An Integrated-Photonics Optical-Frequency Synthesizer

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Optical Frequency Synthesis

NIST

- Accurately producing optical signals with the long term fractional stability of a microwave synthesizer
  - Example at 1 sec: $10^{-13} = \frac{\Delta f}{f_{carrier}} = \frac{1\mu Hz}{10MHz} = \frac{20Hz}{200THz}$

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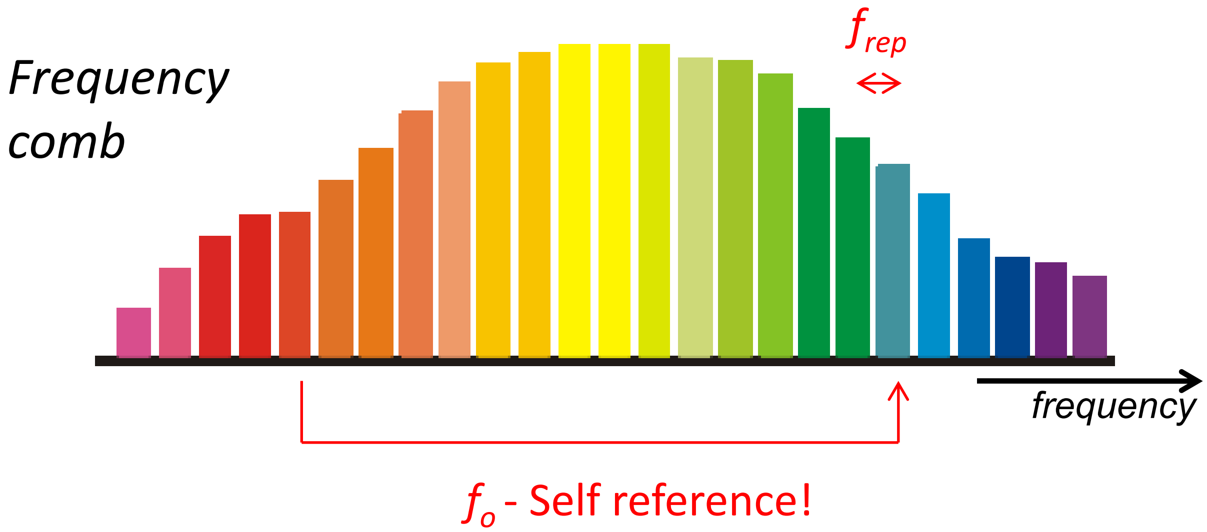
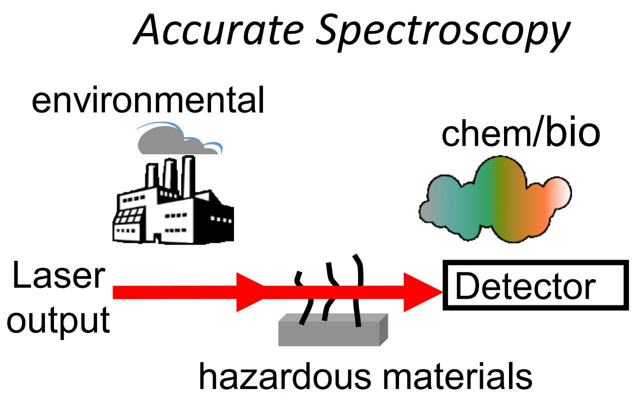
  - Portable metrology, (tunable laser) spectroscopy, quantum science, and optical communications: tighter grids/ precise carrier recovery





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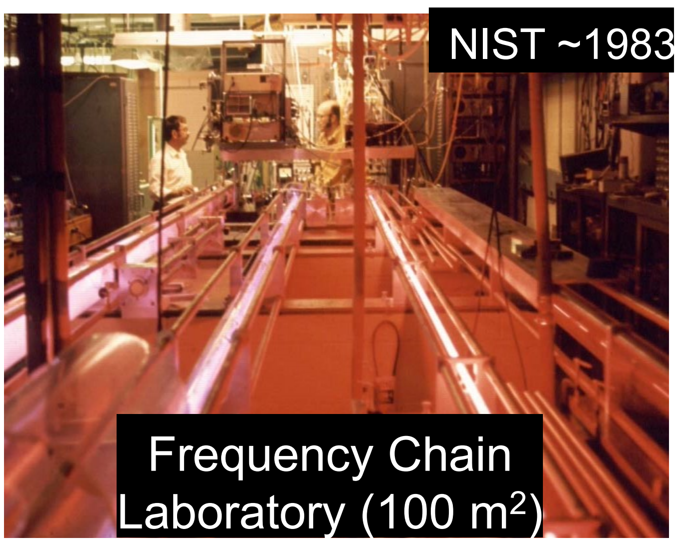
- Octave spanning combs allow precise definition of each comb line, and <u>transfer of stability</u> between optical and microwave domain
  - $f_n = n^* f_{rep} + f_o$
- Systems have scaled down from multiple labs to benchtop systems



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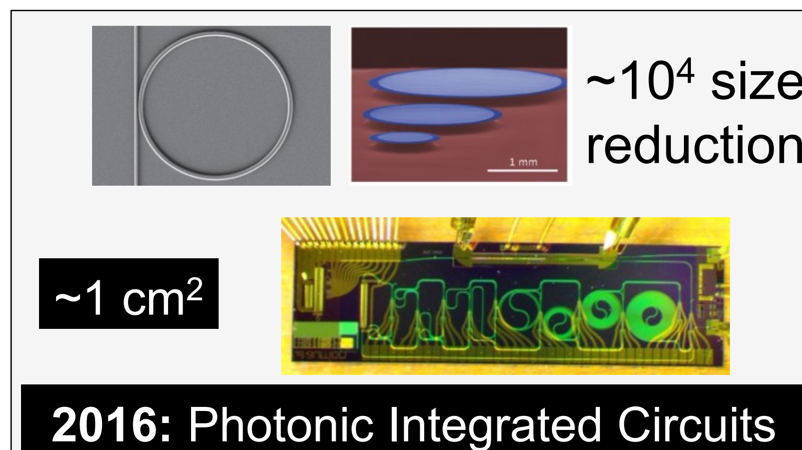
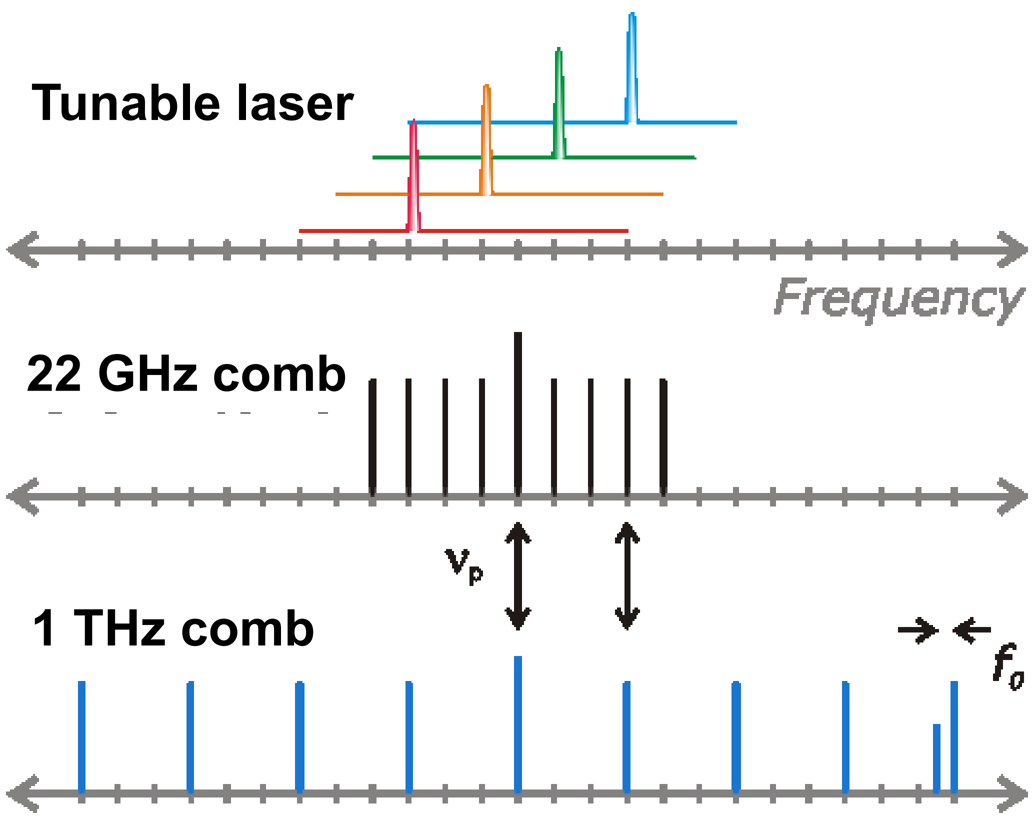
- We aim to push SWAP+C down with integrated photonics, based on emerging microcomb technology
  - Octave spanning Si_3N_4 THz comb
  - High Q silica comb to detect f_{rep}
  - High confinement waveguide PPLN
  - Heterogeneously integrated lasers



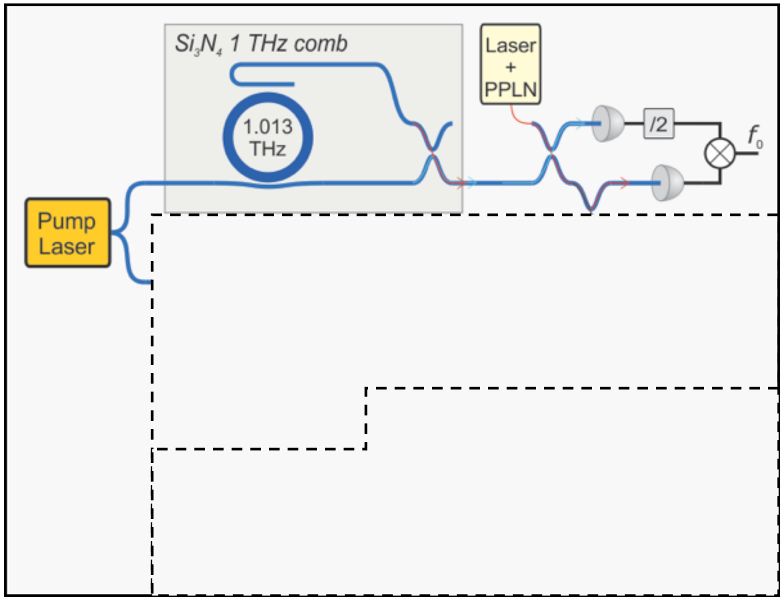
Optical Synthesis with Microcombs

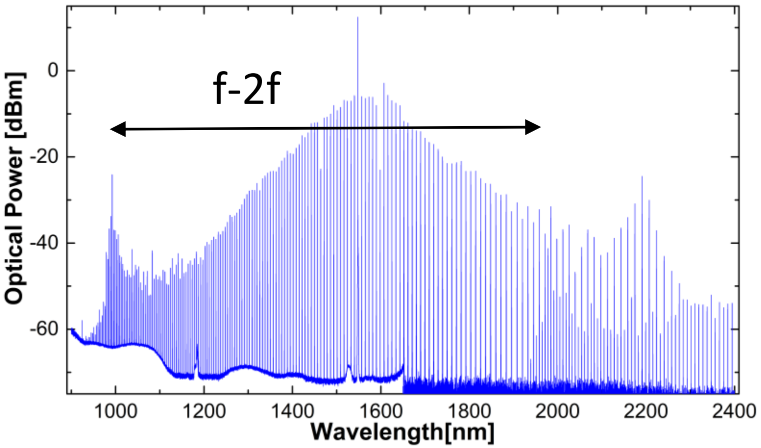
- **Approach:** Dual reduction gear
  - 200 THz → 1 THz → 15 GHz + agile tunable laser
- **Leverage:** Photonic integration (pump laser, PPLN, photodiodes)
  - **Low power, improved frequency control, and enhanced nonlinearities**

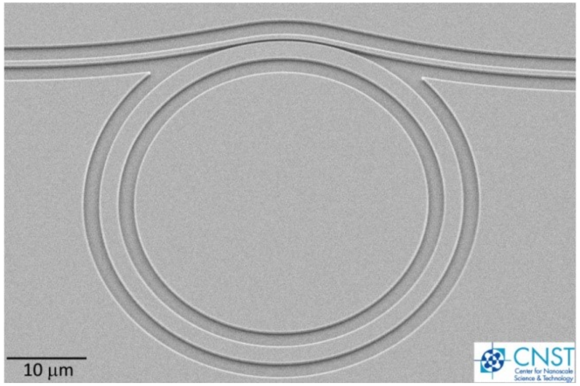


$$f_n = n{*}f_{rep} + f_o$$

Chip-Scale Resonator Enabled Optical Synthesizer (CORES)

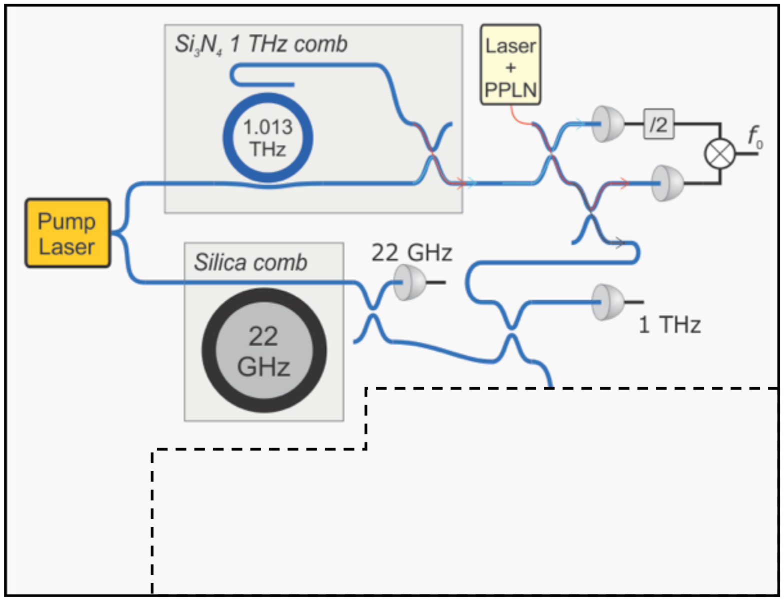


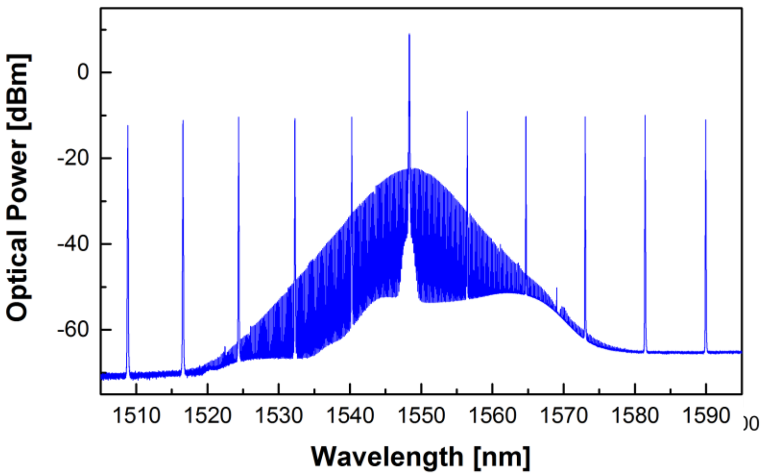


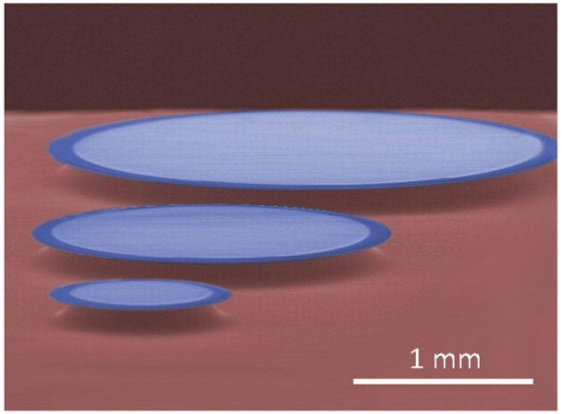


- Si_3N_4 resonators from NIST-Gaithersburg
- Octave bandwidth with dual dispersive waves from dispersion engineering

Chip-Scale Resonator Enabled Optical Synthesizer (CORES)

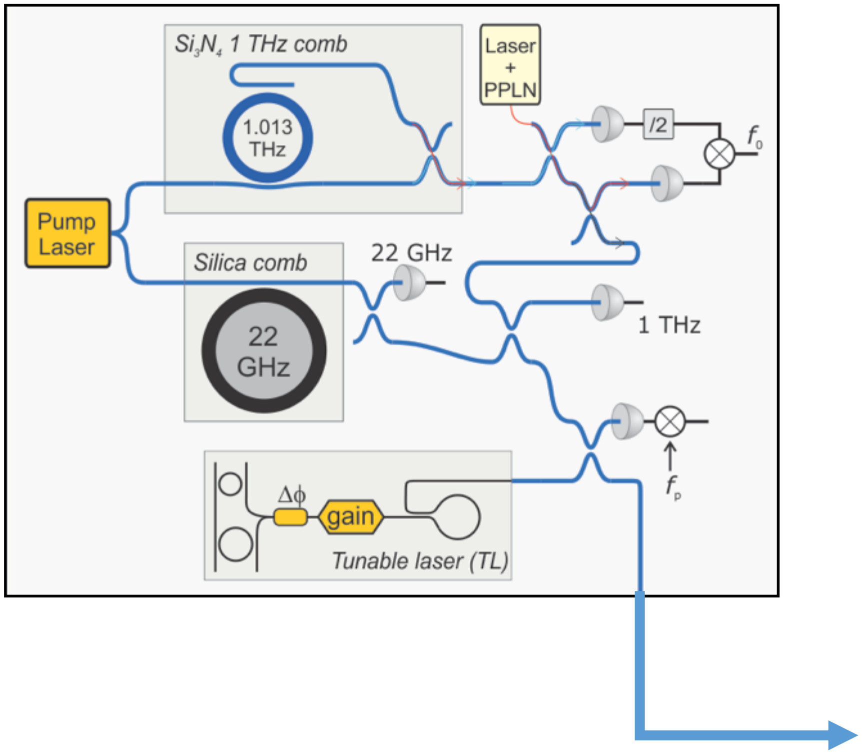


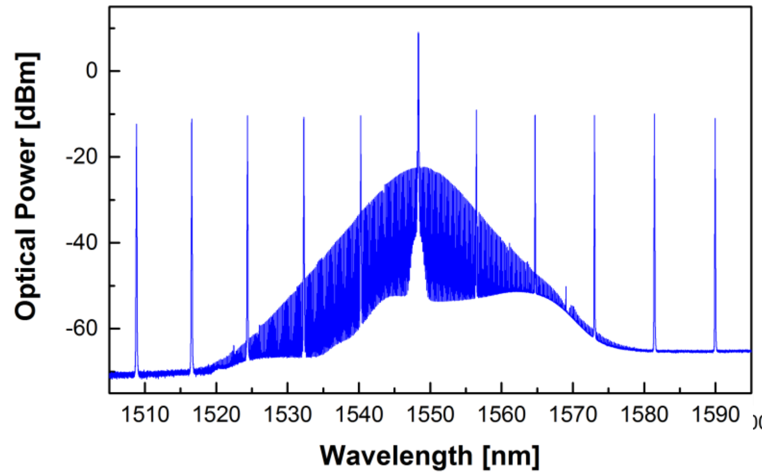


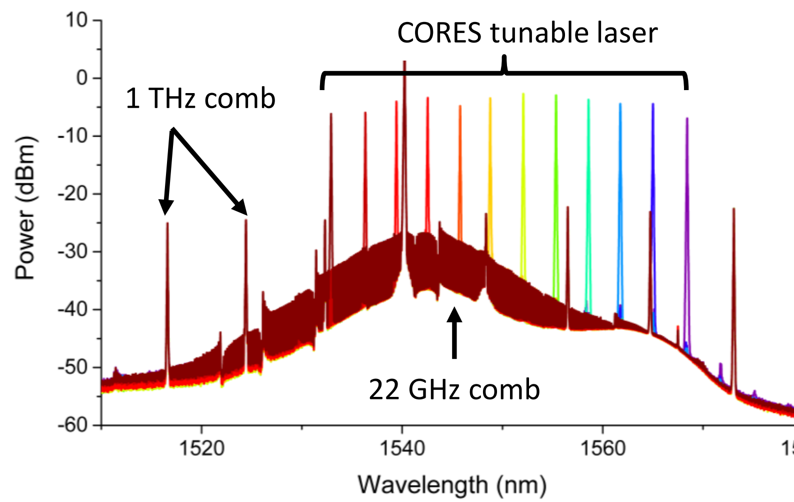


- Caltech wedge resonators
- Ultrahigh (>100M) Q
- Recently waveguide integrated

Chip-Scale Resonator Enabled Optical Synthesizer (CORES)



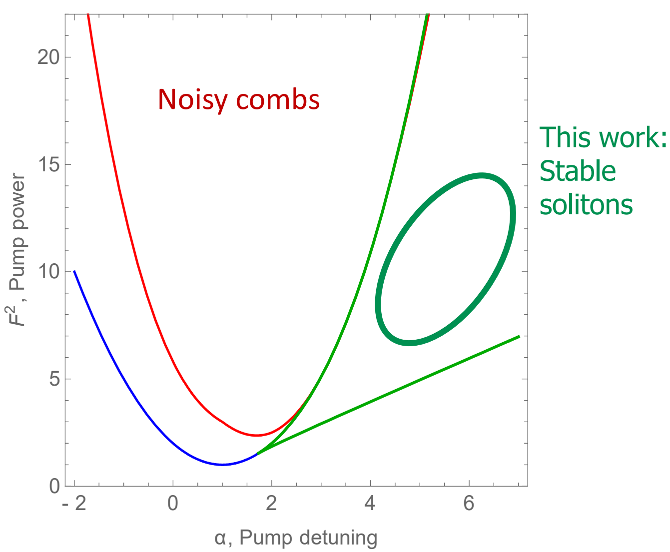


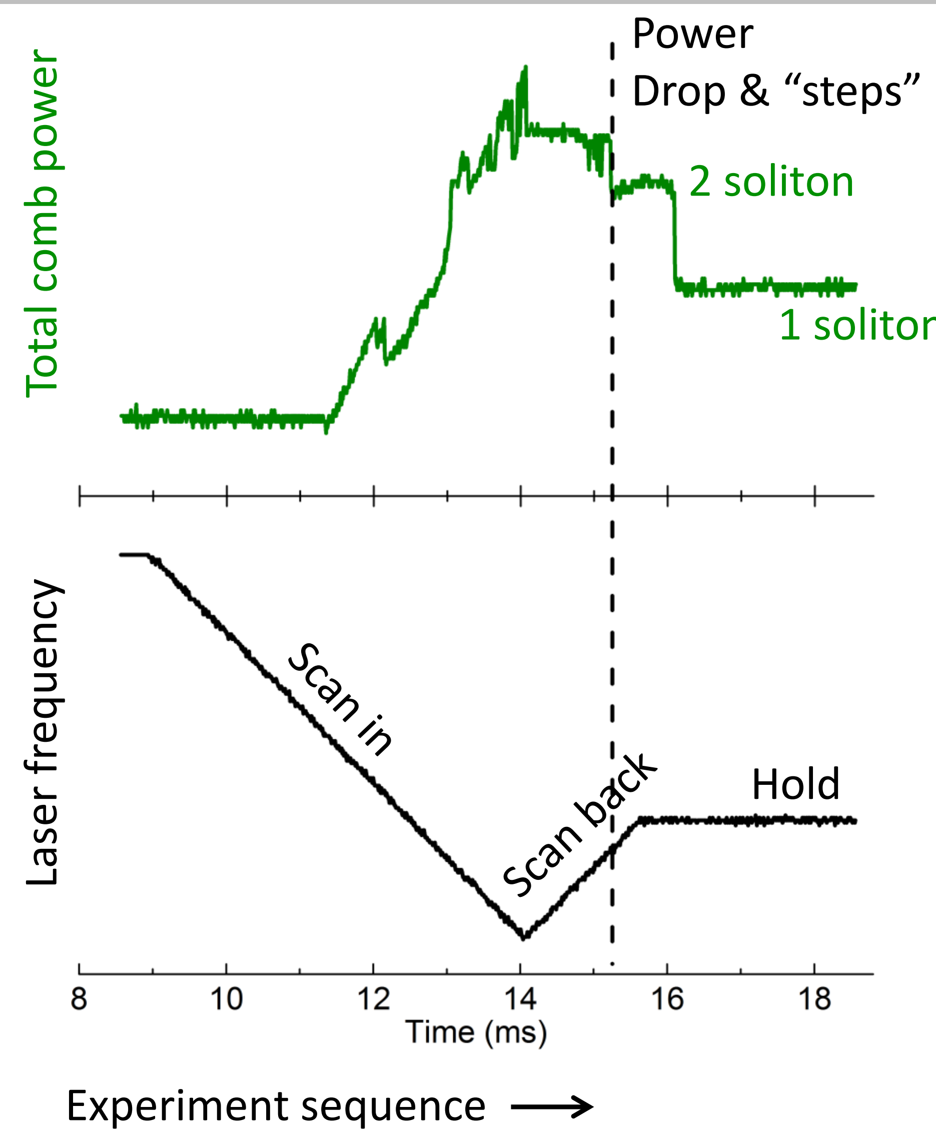


- Tunable lasers from Aurrion, Inc. (now Juniper)
- Integrated on the heterogeneous III/V-Si platform

Dual Kerr Microcombs

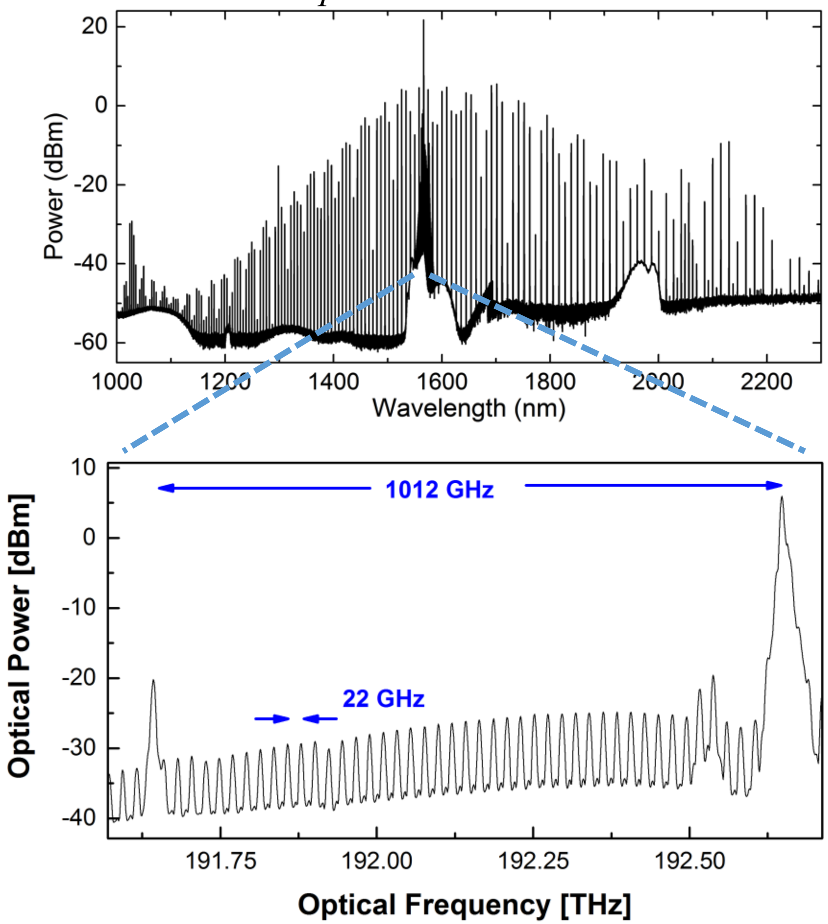
- Solitons initiated by tunable laser scan across resonance
- Need to end scan on red detuning, without appreciable resonator heating
- Fastest sweeps using IQ modulator in single sideband operation

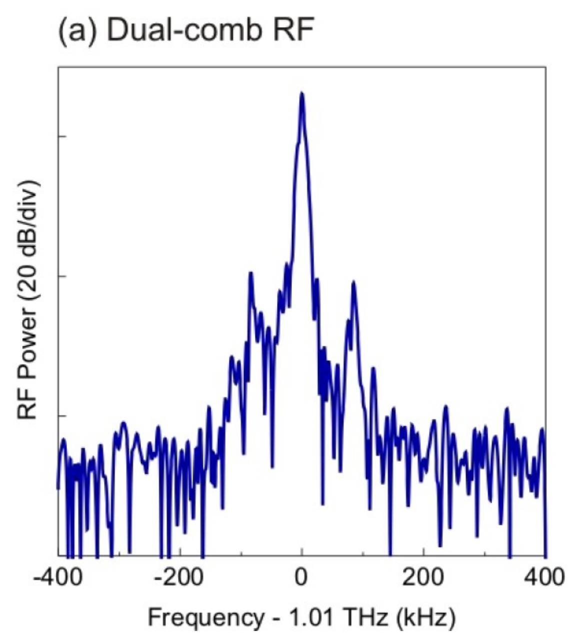




Self-referencing Microcombs

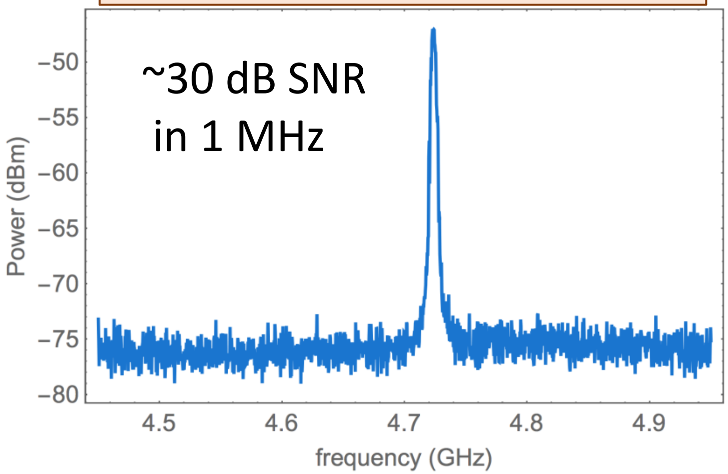
- f_{rep} of 22 GHz silica comb is phase locked by direct microwave detection
- Beat note between 1 THz and 22 GHz combs produce error signal to phase lock – THz f_{rep} stable



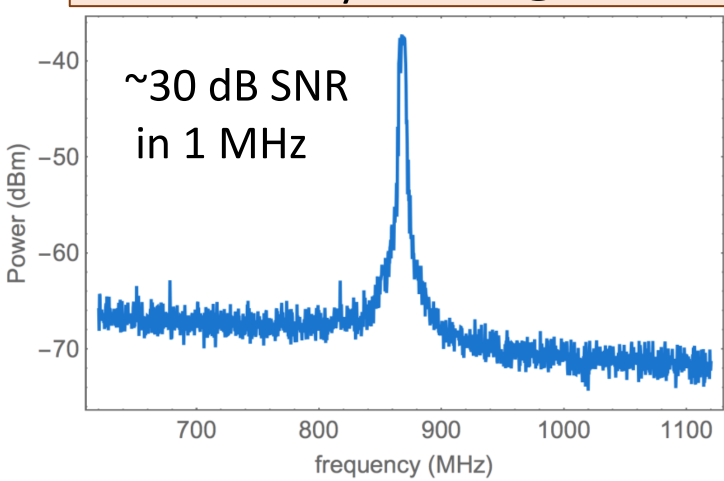


Self-referencing Microcombs

Heterodyne beat @ 1998 nm

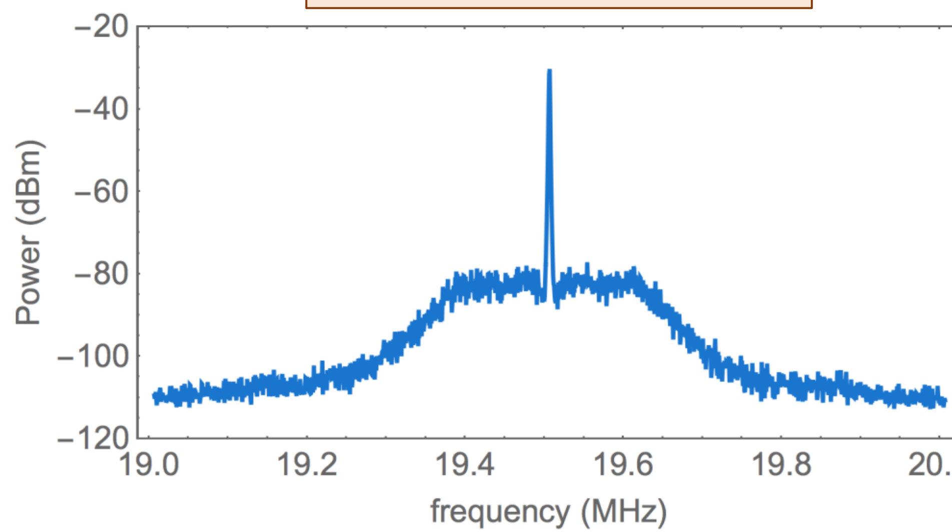


SHG heterodyne beat @ 999 nm



- 1998nm laser allows for strong second harmonic generation (SHG) and high SNR beat notes against THz comb lines.
- f_o phase locked

f_o/64 by processing both signals

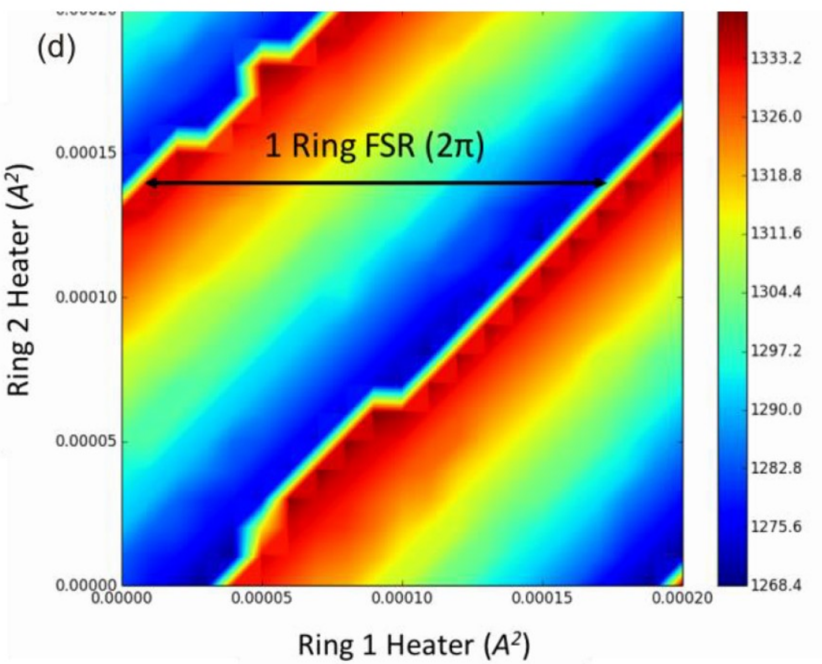


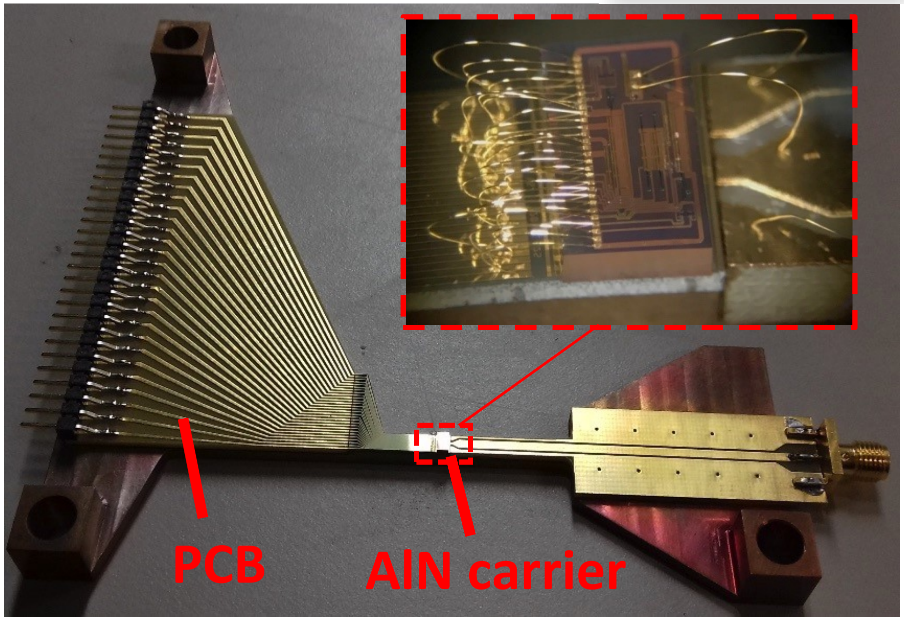
Heterogeneously Integrated Tunable Lasers

NIST

- Vernier tunable lasers on the heterogenous Si platform
  - III/V quantum wells wafer bonded on SOI
  - On chip SOA to compensate facet loss
- Packaged and isolated from air currents in the lab

aurrion



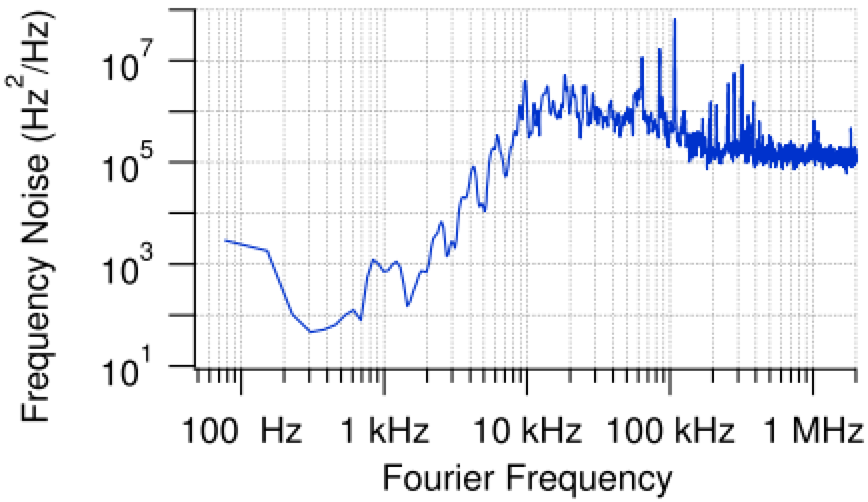


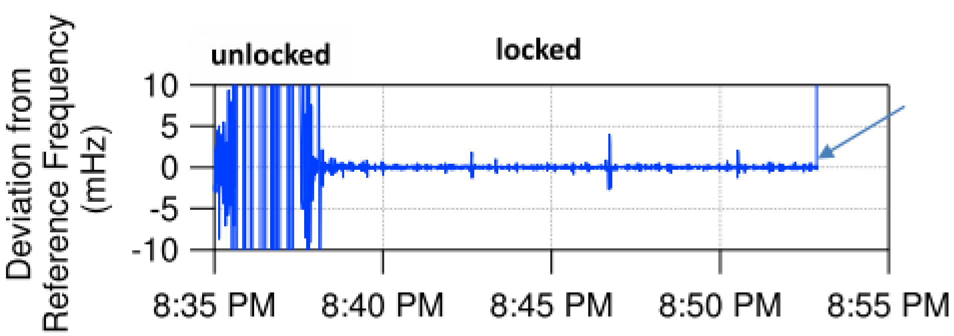
Example: O band laser tuning map

This work: C band tunable laser

Phase Locking Lasers to Resonators

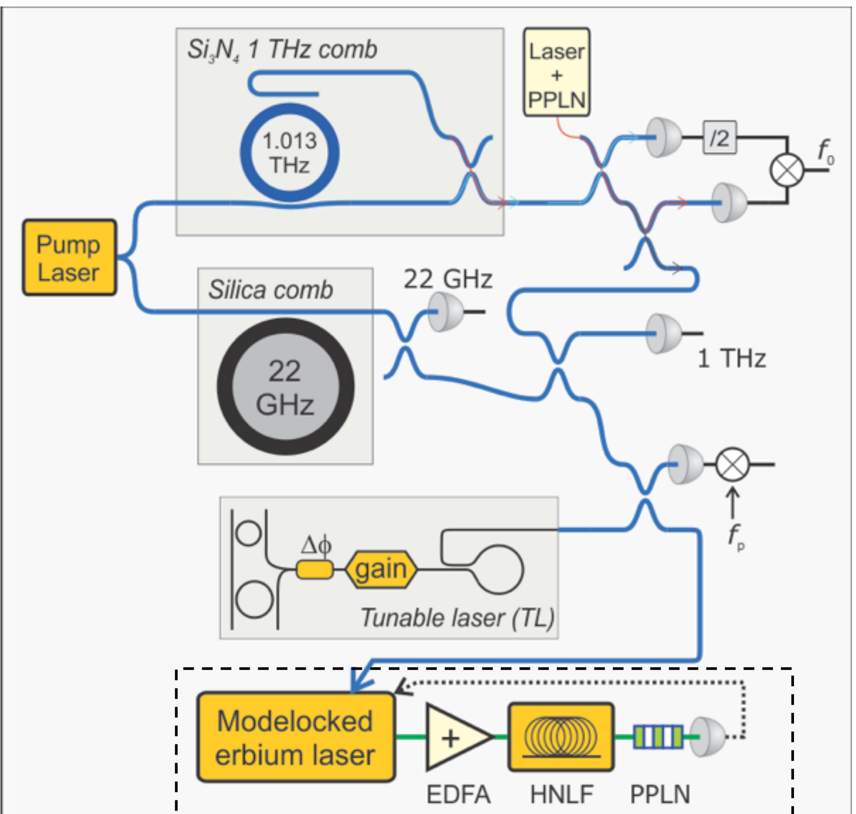
- Comb stability is successfully transferred to tunable lasers with <1 Hz residual stability at 1s.
- Vernier laser tuning to reach arbitrary comb line between 1530 – 1570 nm.
- FPGA implementation of phase frequency detector and PI^{2}D feedback.

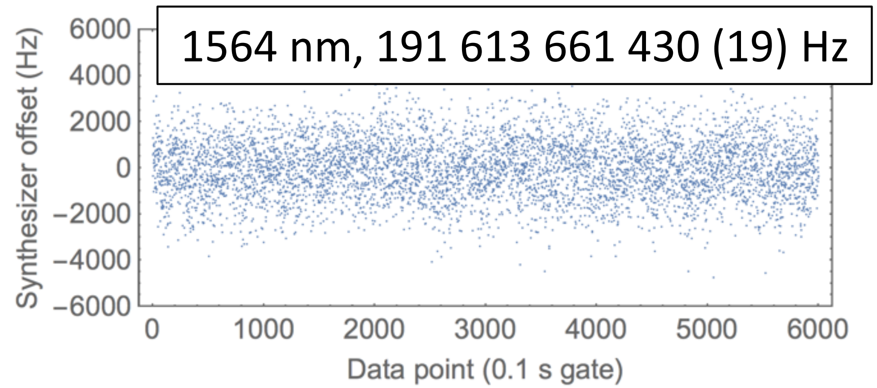


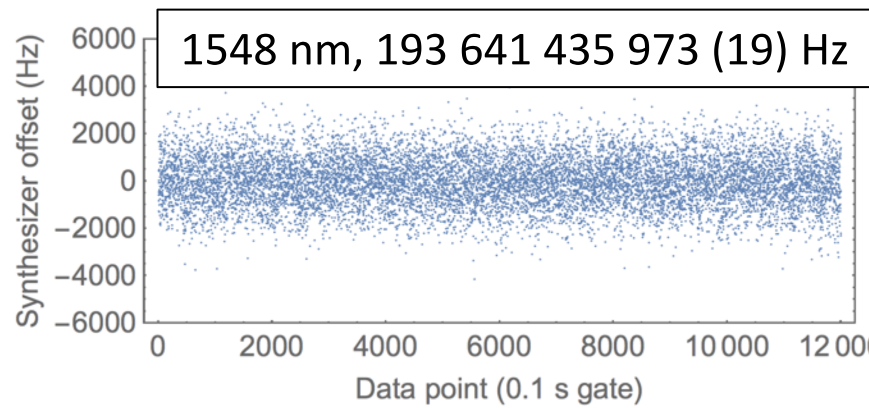


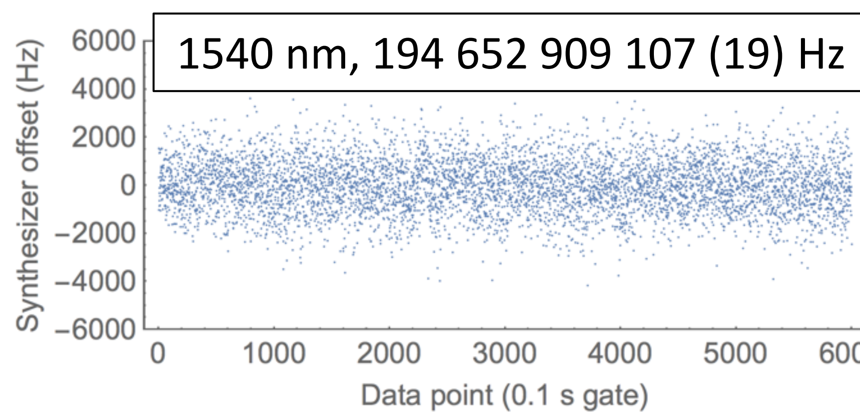
Absolute Tunable Laser Synthesis

- Compare stabilized tunable laser to isolated benchtop self-referenced comb
  - Referenced to same maser RF signal → residual stability (accuracy of reproducing RF signal onto laser)



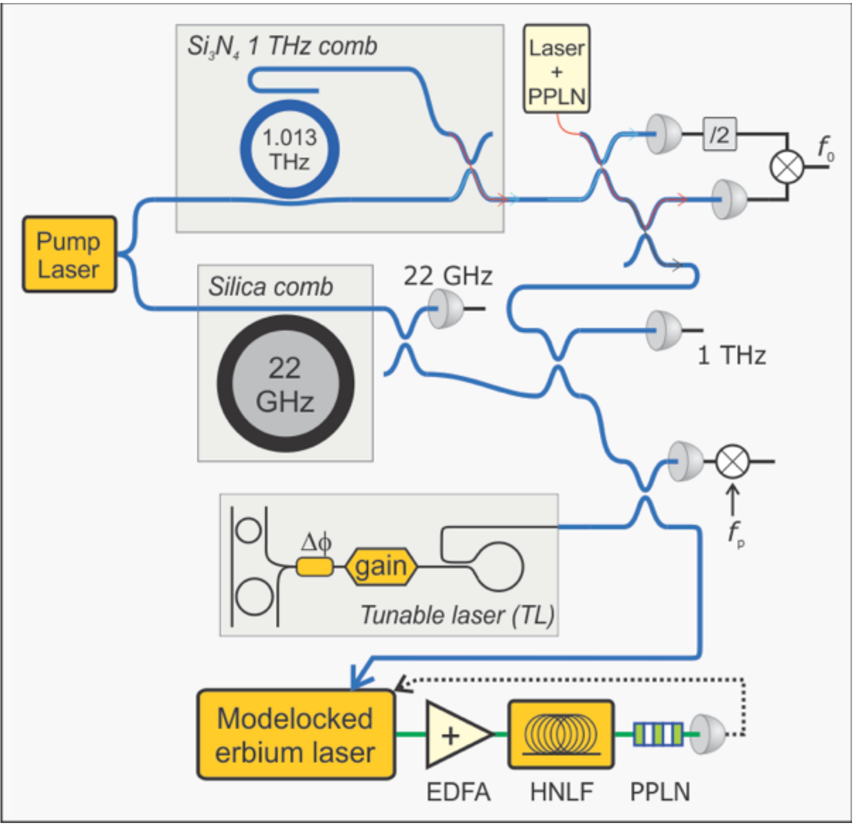


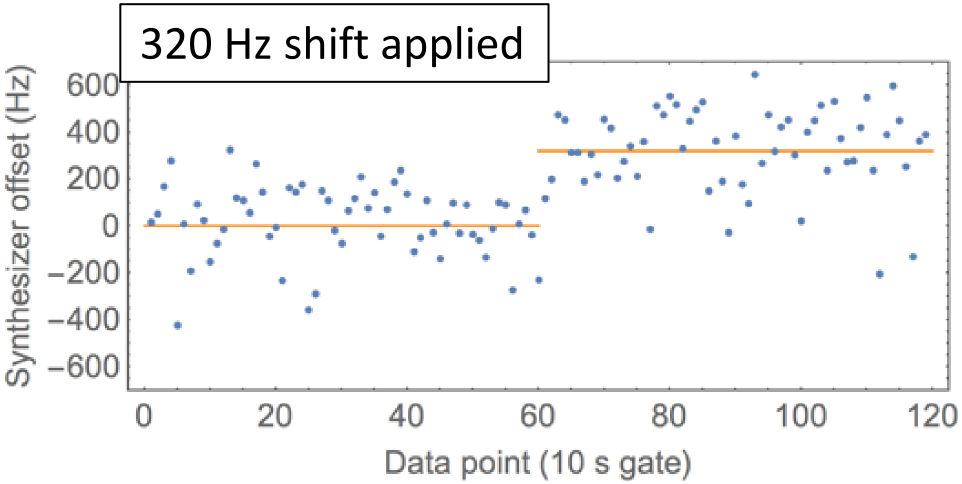


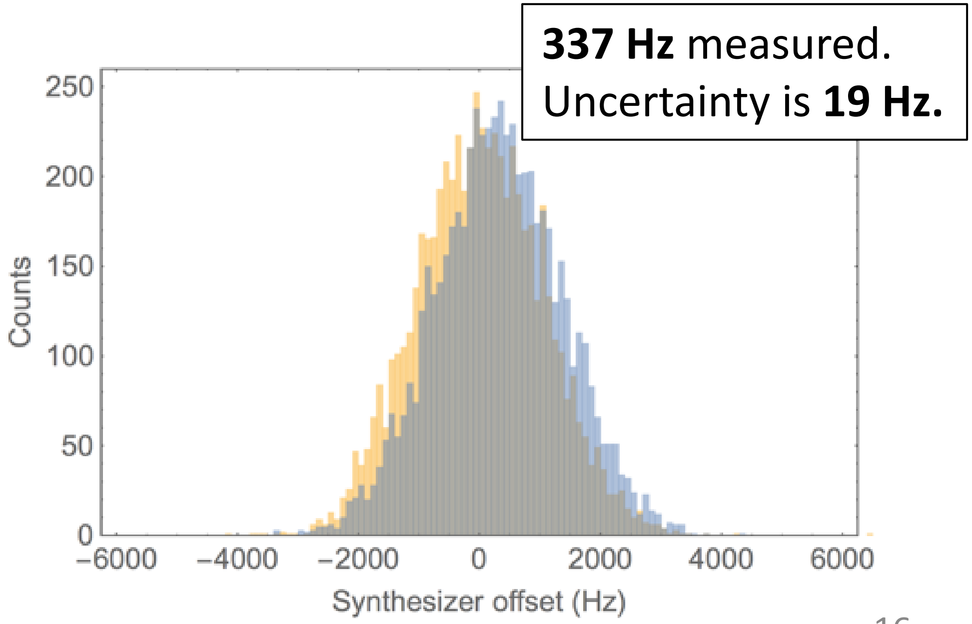


Absolute Tunable Laser Synthesis

- 320 Hz laser jump with 19Hz uncertainty

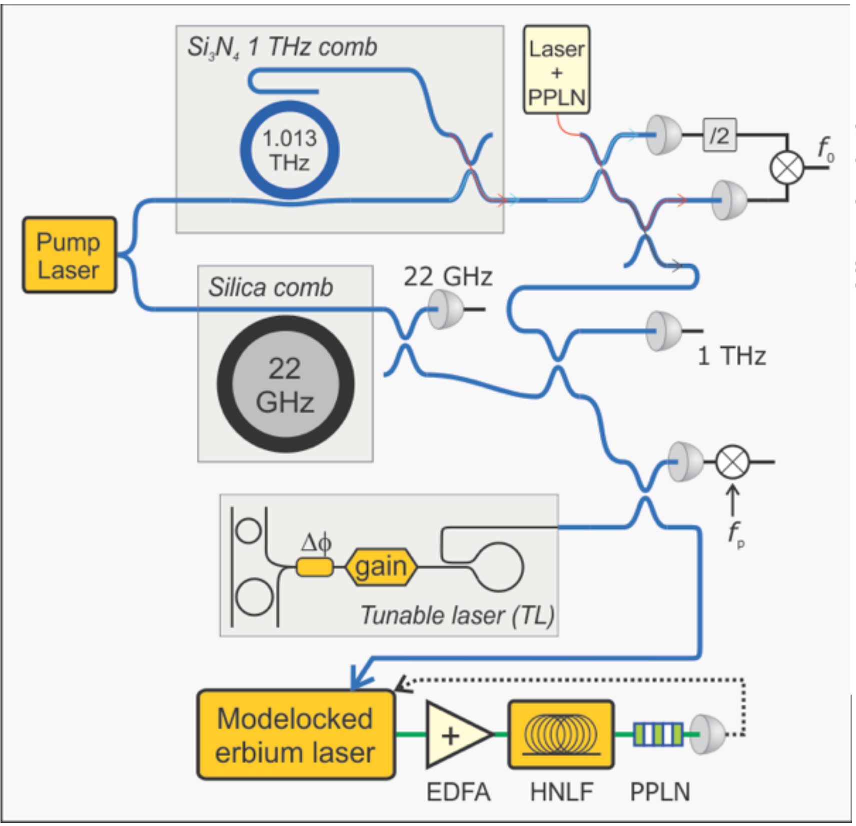


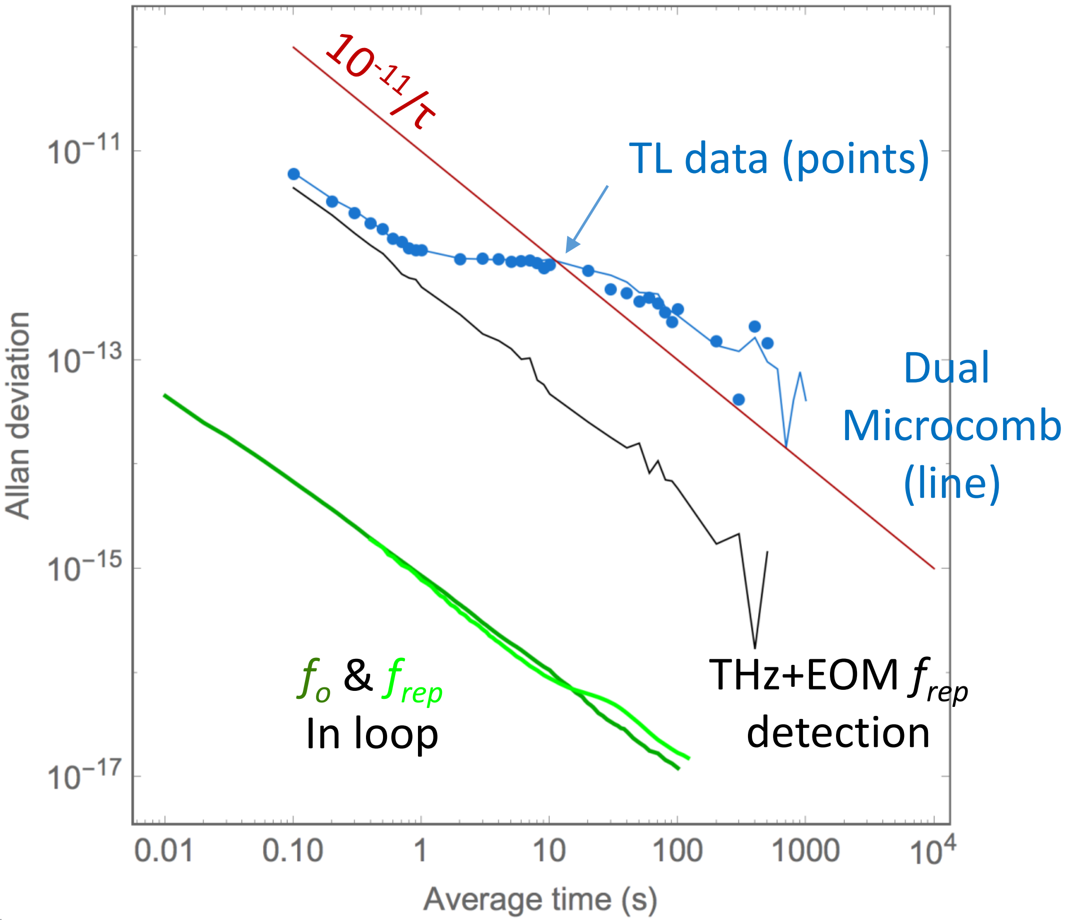




Absolute Tunable Laser Synthesis

- In loop locking: ≈$10^{-15}/\tau$
- Dual microcomb locks: <$10^{-11}/\tau$
- Tunable laser synthesis: <$10^{-11}/\tau$



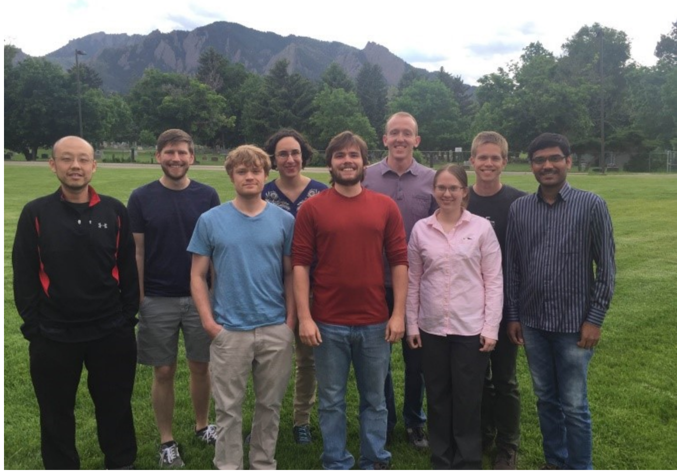


Conclusions

- First demonstration of fully stabilized octave spanning microcomb with direct self-referencing
  - Leveraged by accurate fab and dispersion engineering of Si_3N_4 THz comb
  - Phase locked to microwave signals with < $10^{-11}/\tau$

- First demonstration of optical frequency synthesis utilizing dual microcombs
  - Ultrahigh Q silica resonator allows real time detection/stabilization of f_{rep} for both combs
  - <20 Hz error in knowing the laser's precise optical frequency
  - Laser reproduces microwave stability with < $10^{-11}/\tau$

NIST-Boulder microcomb team



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