An Integrated-Photonics
Optical-Frequency Synthesizer

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Optical Frequency Synthesis

- Accurately producing optical signals with the long term fractional stability of a microwave synthesizer
  - Example at 1 sec: \( 10^{-13} = \frac{\Delta f}{f_{\text{carrier}}} = \frac{1 \mu Hz}{10 MHz} = \frac{20 Hz}{200 THz} \)
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  - Portable metrology, (tunable laser) spectroscopy, quantum science, and optical communications: tighter grids/ precise carrier recovery

\[
\begin{align*}
\Delta f &= \frac{1\mu\text{Hz}}{10\text{MHz}} = \frac{20\text{Hz}}{200\text{THz}} \\
200\text{THz} &= 2 \times 10^{13}\text{Hz} \\
10\text{MHz} &= 10^7\text{Hz} \\
1\mu\text{Hz} &= 1 \times 10^{-6}\text{Hz}
\end{align*}
\]

- Frequency comb
- \(f_{\text{rep}}\) self reference!

Accurate Spectroscopy
- Laser output
- Detector
- Environmental
- Chemical/biological hazardous materials
Optical Frequency Synthesis

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• Octave spanning combs allow precise definition of each comb line, and transfer of stability between optical and microwave domain
  • \( f_n = n * f_{\text{rep}} + f_o \)

• Systems have scaled down from multiple labs to benchtop systems

NIST ~1983

Frequency Chain Laboratory (100 m²)

NIST ~2000

Laser Freq. Comb Table Top (1 m²)
Optical Frequency Synthesis

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• Systems have scaled down from multiple labs to benchtop systems
• We aim to push SWAP+C down with integrated photonics, based on emerging microcomb technology
  • Octave spanning Si\textsubscript{3}N\textsubscript{4} THz comb
  • High Q silica comb to detect \(f_{\text{rep}}\)
  • High confinement waveguide PPLN
  • Heterogeneously integrated lasers

\[ \begin{align*}
\text{~1 cm}^2 \\
\text{~10}^4 \text{ size reduction}
\end{align*} \]
• **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

\[ f_n = n \cdot f_{\text{rep}} + f_0 \]
Chip-Scale Resonator Enabled Optical Synthesizer (CORES)

- $\text{Si}_3\text{N}_4$ 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

Experiment sequence

Laser frequency

Total comb power

Power Drop & “steps”

Hold

Scan back

Scan in

1 soliton

2 soliton

This work: Stable solitons

Noisy combs

\[ F^2, \text{Pump power} \]

\[ \alpha, \text{Pump detuning} \]
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

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

• $f_0$ phase locked

Heterodyne beat @ 1998 nm

Approximately 30 dB SNR in 1 MHz

SHG heterodyne beat @ 999 nm

Approximately 30 dB SNR in 1 MHz

$f_0/64$ by processing both signals
Heterogeneously Integrated Tunable Lasers

- 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

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 19 Hz uncertainty

320 Hz shift applied
337 Hz measured. Uncertainty is 19 Hz.
Absolute Tunable Laser Synthesis

- In loop locking: $\approx 10^{-15}/\tau$
- 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$_3$N$_4$ 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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