The Optical Frequency Comb Technique

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Roadmap

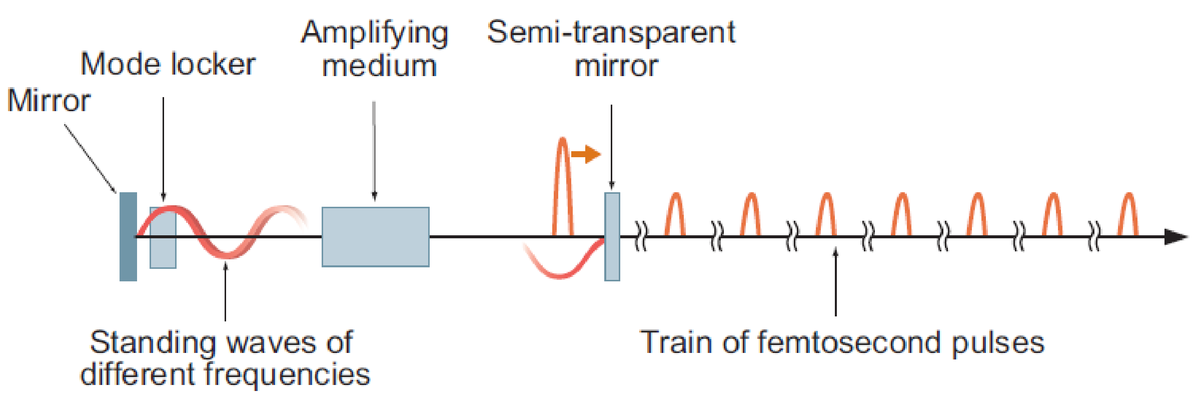
- Motivational scenario
- What is the optical frequency comb technique?
  - Applications
- Complex waveforms: they're natural
- The Fourier Transform
- How to build a wave packet

Scenario

- To study atomic structures on the scale of femtoseconds
  - Extremely difficult with older methods
- To challenge the validity of a fundamental physical constant
  - Do one or more change *slowly* with time?
- Laser-based spectroscopy

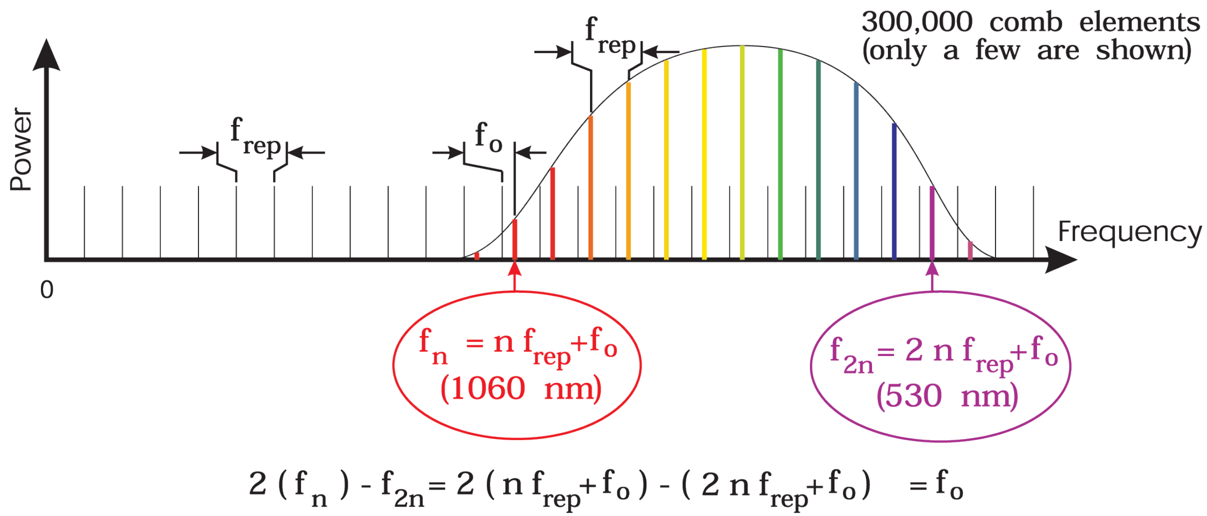
The Technique

- Uses laser to generate light spectrum from monochromatic, ultra short pulses of light
- Results in a comb-shaped spectrum with known (calculable) wavelengths
  - Uniform and extremely short spacing of resulting spectral lines—like a ruler



The Technique (cont'd)

- Compare the wavelength of the electromagnetic radiation emitted to comb
  - *Very* high degree of accuracy
- Can alter the included frequencies by narrowing/broadening the pulse



Modern Applications

- Astronomical observations
- GPS
- (Re)definition of physical units:
  1 m = 1/299,792,458 s
- … and more!

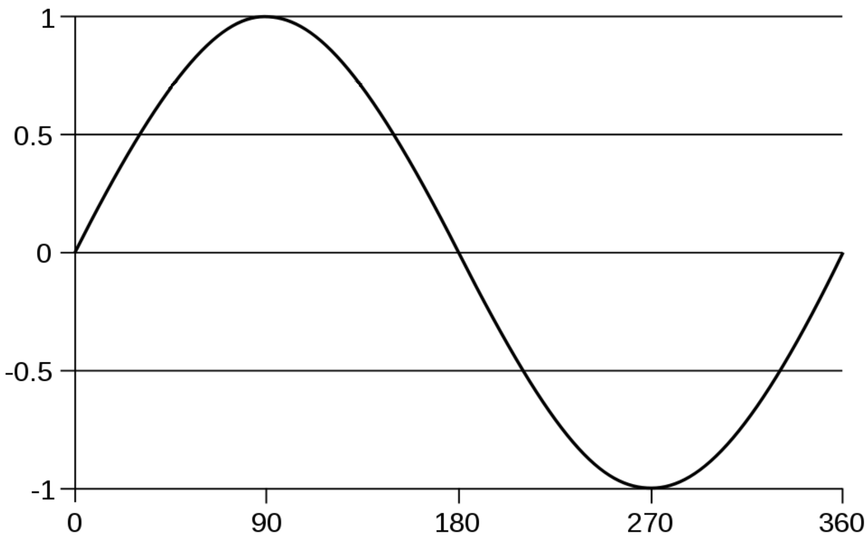
John Hall

Theodore Hänsch

Nobel Prize, 2005

"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"

Complex Waveforms



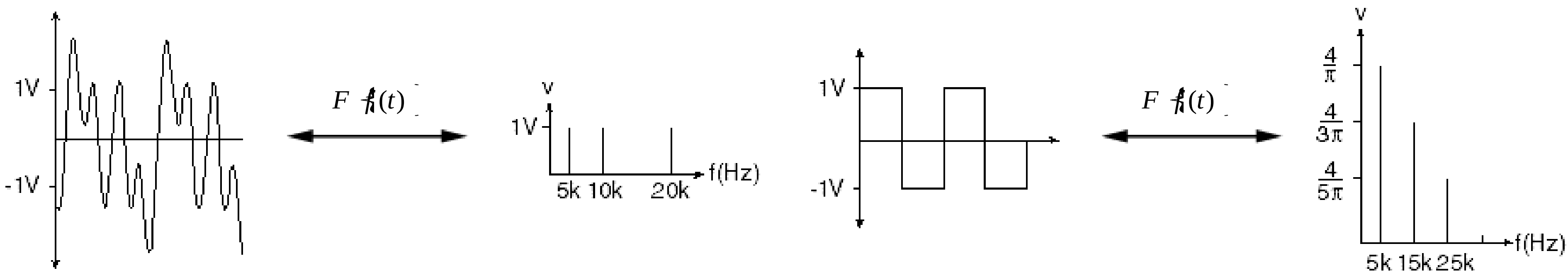
VS

Wave Packets

- Complex waveforms useful in quantum mechanics
  - Can approximate a well-localized particle
- Not periodic functions
- Can be created by linear combinations of sine waveforms
  - Use distinct wave numbers that are not restricted to integer multiples

The Fourier Transform

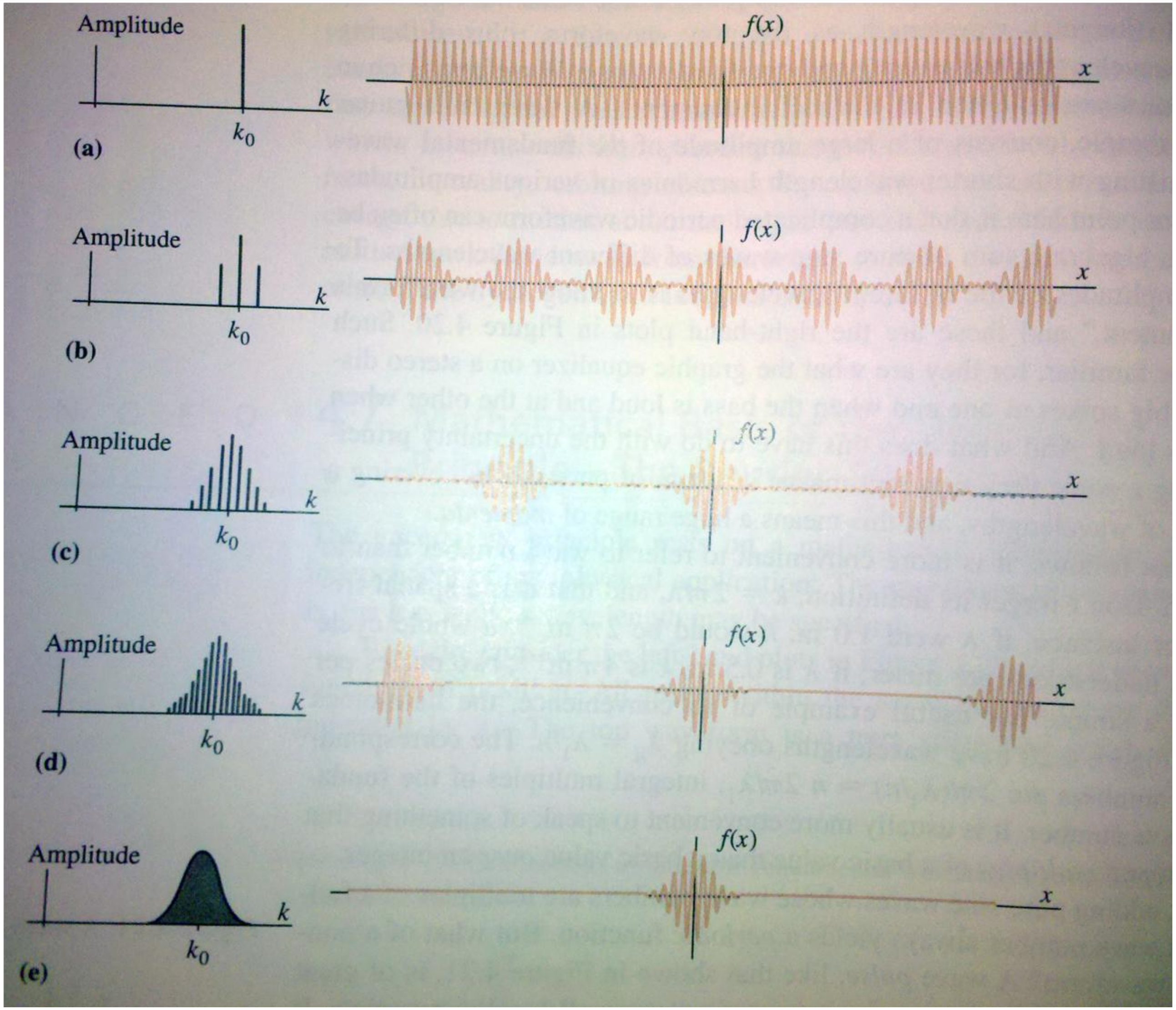
- A waveform's spectral content: know amplitude of composite wavelengths
- Allows for analysis of complex phenomena



The Fourier Transform (cont'd)

- <u>Want</u>: A specific waveform with a dominant k_0
- <u>Idea</u>: Add more distinct wave numbers, k_i, near k_0 with small uniform separation
  - Keep doing this until the separation diminishes
- Construct $A(k)$ to describe spectral content, or the amplitude of each wave number k_i

The Fourier Transform (cont'd)



The Fourier Transform (cont'd)

- Use wave function for plane wave as a building block
- Complex waveforms are linear combinations of the appropriate $A(k_i)$ and the wave function for a plane wave

$$\psi(x) = \int_{-\infty}^{\infty} A(k)\, e^{ikx}\, dx$$

The Fourier Transform (cont'd)

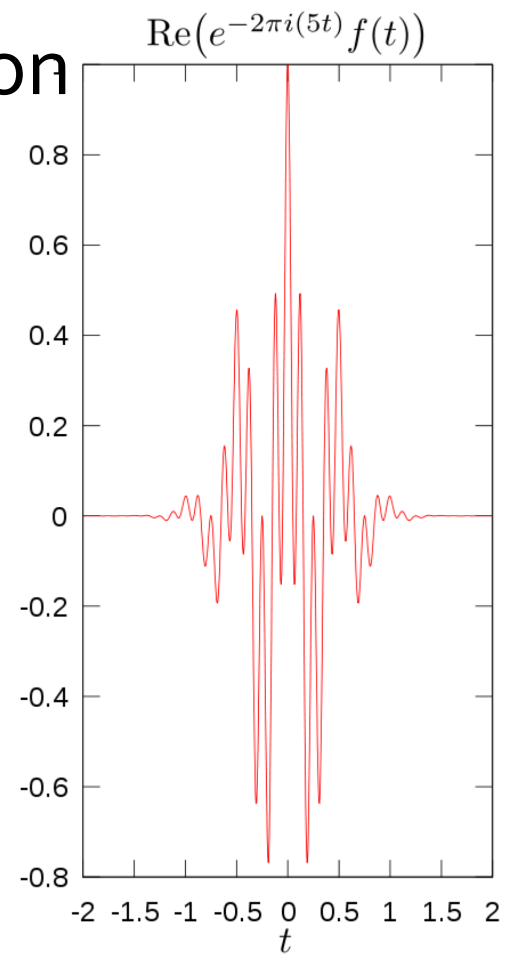
- Solving for spectral content, *A(k)*, yields the Fourier Transform of $\psi(x)$

$$A(k) = \mathcal{F}\{\psi(x)\} = \frac{1}{2\pi} \int_{-\infty}^{\infty} \psi(x)\, e^{-ikx}\, dx$$

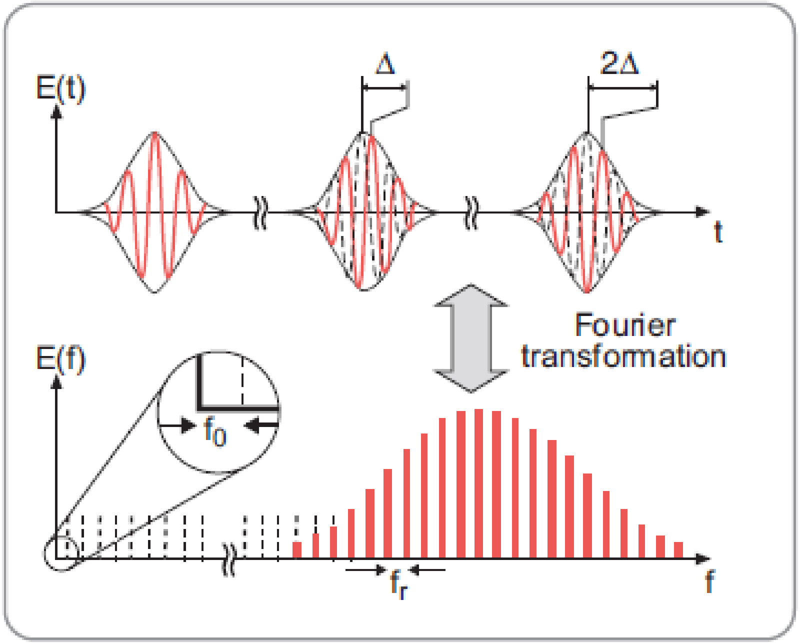
- So what?
  - Tells us exact amplitude of each sinusoidal waveform of a corresponding wave number, k_i

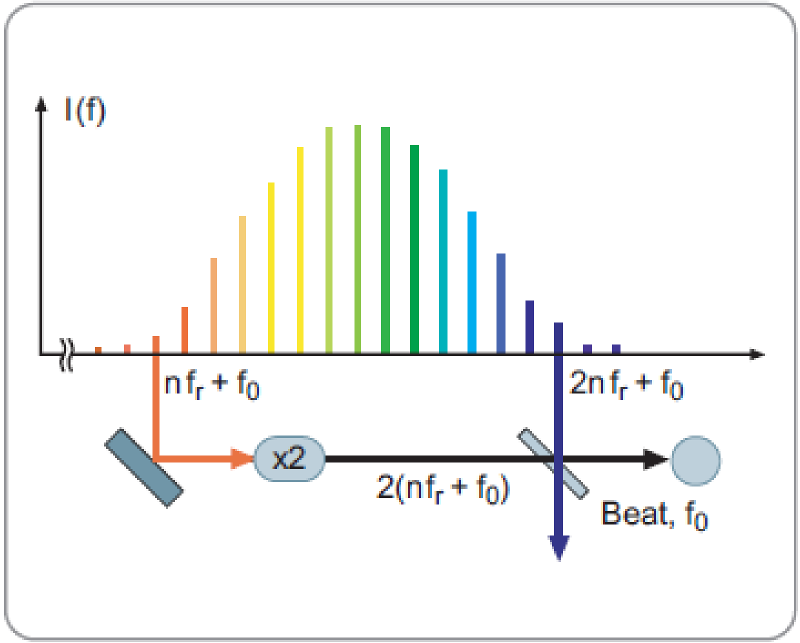
Building Wave Packets

- Use inverse relationship inherent in the Fourier Transform for manipulation
- Want: $\psi(x)$ centered about $x = 0$ and wavelength determined by k_0
  - Build $A(k)$ with a dominance on k_0
  - Perform inverse FT to obtain $\psi(x)$



Building Wave Packets (cont'd)





Thank You!

Questions?

Sources

A bibliography of sorts

1. Hall, John L. “The Optical Freqency Comb: A Remarkable Tool for Metrology, Science and Medical Diagnostics.” Lecture. *NanoHUB*. Purdue, 9 Oct. 2008. Web. 6 Apr. 2010. <http://nanohub.org/resources/6040>.
2. Harris, Randy. “Mathematical Basis of the Uncertainty Principle.” Modern Physics. San Francisco: Pearson/Addison Wesley, 2008. 124-32. Print.
3. “The Laser Frequency Comb.” *CODEX*. Instituto De Astrofísica De Canarias. Web. 6 Apr. 2010. <http://www.iac.es/proyecto/codex/>.
4. *The Nobel Prize in Physics 2005*. Royal Swedish Academy of Sceinces, 2005. <http://nobelprize.org/nobel_prizes/physics/laureates/2005/info.pdf>.
5. Optical Frequency Comb. Digital image. *National Resarch Council Canada*. National Resarch Council Canada. Web. 6 Apr. 2010. <http://www.nrc-cnrc.gc.ca/obj/inms-ienm/images/research_images/optical_comb/COMBFIG6.gif>.
6. “Optical Frequency Combs.” *Optical Frequency Combs*. National Institute of Standards and Technology. Web. 6 Apr. 2010. <http://www.nist.gov/public_affairs/newsfromnist_frequency_combs.htm>.
7. The Royal Swedish Academy of Sciences. *New Light on Modern Optics*. *New Light on Modern Optics*. Nobelprize.org, Oct. 2005. Web. 6 Apr. 2010. <http://nobelprize.org/nobel_prizes/physics/laureates/2005/press.html>.
8. Schewe, Phil, and Ben Stein. “The 2005 Nobel Prize in Physics.” *Physics News Update* 748.1 (2005). *Inside Science Research - Physics News Update*. American Institute of Physics, 4 Oct. 2005. Web. 6 Apr. 2010. <http://www.aip.org/pnu/2005/split/748-1.html>.