Laser and Parametric Optical Frequency Combs

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Learning & Research: A continuous upward climb

Chopicalqui (6354m), Peru

Bramante Staircase, Vatican
Outline

1. Background: Clocks and Precise Timing

2. Counting Cycles of Light
   • The optical frequency comb

3. From Lab Scale to Chip Scale
   • Can we make a frequency comb on a chip?

4. Applications and opportunities for frequency combs
Boulder Colorado

25 square miles surrounded by reality

- Population of ~100k
- 30 min from Denver (1.5 M)
- Federal Research Labs: NIST, NOAA, NCAR (atmospheric research)
- Home of University of Colorado
- Many high-tech companies and startups
Boulder Colorado

25 square miles surrounded by reality
**National Institute of Standards & Technology (NIST)**

**NIST’s mission** is to promote U.S. *innovation*…

*Key roles enabling innovation, education, and infrastructure for investments in the future…*

NIST Boulder assets include *(approximate values):*

- 375 employees.

- 350 associates.
  - Postdocs, grad & undergrad students, contractors, guest researchers, etc.

- $100 million annual operating budget.
  - Appropriations, other agency reimbursements.

- About 20% of NIST Laboratory programs overall.
Time and Frequency Metrology

Cs Fountain Clock

Chip-Scale Clocks

Optical lattice clocks

Single Ion Clocks

Optical Frequency Combs
Background: Clocks and Precise Timing

Salvador Dali: *The persistence of memory* (1931)
Timescales

<table>
<thead>
<tr>
<th>Event</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shortest human-made event</td>
<td>$10^{-18}$</td>
</tr>
<tr>
<td>Bohr orbital</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>Chem/Bio Reactions</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>Computer clock cycle</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Camera flash</td>
<td>$10^0$</td>
</tr>
<tr>
<td>Heartbeat</td>
<td>$10^4$</td>
</tr>
<tr>
<td>Rotation of earth</td>
<td>$10^8$</td>
</tr>
<tr>
<td>Earth around sun</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>Human evolution</td>
<td>$10^{18}$</td>
</tr>
<tr>
<td>Age of universe</td>
<td></td>
</tr>
</tbody>
</table>

Still shorter:
- Top Quark lifetime: $4 \times 10^{-25}$ s
- Planck time: $10^{-43}$ s
# What Makes a Clock?

A clock is made up of two main components:

- **Oscillator**
- **Counting Mechanism**

## Oscillator
- Earth Rotation
- Pendulum
- Quartz Crystal

## Counting Mechanism
- Sundial
- Clock Gears/Hands
- Electronic Counter

### ATOMIC CLOCKS
- Microwave Transition + Oscillator
- Optical Transition + Laser
- Electronic Counter
- Femtosecond Laser
Optical Atomic Clocks

- Isolated cavity narrows laser linewidth and provides short term timing reference.
- Atoms provide long-term stability and accuracy—now now at $10^{-18}$ level!
- Laser frequency comb acts as a divider/counter.

At NIST/JILA: Ca, Hg+, Al+, Yb, Sr
**Types of Clocks**

<table>
<thead>
<tr>
<th></th>
<th>Optical Clock</th>
<th>Primary Standard</th>
<th>Compact Atomic Clock</th>
<th>Precision Quartz Crystal</th>
<th>Wristwatch Quartz Crystal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loses 1 sec. in:</td>
<td>$10^{10}$ yrs</td>
<td>$10^8$ yrs</td>
<td>1000 yrs</td>
<td>1 yr</td>
<td>1 day</td>
</tr>
<tr>
<td>Size:</td>
<td>laboratory</td>
<td>$10^7$ cm$^3$</td>
<td>100 cm$^3$</td>
<td>$1$ cm$^3$</td>
<td>$10^{-3}$ cm$^3$</td>
</tr>
<tr>
<td>Stability (1s):</td>
<td>$10^{-16}$</td>
<td>$10^{-13}$</td>
<td>$10^{-10}$</td>
<td>$10^{-11}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Cost:</td>
<td>$?$</td>
<td>$1$ M</td>
<td>$1,000$</td>
<td>$100$</td>
<td>$1$</td>
</tr>
</tbody>
</table>

**All atomic clocks have:**
- Reference atom
- Local oscillator (pendulum)
- Counter/gears

Figure: J. Kitching, (NIST)
Timekeeping: The long view

Rate of improvement since 1950: 1.2 decades / 10 years
Moore’s Law for Transistors per Chip

Microprocessor Transistor Counts 1971-2011 & Moore’s Law

Rate of growth since 1970:
1.5 decades / 10 years

Wiki: "Transistor Count and Moore's Law"
Timekeeping: Societal and Scientific Impact

- Oscillator Freq. $f = 1 \text{ Hz}$
- $f = 10 \text{ kHz}$
- $f = 10 \text{ GHz}$
- $f = 500 \text{ THz}$
- Gravity shift 10 cm
- $f = 10-100 \text{ PHz}$

## Nobel Prizes Related to Timekeeping

<table>
<thead>
<tr>
<th>Year</th>
<th>Recipients</th>
<th>Work Awarded</th>
</tr>
</thead>
<tbody>
<tr>
<td>1943</td>
<td>Otto Stern</td>
<td>Molecular/atomic beam spectroscopy.</td>
</tr>
<tr>
<td>1944</td>
<td>Isidor Rabi</td>
<td>Atomic beam resonance technique.</td>
</tr>
<tr>
<td>1955</td>
<td>Polykarp Kusch</td>
<td>Magnetic moment of electron; early atomic clocks.</td>
</tr>
<tr>
<td>1964</td>
<td>Charles Townes, Nicolai Basov, Alexandr Prokhorov</td>
<td>Quantum electronics, including maser/laser principles.</td>
</tr>
<tr>
<td>1966</td>
<td>Alfred Kastler</td>
<td>Optical pumping methods.</td>
</tr>
<tr>
<td>1989</td>
<td>Norman Ramsey, Hans Dehmelt, Wolfgang Paul</td>
<td>Atomic clock techniques; trapped ion spectroscopy.</td>
</tr>
<tr>
<td>2012</td>
<td>Dave Wineland, Serge Haroche</td>
<td>Quantum state measurement and manipulation.</td>
</tr>
</tbody>
</table>

*Images correspond to the recipients: Bill Phillips (NIST), Carl Wieman (JILA/CU), Eric Cornell (JILA/NIST), John Hall (JILA/NIST), Dave Wineland (NIST).*
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Counting Cycles of Light
How Do You Count Optical Cycles?

**Optical Frequency:** \( c/600 \text{ nm} = 500 \text{ THz} \rightarrow T=2 \text{ fs} \)

**Fastest electronics:** 1 THz, 1 ps

**Optical Heterodyne:** Measure “beat note” between two optical frequencies

<table>
<thead>
<tr>
<th>500,000,000,000,000 Hz - 10,000,000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier: ((f_1 + f_2)/2)</td>
</tr>
<tr>
<td>Envelope: ((f_1 - f_2))</td>
</tr>
</tbody>
</table>

A countable frequency! But only a relative one.
Direct Multiplication

\[ \frac{V_{\text{optical}}}{V_{\text{microwave}}} \approx \frac{10^{15}}{10^{10}} \approx 10^5 \approx 2^{16} \]

It worked! But not general, practical, cost effective

NBS Laser Frequency Synthesis Chain (1979)

NIST ~1983
What is a laser frequency comb??

Client's quote:
"I used to have only one or two good hair days a month. Now, every day is a good hair day."
Multiple faces of a frequency comb

1. A ruler for light frequencies

2. A perfectly-spaced train of optical pulses
Multiple faces of a frequency comb

3. An optical clockwork

- Comb uncertainty at the 20th decimal place
- Measurement of optical ratios (e.g. $v_1 : v_2$)
- Direct connection from optical to microwave domains
Mode-Locked Laser: Basis of the Frequency Comb

Key Concept:
Direct link between optical and microwave frequencies

\[ \nu_n = n f_r + f_o \]
\[ n \sim 10^5 \]
Group and phase velocity in modelocked lasers

animation from Steve Cundiff
The femtosecond mode-locked laser comb

Cavity modes are locked in phase to generate a short pulse once every roundtrip time $2L/v_g$
How does it work?

→ All femtosecond lasers require:
  • Laser cavity + broadband gain source and optical components
  • Dispersion control $\rightarrow \beta(\omega)$
  • Power-dependent gain or loss $\rightarrow n_2l(r)$
  • Phase modulation $\rightarrow n_2l(t)$

$\text{ideal mode spacing:}$

$\left[ \frac{c}{2L} \right]$

→ Due to dispersion, the cavity modes are not evenly spaced
→ However, the **nonlinear phase-modulation** in a mode-locked laser provides the required synchronization of the modes.
→ Yields a strictly uniform mode comb with spacing $v_g/(2L)$
→ $\beta_2(\omega)$ and all higher orders of dispersion are compensated!
Multiple faces of a frequency comb

3. An optical clockwork

- Comb uncertainty at the 20\textsuperscript{th} decimal place
- Measurement of optical ratios (e.g. $v_1 : v_2$)
- Direct connection from optical to microwave domains
Controlling the femtosecond laser comb

For most applications with the femtosecond laser frequency comb, we need to measure and control the two degrees of freedom of the frequency comb: $f_o$ (offset frequency) and $f_r$ (repetition rate).

\[ f_n = nf_r + f_o \]

- $f_o$ measured by “self-referencing”
  - Need an very broad spectrum (i.e. an octave)

- $f_r$ controlled with a microwave source or a CW laser

- $n$ determined by lower resolution measurement or a combination of measurements
The laser comb and its control

Operational Definition: Comb = Frequency-stabilized Mode-locked Laser

Operation is fully reversible: Can lock at microwave and synthesize optical frequencies.
Measuring/controlling the offset frequency: self-referencing

\[ f_n = nf_r + f_0 \]
\[ f_{2n} = 2nf_r + f_0 \]

- \( f_0 \) is generated from a heterodyne beat between the second harmonic of a group of modes around the \( n^{th} \) mode and another group of modes around the \( 2n^{th} \) mode.

- Main Requirement: A very broad spectrum

  Alternative schemes do exist, for which less than one octave is required: see H. Telle et al. Appl. Phys. B 69, 327 (1999)

Microstructure optical fiber continuum generation

- Tight confinement of light leads to high nonlinearity and anomalous dispersion in the wavelength regime of femtosecond Ti:sapphire lasers
- Such fibers are available from commercial sources (ThorLabs, Crystal Fibre) and are developed in research labs (OFS, Univ. of Bath)

CLEO Postdeadline (CPD8) Baltimore (1999).
Octave-Span Supercontinuum

1 GHz Ti:sapphire

100 MHz Er:fiber

532 nm PUMP

1 GHz broadband TiSaph

180 MHz Yb:KYW + PCF

100 MHz Er:fiber + HNLF

also....

Yb:fiber

Yb:crystalline

Tm:fiber

.....


S. Diddams, JOSA B (2010)
GHz Rep Rate Ti:Sapphire Combs

T. Fortier, A. Bartels, D. Heinecke, M. Kirchner

10 GHz Self-referenced Ti:sapphire Laser

1 GHz Octave Spanning Laser

- Stabilized Comb = 10^6 Modes
- Hz-level linewidths
- Residual frequency noise at 1 \times 10^{-19} level

T. Fortier, A. Bartels, S. Diddams, CLEO (2005)
Er:fiber based frequency combs

→ mode-locking based on nonlinear polarization rotation

Launched polarization state

Ultrashort pulse train

Nonlinearly-rotated polarization ellipse

980 nm pump (x2)

erbium-doped fiber

Octave Spectrum

Relative Power (dB)

Wavelength (nm)
Polarization-maintaining Er:fiber laser comb

- Laser + amplifier + self-referencing are all constructed “in-line” with polarization-maintaining (PM) fiber optics.
- Laser is mode-locked with saturable absorber mirror.
- Robust against environmental perturbations.

Frequency comb operates phase-locked in a moving vehicle.

High-power Yb:fiber laser frequency comb

- Linear cavity design
- Saturable absorber end mirror for mode-locking
- Fiber Bragg grating provides output coupling and dispersion control
- **External amplification to ~80 W** followed by compression to ~100 femtosecond pulses
- Supports **sub Hz linewidths**

Frequency Comb Extension via Nonlinear Optics

• Using a combination of harmonic generation, difference frequency generation and super-continuum, frequency combs have been extended from the UV to the infrared.

Some examples: