Comb-ing the Cosmos

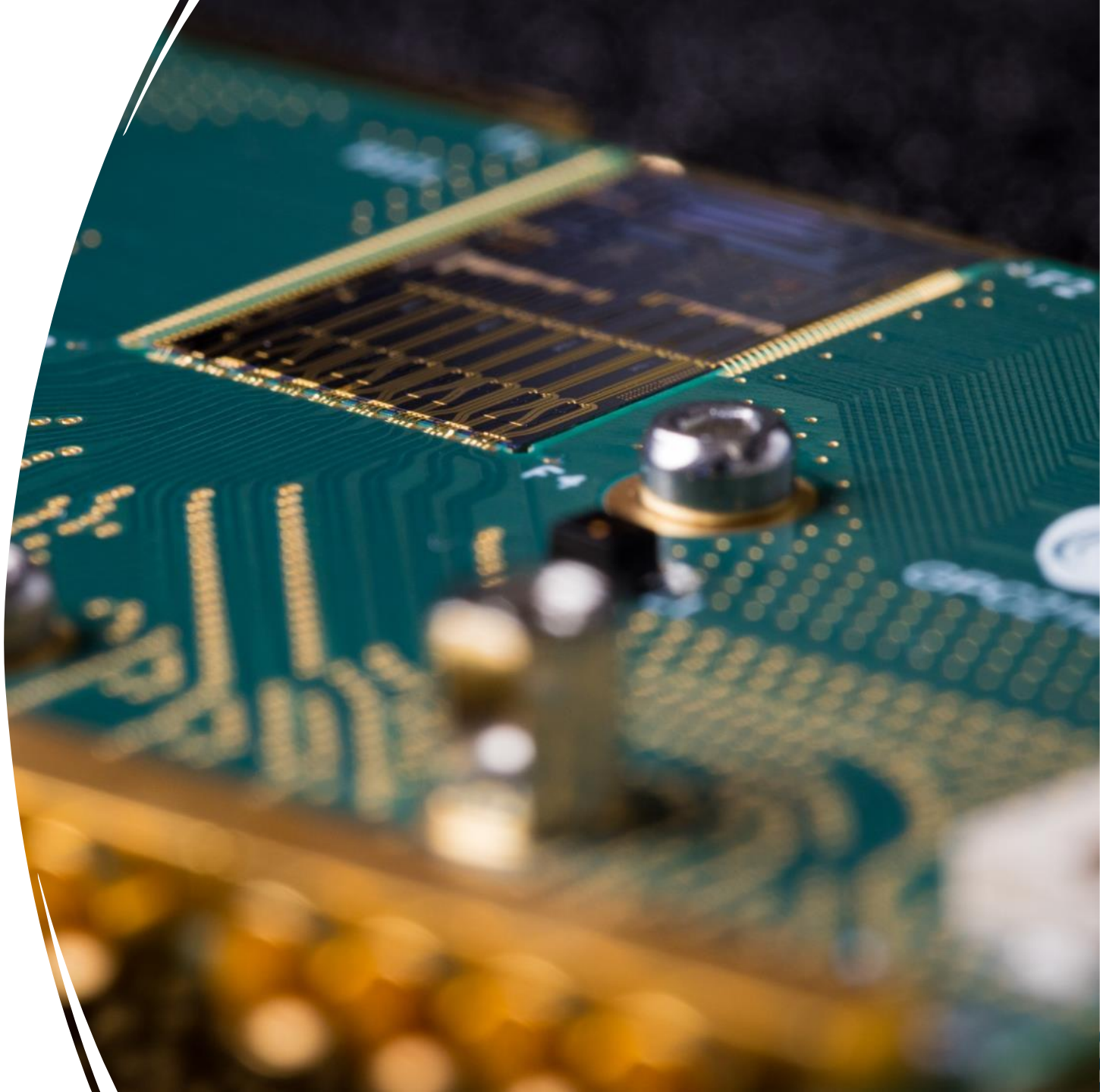
Integrated comb lasers for space applications

EPIC Meeting on Photonics for Space: Opening New Horizons at Exail

21/09/2023

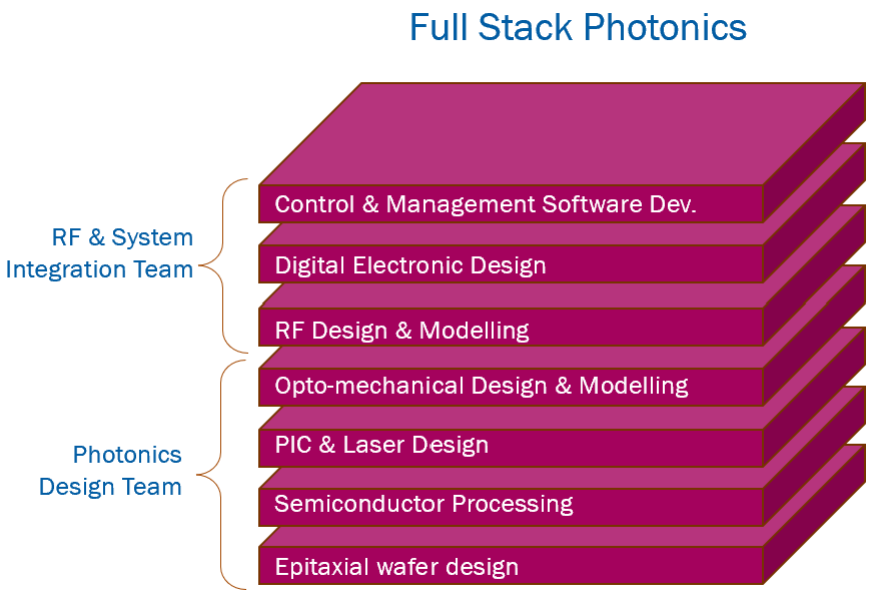
Who are we?

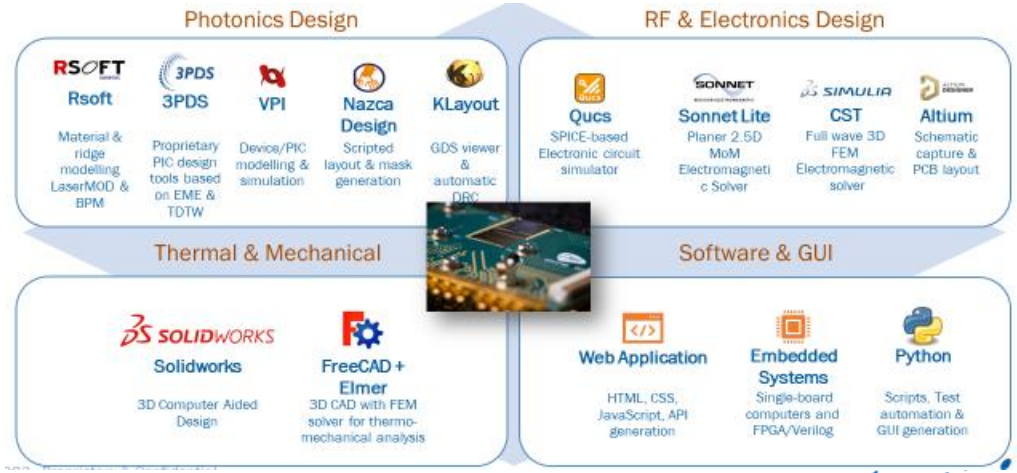
- Photonics product development company founded in 2011
- Unique laser and PIC-based products delivering new capabilities to customer products.
- Engage through OEM partnerships with key players; product supply or manufacture under license.
- Main target market is terrestrial comms, space is a growing sector



“Full Stack Photonics”

- Enables us to design and build photonics products with capabilities beyond those on the market.
- Proprietary:
  - Patents and licensed IPR
  - Proprietary design tools (3PDS)
  - Foundry PDK extensions and enhancements
  - Copyrighted Designs & Models across the full stack
  - Documented Methodologies
- Outsourced manufacturing (fab, pkg, int)
- Internal design verification & test (DVT)

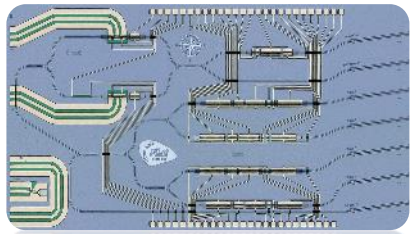




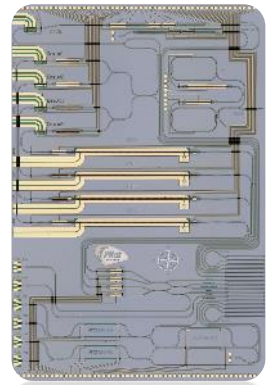
PIC Products

- Exemplar products developed using our Full Stack Photonics platform include:
  - The world's only integrated comb laser suitable for terabit per second coherent transceivers
  - The world's fastest switching low linewidth tunable laser
  - A comb-based low noise photonic mmWave and THz frequency generator
  - A unique wavelength tunable directly modulated laser for high speed PON

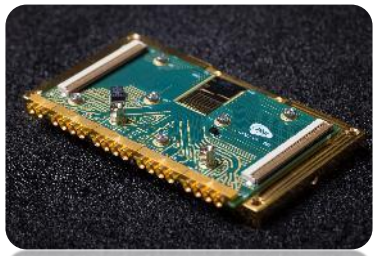
Fast sweeping low linewidth tunable Laser



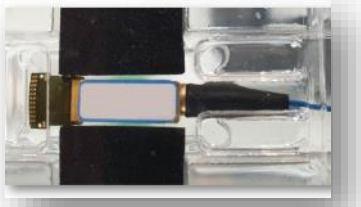
Integrated comb laser assy (iCLA) PIC



Comb-based Tx/Rx for optical comms & mmWave



High I/O PIC Test Assembly



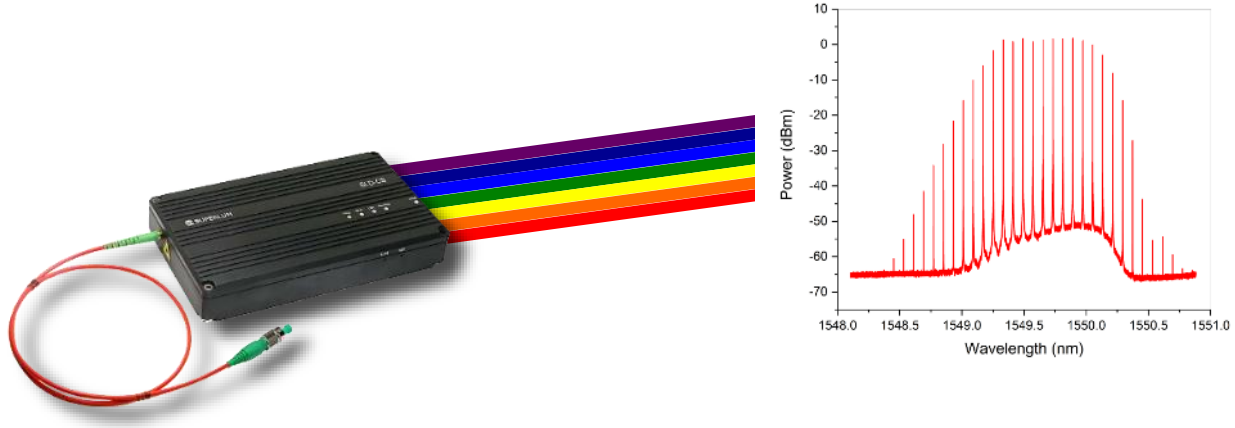
Packaged Lasers & PICs

Integrated PIC Development Systems

Lab Instruments and Tech Demonstrators

Optical Combs

- Lasers that produce multiple *coherent* wavelengths simultaneously

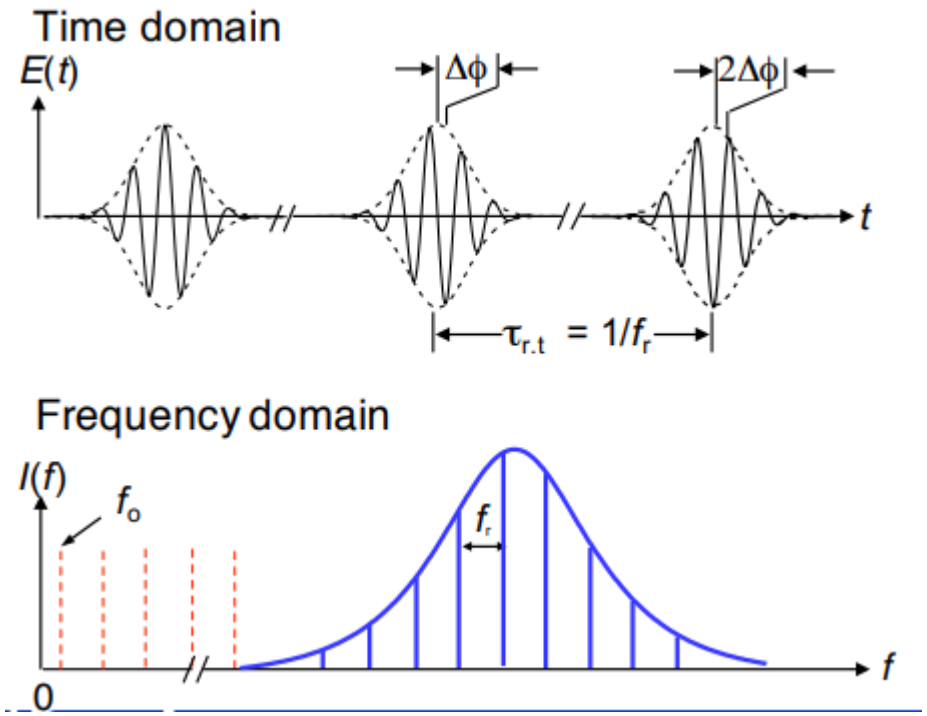


- Subject of the 2005 Nobel Prize in Physics awarded to Hall and Hänsch

"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"

- Widely used in scientific applications, slowly beginning to find their way into industrial applications

Comb fundamentals



Key Concept:

Direct link between optical and microwave frequencies

$$\nu_n = nf_r + f_o$$

$$n \sim 10^5$$

Hänsch & Hall, Nobel Lectures
Fundamentals of frequency combs: What they are and how they work

A ruler for measuring light frequencies

A train of short optical pulses

Create optical frequencies from RF, and vice versa

A broadband light source yet with high resolution

A replacement for laser array with enhanced features

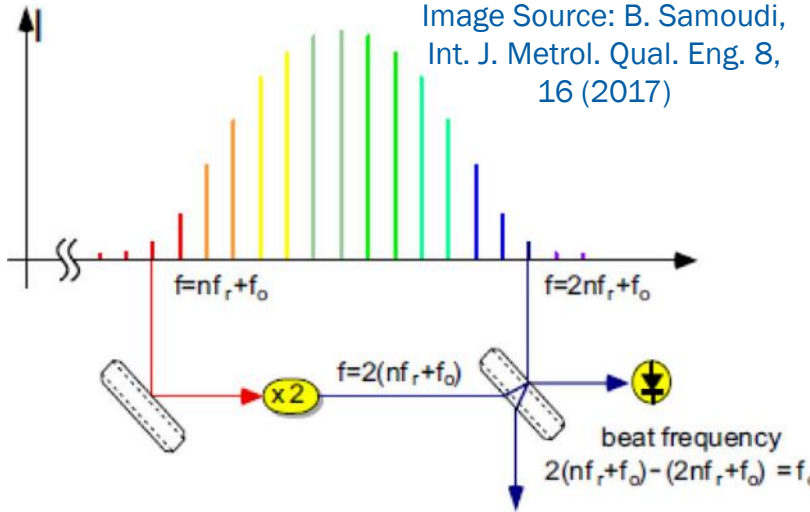
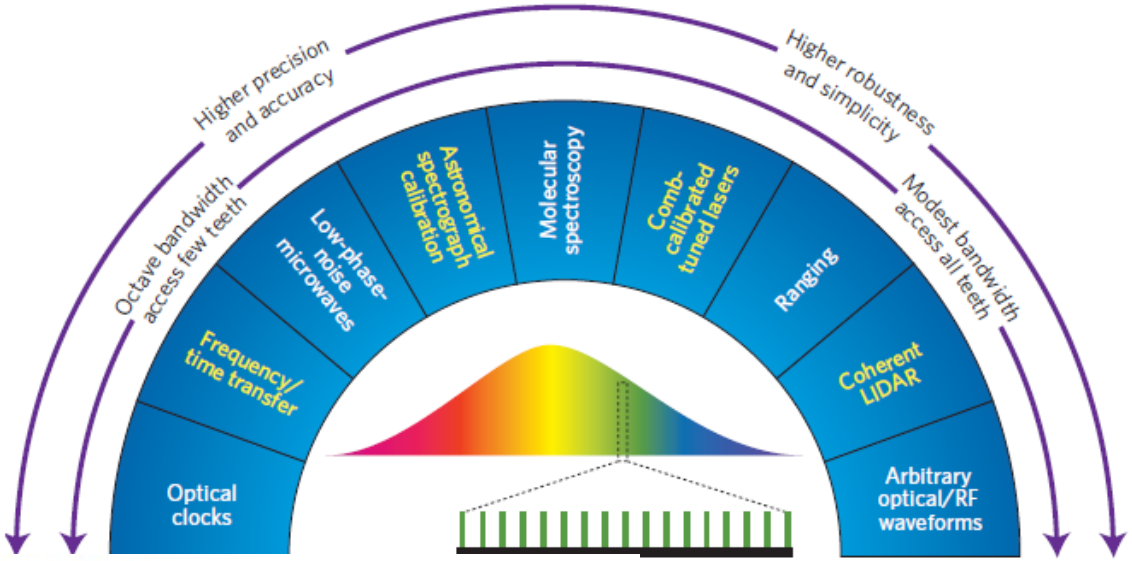


Image Source: B. Samoudi, Int. J. Metrol. Qual. Eng. 8, 16 (2017)

Repetition rate of the pulses equals the frequency spacing of the comb
Pulse width is inversely proportional to the comb bandwidth

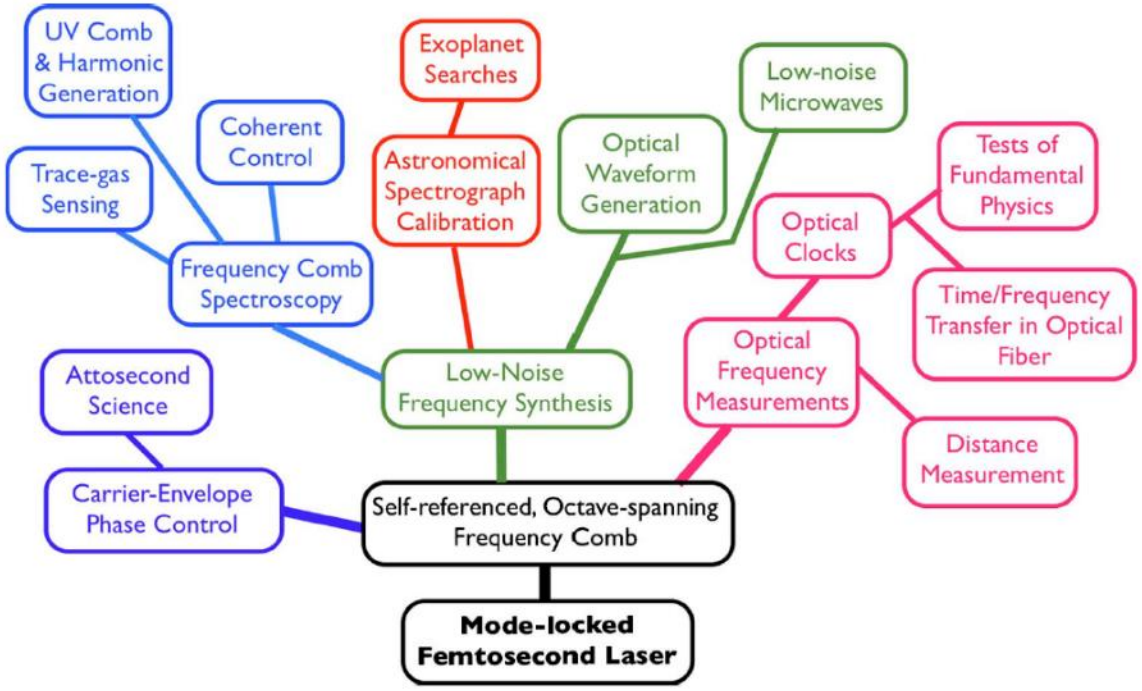
Applications of Optical Combs



Conclusion

This myriad of applications has put an ever-increasing burden on the performance of optical combs, requiring, for example, low phase noise, high repetition rate, high power, wide spectral coverage and, most importantly, great robustness in terms of simplicity, compactness and environmentally stable mode-locking, phase-locking and monitoring. Although

N. Newbury
NATURE PHOTONICS | VOL 5 | APRIL 2011 |



S. Diddams, J. Opt. Soc. Am. B/Vol. 27, No. 11/November 2010

Demonstration of CoWDM using DPSK modulator array with injection-locked lasers

S.K. Ibrahim, A.D. Ellis, F.C.G. Gunning and F.H. Peters

ELECTRONICS LETTERS 21st January 2010 Vol. 46 No. 2

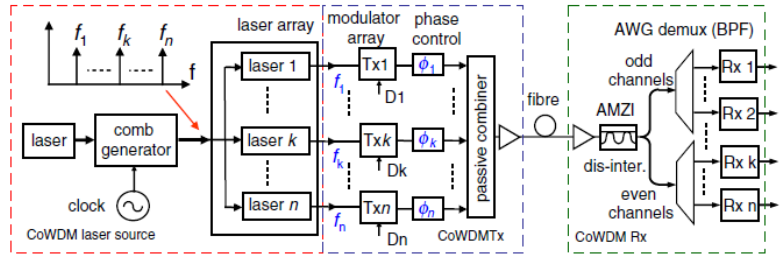
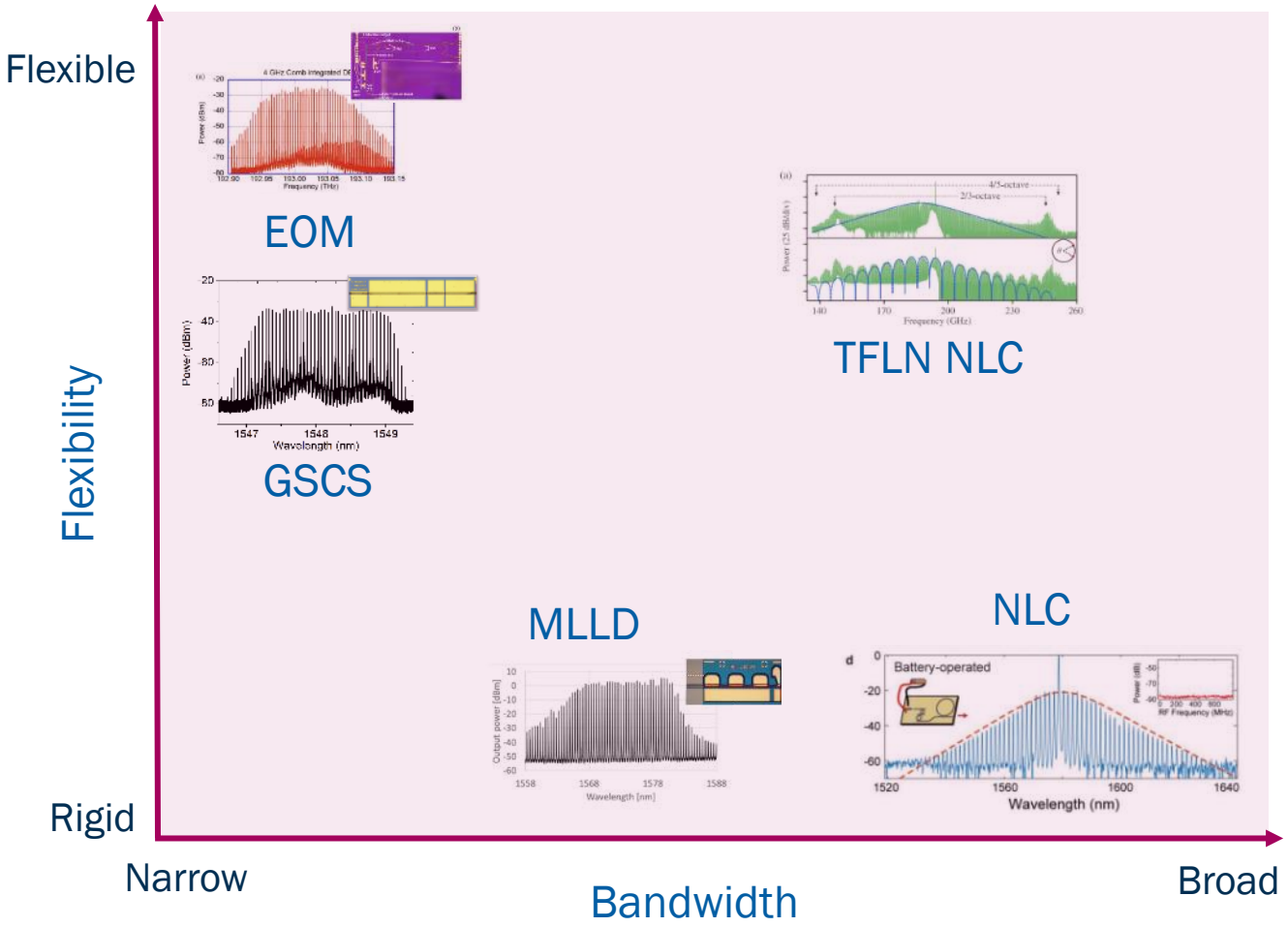


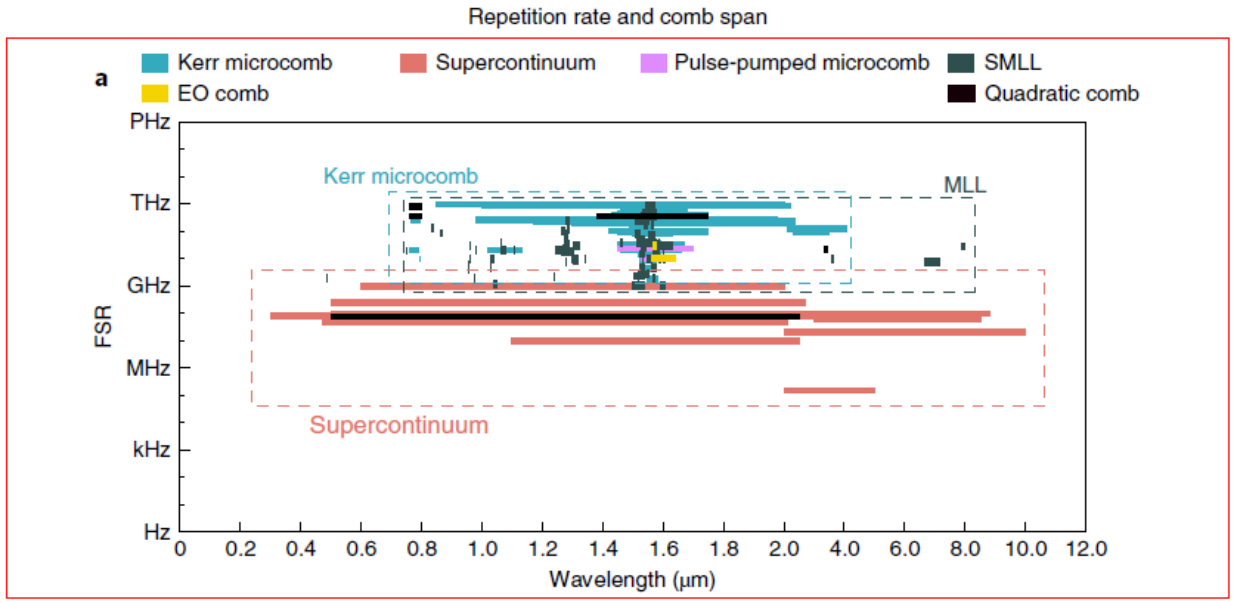
Fig. 1 *Schematic representation of CoWDM system using comb generator and array of injection-locked lasers and modulators*

Categorising *Integrated* Combs

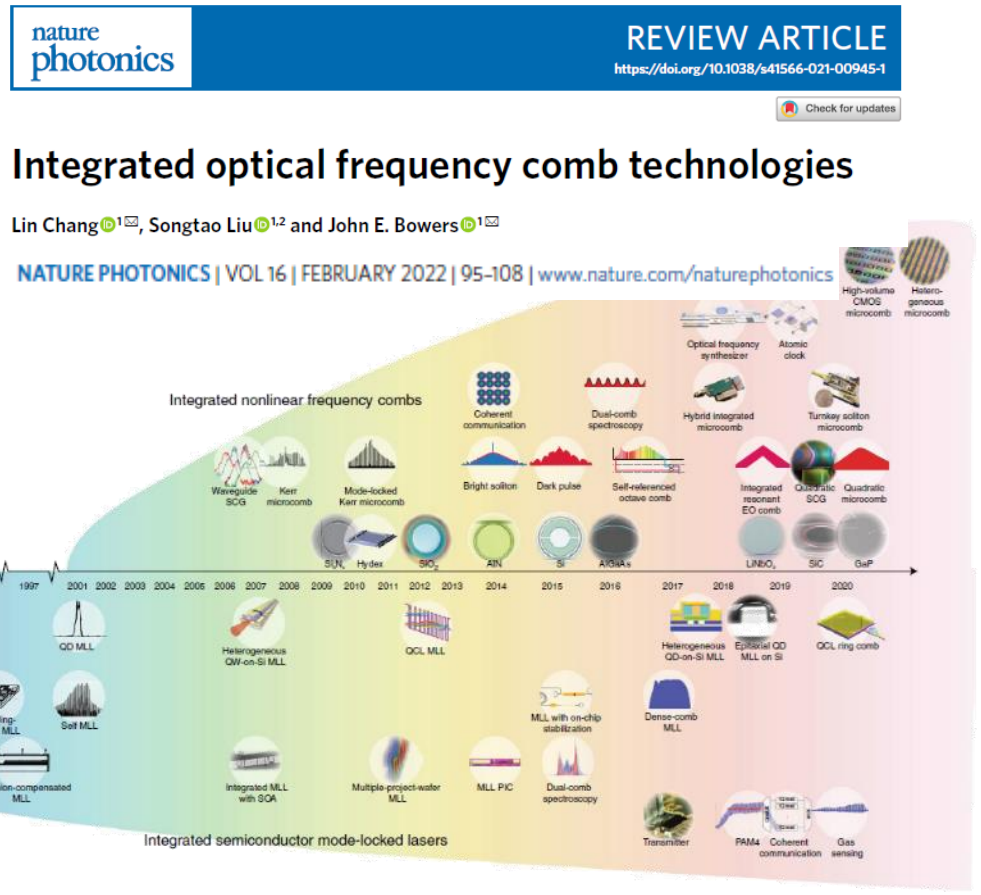


- One way is by achievable bandwidth, and wavelength flexibility
- Narrowband Combs
  - Electro-optic modulator comb
  - Gain switched comb source
  - Mode Locked Laser Diodes
- Broadband Combs
  - Kerr Nonlinear Combs (eg SiN)
  - 2nd & 3rd order nonlinear combs (eg TFLN)

Literature reviews on combs & integrated combs



Images source:

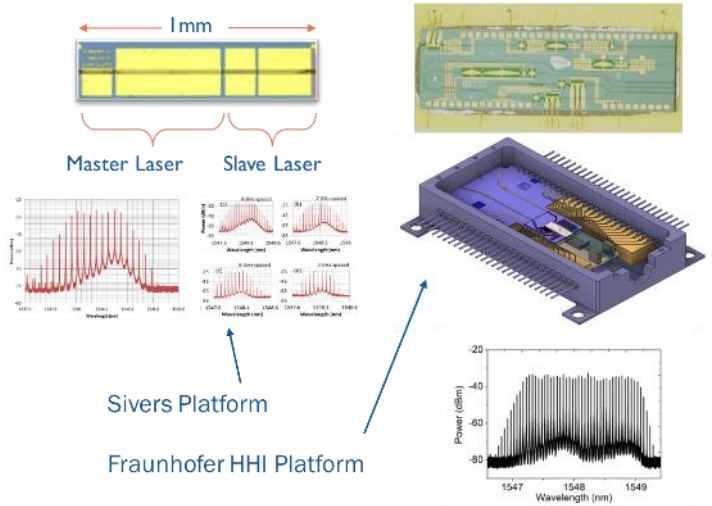


- S. Diddams, JOSAB, Oct 2010, **DOI:** 10.1364/JOSAB.27.000B51
- V. Torres-Company et al, IPOR, Dec 2013, **DOI:** 10.1002/lPOR.201300126
- M. Imran et al, IEEE COMST, 2018, **DOI:** 10.1109/COMST.2017.2775039.
- A. Parriaux et al, AOP, March 2020, **DOI**: 10.1364/AOP.382052
- L Chang at al, Nature Photonics, Feb 2022, **DOI:**10.1038/s41566-021-00945-1

Integrated Combs at Pilot Photonics

Pilot has space related activities ongoing using both narrowband combs and broadband combs

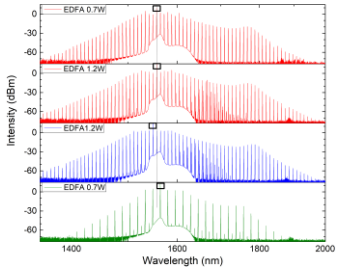
Gain Switched Comb Lasers



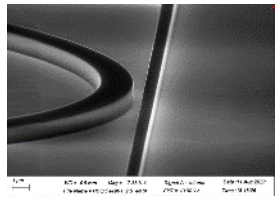
A semiconductor laser is directly modulated with an RF signal to create short optical pulses.

Simple, flexible, narrow, FSR-limited

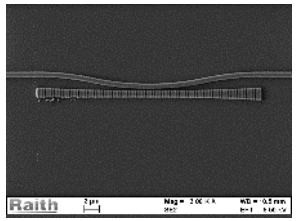
Micro-resonator Comb Lasers



25 THz



120 THz

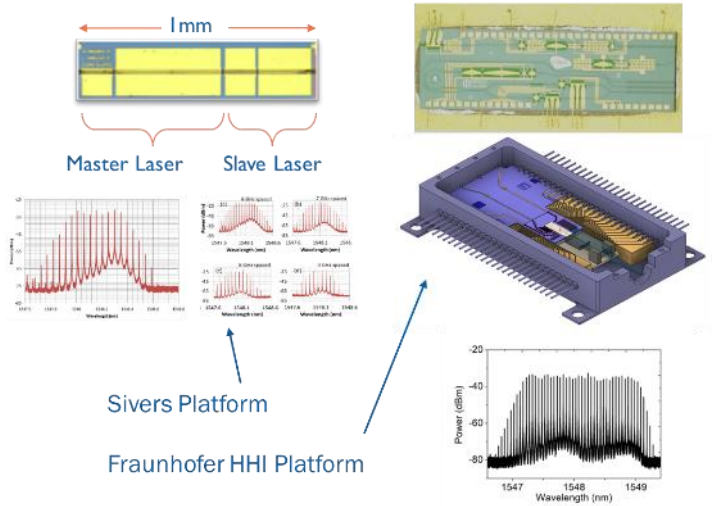


Microring resonator with non-linear properties strongly pumped creating additional wavelengths via four-wave-mixing
Very broad, challenging integration & stability

Integrated Combs at Pilot Photonics

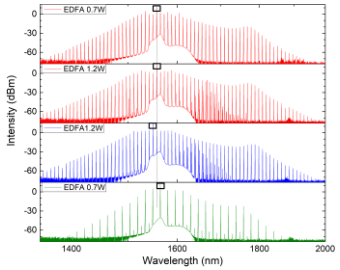
Pilot has space related activities ongoing using both narrowband combs and broadband combs

Gain Switched Comb Lasers

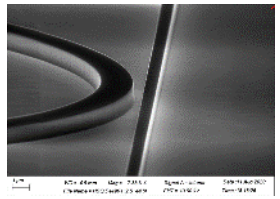


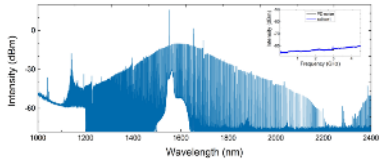
- Optical communication
- mmWave generation
- Precision timing
- Fiber/gas sensing

Micro-resonator Comb Lasers

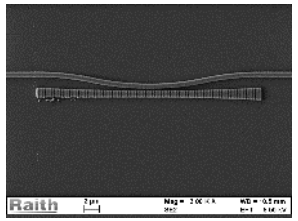


25 THz





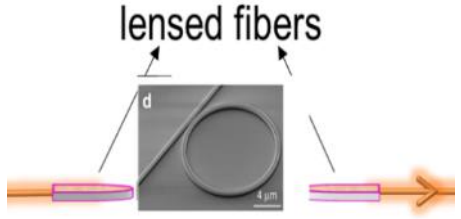
120 THz

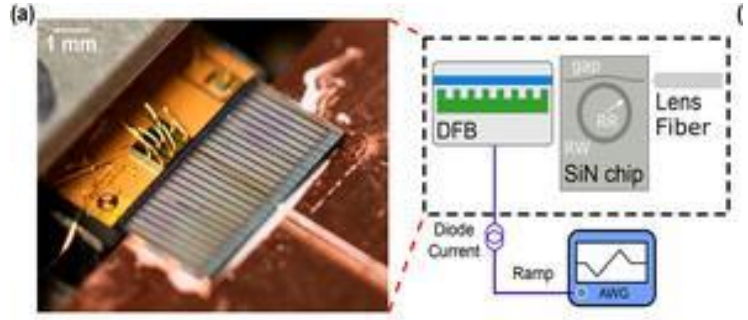


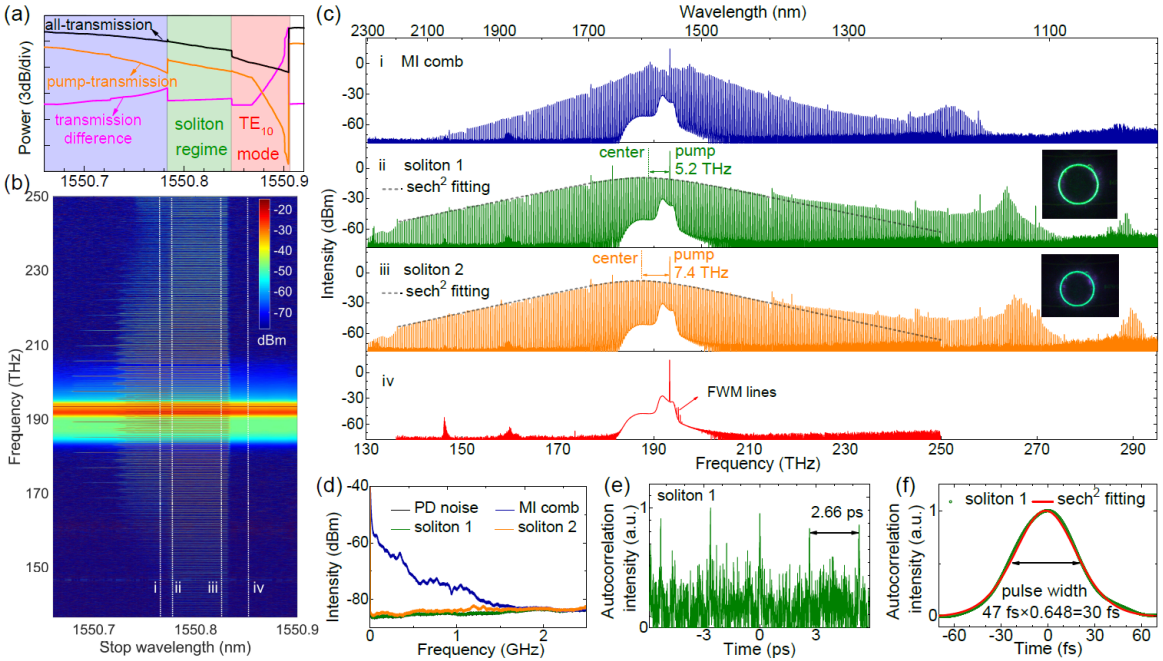
- Optical communication
- THz generation
- Spectrometer Calibration

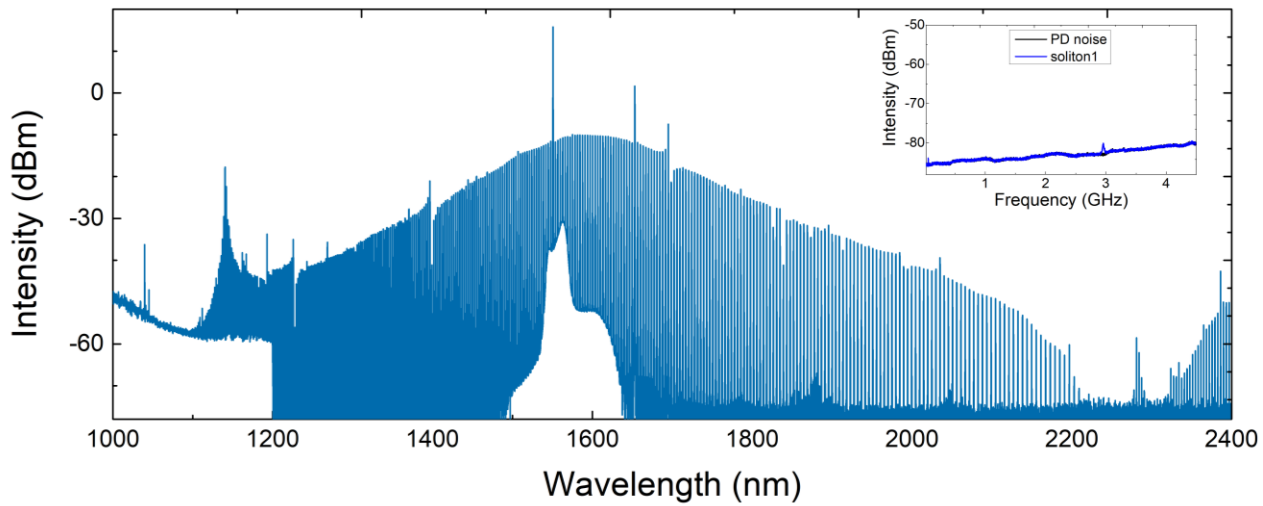
Micro-resonator Combs

Micro-ring Comb Generation









- Octave spanning soliton in AlN resonator
- Significant result from Donegan group

Trinity College Dublin
The University of Dublin

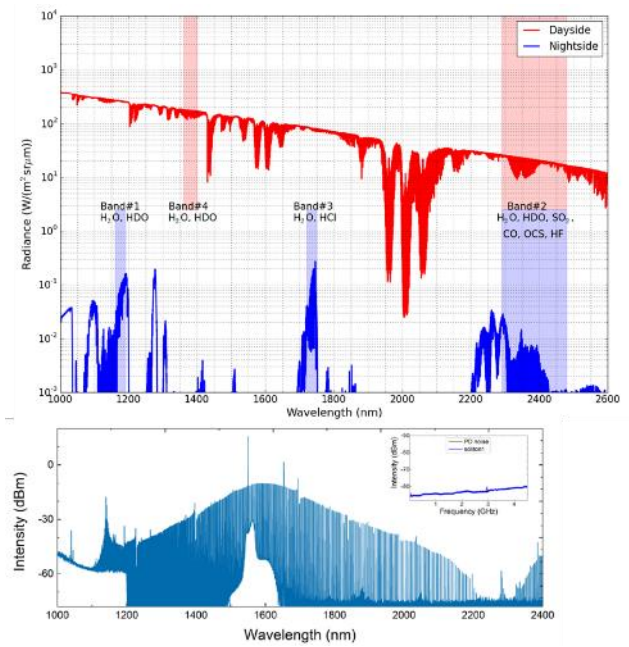
MiCoSMic

Miniaturised Frequency Comb for Science Mission Applications – Contract through ESA Science Directorate

Space Instrument Calibration

Focus instrument is VenSpec-H, on board the ESA M5 mission EnVision (early 2030s).

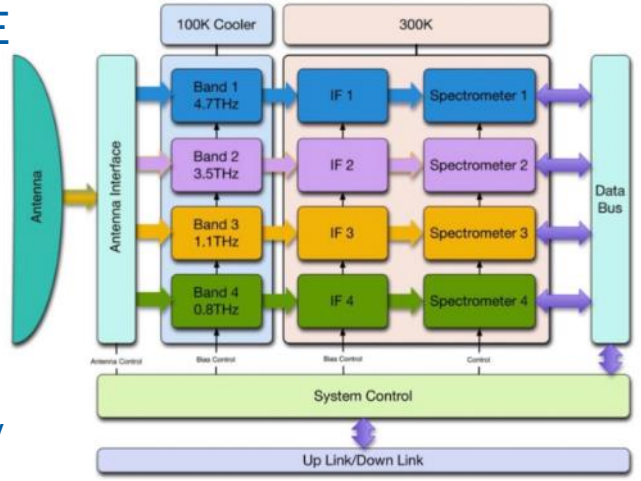
VenSpec-H will measure gases related to volcanism and surface changes on Venus.



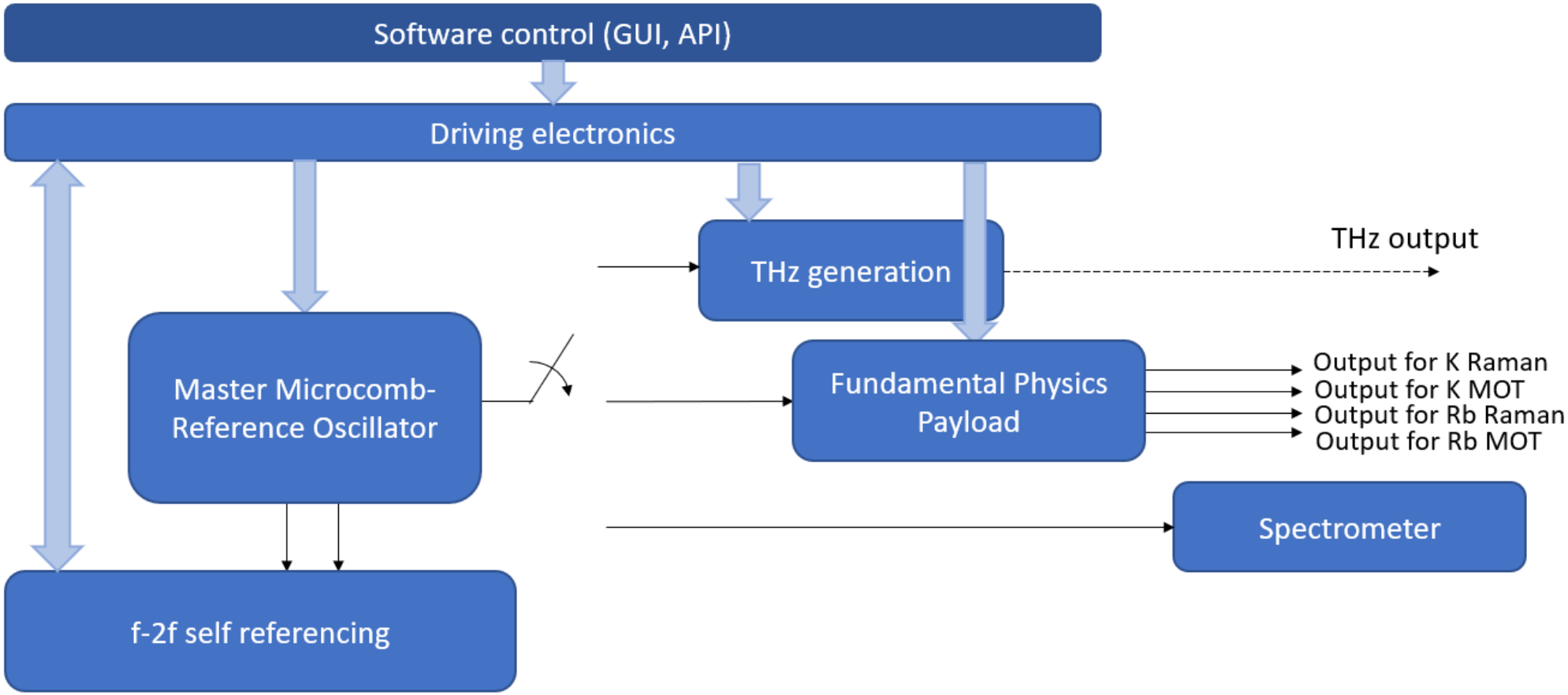
THz Local Oscillator Generation

Focus mission for this application area is KEYSTONE (formerly LOCUS)

Reduced SWaP
Coherent signal chain
Steerability
Receiver flexibility
(complex down-conversion, SDR)



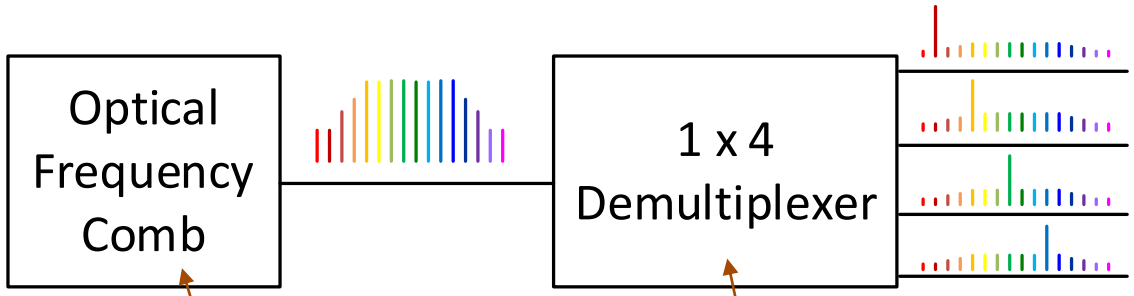
Breadboard - High Level Block Diagram



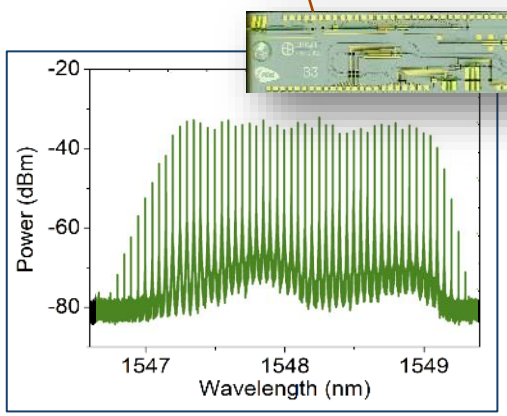
Gain Switched Combs

Pilot's Integrated Comb Laser Technology

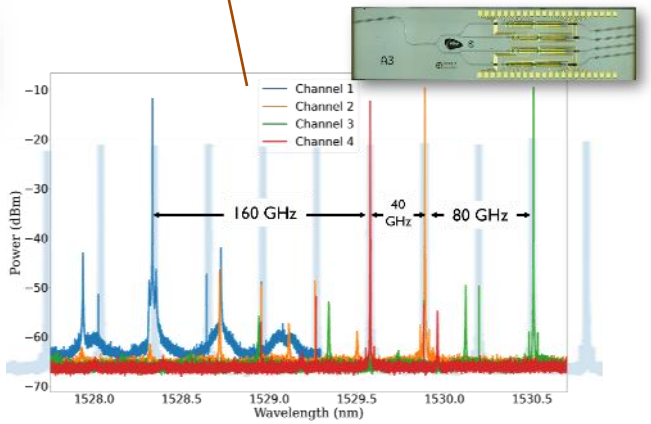
Based on two unique building blocks: Gain switched combs & injection locked demultiplexers



The iCLA is an InP PIC combining a comb laser with a demultiplexer to deliver 4 coherent wavelengths on individual fibers for modulation/ Rx LO



PIC Comb - 225GHz Now, 1THz in development



4 selectable coherent comb-lines on individual fibers for modulation

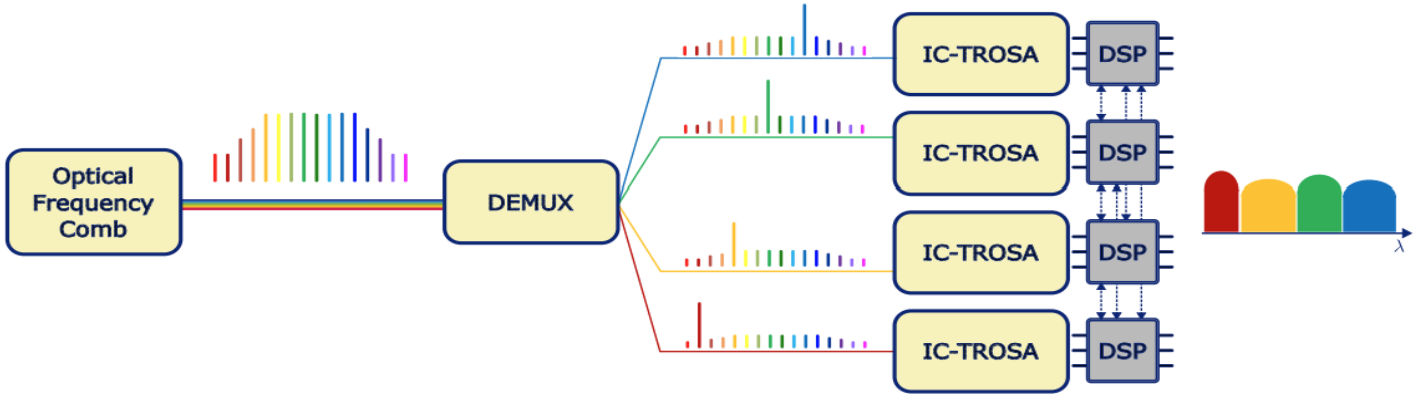
Pilot's patented gain switched comb source technology is used to create the optical comb on-chip

- Easily integratable – direct modulation of InP laser
- Flexible – frequency spacing is precisely tunable
- Efficient – 60% more efficient than EOM combs

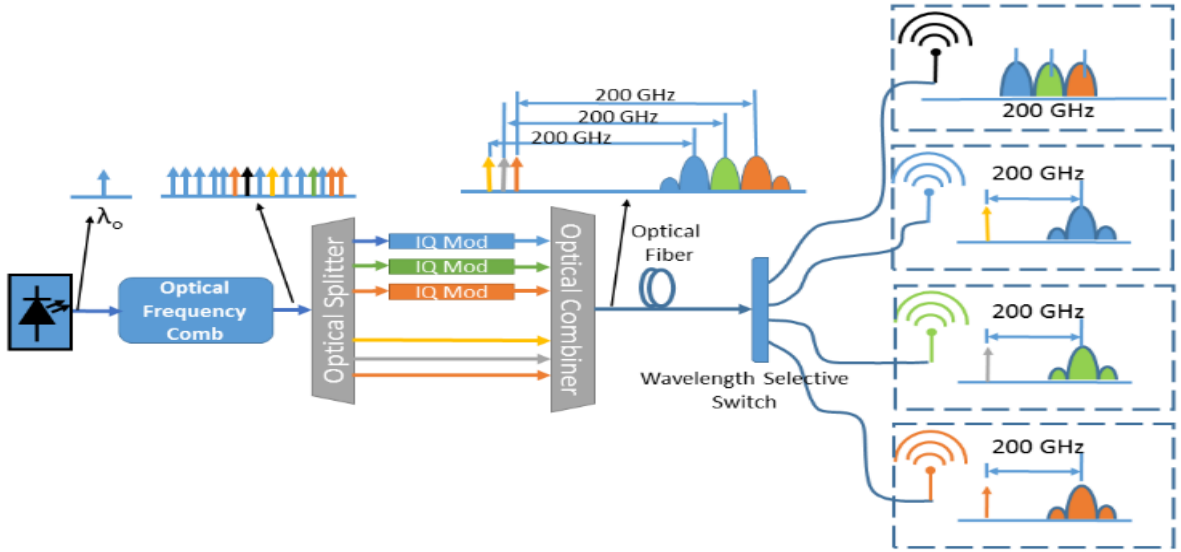
Pilot's injection locked demultiplexing technology is used to separate the wavelengths for modulation

- Fine FSR on-chip comb line selection
- Noise free amplification of comb lines
- Gain flattening
- Maintains phase coherence & linewidth of the comb

Some key applications



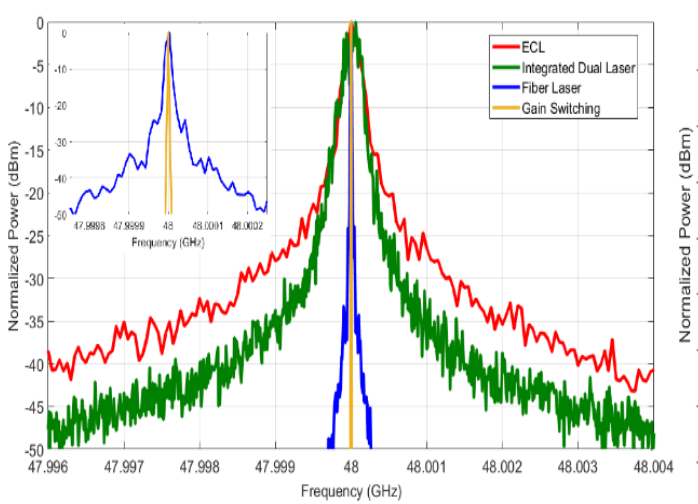
High capacity coherent optical communication

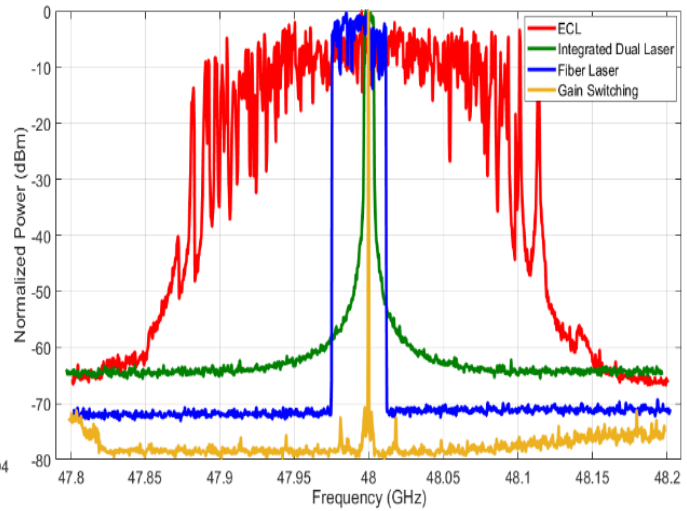


mmWave carrier/data transmission

RoF & mmwave generation

- Excellent optical-comb phase correlation that results in low noise RF signal.





Laser type	*RF linewidth*	*Frequency Offset*
2 x ECL	40 kHz	250 MHz
Integrated dual lasers	34 kHz	35 MHz
2 x Fibre Laser	2 kHz	3 MHz
Gain Switched Comb	~10 Hz	0 Hz

Problem Statement

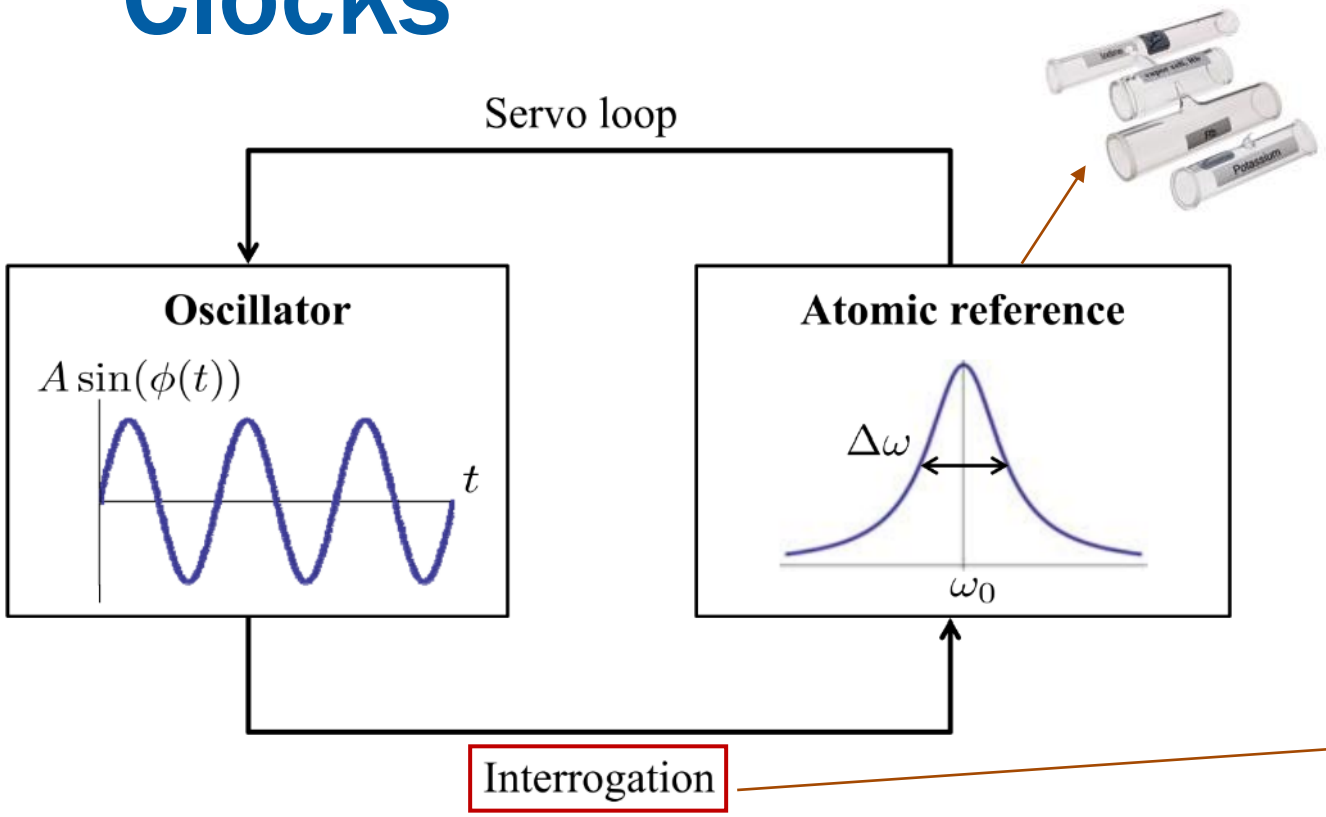
Precision timing systems are critical for applications including navigation, telecoms, search & rescue

Discharge Lamp
Reliable, but high SWaP

VCSEL
Low SWaP, but low performance

We want the performance of a discharge lamp, with the SWaP of a VCSEL

Basic Principle of Operation of Atomic Clocks



Ideal light signal for interrogating Rubidium

λ =795nm

6.8GHz

Two coherent modes

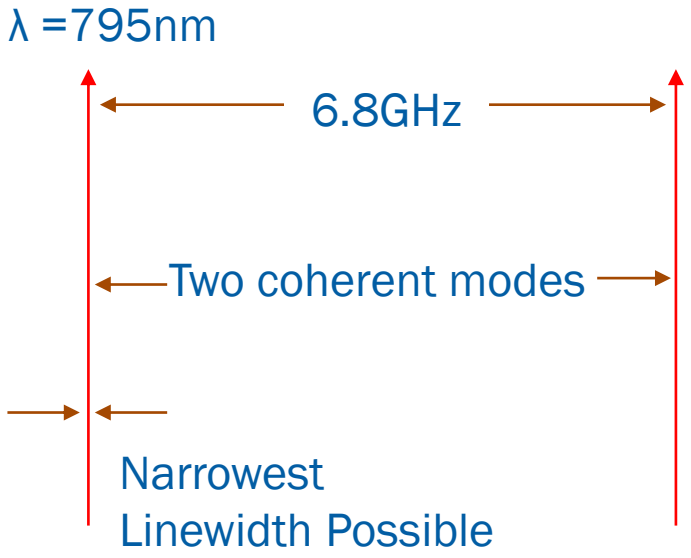
Narrowest
Linewidth Possible

Source: G. Mileti: Frequency Standards and Miniature Atomic Clocks

Proposed Solution

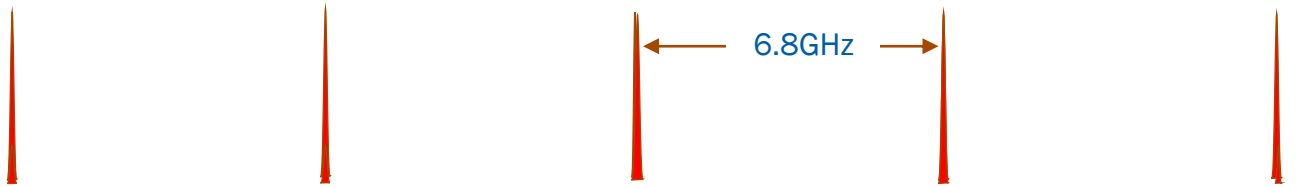
How can we improve on existing approaches?

Ideal light signal for interrogating Rubidium



Rb^{87} Discharge lamp (several lines, > 1 GHz wide)

Directly Modulated VCSEL (3 – 5 lines, 25 – 100 MHz wide)

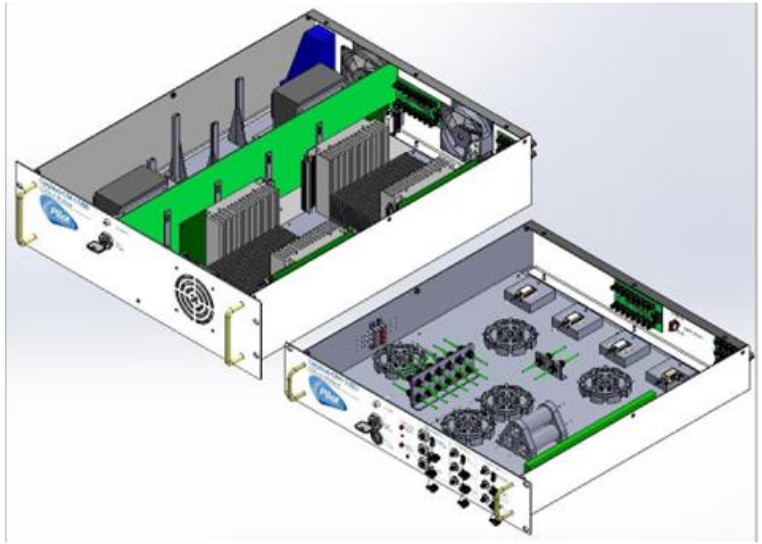


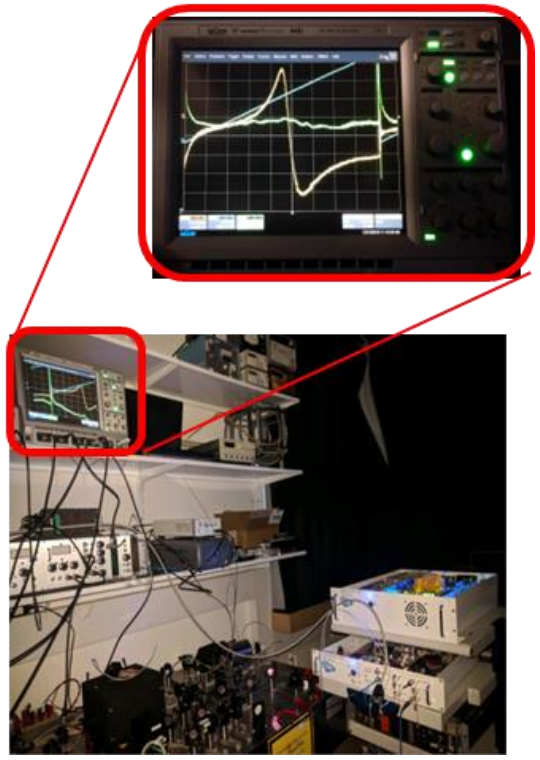
Optical Comb PIC (several lines, < 1 MHz wide)

Optical Demux PIC (2 lines, < 1 MHz wide)

Phase 1

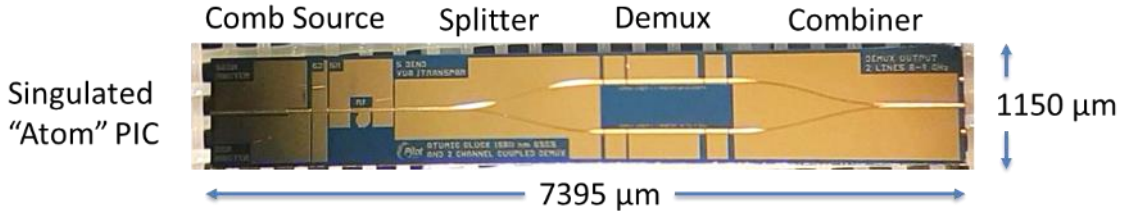
Successful GSTP 6.1 “De-risk” Project to build breadboard prototype

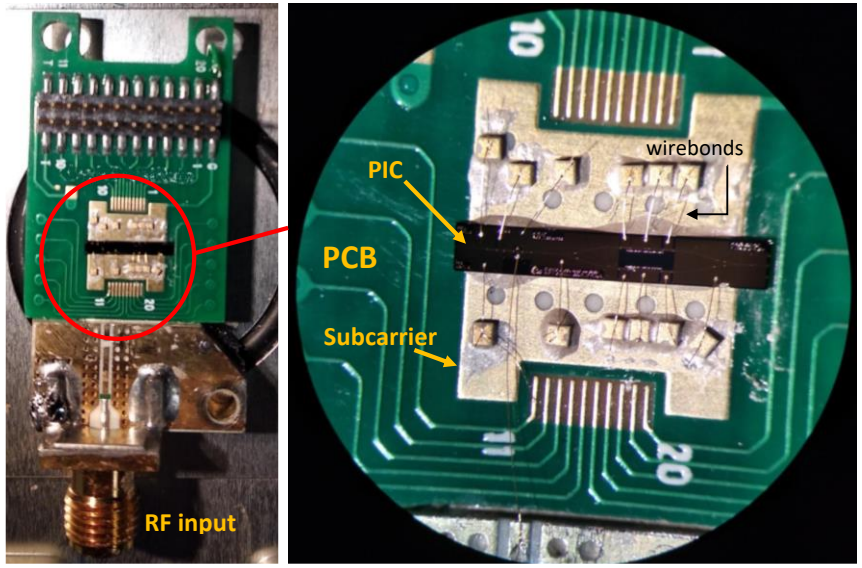




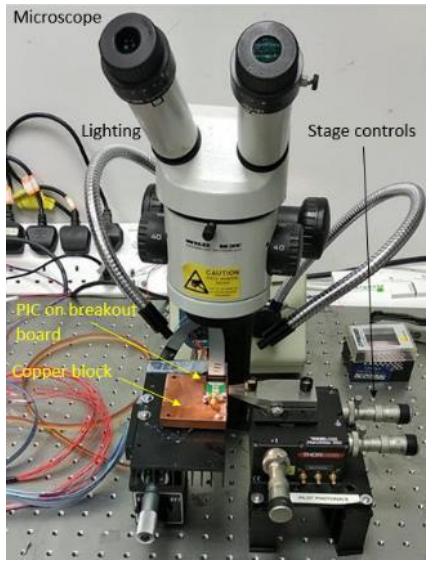
1556 nm PIC Proof of Concept Tests

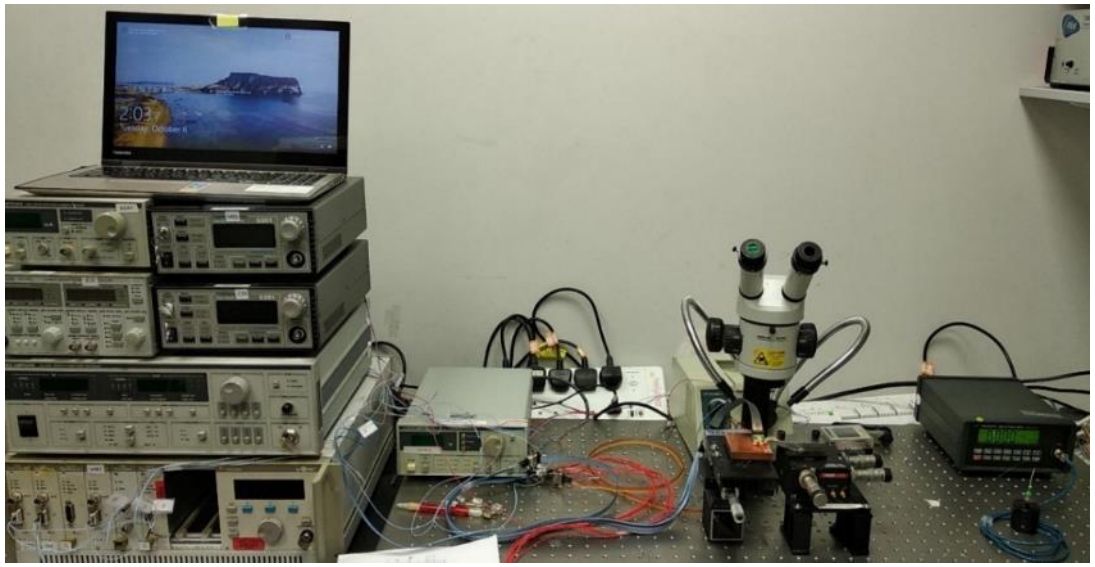
- PIC is mounted on a prototyping board capable of high dc channel count and RF connectivity for comb generation
- Wire-bonded with a K&S 4500 manual wire bonder
- Probe station supports the PIC and PCB
- Driven by bench-top current controllers





Subcarrier and PCB

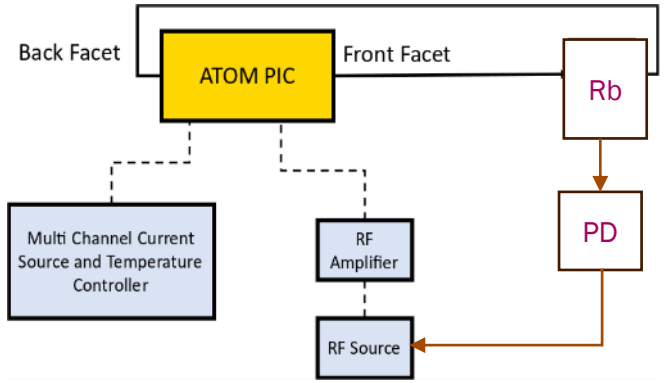




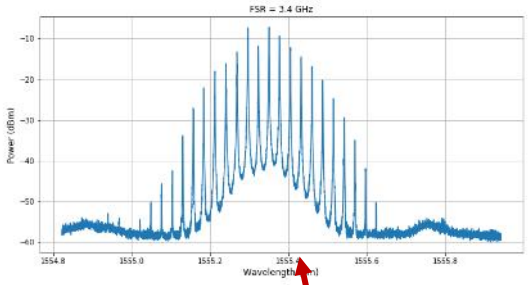
Probe station

Key Functionality Demonstrated

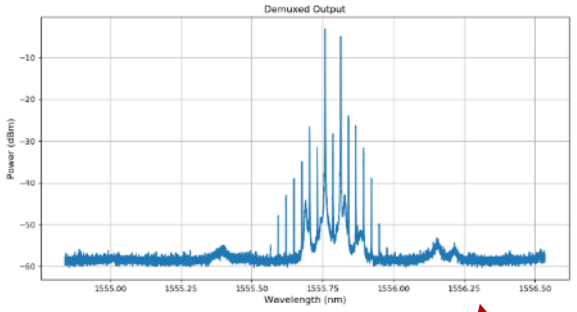
- Two comb lines spaced by the Rubidium atomic resonance frequency are demultiplexed from the comb, coupled back together and beaten on a photodiode.
- The narrow linewidth of the RF beat tone demonstrates the strong coherence between two lines.
- Interferometric issues seen in fiber-based implementation of Phase 1 have been overcome



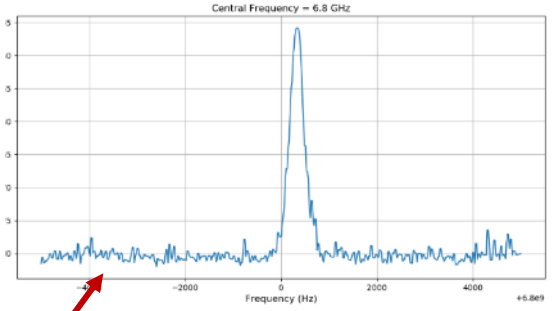
Initial Comb @ 3.4GHz FSR



Two demultiplexed comb lines



RF beat tone at ~6.8GHz with linewidth of 400Hz @ -20dB



Optical spectrum analyser

Photodetector and Electrical spectrum analyser

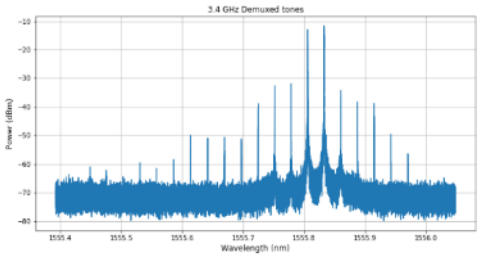
Comb Source Splitter Demux Combiner

Singulated "Atom" PIC

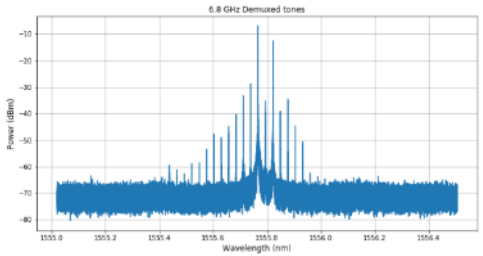
RoF & mmwave generation

Flexibility of RF frequency generated from same PIC.

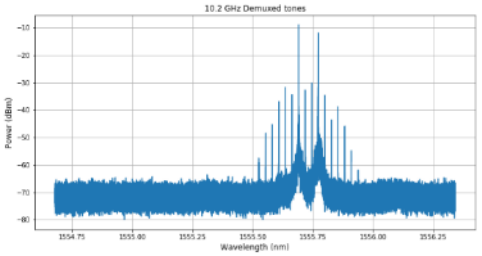
✓ Signals up to 34 GHz generated using PIC, in 3.4 GHz increments.



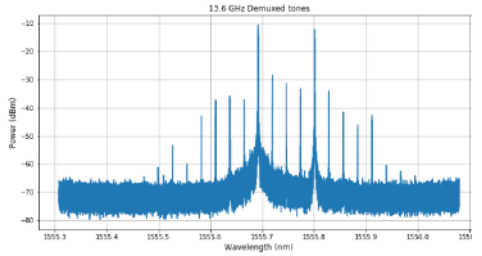
3.4 GHz



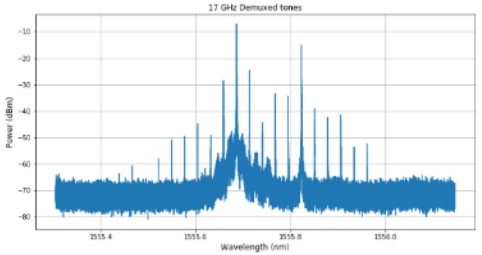
6.8 GHz



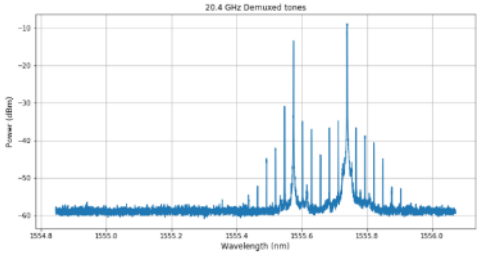
10.2 GHz



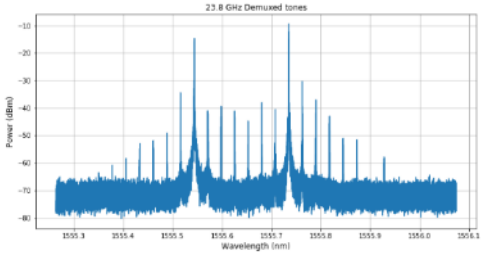
13.6 GHz



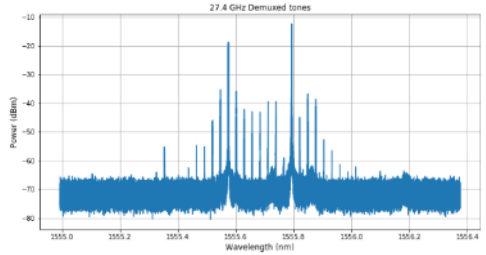
17.0 GHz



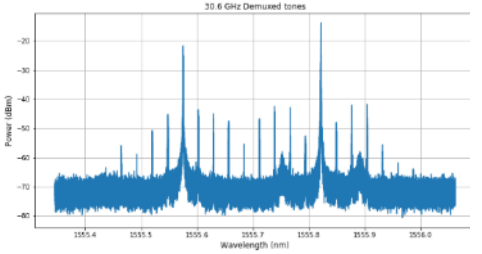
20.4 GHz



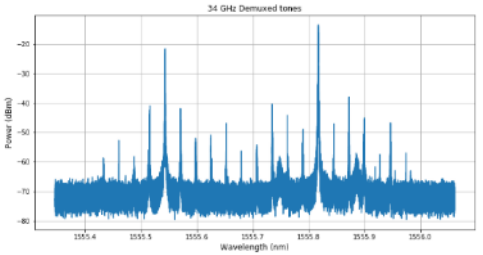
23.8 GHz



27.2 GHz



30.6 GHz

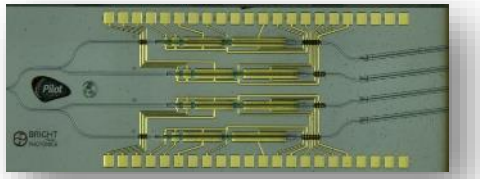


34 GHz

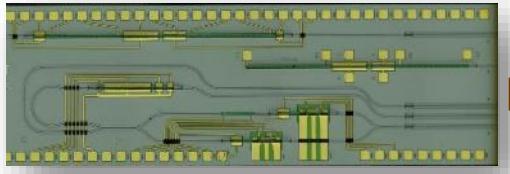
Current Status

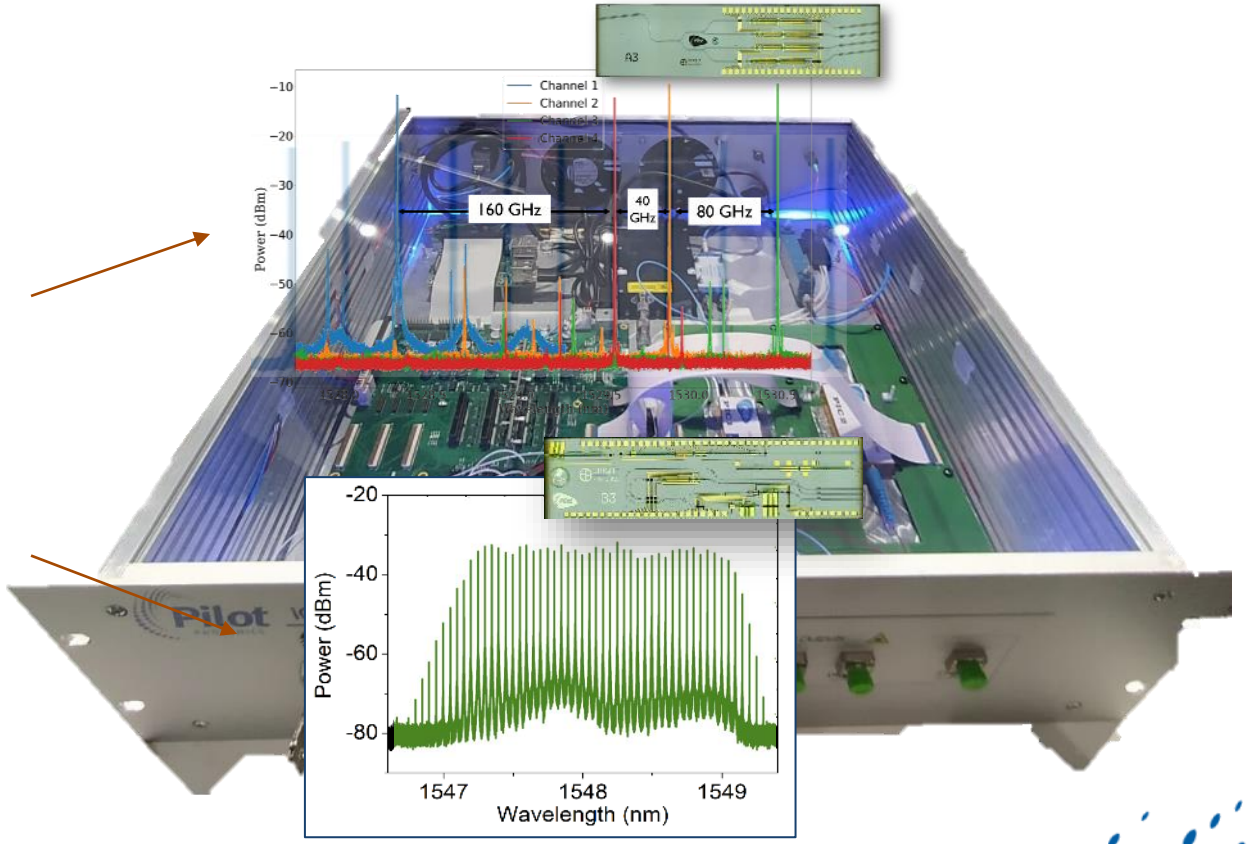
Now comb & demux PICs from same wafer run working together, deeper integration and now driven by Lyra hardware. Power per line starting to approach reasonable values.

iCLA Demux PIC



iCLA Comb PIC





iCLA: Current Status → Product Concept

Monolithic PIC out of fab; packaging, and nano-iTLA form factor module in design

Current Status

- Functionality of separate comb & demux demonstrated
- Pre-Alpha prototype
  - 2 package (comb & demux PICs)
  - Pilot's xDAC PIC controller HW and Lyra software interface
  - External master laser, and booster amp required currently
    - Will be eliminated in upcoming monolithic PIC iterations

Target specifications

- Nano-ITLA formfactor
- 4 x 75GHz coherent wavelengths
  (or 3 x 112.5GHz, or 2 x 225GHz, etc)
- Variable wavelength spacing (on 12.5GHz grid)
- 16dBm per wavelength
- 100kHz linewidth
- <8W power consumption

Partnerships welcome

Pilot PHOTONICS

Take-away points

- Integrated comb lasers bring new capabilities to space applications
- Not a one-size fits all: narrowband combs & broadband combs
- Applications: Lasercom; mmWave for Satcom; precision timing terahertz imaging, spectrometer calibration & more
- Pilot has chip-scale optical comb technology today
- Seeking partnerships for joint technology development

Thank you

For more information about Pilot Photonics please contact:

Dr. Frank Smyth

Founder & CTO, Pilot Photonics

frank.smyth@pilotphotonics.com