Nanophotonic Devices Enable New Applications for Laser Frequency Combs

Featuring Daniel Hickstein from Octave Photonics

12 October 2022
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Nanophotonic devices enable new applications for laser frequency combs

Dan Hickstein
Principal Scientist
Octave Photonics
Louisville, Colorado, USA
Octave Photonics: a small photonics company

• 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!
• 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

Laser frequency comb

Pulses typically <100 fs
1 fs = $10^{-15}$ seconds = 0.000000000000001 seconds
Laser frequency combs: rulers for light

\[ \tau_{r.t} = \frac{1}{f_{\text{rep}}} \]

\[ \nu_N = N f_{\text{rep}} + f_o \]

\[ f_o = f_{\text{rep}} \frac{\Delta \phi}{2\pi} \]
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

Stable CW laser

Atoms

Strontium
Photo: Ye Lab, University of Colorado

Ytterbium
Photo: NIST
Frequency combs: optical clockwork

Optical clock

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
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

Absorbance

CO₂  CH₄  H₂O

Wavelength (nm)

1630  1640  1650  1660  1670

Photo: LongPath Technologies, LLC

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
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

**Typical lab setup**
- High-stability microscope
- Precision nano-alignment stages
- Large enclosure needed

**Fully connectorized device**
- Plug-and-play
- No alignment needed
- Fully enclosed

~ 1 meter

~ 2 cm
Waveguide packaging

Waveguide packages suitable for:

- Vacuum environments
- Low SWaP applications
- High peak power/intensity (>10 kW, >10^{12} W/cm²)
- 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

Deployment ← Packaging ← Lab testing
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

- Nanophotonic waveguide, ~100 pJ
- Nonlinear fiber, ~1000 pJ

Width: 2100 nm

Wavelength (nm)

Relative intensity (dB)

Intensity (10 dB/div)

Nonlinear fiber, ~1000 pJ
Tunable spectrum

Experimental supercontinuum from ~640-nm-thickness SiN waveguides
Nanophotonic chip for strontium clock

$|g = {}^1S_0\rangle$

$|e = {}^3P_0\rangle$

$|e = {}^3P_1\rangle$

$|e = {}^3P_2\rangle$

$|e = {}^3S_1\rangle$

$^1P_1$

$^1D_2$

679 nm
707 nm
7 MHz

679 nm
1.4 MHz

1.9 μm
450 Hz

6.5 μm
620 Hz

460.8 nm
32 MHz

689.4 nm
7.6 kHz

698.4 nm
1 mHz

1 μm

10 μm

689 nm
780 nm
922 nm

689 nm
698 nm
780 nm
922 nm

Spectral flux (dBm/nm)

Wavelength (nm)
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

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conventional 200-MHz comb (HNLF + PPLN)</th>
<th>100-MHz comb + fiber resistive modulator + HNLF + PPKTP</th>
<th>100-MHz comb + passively-cooled pumps + SiN waveguide + PPKTP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature tuning of $f_{cp}$</td>
<td>7.5 W</td>
<td>0.23 W</td>
<td>0.23 W</td>
</tr>
<tr>
<td>Oscillator pump</td>
<td>4.4 W</td>
<td>4.4 W</td>
<td>1.85 W</td>
</tr>
<tr>
<td>Amplifier pumps</td>
<td>20 W</td>
<td>10 W</td>
<td>2.75 W</td>
</tr>
<tr>
<td>Doubling waveguide TEC</td>
<td>~1 W [11]</td>
<td>0 W</td>
<td>0 W</td>
</tr>
<tr>
<td>TOTAL</td>
<td>33 W</td>
<td>14.6 W</td>
<td>4.8 W</td>
</tr>
</tbody>
</table>
Comb-Offset Stabilization Module (COSMO)

COSMO module:

- Supercontinuum, SHG, photodetector, and amplifier
- Complete CEO detection module in <20 cm³
- >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

Menhir Photonics 1 GHz Oscillator

Vescent SLICE-OPL

Octave Photonics COSMO

Dispersion compensating fiber

Locked $f_{SO}$

RF spectrum analyzer
Application 2: Searching for exoplanets

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

Transit Method

Doppler Radial Velocity

- Size
- Density
- Mass
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.

Hobby–Eberly Telescope
Nanophotonic chip simplifies spectrograph calibration

(a) State-of-the-art: Habitable-Zone Planet Finder OFC, Hobby-Eberly

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

Next-gen: EO comb + SWERVI

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

Making microcombs micro

InP DFB laser

SiN ring resonator

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