Laser-based precision spectroscopy and the optical frequency comb technique[1]

[1] Alternatively: Why did Hänsch win the Noble prize?

Dr. Björn Hessmo
Physikalisches Institut, Universität Heidelberg

The Nobel prize in physics for 2005

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2005 with one half to

Roy J. Glauber
Harvard University, Cambridge, MA, USA
"*for his contribution to the quantum theory of optical coherence*“

and one half jointly to

John L. Hall
JILA, University of Colorado and National Institute of Standards and Technology, Boulder, CO, USA and

Theodor W. Hänsch
Max-Planck-Institut für Quantenoptik, Garching and Ludwig-Maximilians-Universität, Munich, Germany
"*for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb techn*

To understand the second half of the prize we need to learn more about two things:

- *What is “laser-based precision spectroscopy”?*
- *What is the “optical frequency comb technique”?*

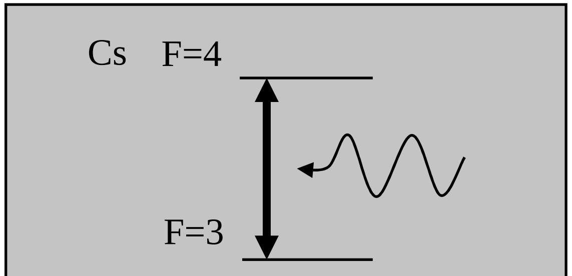
Precision Spectroscopy
-To measure a frequency accurately.

<u>Definition of second:</u>

- Originally defined in 1889 as the fraction 1/86 400 of the mean solar day.
  (not good because of irregularities in Earth's rotation)

- Redefined in 1956 to 1/31 556 925.9747 of the length of the tropical year for 1900.
  (difficult to measure, long measurement times)

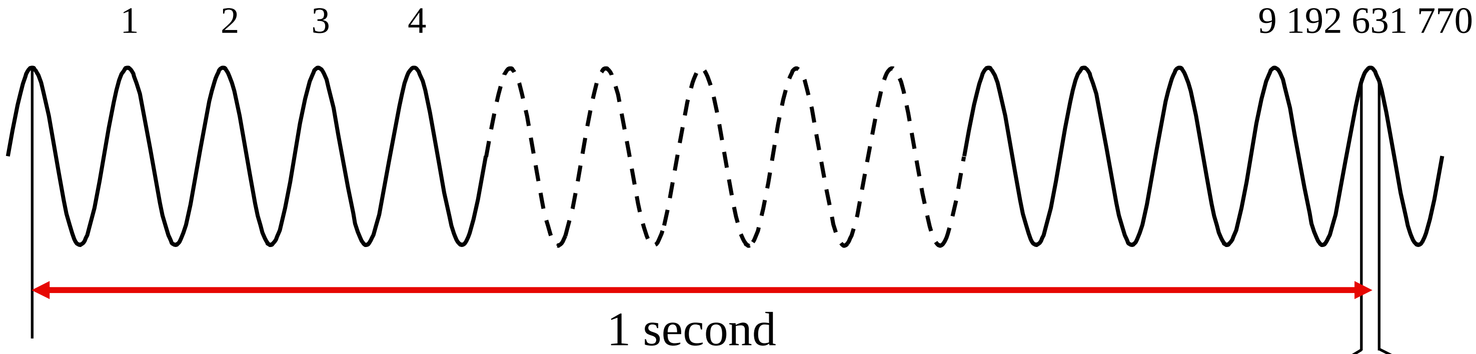
- Redefined in 1967 to an atomic reference.



$$f_{def} = 9.192631770 \text{ GHz}$$

<u>Some adavantages with atomic reference:</u>
1. Fast oscillation (compared to the tropical year).
2. Identical atoms make it easy to "copy" the reference.
3. Precise spectroscopic methods can be used to obtain time

One second is defined as the duration of 9 192 631 770 cycles of microwave light absorbed or emitted by the hyperfine transition of cesium-133 atoms in their ground state undisturbed by external fields.



How accurately can
the position of the peak
be determined?

Estimate:
~1/100th of the oscillation

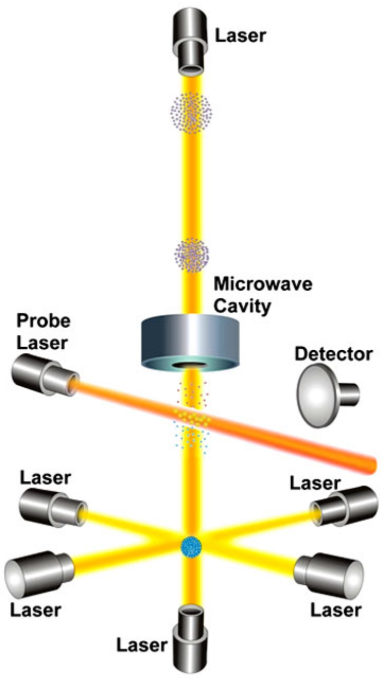
- Direct counting gives an uncertainty of $\sim 10^{-10}$
- Improved peak positioning gives $\sim 10^{-12}$
- Interferometric techniques and signal averaging gives a final uncertainty of $\sim 10^{-15}$

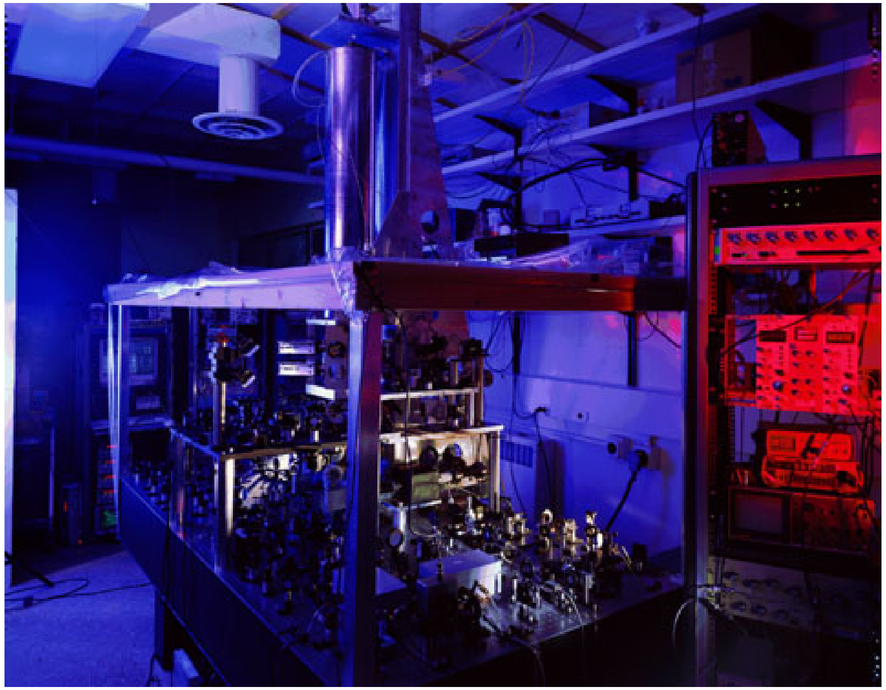
Corresponds to a 1 second drift in 30 million years

Fountain clocks

Observatoire de Paris, **NIST (Boulder),** Observatoire Cantonal de Neuchâtel (Switzerland),…

The NIST-F1 clock





For increased accuracy a faster oscillator is needed!

9.2 GHz
MICROWAVE

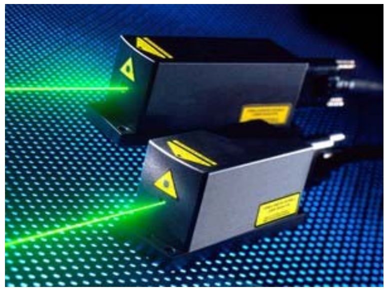
Microwave electronics is highly developed technology!

Optical oscillators!

Green light: 532 nm corresponds to an oscillating frequency o

563000 GHz!

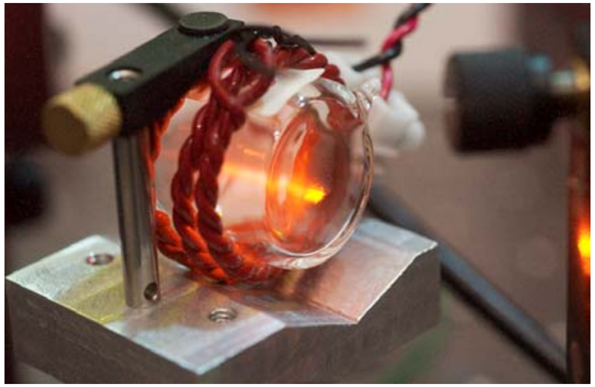
Clock improvement with a factor 10^5 !



Unfortunately, no electronics can handle this speed...

Laser-based precision spectroscopy

Atoms can once more be used as references to stabilize the frequency of laser light.



Tune the laser wavelength to an *optical transition* within an atom

Laser frequencies have been stabilized to within <10 mHz. Comparing this to the frequency 500 THz one obtains a frequency uncertainty of < 10^{-17}!

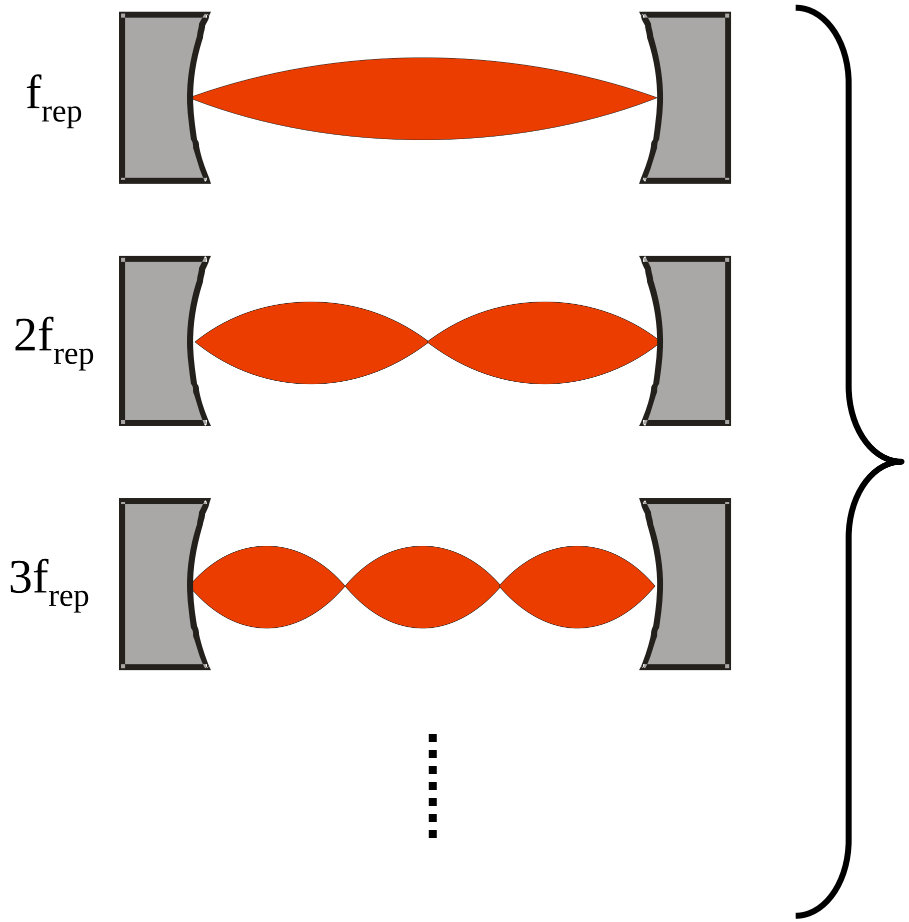
This would be a nice clock... But the problem remains:

How to count the ”tick-tacks” of this clock?

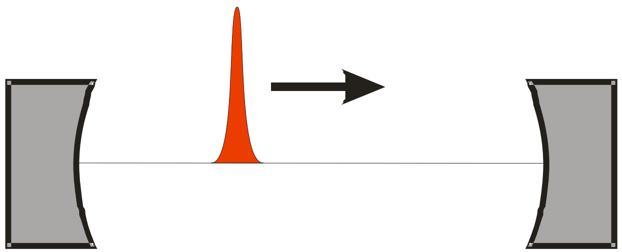
Solution: An optical frequency comb.

Short laser pulses

Laser pulses can be made extremely short, t < 10 femtoseconds. A short pulse has a broad spectrum.

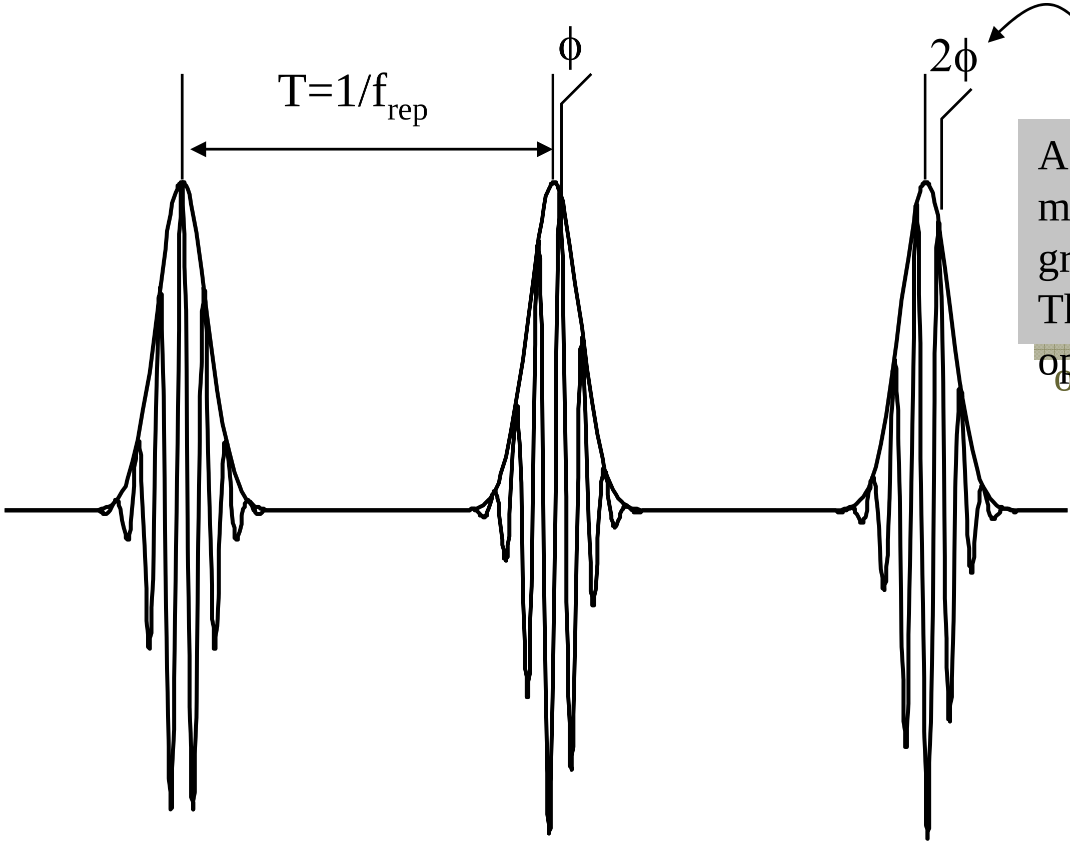


A well-defined phase relation between the frequency components builds up the pulse



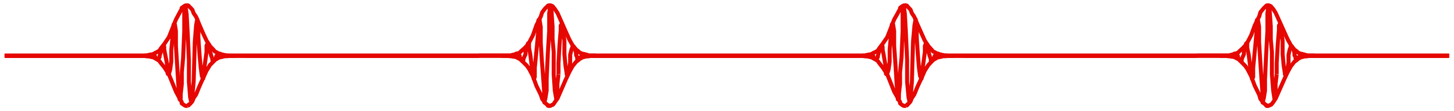
The round-trip frequency is described by f_{rep}

Temporal behavior of a pulse train

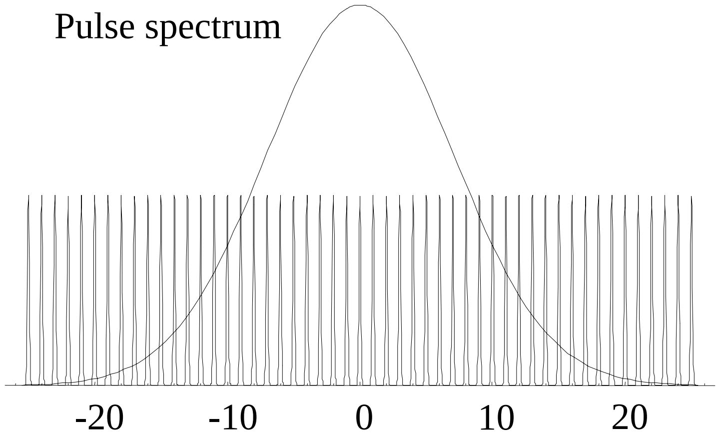


A phase shift between each pulse may appear due to a difference in group velocity and phase velocity. This depends on properties of the optical media etc.

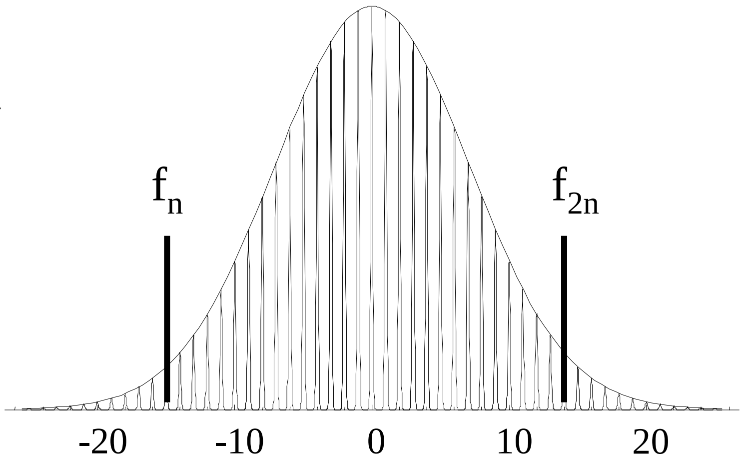
optical media etc.



Spectrum of a laser pulse

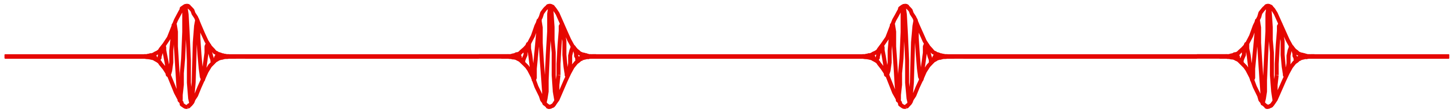


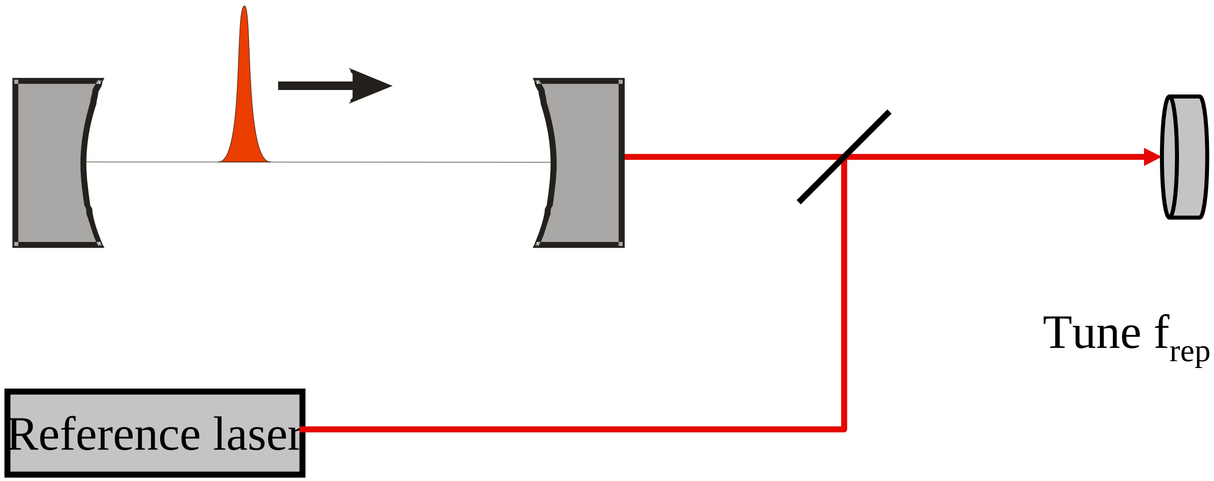
Frequencies supported by the cavity: N f_{rep}



- $f_n = n\, f_{rep} + f_0$, $f_0 = \phi\, f_{rep} / 2\pi$
- $f_{2n} = 2n\, f_{rep} + f_0$
- $2f_n - f_{2n} = 2(n\, f_{rep} + f_0) - 2n\, f_{rep} - f_0 = f_0$

- Tune the laser to remove f_0. **This is done by "self-reference".**
- Removes all dependenices of the laser, and **generates a very uniform frequency comb**.
- Need a full **octave** in the frequency spectrum (non-trivial)





Beat note with frequency similar to f_{rep} can be measured

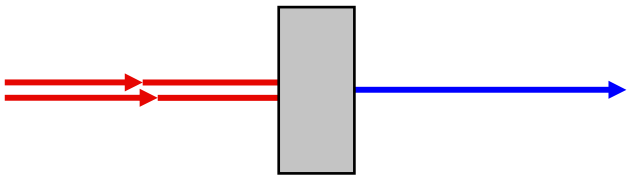
Tune f_{rep} to satisfy: $f_{laser} = N f_{rep}$

N is a rather large number ~10^5

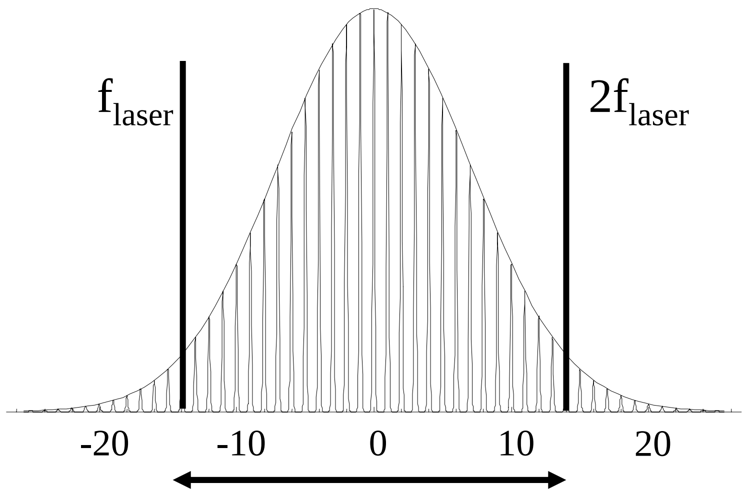
This provides a direct link between the **optical frequency** and a **radio frequency**! Counting of a radio field is simple, and the stability is inherited from the optical clock...

Comparing the spectrum of a reference laser with a frequency comb.

<u>Frequency up-conversion</u>



Convert two red photons into one blue photon. $2f_{red} = f_{blue}$



Count fringes!

f_{laser}=N f_{rep}

Summary

•Precision laser spectroscopy allows us to define optical frequency standards superior to the present Cesium time standard.

•The optical frequency comb allows us to transfer the stability of an optical reference to other frequencies where we can use electronics to handle signals.

•Is it time to redefine the second once more ? Time will tell...