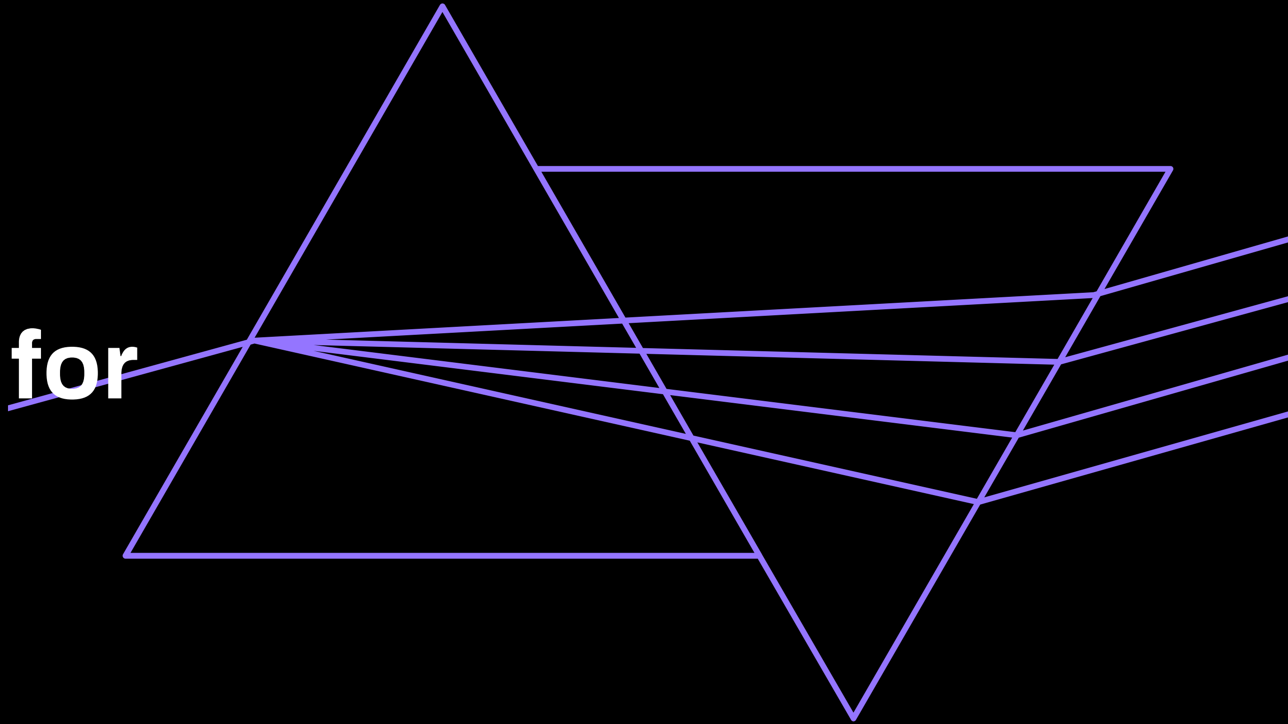
Technical Groups

Nanophotonic Devices Enable New Applications for Laser Frequency Combs



Featuring Daniel Hickstein from Octave Photonics

12 October 2022

A Quick Zoom Tutorial

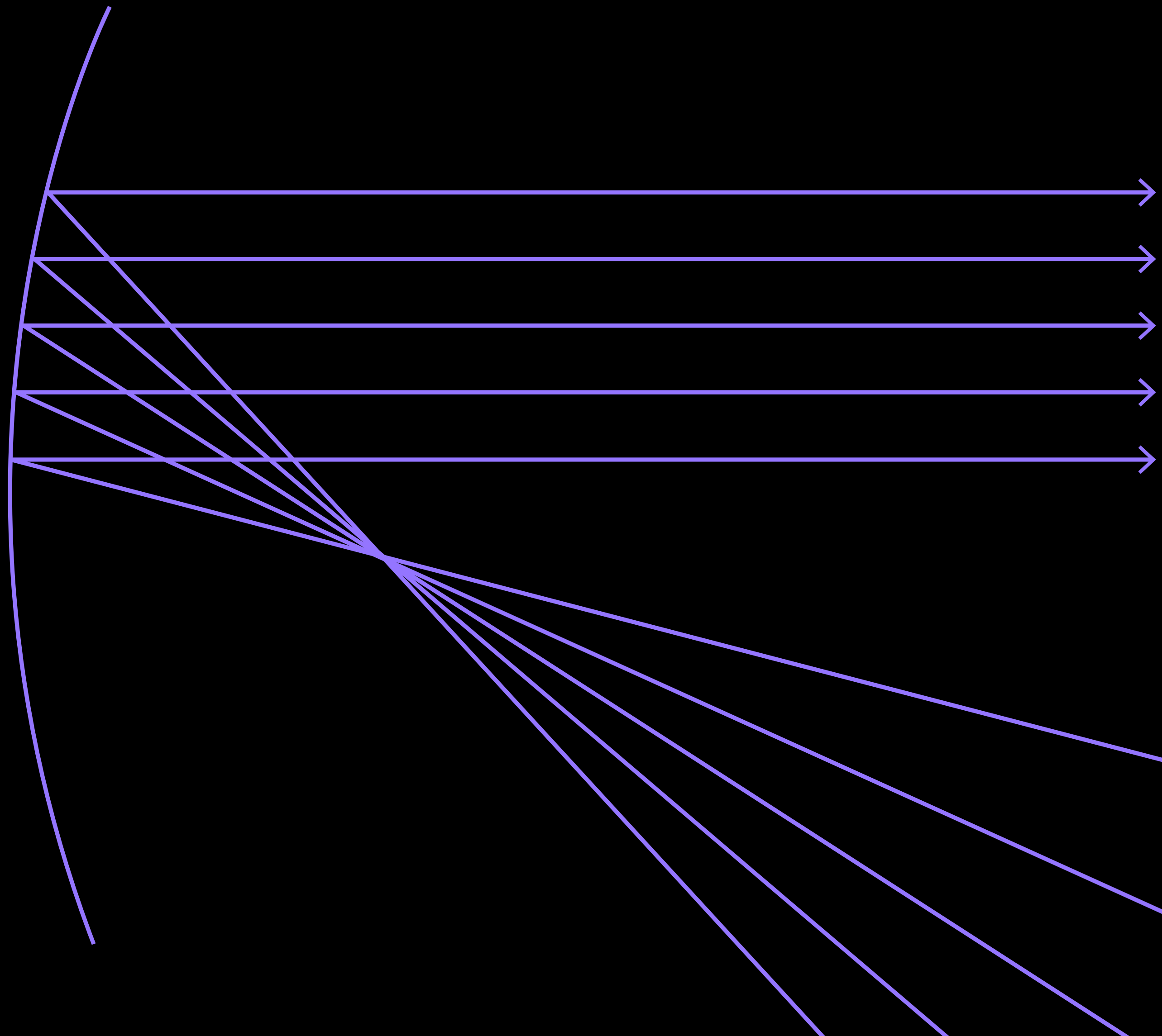
- Submit a question by clicking on “Q&A”
- Like a question that’s been submitted?
  Click the “thumbs up” icon to vote for it.
- Share your feedback in the survey.

OPTICA

Advancing Optics and Photonics Worldwide

Technical Groups

Question & Answer



OCTAVE PHOTONICS

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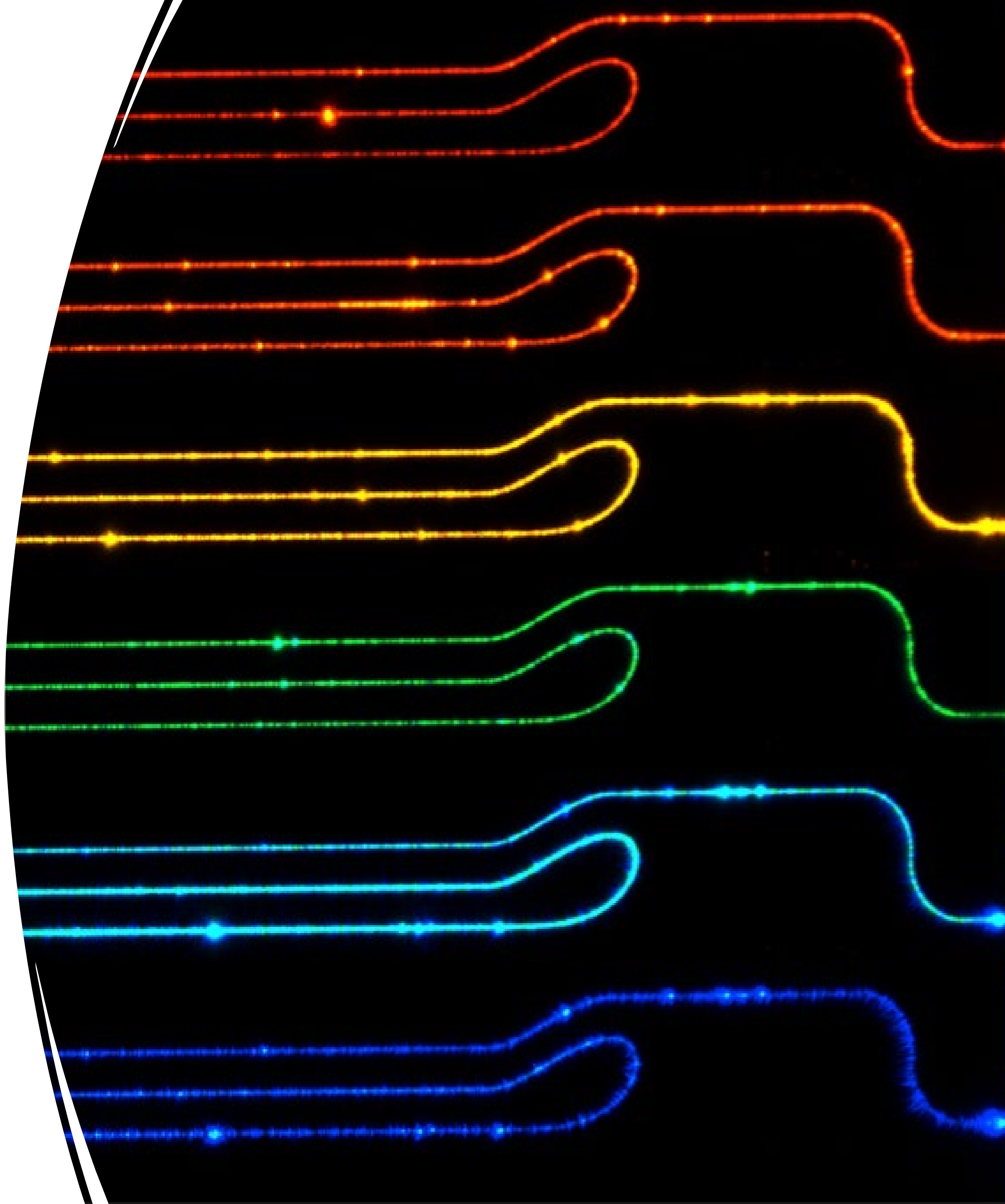


Dan Hickstein

Principal Scientist
Octave Photonics
Louisville, Colorado, USA

Octave Photonics: a small photonics company

OCTAVE PHOTONICS

- Office/Laboratory in Louisville, CO
- Spinoff from NIST.
- Employees: 3 (David Carlson, Zach Newman, Dan Hickstein)
- Funding: 35% sales/65% federal grant
- Goal: easy-to-use nanophotonic devices
- Currently hiring Nanophotonics Engineer/Physicist!

SBIR NASA

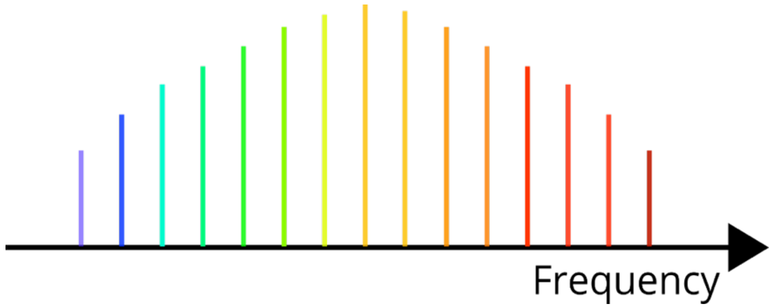
Office of Naval Research ONR Science & Technology

MTO DARPA MICROSYSTEMS TECHNOLOGY OFFICE

OEDIT COLORADO Office of Economic Development & International Trade

Outline

- 1. Introduction to laser frequency combs
  - What is a frequency comb?
  - Applications



- 2. Introduction to nanophotonic devices
  - Nanophotonic devices
  - Octave Photonics: easy-to-use nonlinear nanophotonics
- 3. Applications of nonlinear nanophotonics to frequency combs
  - Compact optical clocks
  - “Astrocombs” for exoplanet detection
  - “Microcombs” for tiny frequency combs

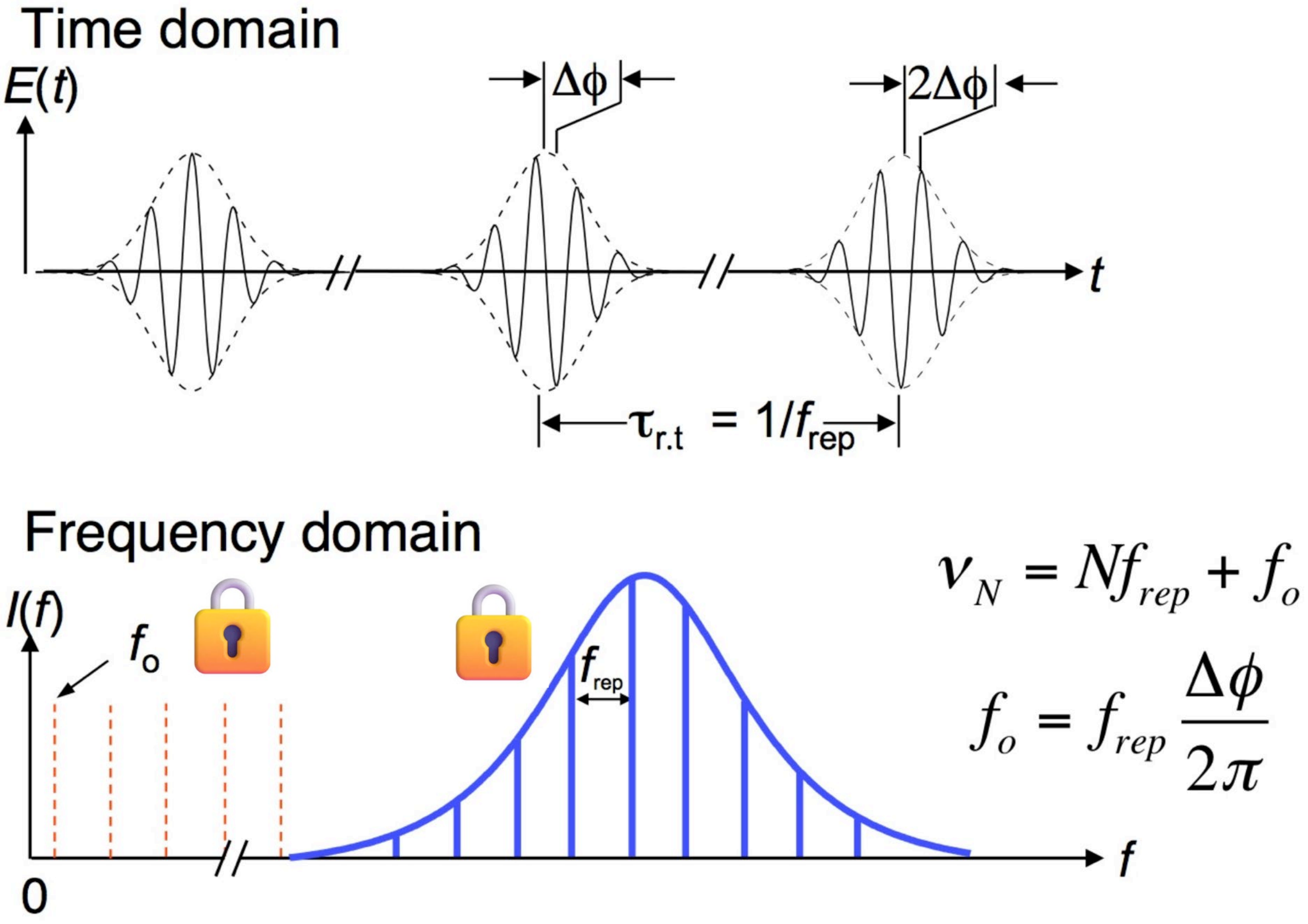
Part 1 – Introduction to laser frequency combs

Optical frequency comb

Pulses typically <100 fs

1 fs = 10^{-15} seconds = 0.000000000000001 seconds

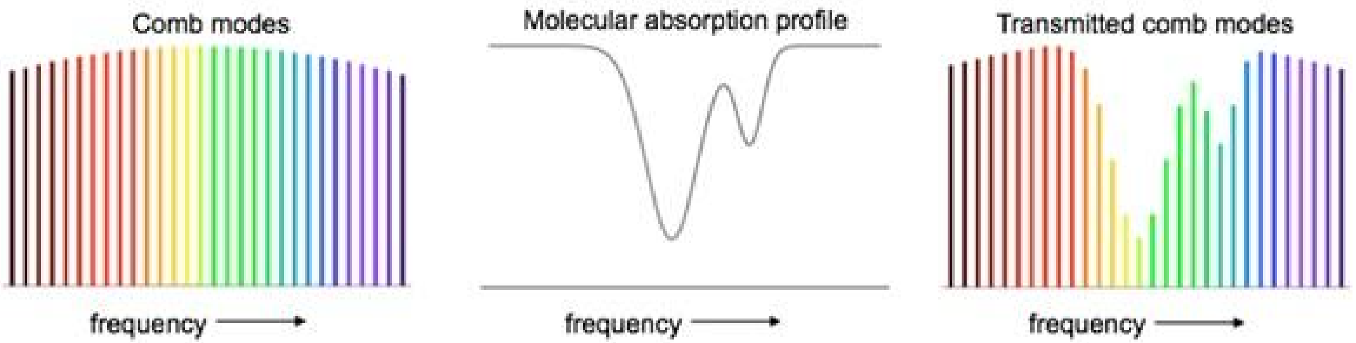
Laser frequency combs: rulers for light

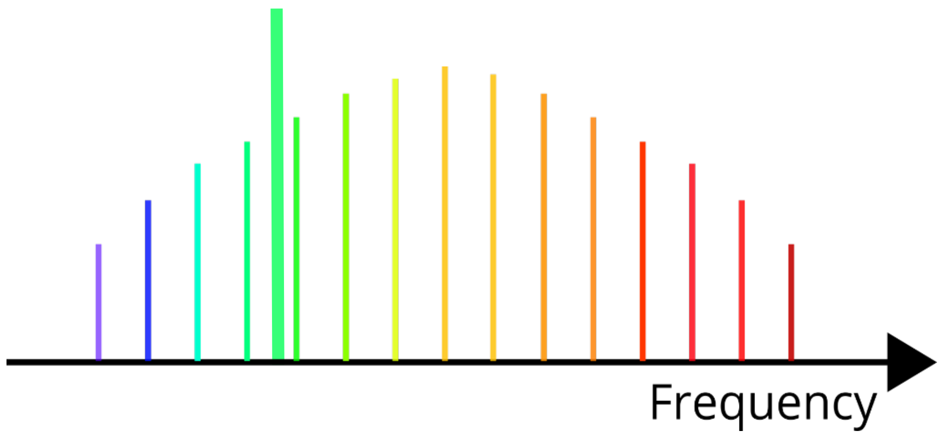


https://www.nist.gov/programs-projects/femtosecond-laser-frequency-combs-optical-clocks

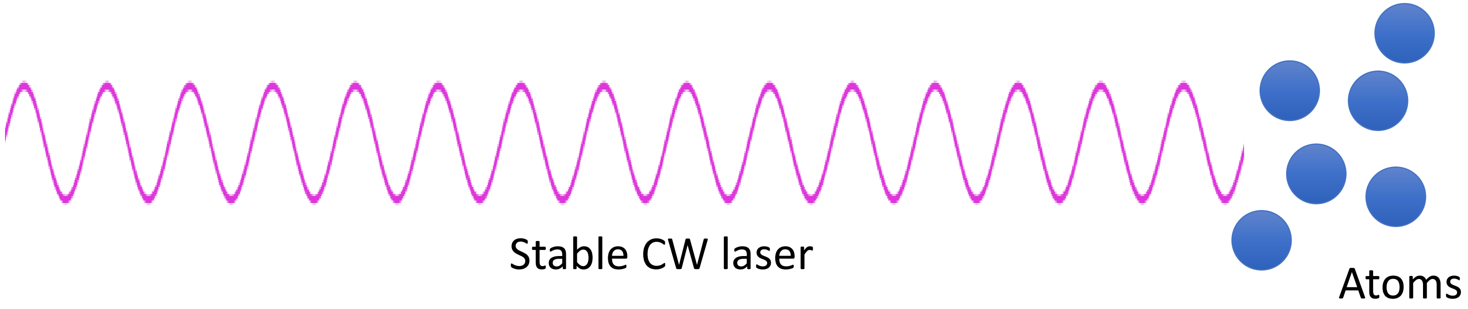
Many types of frequency comb spectroscopy

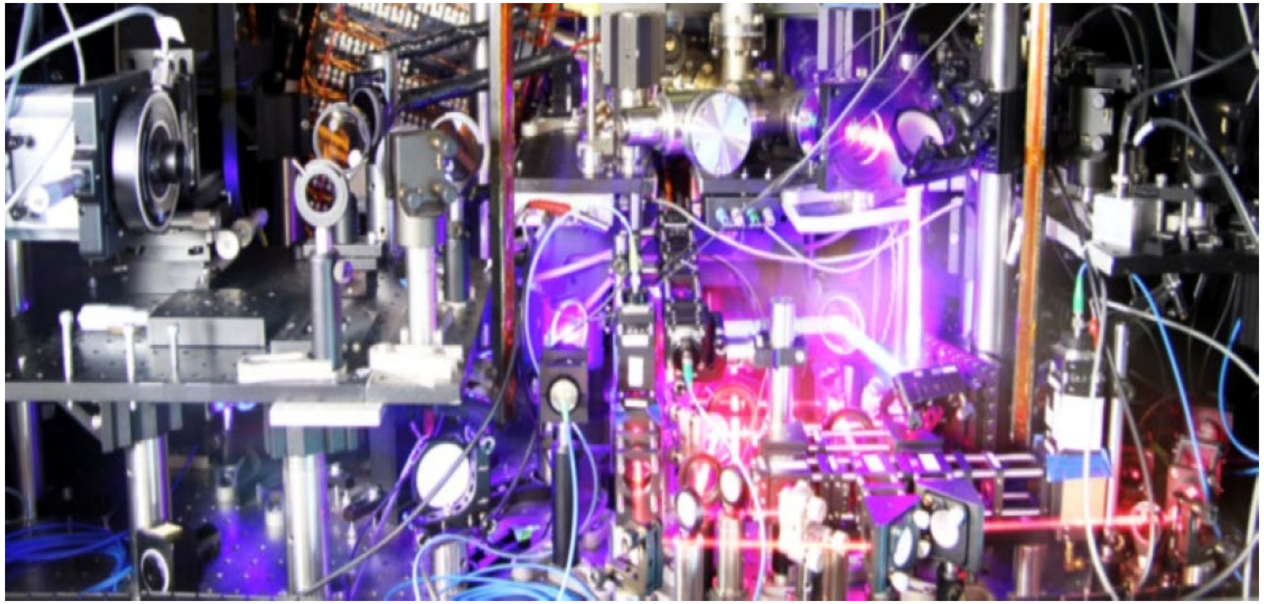
- Direct spectroscopy
  - Using comb as the light source
  - Requires high-res. spectrometer
- Dual-comb spectroscopy
  - Single detector
  - Very high resolution
  - Large frequency range
- Spectrograph calibration
  - Improves accuracy/precision of existing spectroscopy
- CW laser frequency measurement
  - Optical atomic clocks





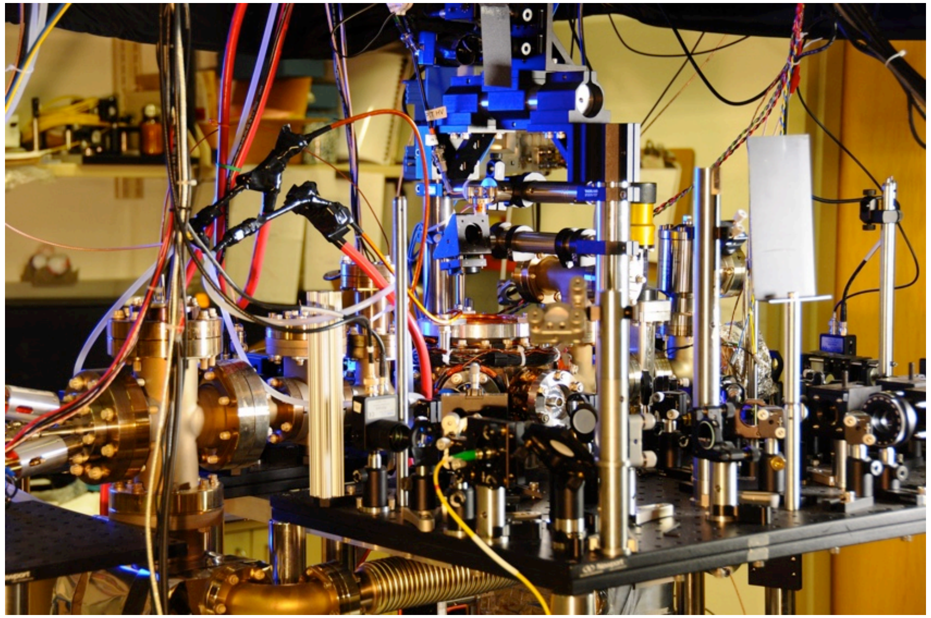
Optical atomic clocks





Strontium

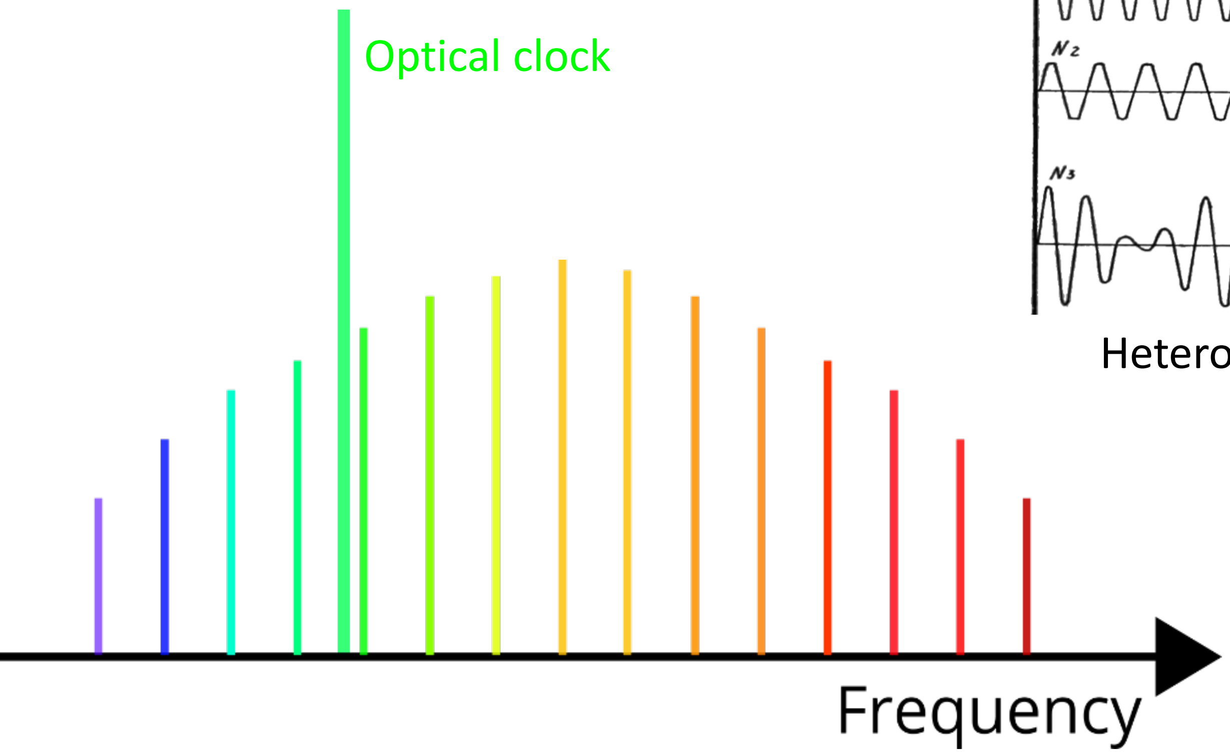
Photo: Ye Lab, University of Colorado

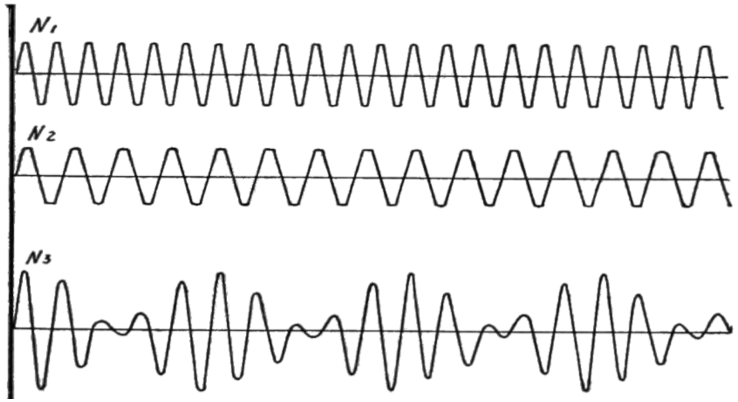


Ytterbium

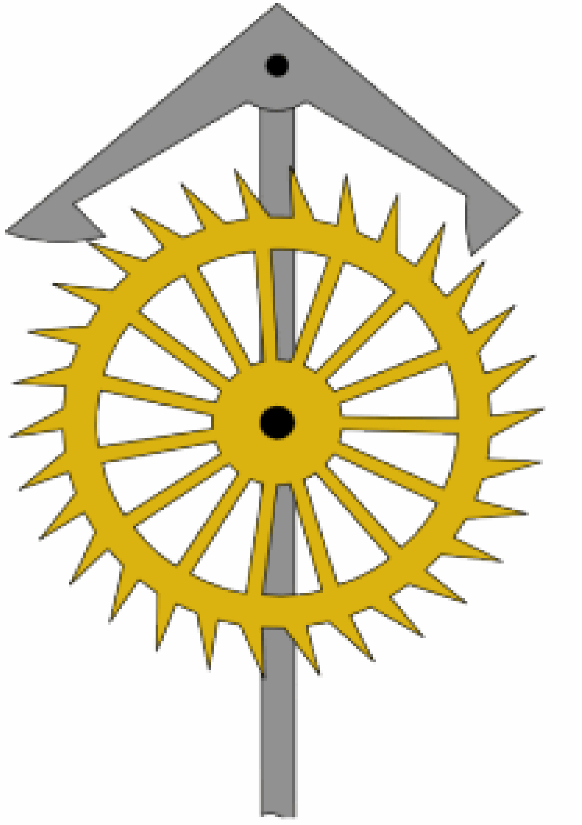
Photo: NIST

Frequency combs: optical clockwork

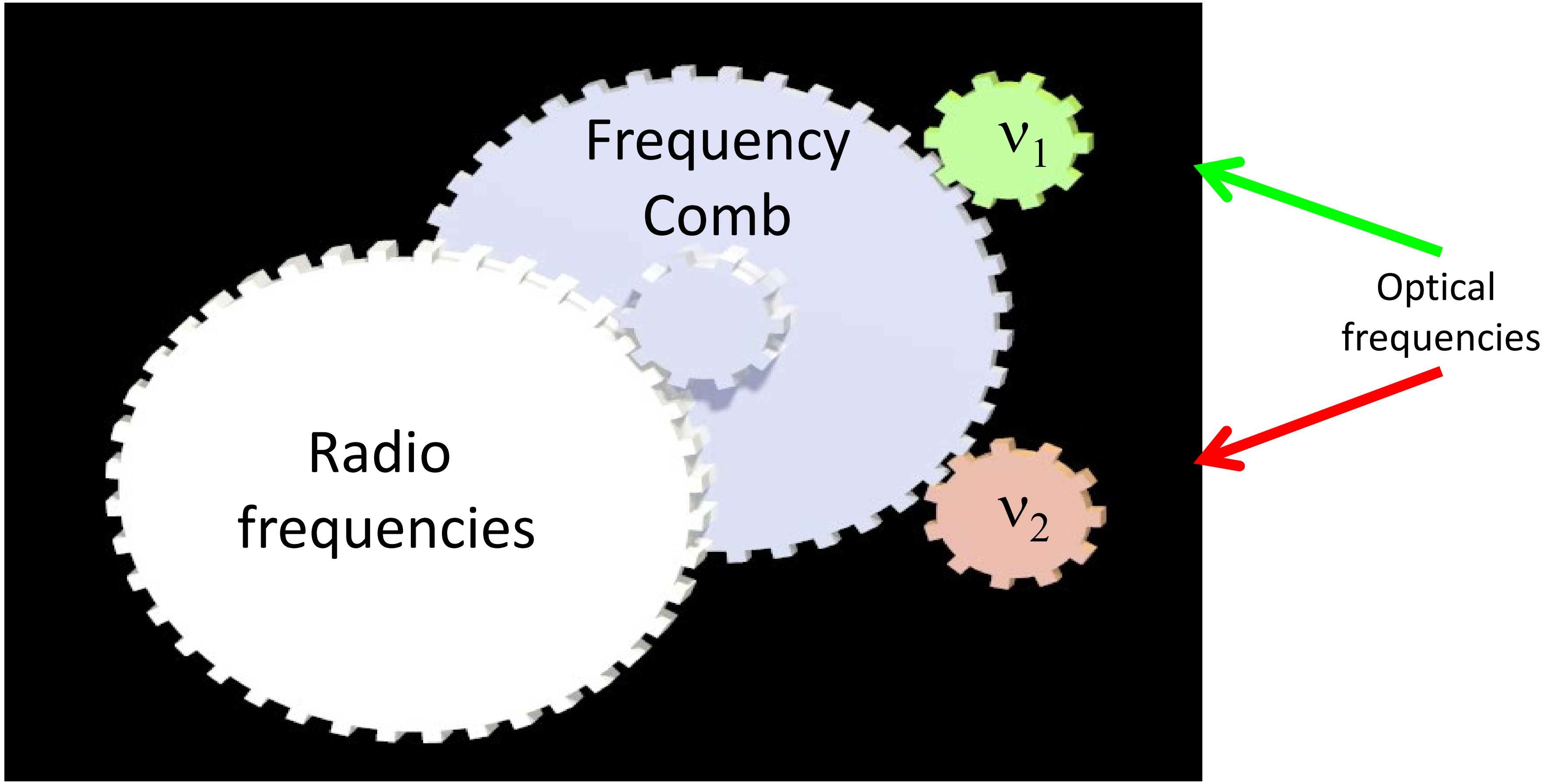




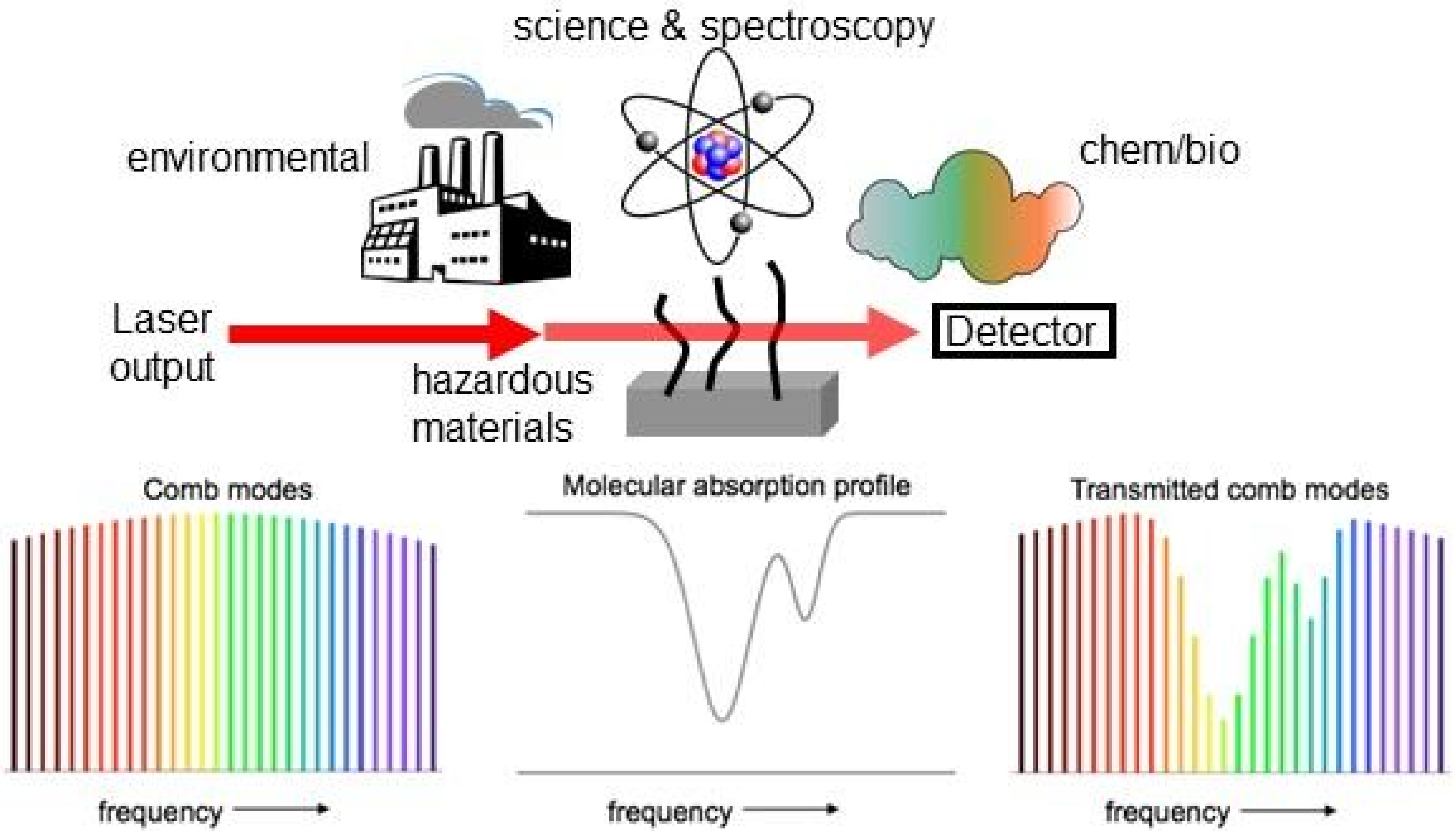
Heterodyne signal -> electronic readout



Frequency combs: optical clockwork



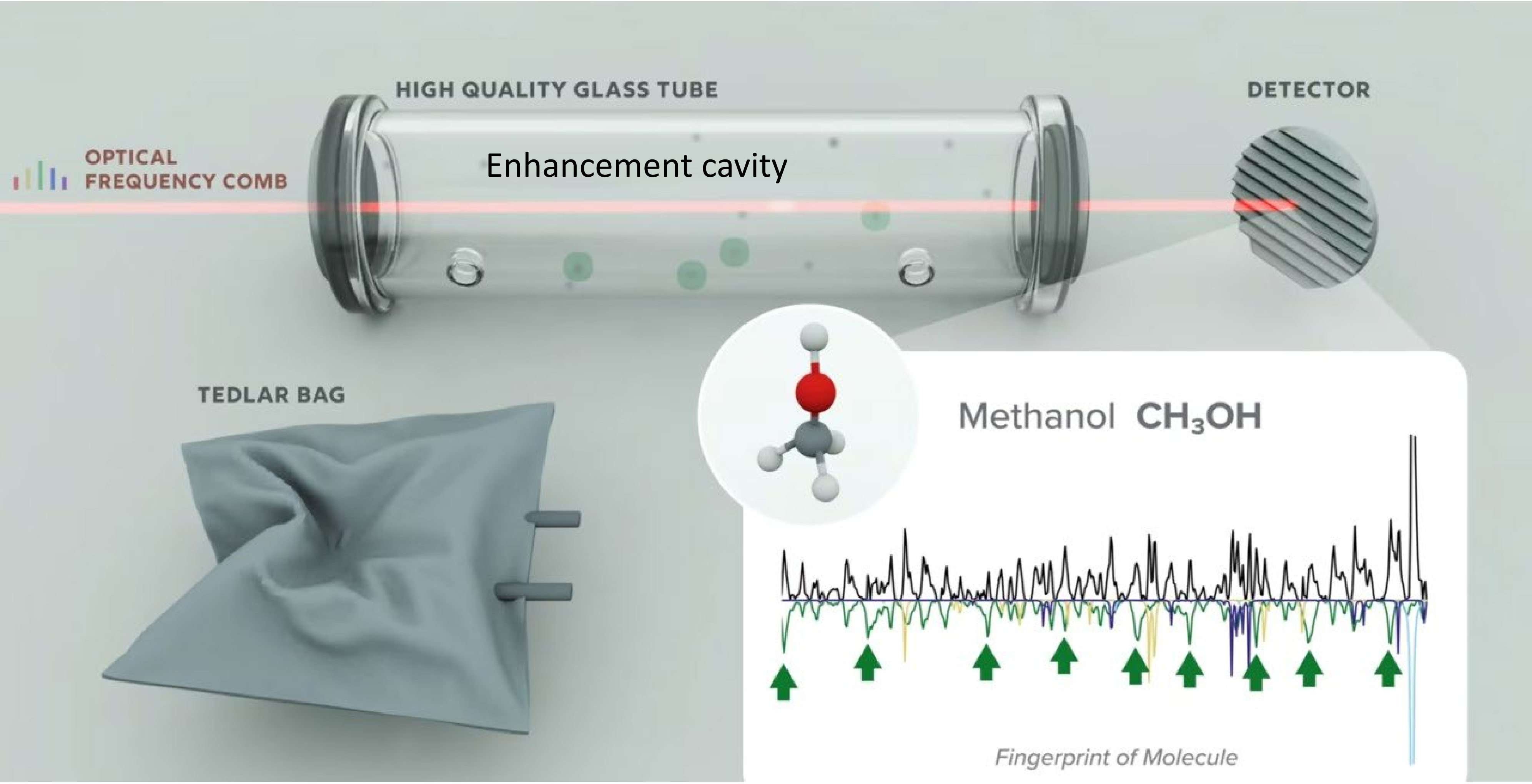
Frequency comb applied spectroscopy



Frequency Comb: rapid + broad bandwidth + good spectral discrimination

Frequency comb breathalyzer

- Broad bandwidth + high resolution
- Can lock to high-finesse cavity
- Recently: can detect COVID! (with limited sensitivity)
- Optica Applied Spectroscopy Webinar by David Nesbitt, Nov 10 2022.



Work from D. Nesbitt and J. Ye groups, JILA, University of Colorado and NIST

Credit: J. Wang, NIST

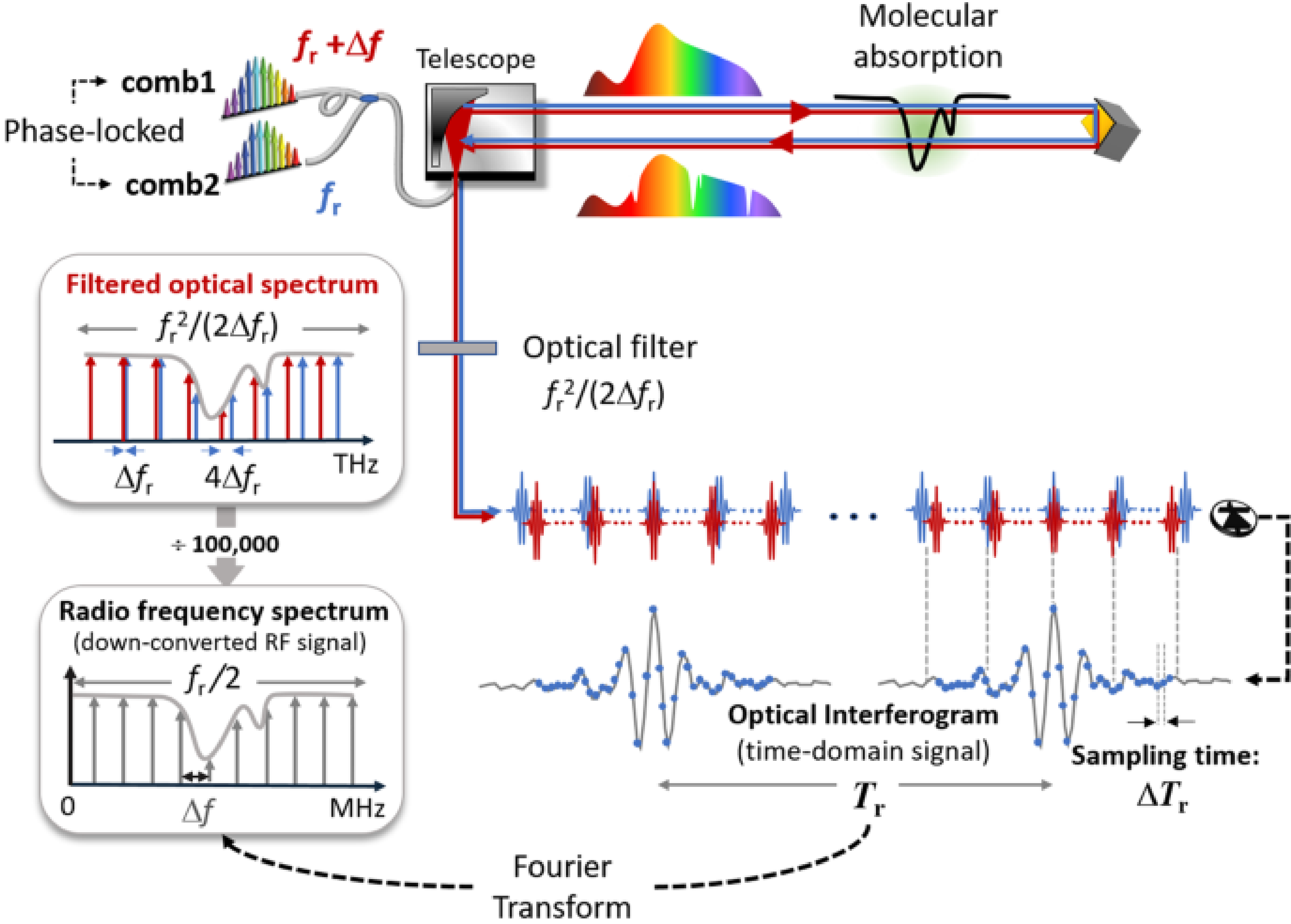
Frequency comb technology: becoming turnkey

- Transition from Ti:sapphire to fiber lasers facilitates field applications

100 MHz Er:fiber comb

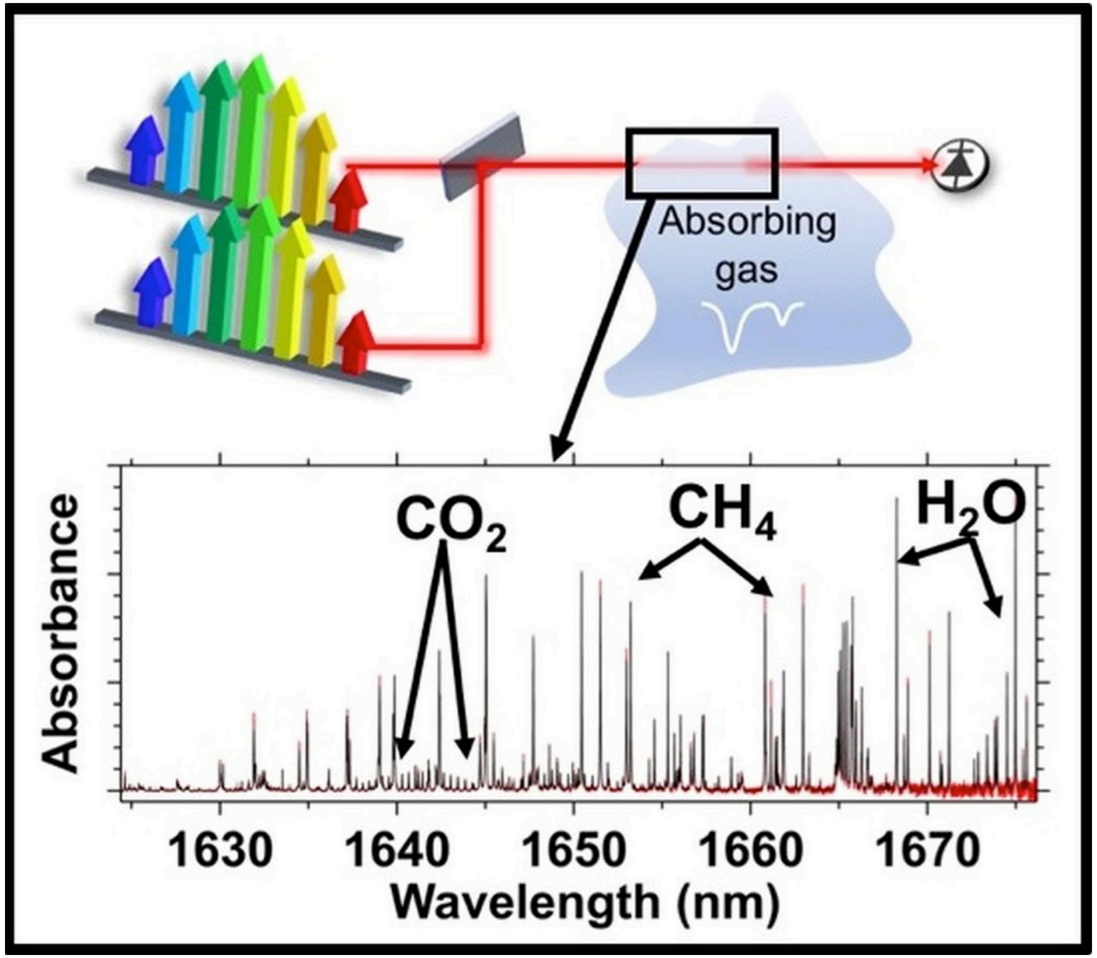
Dual comb spectroscopy: ready for field applications

- Provides the full resolution of the frequency comb.
- Can use a single detector
- Spectra acquired very quickly



From Fortier and Baumann 2019. NIST.
https://www.nature.com/articles/s42005-019-0249-y

Dual comb spectroscopy in the (oil and gas) field



Field-based gas sensing

Photo: LongPath Technologies, LLC

https://www.nist.gov/news-events/news/2018/03/mobile-dual-comb-device-significantly-improves-methane-leak-detection

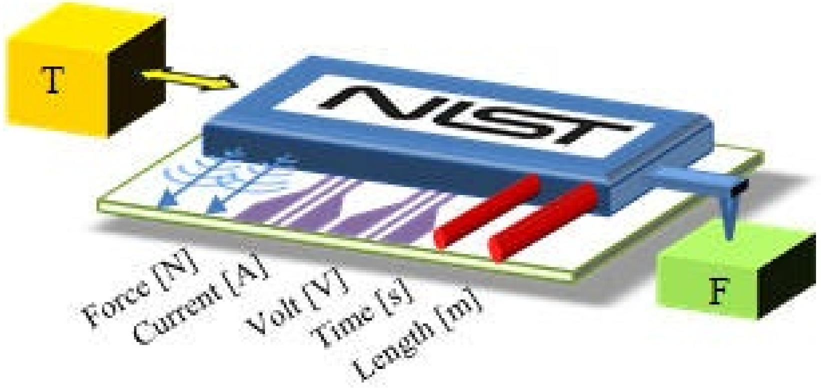
Next-generation comb applications

- Require comb sources that are smaller, lighter, lower-power-consumption, and rugged.

Space-based metrology (e.g., GPS)

Airborne gas sensing

Compact standards references

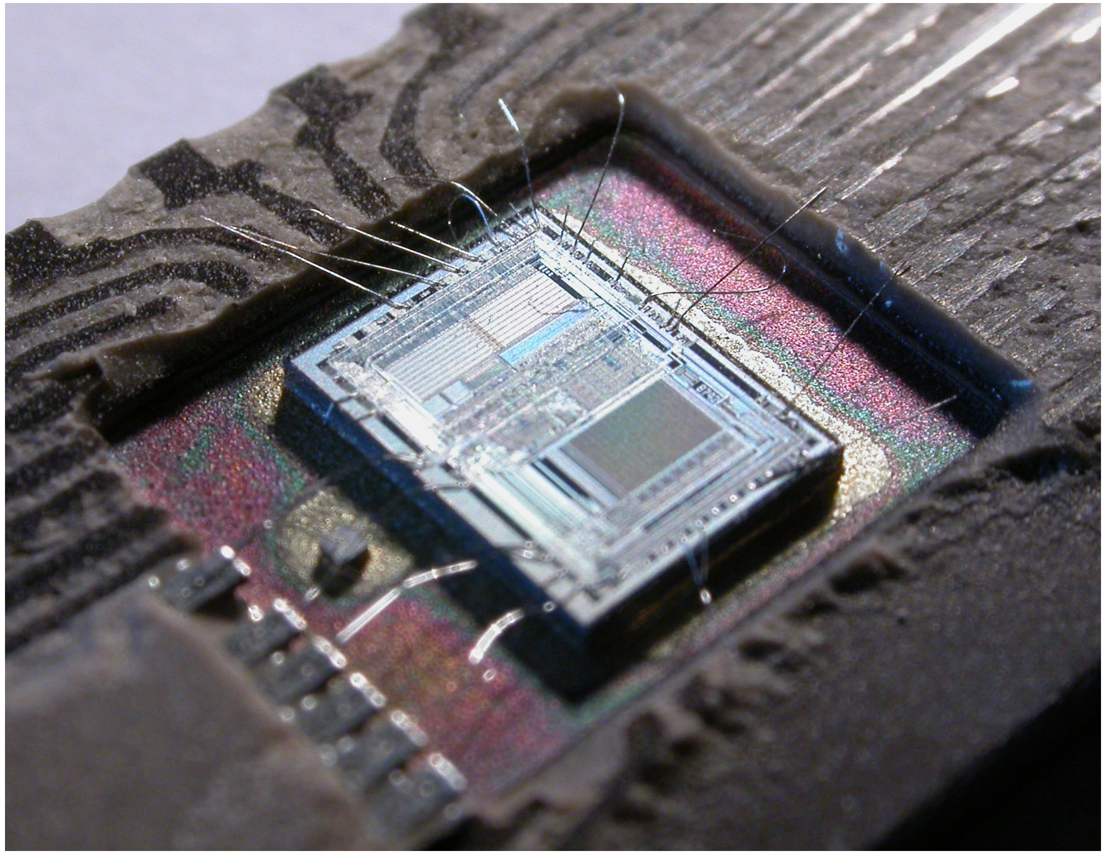


NIST-on-a-chip

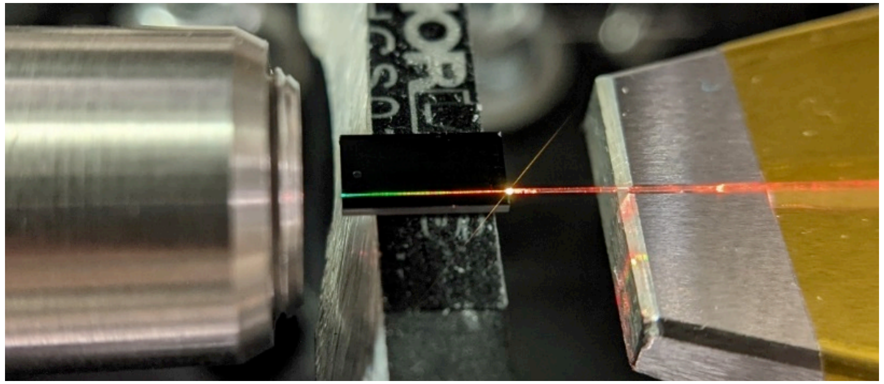
Part 2 - Nanophotonics

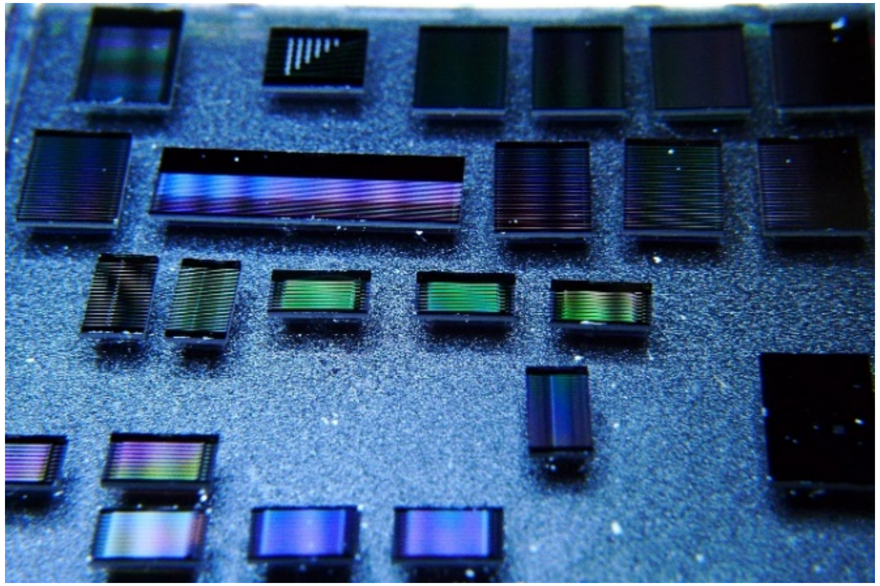
Nanophotonic chips: optics made tiny

Microelectronics



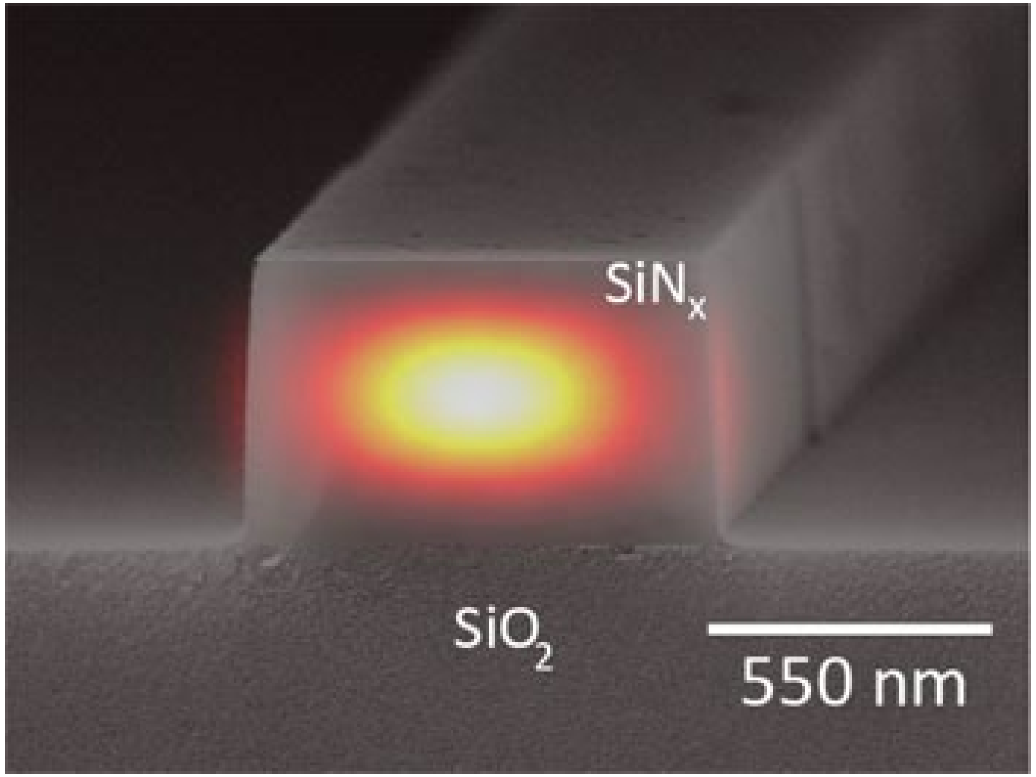
Nanophotonics



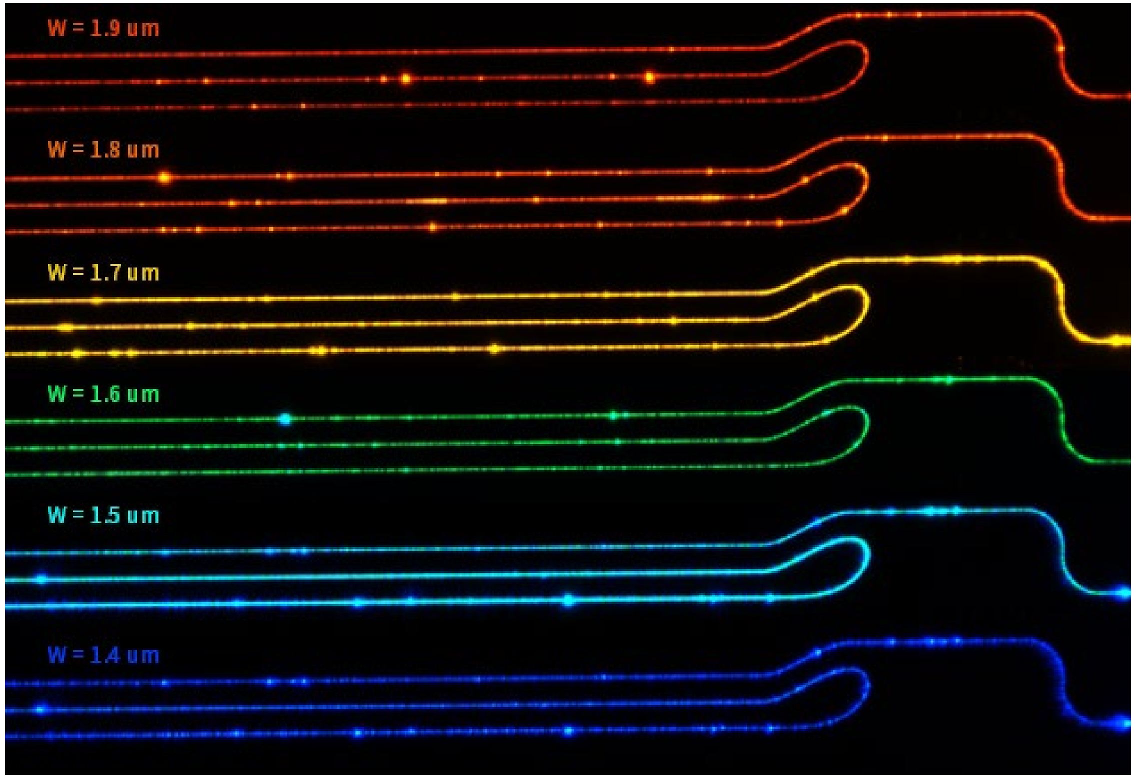


Nonlinear nanophotonics: nonlinear optics made tiny

- Exceptionally high nonlinearity
  - High confinement of light provides maximum peak intensity
- Geometric control of dispersion
  - Allows phase matching of wavelength-conversion processes



1550 nm pumped supercontinuum generation



Nonlinear nanophotonics simplified

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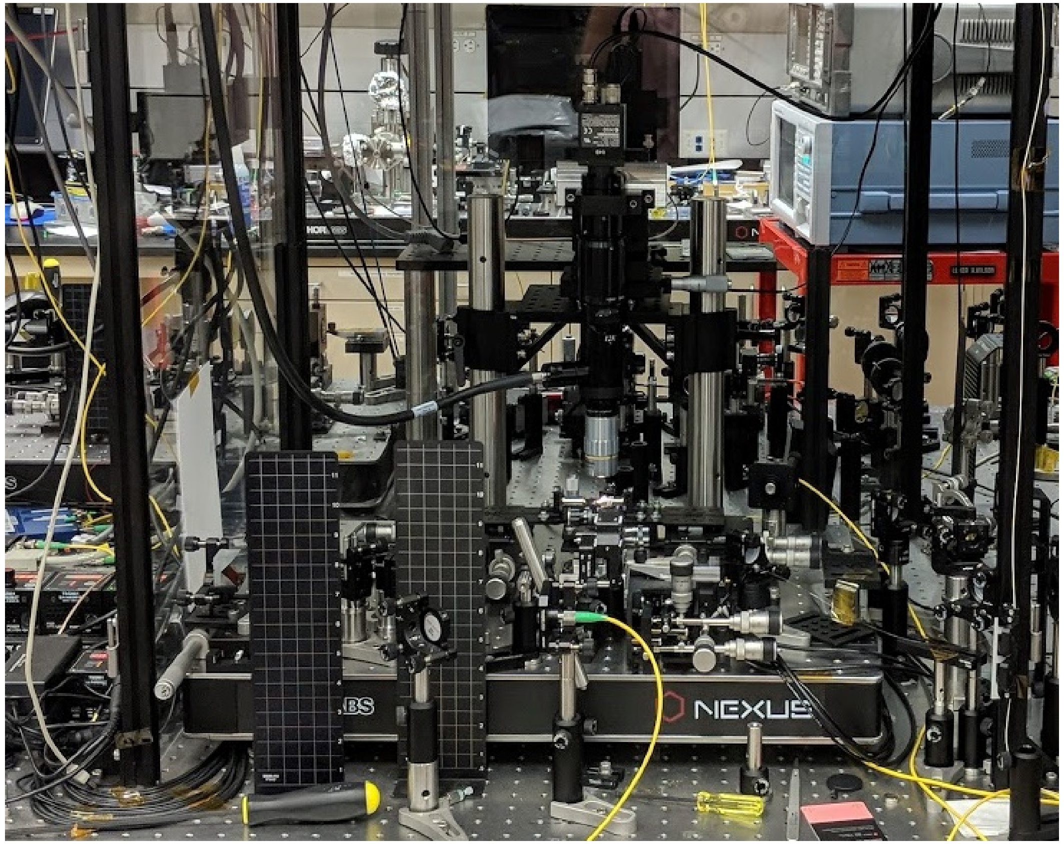
Typical lab setup

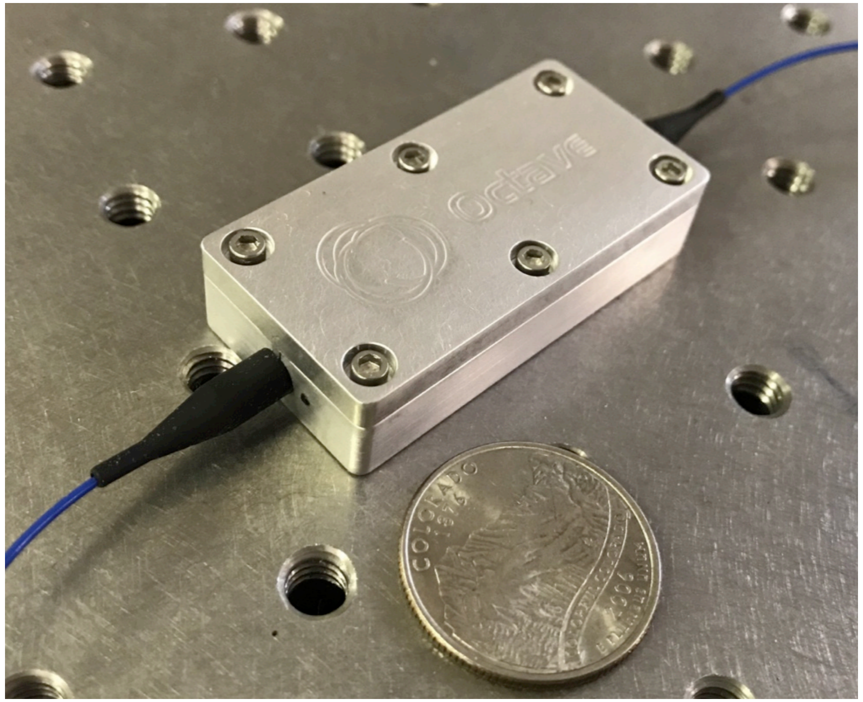
- High-stability microscope
- Precision nano-alignment stages
- Large enclosure needed



~ 1 meter

Fully connectorized device

- Plug-and-play
- No alignment needed
- Fully enclosed

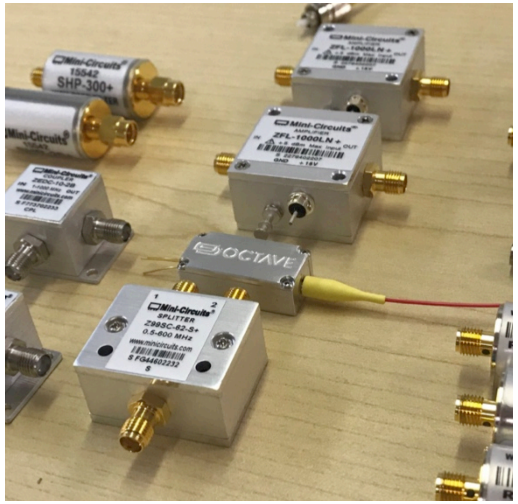


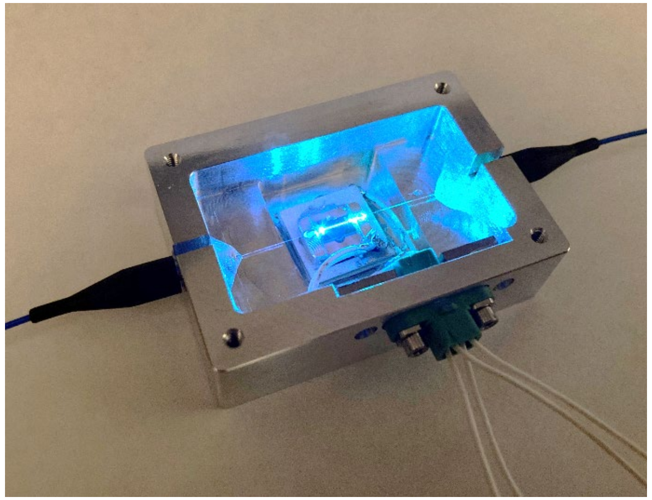
~ 2 cm

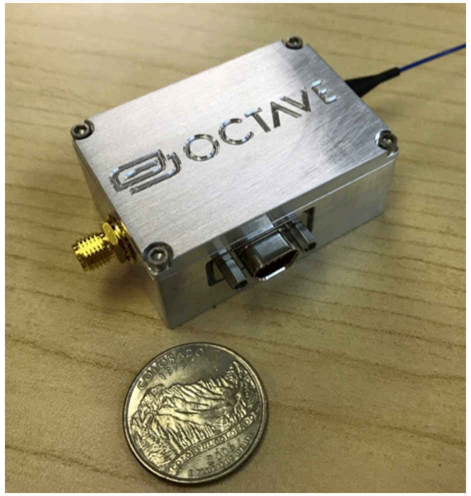
Waveguide packaging

Waveguide packages suitable for:
• Vacuum environments
• Low SWaP applications
• **High peak power/intensity (>10 kW, >10^{12} W/cm^2)**
• **High average power/intensity (>4 Watts, >400 GW)**

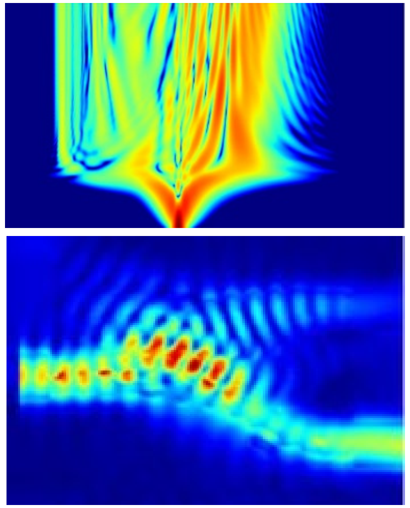
Options include:
• Custom supercontinuum spectrum
• Hermetic sealing
• Active temperature control
• RF output



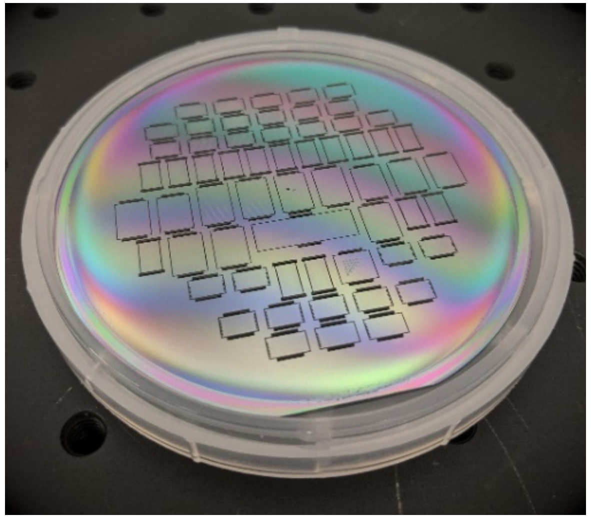




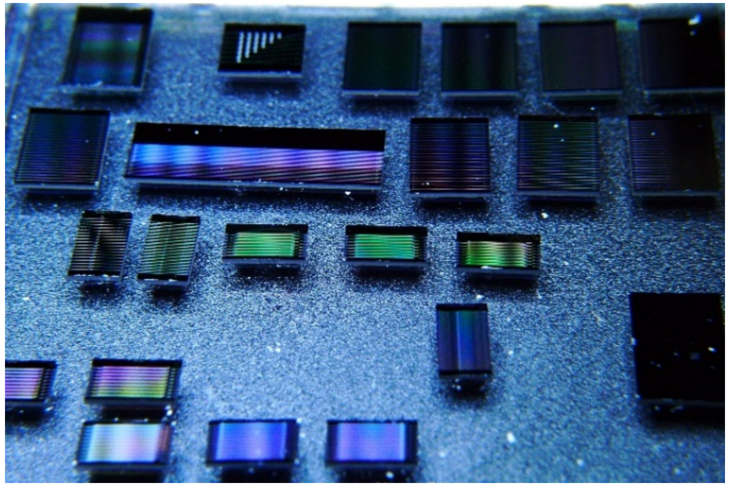
End-to-end development for nanophotonics



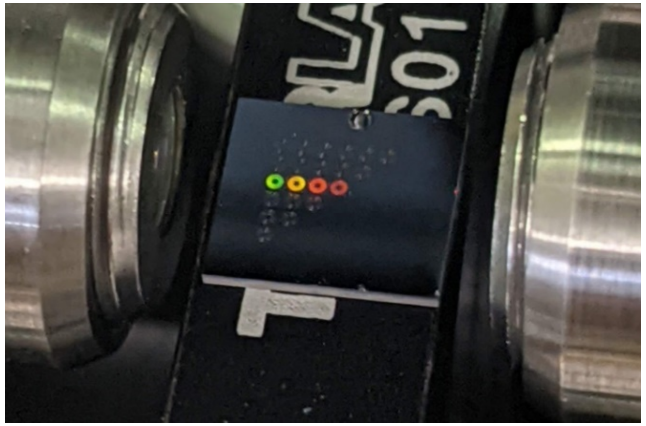
Device simulation



Fabrication



Die separation



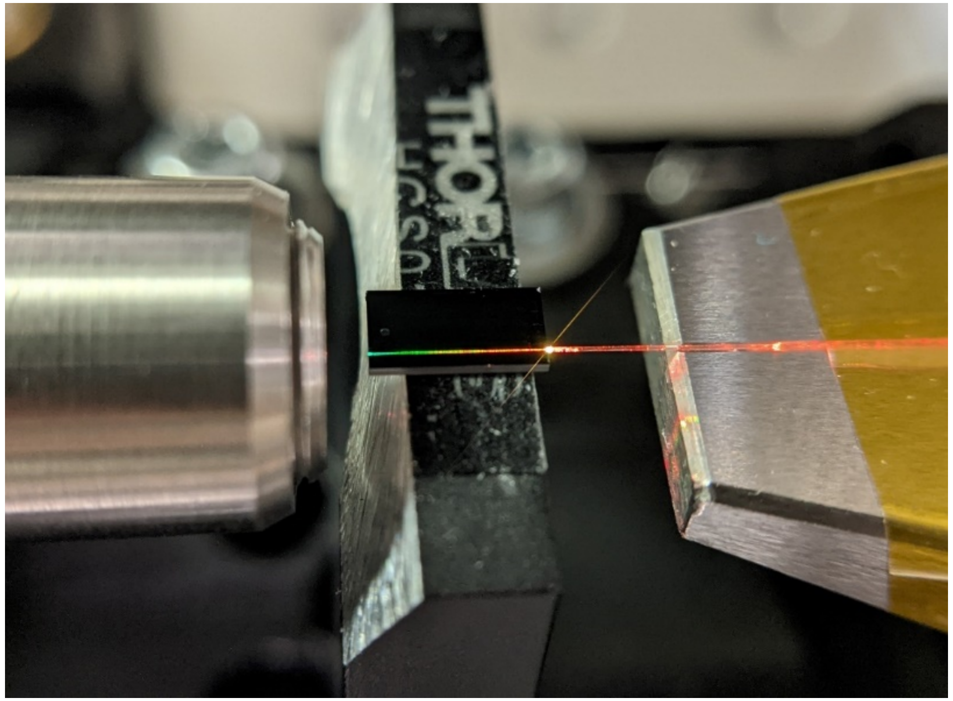
Lab testing

Packaging

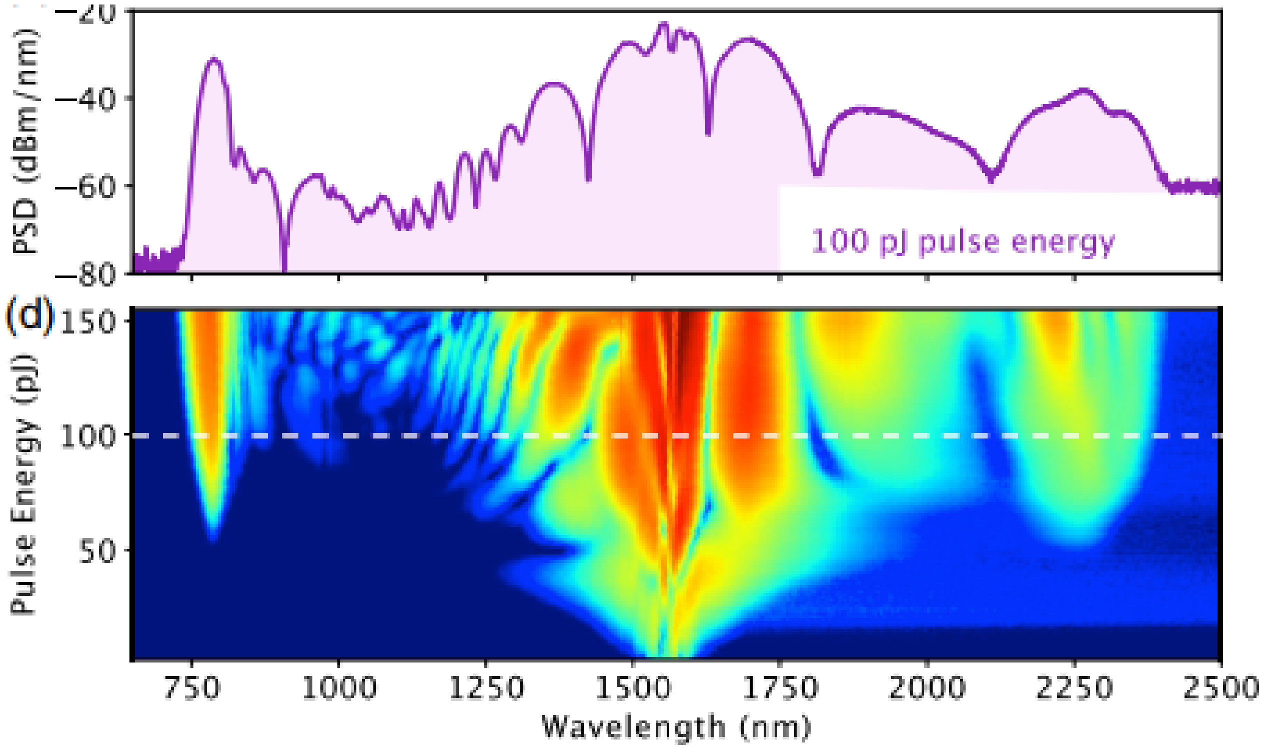
Deployment

Part 3 – Applications of nanophotonics to frequency combs

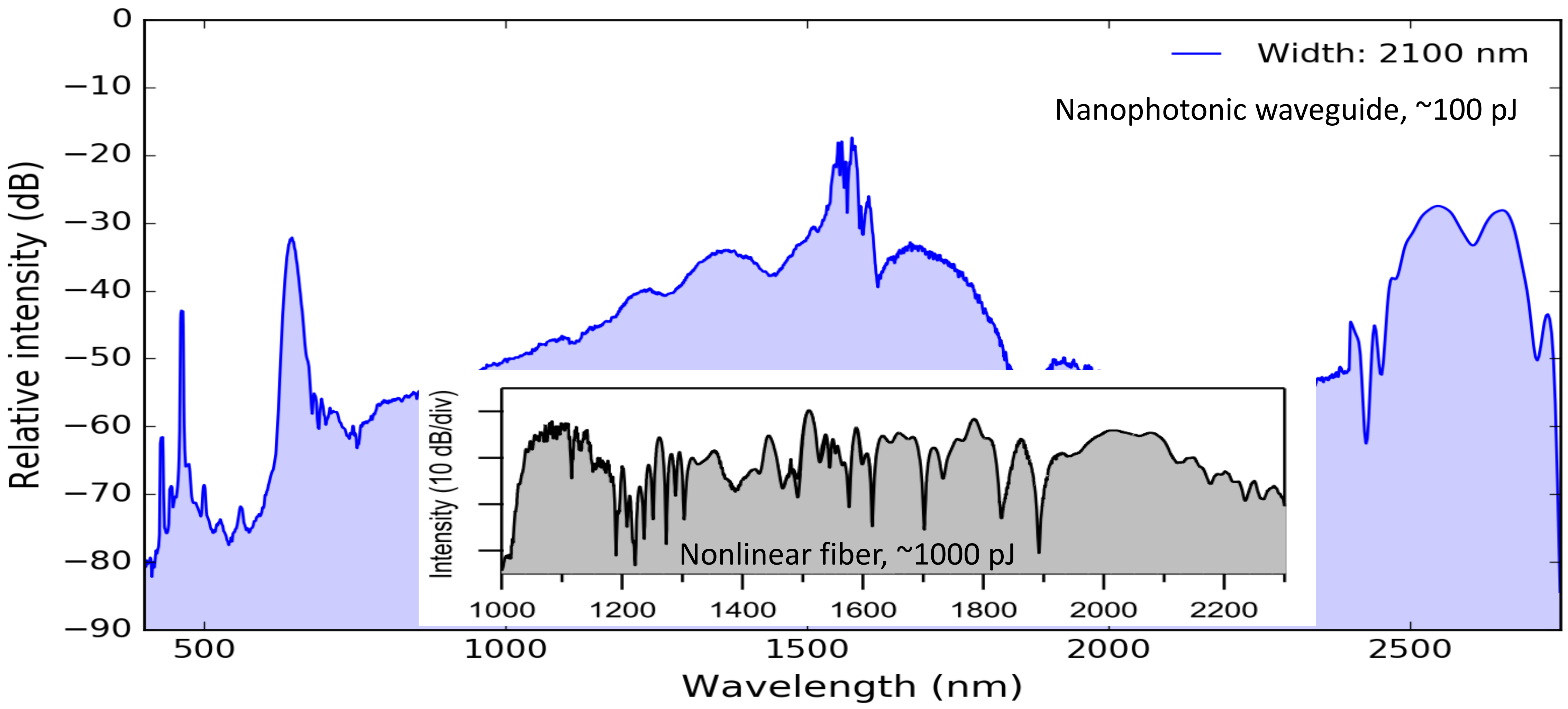
Application 1: Supercontinuum generation



Nanophotonic waveguide for supercontinuum
Pumped with ~100 fs pulses at 1550 nm

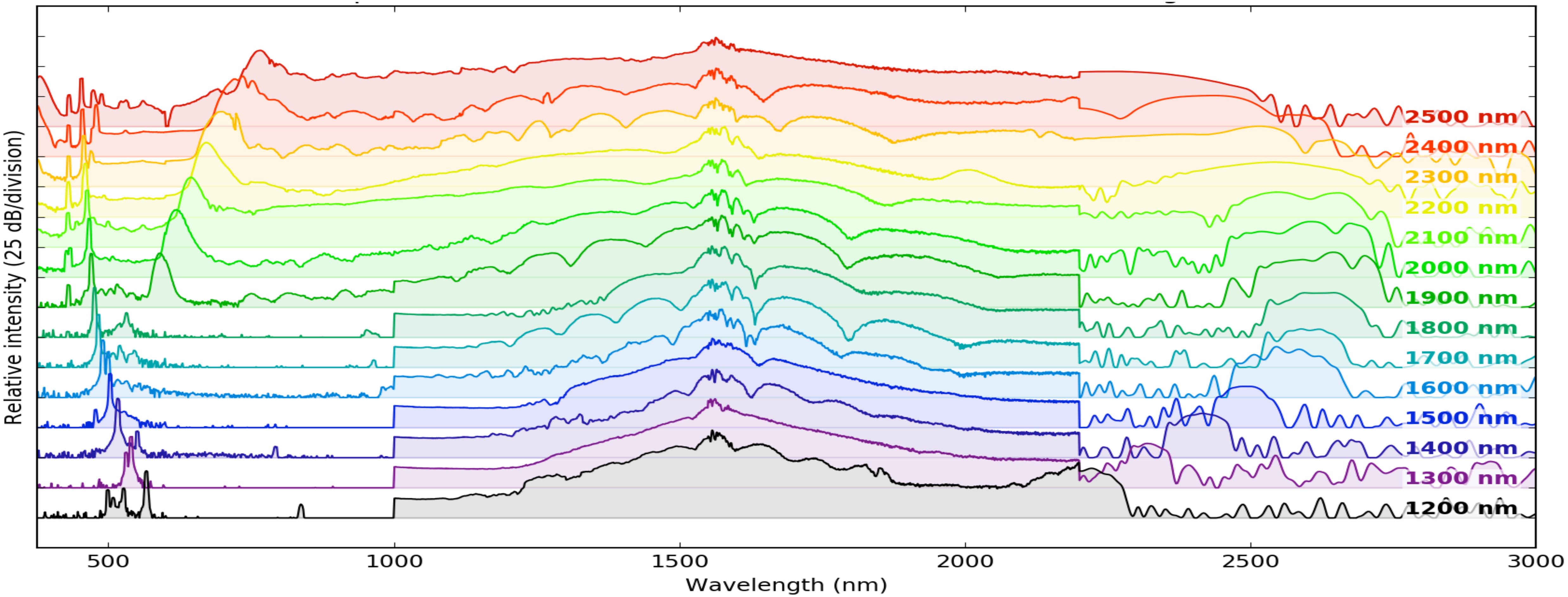


Experimental supercontinuum

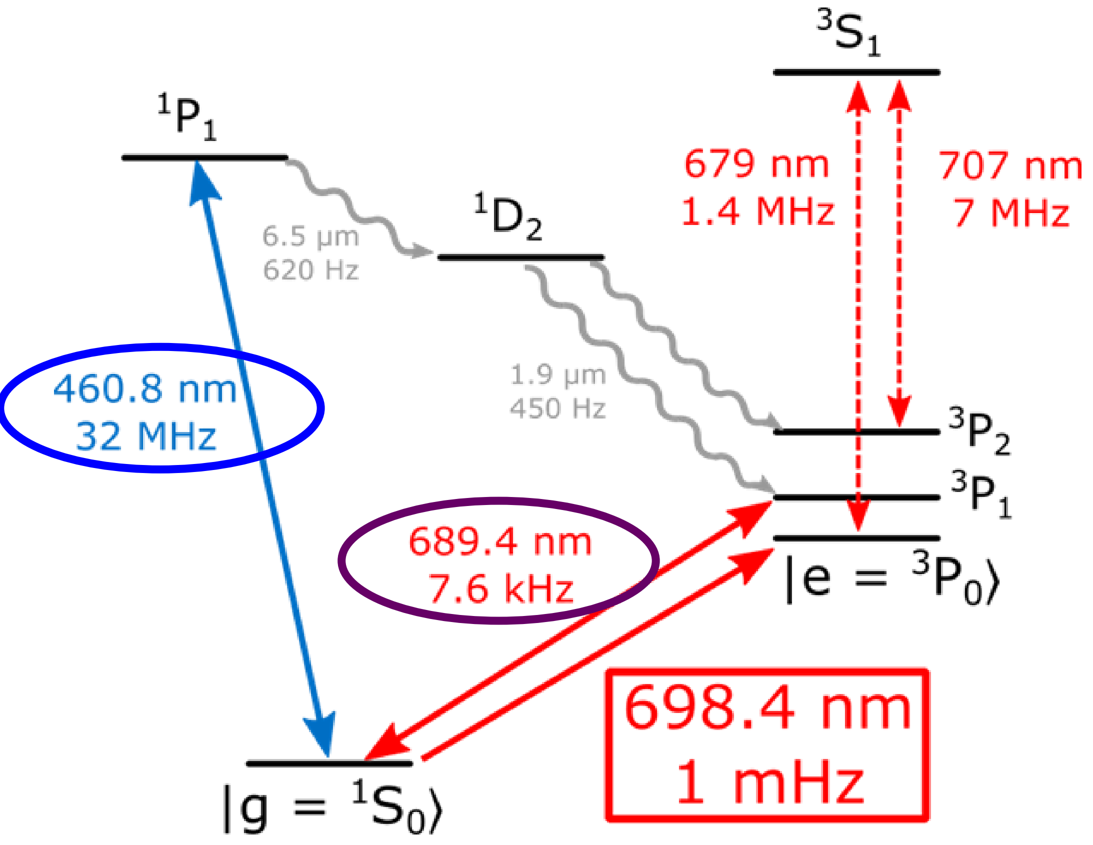


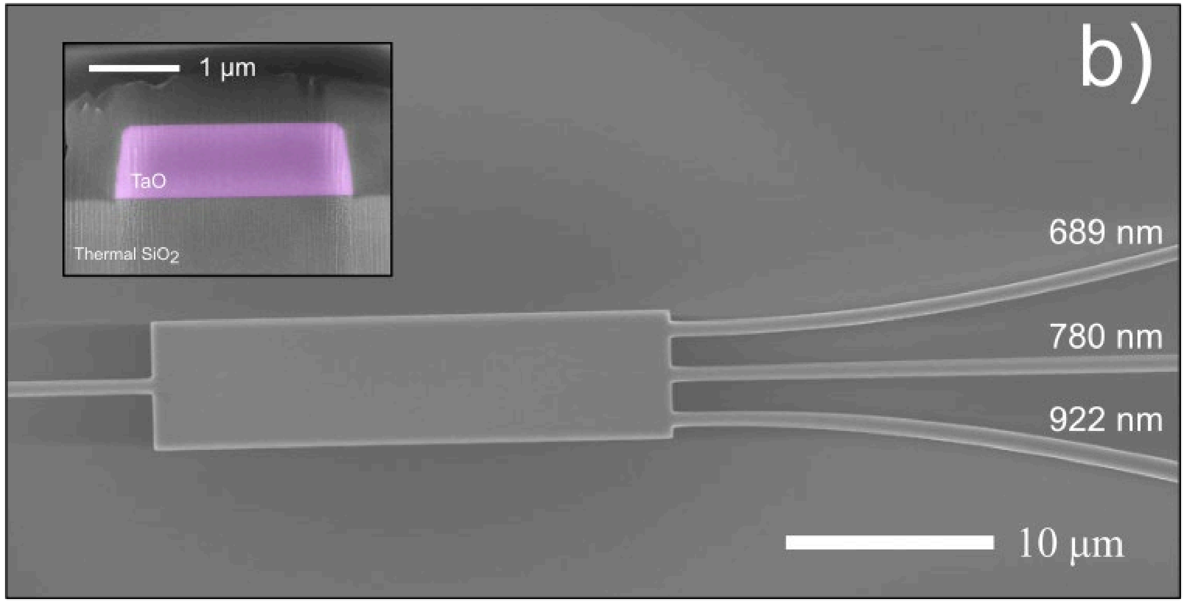
Tunable spectrum

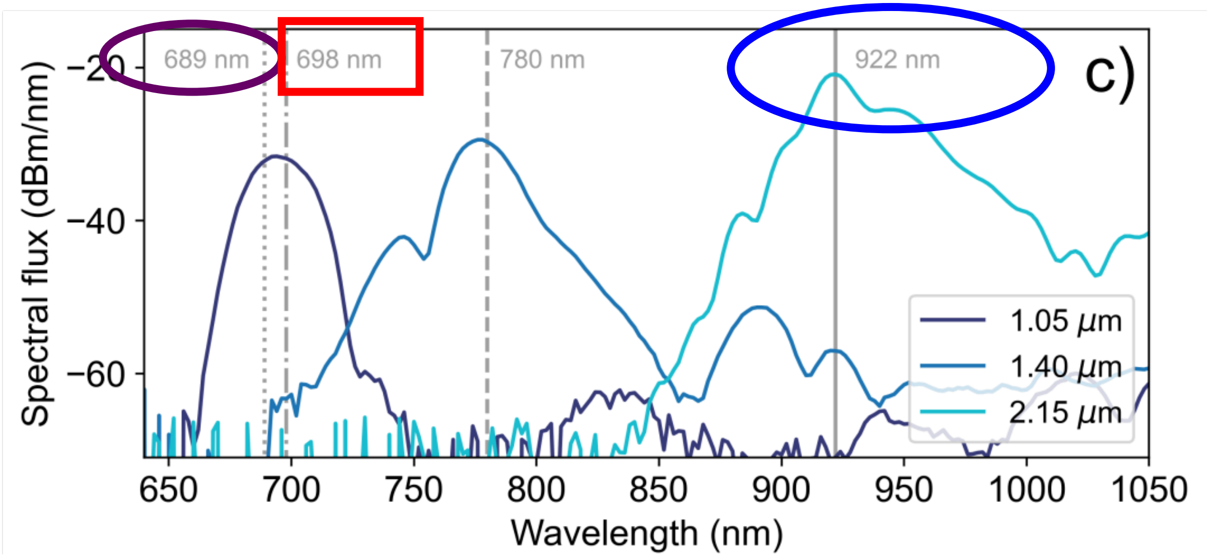
Experimental supercontinuum from ~640-nm-thickness SiN waveguides



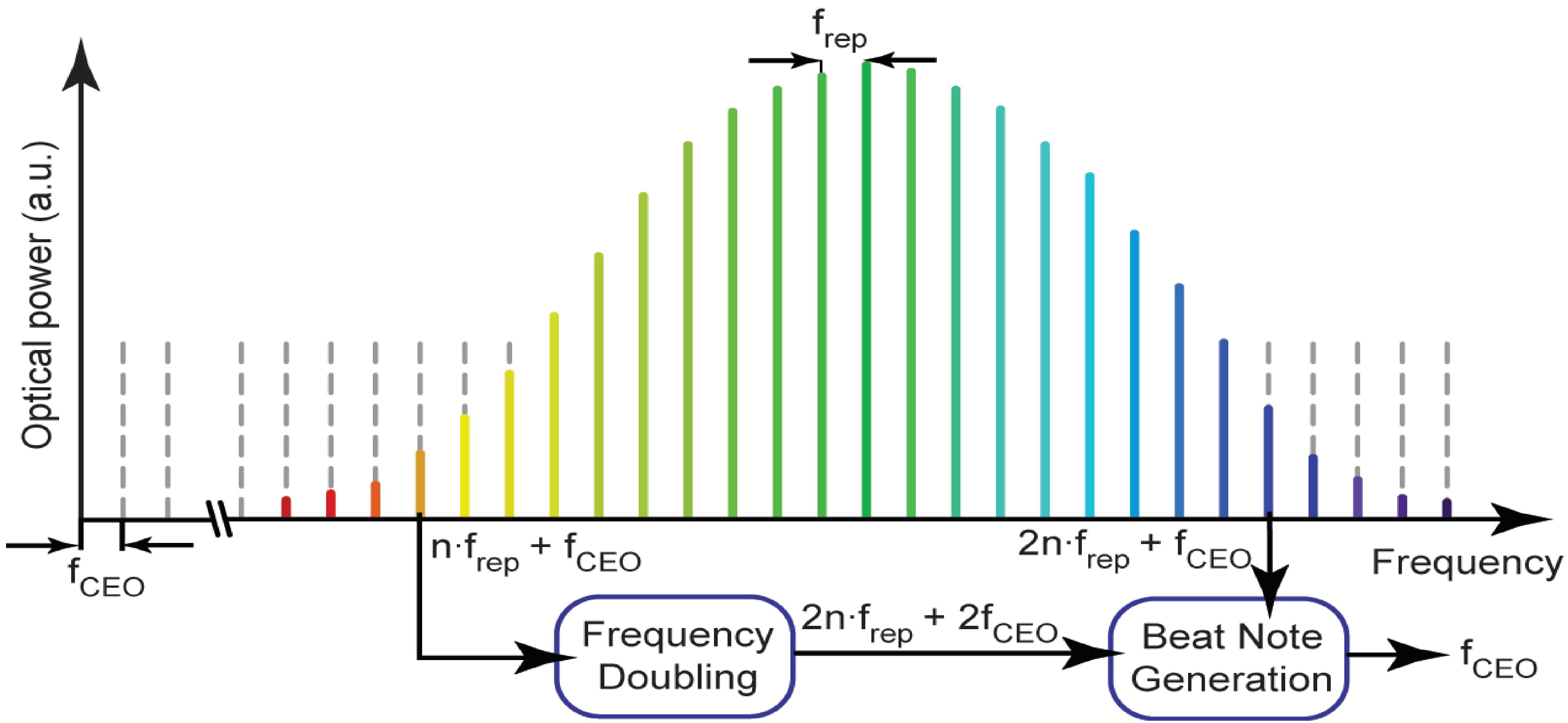
Nanophotonic chip for strontium clock







Frequency comb self-referencing

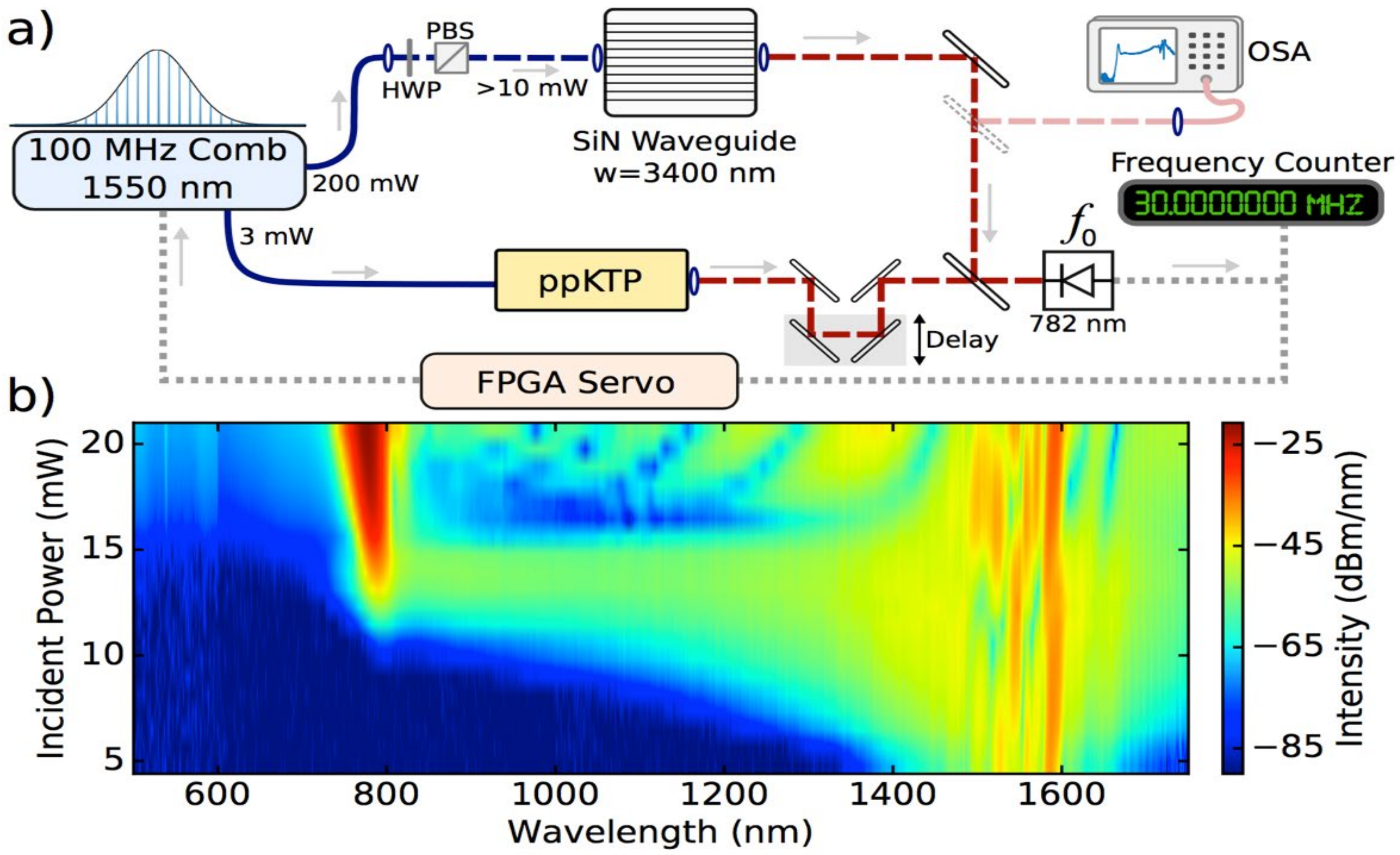


f-2f self referencing

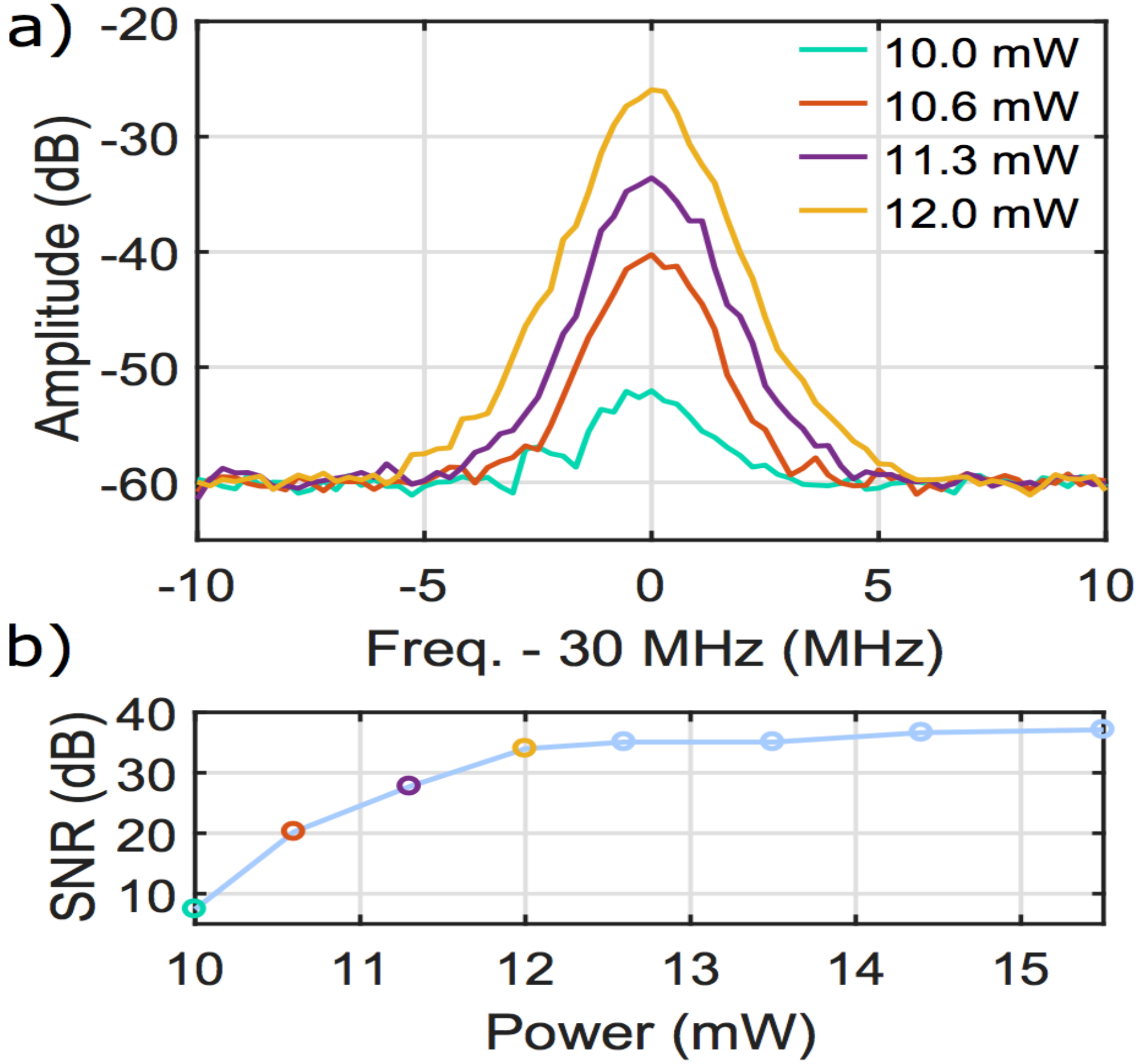
Necessary to use the comb as a calibrated "ruler" for measuring light

Low-power self referencing

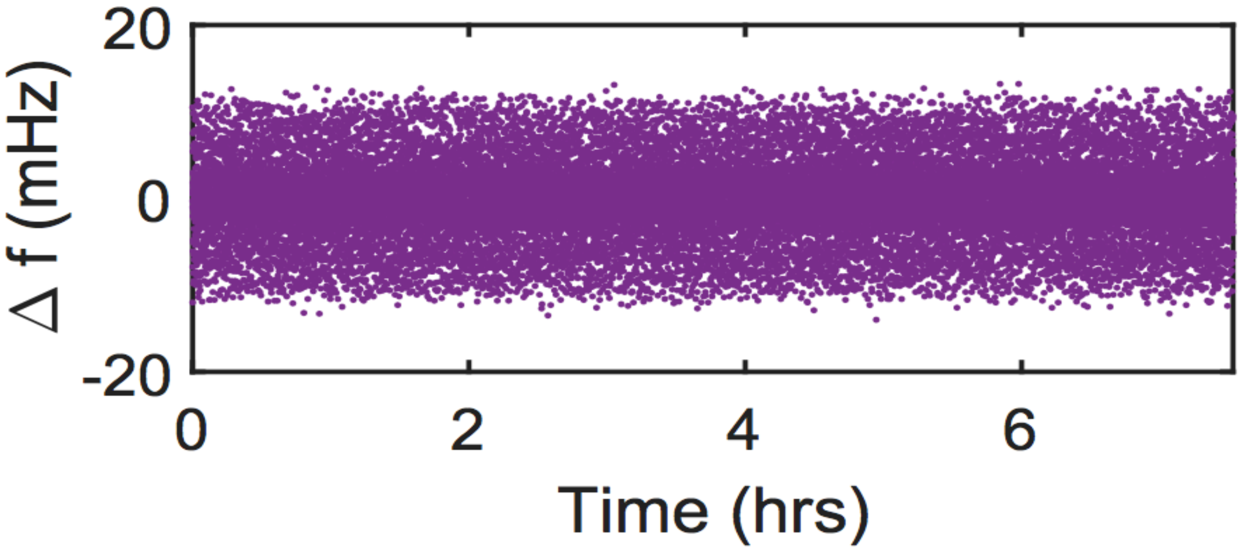
- Low pulse-energy self-referencing due to:
- Increased nonlinearity
- Generate supercontinuum light directly at 2f



Low-power comb stabilization



>30 dB signal-to-noise ratio provides reliable stabilization

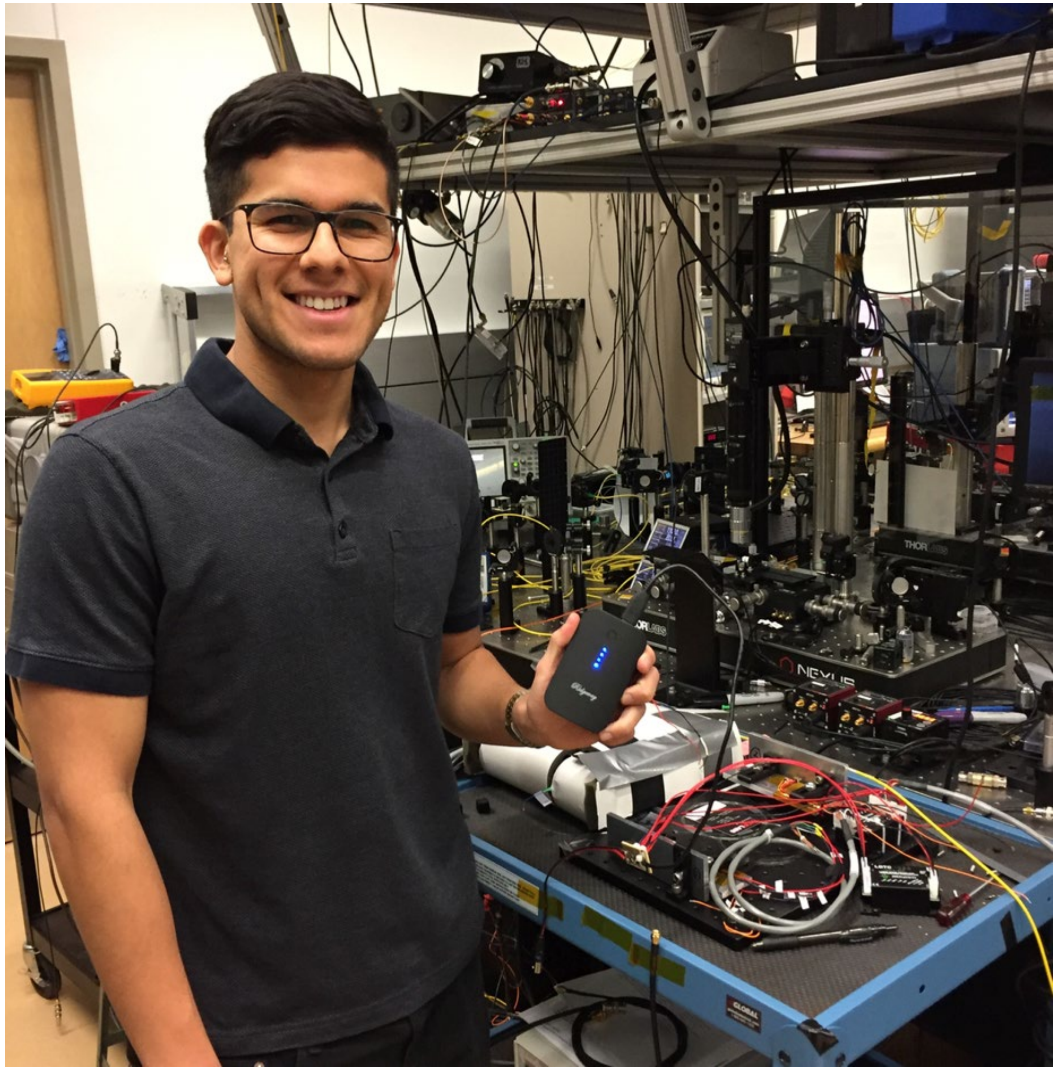


@100 MHz, 12 mW = 120 pJ

Battery operated frequency comb

Parameter	Conventional 200-MHz comb (HNLF + PPLN)	100-MHz comb + fiber resistive modulator + HNLF + PPKTP	100-MHz comb + passively-cooled pumps + SiN waveguide + PPKTP
Temperature tuning of f_{rep}	7.5 W	0.23 W	0.23 W
Oscillator pump	4.4 W	4.4 W	1.85 W
Amplifier pumps	20 W	10 W	2.75 W
Doubling waveguide TEC	~1 W [11]	0 W	0 W
TOTAL	33 W	14.6 W	4.8 W

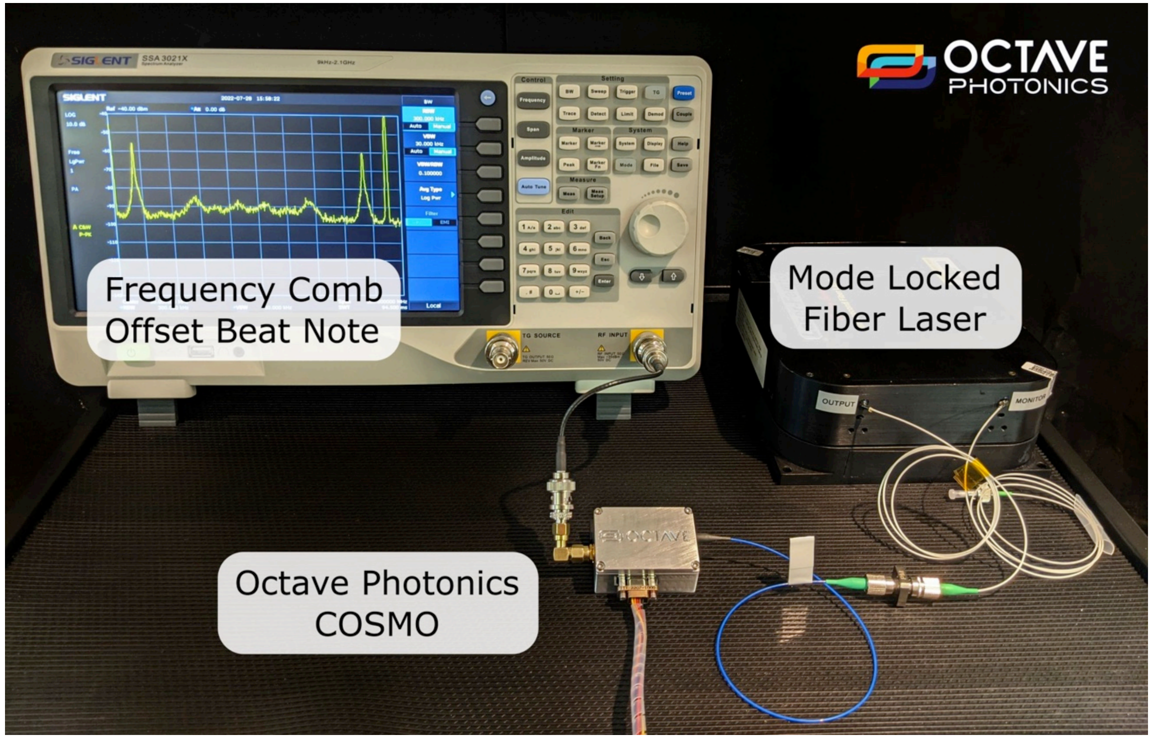
- Power reduced from 33 W to 5 W
- Huge power reduction!
- But still a bulky system



Comb-Offset Stabilization Module (COSMO)

COSMO module:

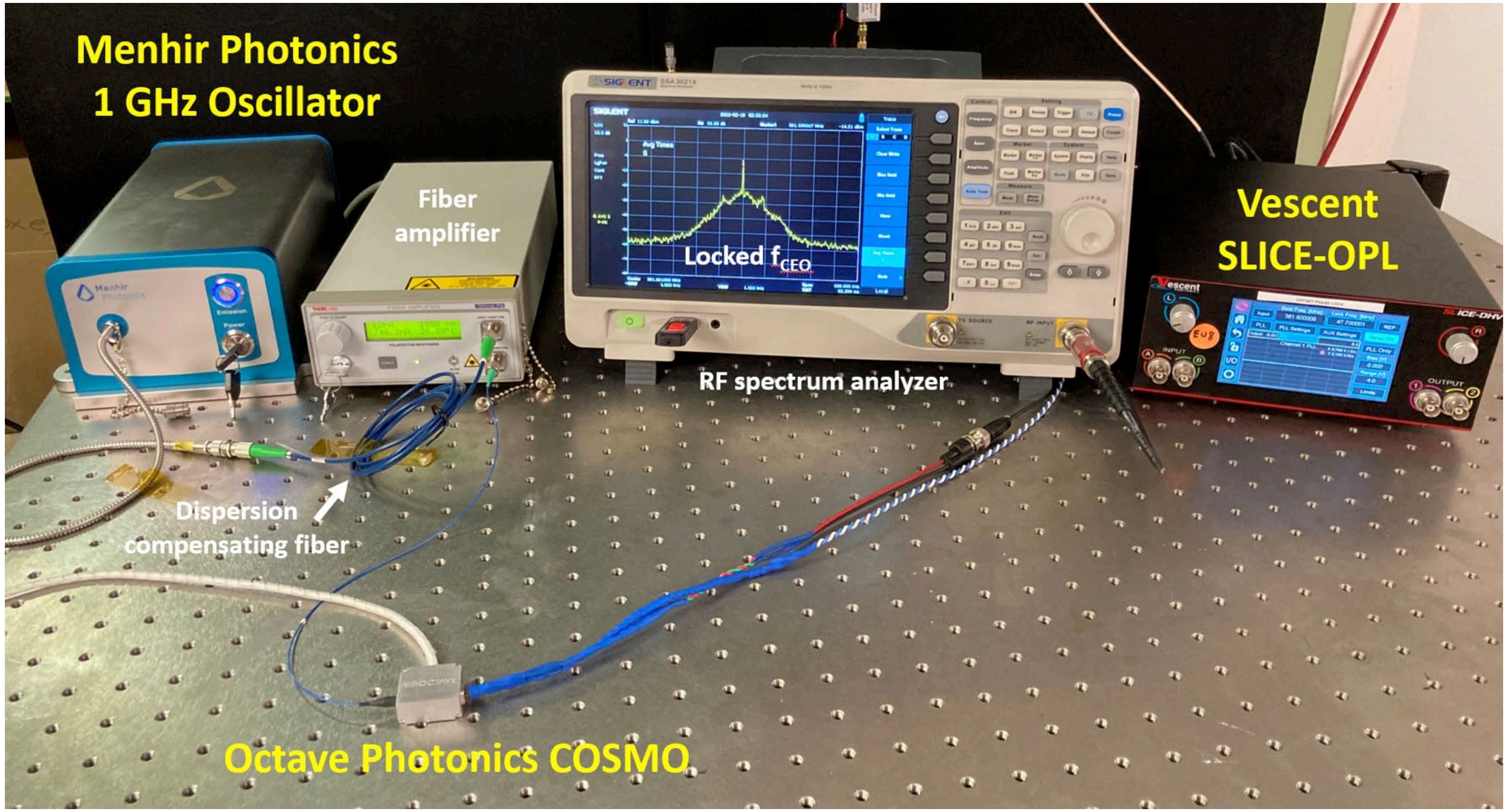
- Supercontinuum, SHG, photodetector, and amplifier
- Complete CEO detection module in <20 cm^3
- >200 pJ pulse at 1550 nm, ~40 dB SNR
- Fiber input, RF output



COSMO: enabling ultra-compact and GHz combs

Compact 100 MHz combs

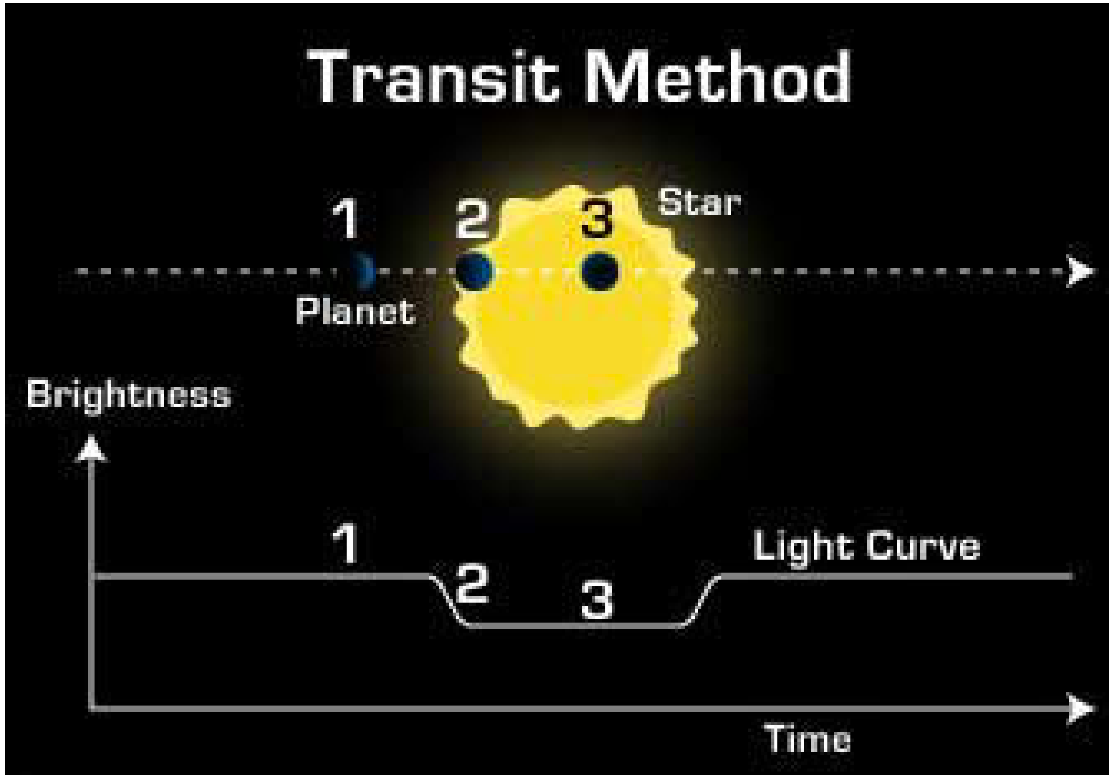
Stabilizing 1+ GHz frequency combs

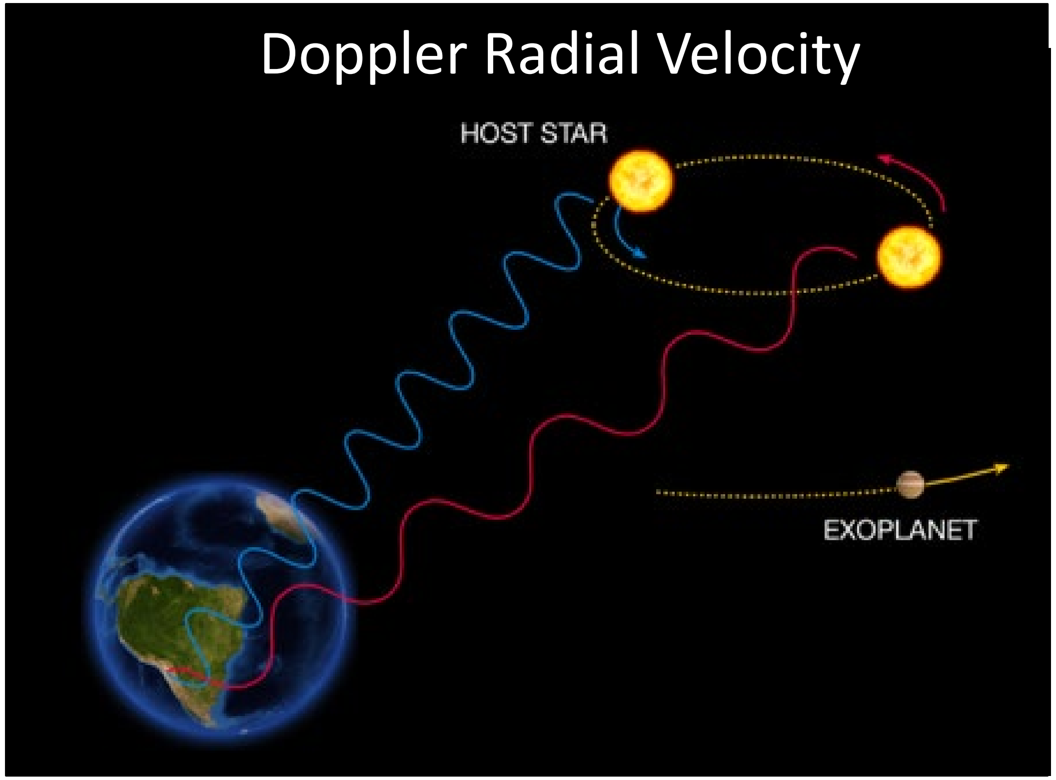


Application 2: Searching for exoplanets

- How do planets form and evolve?
- How diverse are planetary systems?
- Is there life elsewhere?

Searching for exoplanets



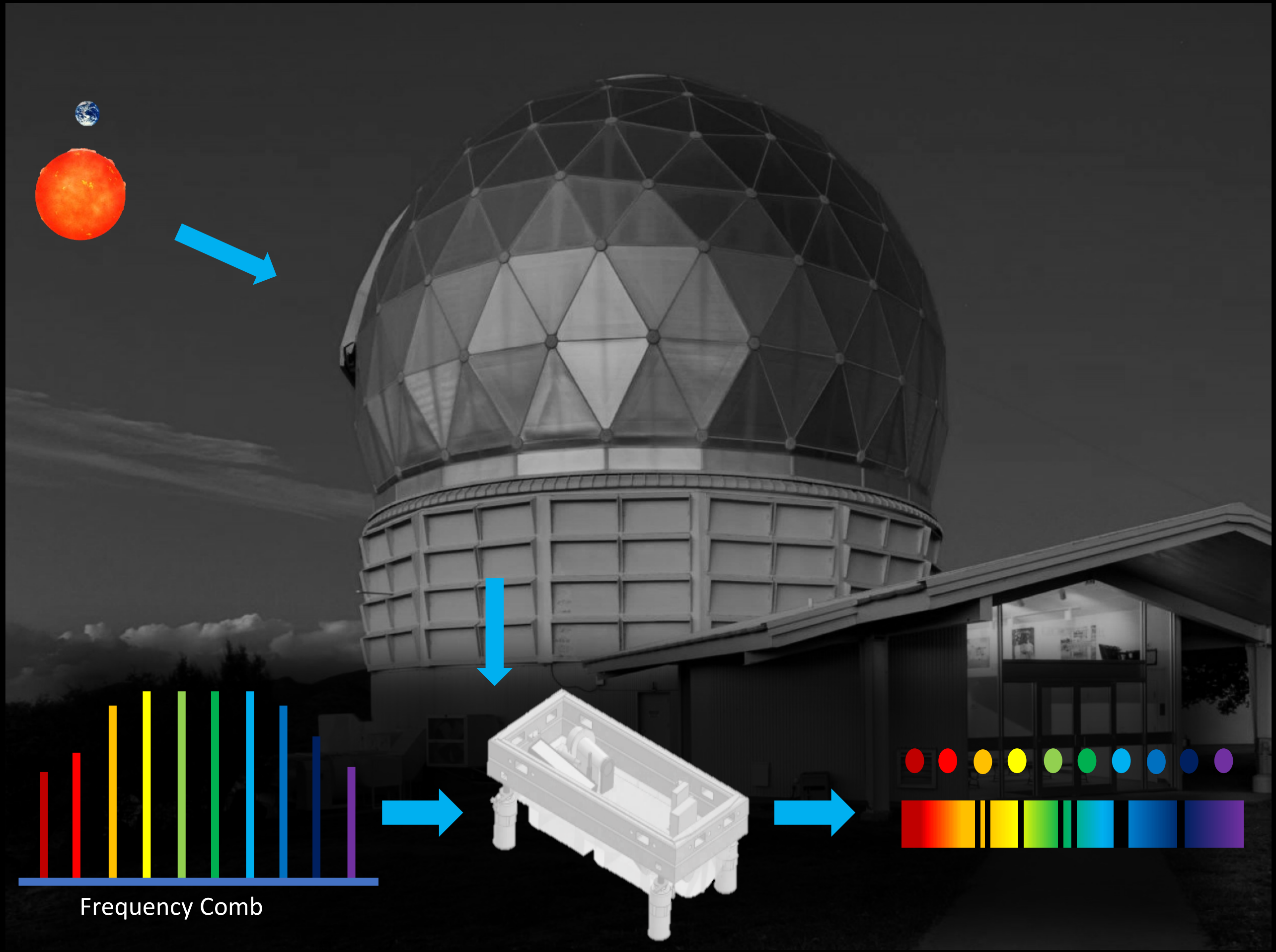


Size

Mass

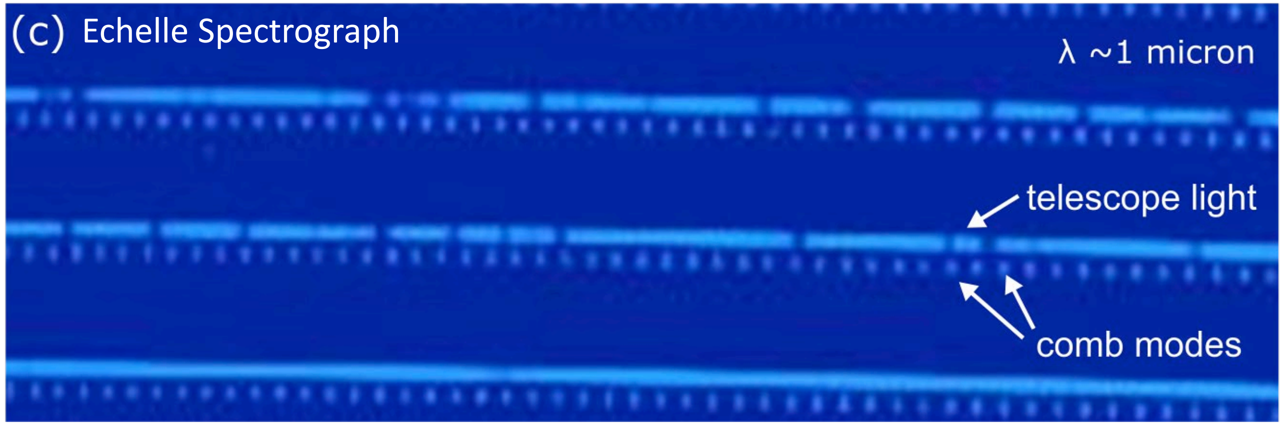
Density

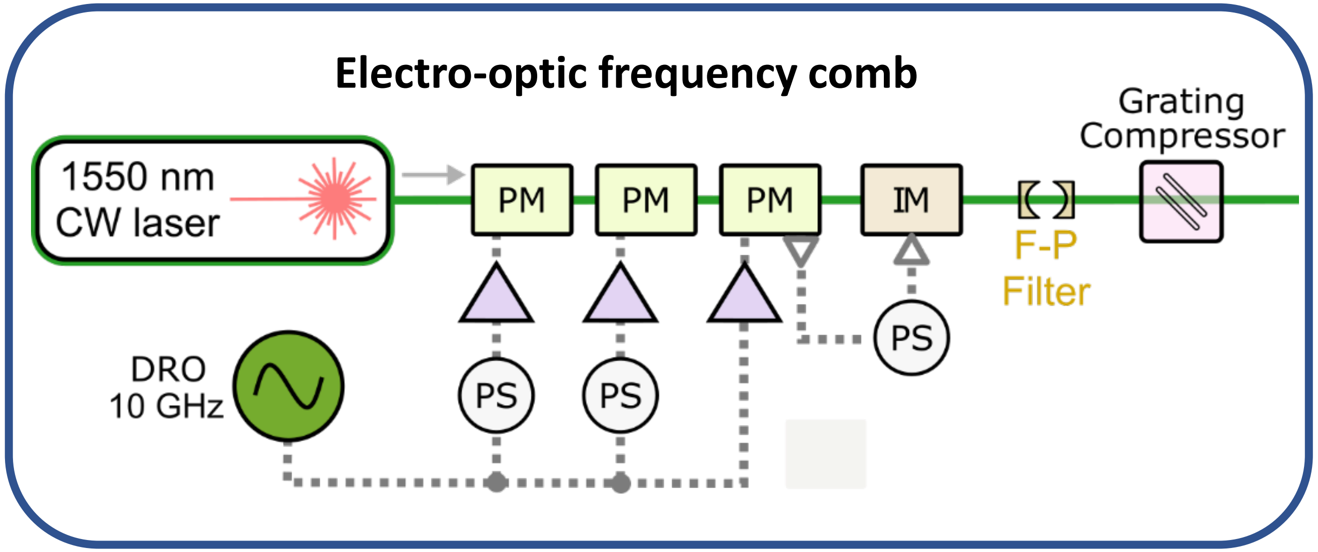
Precision radial velocimetry



Doppler shifts are tiny, so a comb is required

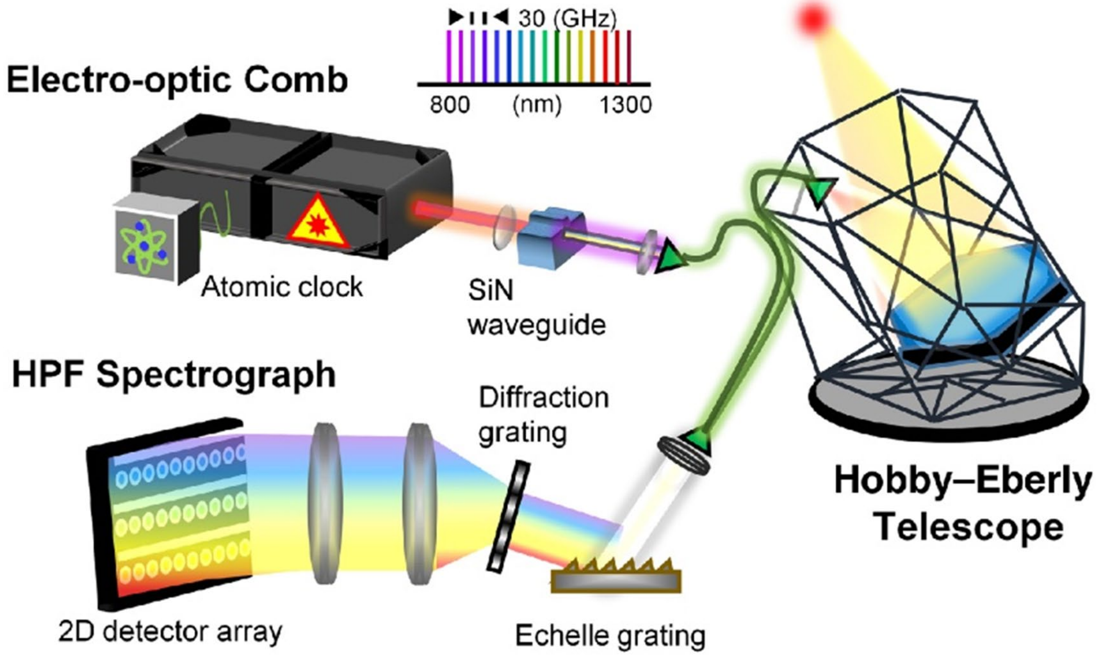
- Earth-like planet:
  ~10 cm/sec = ~100 kHz
- Resolution ~1 GHz/pixel
- ~10 micron pixels -> 1 nm shift!
- Calibration must be optimal
- 10-to-30 GHz comb source is ideal
- But, most combs are 0.1 GHz!
- Use electro-optic combs

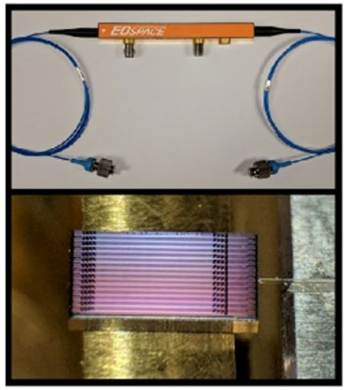


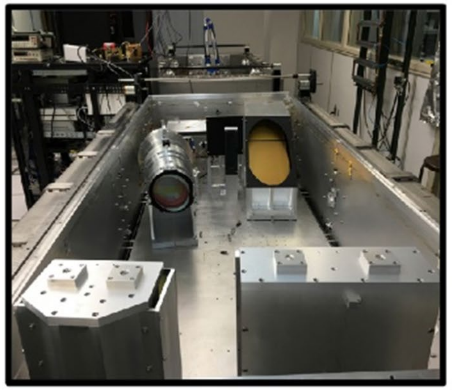


Electro-optic frequency comb

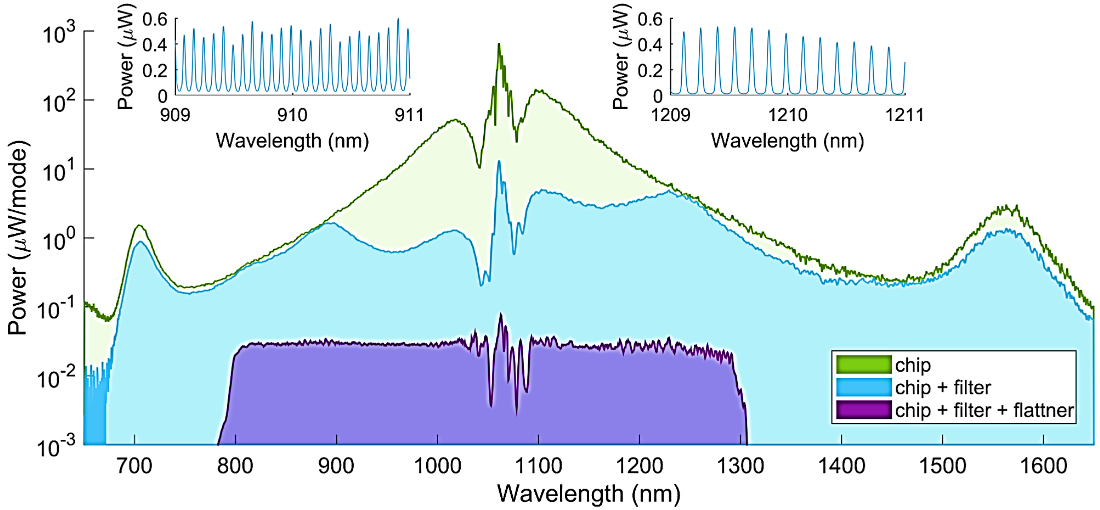
Nanophotonic waveguides for EO comb at Hobby-Eberly

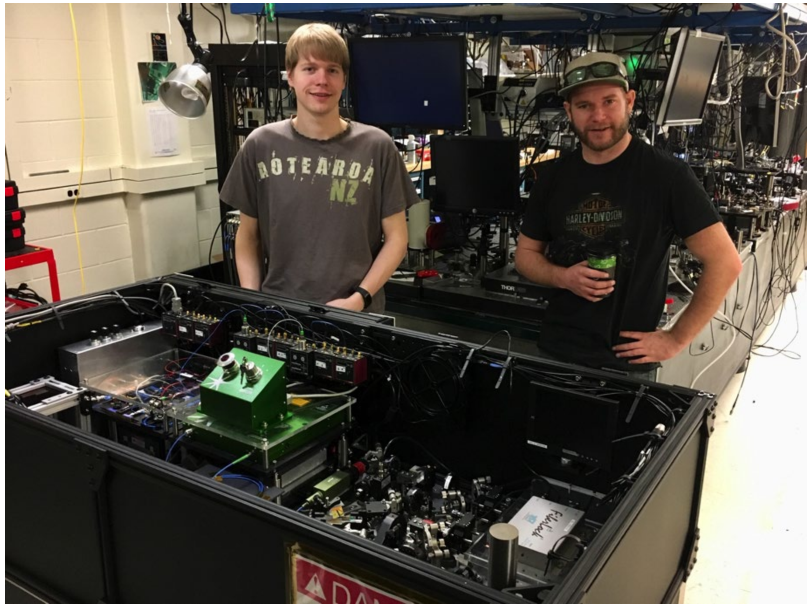




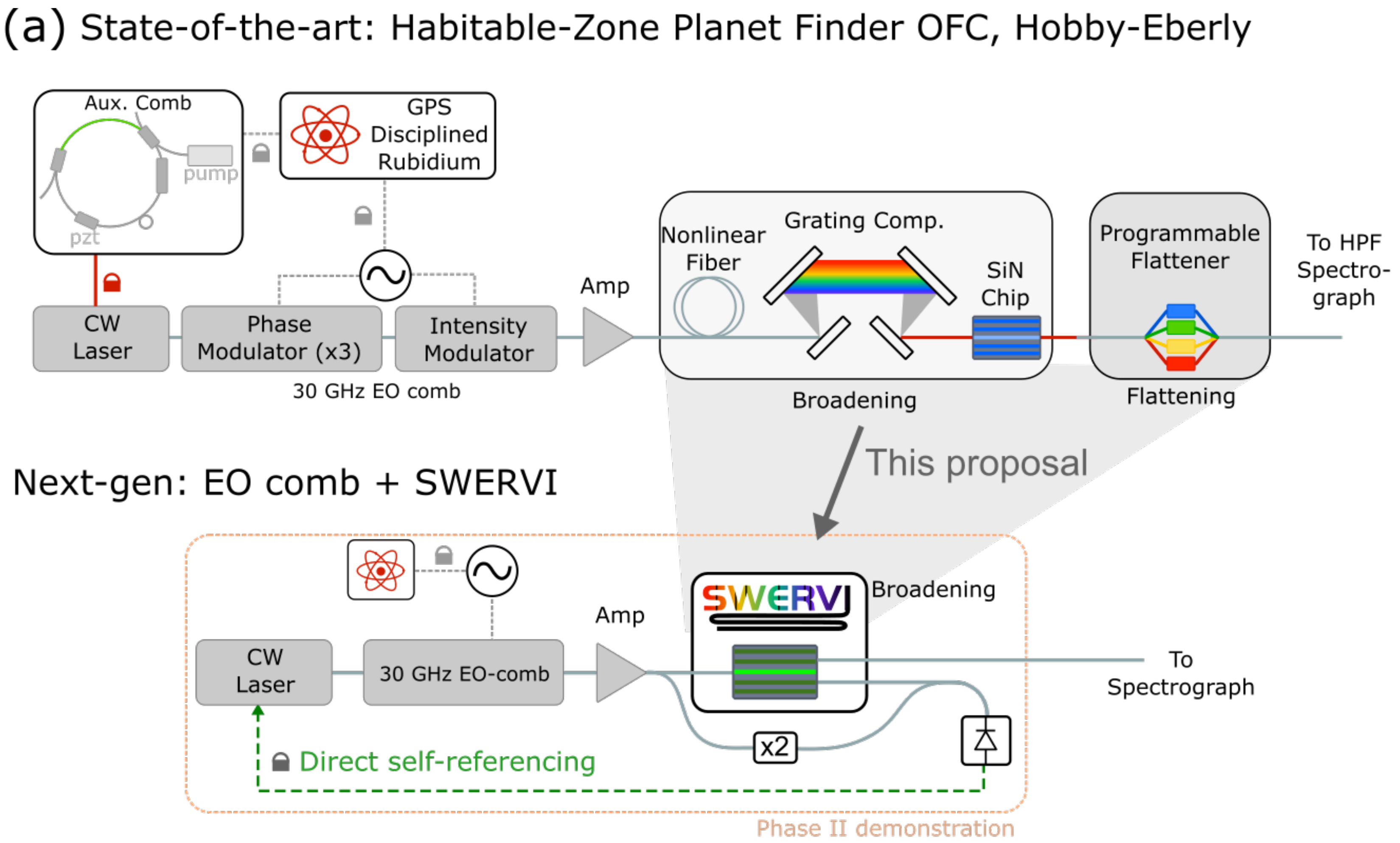


Success! 99+% uptime. But, complicated.





Nanophotonic chip simplifies spectrograph calibration

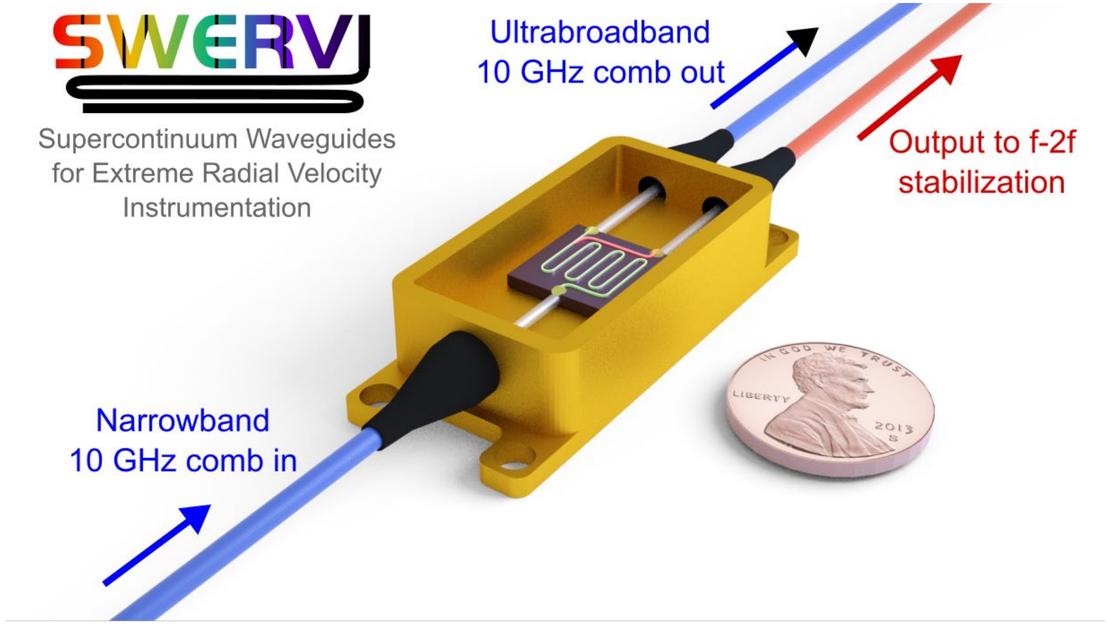


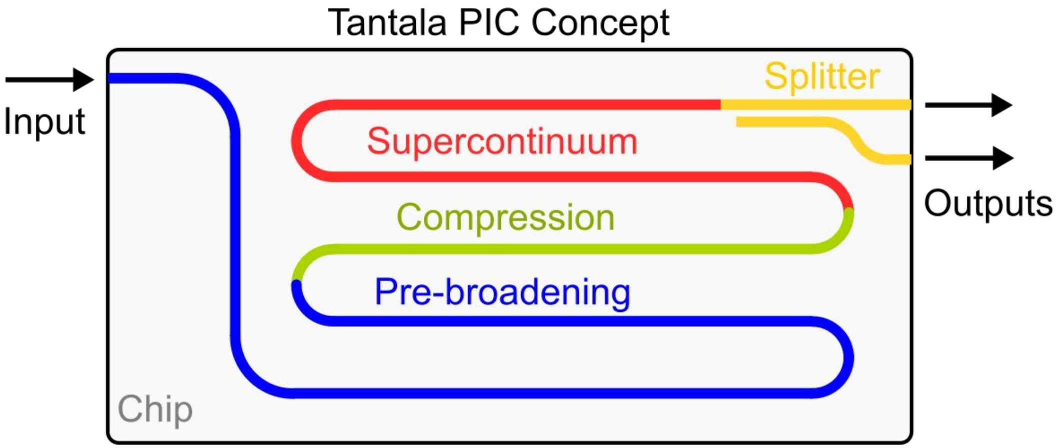
1. Eliminate coupling stages
2. Eliminate auxiliary comb
3. Eliminate nonlinear fiber
4. Eliminate grating compressor
5. Eliminate flattener

Supercontinuum Waveguides for Extreme Radial Velocimetry Instrumentation (SWERVI)

Astrocomb system

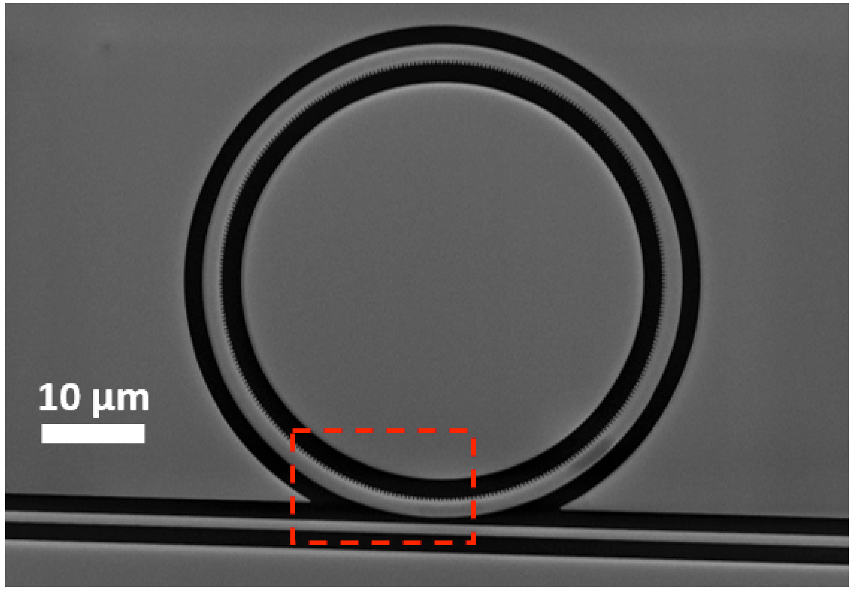
- Coupling stages eliminated with packaged device.
- Replace normal dispersion fiber with normal dispersion waveguide
- Replace free-space grating-based pulse compressor with on-chip pulse compression
- On-chip splitter sends 780-nm light to f-2f self-referencing system.
- Splitter+flattener design replaces the programmable spectral flattener.



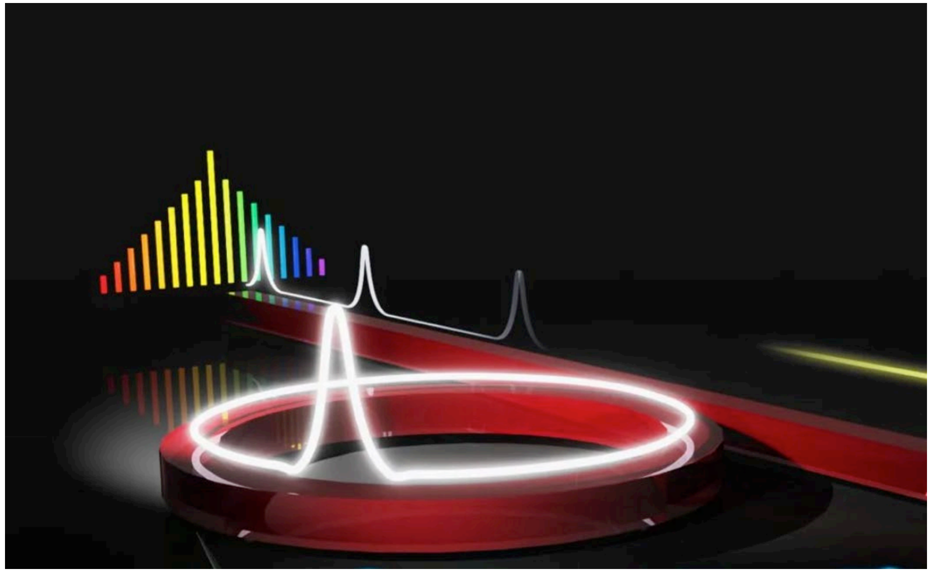


Application 3: microcombs

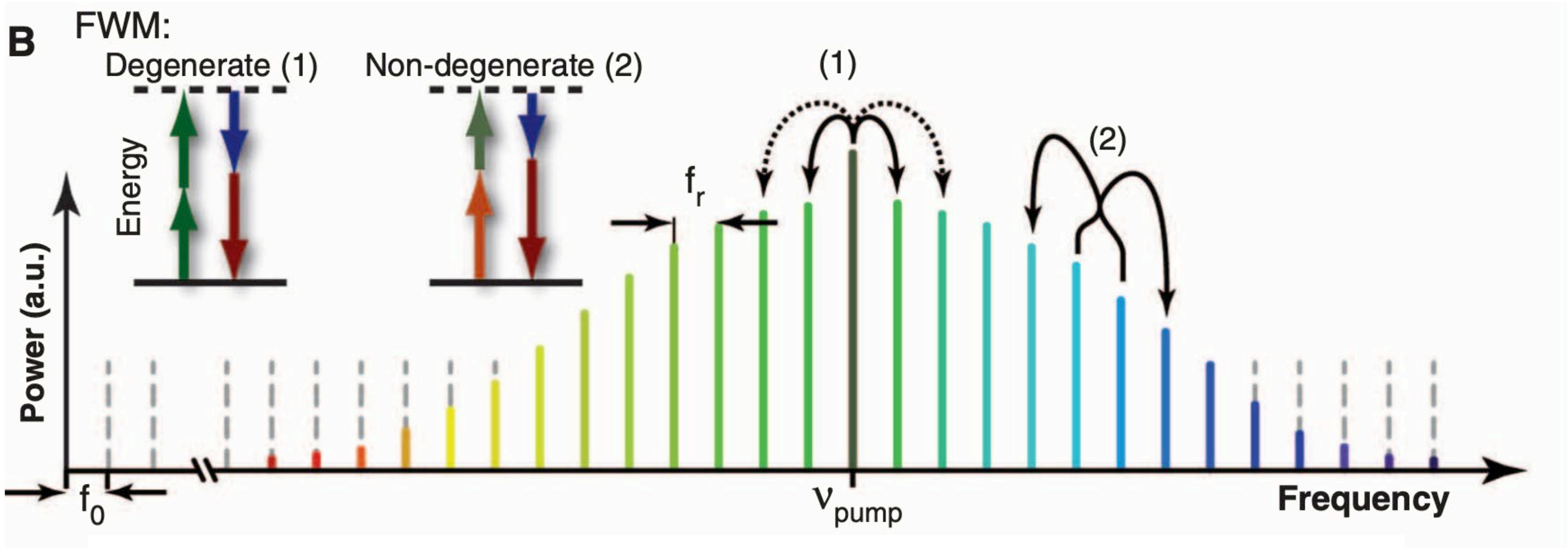
Continuous wave (CW) laser in

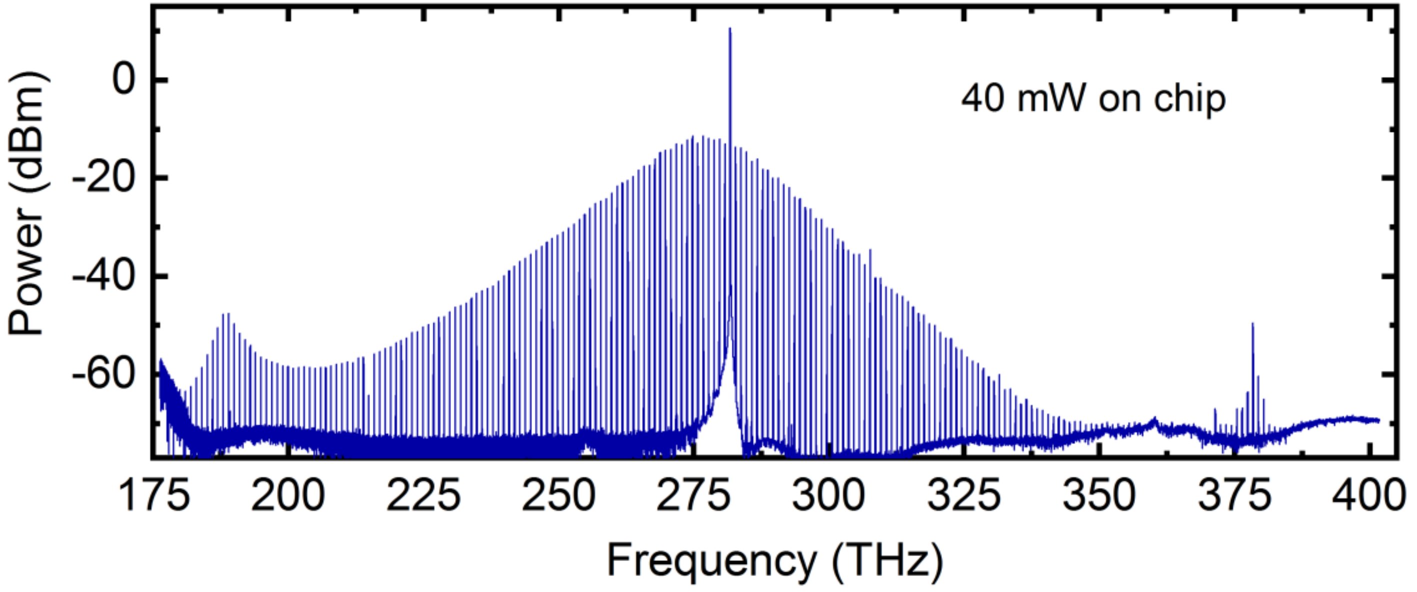


Comb out



Microcomb generation

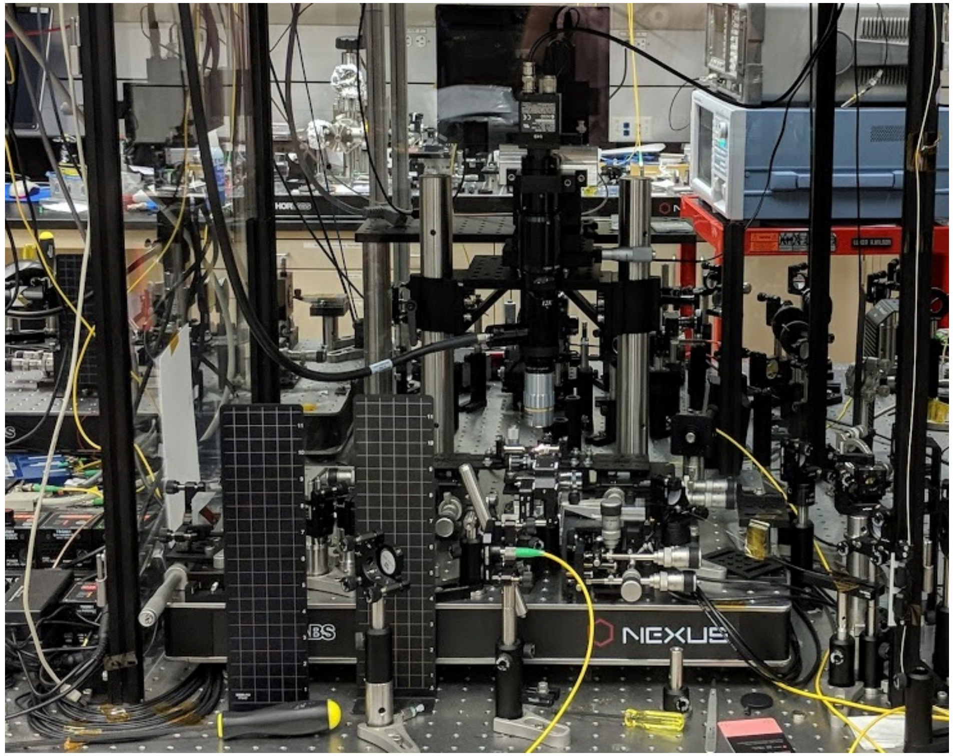


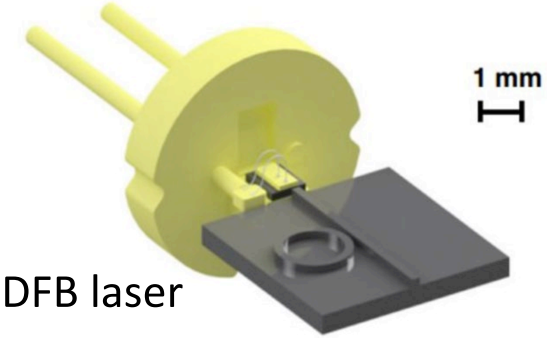


Briles et al., PRApplied 2020, https://journals.aps.org/prapplied/abstract/10.1103/PhysRevApplied.14.014006

Making microcombs micro

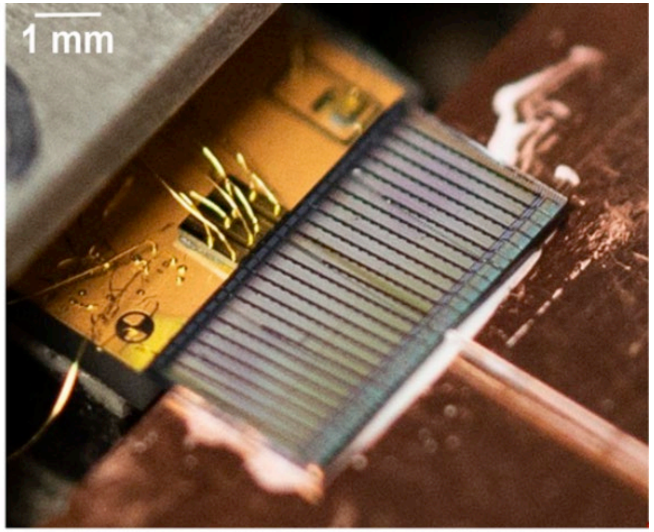
OCTAVE PHOTONICS



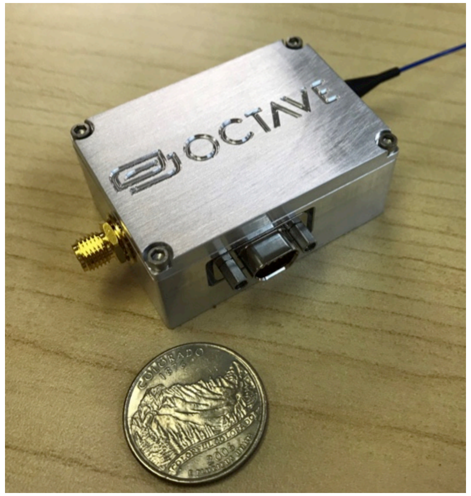


InP DFB laser

SiN ring resonator



SBIR NASA



Briles et al., APL Photonics, 2021- https://doi.org/10.1063/5.0035452

Summary

- Frequency combs: emerging spectroscopy applications
- Nanophotonics: making frequency combs smaller and more capable
- Nanophotonics enables:
  - Compact optical clocks
  - Astrocombs
  - Microcombs
  - and more!
- www.octavephotonics.com
- www.linkedin.com/company/octavephotonics
- Thanks! Questions?
- daniel.hickstein@octavephotonics.com

Flat spectrum via waveguide-width change

- Replace auxiliary comb via direct self-referencing with octave span
- Generate flat spectrum via dispersion-changing waveguide