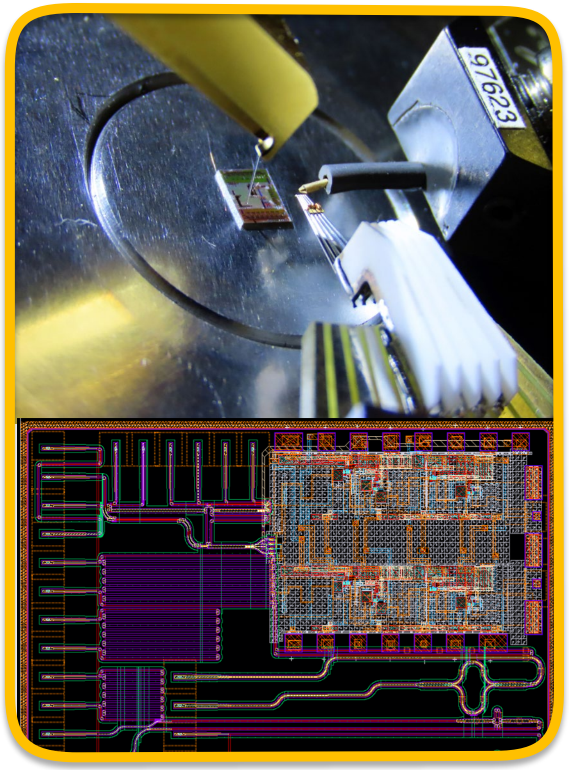
CREOL UCF · Georgia Tech · VANDERBILT UNIVERSITY



Electronic-Photonic Integrated Circuits for Aerospace

EPICA

An NSF IUCRC

Designing and validating advanced electronic-photonic integrated circuits and systems for harsh environments

Center Director: Prof. Stephen E. Ralph
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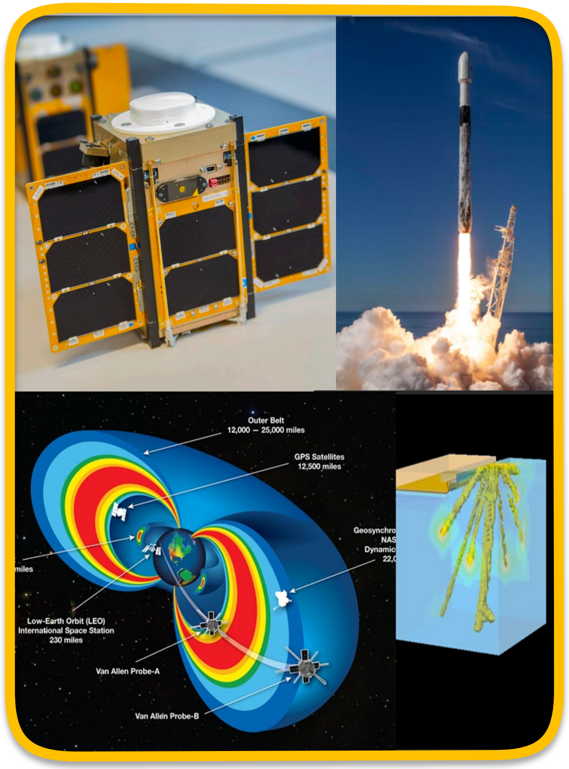


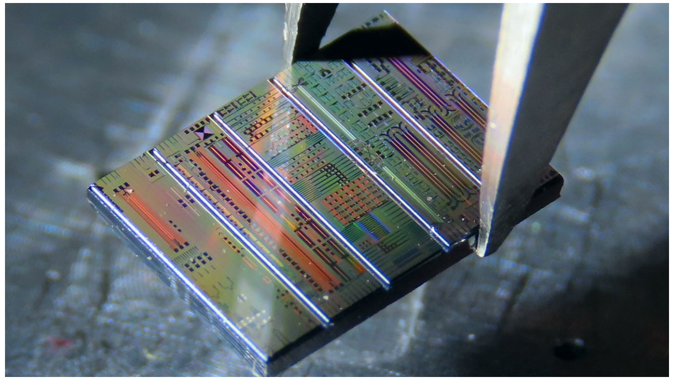
The Georgia Institute of Technology together with Vanderbilt University and the University of Central Florida have been awarded funding from the National Science Foundation to lead a new Industry-University Cooperative Research Centers Program (IUCRC) in Integrated Photonics for aerospace applications

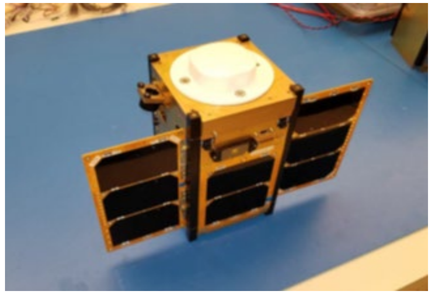
https://hg.gatech.edu/node/647328

Part I: EPICA Program Summary and Membership Opportunities

Electronic and Photonic Circuits for Aerospace: EPICA

EPICA is an Industrial Research Collaborative Research Center (IUCRC)
Funded by the National Science Foundation and Industrial Partners





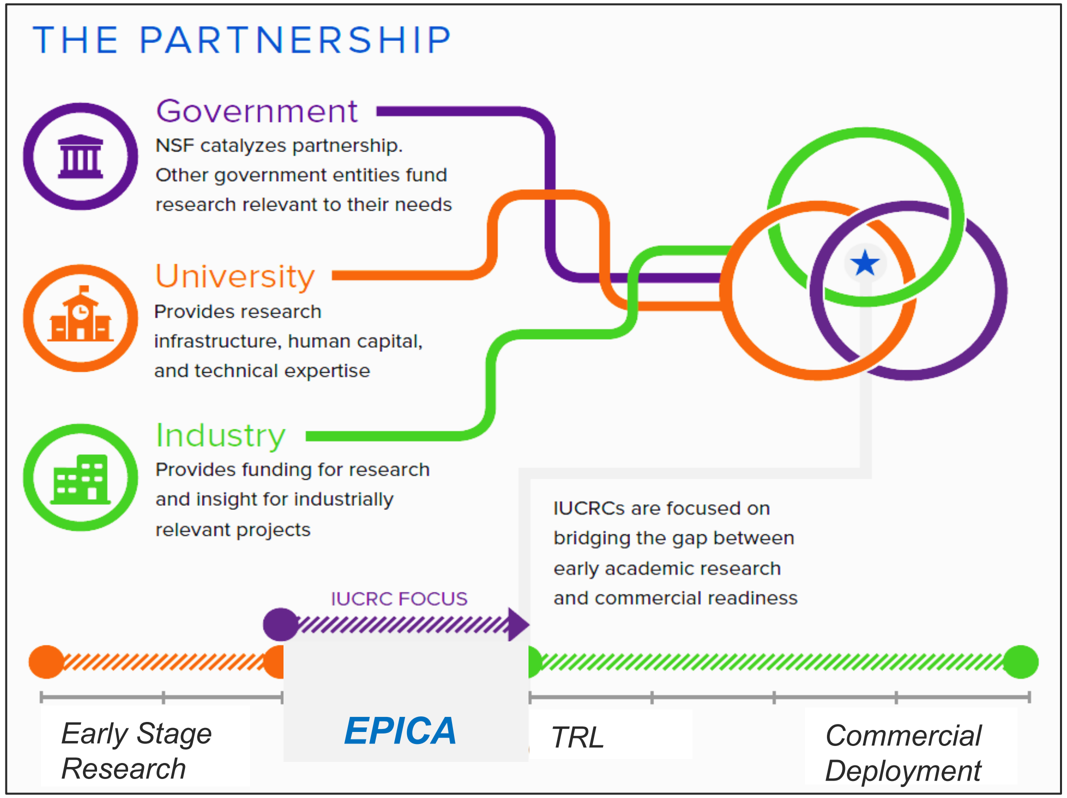
EPICA's mission is to enable the use of integrated photonics and electronics in communications and sensing applications for spaceborne and aerospace platforms

The NSF IUCRC Program

NSF funds all management and administrative costs

Memberships provide funds for all directed research

- The IUCRC program catalyzes breakthrough pre-competitive research by enabling close and *sustained* engagement between industry innovators, world-class academic teams, and government agencies
- IUCRCs help industry partners and government agencies achieve three primary objectives:
    1) Conduct high-impact research to meet shared and critical industrial needs in companies of all sizes;
    2) Enhance U.S. global leadership in driving innovative technology development, and
    3) Identify, mentor and develop a diverse, highly skilled science and engineering workforce



EPICA Mission

- Aerospace and spaceborne platforms have become essential infrastructure that support communications, climate monitoring, sensing and exploration
  - Integrated photonics has emerged as a technology that enables systems with unmatched functionality, power efficiency, longevity and thus dramatically improving the capability of these platforms
  - It is therefore imperative to establish the viability and safety of key enabling integrated electronics and photonic technologies for operation in harsh environments

- EPICA is focused on three *activity thrusts* that will greatly benefit scientific, defense, and industrial sectors:

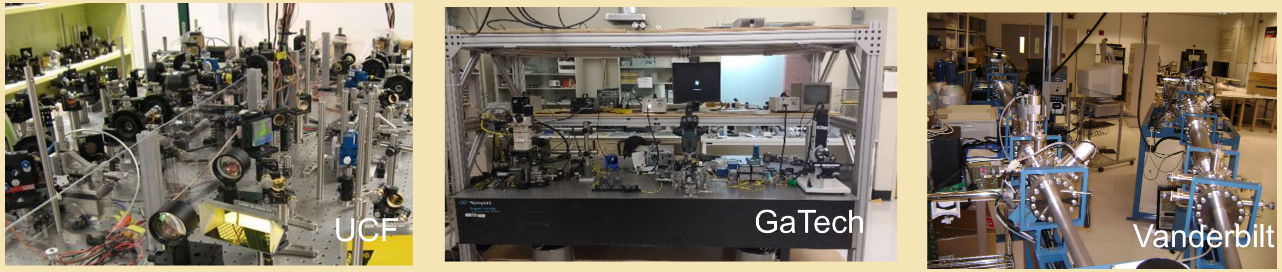
  1) Develop components and architectures using system-level methods and tools to extract maximum advantage of integrated photonic systems for aerospace platforms, including the impact of DSP and machine learning and considerations of SWaP

  2) Assessment, understanding, and development of robust integrated photonic hardware (architectures, devices, circuits and packaging) for reliable operation under extreme environment conditions, primarily radiation and temperature extremes

  3) Develop flight hardware and mission architectures for subsequent flight demonstration

Device Design to System Validation

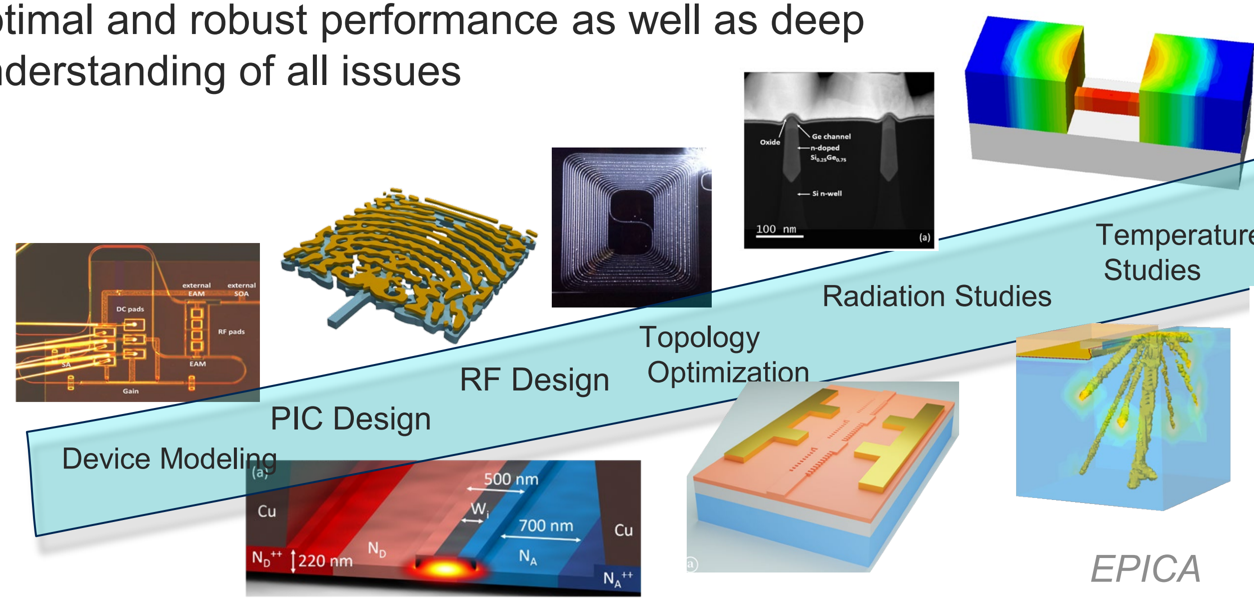
Emphasis on experimental results to validate models and performance

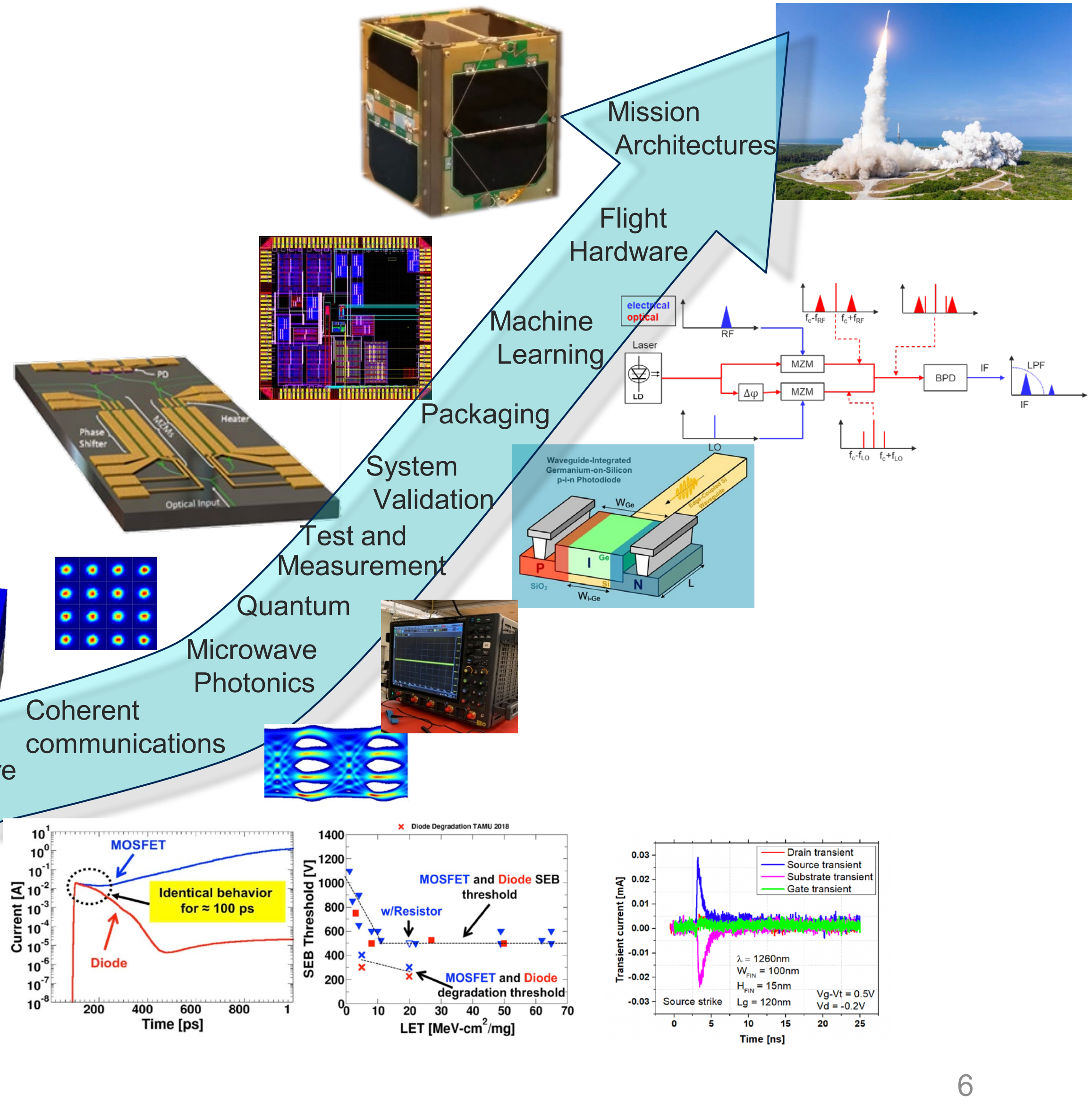


The team has unmatched design, modeling and simulation tools

RF characterization spans DC to 300GHz and lightwave covering visible to near IR

- The collaborative efforts are organized to support multiple design and test iterations thus ensuring optimal and robust performance as well as deep understanding of all issues





EPICA Universities

Georgia Tech

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Sasan Fathpour

- The three-university team has complementary expertise and facilities spanning device and circuit design, systems evaluation, packaging, radiation and temperature studies and space mission design
- This enables us to apply both fundamental and practical requirements in the development of new functionalities and as well as in the understanding of failure mechanisms when these systems are subject to extreme environments
- The diverse team of component, systems and aerospace researchers will collaborate to advance knowledge of associated environmental considerations and craft specific components and architectures to meet the unique reliability and performance requirements

Foundry Access of EPICA

The team has extensive and sustained efforts with many foundries

Access to many foundries will be available, many will be EPICA members

- Global Foundries (GF)
  - 45CLO: 45nm monolithic RF electronic/photonic platform
  - C and O-band (1260 to 1360 nm and 1530 to 1565)
  - f_T, f_M~ 300 GHz
  - Photonic packaging, fiber attach and laser attach
- Infinera
  - InP platform
  - C-band (1530nm to 1565nm)
- TowerJazz
  - 180nm Silicon Photonic Platform
  - C and O-band
- AIM Photonics
  - 300mm CMOS based SiP
  - Heterogeneous 3D Integration w/ active interposer
  - Chip-scale test, assembly and packaging
- Sandia National Labs
  - 250nm, Silicon on insulator (SOI) platform
  - C-band (1530 to 1565 nm)

Financial and Membership Structure of EPICA

NSF Support

- *$450k per year for 5 years*
- *Covers all management and administrative costs*
- *Distributed among the three universities annually*

Center Members

Full Membership

- *$100k annual fee: membership and 2 votes for project selection*
- *$50k annual fee: membership and 1 vote for project selection*
- No overhead costs
- Participation in all Industry Advisory Board meetings (two annually)
- Collaboration and insight into all projects of the center

Affiliate Membership

- In-kind contributions*:* equipment/instruments/software
- Participation in all Industry Advisory Board meetings (two annually)
- Collaboration on projects

EPICA Members include: device and fiber manufacturers, foundries, Laser com companies, Gov. agencies and DoD Primes

Part II: Team Capabilities and Recent Innovations

Motivations: The Space Data Highway System

Space systems create new opportunities and challenges for deployment of electronic and photonic systems guided by artificial intelligence

Interplatform crosslinks: >100G optical

Terrestrial $\Leftrightarrow$ platform: microwave and optical

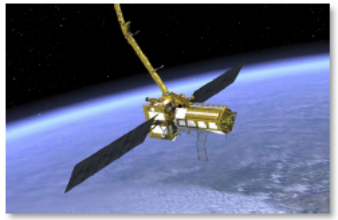
Intraplatform: copper $\Rightarrow$ optical

Motivations: Aerospace and Space-borne Applications

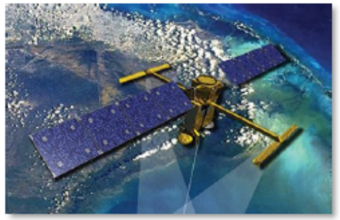
present unique opportunities for sensing and communications

Large Data Volumes on LEO Platforms

Large and Medium Satellites

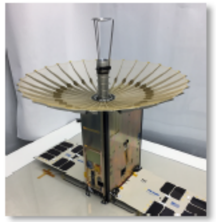


NASA-ISRO Synthetic Aperture Radar (NISAR) 2021

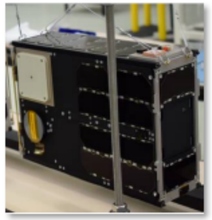


Surface Water & Ocean Topography (SWOT) 2021

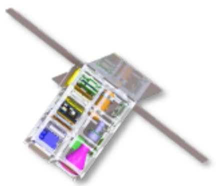
Micro/Nano Satellites



RainCube (JPL) In-orbit



GOMX-4B In-orbit



HYTI (UH Manoa) 2021

	NISAR	SWOT	RainCube	GOMX-4B	HYTI
Raw Data Volume Generated	33 TB/day	18 TB/day	1 TB/day	2 TB/day*	8 TB/day

Instruments on LEO platforms of all sizes are capable of generating enormous raw data volumes on the order of TBytes per day

TBIRD SmallSat 2019 - 2

*Assumes 25% operational duty cycle

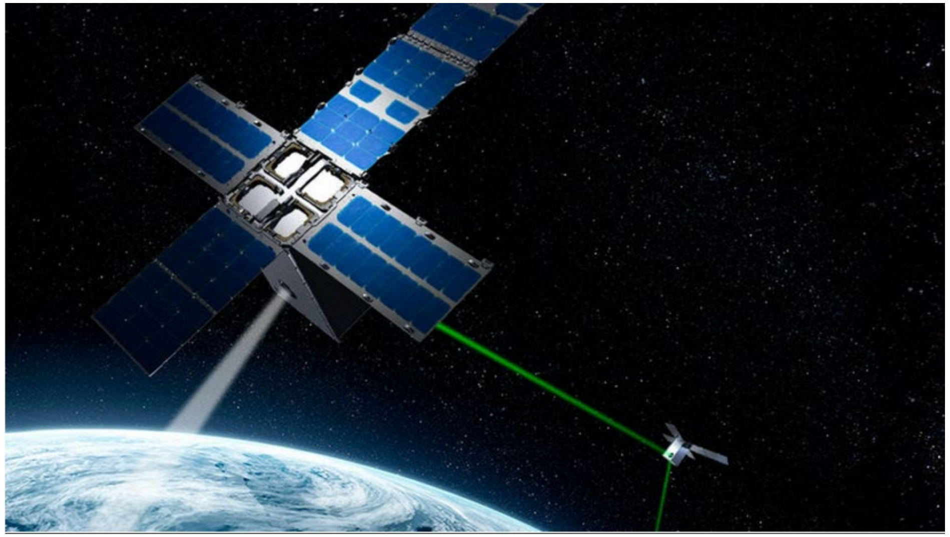
Image Credits, Left to Right: JPL, JPL, JPL, GomSpace, UH Manoa

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Motivations: DoD

- LEO constellations require satellite-to-satellite optical crosslinks
  - Low latency
  - Optical: best data per Watt
  - Secure optically meshed network in LEO can provide global secure communications
  - Power efficiency is key
  - Effects of space radiation on optics and electronics need more understanding of reliability

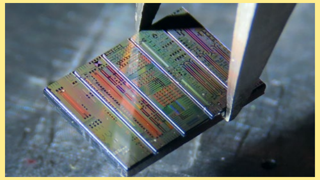
- Air-to-space lasercom system
  - LCT135 terminal, which is already in orbit
  - Supports data exchange at speeds up to 1.8 Gb/s over distances of up to 80 thousand km



Georgia Tech Team

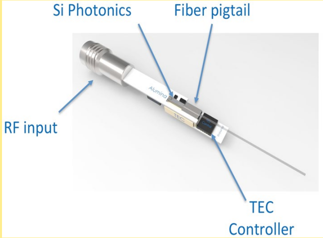
Technologies

- **Devices**
  - Integrated Photonics, Silicon, III-V, LiN
  - Device Physics, Modeling, Scaling Limits, reliability
  - Radiation Effects in Devices and Circuits
  - High optical power handling
  - Wide-Temperature Range Electronics (50 mK to 300°C)
  - Optimized devices with environmental robustness
- **Architectures**
  - Massive scaling of photonic processing
  - Optimized architectures with environmental robustness
  - Disaggregated systems
  - Monolithic Photonics and RF electronics
- **Topology Optimization**
  - Temperature and radiation tolerant devices and architectures
  - Compact monolithic systems
- **Machine Learning**
  - Signal Intelligence
  - Accelerated performance validation
  - System optimization/performance monitoring



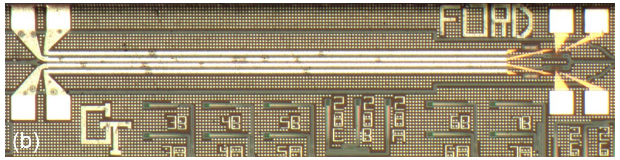
Deployments

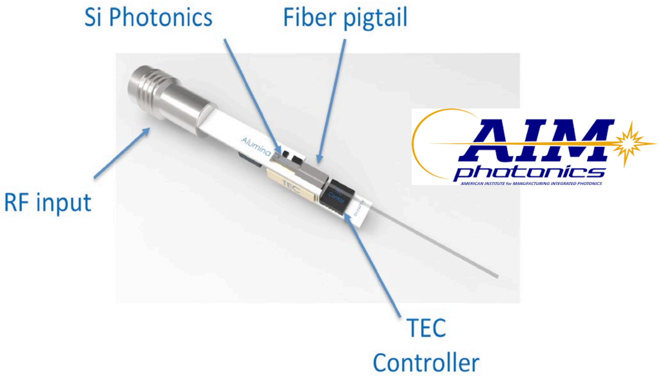
- **Communications**
  - Active optical cables
  - Optical signal switching/routing
  - Analog signal processing
  - Optical Interconnects and Packaging
  - Quantum
- **Microwave Photonics**
  - Fully integrated wideband frequency conversion
  - High spectral purity RF->THz sources
  - RF/optical phased array beamformers
  - Radar and Radiometry Systems (RF to mm-Wave)
- **Sensing**
  - Imaging Transceivers
  - Spectrometers
  - Chem/Bio sensing
  - Health monitors
- **Mission Design**
  - System Requirements
  - Full Mission Life Cycle
  - Mission Operations

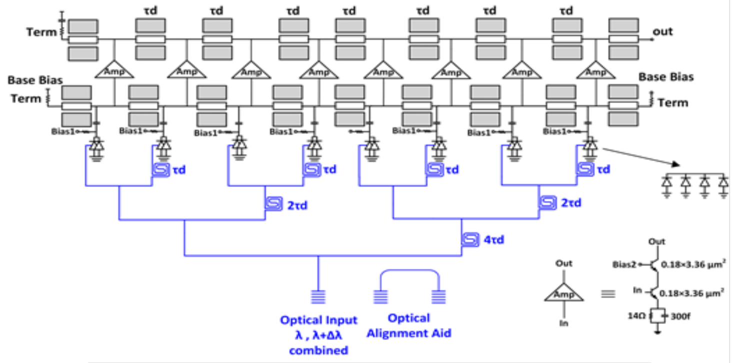


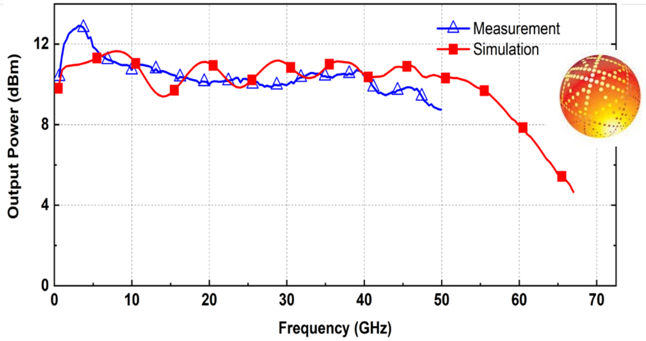
Integrated RF Photonic Systems

Georgia Tech

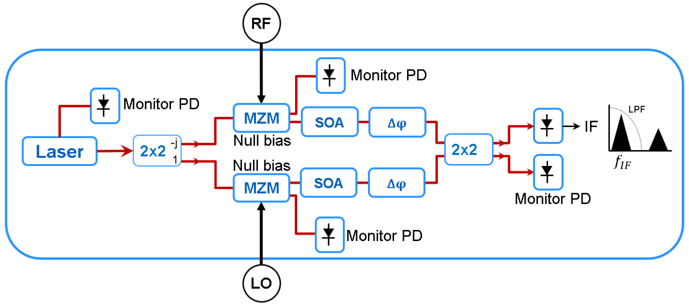


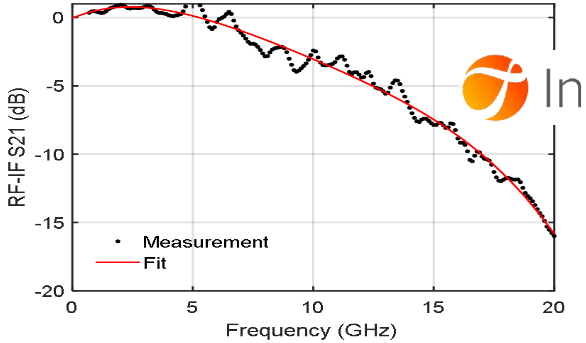






GLOBAL FOUNDRIES



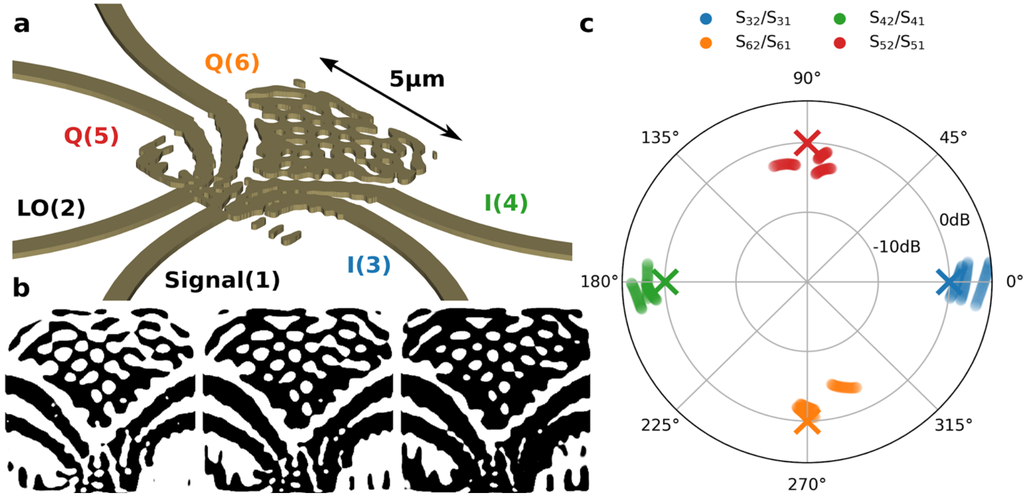


Infinera

- Silicon Photonic Platform
  - DC Kerr Effect linearized modulator
  - Supports SFDRs >100 dB·Hz$^{2/3}$
  - Key element needed to replace coax connections with lower SWaP and higher reliability for Airborne, UAV, UUV and space deployment
- Silicon Photonic/RF electronics Platform
  - Mixing occurs in high-bandwidth photodiodes
  - Monolithic traveling wave electronic amplifier produces higher power
  - System is tunable 1->50GHz and maintains the high purity created by the narrow linewidth optical source
- InP platform
  - Downconverter with exemplary analog metrics, SFDR > 104 dB·Hz$^{2/3}$, near unity gain, and 10.0 GHz bandwidth
  - This demonstrates that InP PICs can achieve performance commensurate to that achievable with discrete components

Photonic Topology Optimization

- Photonic topology optimization (TO) or “inverse design” is a powerful device-design methodology in which performance is optimized over millions of degrees of freedom characterizing every device “pixel”
  - TO allows completely unexpected designs with unprecedented performance to emerge
  - TO allows incorporates fabrication design rules and user constraints including performance over temperature and wavelength range, alignment tolerance or radiation impairments



GaTech Created world’s smallest, most scalable coherent receiver

a) 5 µm x 5 µm area, conforms to foundry DRC constraints

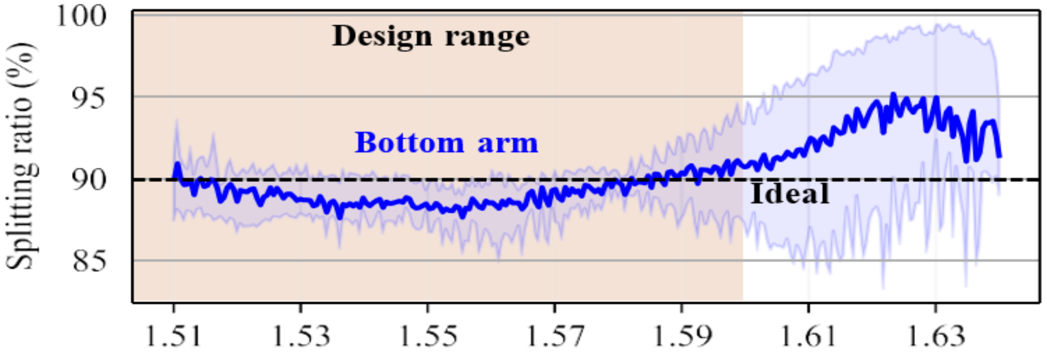
b) Optimized design fields representing; ideal device (center), over-etched device (left), and under-etched device (right). These variations are significantly higher than expected from foundry

c) The demodulation transfer function of the metastructure across the entire C-band and all design variations

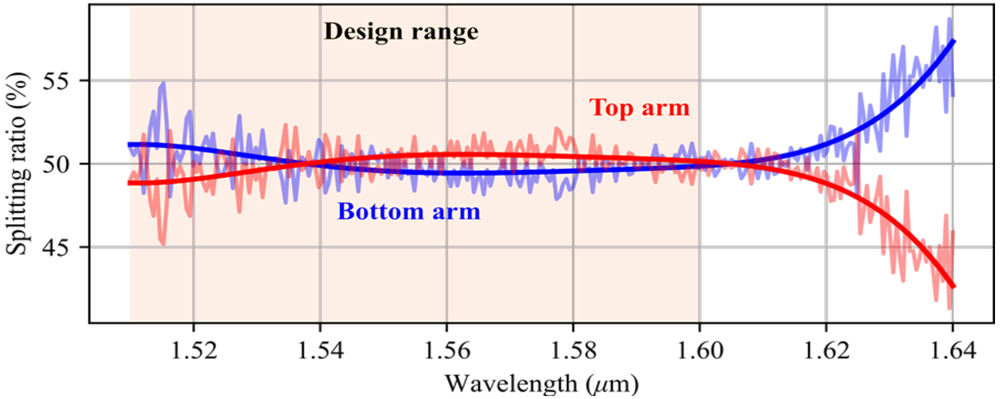
Georgia Tech has developed a unified framework for density-based topology optimization which produces integrated photonic devices that fully comply with commercial foundry design rule checks (DRC)

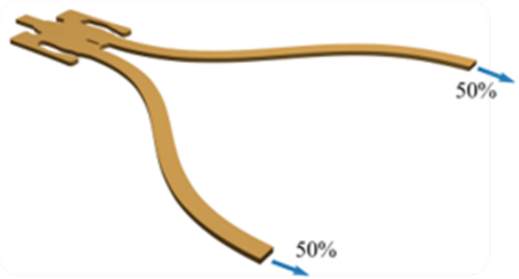
Straight Splitter Design

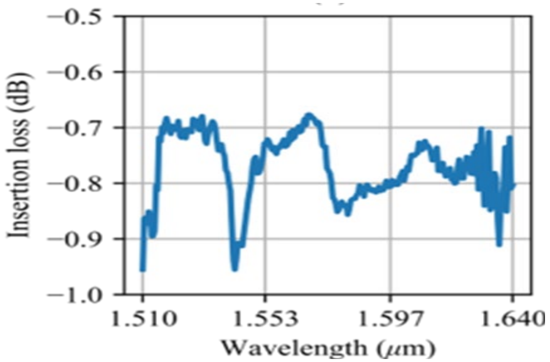
- Design evolution of a 90-10 straight splitter designed for GlobalFoundries 9WG
- Measured Performance
  - Across three devices randomly sampled from different wafers
    - Dark blue line: mean value
    - lighter shaded: minimum and maximum values
  - 2% variation in mean splitting within the design range (1.5 μm-1.6 μm)
- Other split ratios demonstrated similar performance
  - 50:50 and 99:1
- Experimental loss of a 3dB splitter



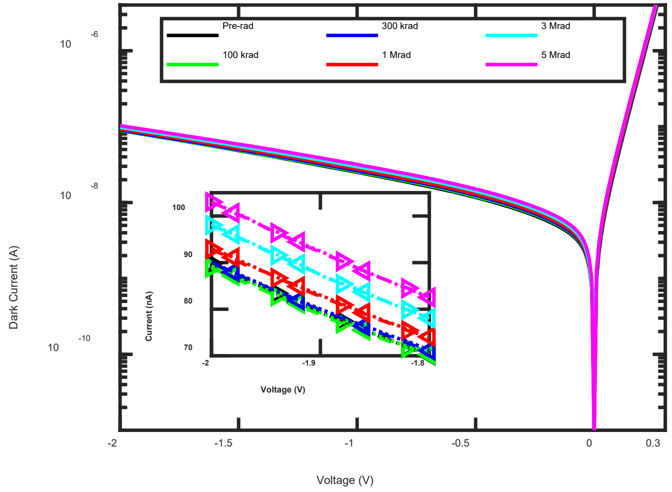
(c)

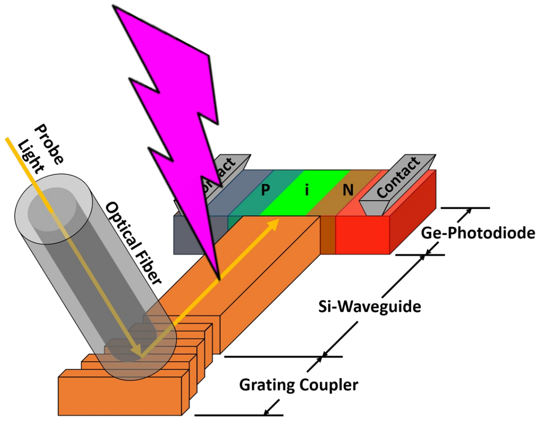


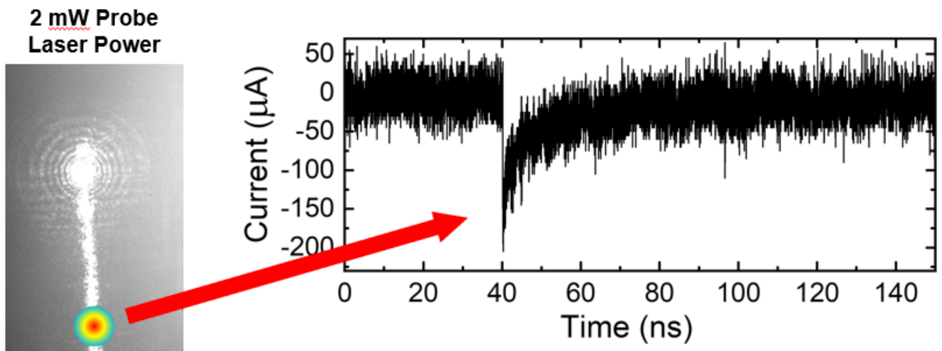




Radiation Effects and Temperature Extremes





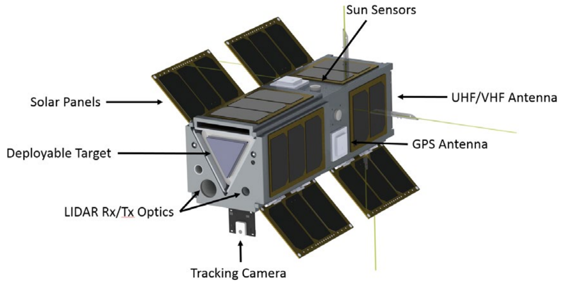


First Experimental Observation of Single-Event Transients in Integrated Waveguides (Purely in Optical Domain)

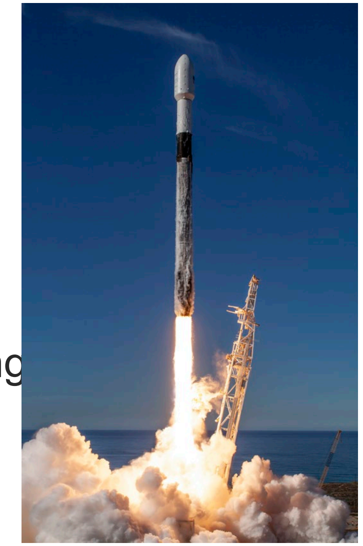
- Photonic components are generally robust to total ionizing dose (TID) and displacement damage, but are sensitive to transient radiation events (single event effects - SEE)
- Electronics are sensitive to both TID and SEE, and the radiation-induced coupling between electronic and photonic domains remains largely unexplored w.r.t both effects and mitigation approaches
- Extremes in temperature can couple strongly both electronics and photonic elements and can easily exceed commercial specs (0 to 85°C) and mil specs (-55 to 125°C), mandating further investigation
- New in-beam testing techniques for SEE do not exist at present and must be developed
- Existing redundancy and error correction schemes may prove insufficient to immunize photonic systems

Flight Hardware Development and Mission Architectures

- Georgia Tech has designed, built, and launched multiple small satellites
- Demonstrated experience with…
  - Space systems engineering & requirements
  - Flight software development
  - Orbital mechanics and spacecraft dynamics
  - Environmental testing
  - Mission operations
- Resources include
  - State-of-the-art orbit and spacecraft dynamics simulation software
  - Spacecraft hardware testing facilities, e.g., air-bearing/Helmholtz cage, solar simulator, etc.
  - Thermal-vacuum chamber, vibration table, and small-satellite prototype systems
  - Complete fabrication capabilities, e.g., machine shop, clean-rooms, custom PCBs, etc.
  - Multiple radio ground stations (UHF/VHF/S-band)



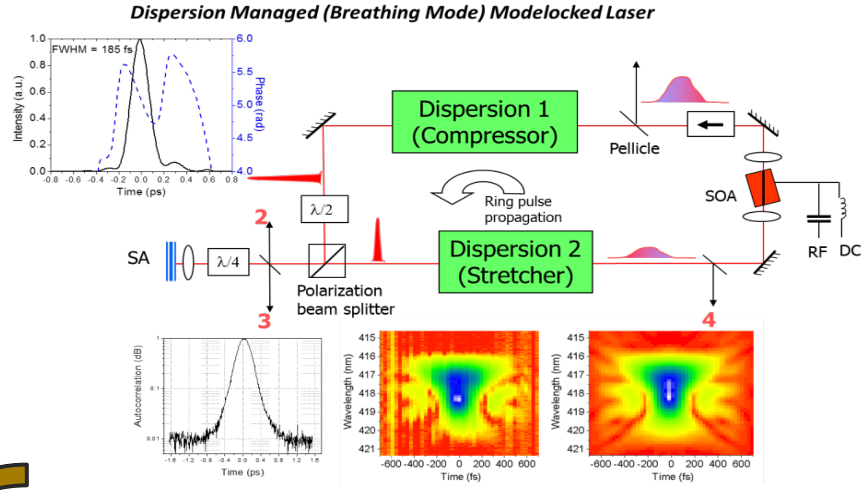
- Space systems
  - Small satellite missions
  - Formations/constellations
  - Precise orbit and attitude determination
- Novel space technologies
  - Optical communications
  - LiDAR
  - Multi-satellite computing/networking/tasking
- Applications
  - Remote Sensing
  - Communications
  - Space Domain Awareness (SDA)
  - Proximity operations
  - Planetary/cislunar



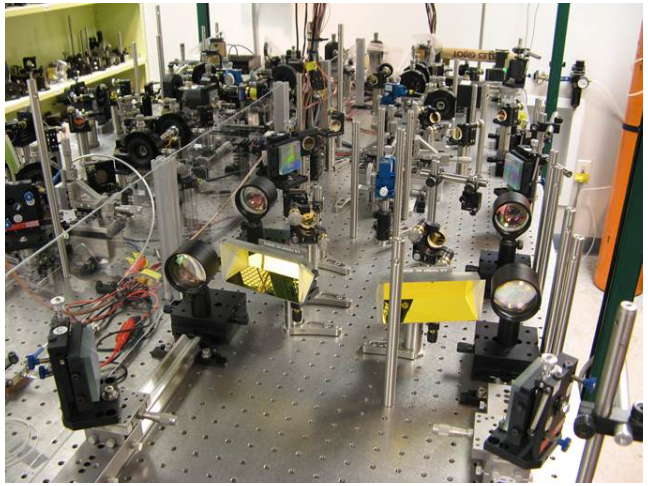
High Performance Photonic Systems in Chip-scale Solutions

Example 1: Chip-scale Optical Frequency Comb Generation

System Concept



Breadboard Demonstration

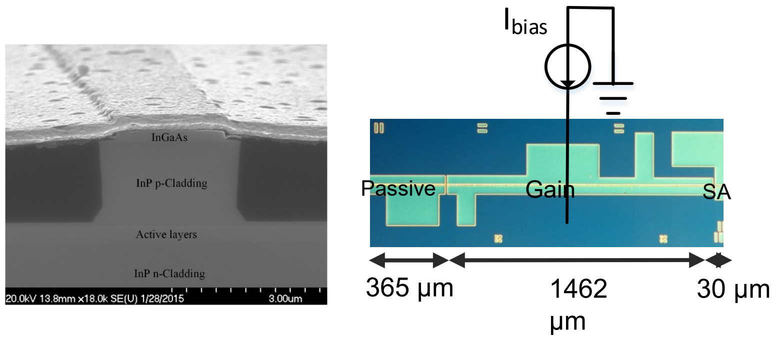


Novel system designs are numerically and experimentally verified using table-top test beds.

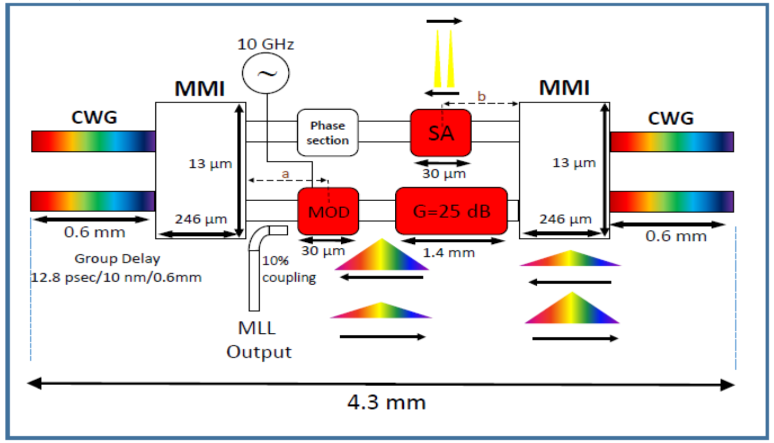
Key parameters are identified and optimized to demonstrate world class levels of performance.

Chip scale solutions are designed and implemented based on test bed Performance.

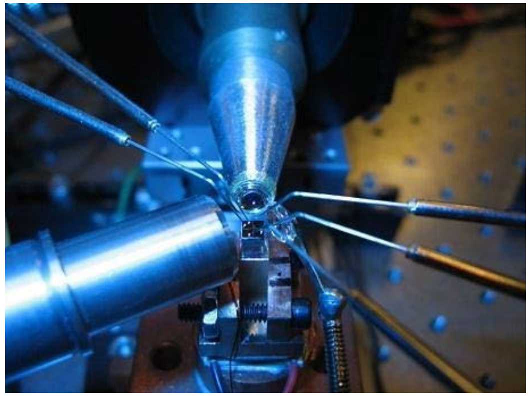
Initial Device Demonstration



Full System Development



Test Characterization

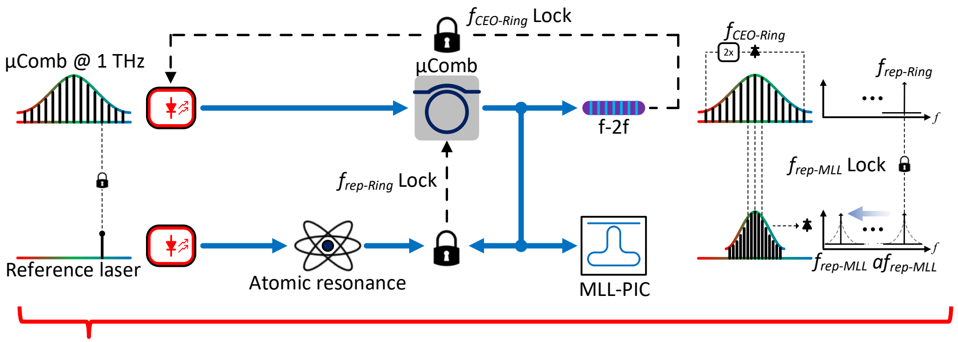


High Performance Photonic Systems in Chip-scale Solutions

Example 2: Chip-Scale Low Noise Microwave Signal Generation via Optical Frequency Division

Low noise microwaves are desired for many applications, e.g. radar
We first develop an innovative concept with potential for chip scale development

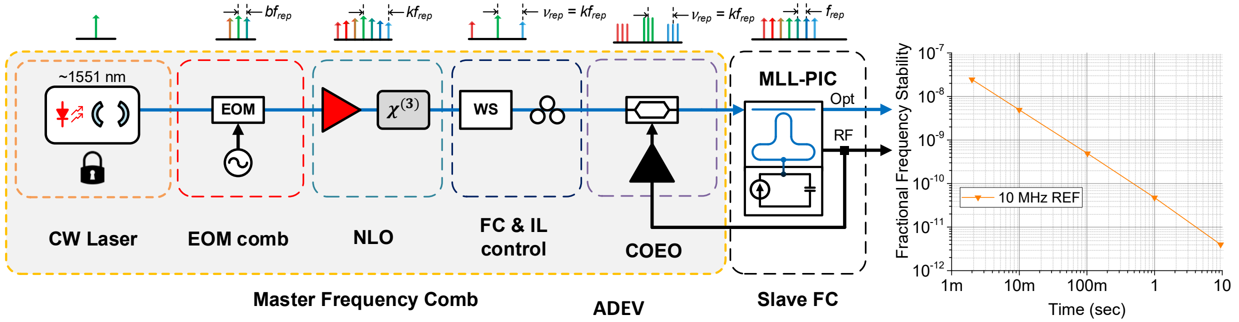
Direct optical to RF link via injection locking - System Concept



- **Achieve self-stabilized optical frequency comb on an integrated platform**
- **THz to GHz all-photonic link utilizing harmonic optical injection locking (*State-of-the-art* 300 GHz-10 GHz)**

Next, a table-top test bed is developed to provide proof of viability and identify key parameters that influence system performance

Simplified Table-top Setup

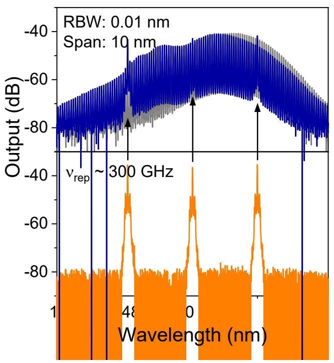


Master OFC
Optical linewidth ~ 30 Hz
Comb spacing: 30-300 GHz

MLL-PIC
f_{rep}: 10 GHz
P_{in}: 600 mW
BW: 2-6 nm

Initial Characterization and Experimental Results are obtained to identify areas for improvement

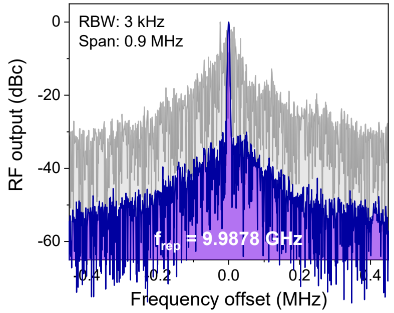
Optical Spectrum



Optical frequency division

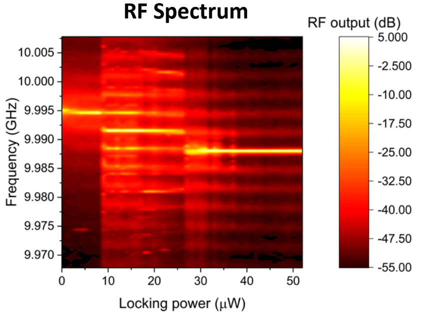
- Repetition rate directly detected from chip-scale MLL
- Low power technique uses less than 100 μW optical power from master laser

RF Spectrum

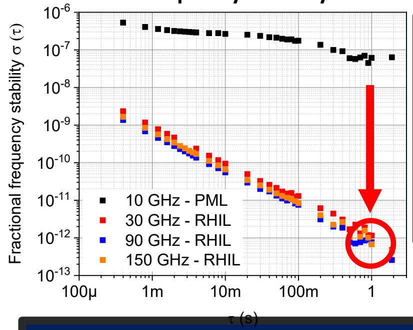


Improvement incorporated to demonstration of World Class Performance

RF Spectrum



Frequency Stability

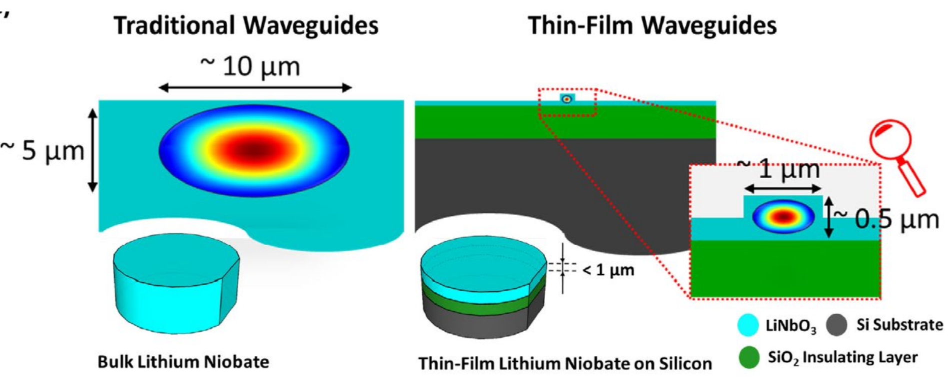


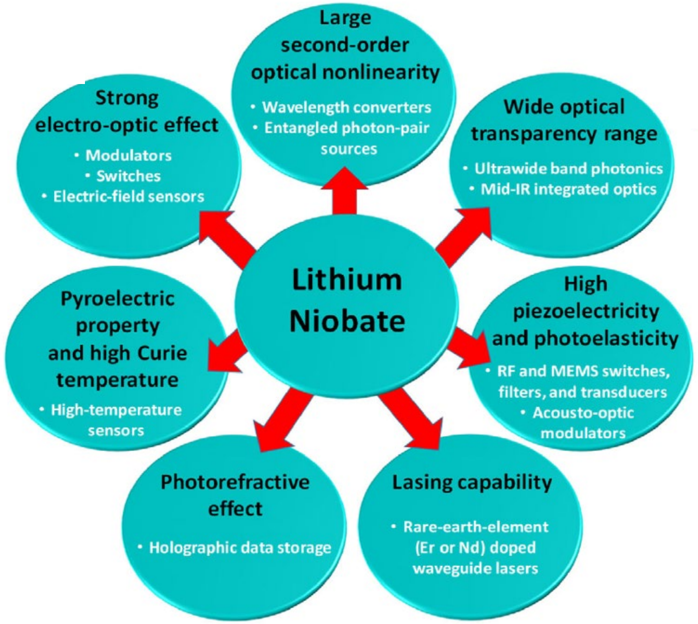
10 GHz source with 10mHz accuracy

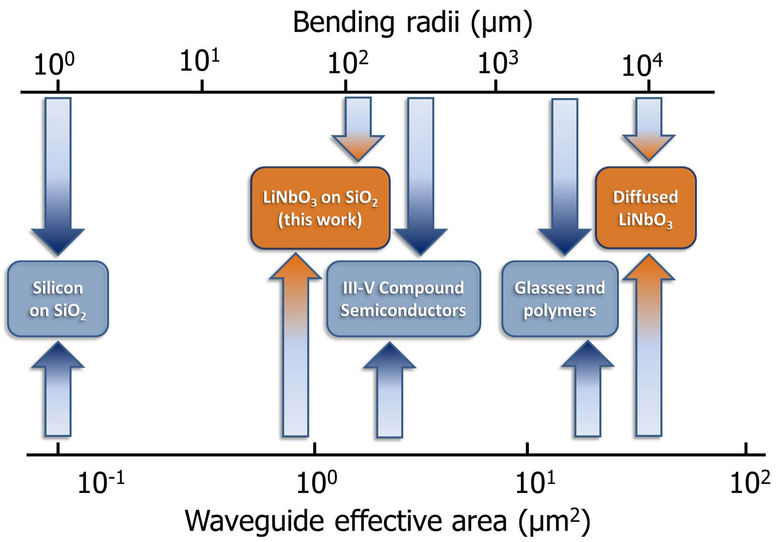
Optical frequency division via RHIL with a 30x1 ratio!

Repetition rate ADEV improvement from 10^{-7} to 10^{-12} at 1 second at 150 GHz RHIL

Thin-Film Lithium Niobate Photonics

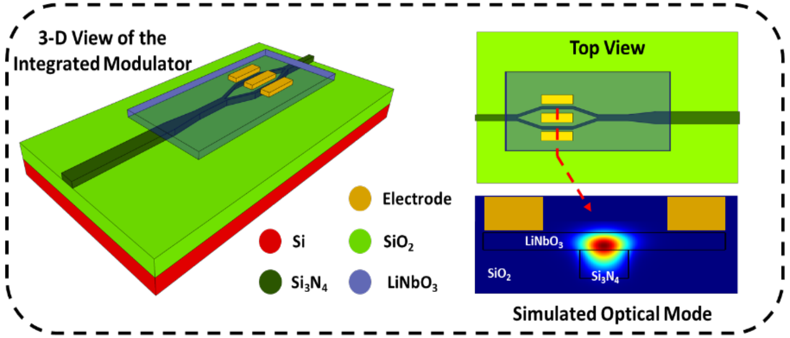


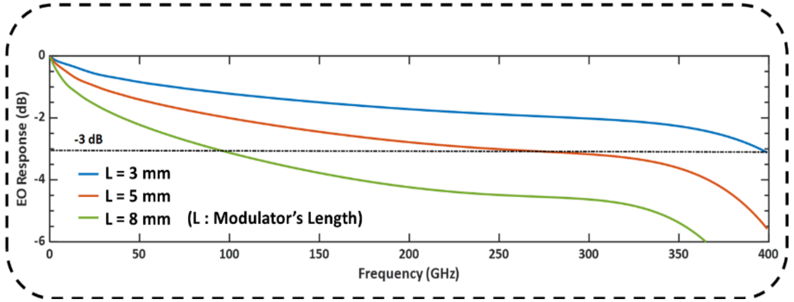




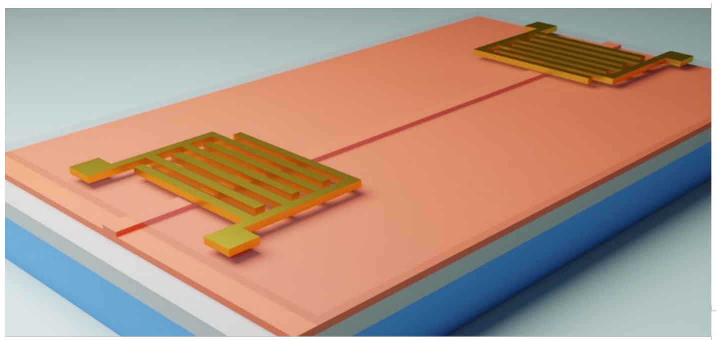
- Advantages of heterogeneous integrated photonics on thin-film lithium niobate (LN) on silicon (Si)
  - Lithium Niobate (LN) offers superior optical properties, i.e., large linear electro-optic (EO), and second-order nonlinear optical coefficients, as well as a broad transparency range in the electromagnetic spectrum (0.4 – 5.5 µm)
  - Reliance on a robust photonic integrated circuit (PIC) platform on Si substrates (rather than bulk optics), with high optical confinement, low-loss and high-level of integration
  - Compatibility with silicon photonics and hence potential for hybrid integration with lasers and other compact photonic devices, as well as foundry-based production

Thin-Film Lithium Niobate Photonics

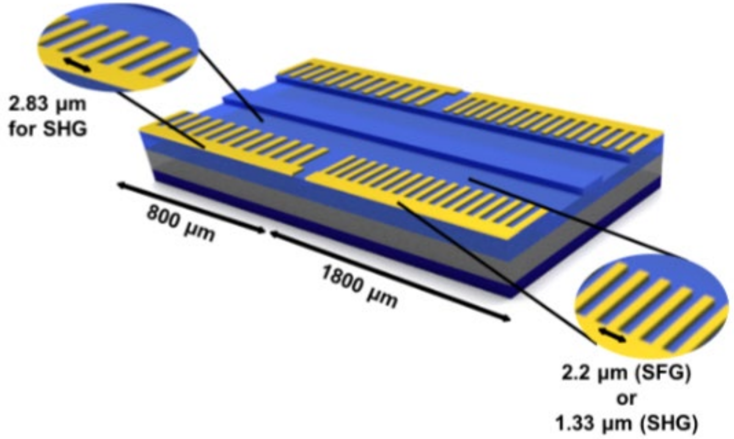




- Subterahertz electro-optic modulators
  - RF photonic systems for military and aeronautical requirements exceed the current SWAP-C
  - A key component that needs performance improvements is ultrahigh-bandwidth optical modulators
  - Design of thin-film LN modulator with EO bandwidths up to 400 GHz are shown



- Acousto-optic modulators
  - Surface-acoustic wave (SAW) filters on bulk LN have been long commercialized for RF filtering up to ~ 3 GHz
  - The goal here is to demonstrate filters and optical gravitational sensors, using acousto-optic modulators on thin-film LN on Si substrate
  - Electrical signals are converted into acoustic waves in a piezoelectric sensor, via two (input and output) interdigital transducers



- Nonlinear devices and optical isolators
  - The thin-film LN will be used for coherent light generation in the below 500-nm range
  - The submicron cross-section of the LN waveguides ensures efficient nonlinear processes at low pump powers
  - Shown are examples of our third- and fourth-harmonic generation demonstrations, using cascaded periodically-poled waveguides

Vanderbilt Microelectronics (ISDE/RER)

VANDERBILT UNIVERSITY

World's largest university-based radiation effects program

Radiation Effects Research (RER) Group

- 20+ graduate students
- Undergraduate interns
- Open access
- Hundreds of technical publications
- Basic research and support of ISDE engineering tasks
- Training ground for rad-effects engineers

Institute for Space and Defense Electronics (ISDE)

- 5 full time engineers + 2 support staff
- Controlled access, ITAR compliant, IP protection
- Active DD2345 Certification (University)
- Document control, milestone tracking, structured management
- Task driven support of specific engineering needs in government and industry

Collaborative Across all EPICA Sites

- 15 faculty with extensive expertise in materials, electronics, radiation effects
- Beowulf supercomputing cluster
- Custom software codes
- EDA tools from multiple commercial vendors
- Multi-million $ aggregate annual funding
- Test and characterization capabilities and partnerships

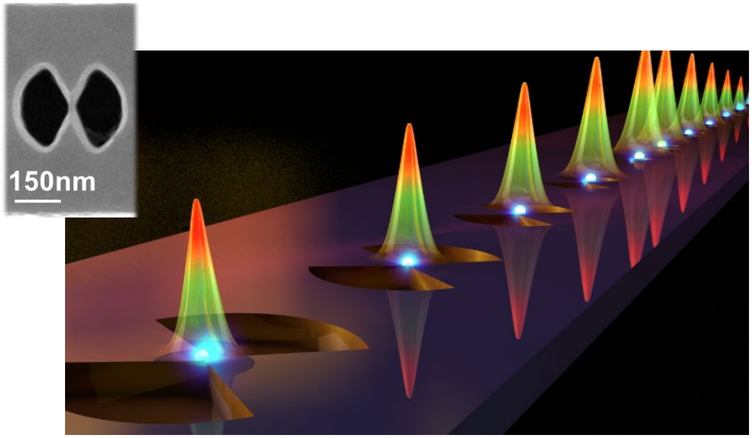
Vanderbilt Microelectronics (Weiss : Nano-Optics)

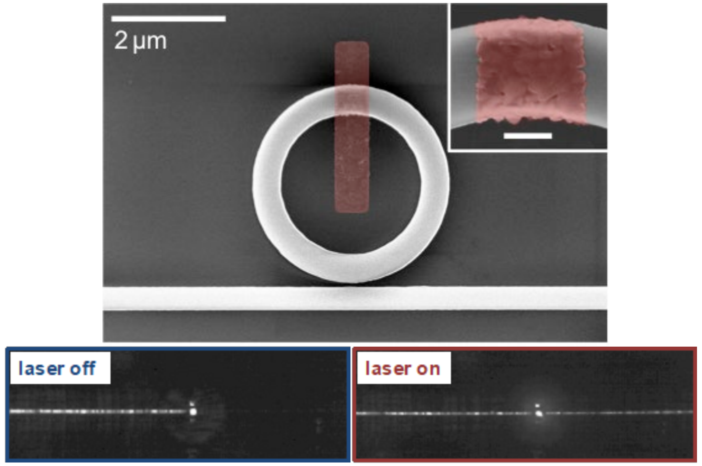
VANDERBILT UNIVERSITY

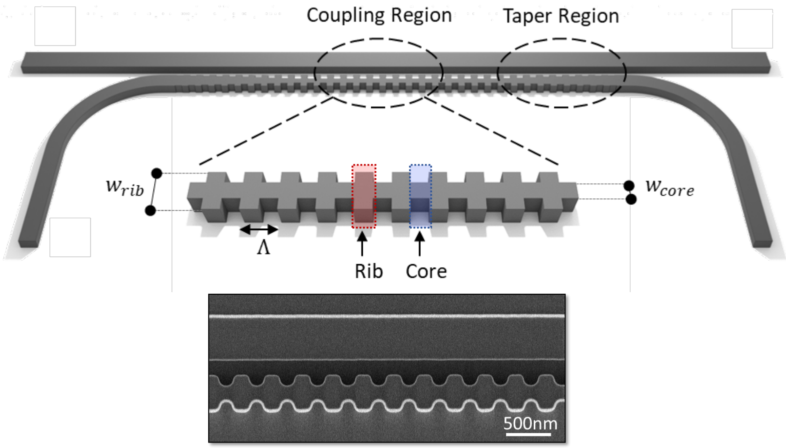
Fundamental Light-Matter Interaction

Applied Photonics Research

Collaborative Research with Industry







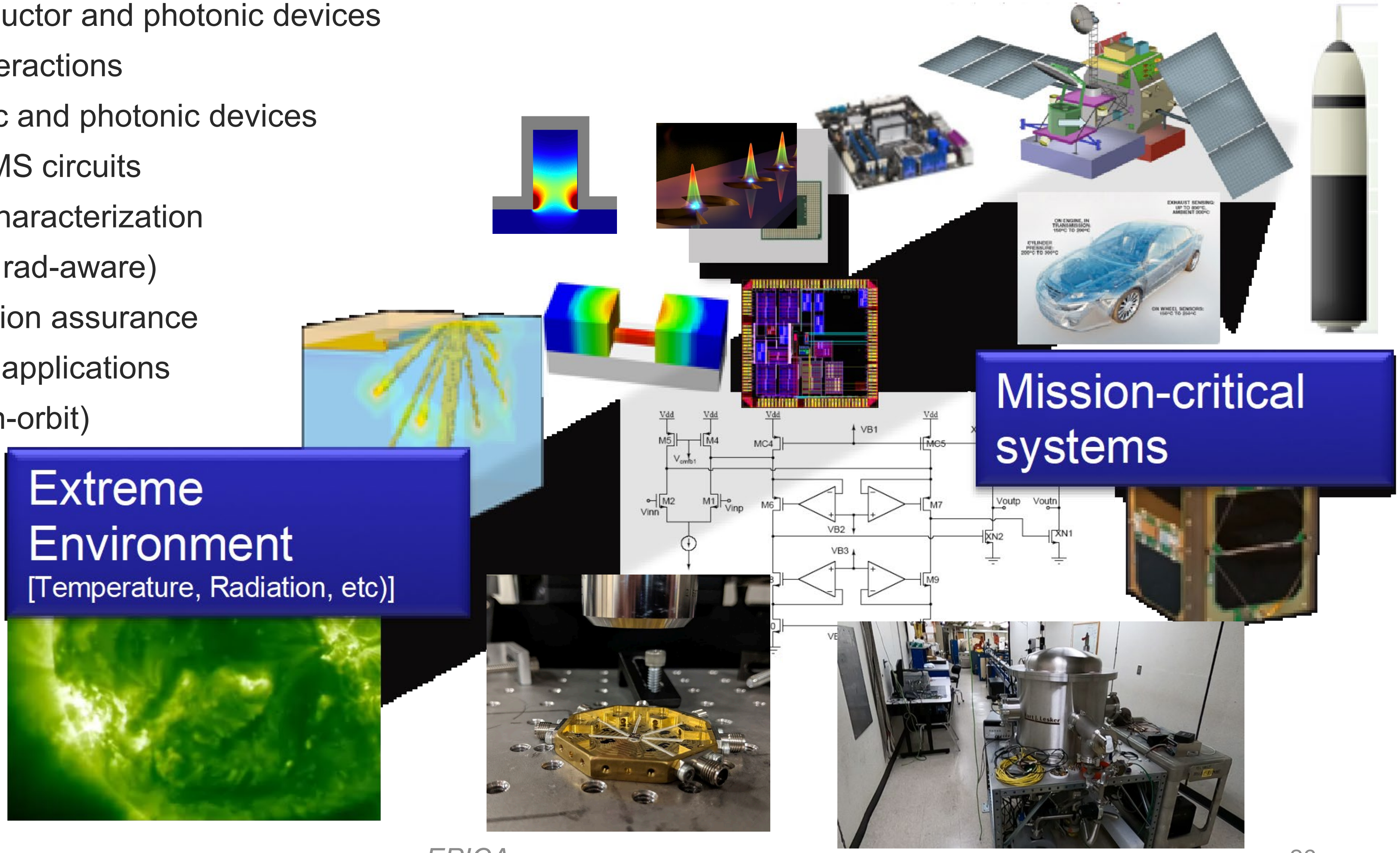
- Bowtie photonic crystal enables 10^6 times increase in peak energy density
- Impact in nonlinear optics, quantum information processing, optical switching and light emission applications

- Hybrid Si-VO_2 photonics for ultrafast optical switching*
- Recent demonstration of sub-ps all-optical switching suggests Tbps data rates are possible

- Subwavelength grating filters fabricated at GlobalFoundries (NSF GOALI program)
- Ultra-small footprint compared to traditional on-chip filters fabricated in foundry

RER / ISDE and Weiss Group Expertise

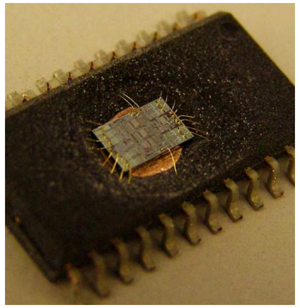
- Physical modeling of semiconductor and photonic devices
- Physical modeling radiation interactions
- Design and testing of electronic and photonic devices
- Design and testing of digital/AMS circuits
- Test chip design for radiation characterization
- EDA model development (esp. rad-aware)
- Systems Engineering for radiation assurance
- Tech transfer to designers and applications
- CubeSat Payload Designs (4 in-orbit)



Vanderbilt Radiation Facilities
Testing of Center Wide Components

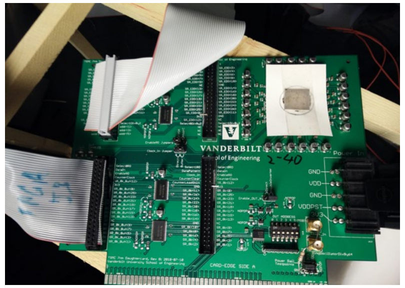
Sample prep

Die wire bonding



Decapsulation

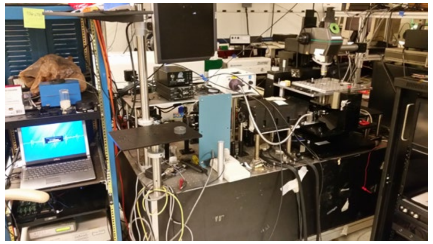
De-lidding packaged parts



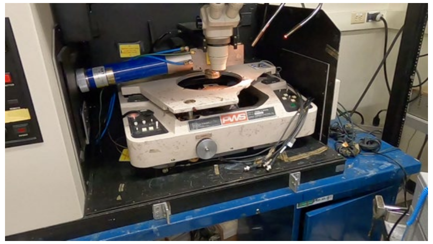
Board design and fab

Radiation testing as part of research projects or available as an external service

Radiation testing



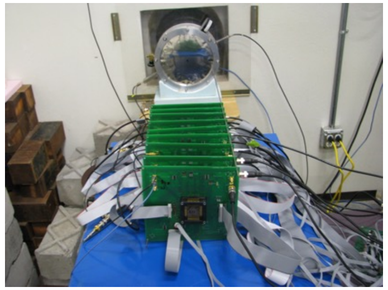
Pulsed laser @ VU



Aracor 10 keV X-rays @ VU

Pelletron accelerator @ VU

VU cryogenic vacuum chamber

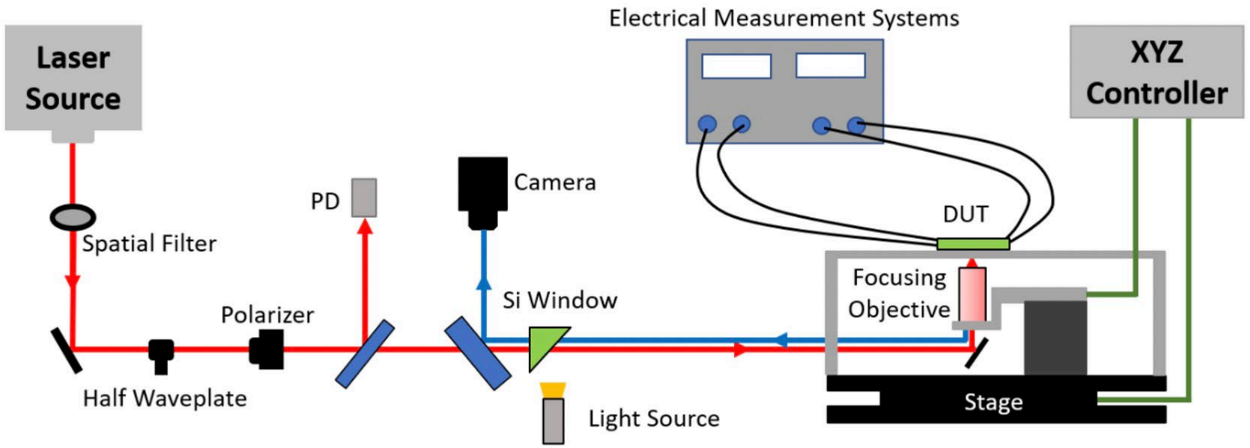


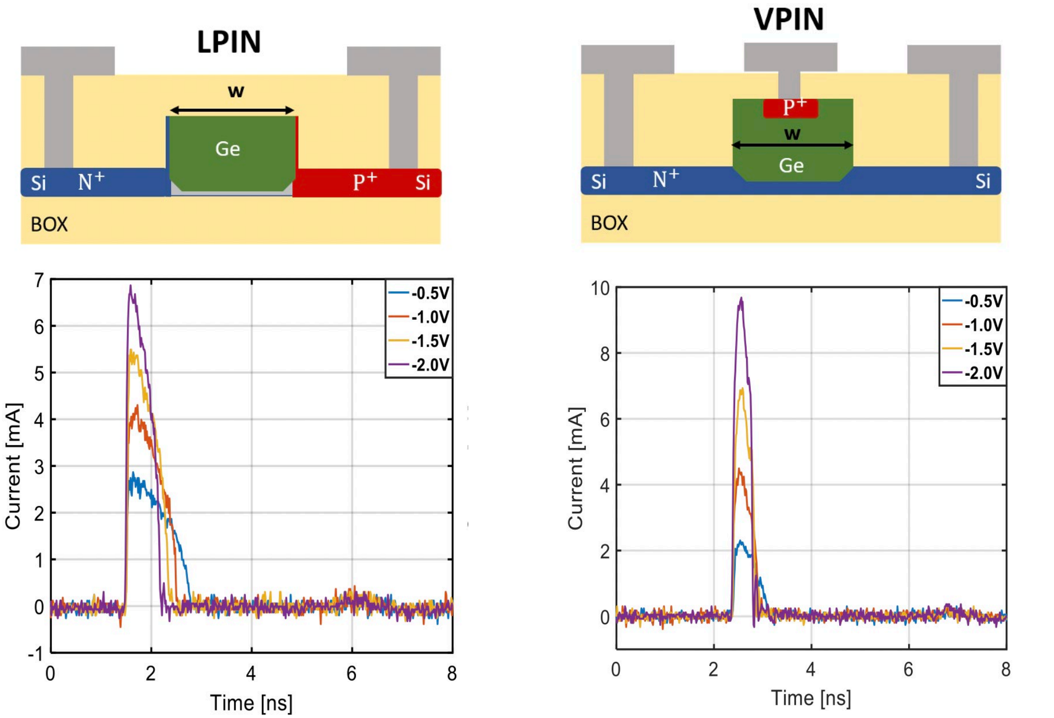
Testing at external facilities such as LBNL, TAMU, Crane, etc.

Example of Photonics Radiation Effects Research

VANDERBILT UNIVERSITY

Single Event Transient Response of Vertical and Lateral Waveguide-Integrated Germanium Photodiodes





Nonlinear Optical Simulations

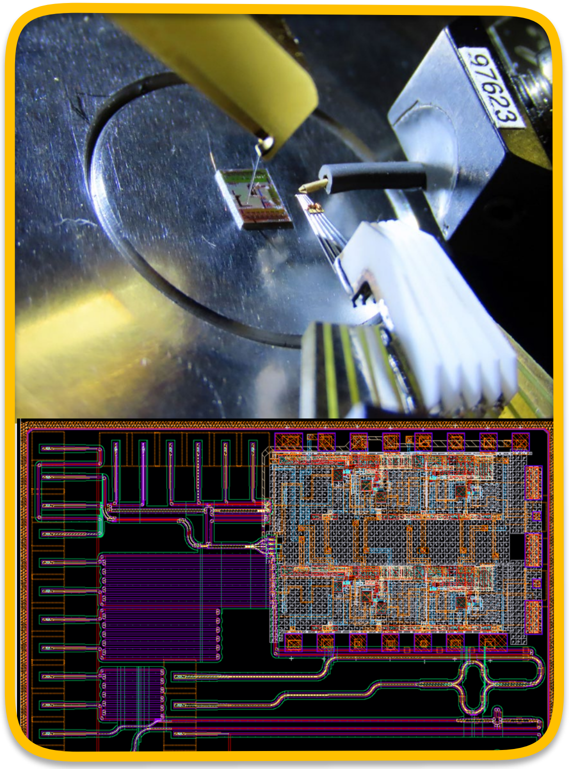
- Input: doping, device layout, pulse information
- Output: 3-D distribution of optically generated carriers

→

Charge Transport Simulations

- Input: doping, device layout, bias, 3-D distribution of optically generated carriers
- Output: Electrical measurements

- VPIN: voltage-independent temporal duration smaller than transients collected from LPIN
- LPIN: voltage dependent temporal duration
  - ➢ Simulations suggest that this is associated with electric field amplitudes that directly affect carrier velocity



Electronic-Photonic Integrated Circuits for Aerospace

EPICA

An NSF IUCRC

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