Highly stable femtosecond laser frequency combs

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Outline

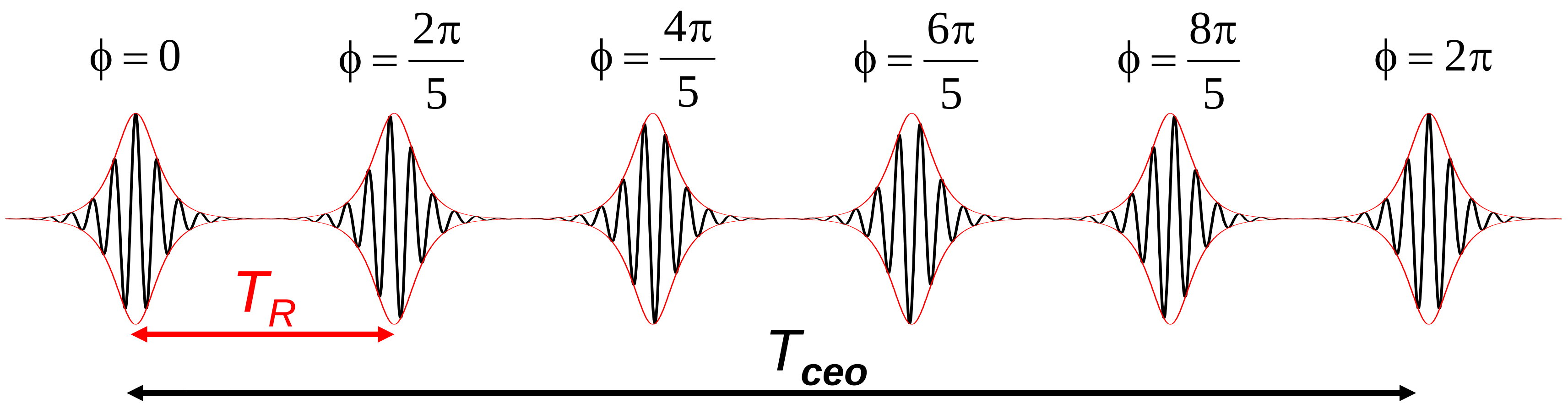
- Motivation
- Carrier envelope phase stabilization of 200 MHz TiSa-laser
- Optical clocks
- Outlook

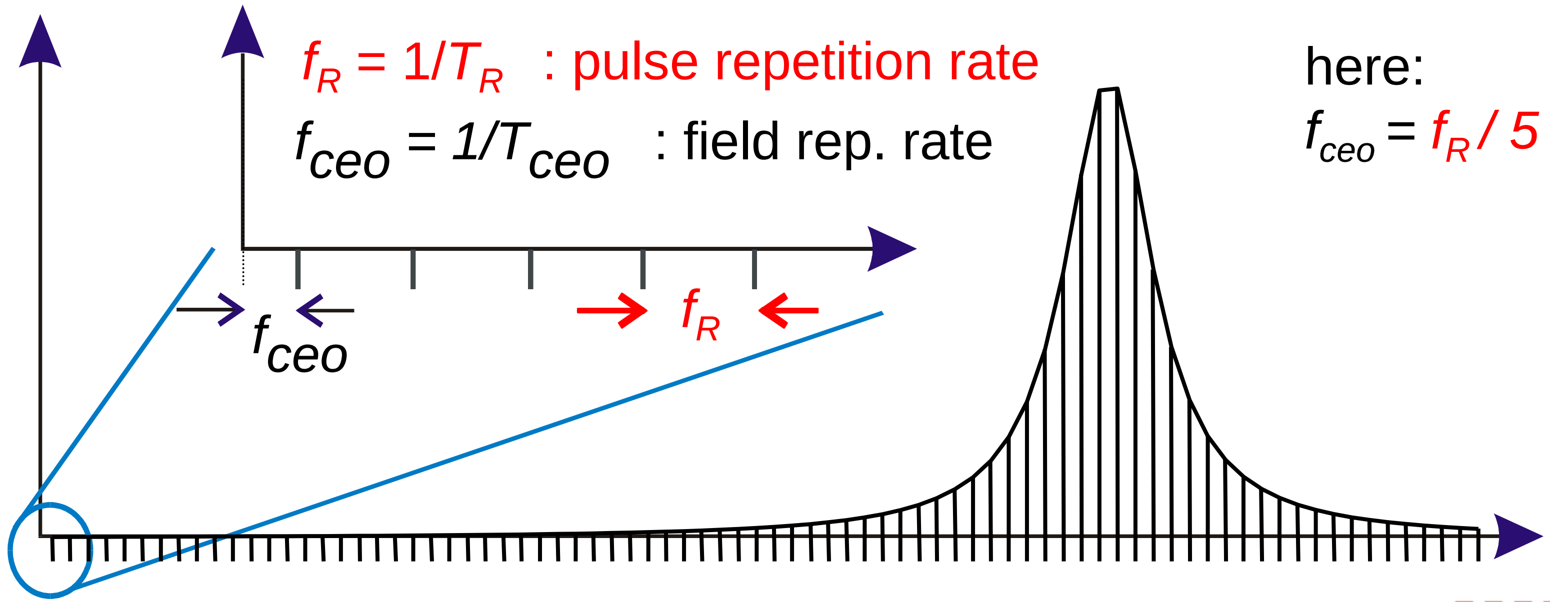
Motivation

carrier-envelope phase stabilized high-repetition rate lasers have impact on:

- optical frequency metrology:
- ultrafast time-domain spectroscopy:
- Ultrastable clocks:
  - Few-femtosecond stable pulse trains
  - Few-femtosecond stable microwave oscillators
  - Next generation, all optical master oscillators
  - Stabilized TiSa oscillators for slicing

The Carrier-Envelope Phase



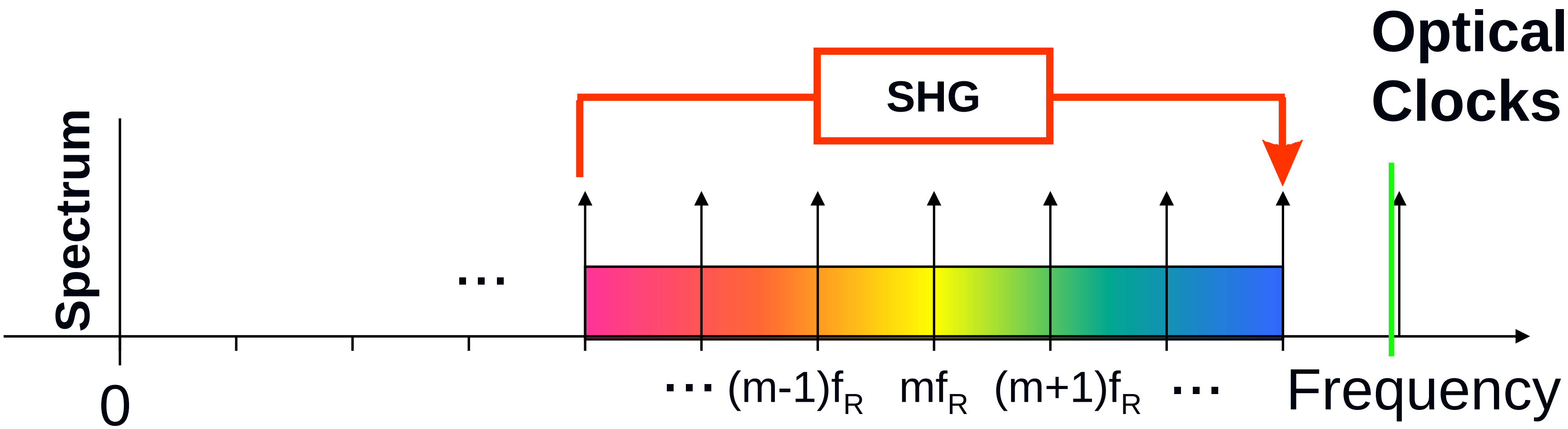


Why carrier envelope phase stabilization ?

- Present concept: combine low jitter of fiber lasers (high frequency regime) with low jitter of microwave oscillator (low frequency regime)
- Feasible: use optical frequency to absolutely stabilize optical frequency comb and use it as divider
- In RF terms: synchronize laser to optical reference frequency (phase detector @100THz reference frequency)

- To supply intrinsically stable optical oscillator:
  1. Stabilized repetition rate through lock onto atomic transition
  2. Stabilized “offset” of frequency comb

Carrier-Envelope Phase and Frequency Metrology



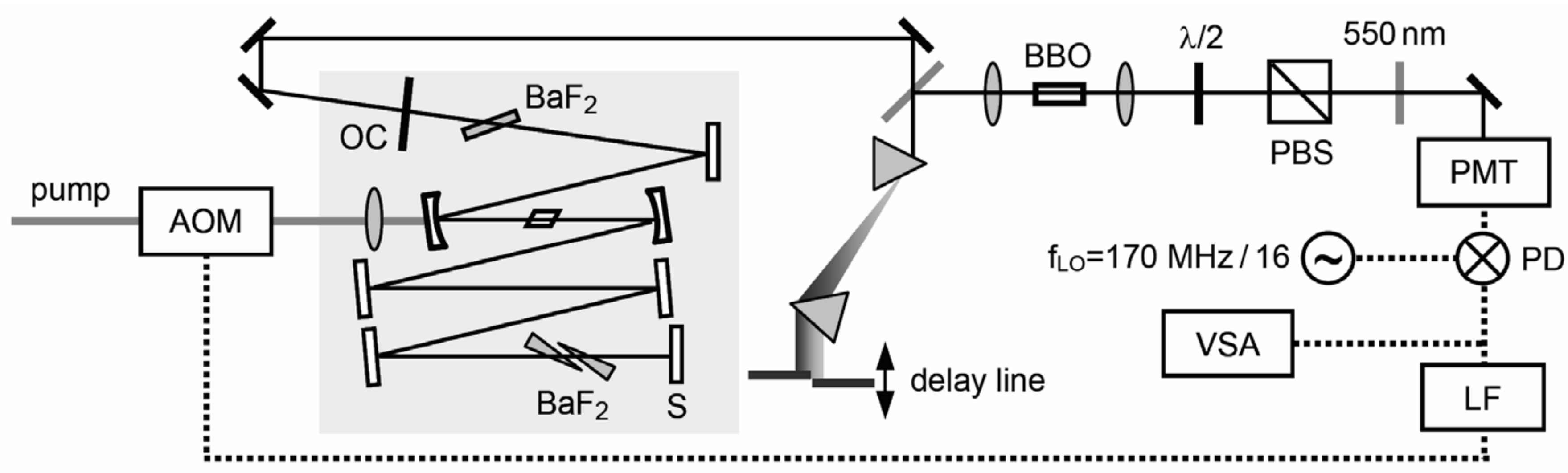
Periodic Pulse Train with $T_R = \frac{1}{f_R}$

T. Udem, et al., PRL **82**, 3568 (1999)
D. Jones, et al., *Science* **288**, 635-639 (2000)

- **Ultra-stable pulse train of optical pulses**
- **Photodetection → ultrastable microwave oscillator or optical clock**

Needs one octave of spectrum!

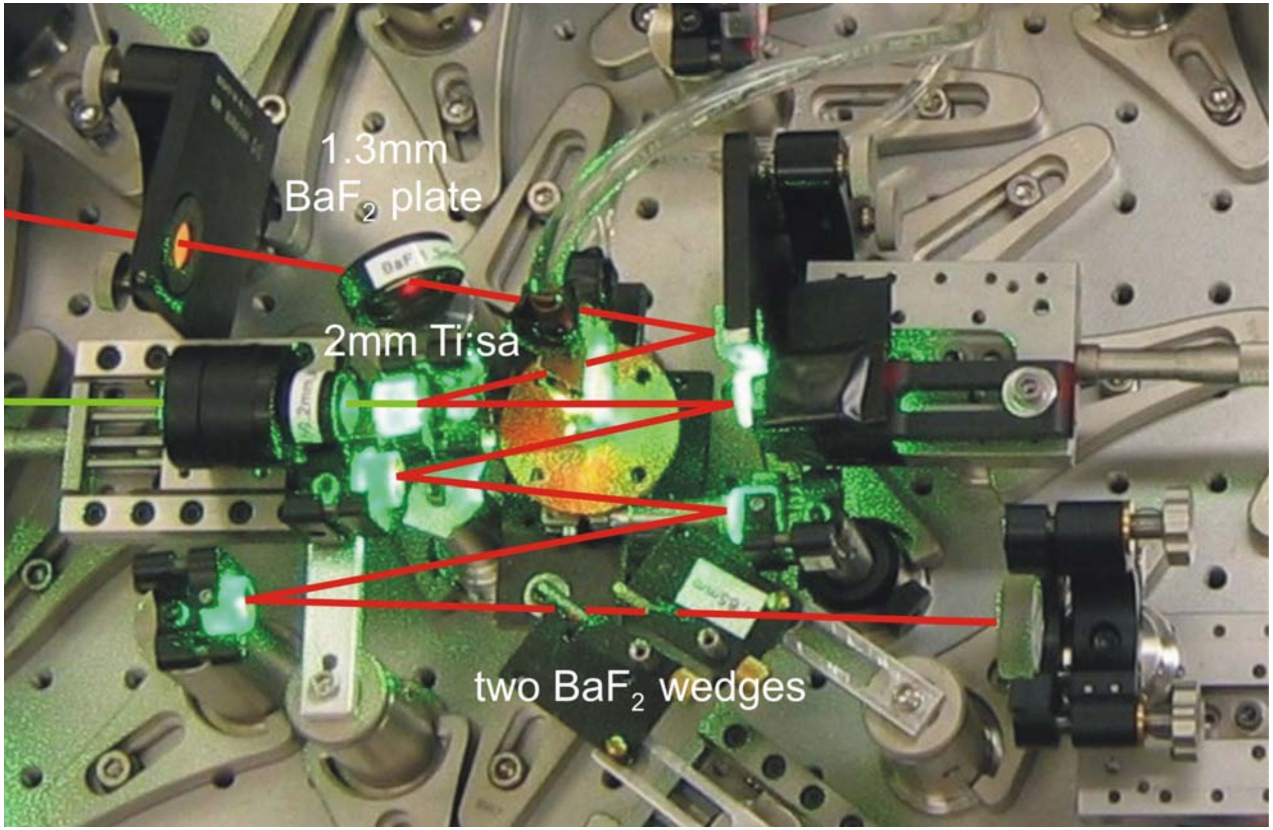
Carrier-envelope phase stabilized 200 MHz octave-spanning Ti:sapphire laser



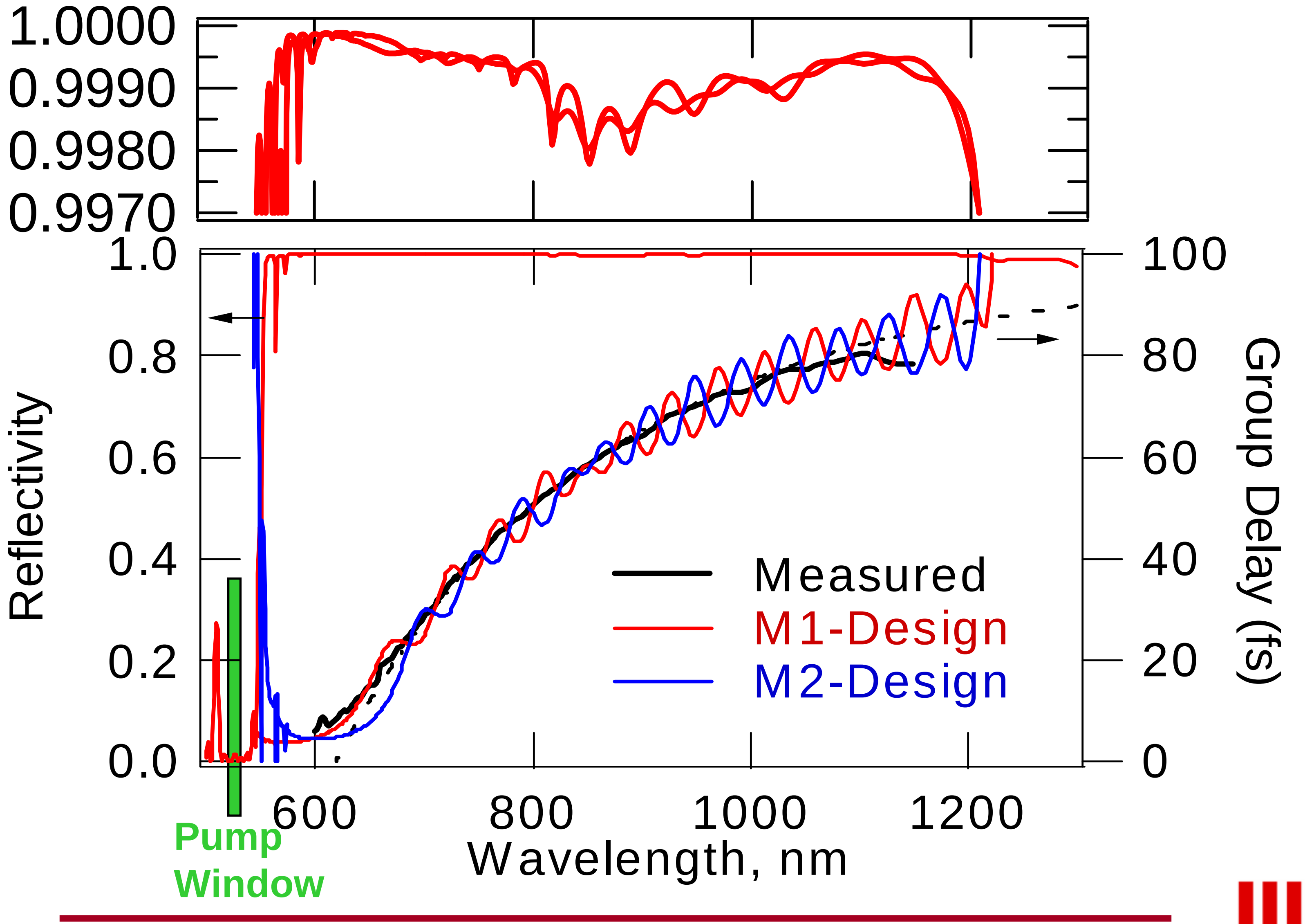
200 MHz octave-spanning Ti:sapphire laser

6.5 W pump @ 532 nm, ~200 mW average output power

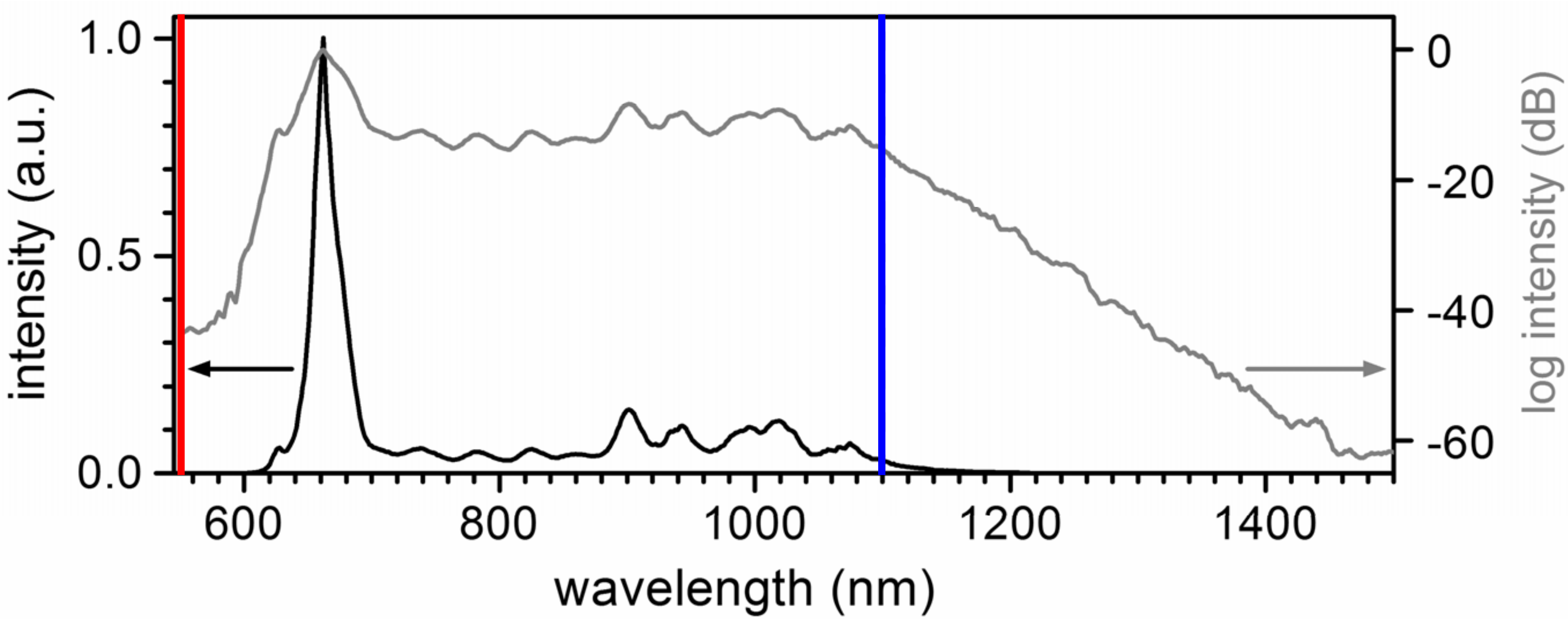
2 mm Ti:sapphire crystal, double-chirped mirror pairs, BaF_2 plate/wedges



Double-chirped mirror pair covering one octave



200 MHz octave-spanning Ti:sapphire laser



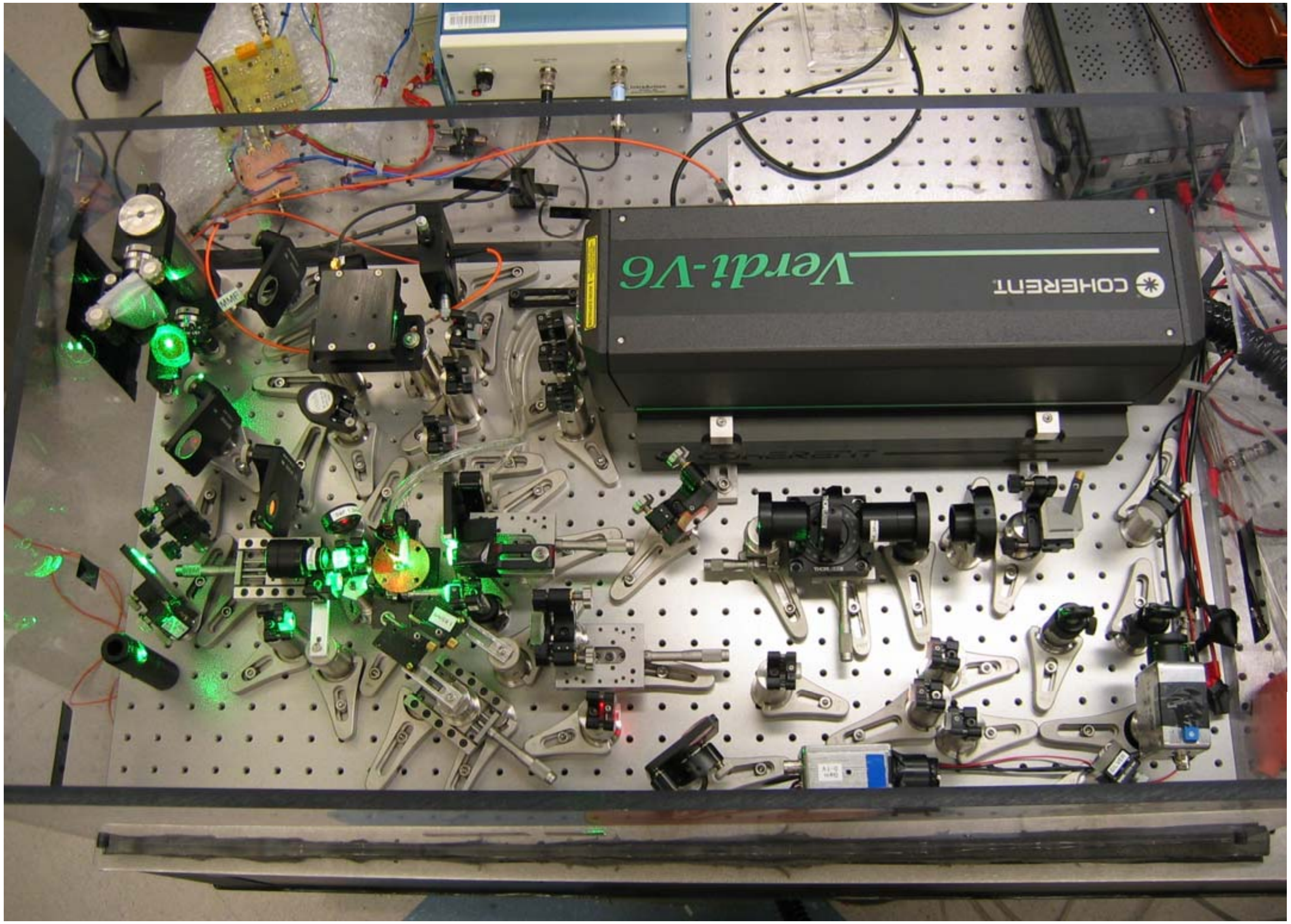
f-to-2f self-referencing:

~1 µW in 10 nm @ 550 nm

~1 mW in 10 nm @ 1100 nm

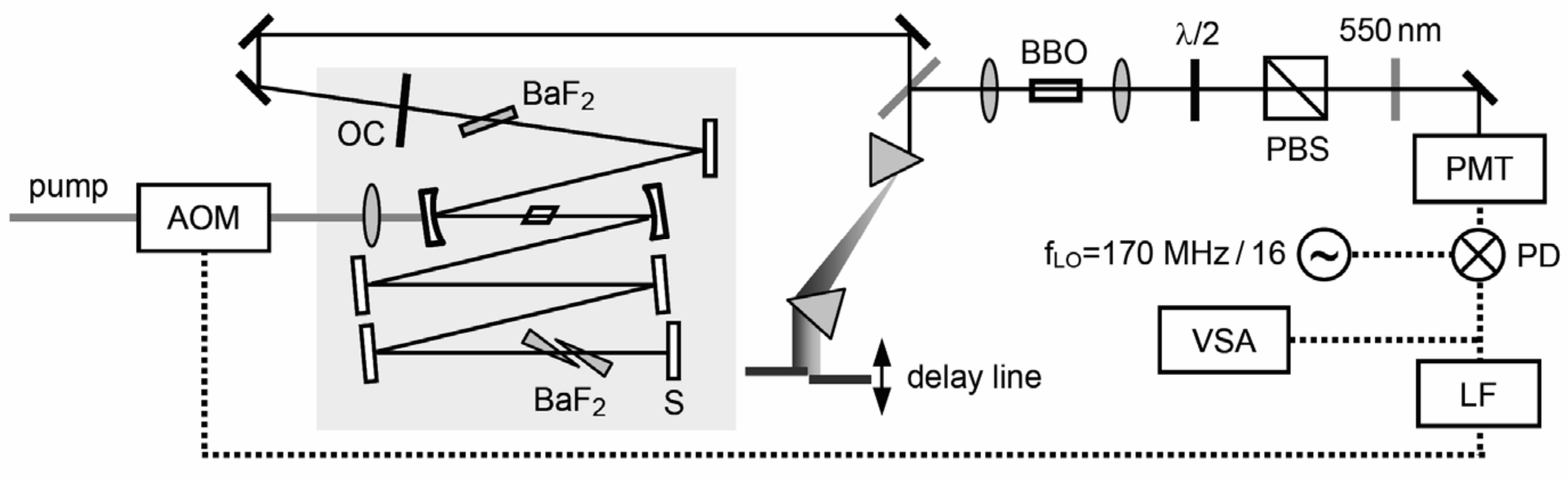
SHG conversion efficiency ~10^{-3} in 2 mm BBO

Carrier-envelope phase stabilized 200 MHz octave-spanning Ti:sapphire laser



Carrier-envelope phase stabilized

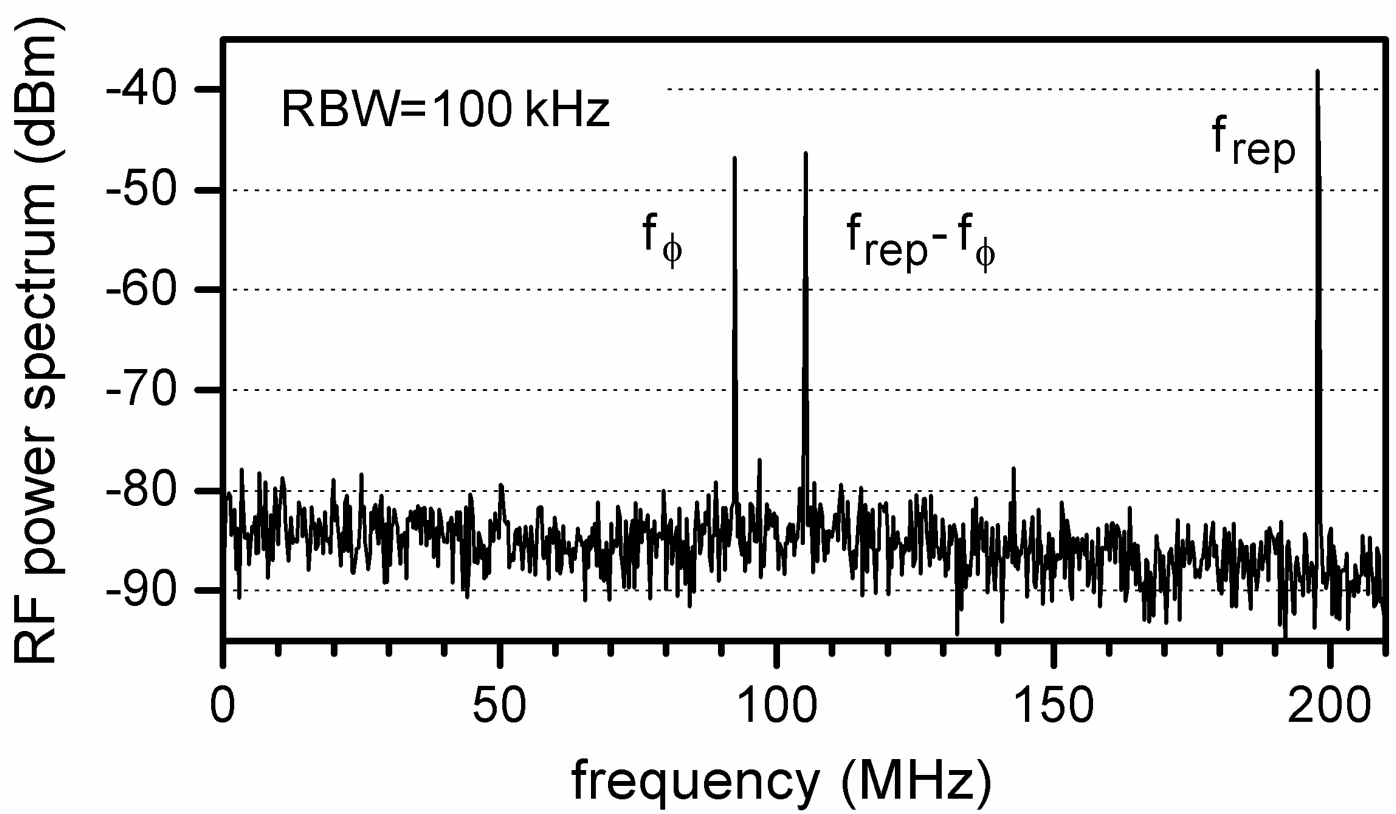
200 MHz octave-spanning Ti:sapphire laser



Heterodyne beat

~ 35 dB in 100 kHz bandwidth

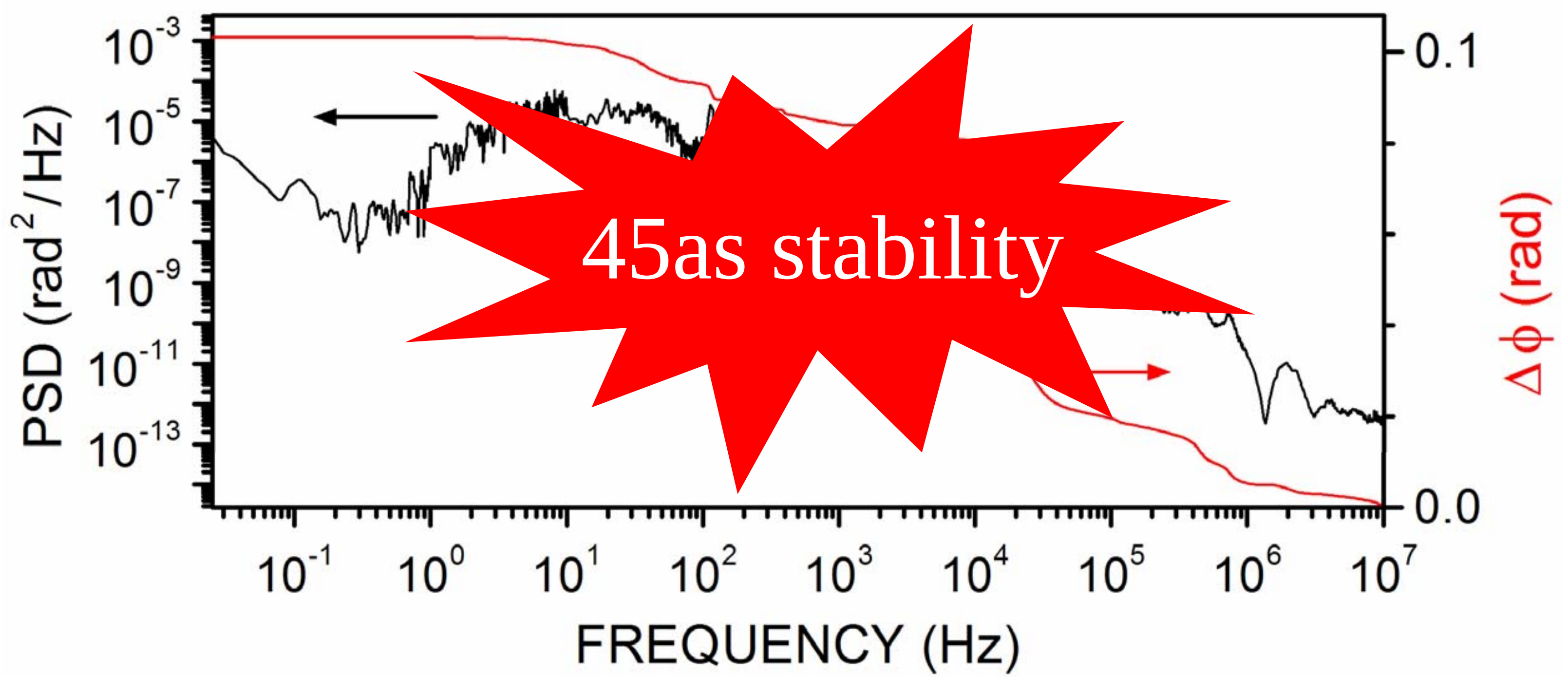
carrier-envelope beat linewidth < 10 Hz (measurement limited)



Carrier-envelope phase noise

power spectral density (PSD) of carrier-envelope phase fluctuations

integrated carrier-envelope phase error $\Delta\phi$



$\Delta\phi$=0.10 rad (integrated from 2.5 mHz to 10 MHz)

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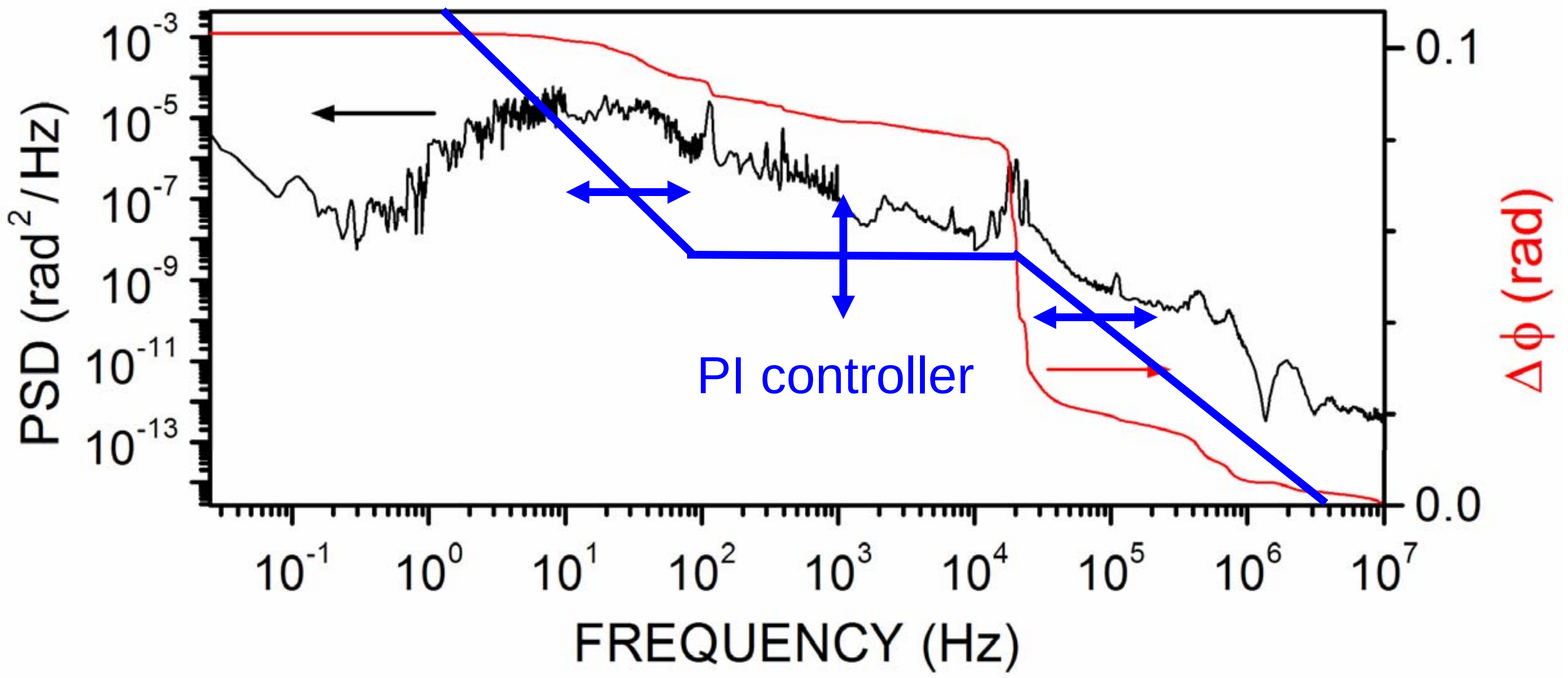

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(intermediate) Conclusions

- carrier-envelope phase stabilized
  200 MHz octave-spanning Ti:sapphire laser
- compact and stable f-to-2f self-referencing scheme
  without separating and recombining the f and 2f components
- carrier-envelope beat with 35 dB signal/noise (100 kHz bw)
- carrier-envelope beat linewidth < 10 Hz (measurement limited)
- integrated carrier-envelope phase error 0.10 rad (45 as @ 800 nm)
- Jitter can be further reduced by using EOM instead of AOM (lower latency)

Outlook down the track

- Possible to replace Ti:Sapphire laser with EDFL and external spectral broadening for use as master oscillator
- Similar locking technique for the carrier-envelope phase and referencing to atomic transition to compensate for long-term drifts.
- Benefit: few femtosecond stable, self-referenced clock at telecom wavelengths

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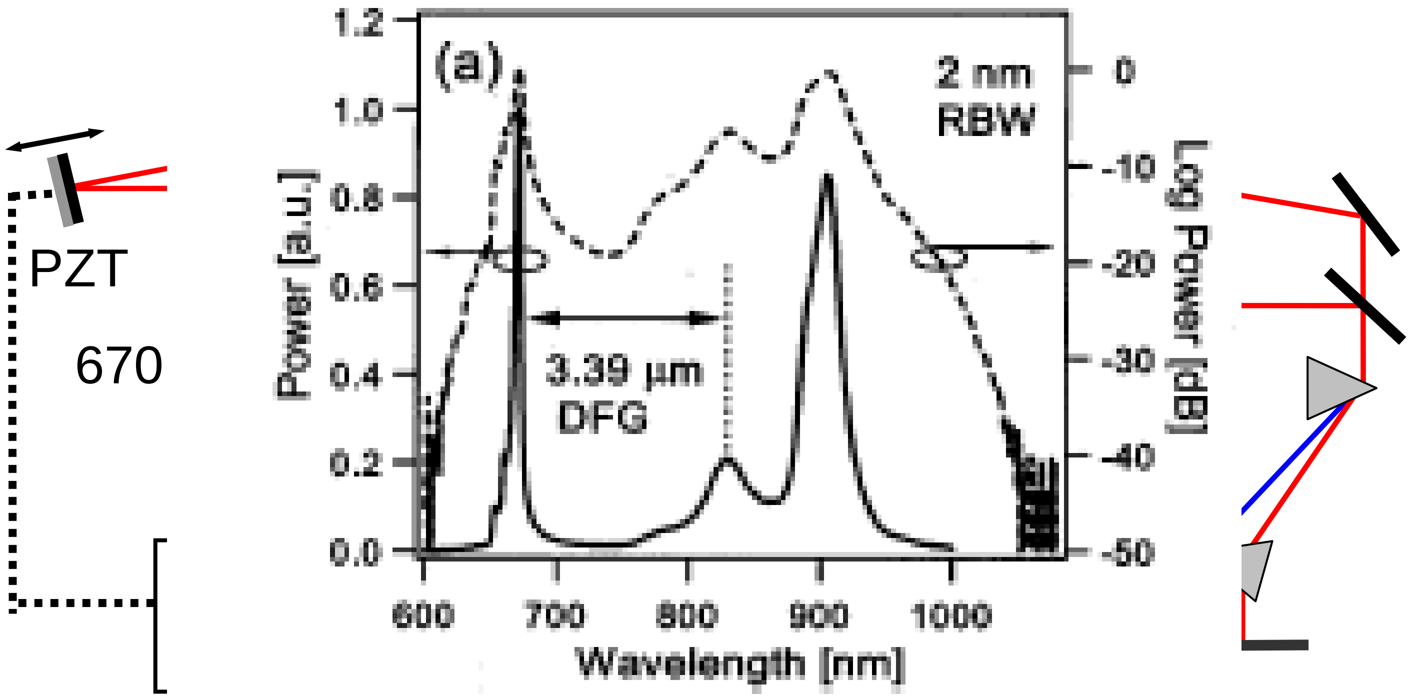
SFG-based optical clockwork

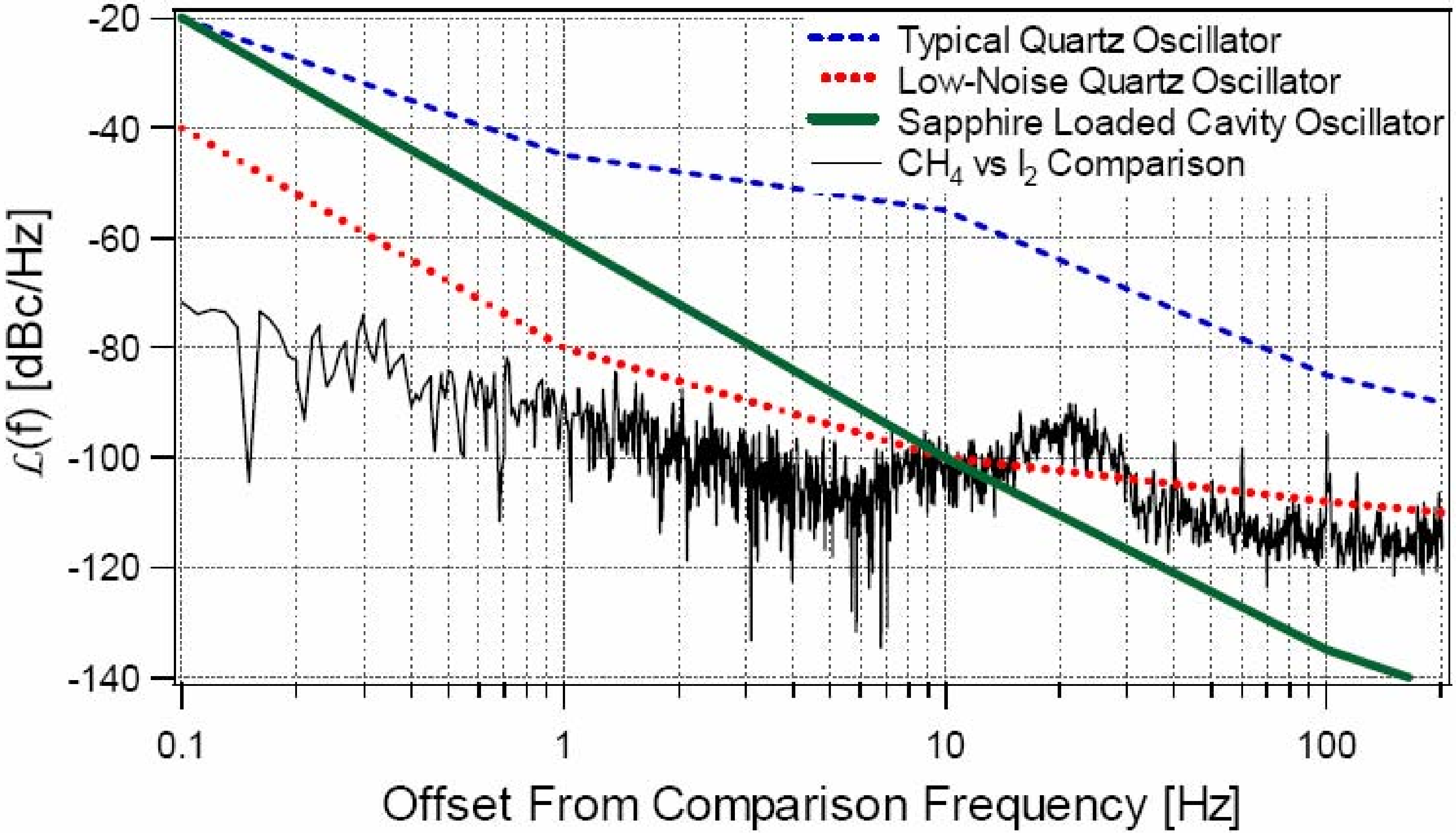


Benefit: lock at 88 THz gives extremely high phase resolution
Frequency comb acts as “zero”-noise divider

Collaboration with J. Ye, JILA and M. Gubin, Lebedev Phys. Inst.
to appear in Optics Letter

Single sideband phase noise of CH_4 clock

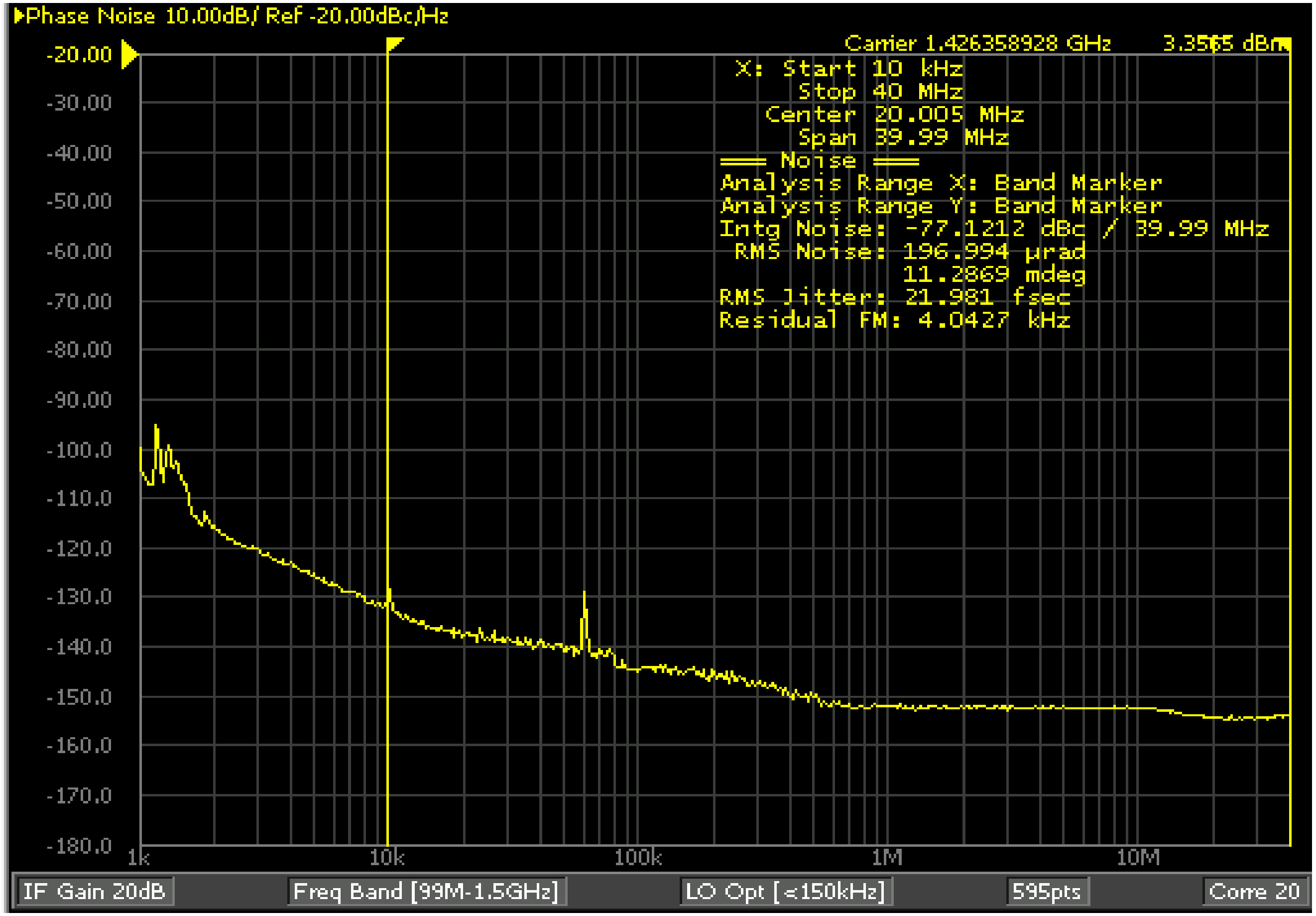
(compared to iodine-clock)



Data scaled to a 1 GHz carrier

Present high frequency phase noise of fiberlasers

Yb-fiber laser: <22 fs jitter (10kHz to Nyquist)



PRELIMINARY DATA

Summary

- High-repetition rate robust TiSa-laser with high quality carrier-envelope phase stabilization demonstrated
- Possible to also use EDFL with external spectral broadening
- Experiments underway to produce optical clocks with few-femtosecond stability

- Road to purely optical master oscillators open

Thank you for your attention