Ultrafast Laser Physics

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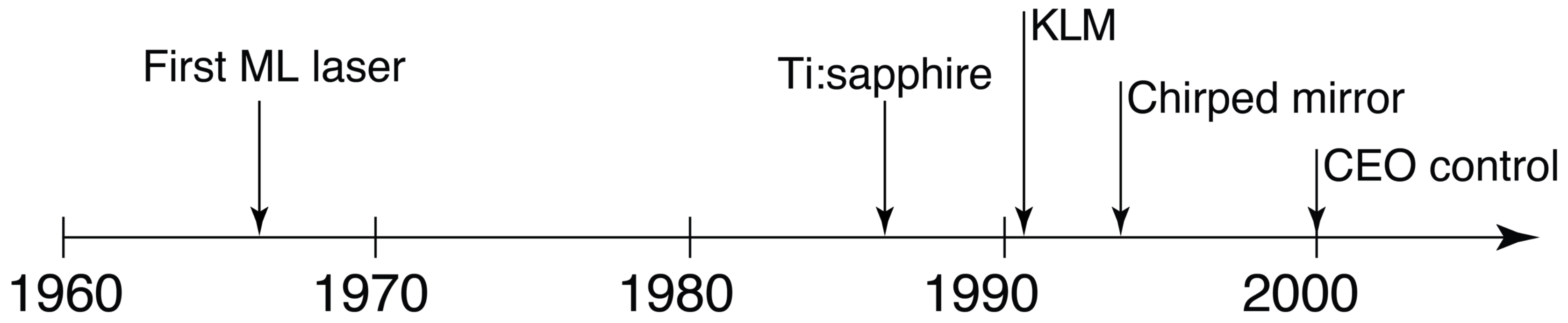
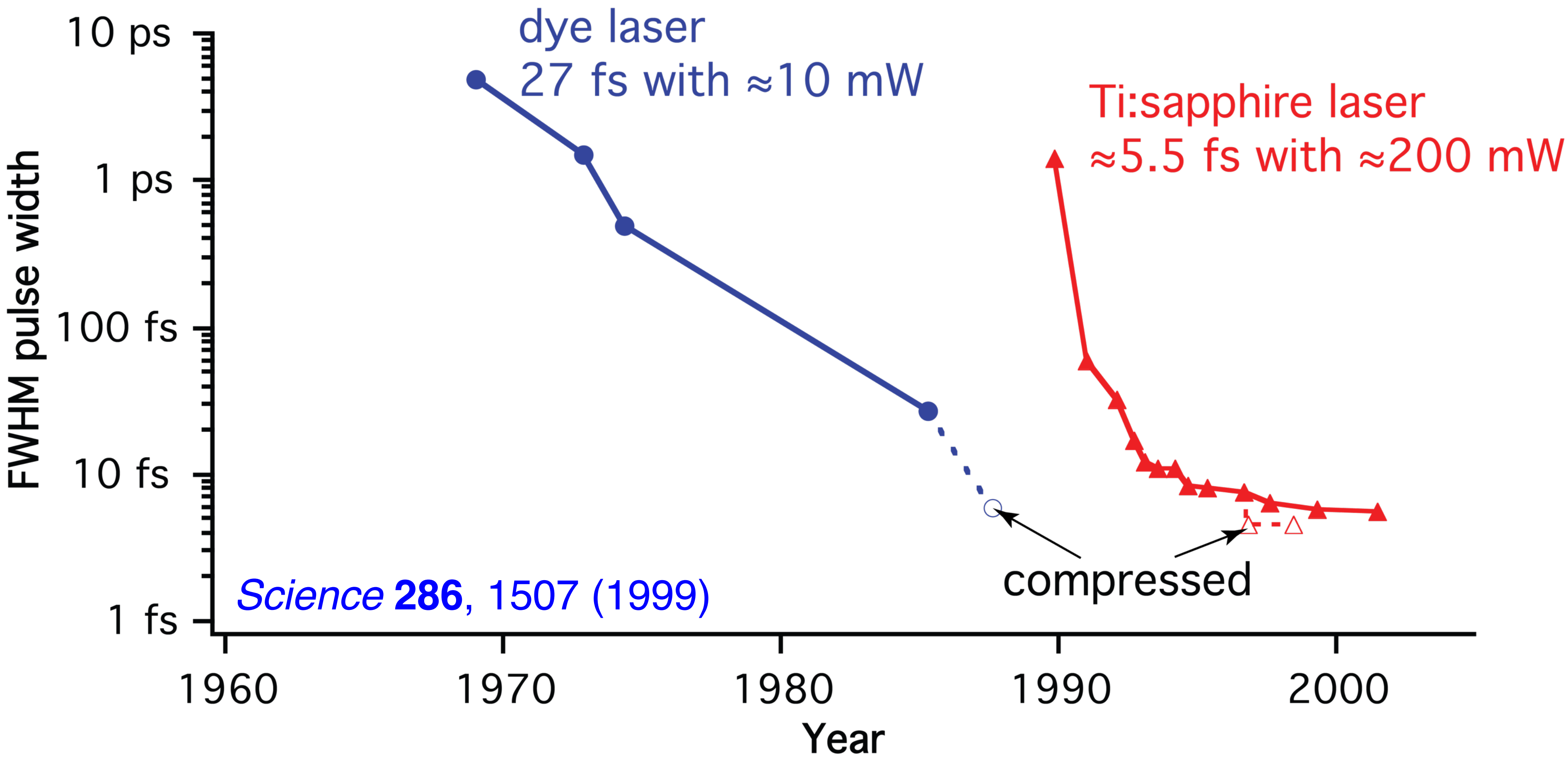
Chapter 11: Frequency comb and carrier envelope offset phase

Frontier: Ultrashort pulse generation



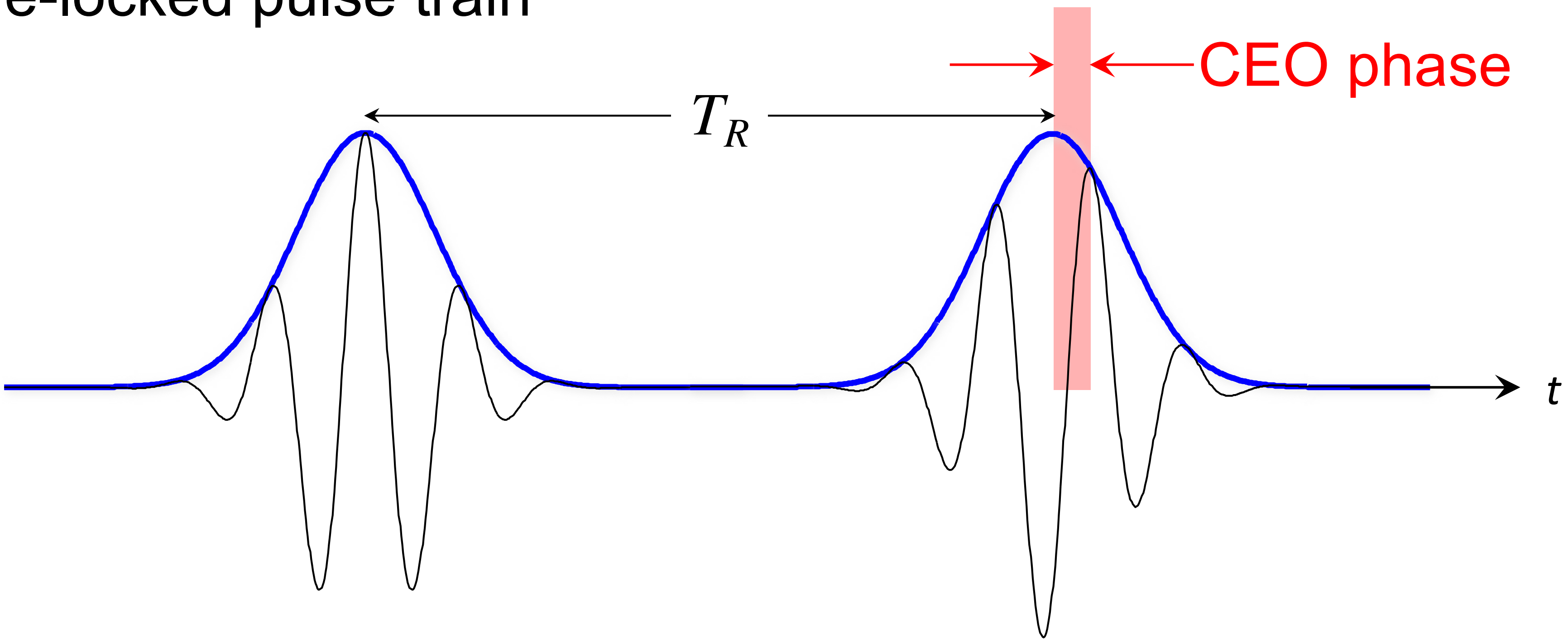


Science **286**, 1507 (1999)

Carrier-Envelope Offset (CEO) Phase

H.R. Telle, G. Steinmeyer, A. E. Dunlop, J. Stenger, D. H. Sutter, U. Keller
Appl. Phys. B **69**, 327 (1999)

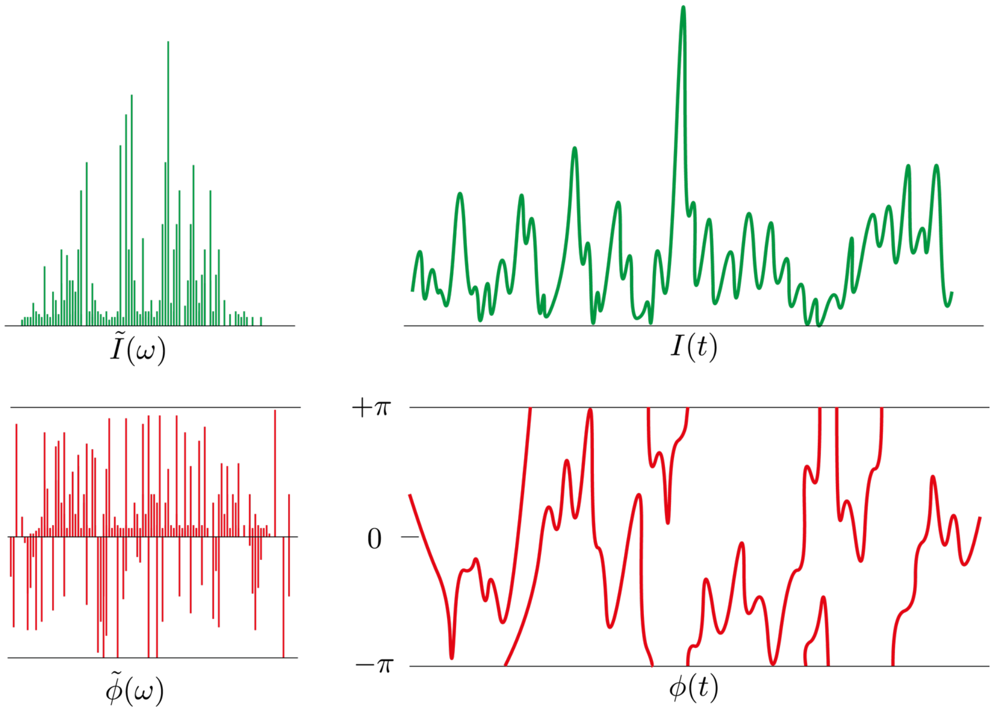
Mode-locked pulse train



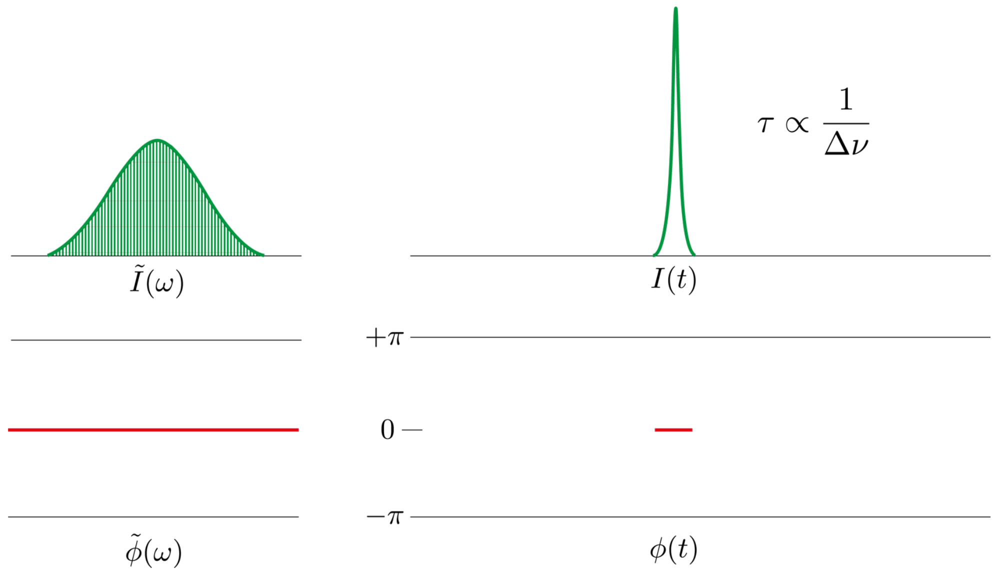
CEO phase controlled
in laser oscillator

Mode locking

by forcing all modes in a laser to operate phase-locked, “noise” is turned into ideal ultrashort pulses



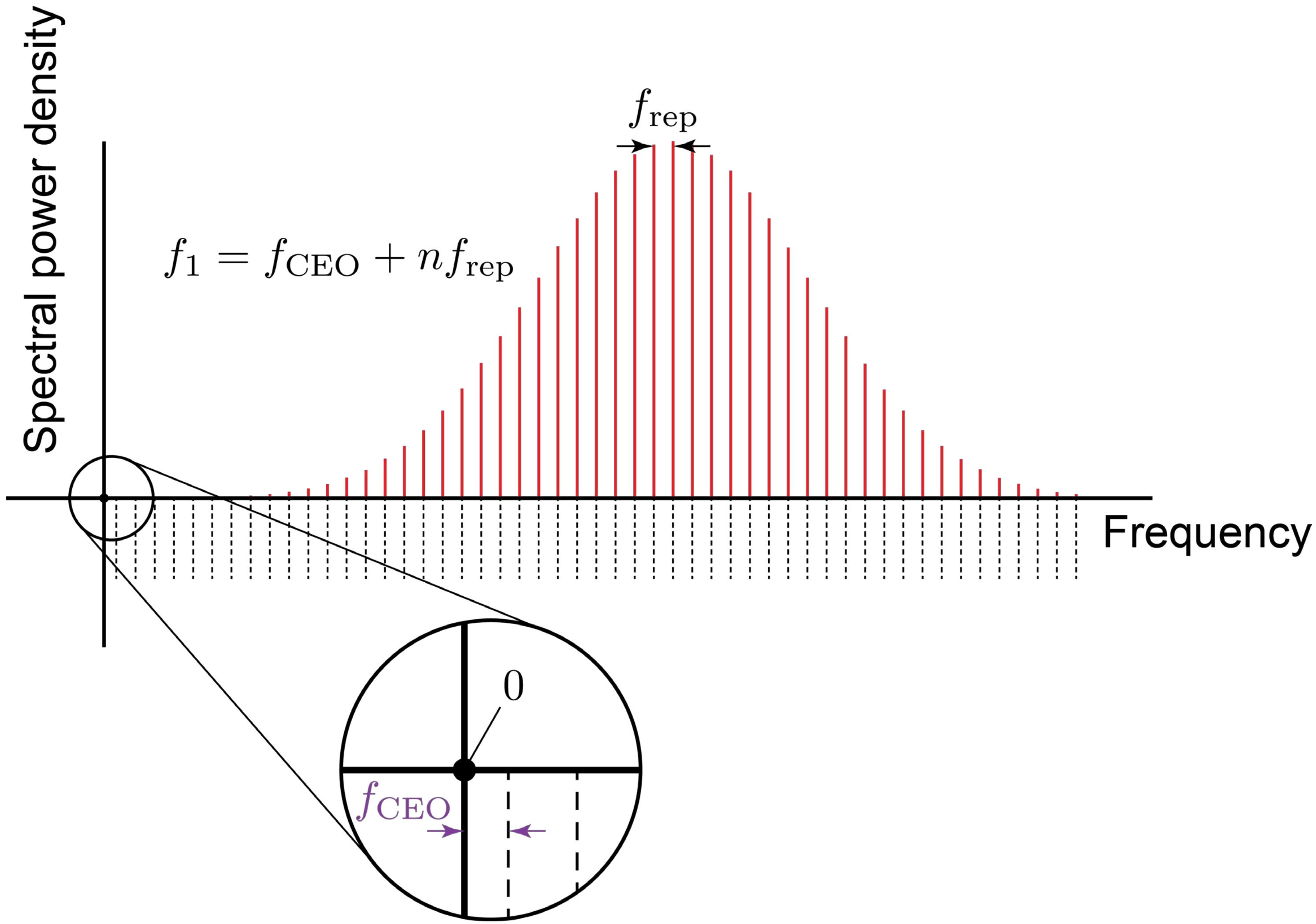
- **axial modes in laser not phase-locked**
- **noise**



- **axial modes in laser phase-locked**
- **ultrashort pulse**
- **inverse proportional to phase-locked spectrum**

How can we stabilize the frequency comb ?

f_{rep} : pulse repetition rate frequency , f_{CEO} : carrier envelope offset frequency



First proposed: H.R. Telle, G. Steinmeyer, A. E. Dunlop, J. Stenger, D. H. Sutter, U. Keller
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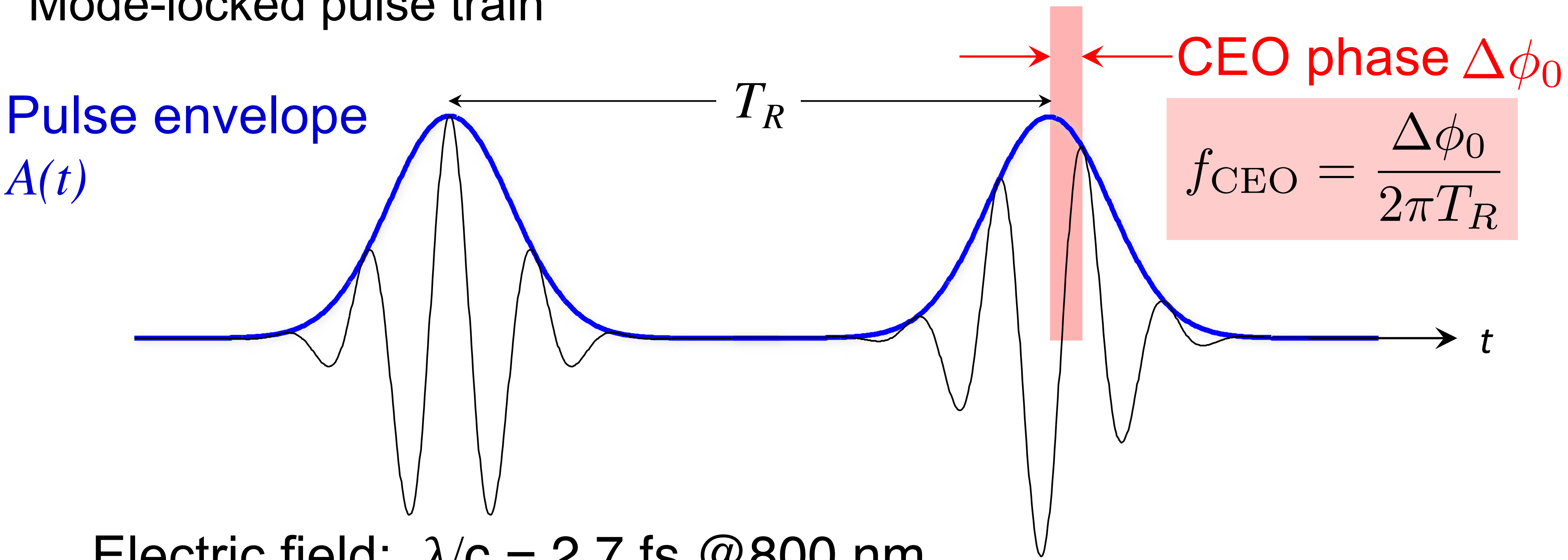
F. W. Helbing, G. Steinmeyer, U. Keller
IEEE J. of Sel. Top. In Quantum Electron. **9**, 1030, 2003

Mode-locked pulse train



$$f_{\mathrm{CEO}} = \frac{\Delta\phi_0}{2\pi T_R}$$

Electric field: λ/c = 2.7 fs @800 nm

$$E(t) = A(t)\exp\left(i\omega_c t + i\varphi_0(t)\right)$$

CEO phase controlled in laser oscillator

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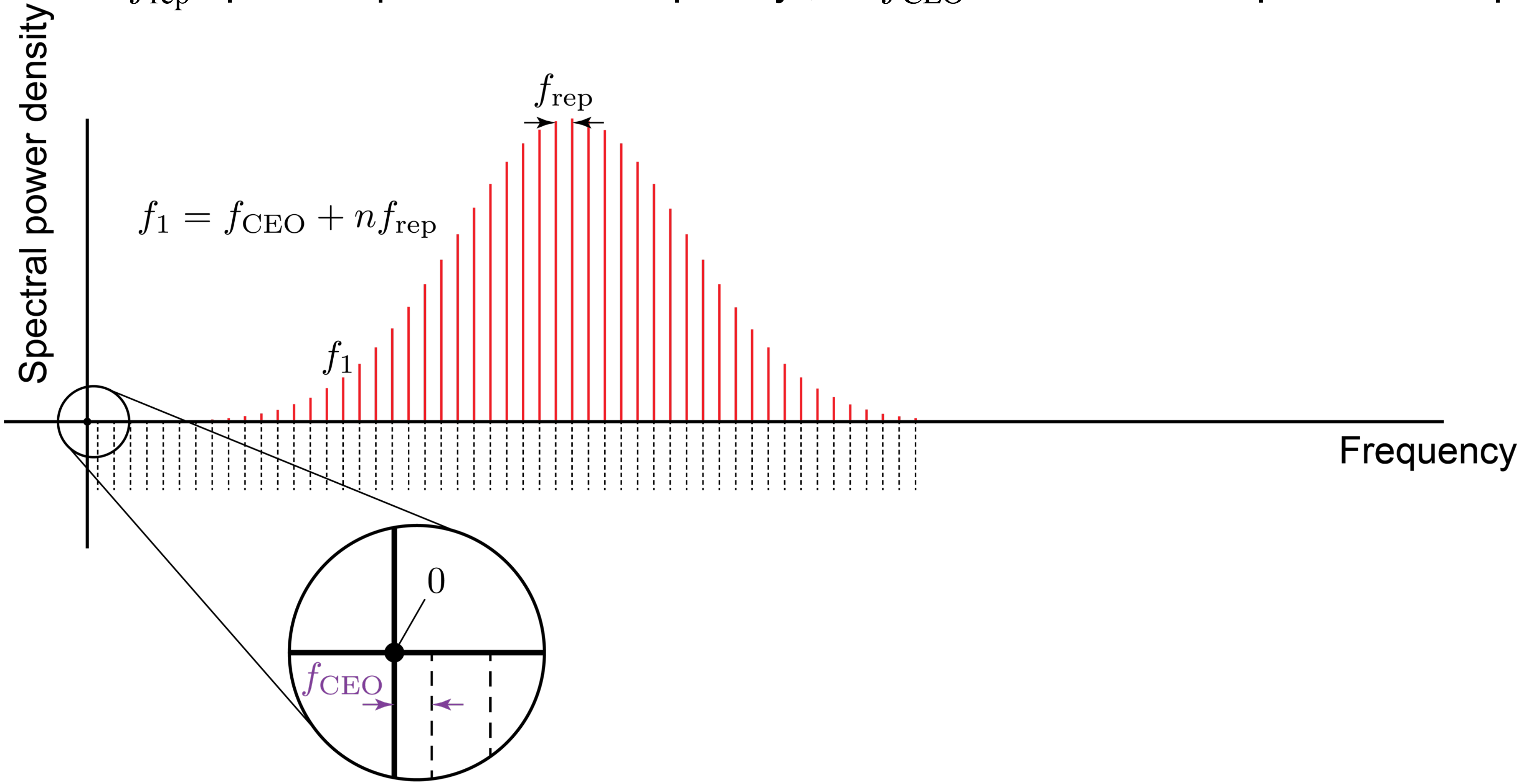

Goal: Mode beating of fundamental and second harmonic frequency comb

f-to-$2f$ interference technique: $f_{\text{CEO}} = 2f_1 - f_2$

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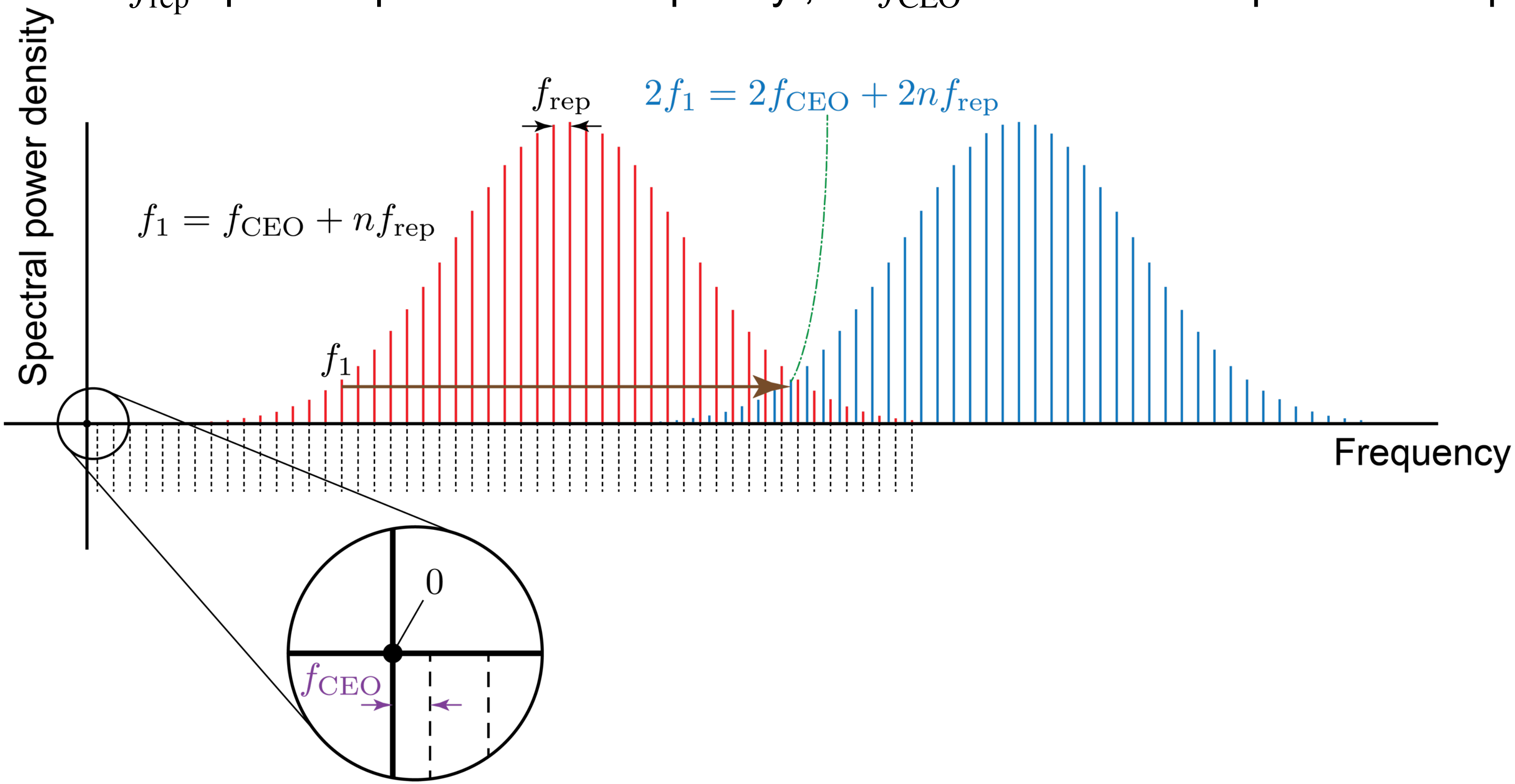

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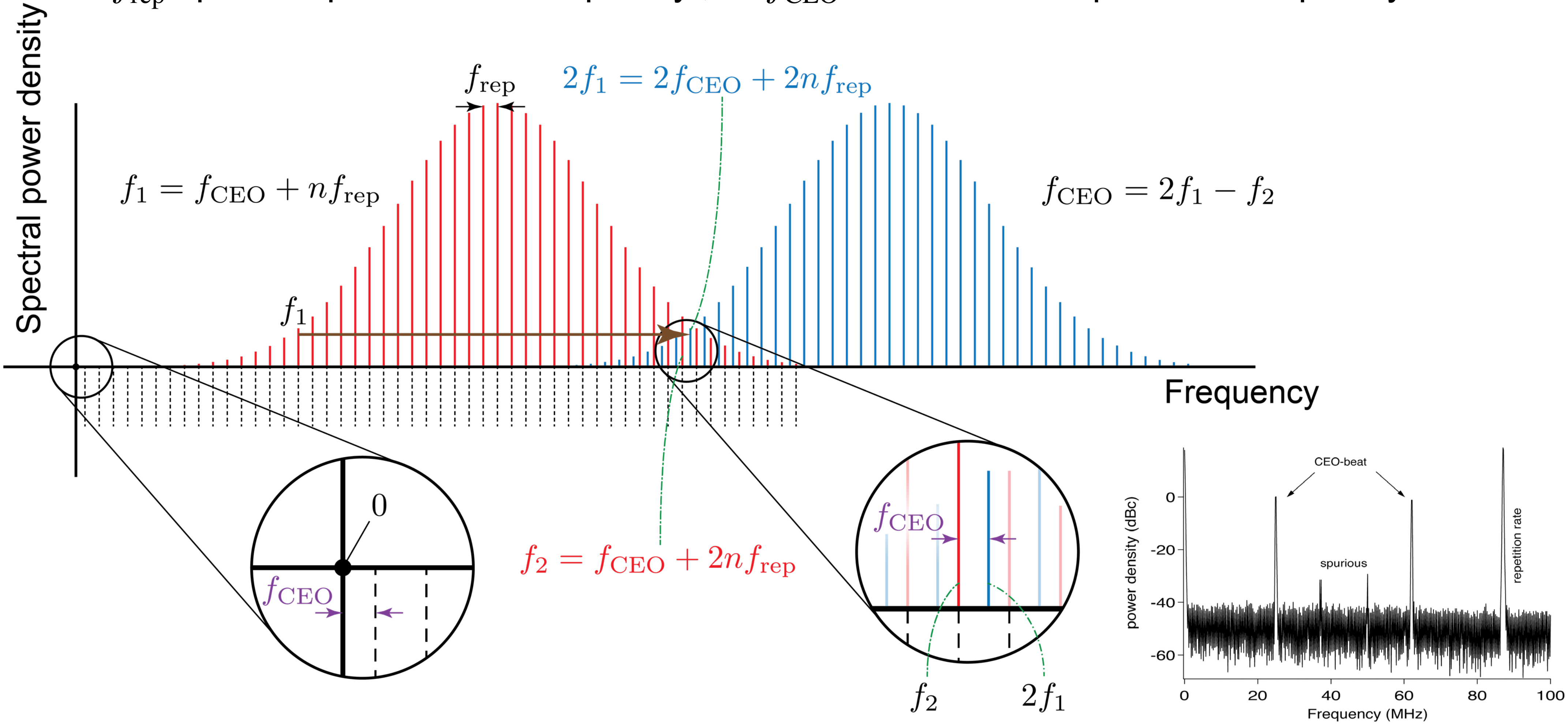

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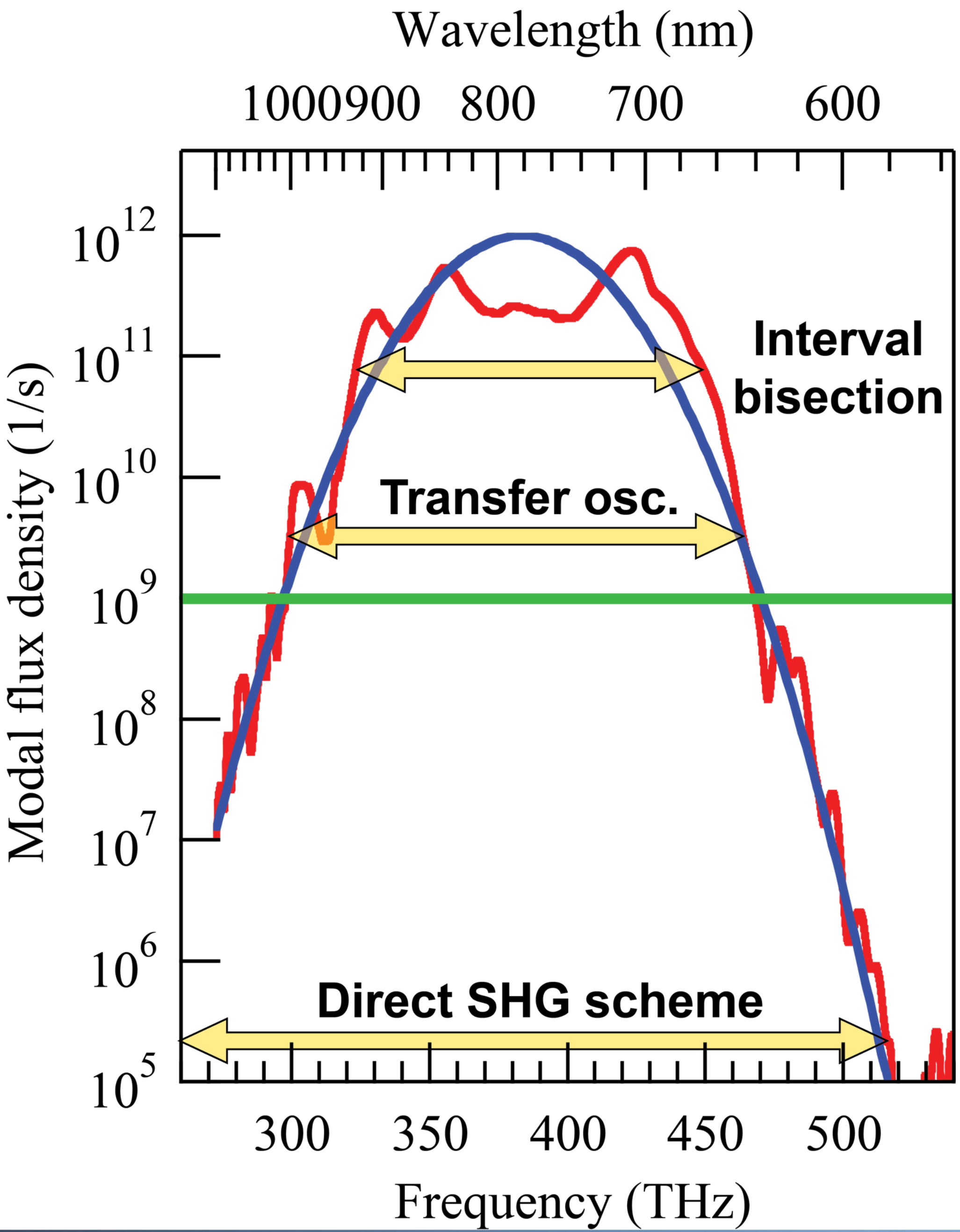
Ti:sapphire laser spectrum



Schemes and feasibilty test to measure and stabilize carrier envelope offset (CEO)

H. R. Telle et al.
Appl. Phys. B 69, 327, 1999

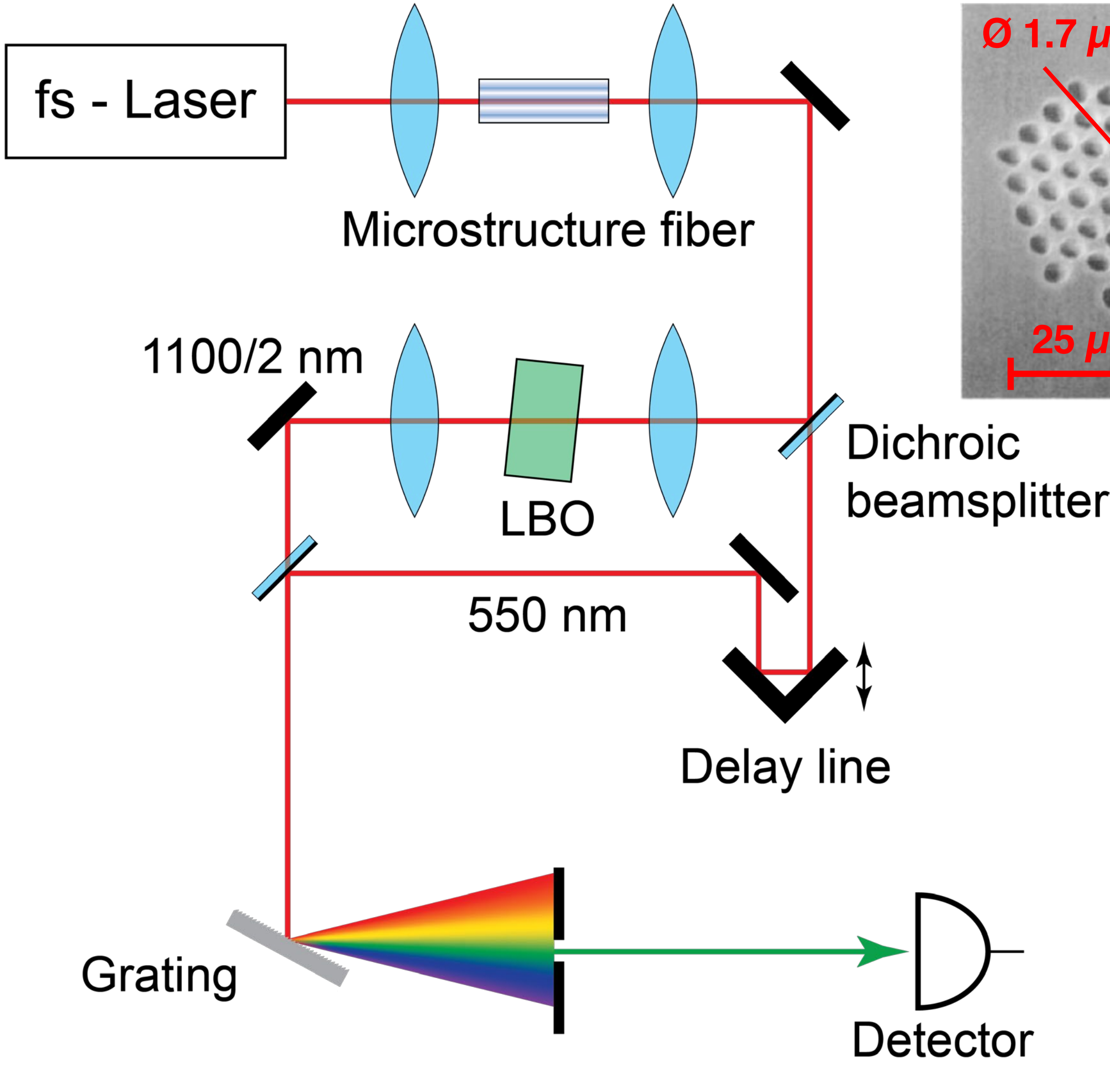
detection limit required to avoid cycle slips

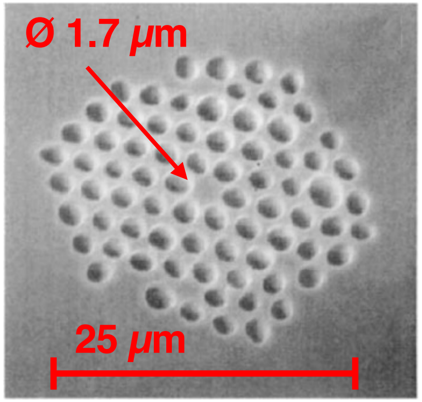
First demonstration using continuum generation

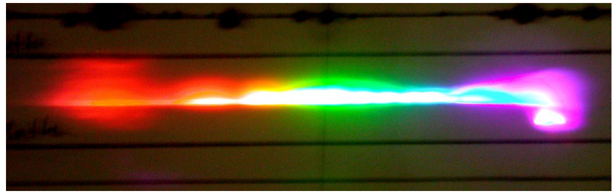
D. J. Jones et al.,
Science 288, 635, 2000 (April)

A. Apolonski et al,
Phys. Rev. Lett. 85, 740, 2000 (July)

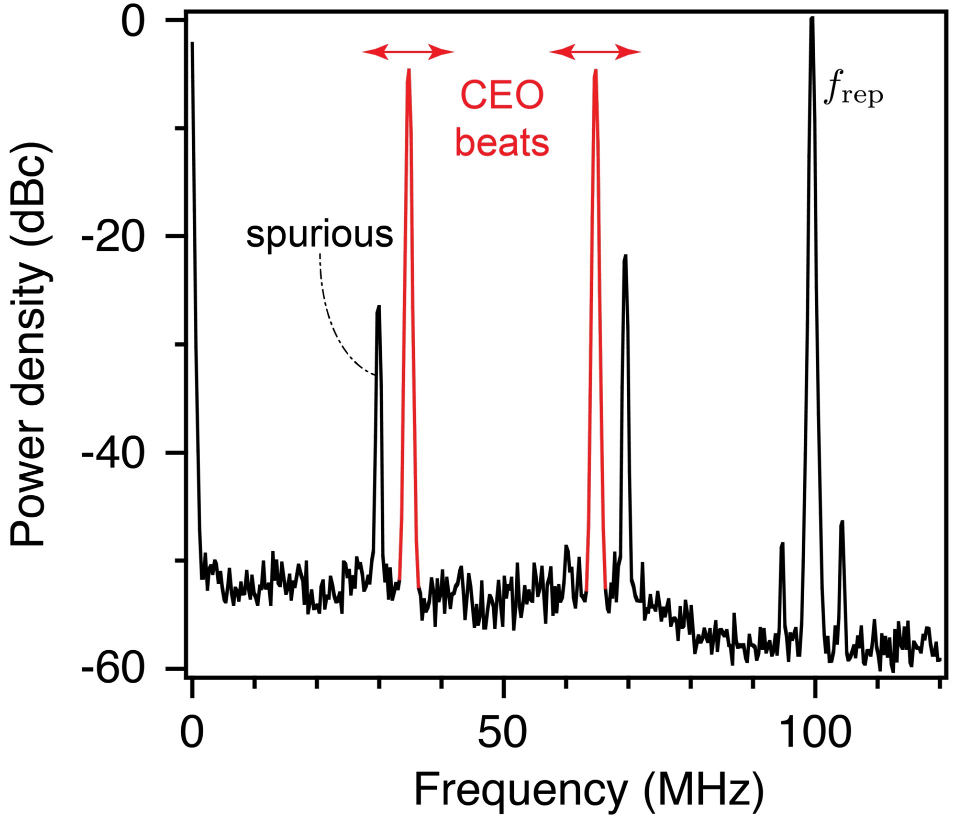
Measurement set-up





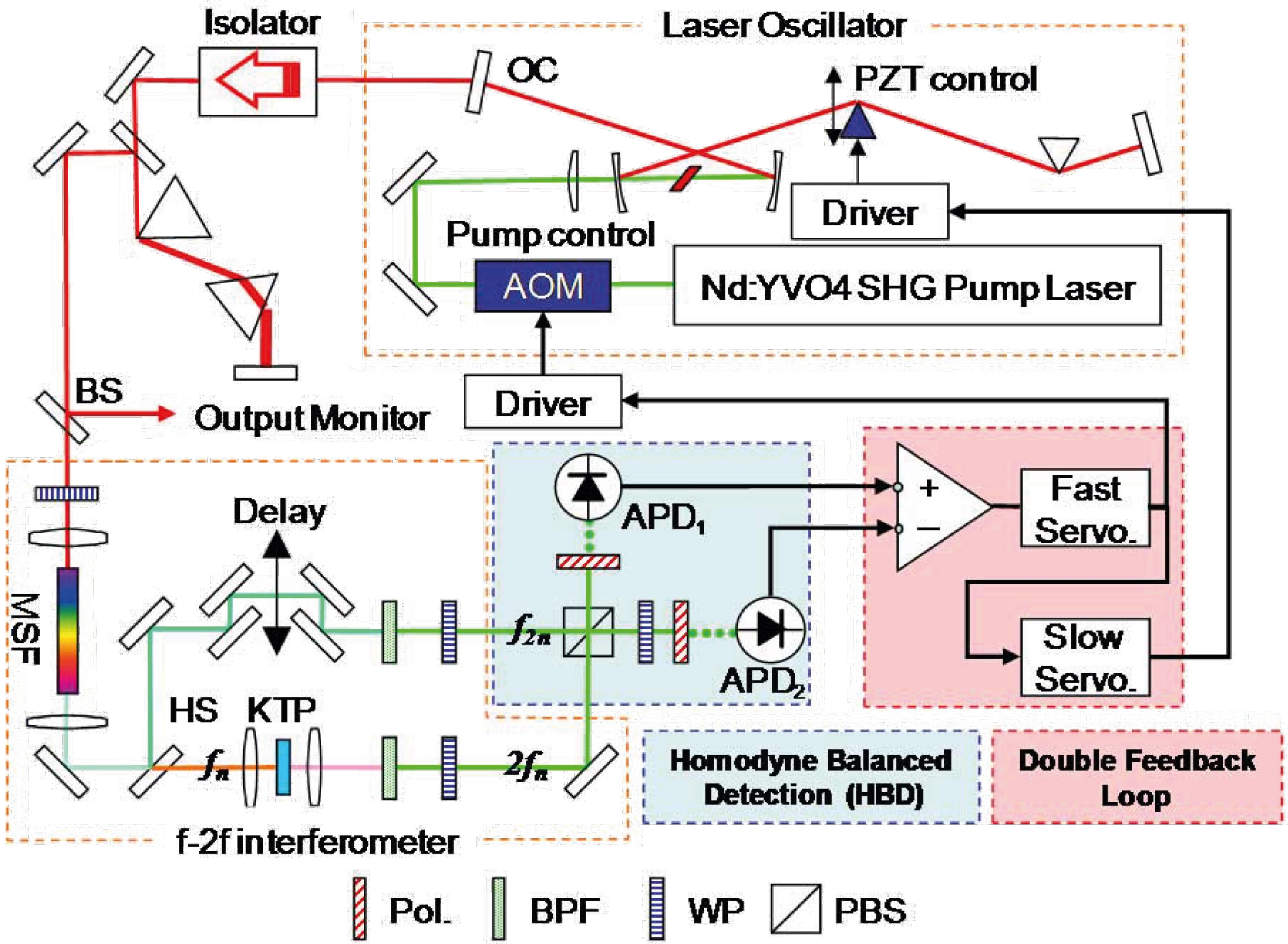


Microstructure fiber:
J. Ranka et al., *Opt. Lett.* **25**, 25 (2000)



First experimental demonstration:
D.J. Jones et al., *Science* **288**, 635 (2000)
A. Apolonski et al., *Phys. Rev. Lett.* **85**, 740 (2000)

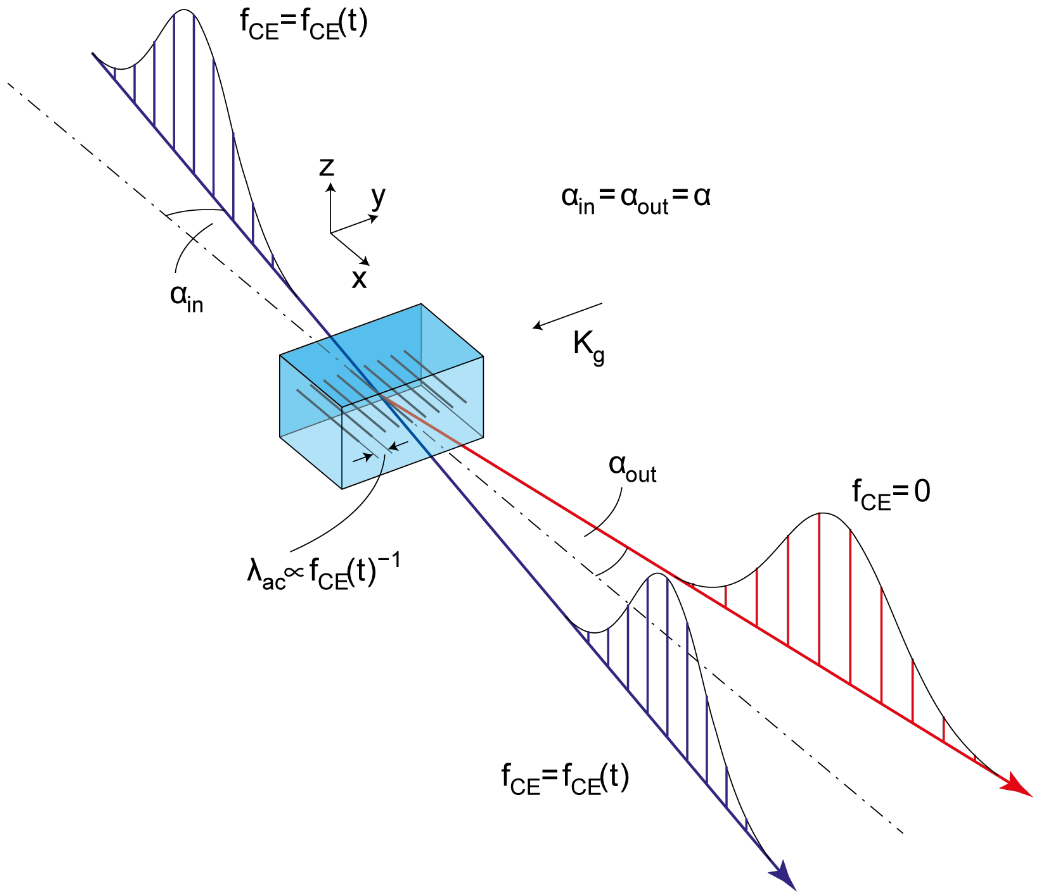
Ti:sapphire oscillator with stabilized CEO-frequency

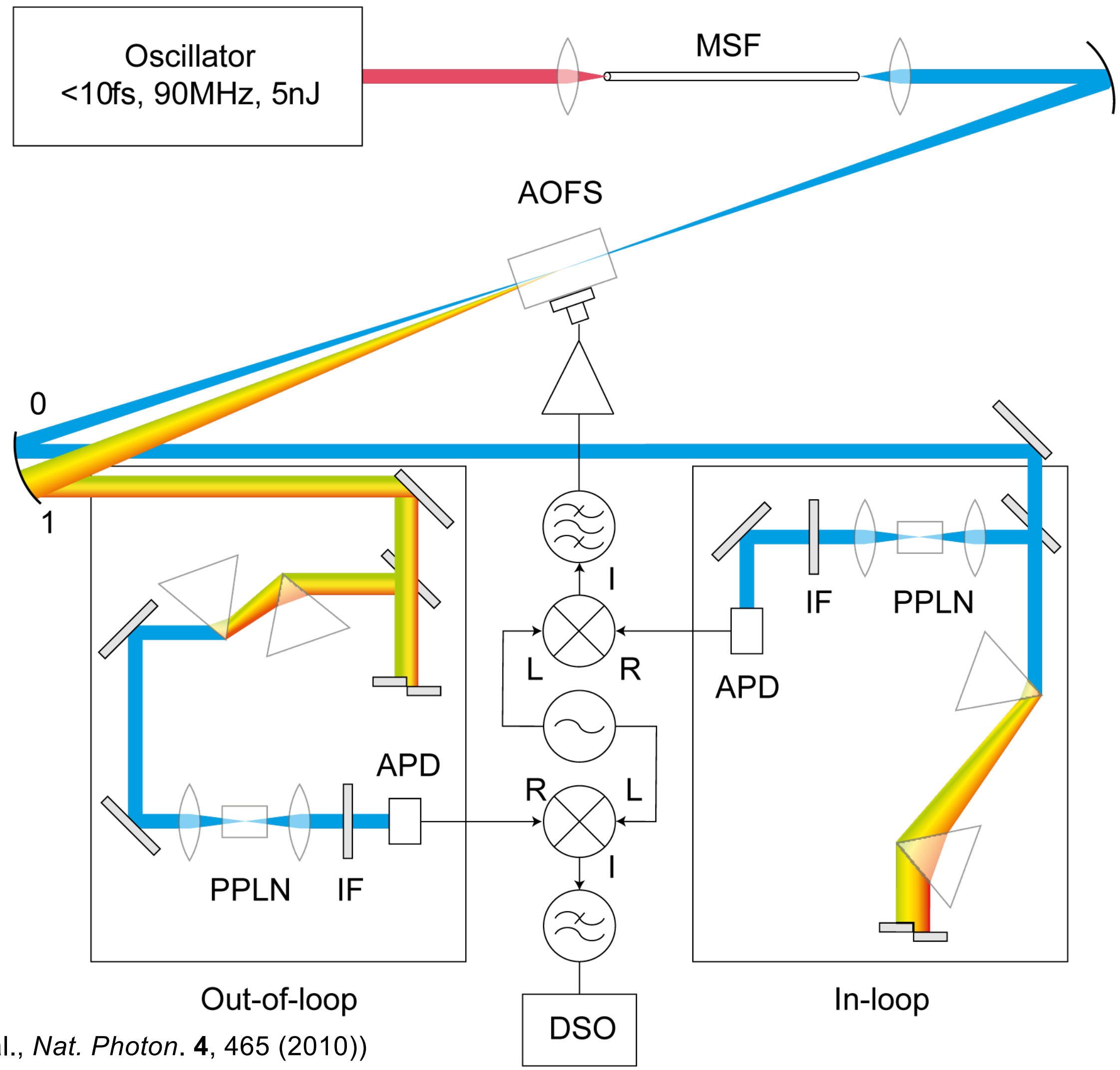


(Implementation example from Yu et al., *Opt. Express* **15** (13), 8203 (2007))

- Group vs. phase velocity balance: fast fine control via pump power (AOM), slow coarse control via prism insertion

Feed-forward scheme for $f_{CEO} = 0$ locking



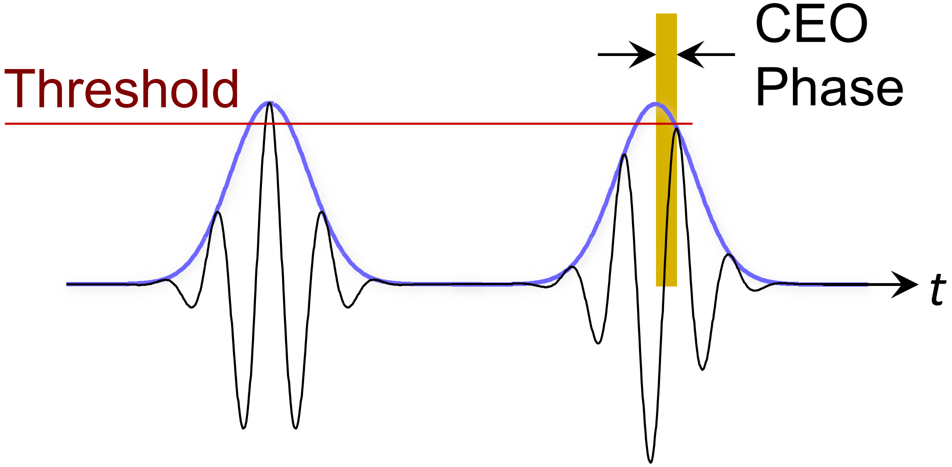


(Figures from Koke et al., *Nat. Photon*. **4**, 465 (2010))

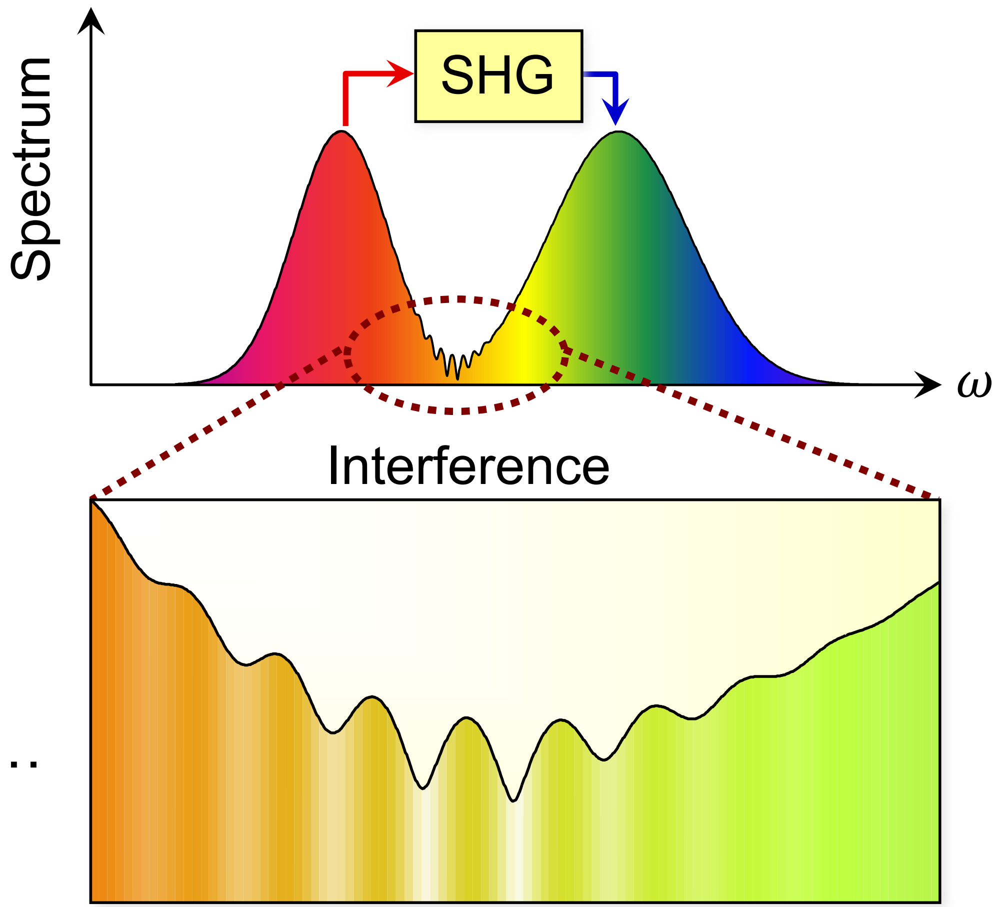
- f-to-2f interferometer measures CEO frequency
- Acousto-optical frequency shifter shifts frequency comb by measured frequency to zero offset

Carrier–Envelope Offset (CEO) Phase

Mode-locked Pulse Train*



Individual Pulses* †



Controlled in Oscillator

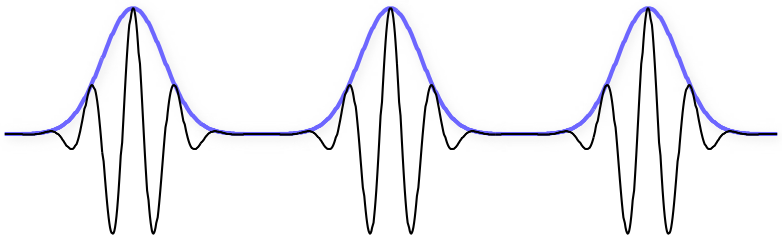
Amplifier

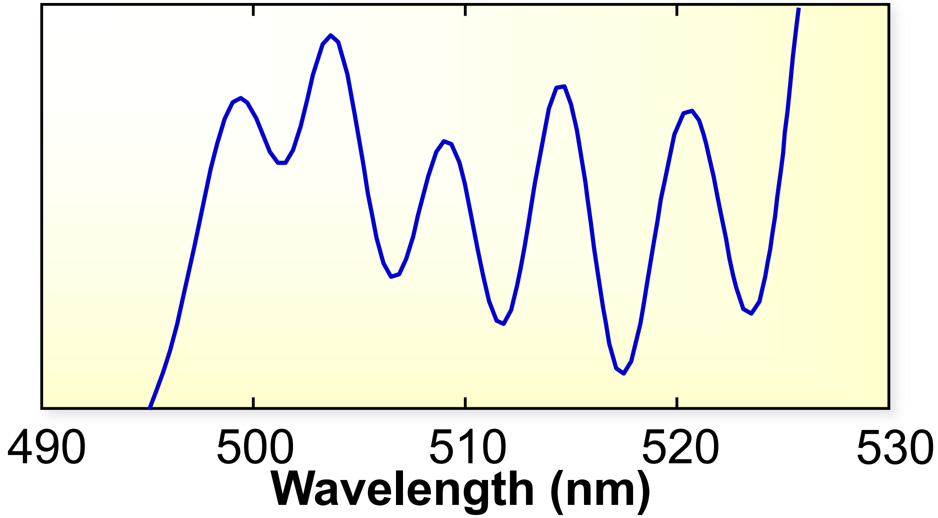
- Preserved by CPA, OPCPA, filament …
- Disturbed by long beam paths

* H.R. Telle *et al*, *Appl. Phys. B* **69**, 327 (1999)
† M. Mehendale *et al*, *Opt. Lett.* **25** 1672 (2000)

CEO Phase Measurement

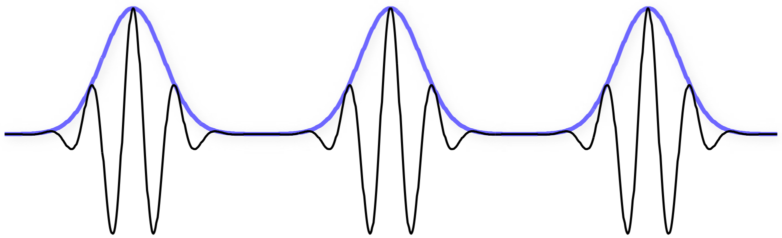
Phase-Stabilized



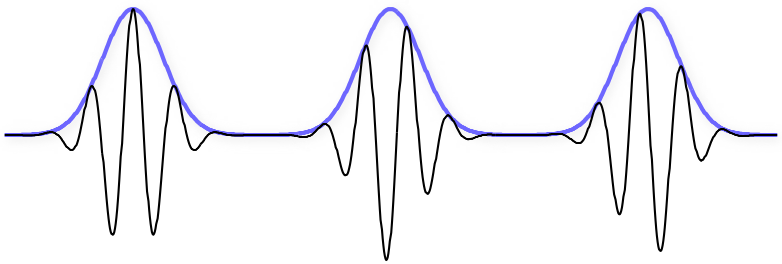


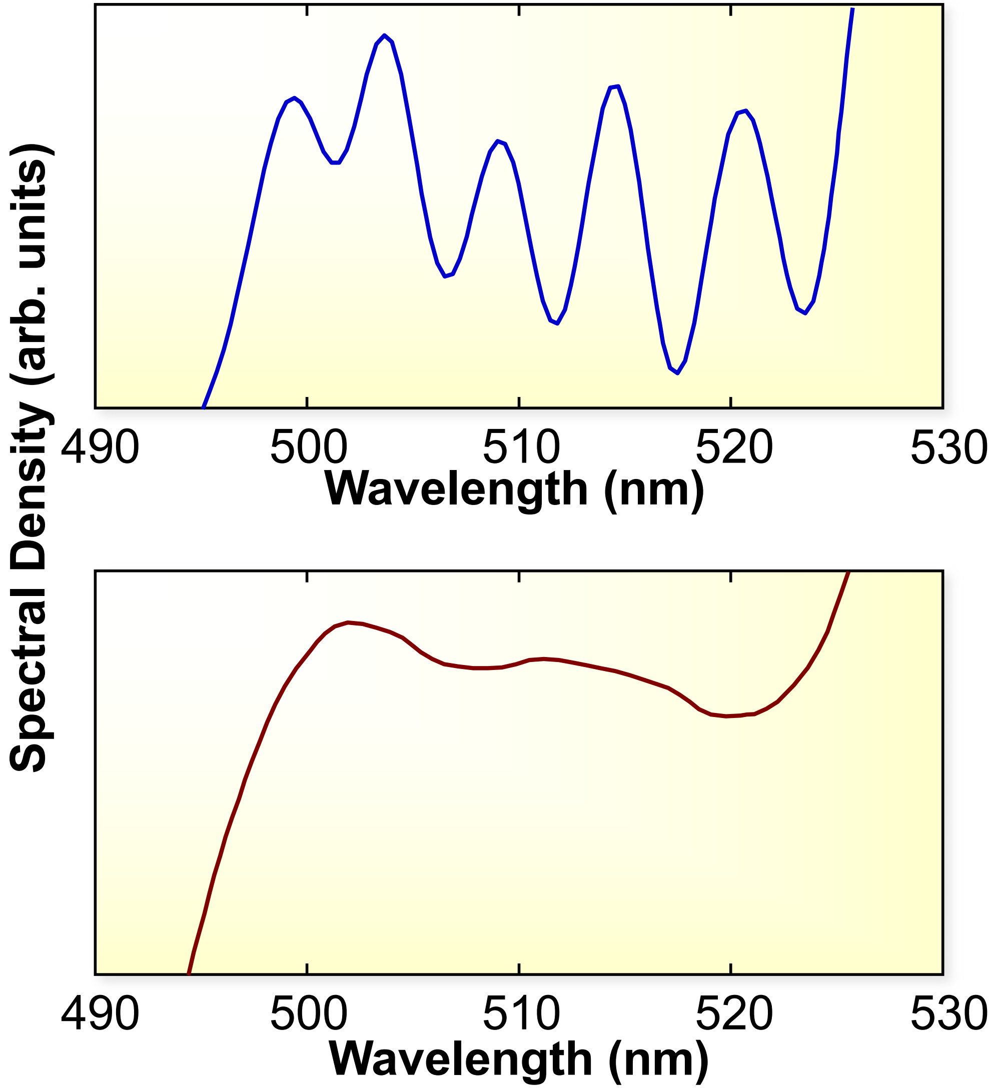
CEO Phase Measurement

Phase-Stabilized

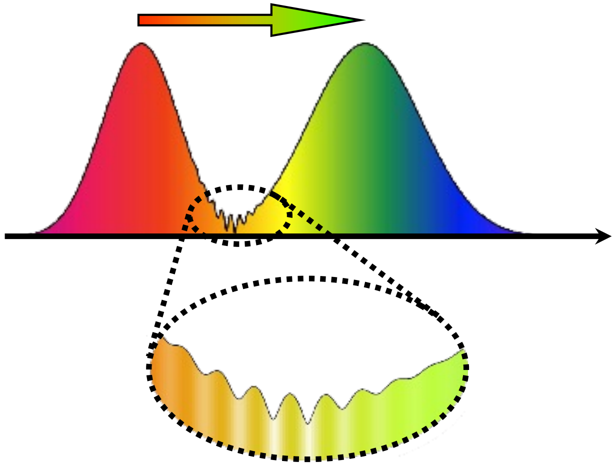


Free-Running

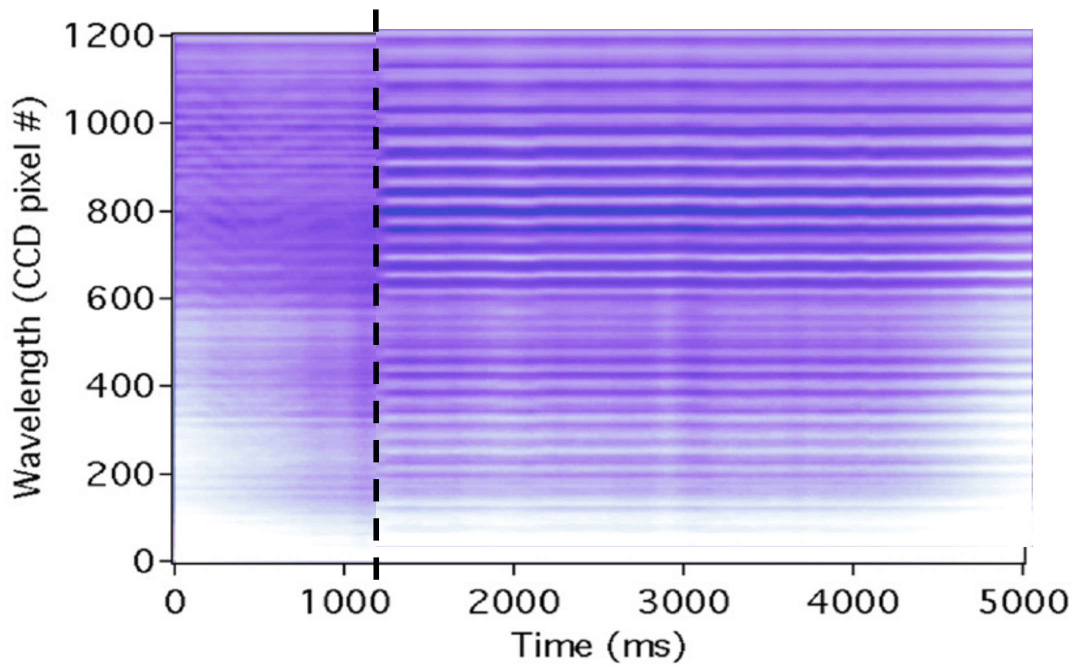


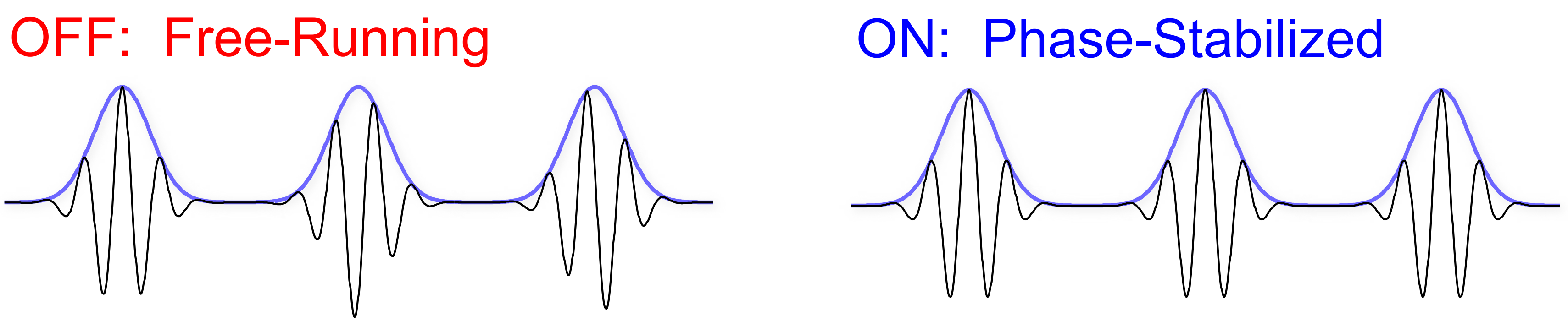


CEO stabilization is maintained!



$$\Delta I(\omega) \propto \cos\left(\theta(\omega)\right) = \cos(\omega\tau + \phi_{\mathrm{CEO}} + \alpha)$$

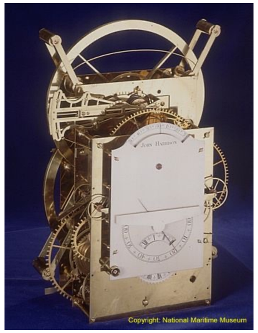
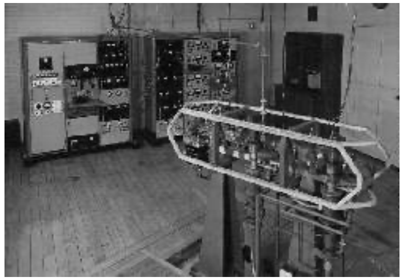
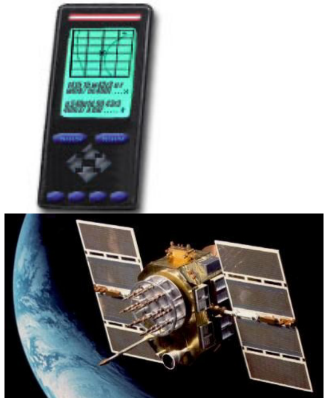




H. R. Telle et al., Appl. Phys. B **69**, 327 (1999)

M. Kakehata et al., Optics Lett. 26, 1436 (2001)

Accuracy of clocks

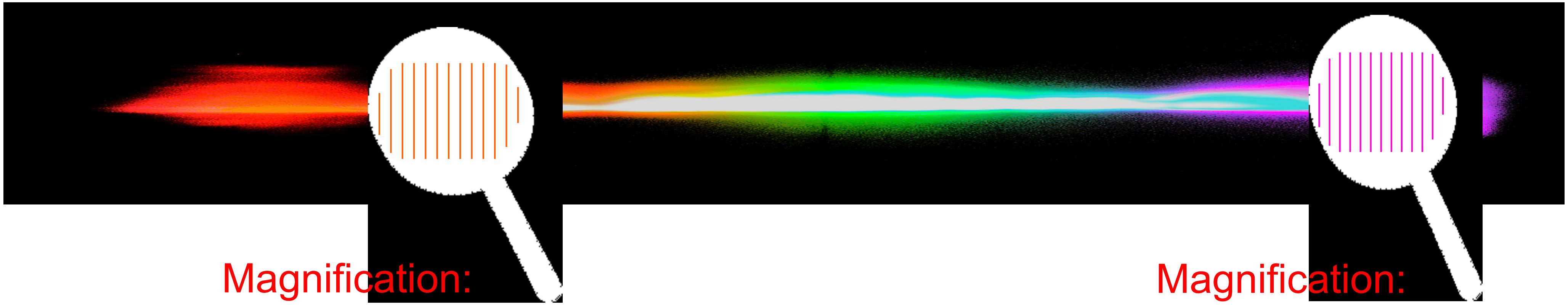
Hour glass	Best mech. clocks	Quartz clock	GPS	Atom clock (ON, PTB,..)
				
	1 min/d	1s/10 yr		1s/1'000'000 yr
10^{-3}	10^{-6}	10^{-9}	10^{-12}	10^{-15}

Oscillation (e.g., pendulum) frequency:

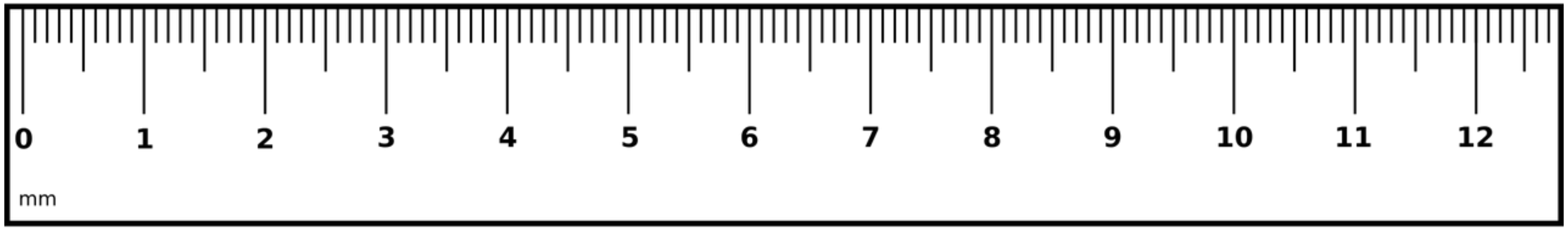
0.001 Hz | **1 Hz** | **10 MHz** | **9 GHz** (for 10^{-12} – 10^{-15})

- **the higher the oscillation frequency, the more accurate the clock can be**
- **optical clocks oscillate 10'000x faster than present atomic (Cs^+) clocks**

Femtosecond lasers as clockworks

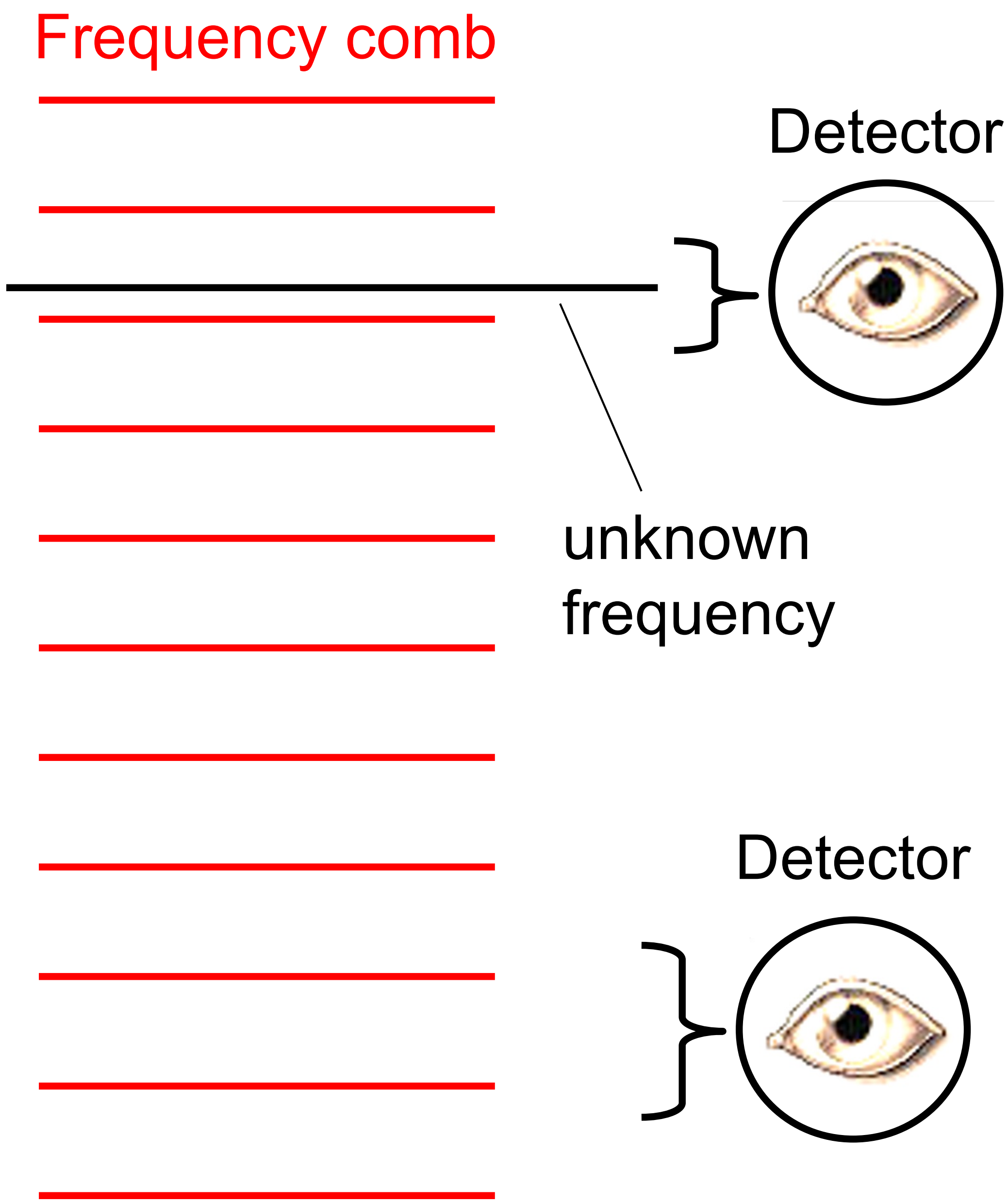


- **Spectrum of a femtosecond laser pulse consists of millions of sharp lines**
- **These lines are aequidistant across the entire spectrum**
- **A femtosecond laser is a „ruler" for frequencies !**



The frequency ruler is extremely accurate
T. Udem, R. Holzwarth, T. W. Hänsch, *Nature* **416**, 233 (2002)

How to measure time with femtosecond laser

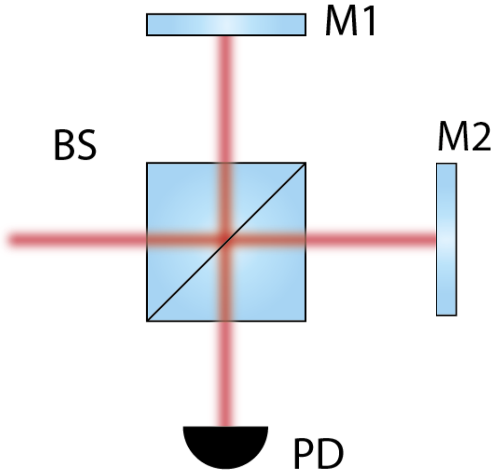


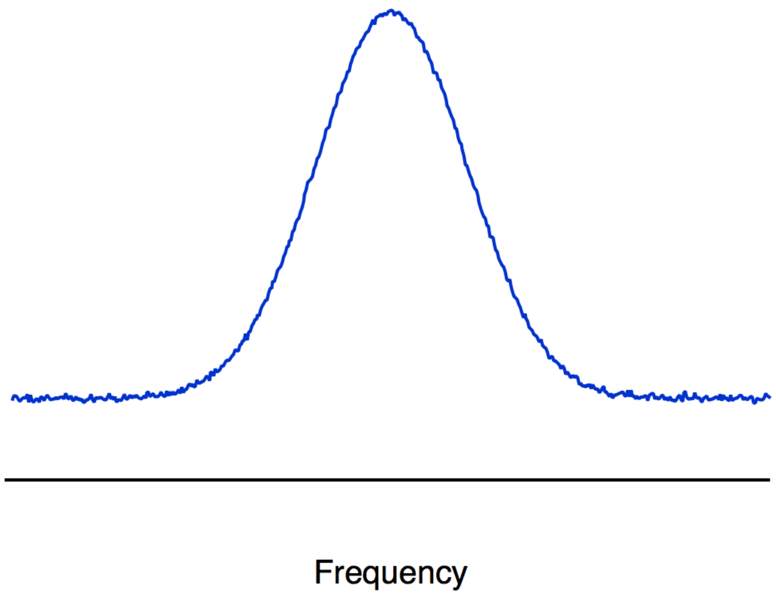
- measuring time means counting the tick-tocks of the “pendulum”
- optical frequencies are too fast to be counted directly
- thus, detector measures beating between two nearby frequencies
- measure distance between comb lines
- measure distance between unknown frequency and neighboring comb line
- read frequency ruler (count number of comb lines)
- optical gear box or clockwork
- optical frequency becomes countable

Conventional Fourier-transform spectroscopy

Conventional FT spectroscopy

- Michelson type interferometer
- Scan with moving mirror
- Collect interferogram
- Fourier transform to frequency domain



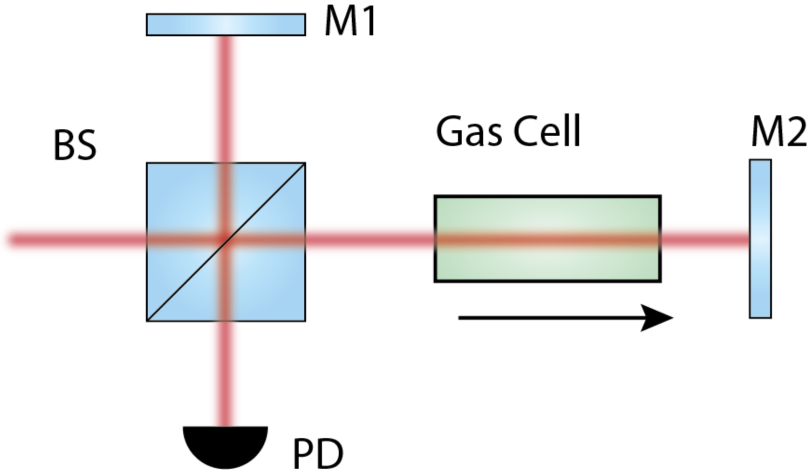


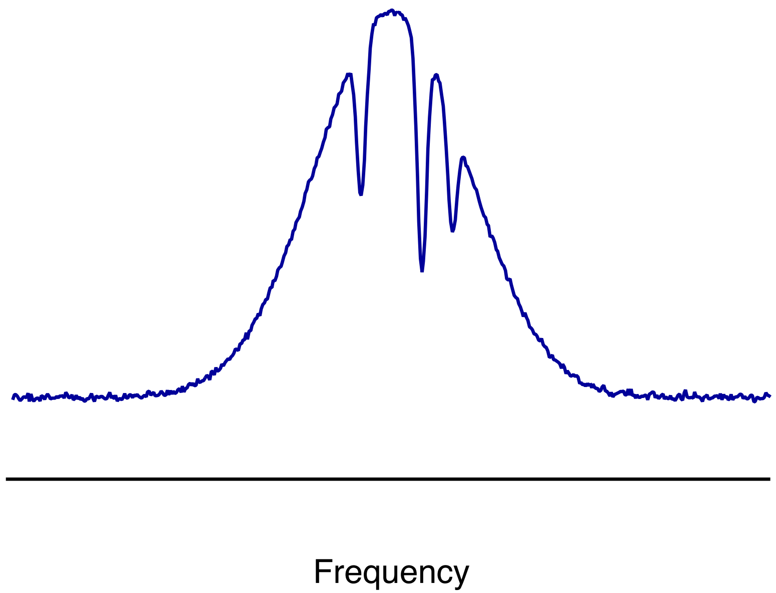
Displacement

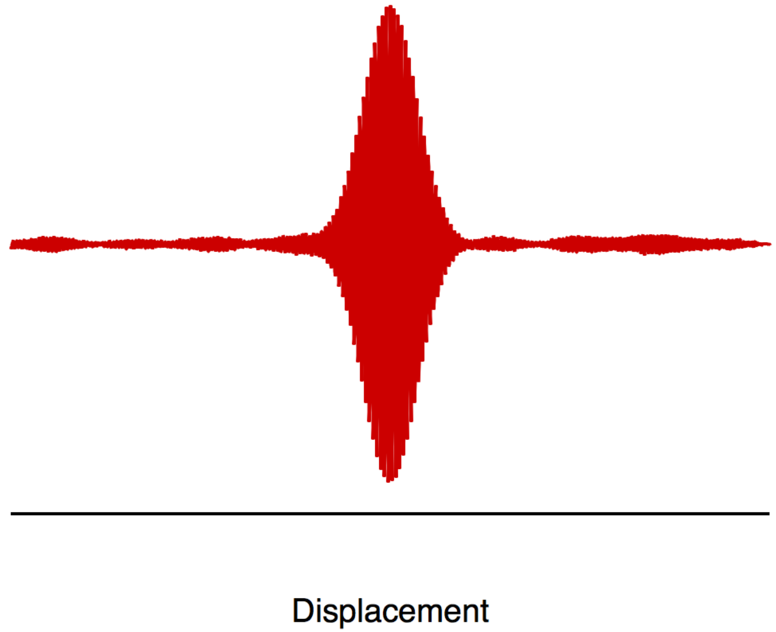
Conventional Fourier-transform spectroscopy

Conventional FT spectroscopy

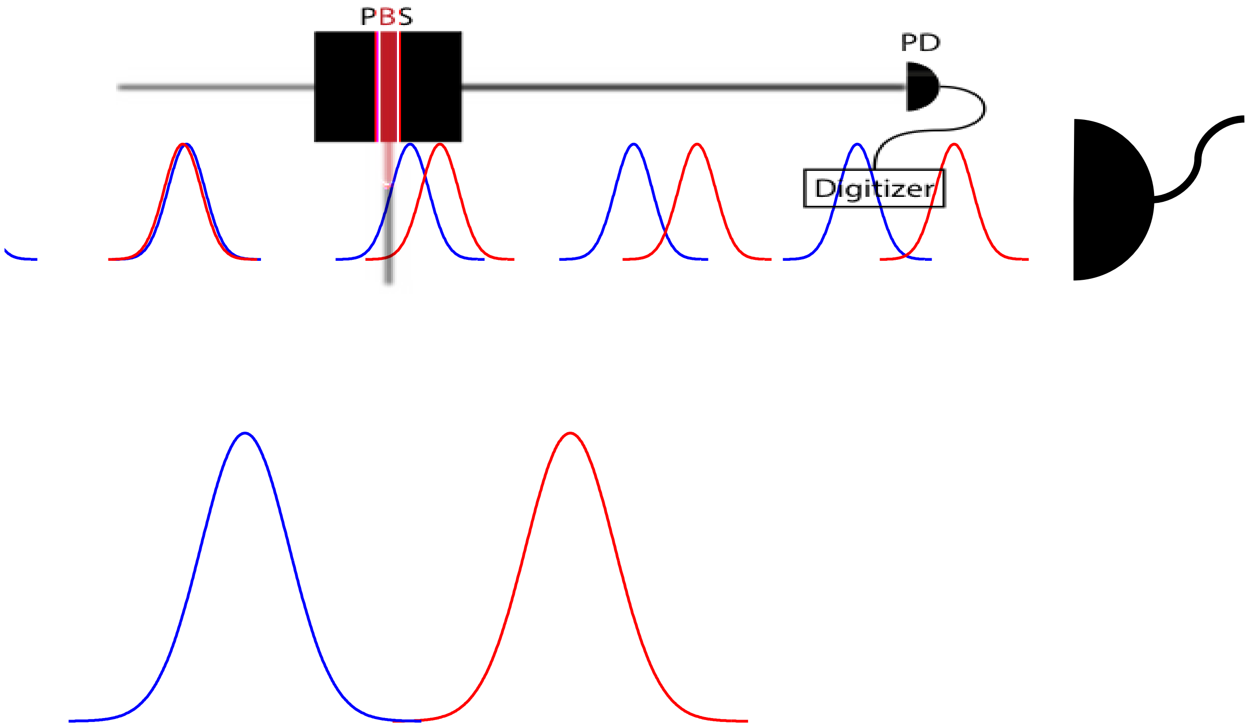
- Michelson type interferometer
- Scan with moving mirror
- Collect interferogram
- Fourier transform to frequency domain







Dual-comb spectroscopy



Dual-comb spectroscopy

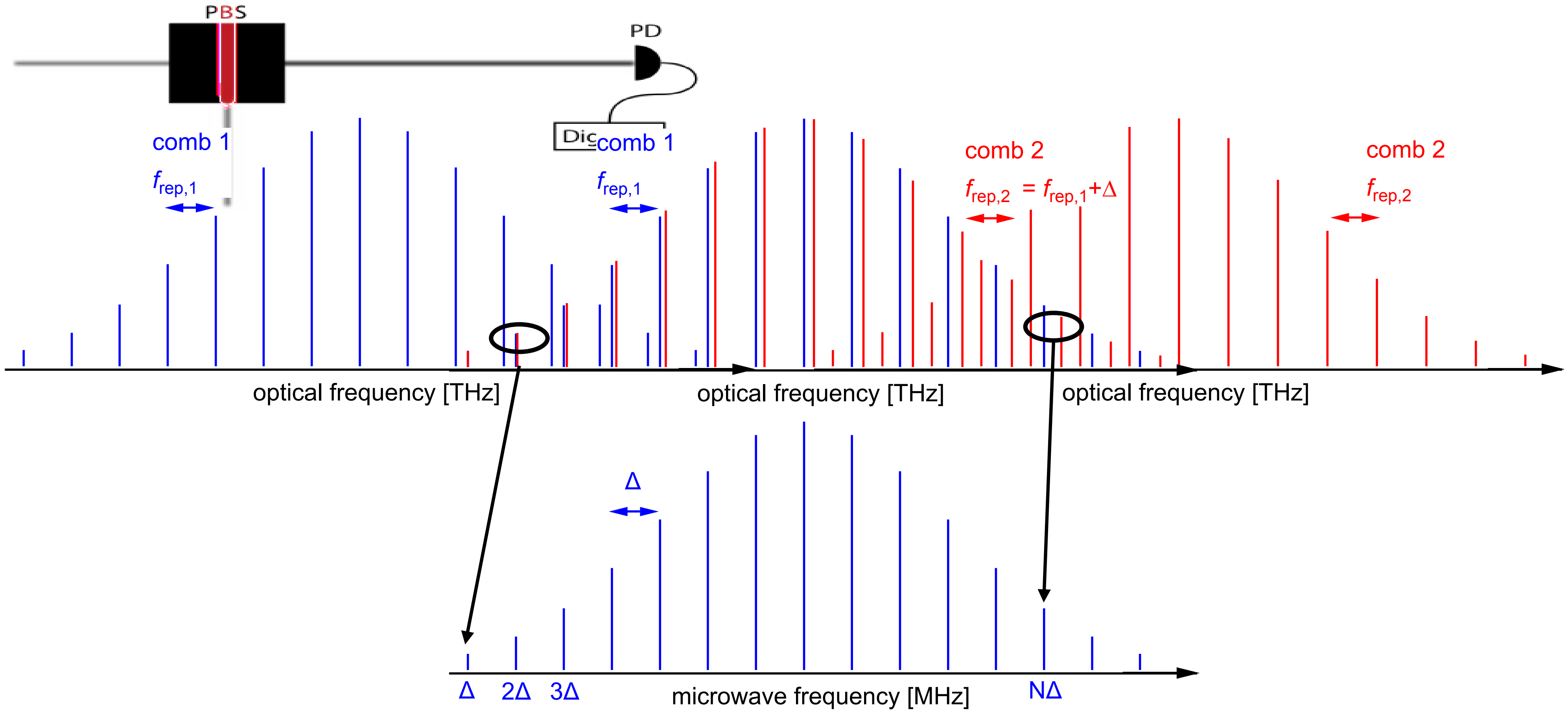
- Two pulse trains with different repetition rates
- One pulse scans the other
- Collect interferogram
- Fourier Transform

Time

[1] S. Schiller, Opt. Lett. **27**, 766 (2002).
[2] I. Coddington, N. R. Newbury, and W. Swann, Optica **3**, 414 (2016).

Dual-comb spectroscopy

- Combine two optical frequency combs
- Intensity beat on photodetector
- Down-conversion to radio frequencies (RF)



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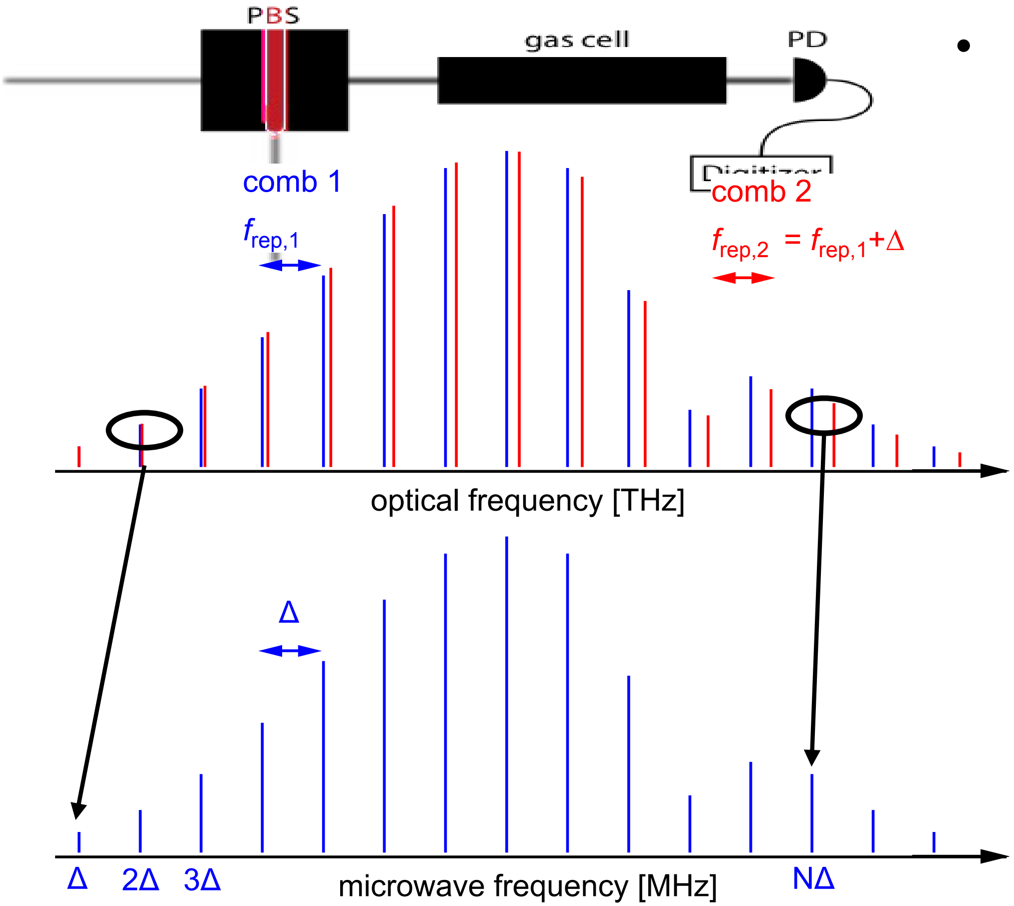


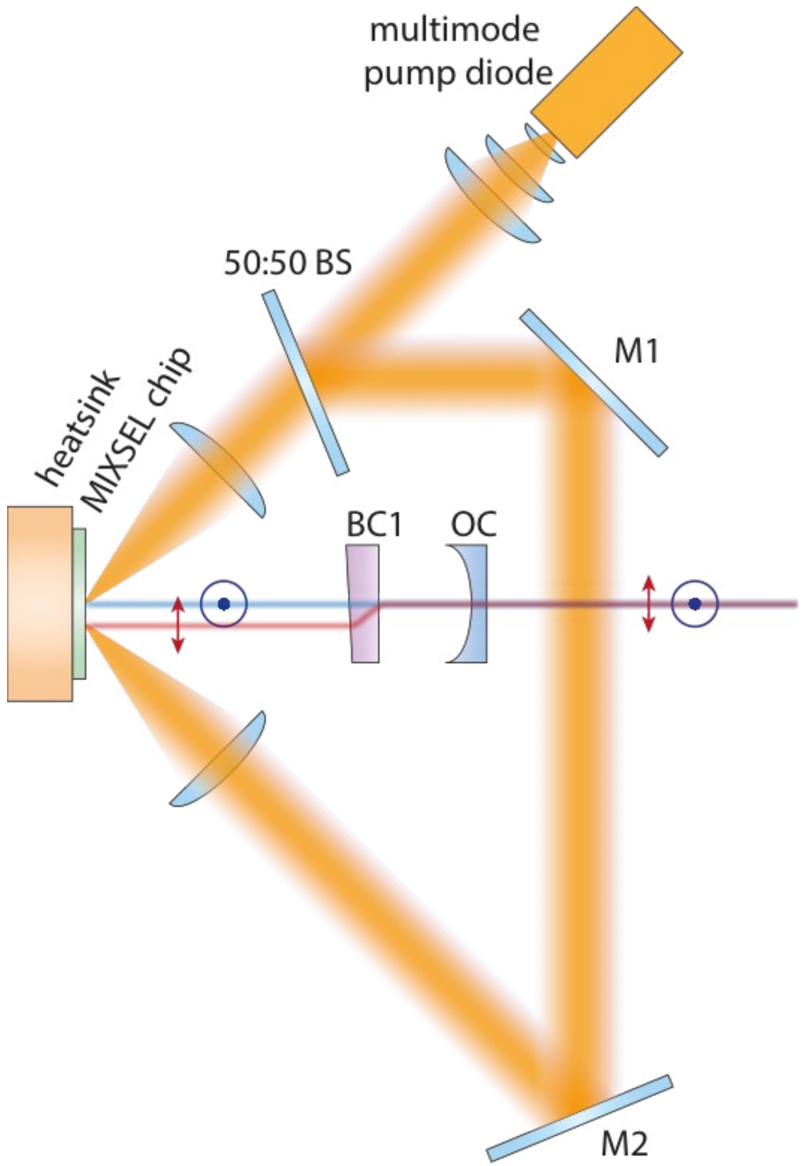
- Combine two optical frequency combs
- Intensity beat on photodetector
- Down-conversion to radio frequencies (RF)
- Absorption mapped to RF-domain

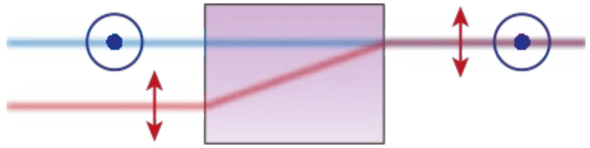
\+ very fast acquisition
\+ high precision
\- two frequency combs: complex & expensive

Dual-comb SDLs
- **Versatile**
- **Cost efficient**
- **Compact**

[1] S. Schiller, Opt. Lett. **27**, 766 (2002).
[2] I. Coddington, N. R. Newbury, and W. Swann, Optica **3**, 414 (2016).

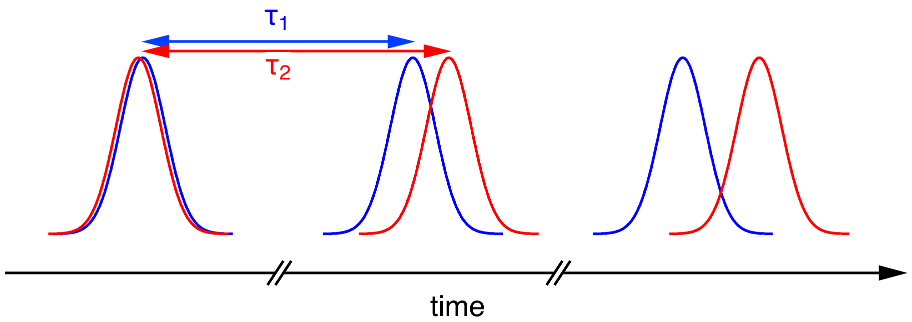
Dual-comb MIXSEL (semiconductor disk laser)

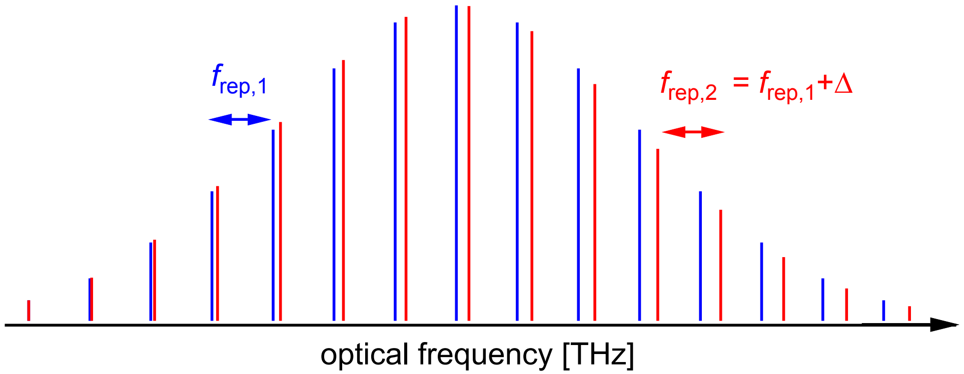




Intracavity birefringent crystal (BC)

- Two spatially separated beams
- Orthogonal polarizations
- Different optical path length





[1] S. M. Link, A. Klenner, M. Mangold, C. A. Zaugg, M. Golling, B. W. Tilma, and U. Keller, Opt. Express **23**, 5521 (2015).
[2] S. M. Link, D. J. H. C. Maas, D. Waldburger, and U. Keller, Science **356**, 1164 (2017).