Frequency Combs

250 Special Topics
Jennie Guzman
Frequency Comb

http://www.nist.gov/public_affairs/newsfromnist_frequency_combs.htm
Ultrafast Laser

Kerr-lens mode-locked Ti:sapphire laser
Kerr Effect

- Index of refraction is proportional to intensity

\[ n(I) = n_0 + n_2 I \]

- Kerr medium acts like a lens for high intensity
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Cundiff, Steven T., Ye, Jun, Reviews of Modern Physics, Vol. 75, 2003
Ultrafast Laser

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Dispersion

- Spectral dispersion due to variation in refractive index
  - Results in temporal spreading
  - Longer wavelengths travel faster than shorter ones (normal dispersion)
- 2-Prism sequence
  - The first prism spatially disperses the pulse
  - Long wavelength components travel through more glass of prism 2
- Net effect is to generate “anomalous” dispersion to counteract the normal dispersion of the crystal
fs Laser Spectrum

\[ f = n f_{rep} + f_0 \]

Cundiff, Steven T., Ye, Jun, Reviews of Modern Physics, Vol. 75, 2003
Laser Cavity

\[ \text{f}_{\text{rep}} = \frac{c}{2d}, \text{ where } d \text{ is the path length in the cavity} \]
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- \( f_{\text{rep}} = \frac{c}{2d} \), where \( d \) is the path length in the cavity
Definition of the Second

• Defined with respect to oscillation frequency between hyperfine levels in $^{133}\text{Cs}$
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Absolute Frequencies

- Reference to $^{133}\text{Cs}$
- Two measurements: $f_n$ and $f_0$
- $f_{\text{rep}}$ can be measured using a fast photodiode
- $f_0$ requires that the comb span one octave

$$f_n = n f_{\text{rep}} + f_0$$
Spectral Broadening

• air-silica microstructure fiber
  • small diameter
  \( \sim 1.7\mu m \)
  • nonlinear medium leading to nonlinear optical effects, ie: four-wave mixing, self-phase modulation

Spectral Broadening

Cundiff, Steven T., Ye, Jun, Reviews of Modern Physics, Vol. 75, 2003
Stabilization

$f_{\text{rep}}$ can be stabilized via microwave reference
Stabilization

• $f_0$ can be stabilized through self-referencing
• “self-referencing” refers to second harmonic generation to compare extremes of the comb

Cundiff, Steven T., Ye, Jun, Reviews of Modern Physics, Vol. 75, 2003
Frequency Comb

Hansch, T.W. et al., Nature 416, 2002
Stability

- Cs clock short-term stability: $5 \times 10^{-12}$ at 1 second
- Fs optical comb short-term stability: $4 \times 10^{-14}$ at 1 second

- Commercial fs combs:
  - Stability: $5 \times 10^{-13}$ at 1 second
  - Accuracy: $\approx 10^{-14}$
Frequency Comb Numbers

- KLM Ti:sapphire laser
  - Pulse duration < 6 fs
  - \(10 \text{ MHz} < f_{rep} < 10 \text{ GHz}\)
  - \(-\frac{f_{rep}}{2} < f_0 < \frac{f_{rep}}{2}\)
  - 700 - 1000 nm (before spectral broadening)
- 400-1200 nm
- Erbium-doped fiber lasers: 1000-2400 nm
- Ytterbium-doped fiber lasers: 600-1600 nm
Spectral Coverage

The diagram illustrates the spectral coverage for various processes and phenomena, including:

- **1: Atomic and molecular spectra**
- **2: Frequency comb spectra**
- **3: HHG**
- **4: Ti:Sapph**
- **5: SHG & SFG**
- **6: Er^3+ fiber**
- **7: Yb fiber**
- **8: e) OPO**
- **9: DFG**

The log₂[wavelength] (nm) is plotted on the x-axis, showing the range of wavelengths covered by these processes.
Astro-Comb

• Current Limitations
  • accuracy and long-term stability are limited by wavelength calibration sources
  • Sources limited in red - near IR
  • Iodine absorption cells
    • few spectral lines
  • Thorium-argon lamps
    • limited spectral lines
    • unstable bright features - saturate detectors
Astronomical Spectrograph
Astro-Comb

• Possible solution - Frequency comb
• Absolute frequency is determined by rep. rate and offset frequency
  • Can be referenced to rf sources
  • Current fractional stability exceeds needs
  • $3 \times 10^{-11}$
Astro-Comb

[Diagram showing the setup of an Astro-comb system, including components such as a Diode laser, current modulation, lock-in amplifier, Fabry–Perot cavity, and an optical spectrum analyser.]
Astro-Comb
Astro-Comb Proposal

LRIS: Home page  http://www2.keck.hawaii.edu/inst/iris/
References

Cundiff, Steven T., Ye, Jun, Reviews of Modern Physics, Vol. 75, 2003

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Hansch, T. W. et al., Nature 416, 2002

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