# Towards Attosecond Synchronization in Ultrafast Light Sources

Russell Wilcox, Gang Huang, Lawrence Doolittle, John Byrd,
Klaus Hartinger, Ronald Holzwarth

NAPAC, Chicago

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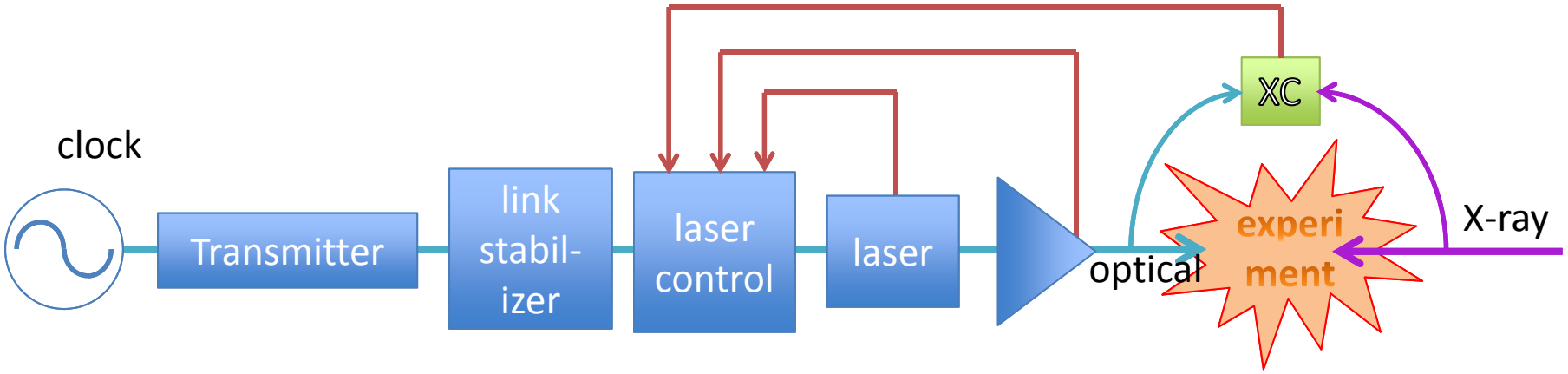
# Outline

- Locking lasers to transmitted EM wave phase
- GHz modulated optical signal
- Synthesized THz modulation
- THz bandwidth pulse modulation
- 200THz optical carrier
- Conclusions

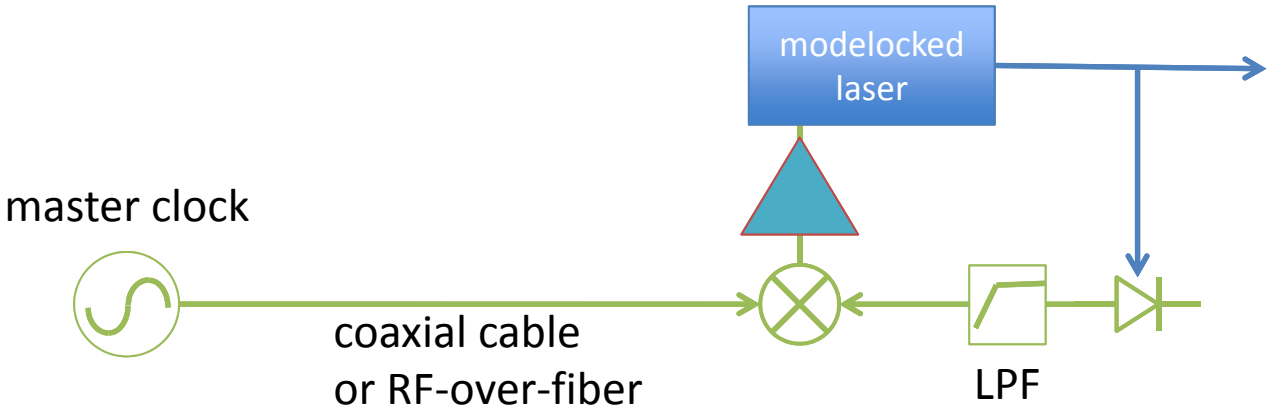
- Concentrating on *short term jitter* (≥1Hz)
  - Long term drift measured at interaction point, fed back
  - Link drift is not important

# Single shot cross-correlator cancels drift




- For pump-probe, measure at the experiment
  - Compensates for intermediate components' drift (beam paths)
  - Light source operates at relatively low reprate
  - Jitter is controlled separately

# RF laser stabilization with phase-locked loop

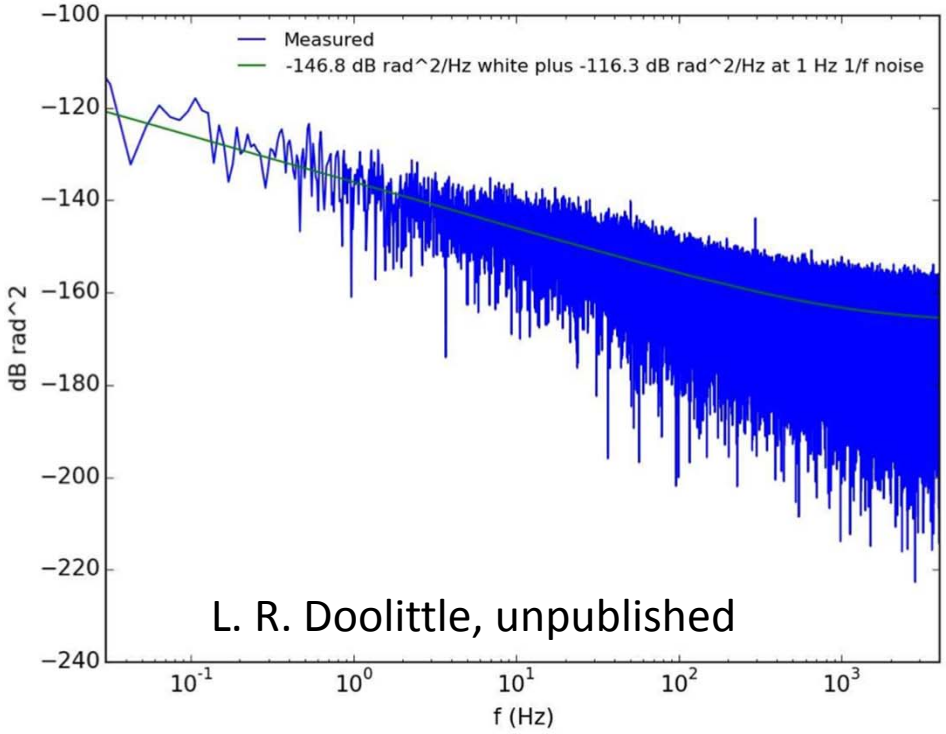



- Transmit RF clock, detect phase, lock with PLL
  - ≤500MHz on coax, >10GHz on fiber
- Laser is like voltage-controlled oscillator (VCO)
  - Changing cavity length changes $f_{rep}$ and harmonics
  - Piezo actuator (10s of kHz)
    - EOM actuator (~1MHz)

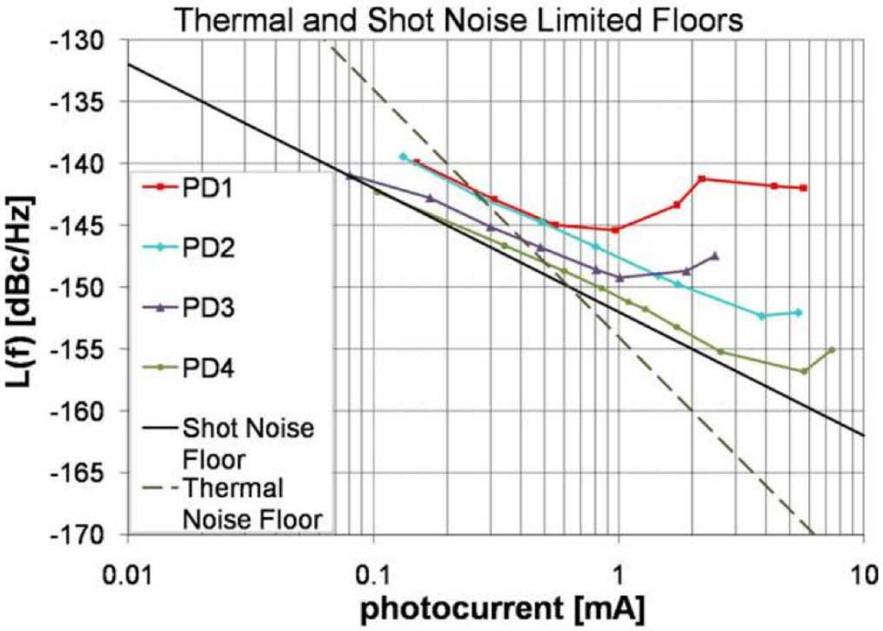
$$\Delta t = \frac{\Delta \phi}{2 \pi f}$$

# Phase detection at GHz noise limited at few-fs

- RF phase comparison
  - Example: digital detection at 1.3GHz, 1.4fs RMS, 0.1Hz - 30kHz
- Photodetection of laser or modulated CW
  - Photodiode shot noise dominates
  - At 1mW optical, 3GHz, 2.6fs RMS error in 10MHz BW



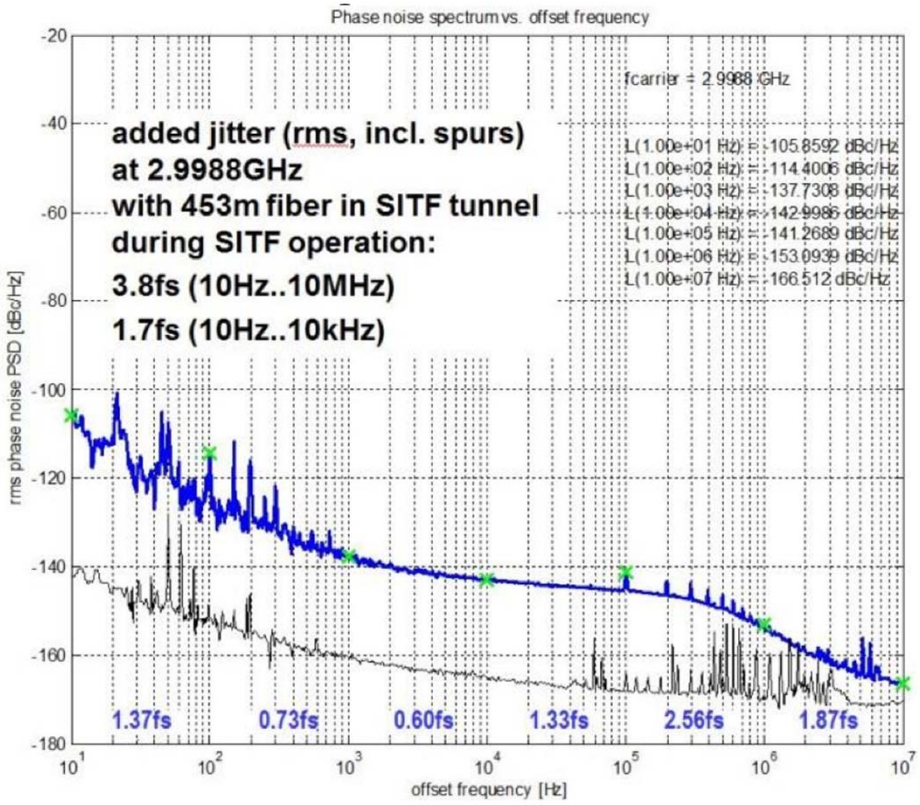

L. R. Doolittle, unpublished




Taylor et al, Proc. IEEE IFCS p684 (2010)

# Few-fs jitter RF link example

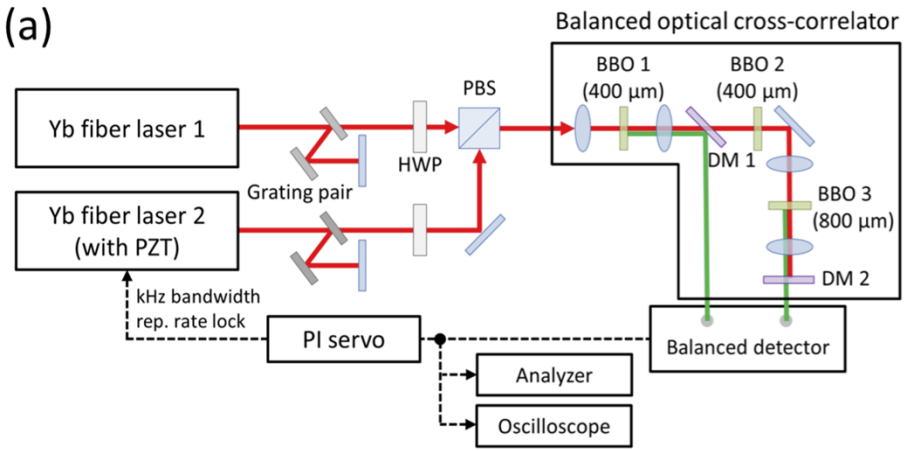
- 3GHz modulated optical carrier
- Link only, 3.8fs, 10Hz to 10MHz, 453m fiber
- Laser was locked to RF reference with 1.7fs jitter, 10Hz – 1kHz
- *Need to increase frequency for sub-fs*

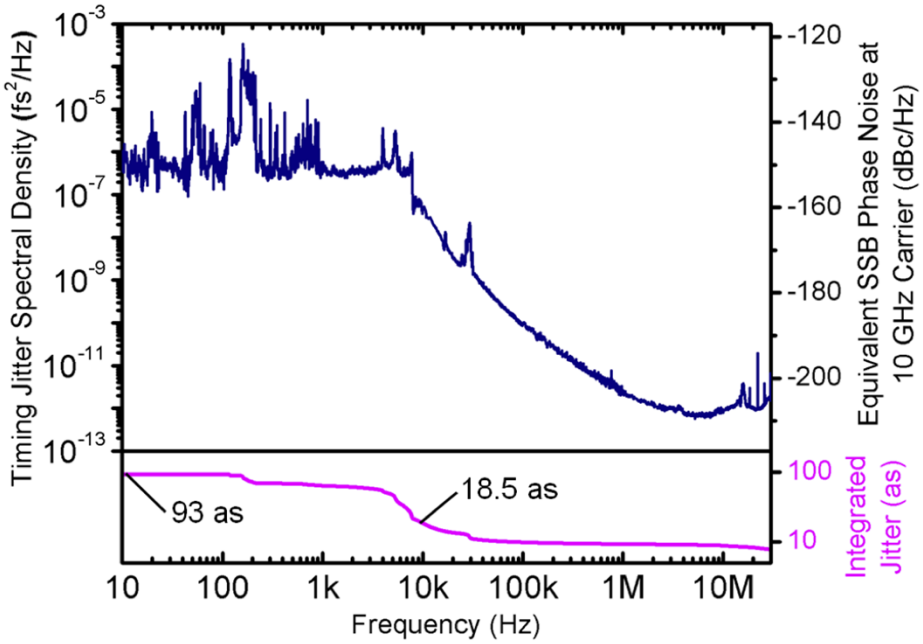



Hunziker et al, IBIC2014, Monterey, MOCZB2 (2014)

# Lasers have sub-fs noise

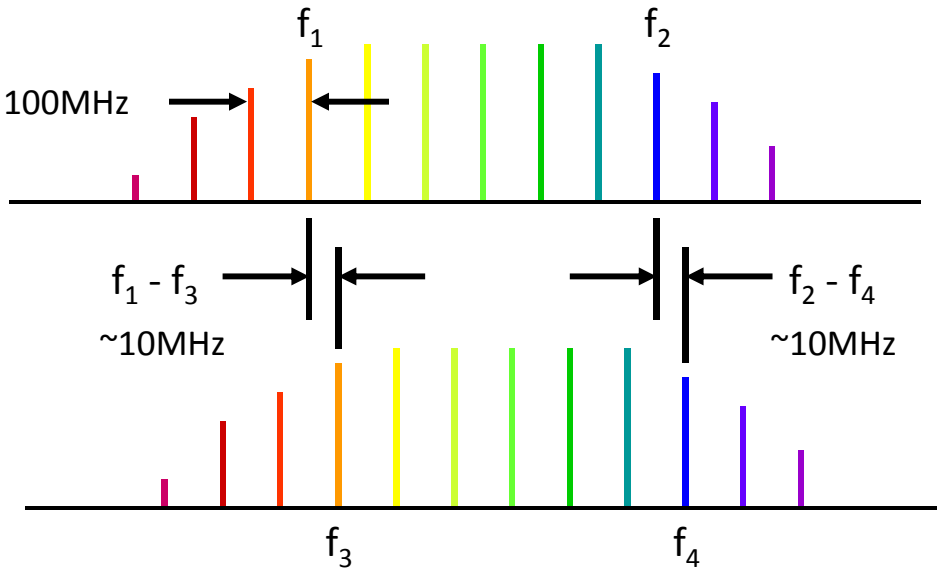
- Lasers are quietest oscillators
  - Noise above control bandwidth must be negligible
  - Intracavity actuators at 10kHz – 1MHz define control bandwidth
- Example: two lasers locked using cross-correlation, 10kHz piezo
  - 100as from 10Hz to 100MHz

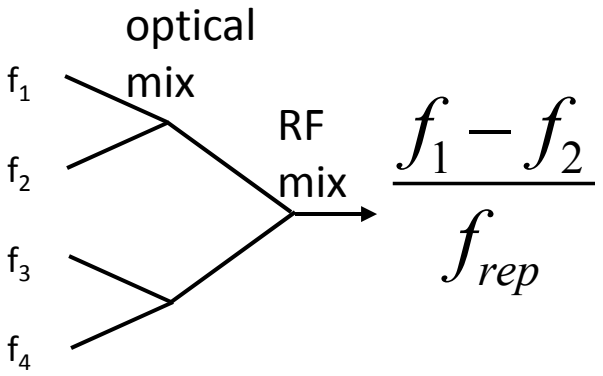


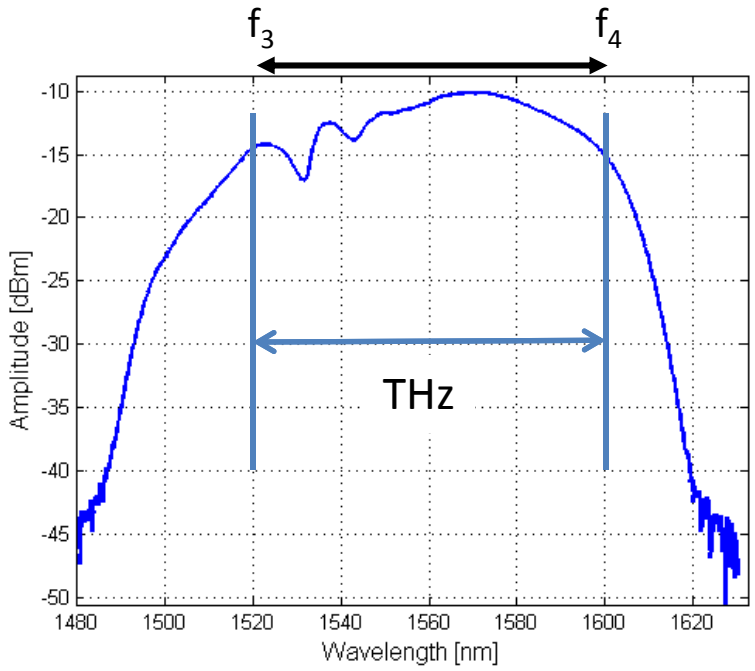




Kim et al, IEEE STQE 20, 901108 (2014)

# Locking optical frequencies at THz equivalent



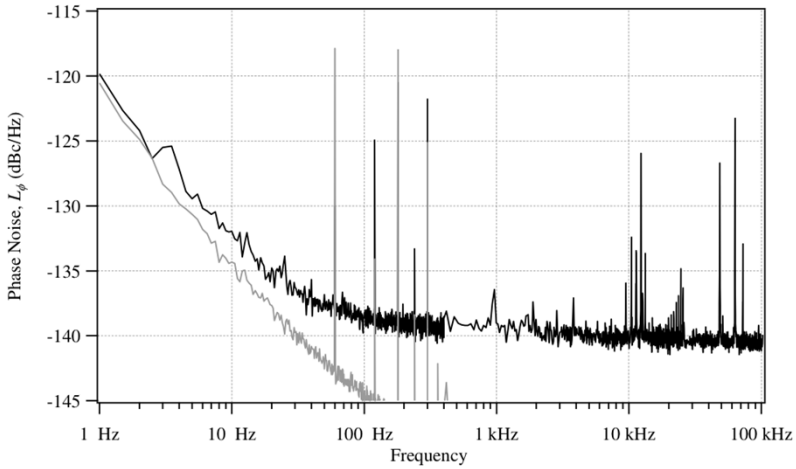



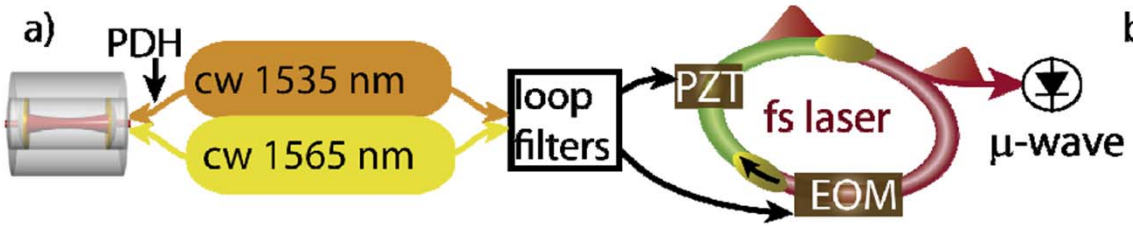



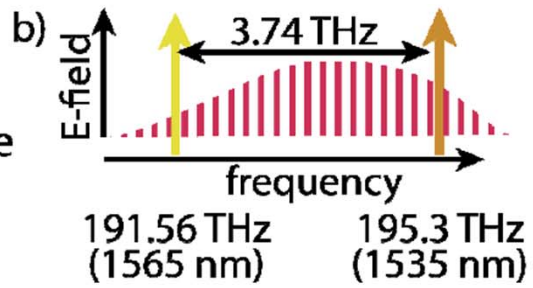

- $(f_1 - f_3) - (f_2 - f_4)$ = error signal
- Like synthesizing THz modulation
- Offset frequency is cancelled

# Synchronizing lasers with 2 wavelengths

- Optical master clocks at two harmonics of cavity
  - 3.74 THz difference
  - 1.5GHz noise compared between two fs lasers with fast actuators
  - Equivalent ~4.5fs jitter, 1Hz to 100kHz
  - Intensity and thermal noise limits

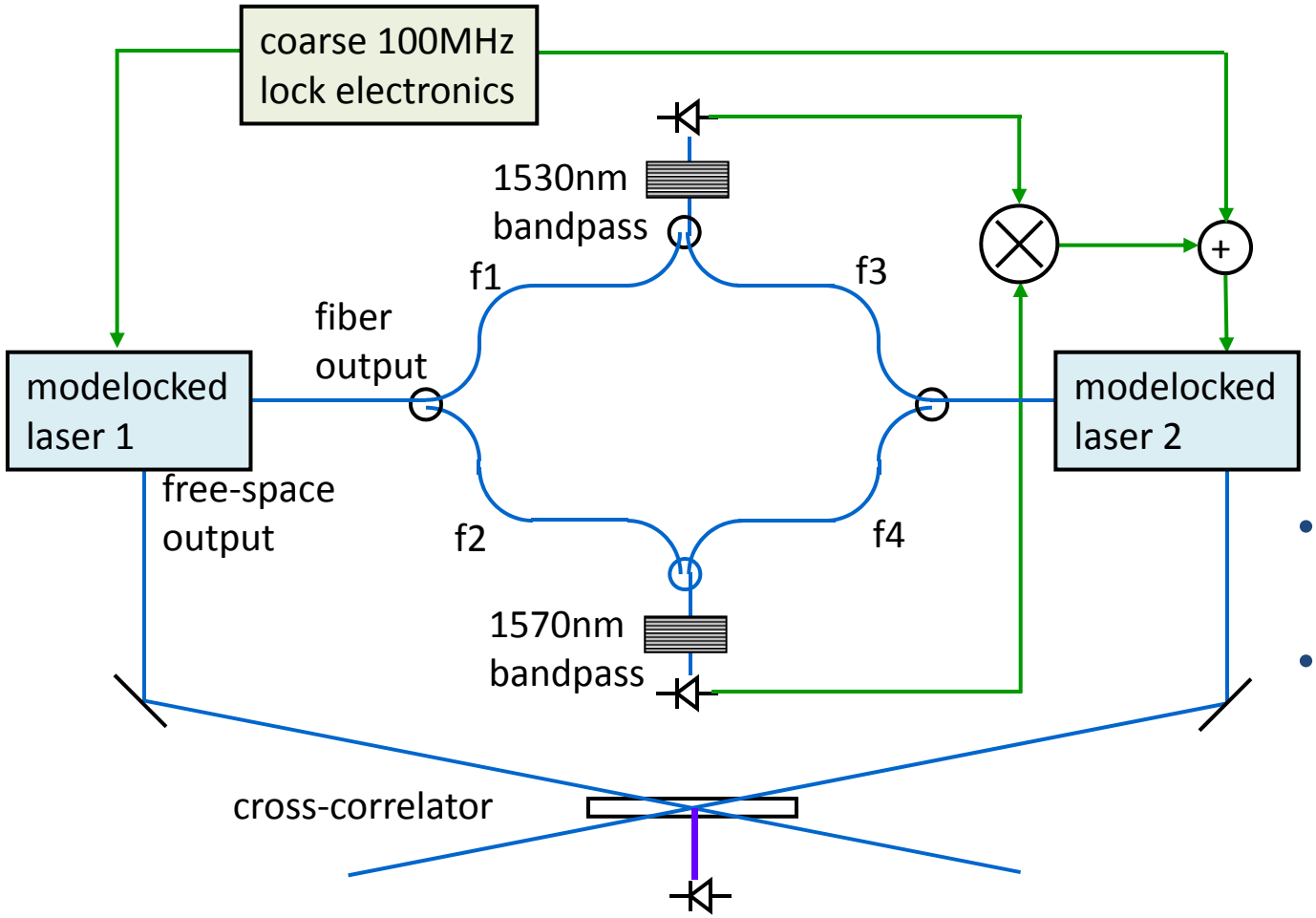



Swann et al, Opt. Exp. 19, 24387 (2011)

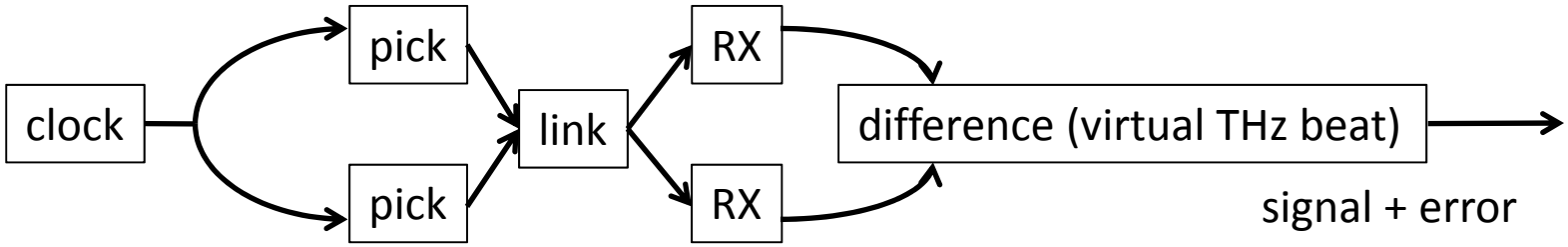
# Locking two lasers with 10THz equivalent frequency




Staples and Wilcox, FEL2005

- 5.7fs RMS from 1Hz to 1MHz
- Sensitivity 0.13mV/fs

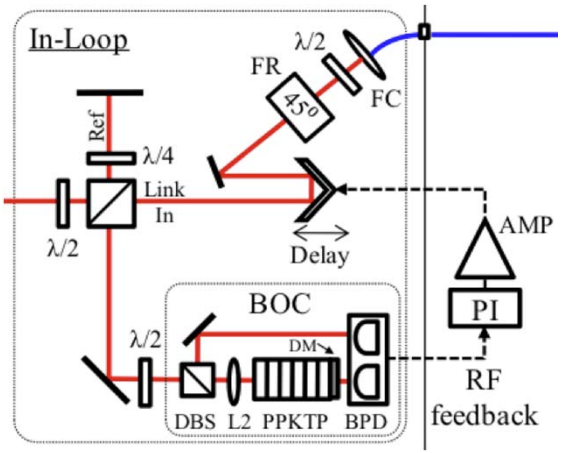
# Problem with synthesis using independent frequencies

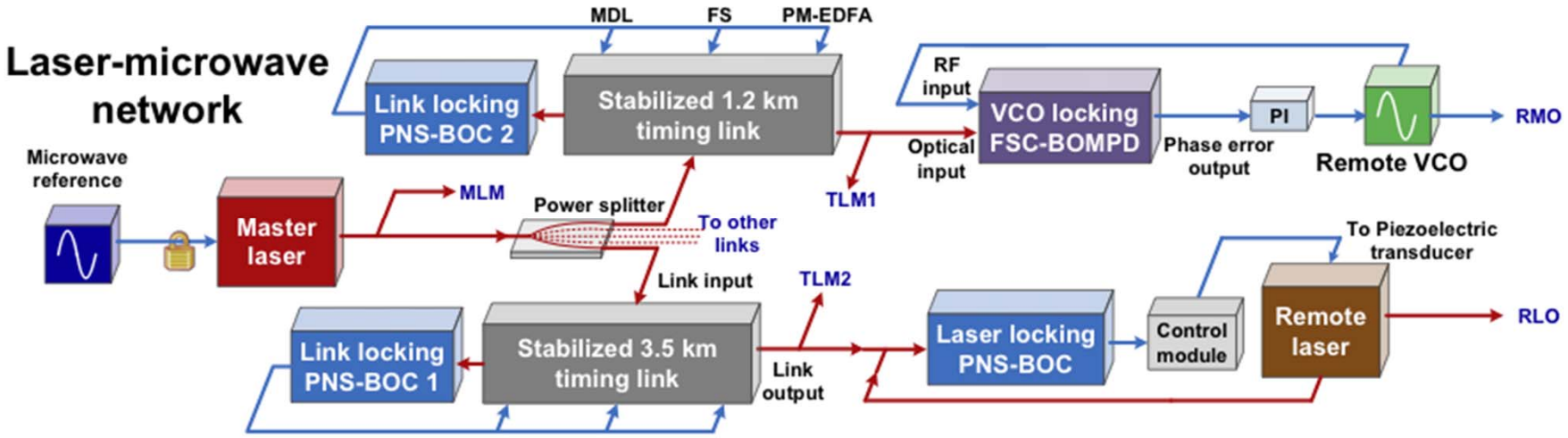



- Optical phase errors are *multiplied* by $f_1/(f_2 - f_1)$
  - which is, e.g., 200THz/10THz = 20
  - It's the phase of the *difference* that matters
- This why 2-frequency control is not sub-fs

# Sub-fs links, laser sync achieved using short pulses

- Cross-correlation of pulses detects timing
  - Transmit ~200fs pulses, get ~2THz of BW
  - Detect using wide BW nonlinear optics
  - 10s of mV/fs sensitivity
  - Laser and microwave sync over muliti-km links
  - 0.68fs, 1Hz – 1MHz

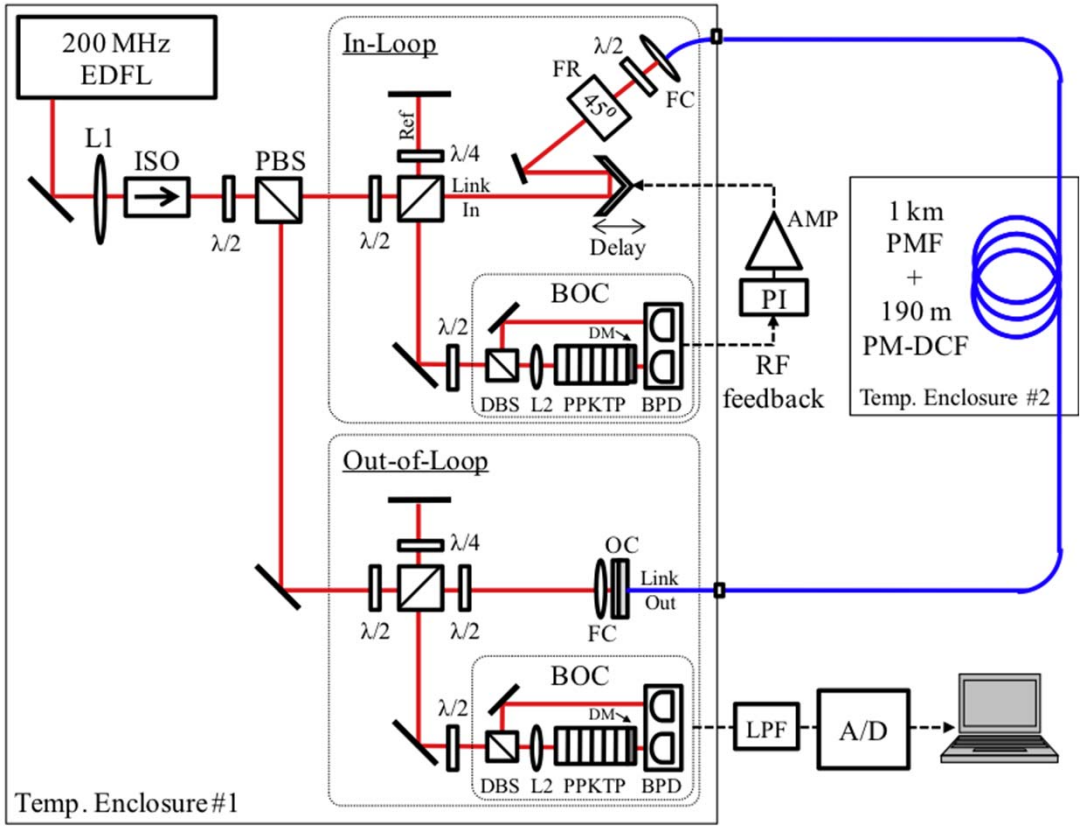



Xin et al, IEEE JSTQE, vol.PP (2016)

# Problems with short pulse transmission

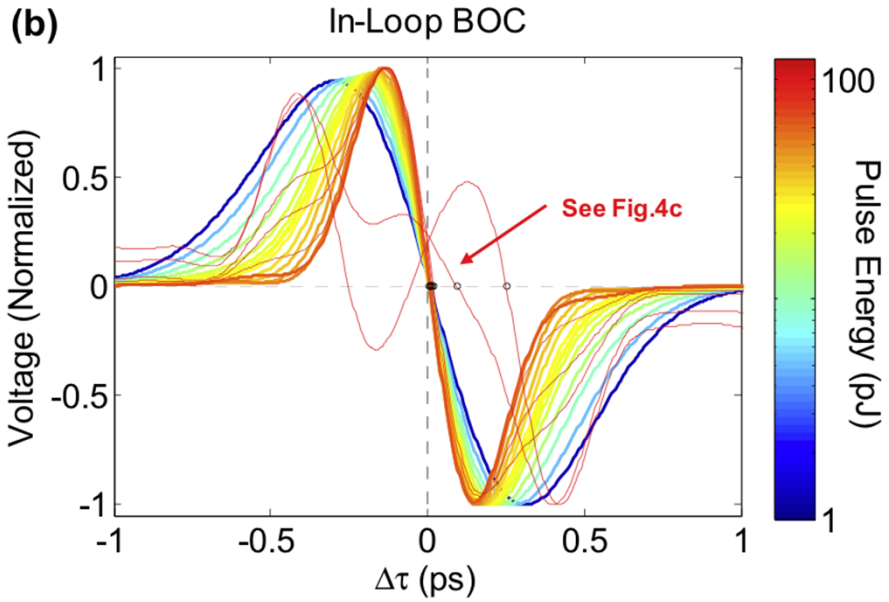
- Dispersion
  - Lengthens pulse
  - Wavelength instability causes jitter
  - Compensate with additional fiber
- Mechanical envelope delay
  - Slow moving parts

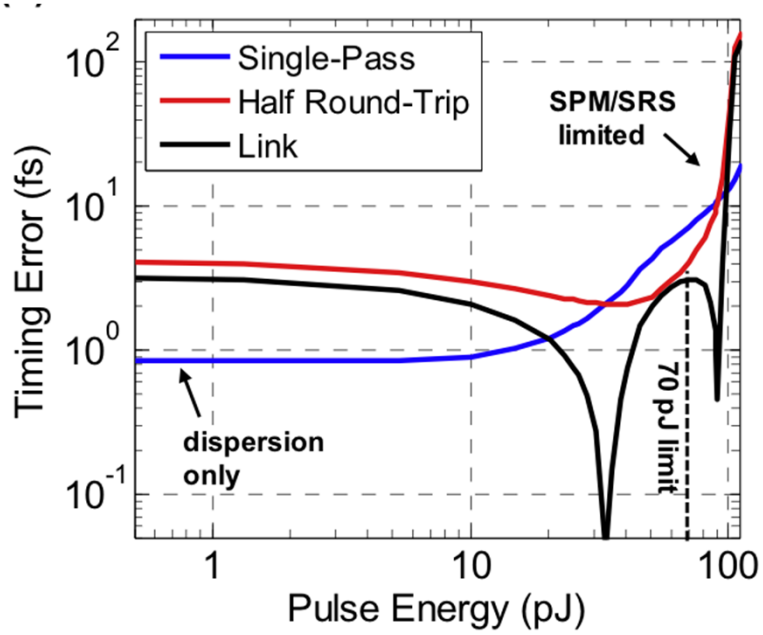



Callahan et al, Opt. Exp. 22, 9749 (2014)

# Problems with short pulse transmission 2

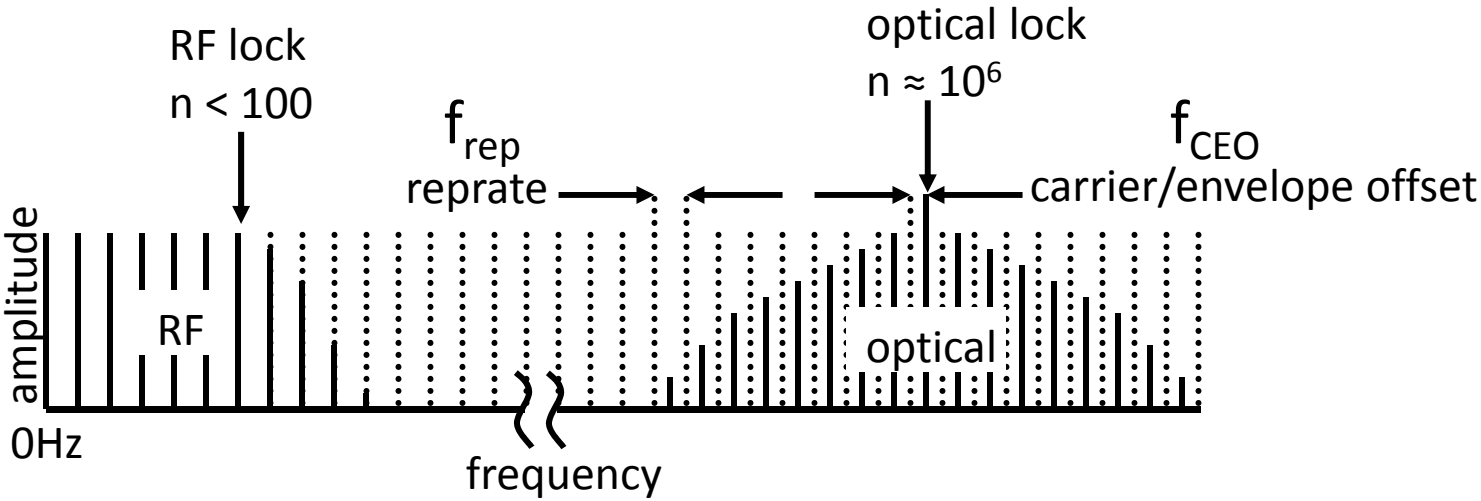
- Nonlinearity plus dispersion re-shapes pulse
  - Can reverse detection slope, create jitter
  - Imposes power limit
- Need power for efficient SHG
  - Use waveguide to increase efficiency
- No signal without overlap




Peng et al, Opt. Exp. 21, 19982 (2013)

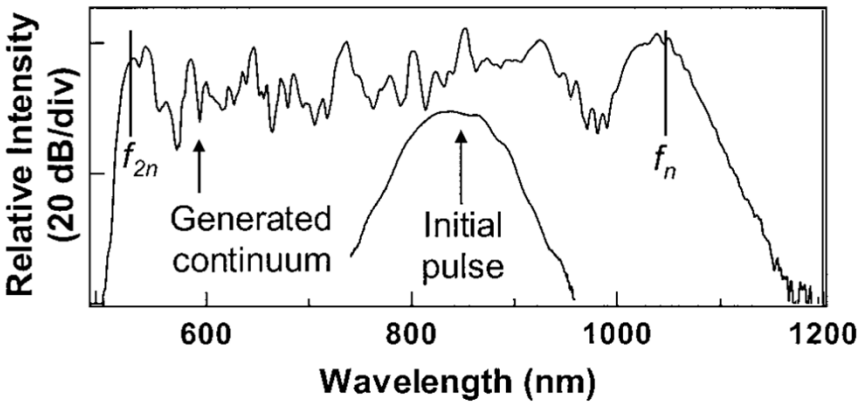
# Lock to optical carrier at 200THz

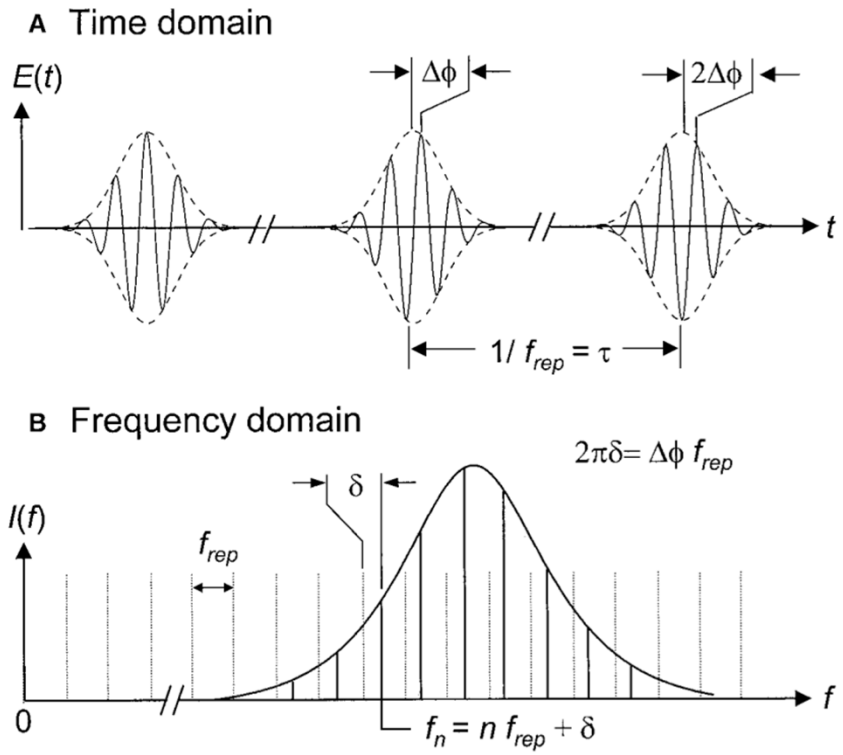



- $f_{line} = n\, f_{rep} + f_{CEO}$
  - A CEP stable laser fixes $f_{CEO}$
  - Send single frequency to control $n\, f_{rep}$
  - For 200THz optical, $n \approx 2 \times 10^6$, 1fs is 72°

# How CEP lock works

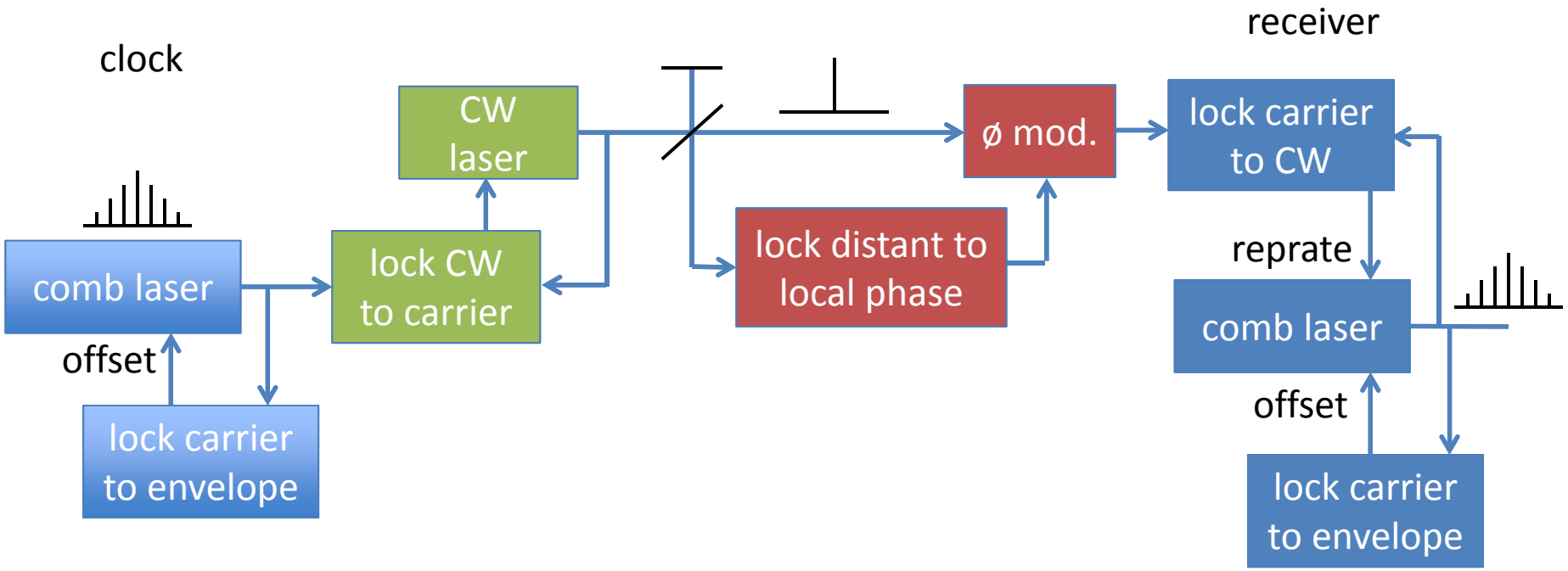
- Optical comb frequencies are $f_n = nf_{rep} + f_{offset}$
- Generate harmonics of reprate
  - Supercontinuum
- Also, harmonics of carrier
  - SHG
- Subtract, and $f_{offset}$ remains
  - Lock to submultiple of reprate or zero




Jones et al, Science 288, 635 (2000)

# Pulsed lasers can be synced using optical phase

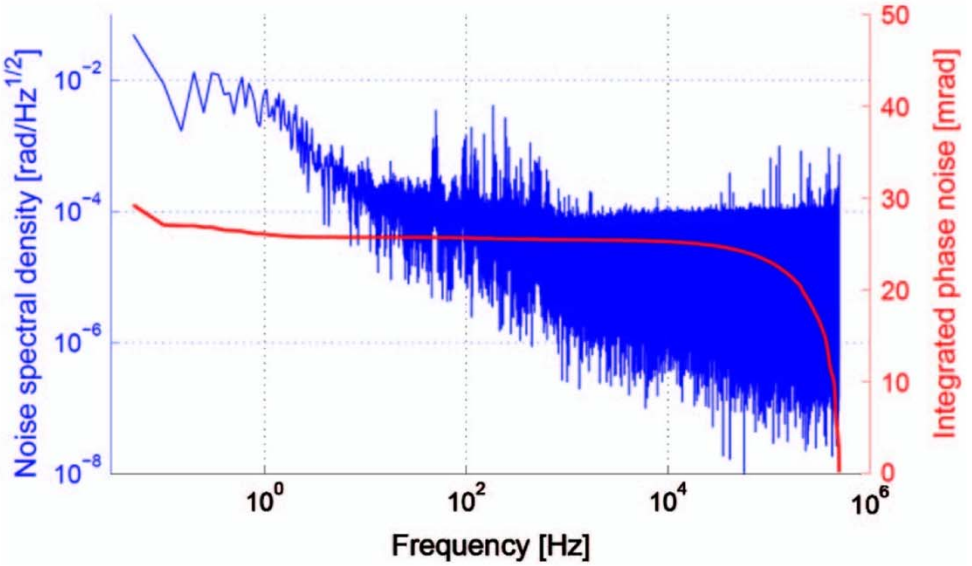



Wilcox et al, J. Mod. Opt. 58, 1460 (2011)

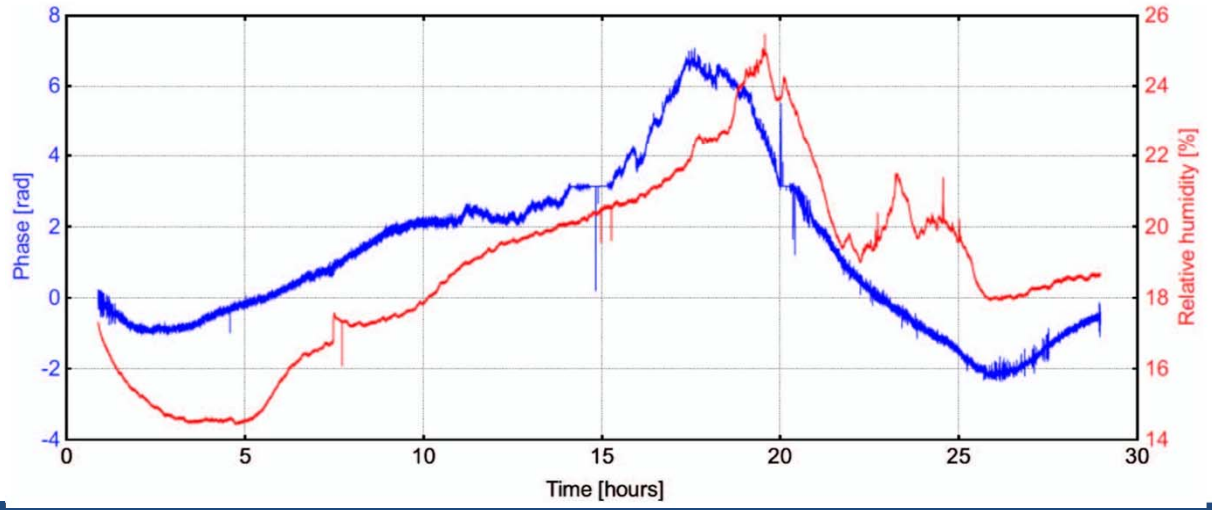
- With optical interference, mixer is photodiode
  - Sensitivity of 500mV/fs with 10mW incident power, 1550nm
  - Far above shot noise floor

# CEP can be stabilized long term, with low jitter

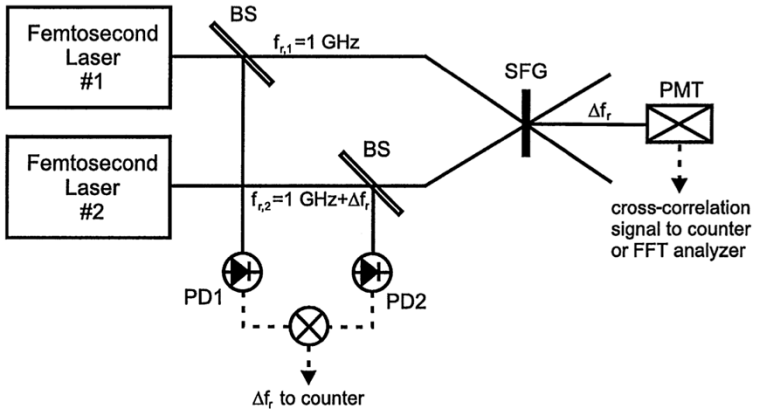
- Can lock for many hours with low noise
  - Fast AOM actuator
  - Experimental 30 mrad is 13as (800nm)
  - Drift ~3fs

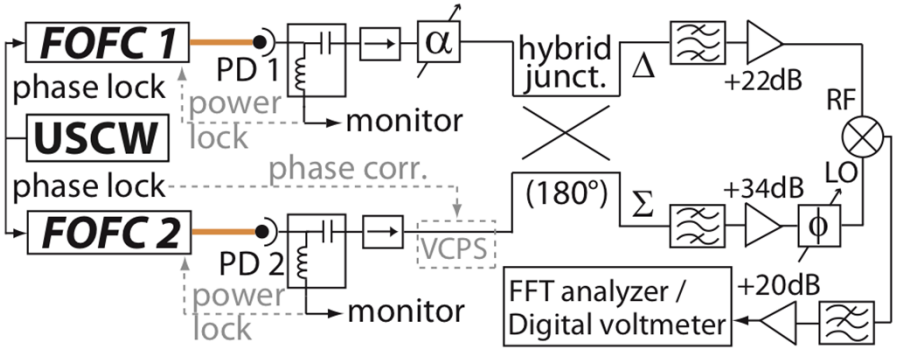


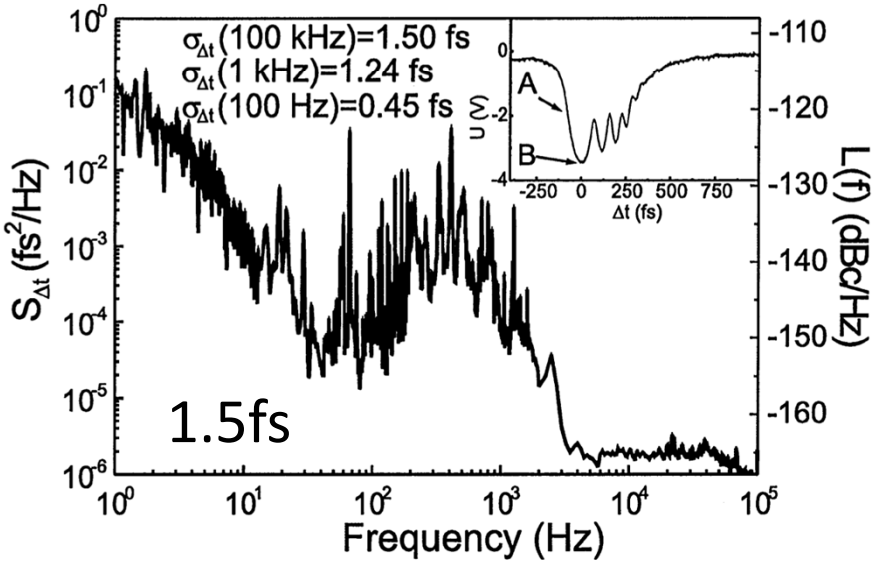

Lucking et al, Opt. Lett. 37, p2076 (2012)



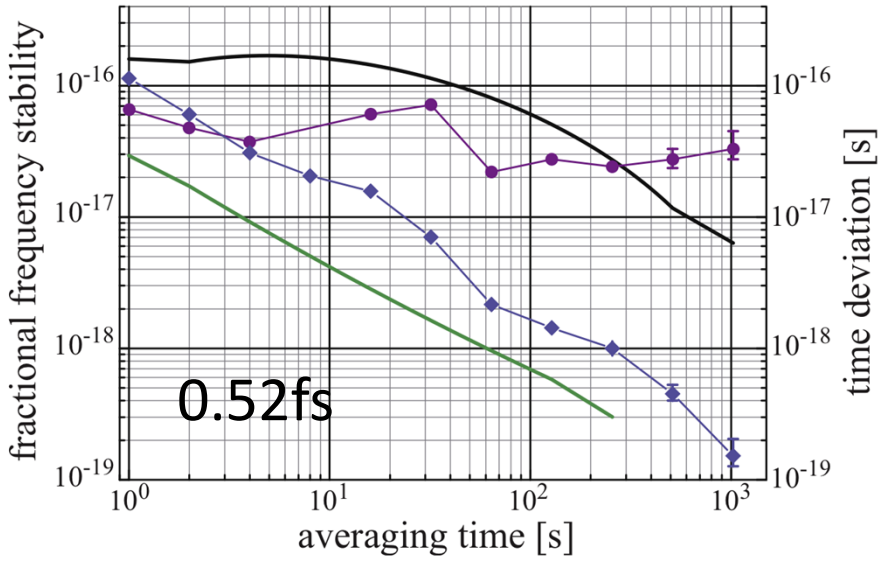
# Examples of two lasers locked to stable CW



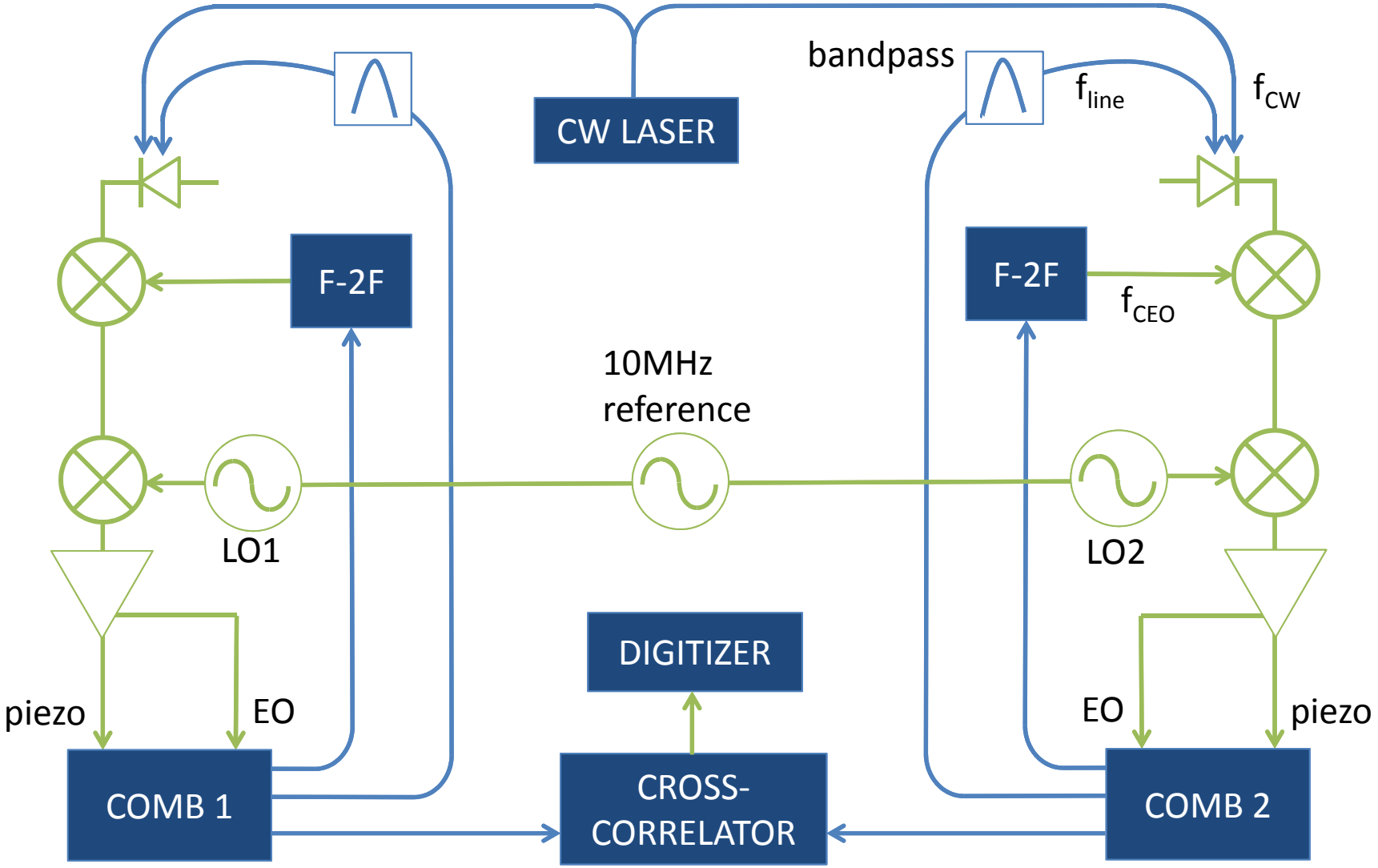




Bartels et al, Opt. Lett. 28, 663 (2003)

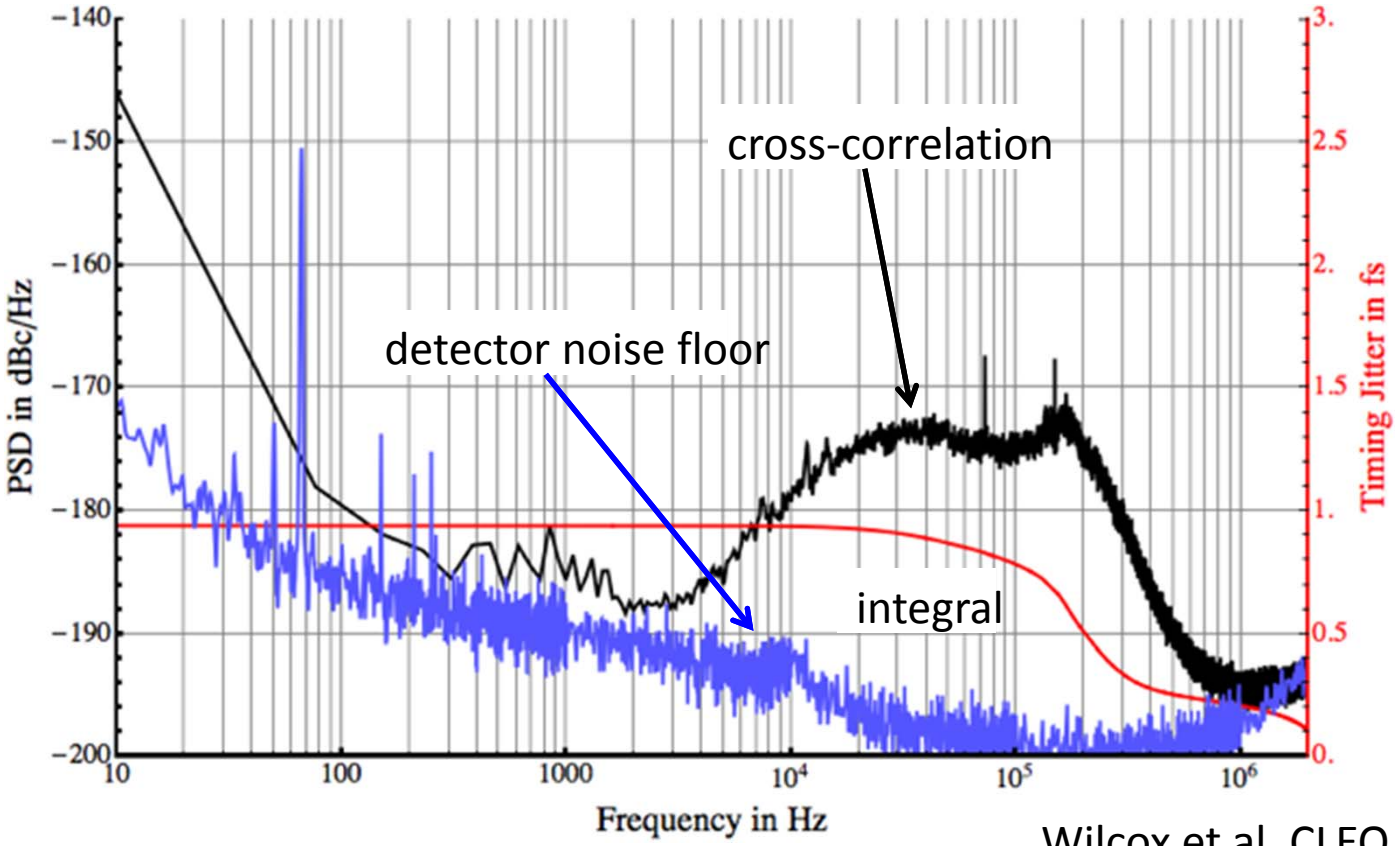



Zhang et al, Appl. Phys. Lett. 96, 211105 (2010)

# Experiment using commercial lasers locked to CW



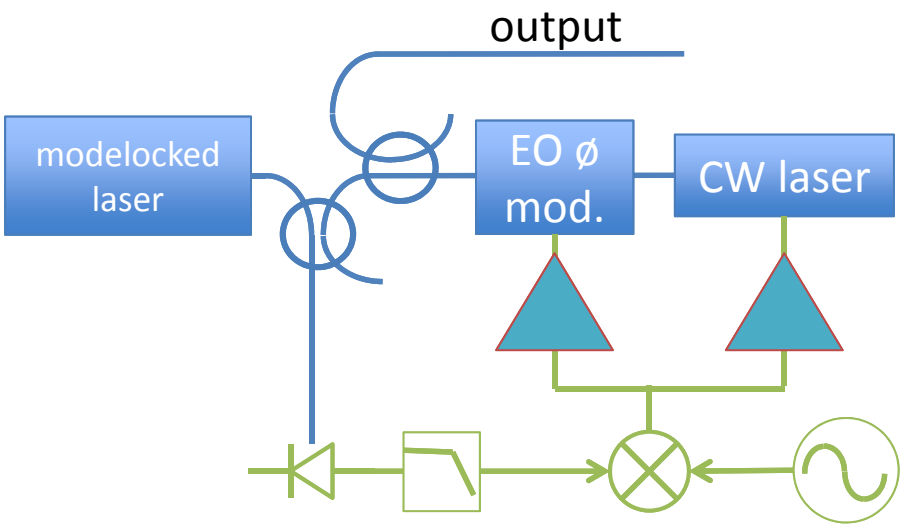
# The lasers easily locked to <1fs

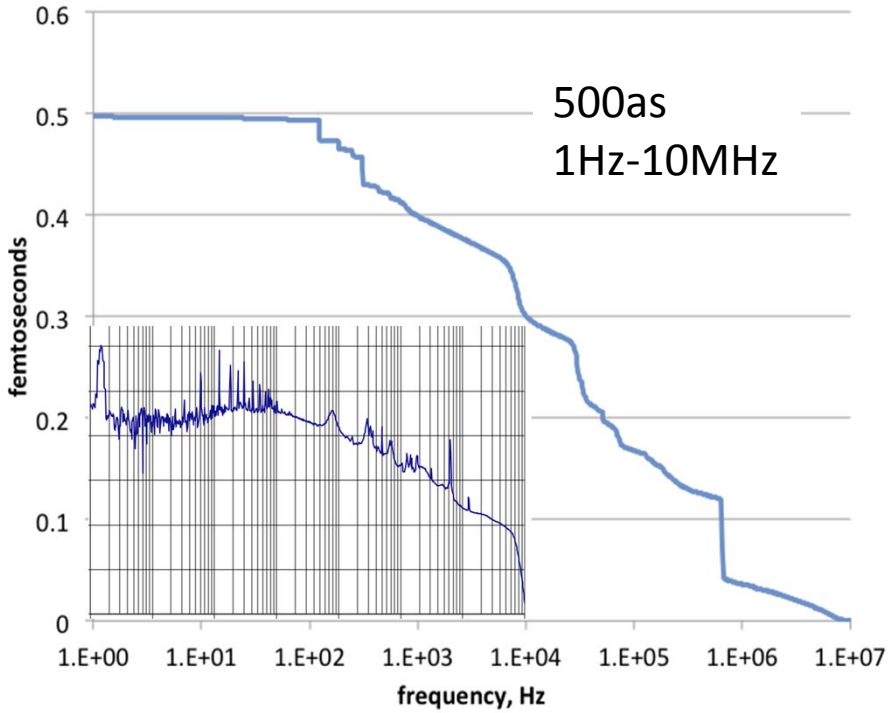



Wilcox et al, CLEO 2014

- 0.9fs from 10Hz to 2MHz
- Completed in ~3days, using commercial lasers, no special isolation
- Leverage of optical frequency provides high SNR

# Deriving single frequency from comb using optical PLL

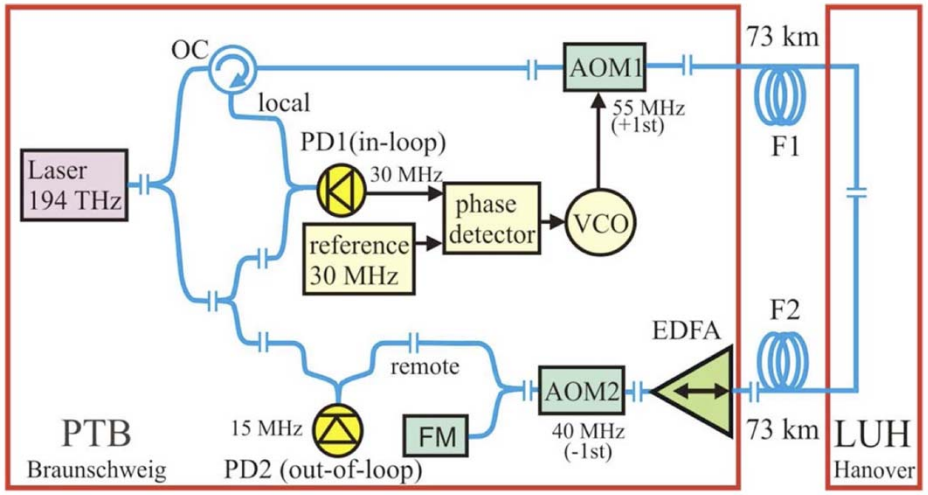


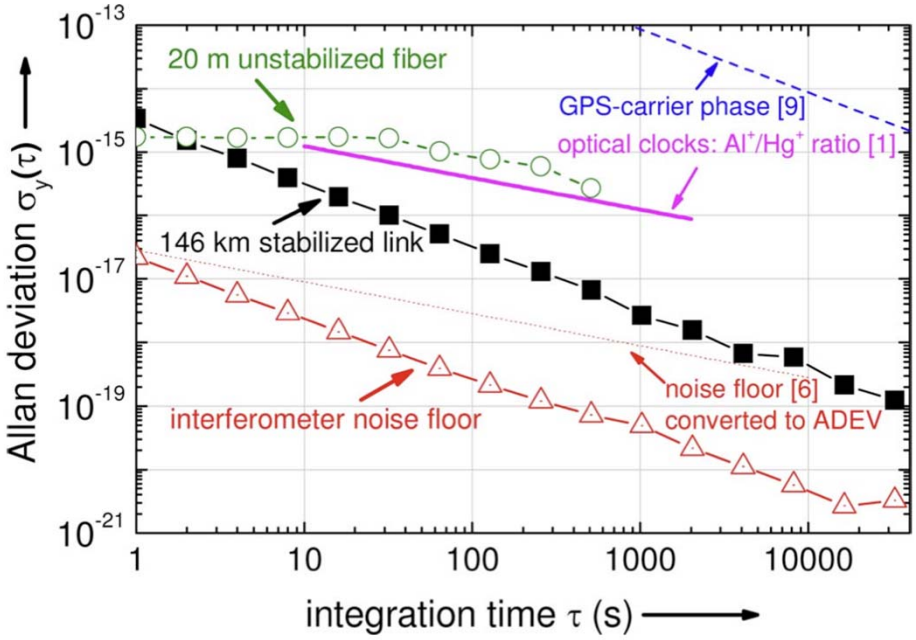




- Laser was ~1kHz linewidth, no special acoustic isolation
- EO phase shifter used as high speed extracavity modulator

# Optical phase is transmitted via interferometer

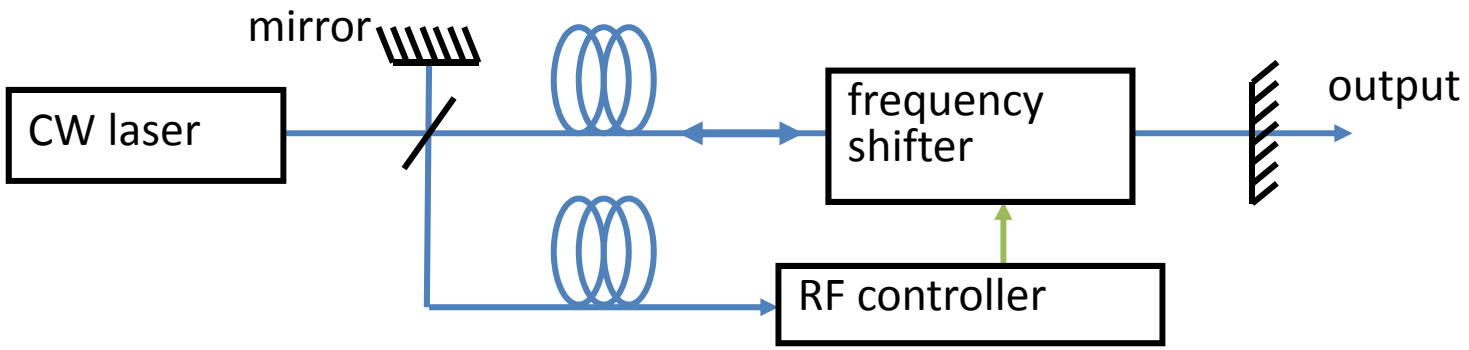
- Example of stable frequency transfer
  - 3fs over 146km, 30as over 20m

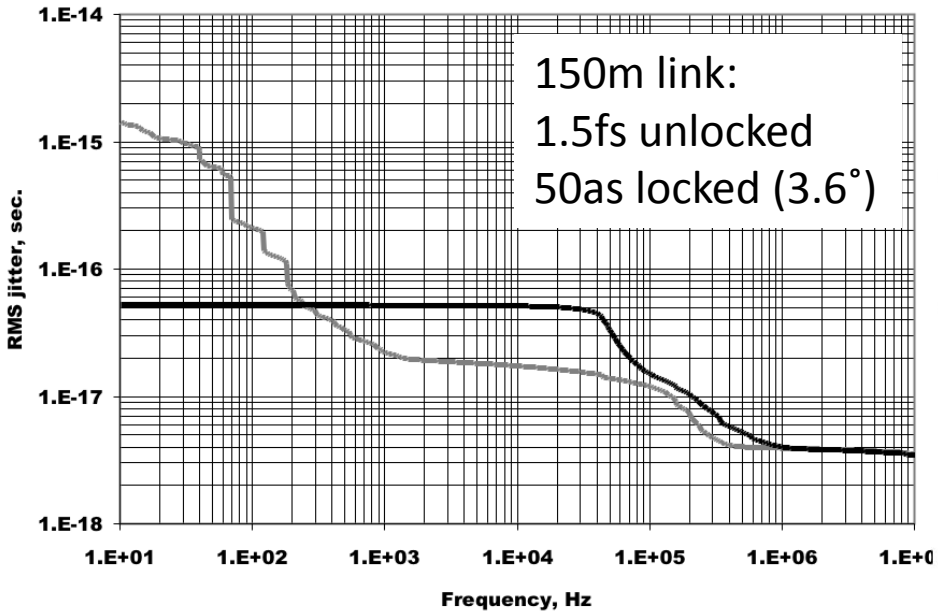


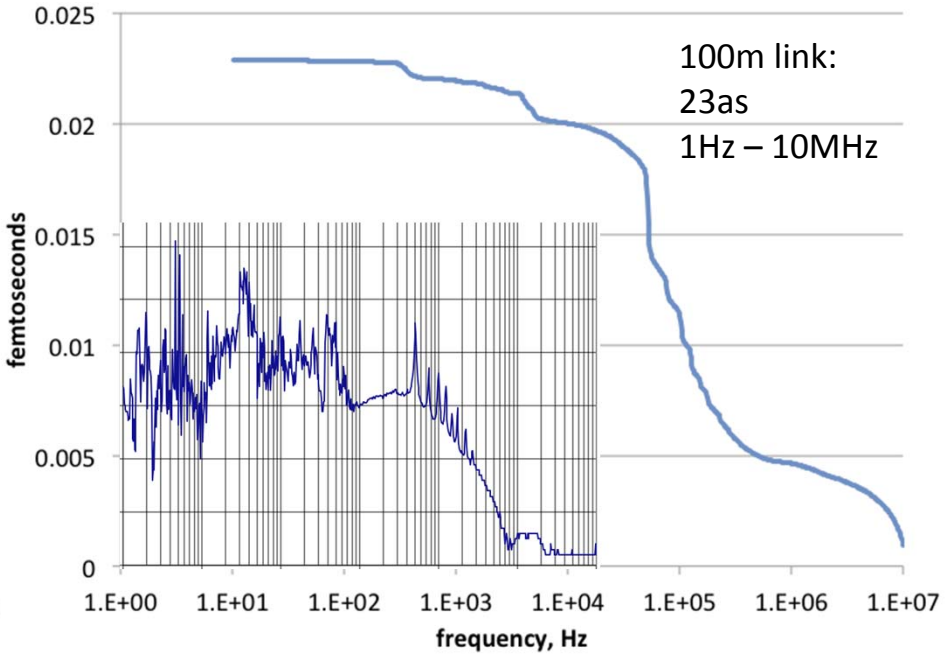




Grosche et al, Opt. Lett. 34, 2279 (2009)

# Heterodyne interferometer using digital processing

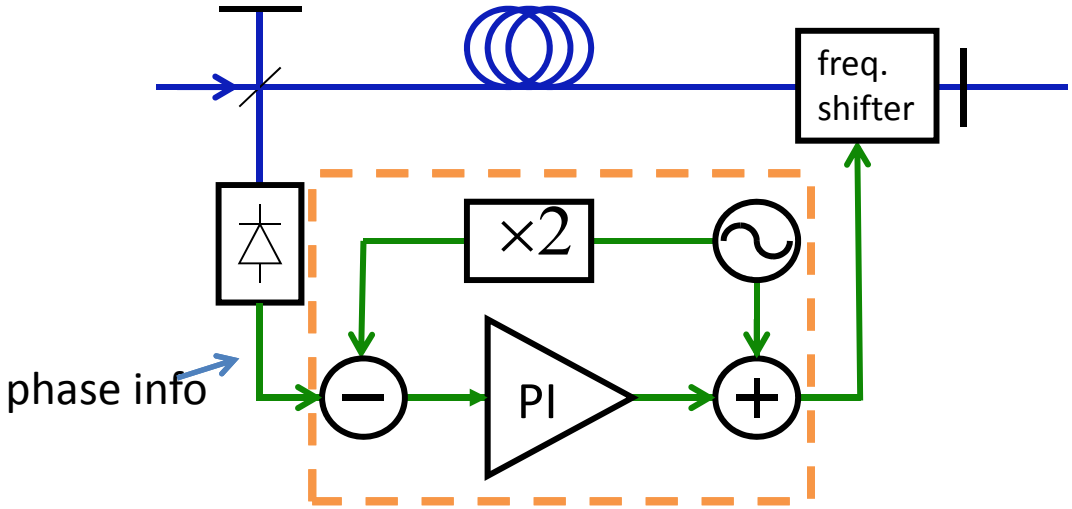


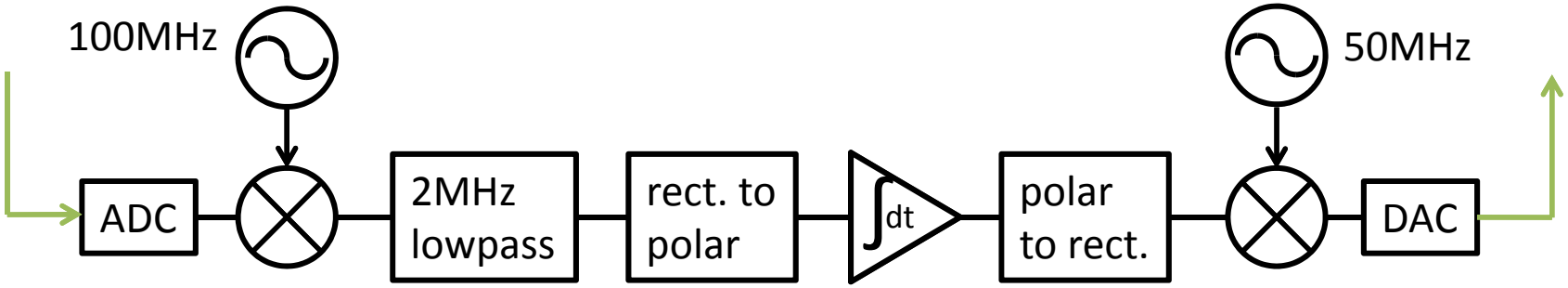



# Digital controller tracks phase over ns of perturbation

- Not just one fringe
- 5ns locking range
- 0.04as resolution
- 2MHz signal bandwidth



# Conclusions

- GHz modulation of optical carrier
  - Few-fs jitter RF links
  - Noise limited
- THz synthesis, two frequencies
  - Few-fs jitter laser control
  - Negative leverage
- THz bandwidth pulses
  - Sub-fs jitter laser control links
  - Hard to transmit
- 200THz optical carrier
  - Sub-fs system elements
  - Easier to transmit
- Improvements can be made to all these techniques