiometer



Cross JPL Collaboration Fuels Rapid Technology Infusion with Reduced Risk

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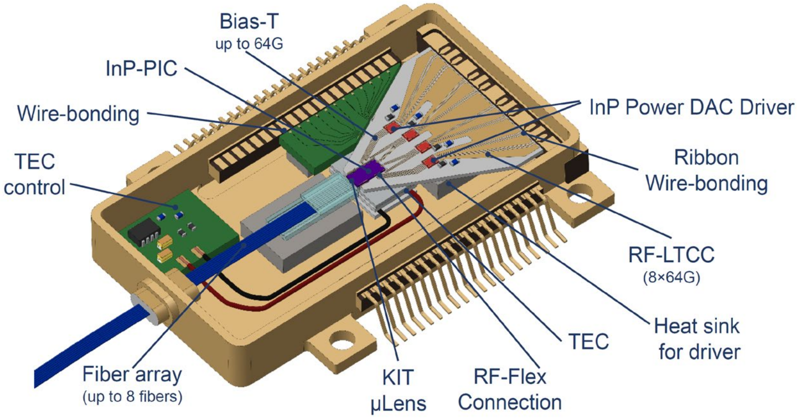
Photonics Space Qualification Challenges

- **Materials, Process, Performance Unknowns**
  - Lack of radiation and reliability data – radiation tolerance, failure modes & mechanisms unknown (no standards for component selection/design)
  - Many PIC materials
  - Lack of physics models to base design of reliability/accelerated life tests

- **Space Packaging Challenges**
  - Effect of packaging design on functional performance (no standards exist)
  - Sensitivity to launch environments and outgassed materials
  - High level of electronic-photonic integration results in complex packaging with control circuitry, amplifiers, and electronic drivers.
  - Die processing varies therefore assembly is more complex



Background of Heavy Ion NEPP Testing of Integrated Waveguides

- Limited radiation studies on PICs have focused on TID (Mrad hard technology). In particular, TID (x-ray) and displacement damage testing on waveguide-integrated germanium photodiodes indicates minimal impact on device performance.
- Heavy-ion induced single event effects remains an unproven/unknown, but critical area of PIC radiation research. Models indicate SET sensitivity will likely be dominant radiation concern for silicon integrated waveguides, with charge deposited from an ionizing particle interacting with the optical signal or being collected by the photodiode and corrupting the signal integrity if it overwhelms the electronic response of the device.
- **Specifically, this work examines optical single event transients (OSETs), which pose a potential concern when using integrated optical systems in space.**
  - ➢ Definition of OSET: perturbation of optical power within an integrated optical component that strictly exists in the optical domain and does not affect the functionality of any electronics that precede it. This perturbation is due to a sudden increase in electron hole pairs (EHPs) generated by an incident ionizing particle or photon, and results from transient free carrier absorption (TFCA).
  - ➢ TFCA mainly impacts the transmission properties of the optical component.
  - ➢ Other optical components that could exhibit OSETs are PN-based optical phase shifters, Mach-Zehnder interferometers, and ring-resonators.
- **There has been no experimental validation of the existence of optical-SETs (OSETs) in the heavy-ion environment.**
- GT-JPL collaboration goals:
  - Demonstrate first measured heavy-ion induced OSET to study transient-induced phase shift and power loss at output of these test structures.
  - Examine how these device performance metrics change as the SEE propagates through the integrated photonic structure.
  - Understand/explore mechanism by which sudden increase of free carriers in an integrated waveguide modifies its optical properties and causes the OSET
  - Validate SEE modeling for PIC structures for various ion energy levels as well as for various device fabrication dimensions and materials. Consequently, methods for improving the radiation hardness of photonic devices may be established through the analysis of these models and test results.

Georgia Tech Simulation Results

- Waveguide modeled in Lumerical software.
- Heavy-ion absorbs fraction of optical signal. OSETs are direct result of reduction in the optical transmission ratio due to transient free-carrier absorption.
- The peak of the largest measured OSET degraded the transmission ratio by 15%, which, according to simulations, corresponds to ~9 × 10^{19} cm^{-3} peak EHP generation.
- Simulation results suggest EHP density levels generated by heavy ions in space could potentially cause up to 100% fractional extinction of light in the waveguide (i.e. total loss of the optical signal).
- The results of this study pose concerns for use of integrated silicon photonics in radiation-intensive space applications.

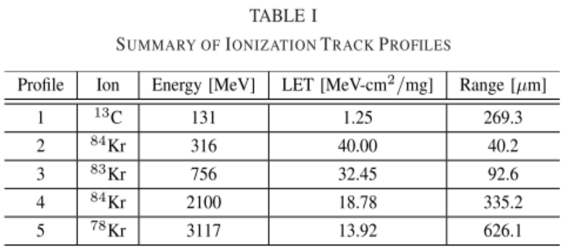
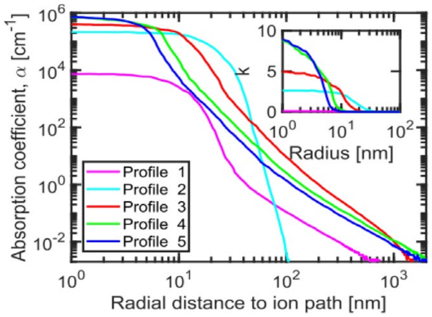


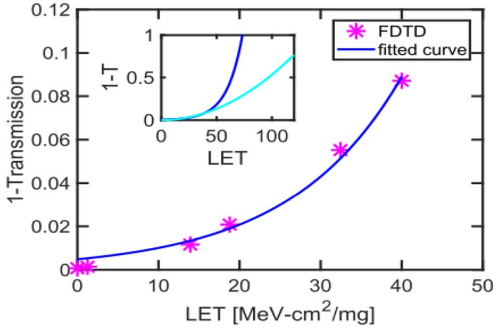
TABLE I

SUMMARY OF IONIZATION TRACK PROFILES

Profile	Ion	Energy [MeV]	LET [MeV-cm^2/mg]	Range [μm]
1	^{13}C	131	1.25	269.3
2	^{84}Kr	316	40.00	40.2
3	^{83}Kr	756	32.45	92.6
4	^{84}Kr	2100	18.78	335.2
5	^{78}Kr	3117	13.92	626.1



Predicted Ion-Induced Degradation of Light



As presented by G. Tzintzarov (Georgia Tech)

Georgia Tech Si Waveguide Heavy-Ion Test Results Summary

- **Heavy-ion characterization of critical building block of photonic integrated circuits – integrated silicon waveguides:**
  - ➢ Completed heavy ion testing with GT on 1310 nm silicon waveguides with integrated Ge (LPIN) photodiodes.
  - ➢ We did not observe optical single event transients in the silicon waveguides, but we did characterize the transients at output of the photodiode (explored SET dependence with and without laser light). Transients on the order of a few hundred mV and ps.
  - ➢ Mapped out cross-section for photodiode transients – low likelihood of occurrence, first step in demonstrating silicon photonics is rad hard.
  - ➢ Recorded distribution in transient amplitude and duration for varying laser bias.
  - ➢ Tested at higher LETs to induce optical signal event transients in the waveguide at Texas A&M in May. Will demonstrate rate of occurrence for any radiation environment will be low for optical SETs.
  - ➢ Will test 1550 nm and SiN test structures, and Mach Zehnder Modulators.