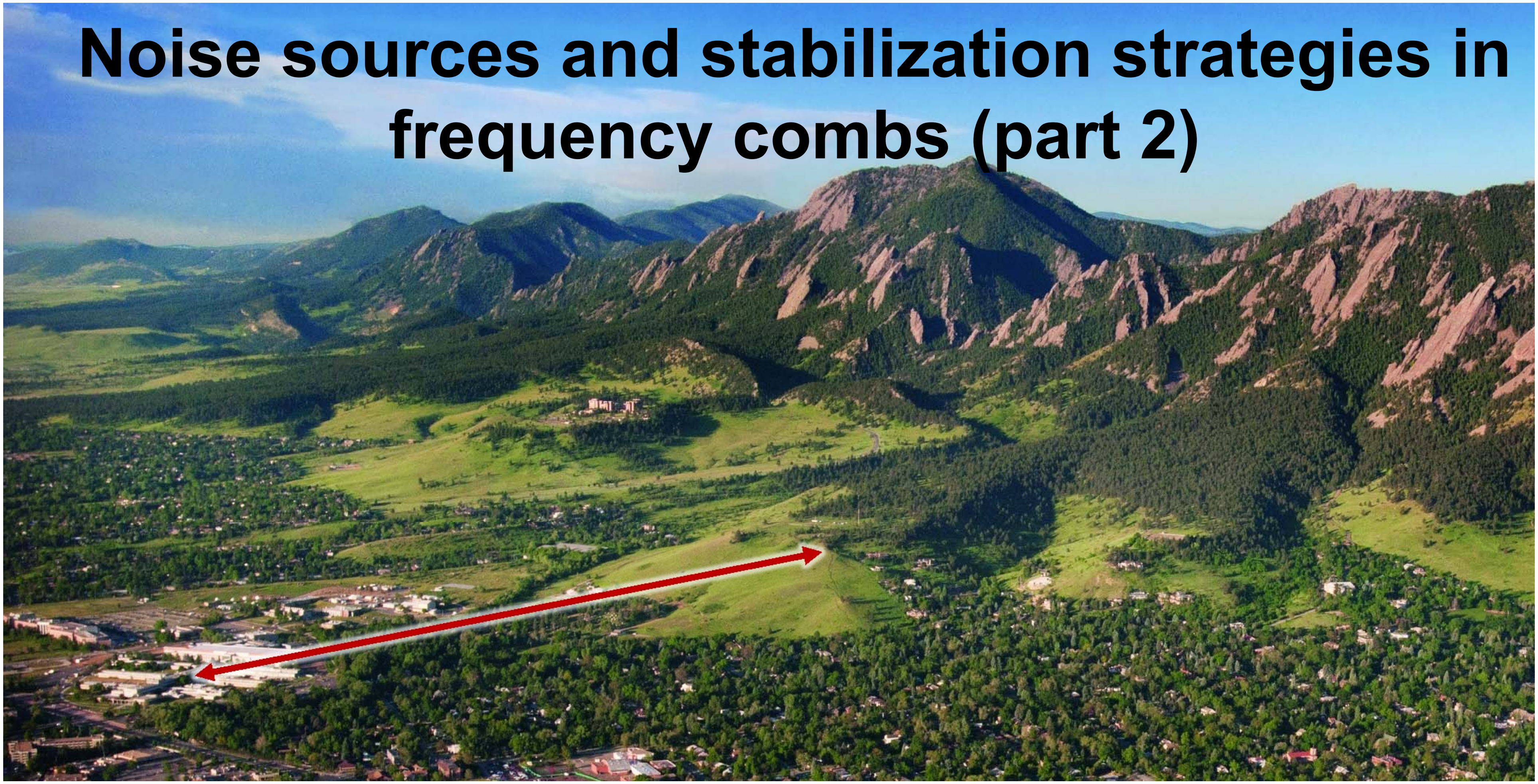
Noise sources and stabilization strategies in frequency combs (part 2)



ICTP Winter College on Optics
Trieste, Italy
February 17, 2015

Nathan Newbury
National Institute of Standards and Technology, Boulder, CO
nnewbury@boulder.nist.gov

Outline

- Applications and their requirements: what comb is right?
- Important options for overall design
- Fiber Frequency combs at NIST over the past decade
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  - Ring laser frequency comb
  - Double-pinned ring laser comb
  - Vibrationally robust PM Figure 8
- Latest NIST design: robust SESAM-based system

Recent review articles

RSI Review article on current NIST comb design:

L.C. Sinclair, J.-D. Deschênes, L. Sonderhouse, W. C. Swann, I.H. Khader, E. Baumann, N. R. Newbury, and I. Coddington, **Invited Article: A Compact Optically-Coherent Fiber Frequency Comb,** Review of Scientific Instruments 86, 081301 (2015);

See also**:** http://www.nist.gov/pml/div686/grp07/fpga-based-digital-control-box-phase-stablization-frequency-comb.cfm

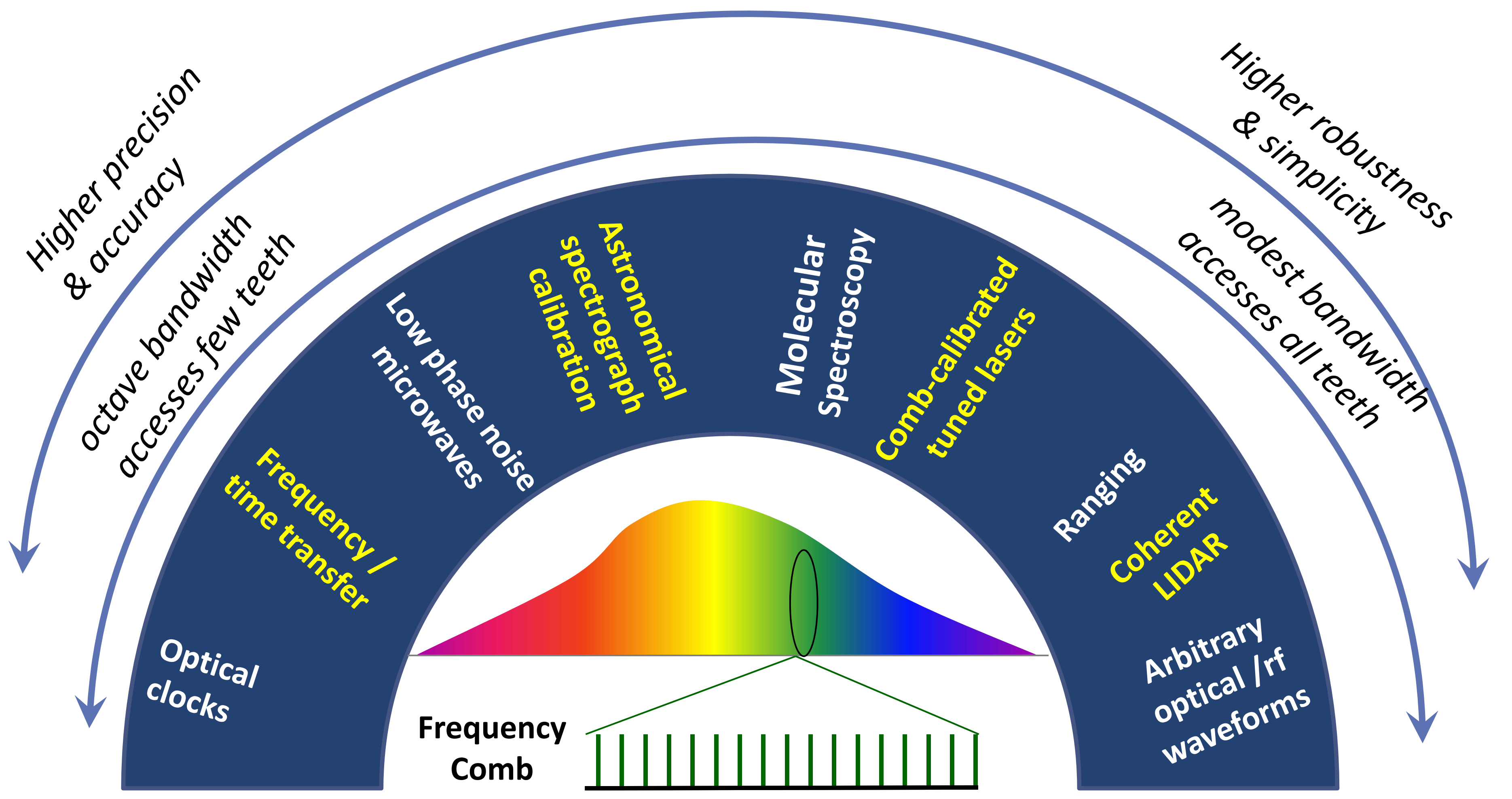
Nanophotonics upcoming review on fiber combs:

S. Droste, G. Ycas, B. R. Washburn, I. Coddington, NRN, **Optical Frequency Comb Generation based on Erbium Fiber Lasers**, Nanophotonics, to be published

Fiber frequency Comb noise

N. Newbury, W. Swann, J. Opt. Soc. Am. B, **Low-noise fiber-laser frequency combs,** 24, (2007)

Frequency Combs Support a Dizzying Array of Applications

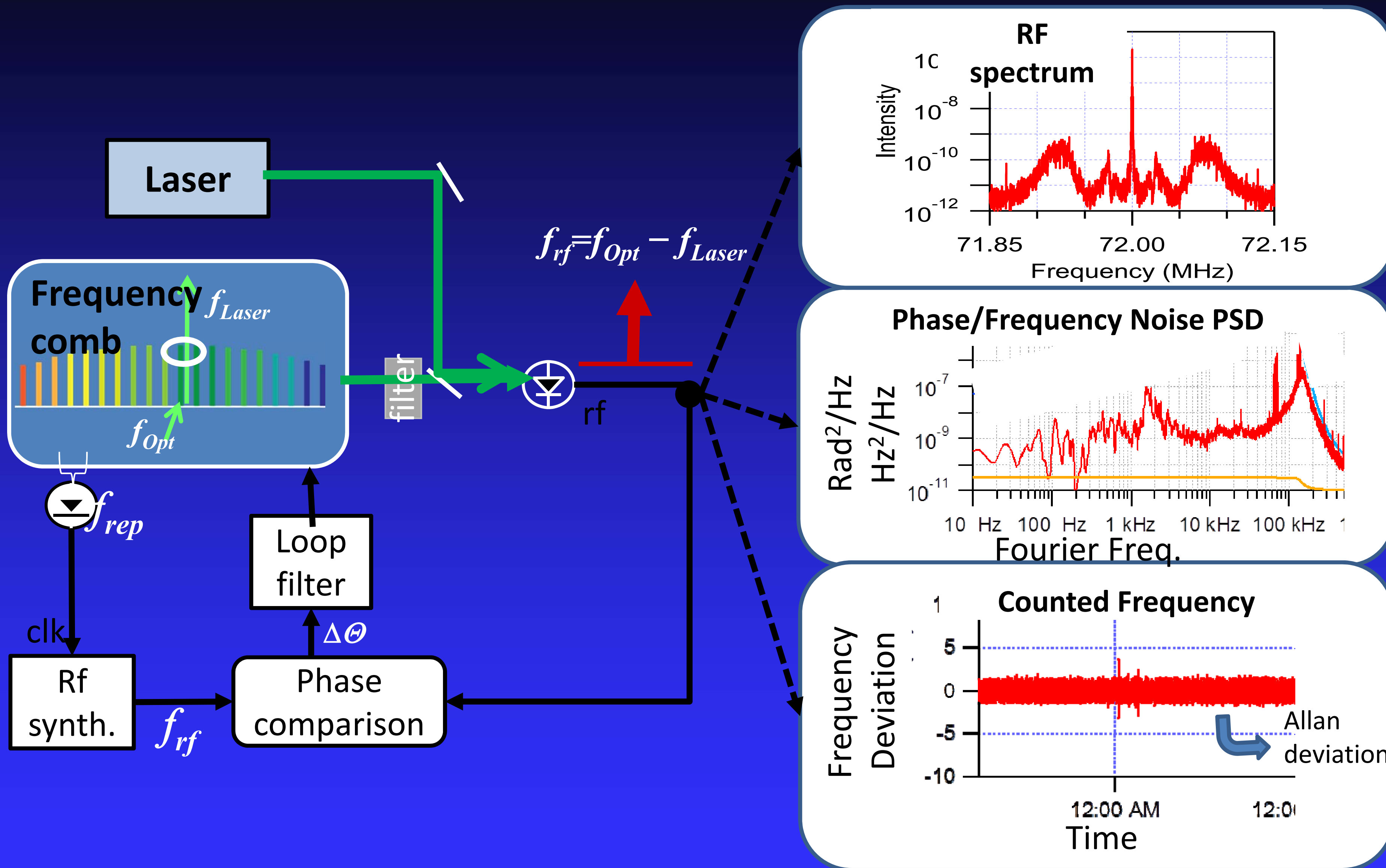


Newbury, Nature Photonics, *5*, 186 (2011)

Design considerations: What performance do I need?

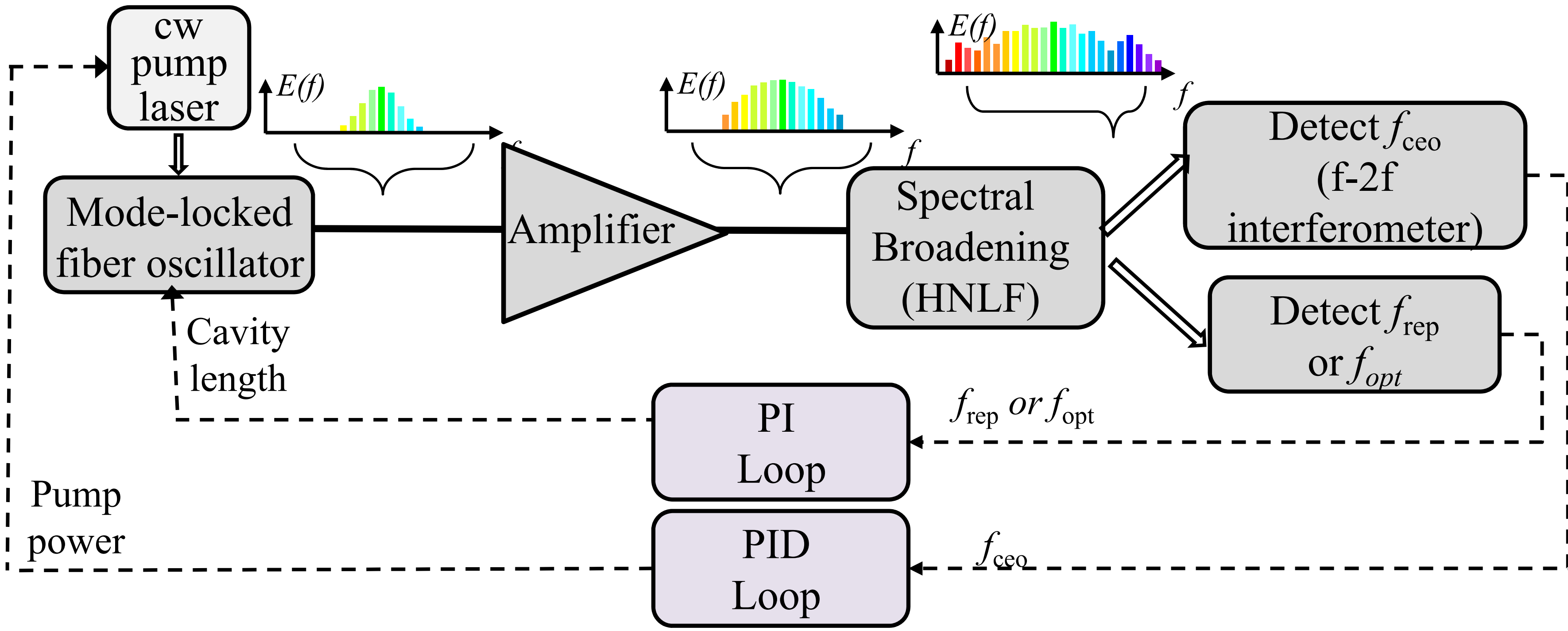
- Robust operation outside or close-to-perfect laboratory operation?
  - Ring laser vs SESAM laser, phase locking electronics, number/type of actuators, PM design, etc.
- Single comb experiment or multiple comb experiment?
  - Cost, interchangeability of sub systems, combined controls, ….
- Do I need self-referencing or not ?
  - Avoid f—2f doubling (ppln, EDFA, supercontinuum generation…)
- Optical stabilization or rf stabilization?
  - If RF stabilization, no reason for high bandwidth actuators…
  - If Optical, do I need optical coherence (< 1 rad phase noise)?
- How flat spectral coverage (e.g. spectroscopy or clocks)?
  - Dual branch or single branch, UV gratings,DFG branch etc.
- What type of coherence needed:
  - Absolute frequency accuracy?
  - Pulse to pulse timing jitter
  - High optical coherence
  - No phase slips …

Optical Phase Locked Loop



"in-loop" measures of comb phase coherence and frequency stability

Basic Comb Setup



Within this general setup, there are many different configurations

Mode-locked laser choice

- mode-locking mechanism
- PM or non-PM
- Cavity dispersion

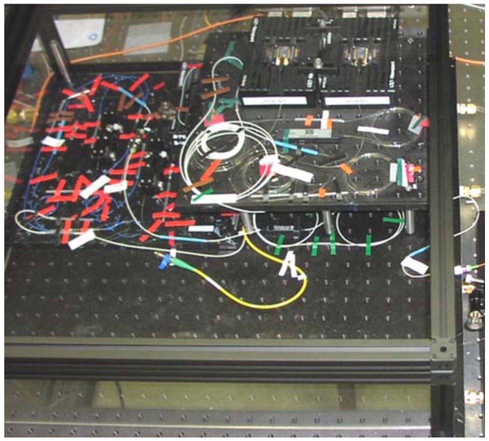
Actuator choice

Active control vs signal processing

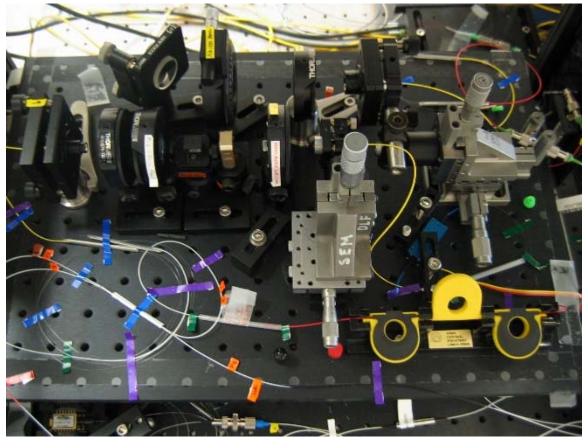
Analog vs Digital

f-2f detection

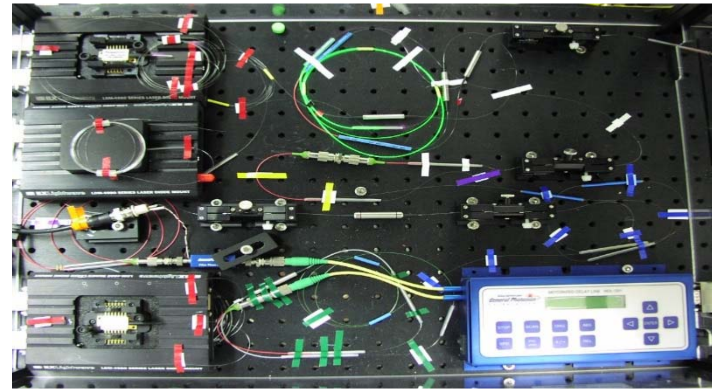
Some Different NIST Fiber Combs



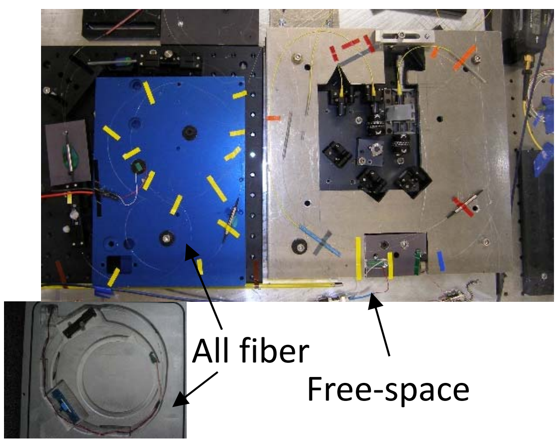
NIST/OFS Figure-8
Fiber Frequency Comb
Washburn et al., Opt. Lett. **29**, 250 (2004)



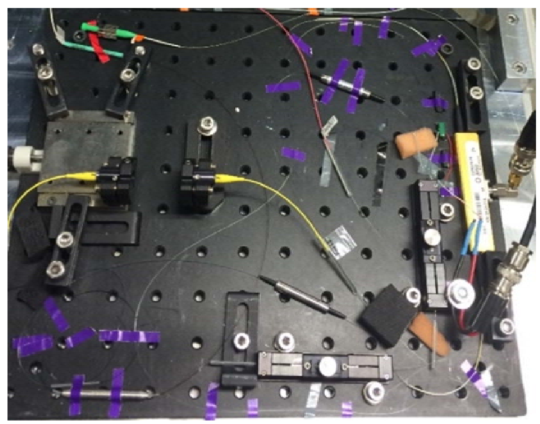
stretched-pulse ring laser
Fiber Frequency Comb
McFerran et al., Opt. Lett. 31, 1997 (2006)
Swann, Opt. Lett. **31**, 3046 (2006).



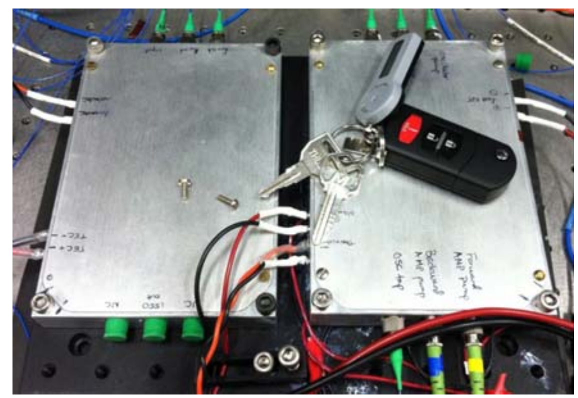
stretched-pulse ring laser with variable rep rate
Fiber Frequency Comb
Washburn et al, OE, 12, 4999 (2004)



Stretched-pulse ring lasers
Fiber Frequency Combs
Coddington et al, PRA, 81, 043817 (2010)



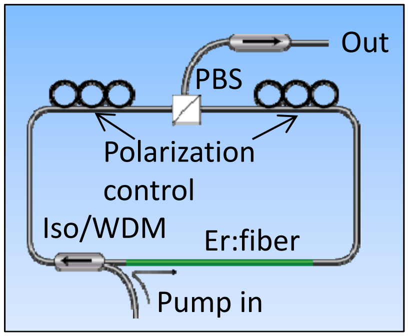
Ring laser with intracavity EOM
Swann et al. OE, 19, 243817(2011)



Linear SESAM Linear cavity Fiber Frequency Comb
Sinclair, OE, 22, 6996 (2014)
Sinclair, RSI, 86, 081301 (2015);

Some Different Modelocked laser designs

Ring Laser

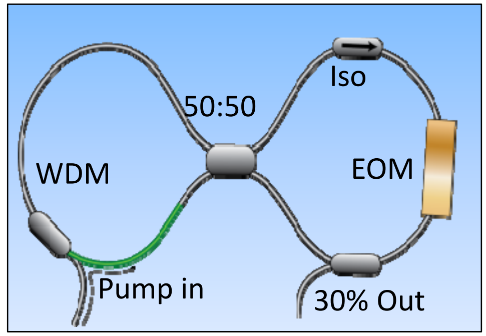


- Soliton or stretched pulse
- “Instantaneous” effective saturable absorber
- Short pulses (broad bandwidths)
- Quiet
- Not PM compatible
- Touchy

K. Tamura, *et al*, Opt. Lett. 19, 46 (1994).

W. C. Swann, *et al.* Opt. Lett., **31**, 3046 (2006).

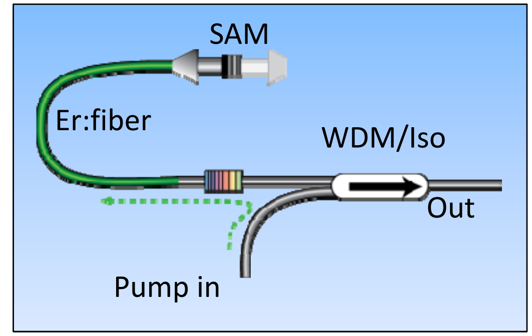
Figure 8 Laser



- Soliton or stretched pulse
- “Instantaneous effective saturable absorber
- Short pulses (broad bandwidths)
- Quiet
- High rep. rates challenging
- PM compatible
- Non-PM version touchy

J. W. Nicholson, *et. al*, Opt. Express 14, 8160 (2006).
E. Baumann, *et. al*, Opt. Lett. **34**, 638 (2009).

Linear Saturable-absorber Laser



- Normally soliton operation
- Performance SAM dependant (SESAM, carbon nanotube …)
- Usually longer pulses (narrow bandwidth)
- PM compatible
- High repetition rates
- Reproducible (with same SESAM)

I. Hartl, *et. al.*, Opt. Express **13**, 6490 (2005).
H. Byun, *et. al*, Opt. Lett. **33**, 2221 (2008).
T.-A. Liu, *et. al*, Opt. Express **19**, 18501 (2011).

Many other variants (e.g. Figure 9 laser, ring with saturable absorber ….)

Actuator Choices

	Actuator	Bandwidth [kHz]	Modulation depth on f_{rep}	Fixed point [THz]
Always need	Cavity length (Temperature)	<0.001	1 kHz/K	~1
Always need	Pump power modulation	10 - 1000	20 Hz/mW	~200
Always need	Cavity length (PZT)	1 - 100	0.1 - 10 kHz	0-1
Sometimes	EOM	500 - 4000	100 Hz	~1-100
Sometimes	AOM	100 - 1000	0 Hz (5-10 MHz only on f_{ceo})	∞
Future?	Graphene	1000	~10 Hz	~200

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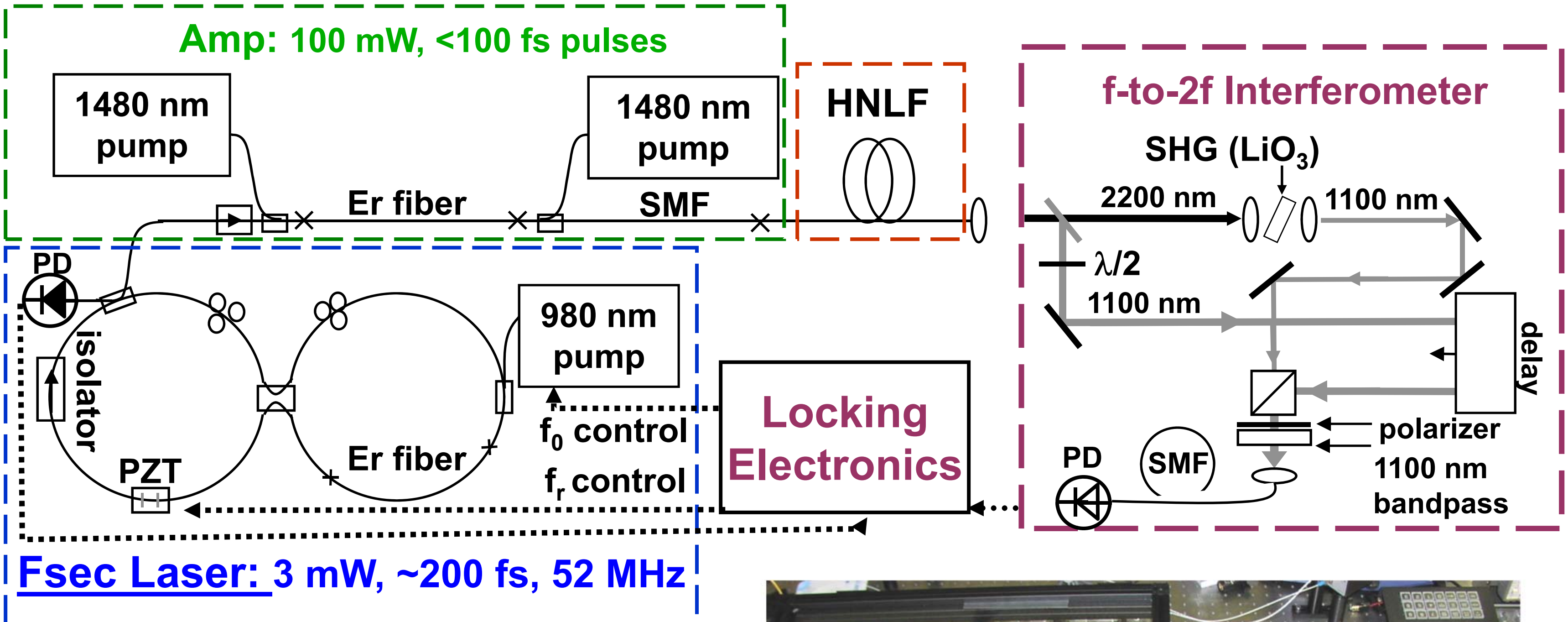
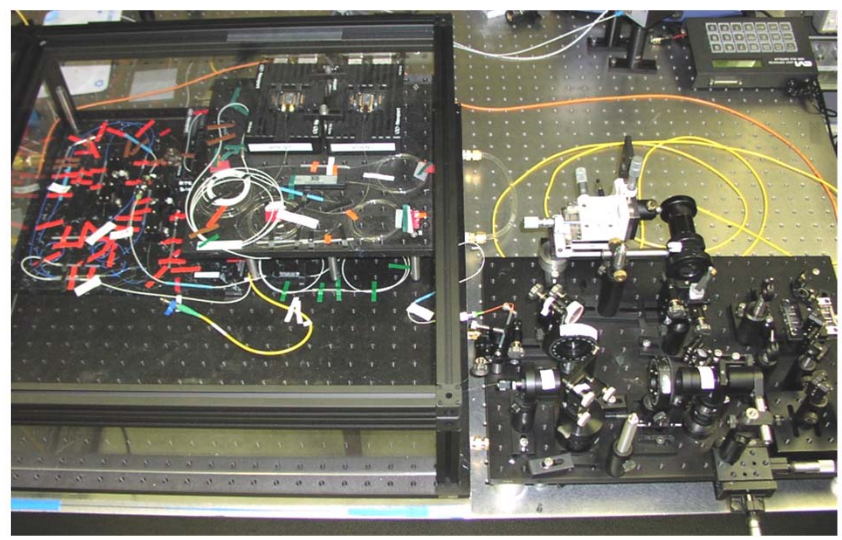
  - Not record breaking laboratory performance
  - But it is reproducible, with interchangeable parts, and works outside

Figure-8 Based Frequency comb (2003-2005)

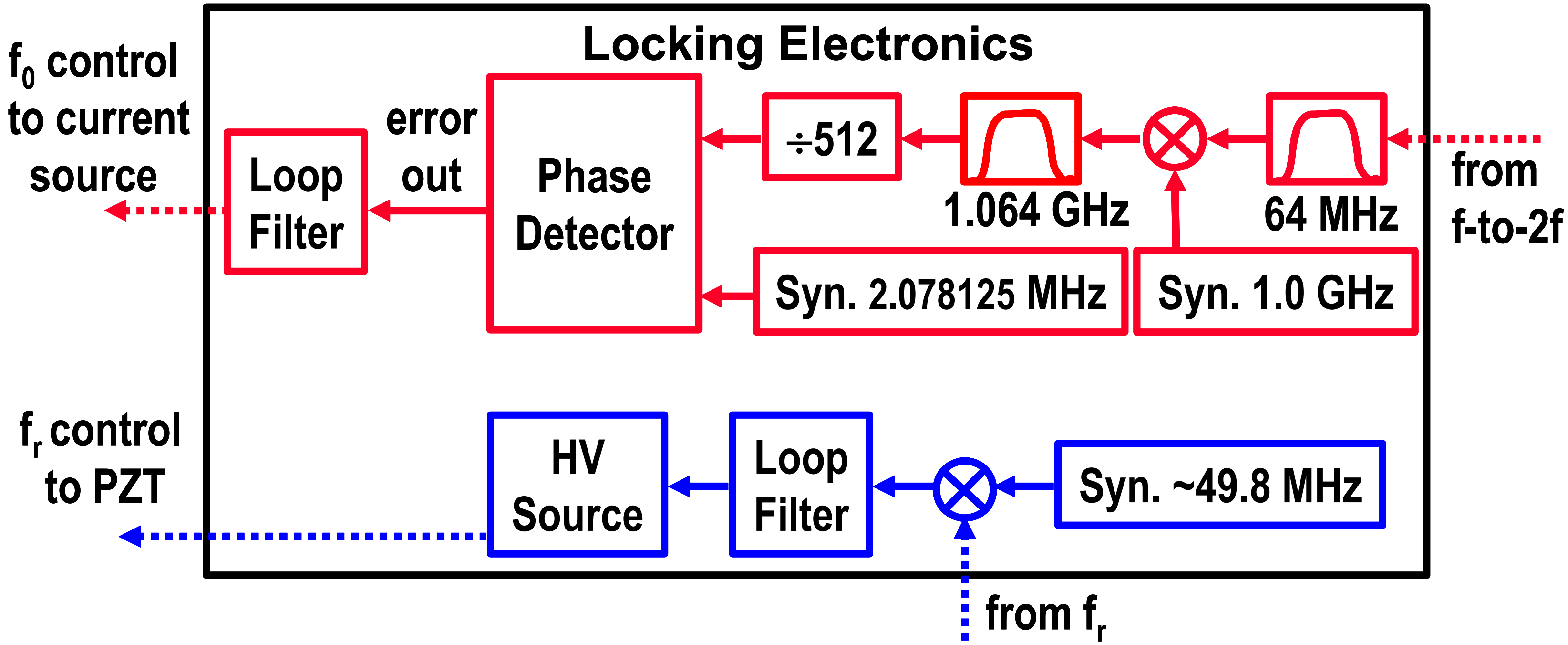
NIST





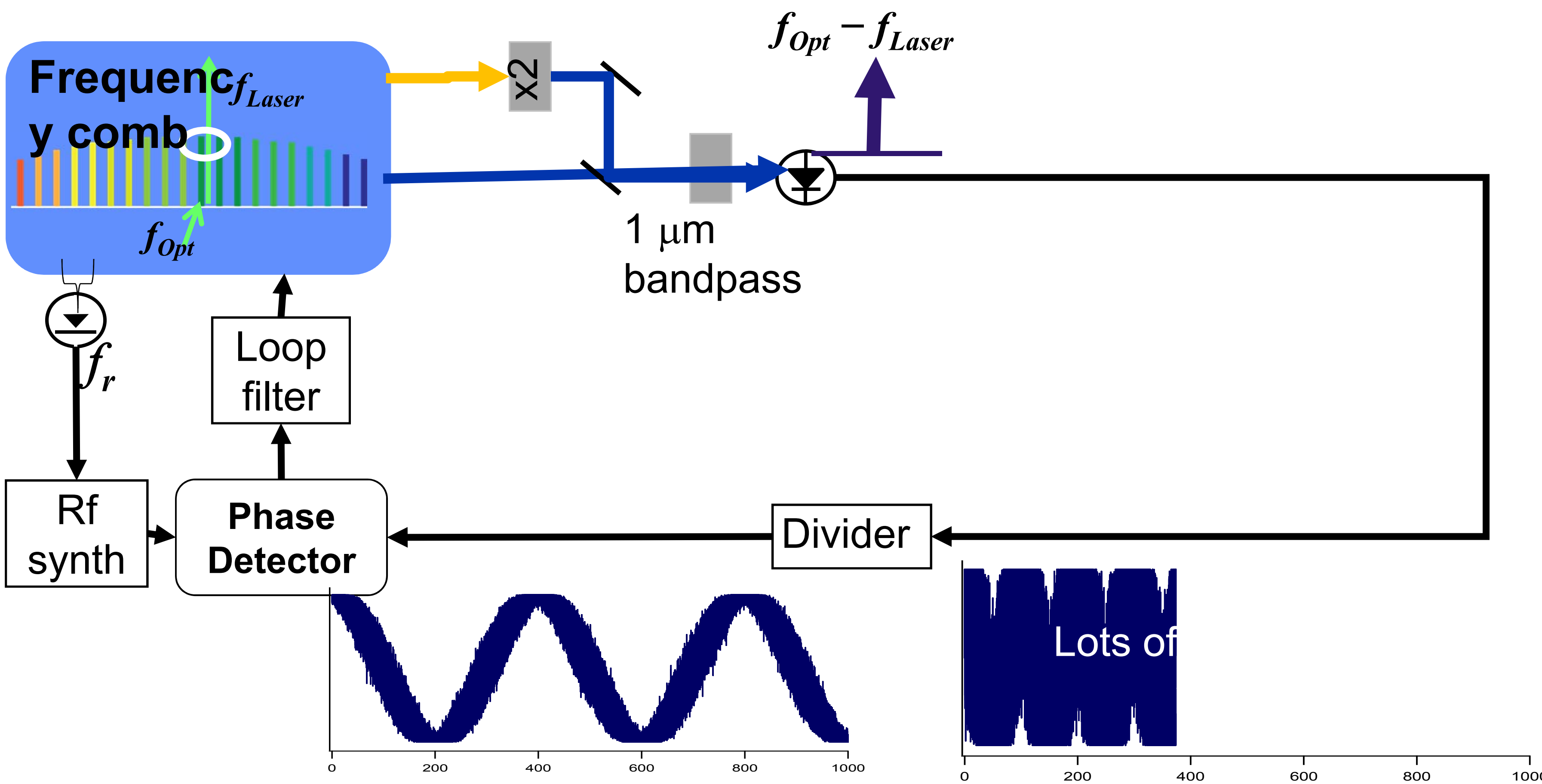
- Self-referenced lock to rf oscillator
- Non-PM Figure 8 laser: difficult to modelock
- Used "frequency division" to capture offset lock
  - Phase lead not yet implemented

Locking Electronics

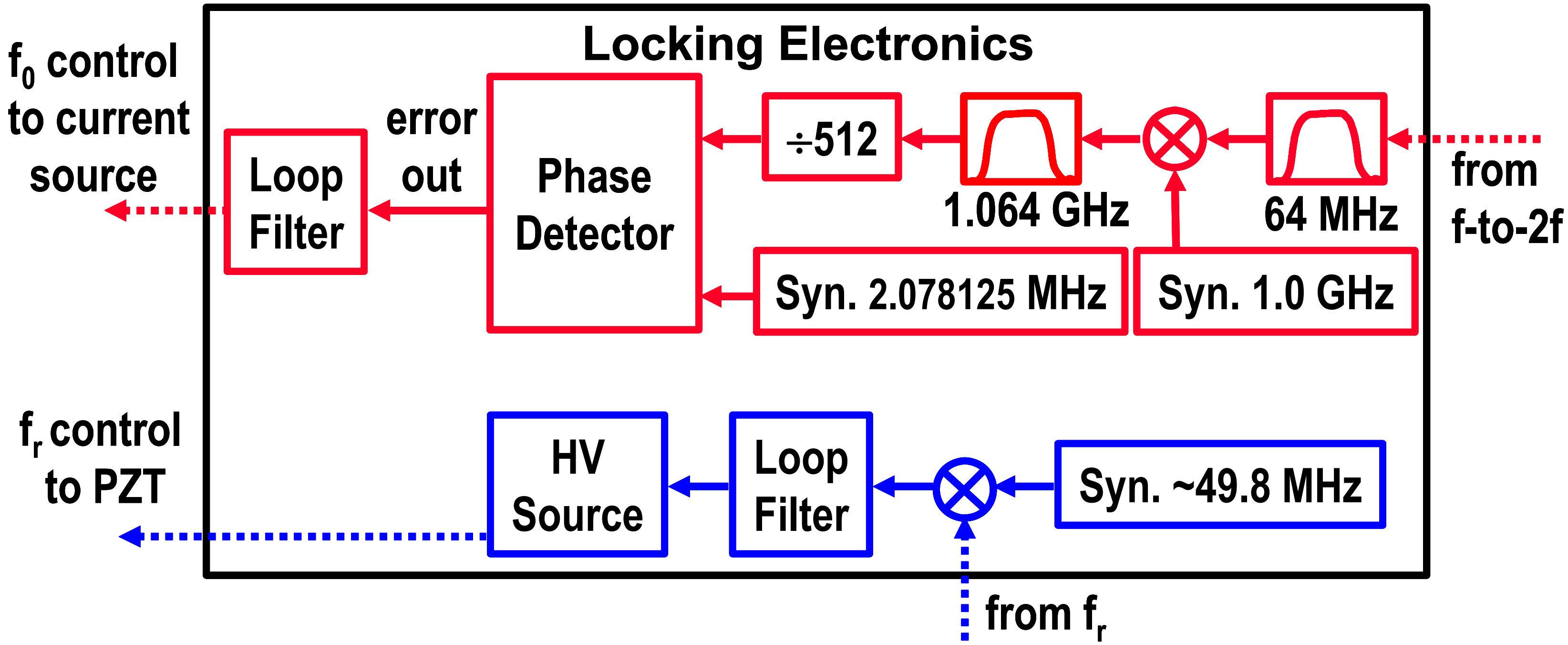


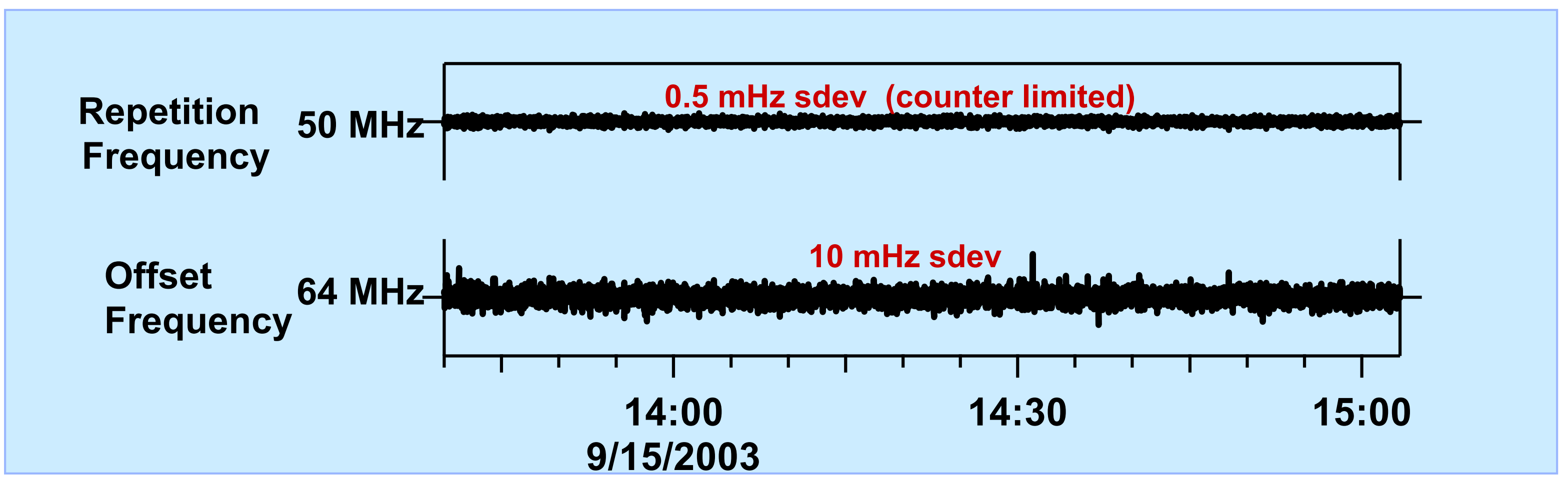
Offset Frequency Phase Lock

Why include a divider?
Trick to increase dynamic range of phase capture



Locking Electronics

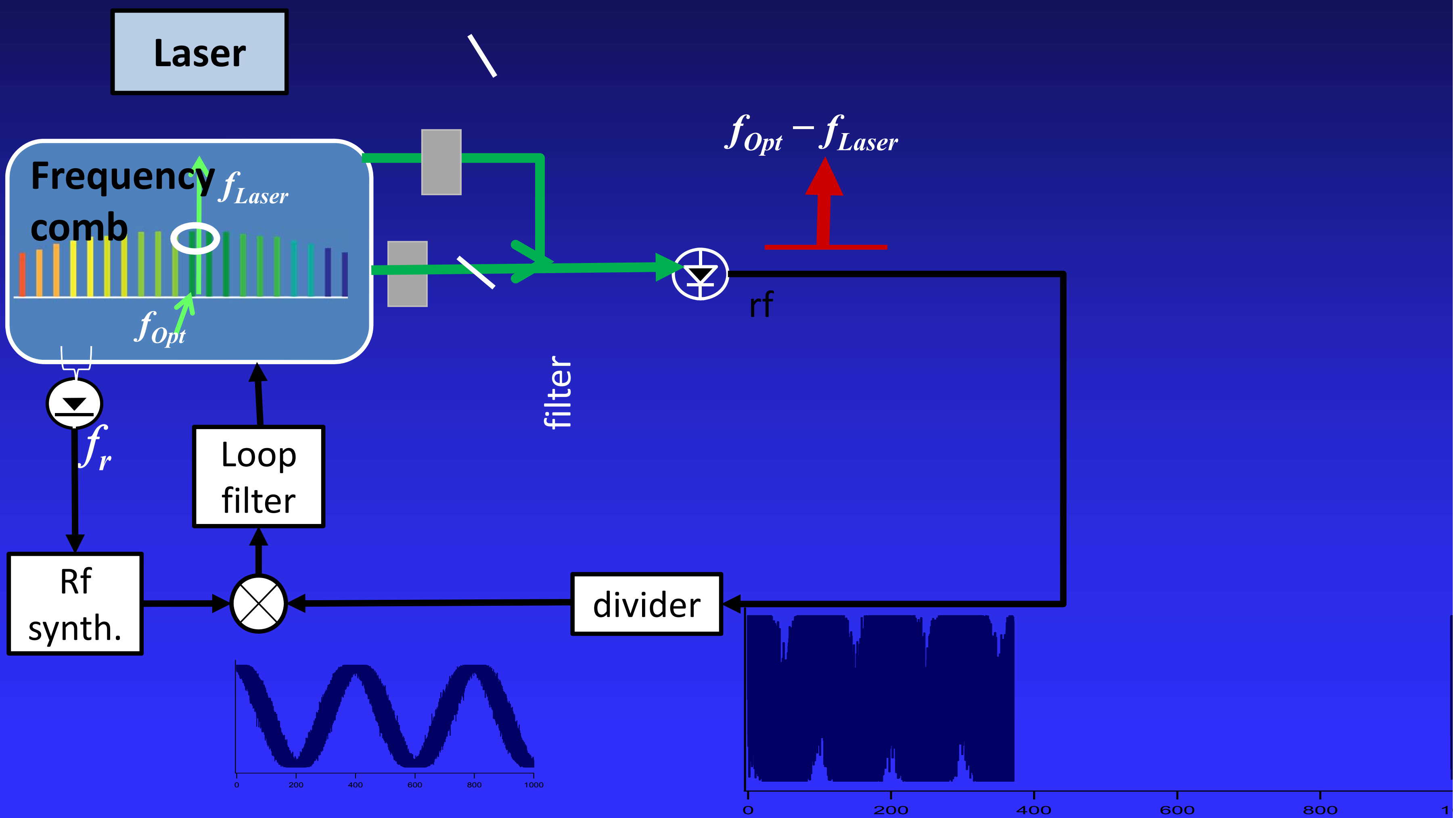




Offset Frequency Phase Lock

Why include a divider?

Increases dynamic range of phase capture



Also use digital phase detector rather than a mixer for improved phase dynamic range

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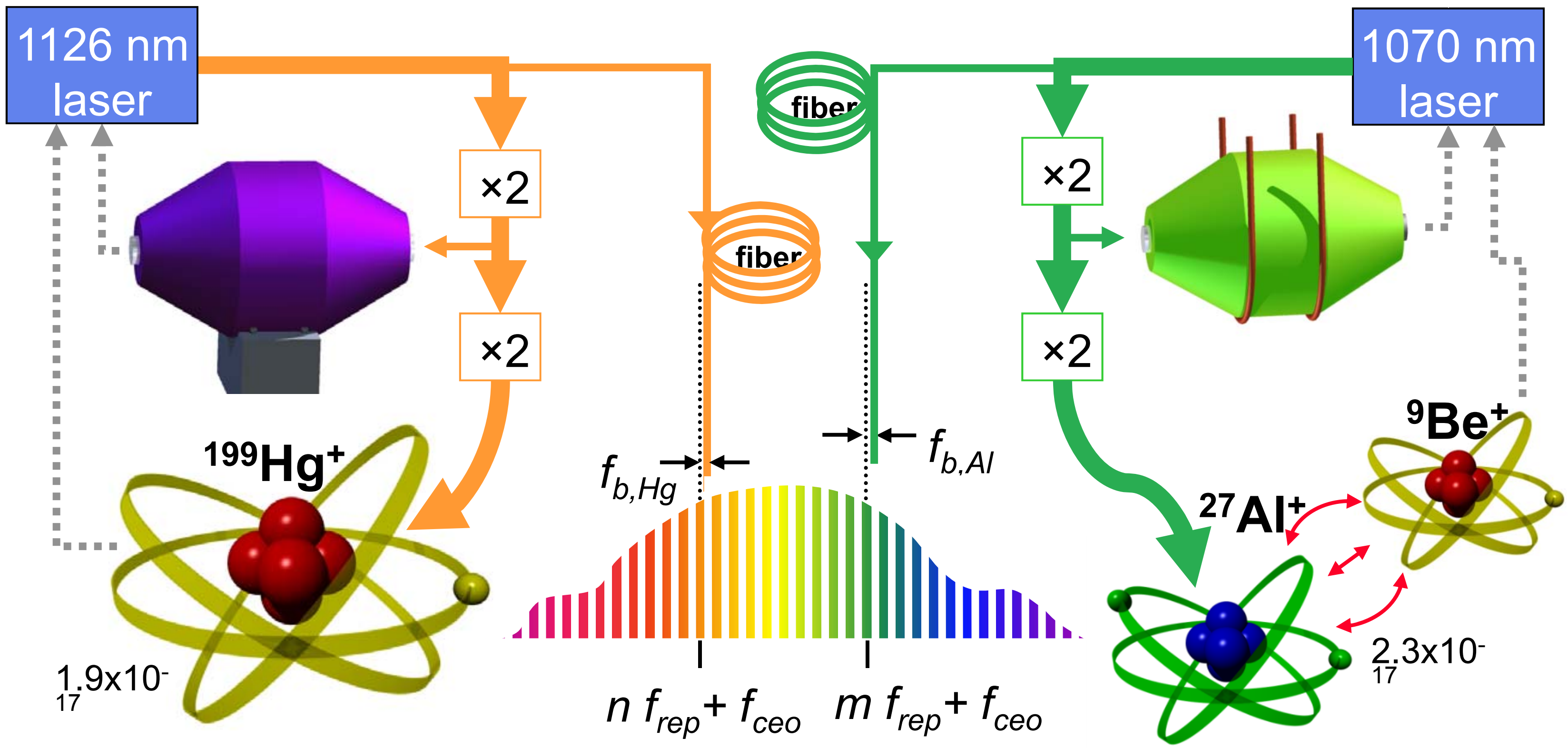
Ion Clock Comparisons:
Need an optically self-referenced comb



Al^+/Hg^+ ratio known to clocks agree to 5.3×10^{-17}

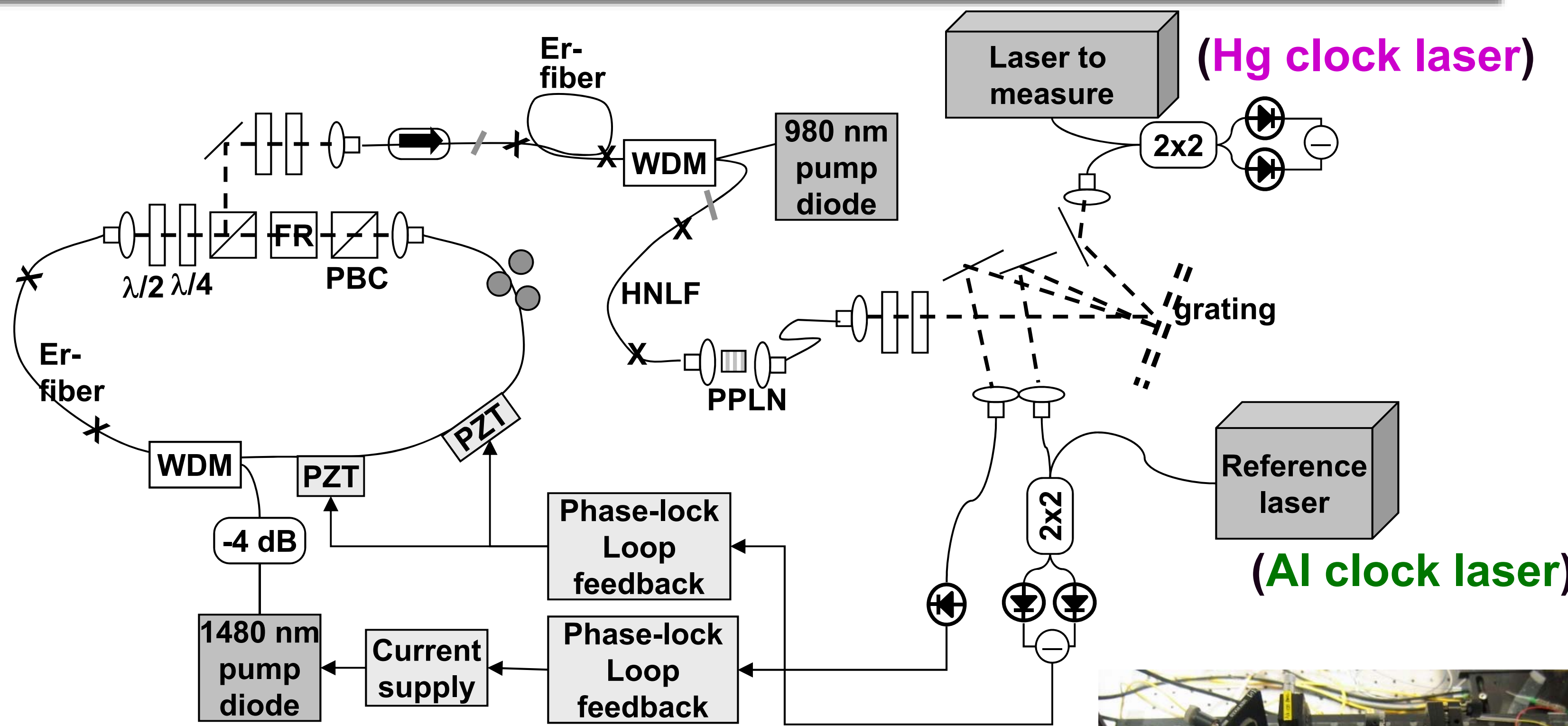
First absolute fractional frequency uncertainty below 10^{-17}

Two Al^+ clocks agree to 1.8×10^{-17}

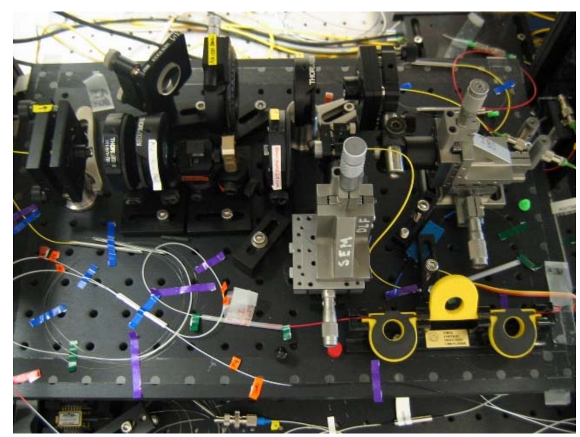
T. Rosenband et al., Science ***319****, 1808 (2008)*

Optically Stabilized Fiber Comb

Stretched Pulse Ring Laser Design



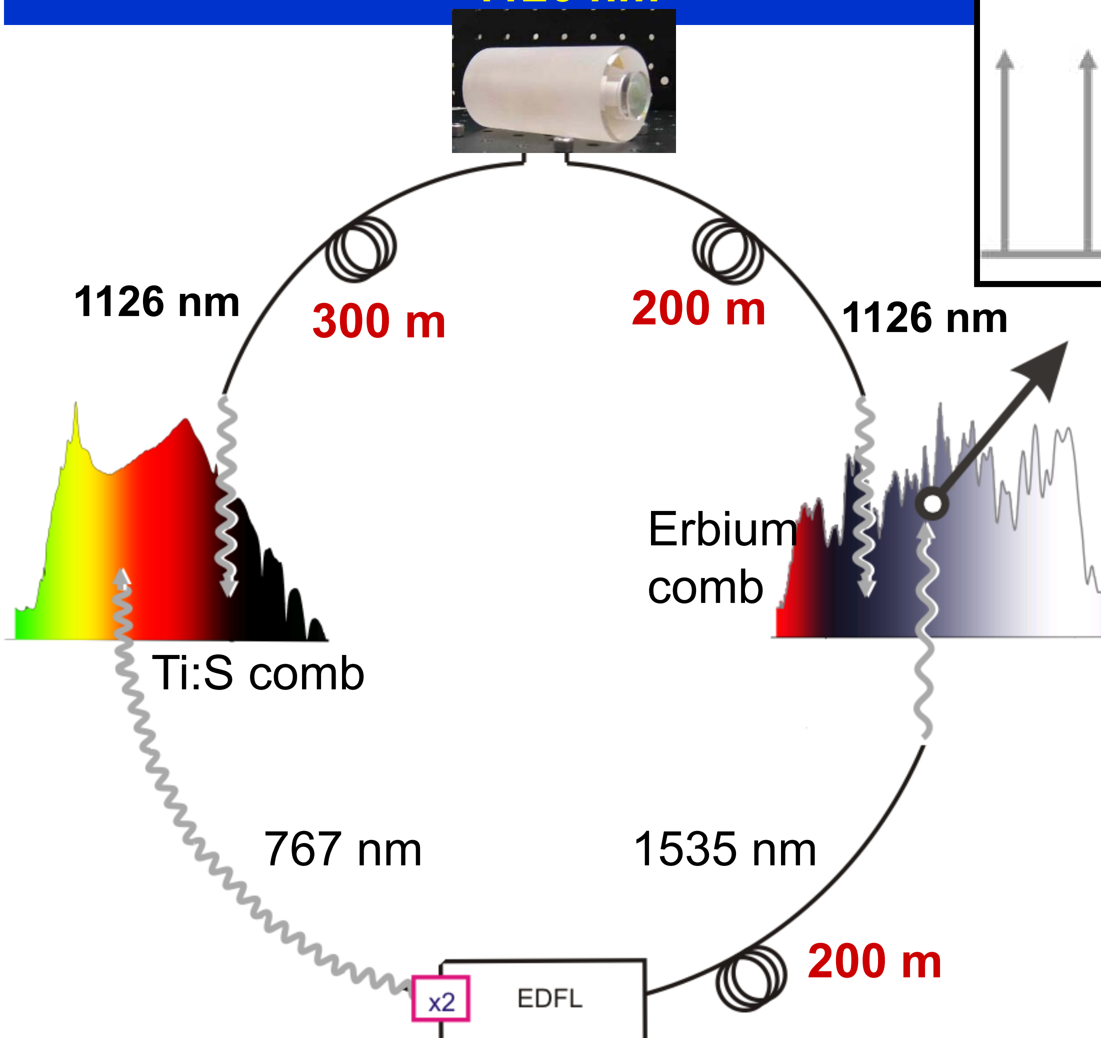
- Greater than 50 kHz feedback
  - Phase-lead compensation of pump control
  - Modified PZT mounting
- “In line” PPLN f-2f -> with higher SNR
- Performance = Ti:Sapphire comb
- Robustness > Ti:Sapphire comb

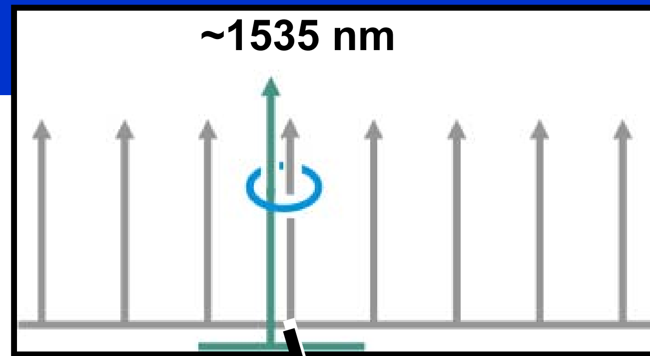


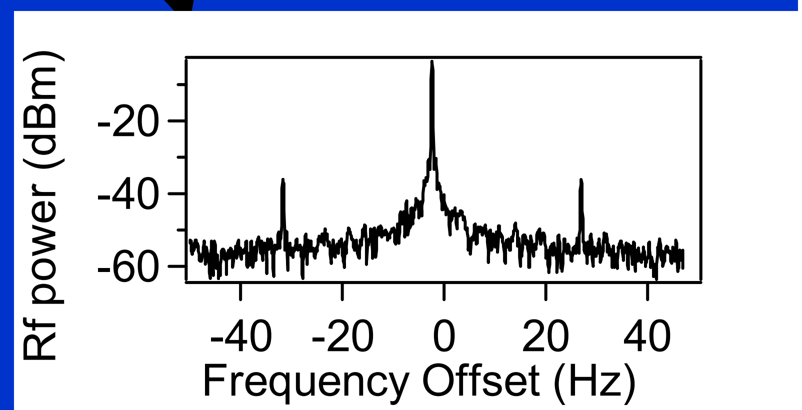
McFerran et al., Opt. Lett. 31, 1997 (2006)
Swann et al, Opt. Lett., (2006)

Coherent Network: Er comb <-> Ti:Sapph comb

Cavity stabilized CW laser
1126 nm







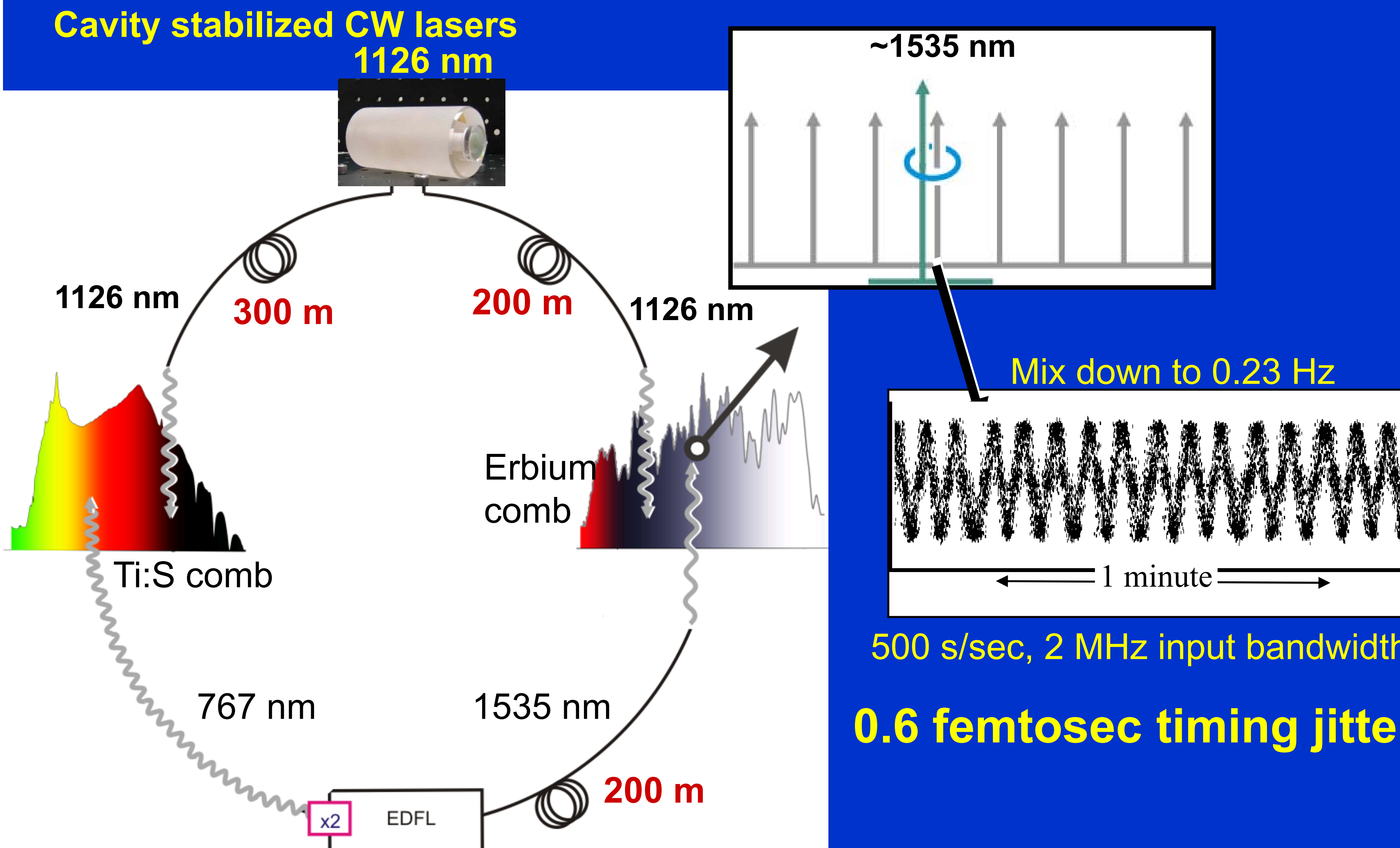
0.1 Hz line width

(Instrument-limited)

CW Transfer oscillator and doubling PPLN

I. Coddington et al., Nature Photonics, Vol 1, 283 (2007)

Coherent Network



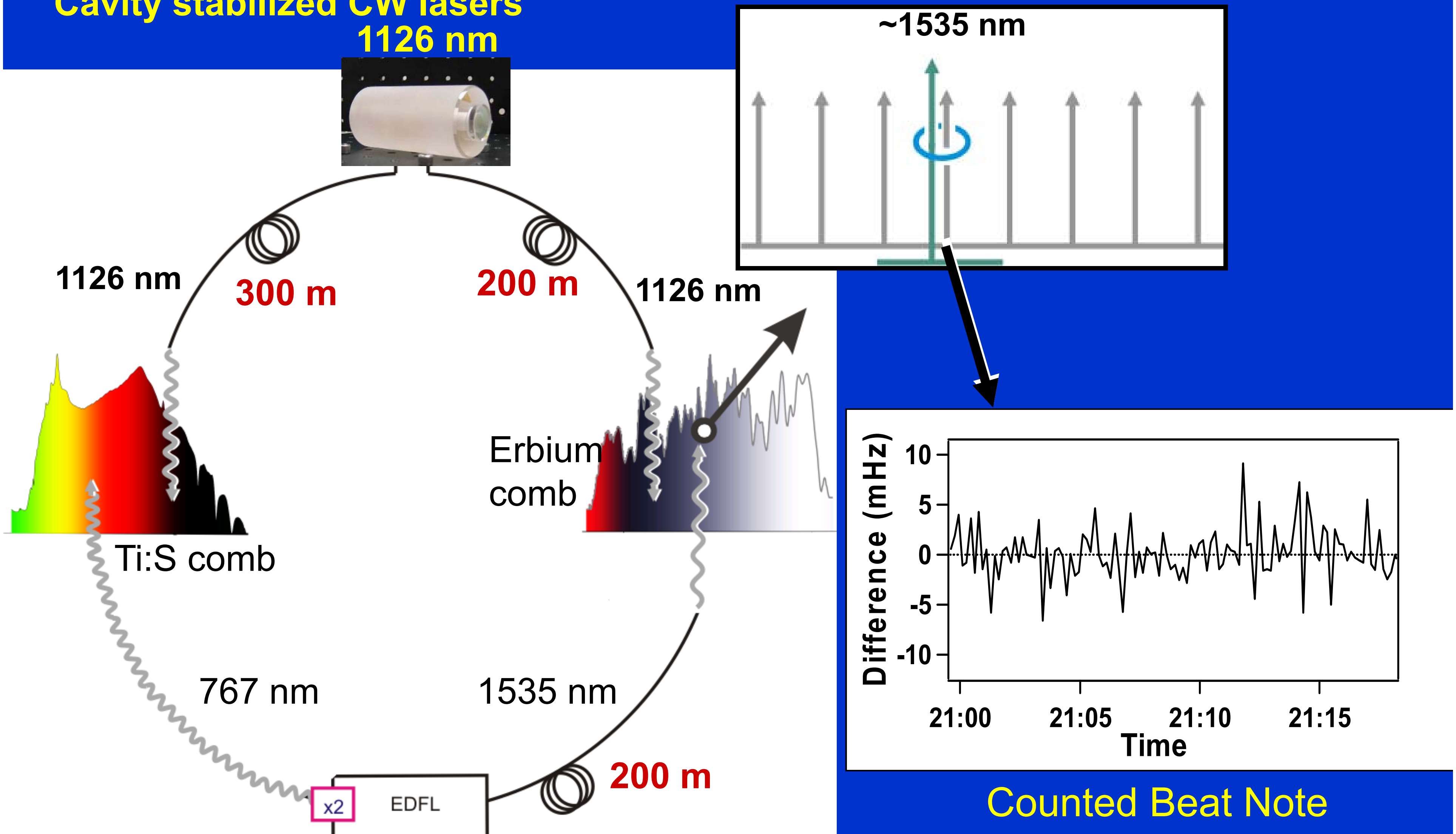
0.6 femtosec timing jitter

CW Transfer oscillator and doubling PPLN

I. Coddington et al., Nature Photonics, Vol 1, 283 (2007)

Coherent Network

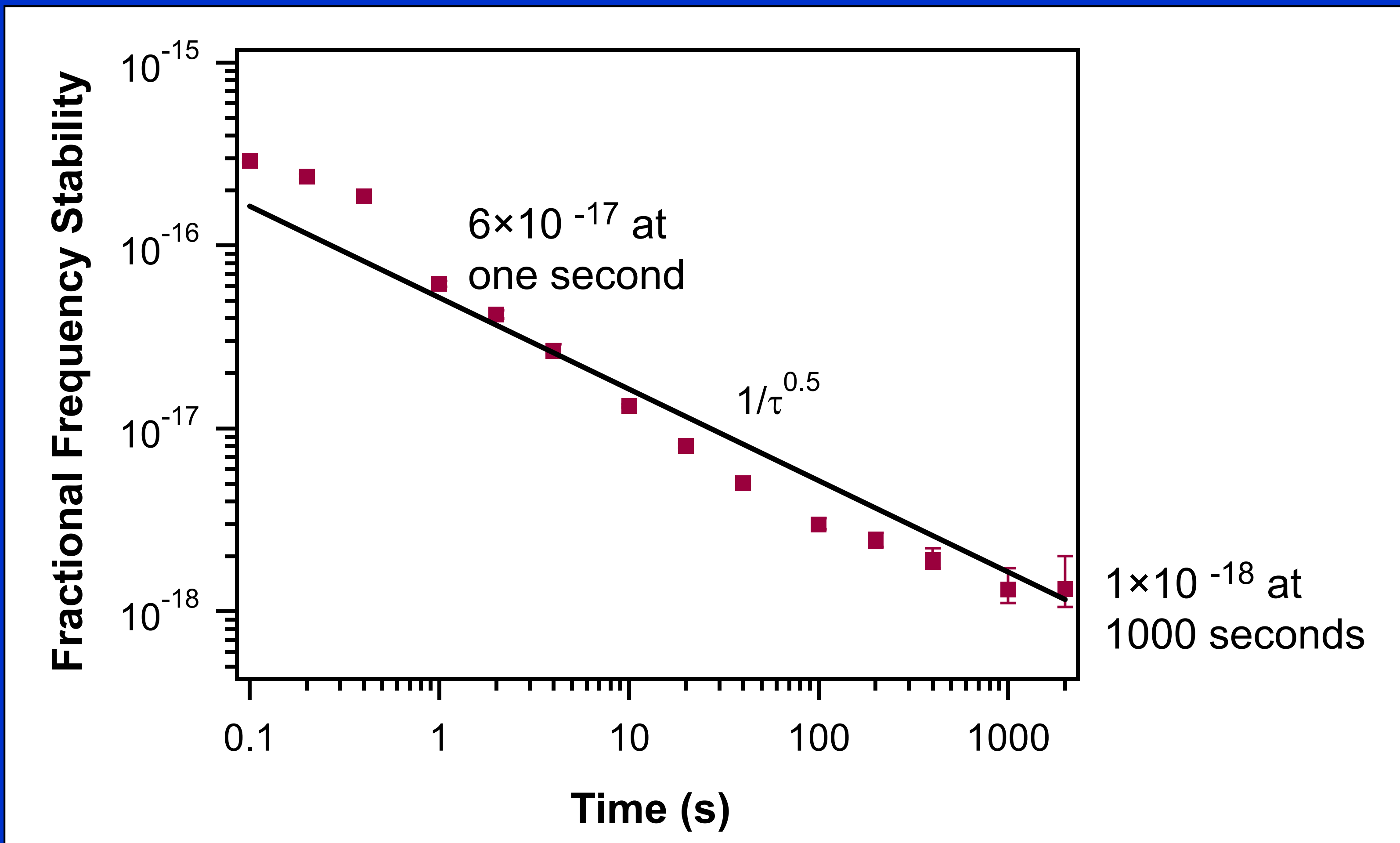
Cavity stabilized CW lasers
1126 nm



CW Transfer oscillator and doubling PPLN

Counted Beat Note
(Measured – Predicted)

Residual Comb Stability
Allan deviation



In other words, our 200 THz optical frequency has 12 mHz of noise in 1 sec.

An upper limit on comb stability

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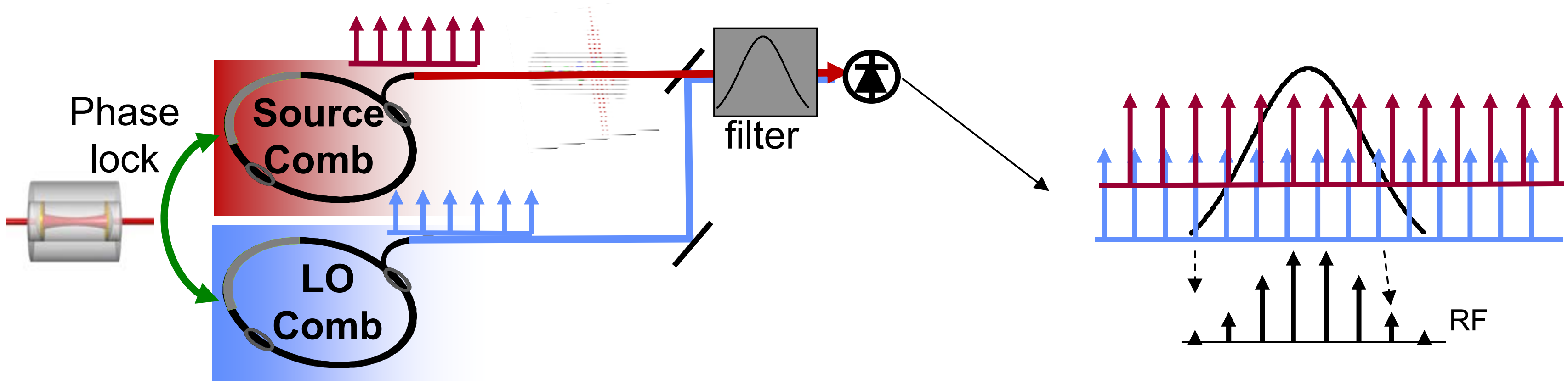
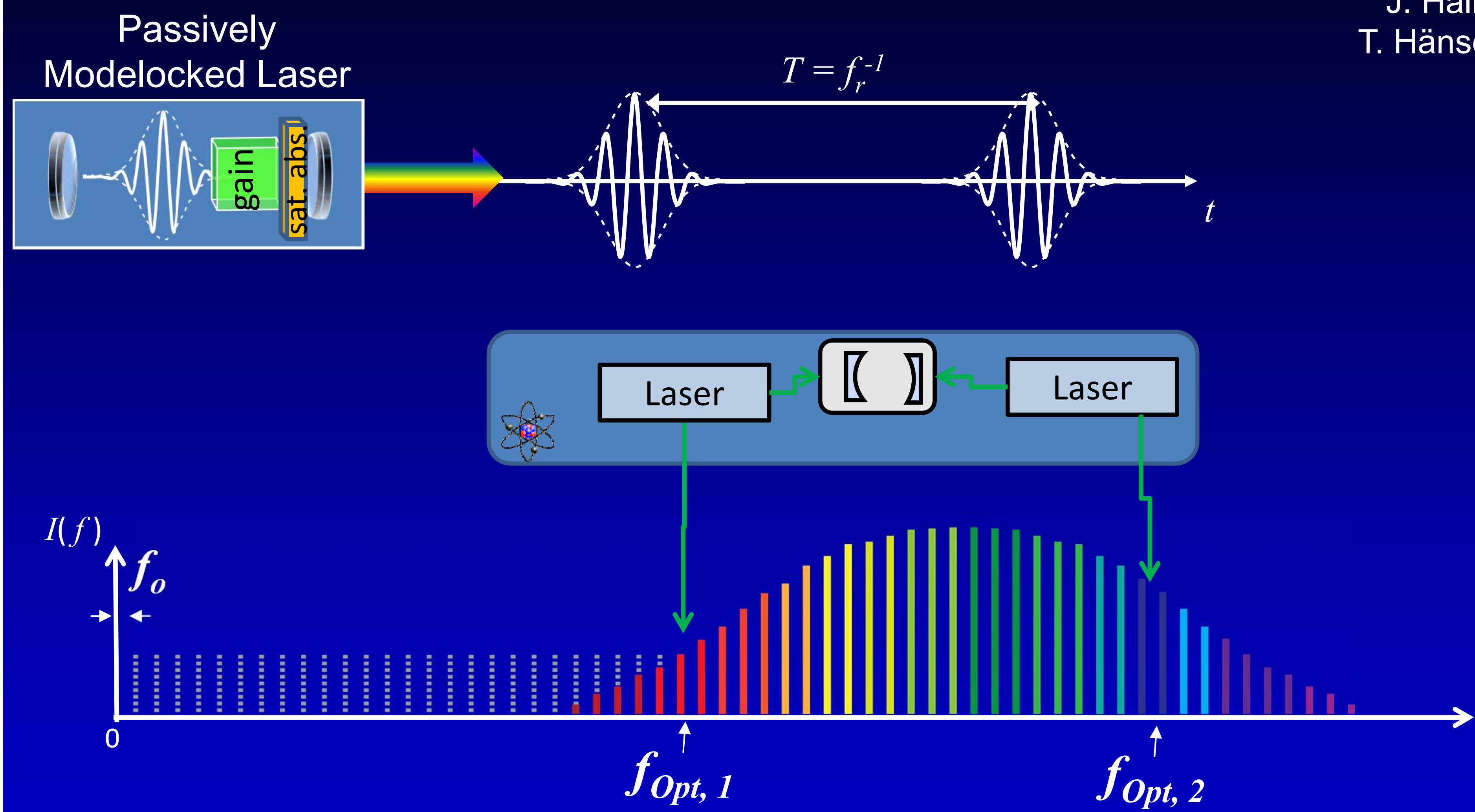
Stabilizing Frequency combs for Dual-comb spectroscopy



- **Mutual coherence critical**
  - Need < 1 radian optical phase noise
  - Use high bandwidth PZT + external AOM (+ EOM)
- **Absolute frequency accuracy less critical**
  - ~ 1 MHz more than enough
- **Use double pinning approach**
  - Avoids need for self-referencing!
  - Optimize supercontinuum for spectroscopy instead

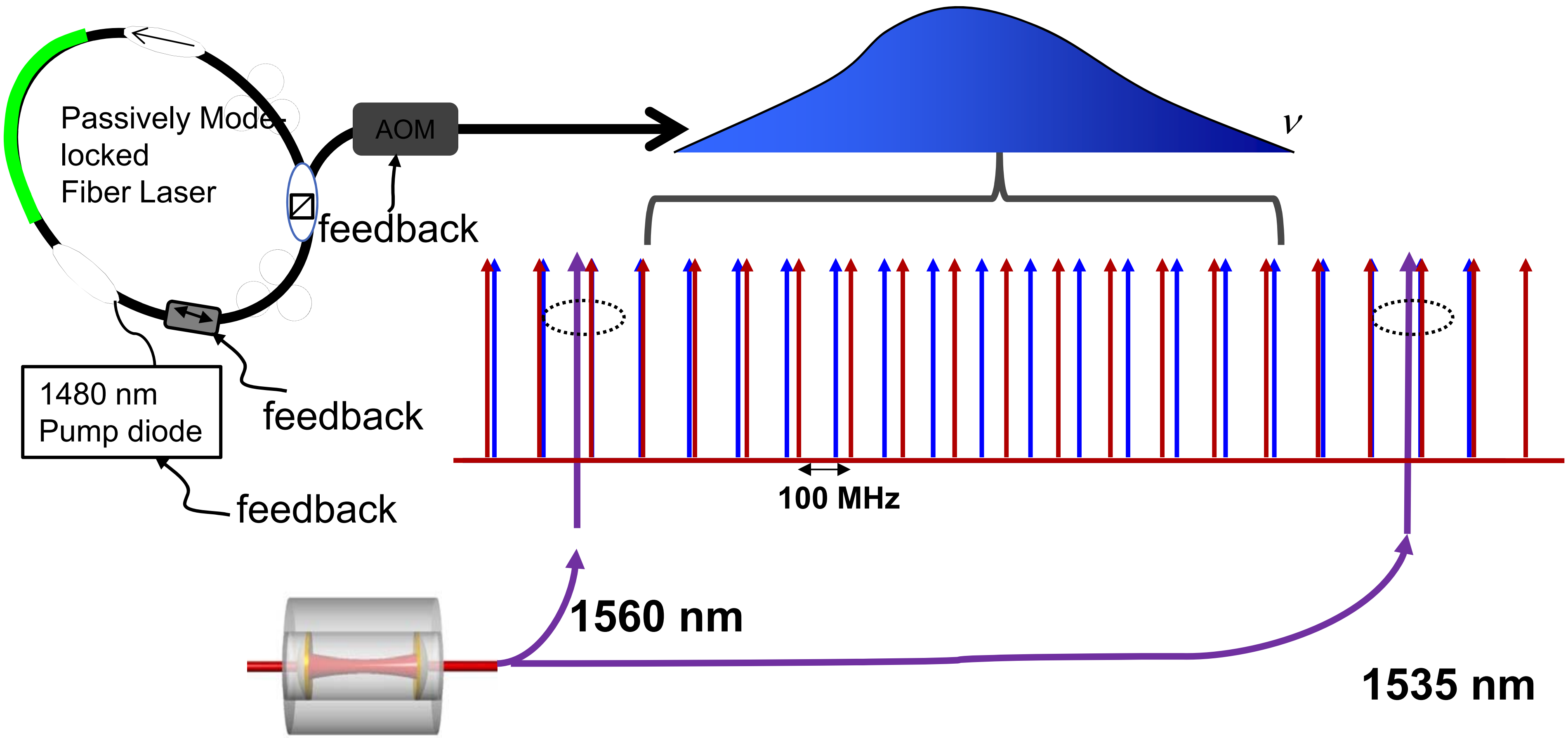
Ian Coddington, Bill Swann, PRL **100**, 013902 (2008

Other Stabilization Options: double pinning



NO Offset frequency stabilization -> no need for octave supercontinuum
But no absolute frequency knowledge (unless cavity separately measured)

Double pinning approach

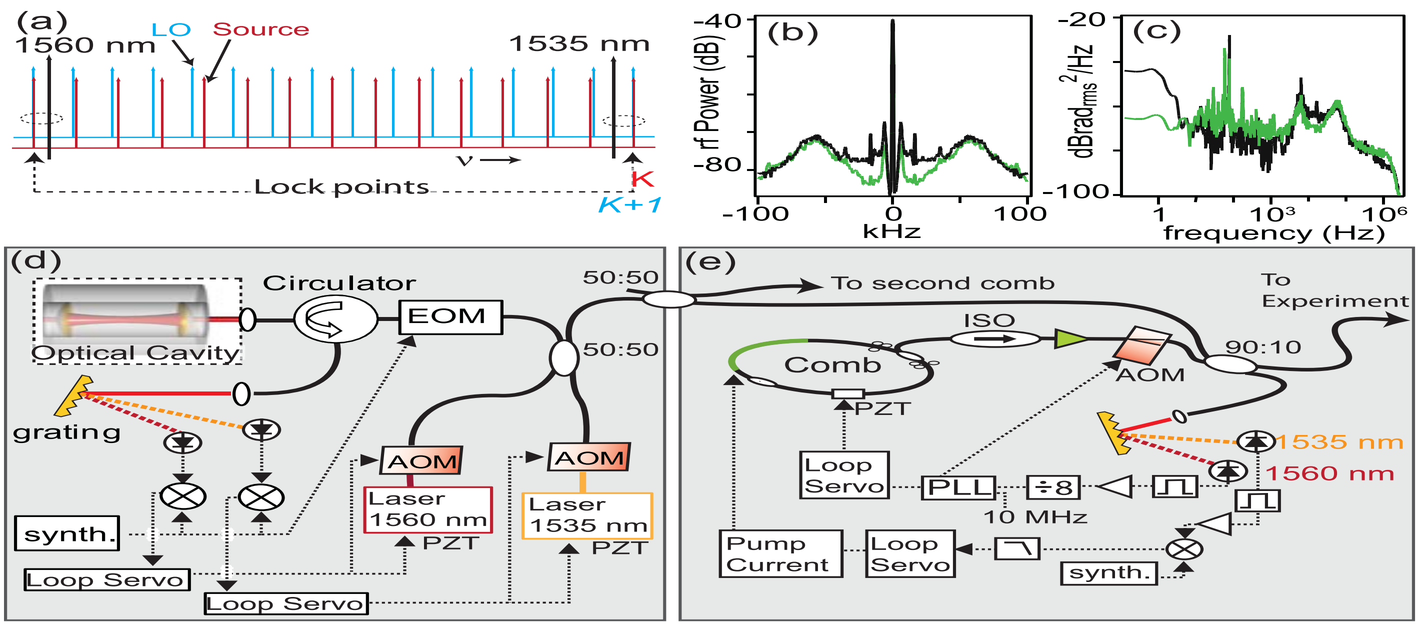


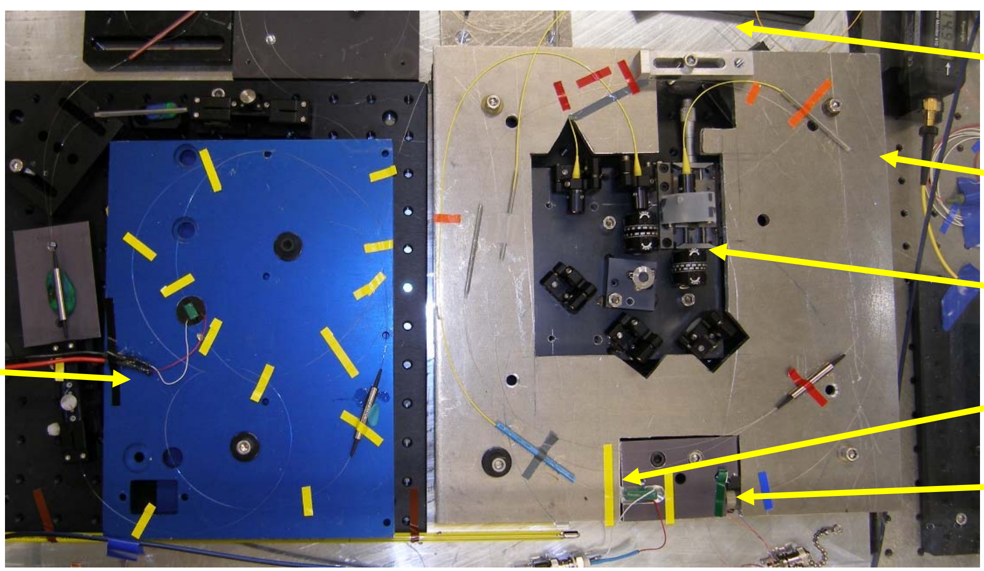
Cavity stabilized Lasers
~10 kHz linewidths
~ kHz accuracy (when referenced back to comb)

Coddington et al, PRA, 81, 043817 (2010)

Ring-laser based frequency comb pair for dual-comb spectroscopy

NIST





AOMs (off picture)

Temp-controlled baseplate

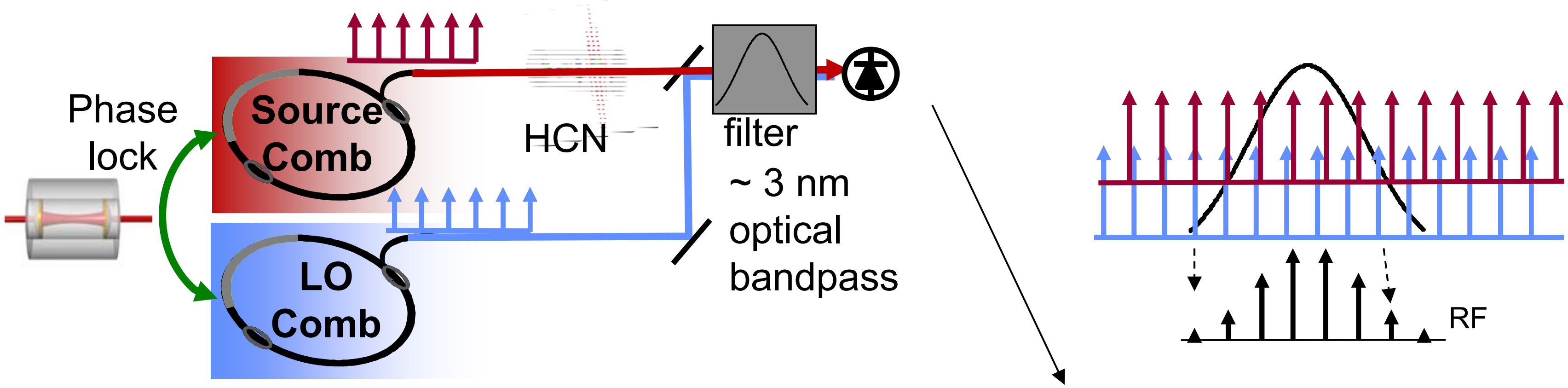
Variable air gap

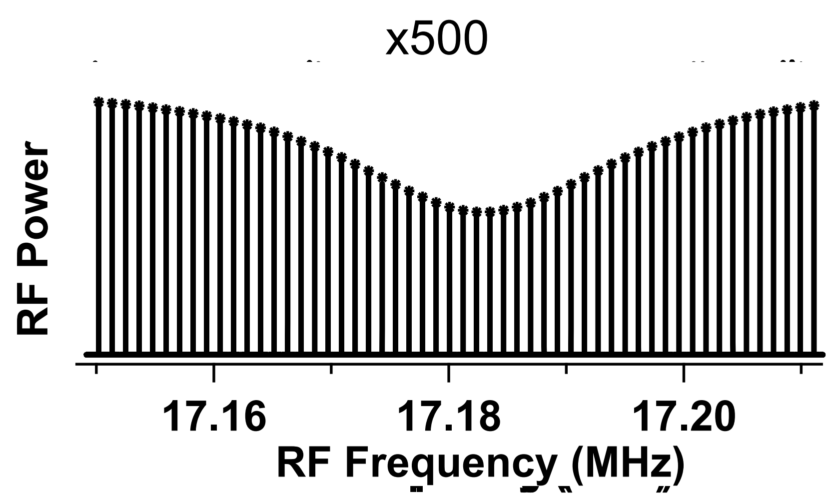
PZT (Low BW)

PZT (High BW)

2nd “All fiber” ring laser

Mutually coherent frequency combs





Ian Coddington, Bill Swann, PRL **100**, 013902 (2008

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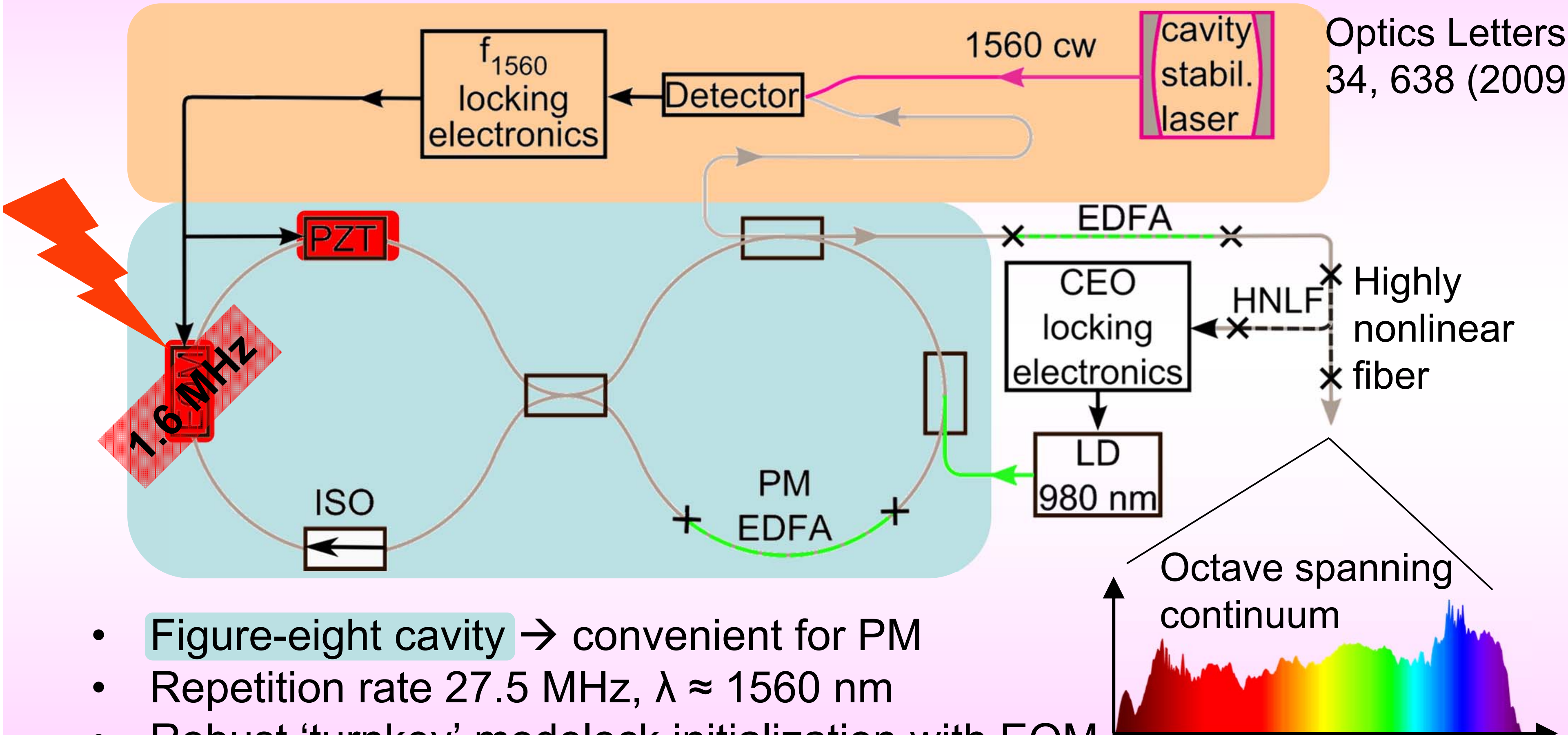
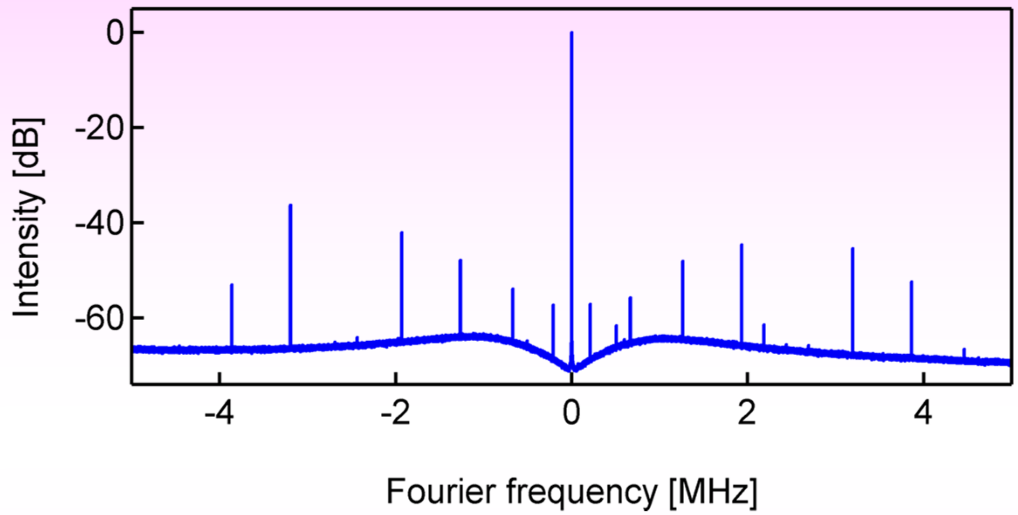
Comb based on an all PM-fiber figure eight laser

E. Baumann
F. Giorgetta
J. Nicholson
Optics Letters, 34, 638 (2009)



- Figure-eight cavity → convenient for PM
- Repetition rate 27.5 MHz, λ ≈ 1560 nm
- Robust 'turnkey' modelock initialization with EOM
- Comb referenced to cw stabilized light at 1560 nm
- Optical lock: inline EOM and PZT → High bandwidth

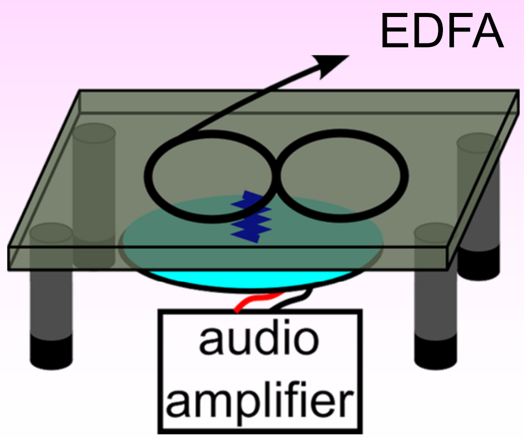
Low Phase Noise



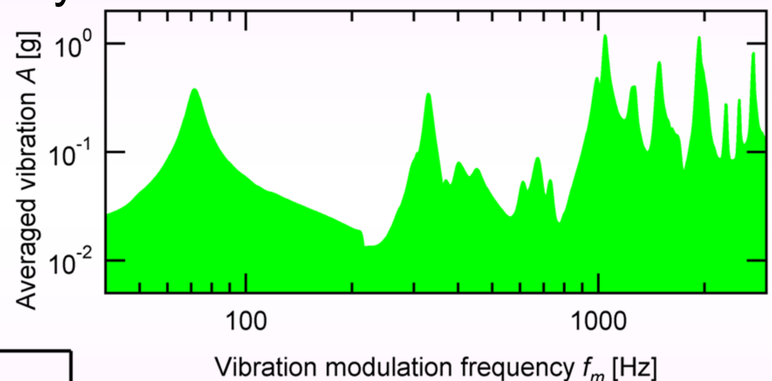
EOM → tight optical lock:

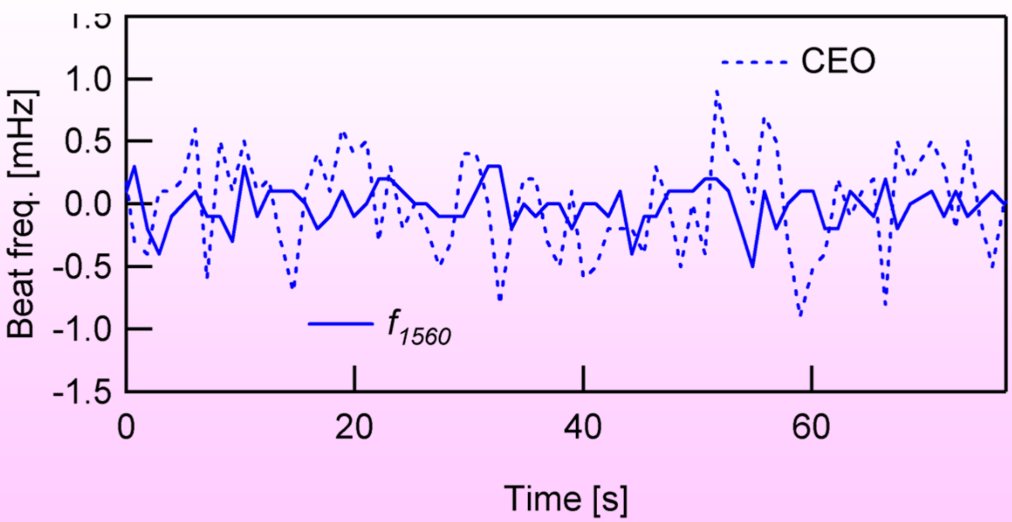
- Resolution limited linewidth
- Low phase noise at low frequency
- Lock can dig into shot noise floor: –94 dBc/Hz → –104 dBc/Hz
- Bandwidth increased ~ 10× to 1.6 MHz
  - ➢ Tight lock can compensate for vibration in out of lab settings

PM figure 8 Comb remains locked under 1 g vibration

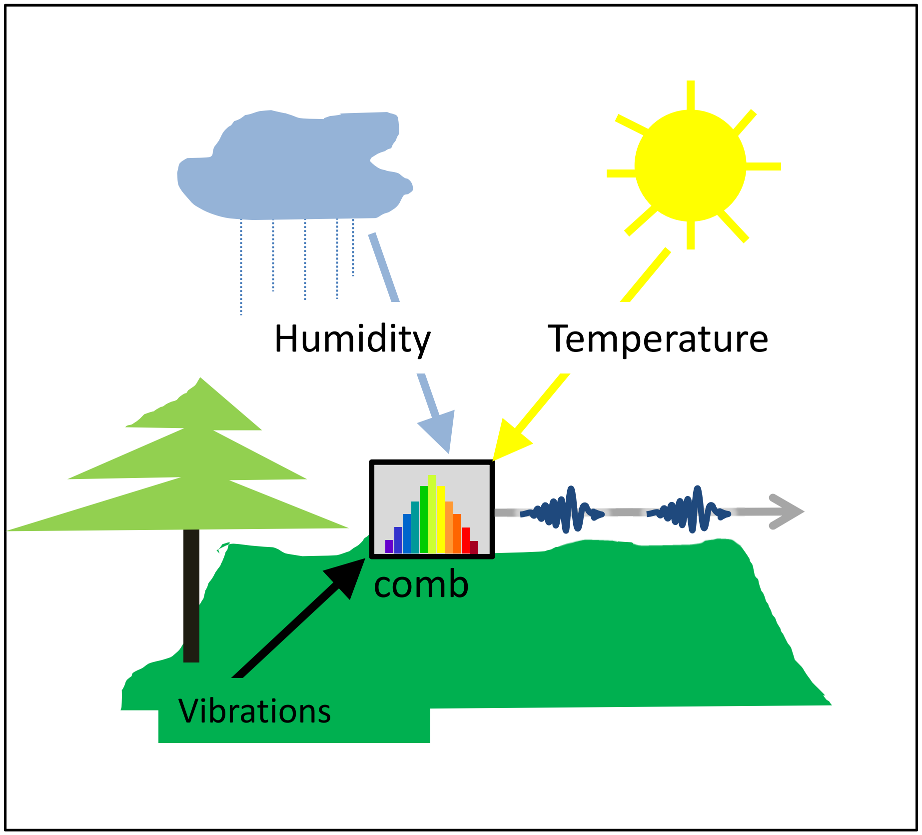


- Figure-eight cavity covers the entire breadboard
- Drive speaker with white noise or swept sine
  - Complex vibration pattern as function of frequency and location





Beyond the lab



Environmental Changes
→ changes in fiber birefringence
→ polarization wander

It's not just the laser

Polarization wander impacts supercontinuum generation with HNLFs → Use PM HNLF *

Coupling into the PPLN needs to be stable → Use waveguide coupled PPLN **

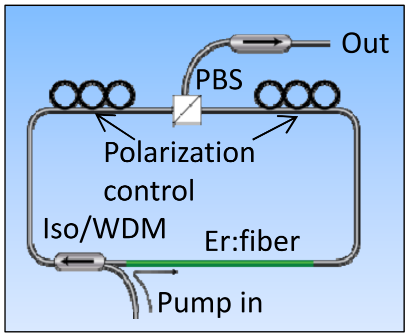
The application…

* M. C. Stumpf et al, *Appl. Phys. B*, **99**, 401 (2010)
** I. Hartl et al, *Opt. Express*, **13**, 6490, (2005)

Beyond the lab

Femtosecond Fiber Laser Design

Ring Cavity

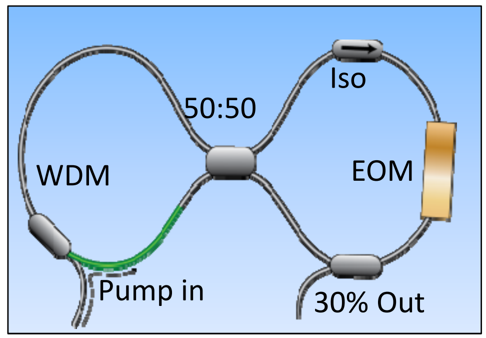


Good performance BUT polarization wander kills mode-locking!

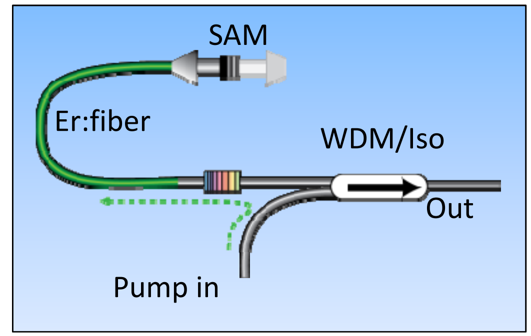
K. Tamura, *et al*, Opt. Lett. 19, 46 (1994).

W. C. Swann, *et al.* Opt. Lett., **31**, 3046 (2006).

PM Figure 8 Cavity



PM Linear Cavity



Both designs can be PM, all-fiber

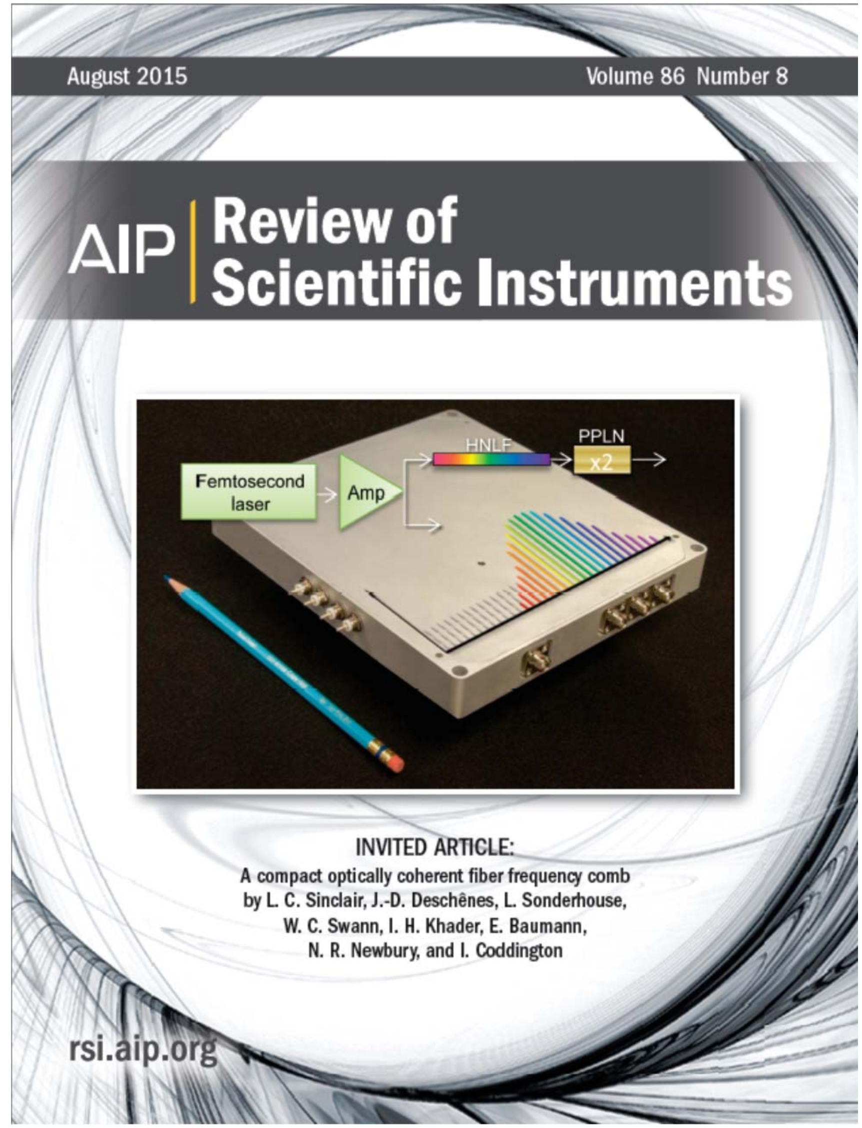
Linear cavity design is simpler and easier to reach higher repetition rates

J. W. Nicholson, *et. al*, Opt. Express 14, 8160 (2006).
E. Baumann, *et. al*, Opt. Lett. **34**, 638 (2009).

I. Hartl, *et. al.*, Opt. Express **13**, 6490 (2005).
H. Byun, *et. al*, Opt. Lett. **33**, 2221 (2008).
T.-A. Liu, *et. al*, Opt. Express **19**, 18501 (2011).

Current NIST comb: emphasize robustness over performance

- Development of a Robust Frequency Comb:
  - Version 1
  - Version 2 with digital control
- Environmental "Testing":
  - Vibration Testing on an Industrial Shaker
  - Mobile Van Testing
- Currently have >9 of these combs running continuously at NIST
- Not record breaking phase/frequency noise but "good enough" & robust operation is more important
  - Sufficient for dual-comb spectroscopy
  - Sufficient for state-of-art clock comparisons

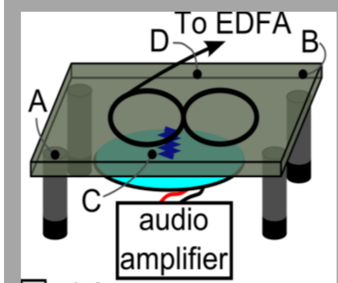


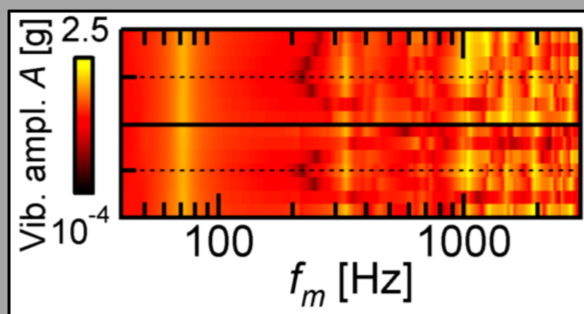
Putting the Pieces Together

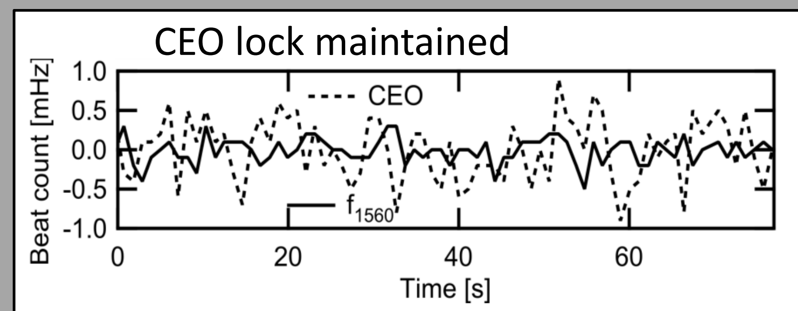
Leverage existing work to generate a new system that is:

- completely polarization-maintaining,
- all fiber,
- fully stabilized with noise performance for precision measurement applications

<u>PM figure-8 femtosecond laser on a shaker table</u>





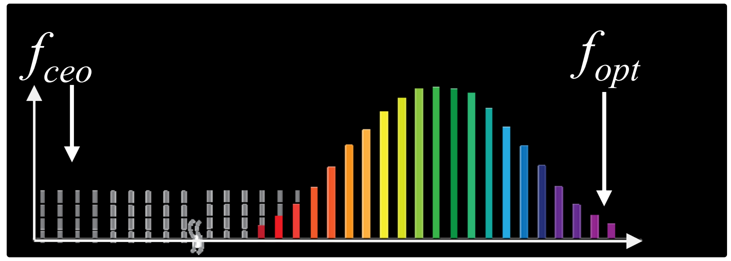


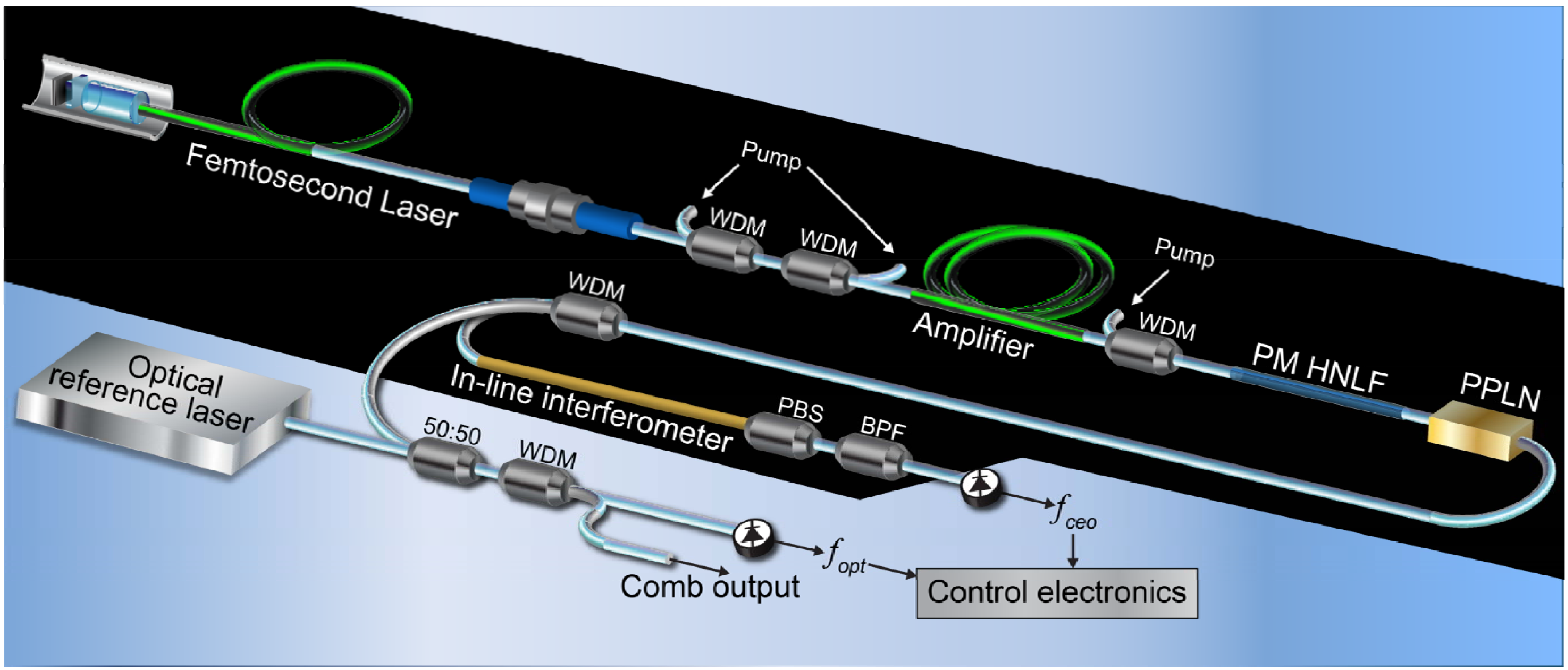
E. Baumann, *et. al*, Opt. Lett. **34**, 638 (2009). (OFS and NIST collaboration)

<u>PM Fiber and Components</u>

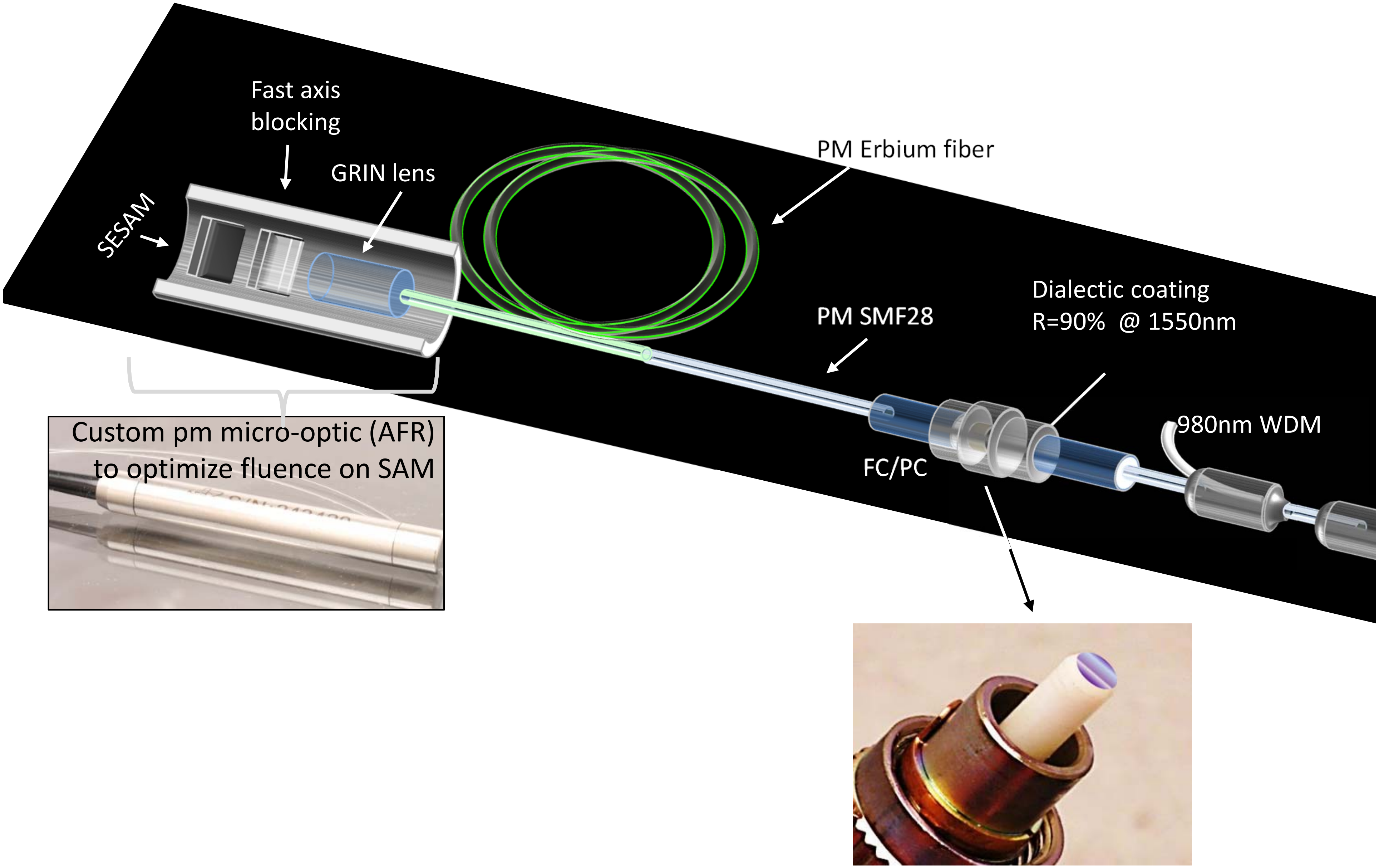
- Highly doped Er-fiber
- Highly Nonlinear Fiber (HNLFs)
- Waveguide PPLN

Full Coherent Comb Design

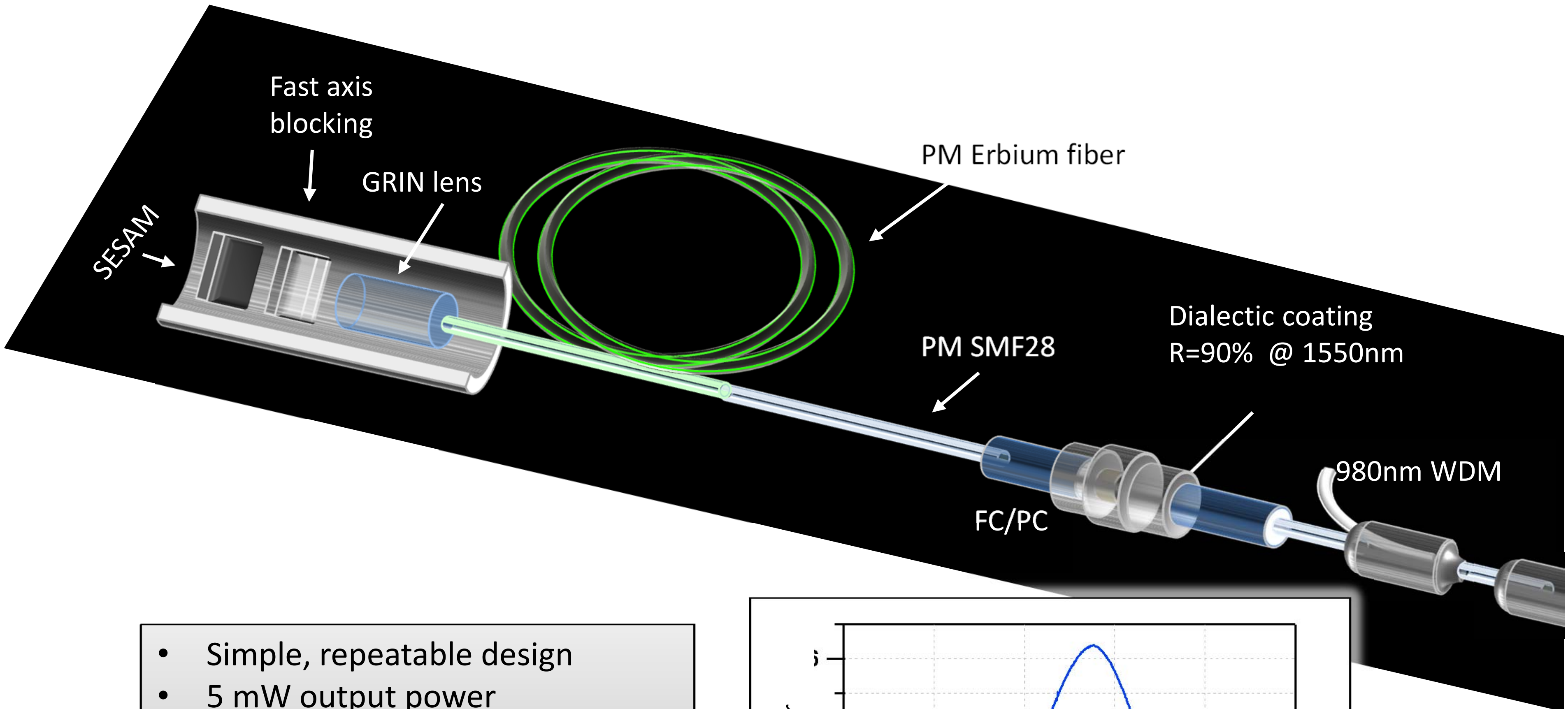




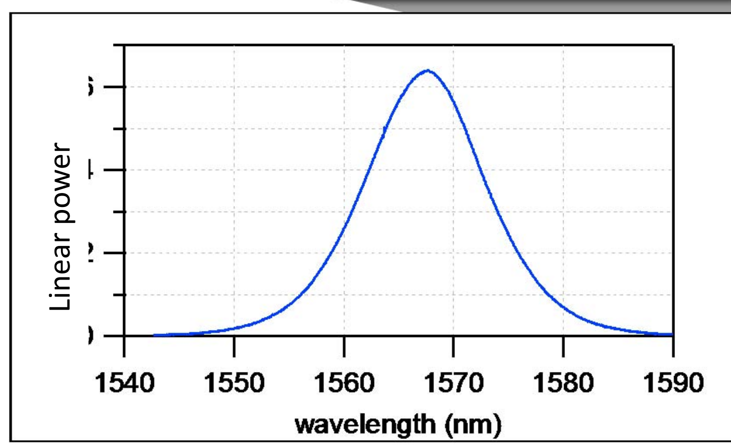
Femtosecond Fiber Laser



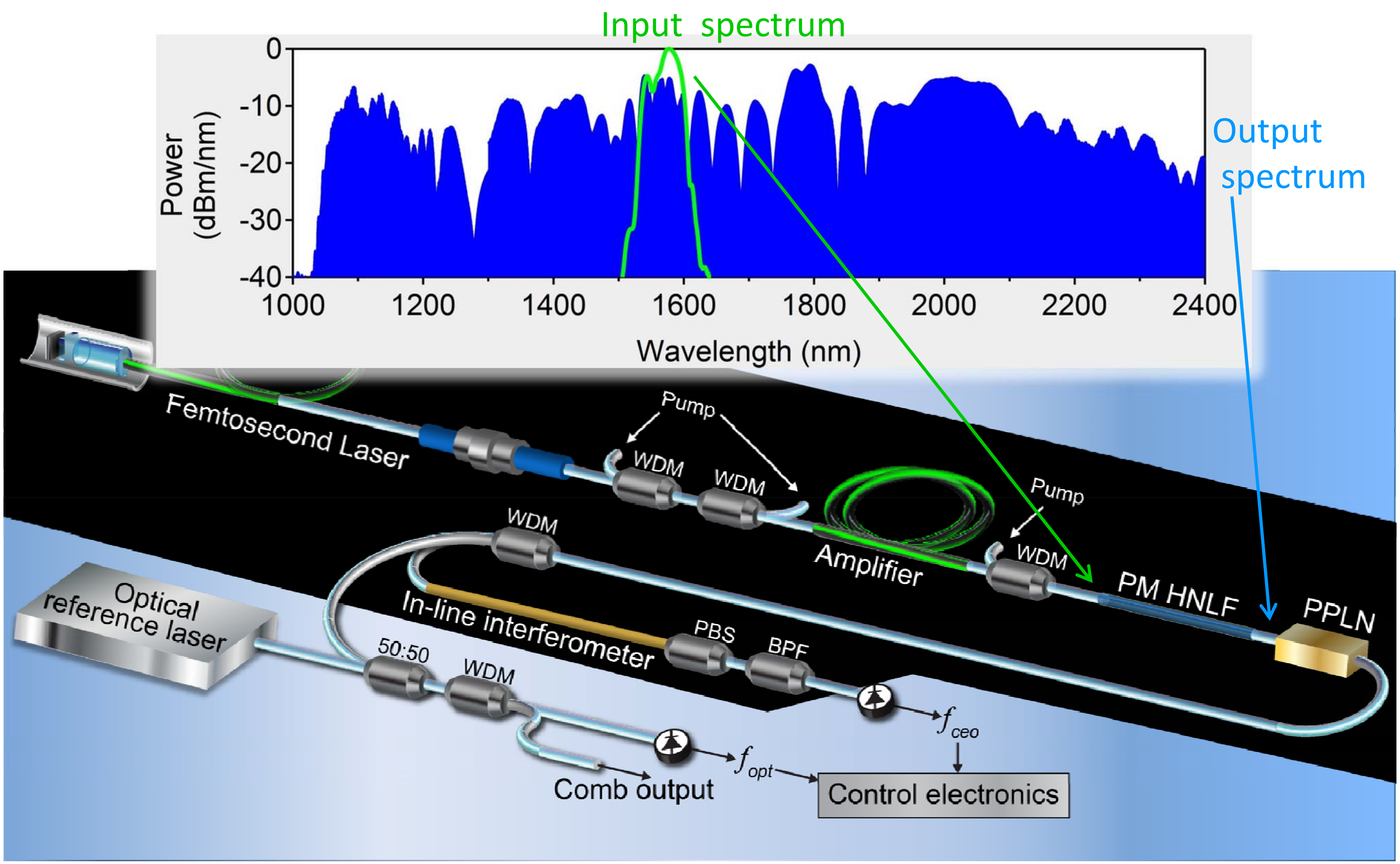
Femtosecond Fiber Laser



- Simple, repeatable design
- 5 mW output power
- 220 fs pulses
- 11 nm output spectrum
- 200 MHz
- Self-starting mode-locking



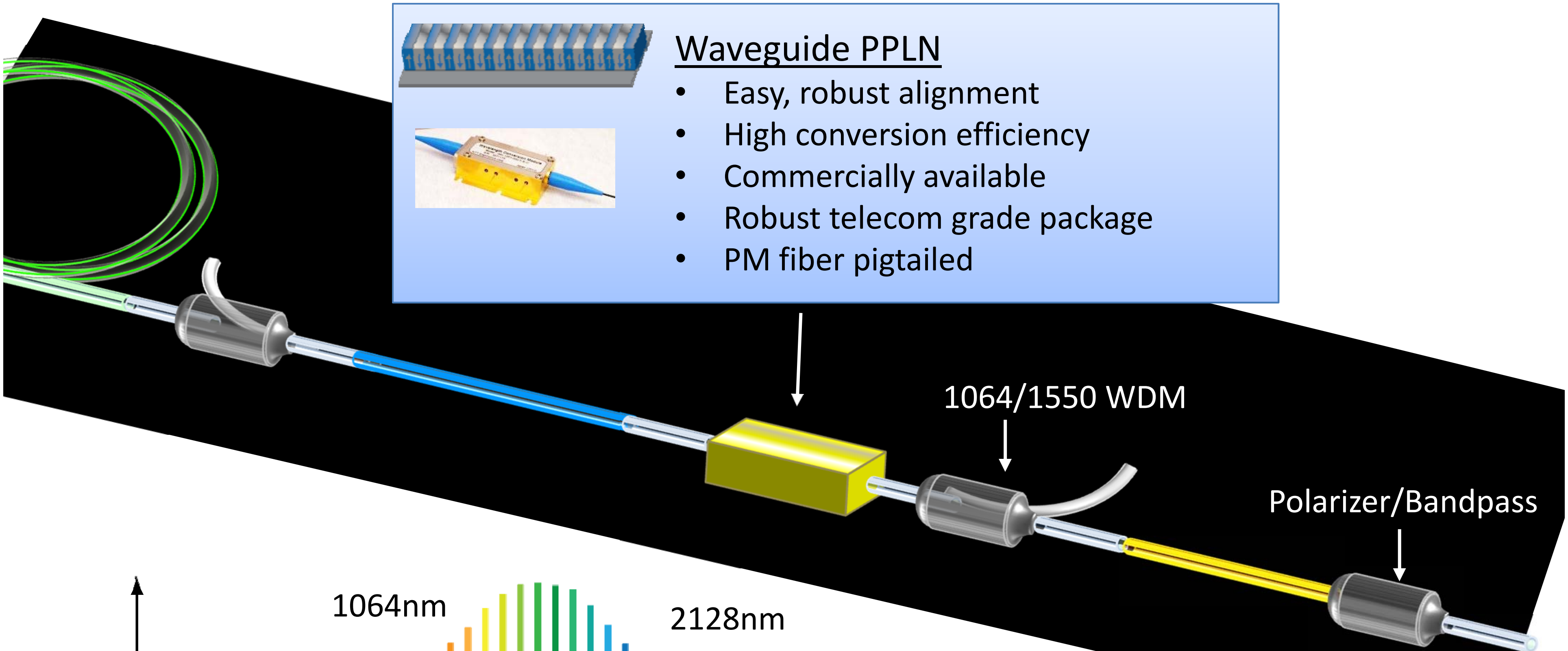
Supercontinuum generation

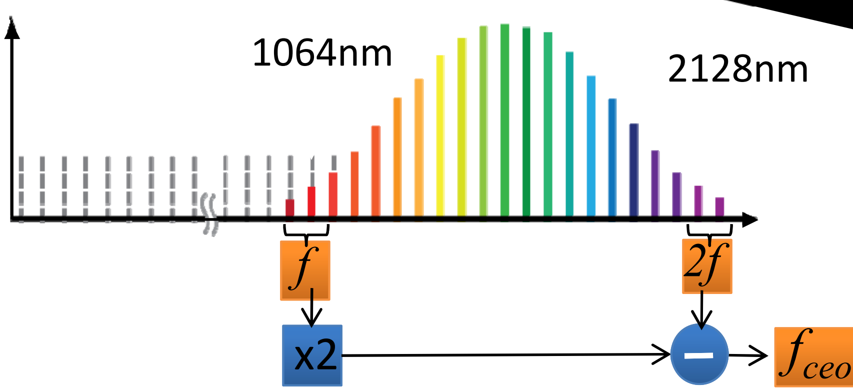


Detection of f_{ceo}

Waveguide PPLN

- Easy, robust alignment
- High conversion efficiency
- Commercially available
- Robust telecom grade package
- PM fiber pigtailed



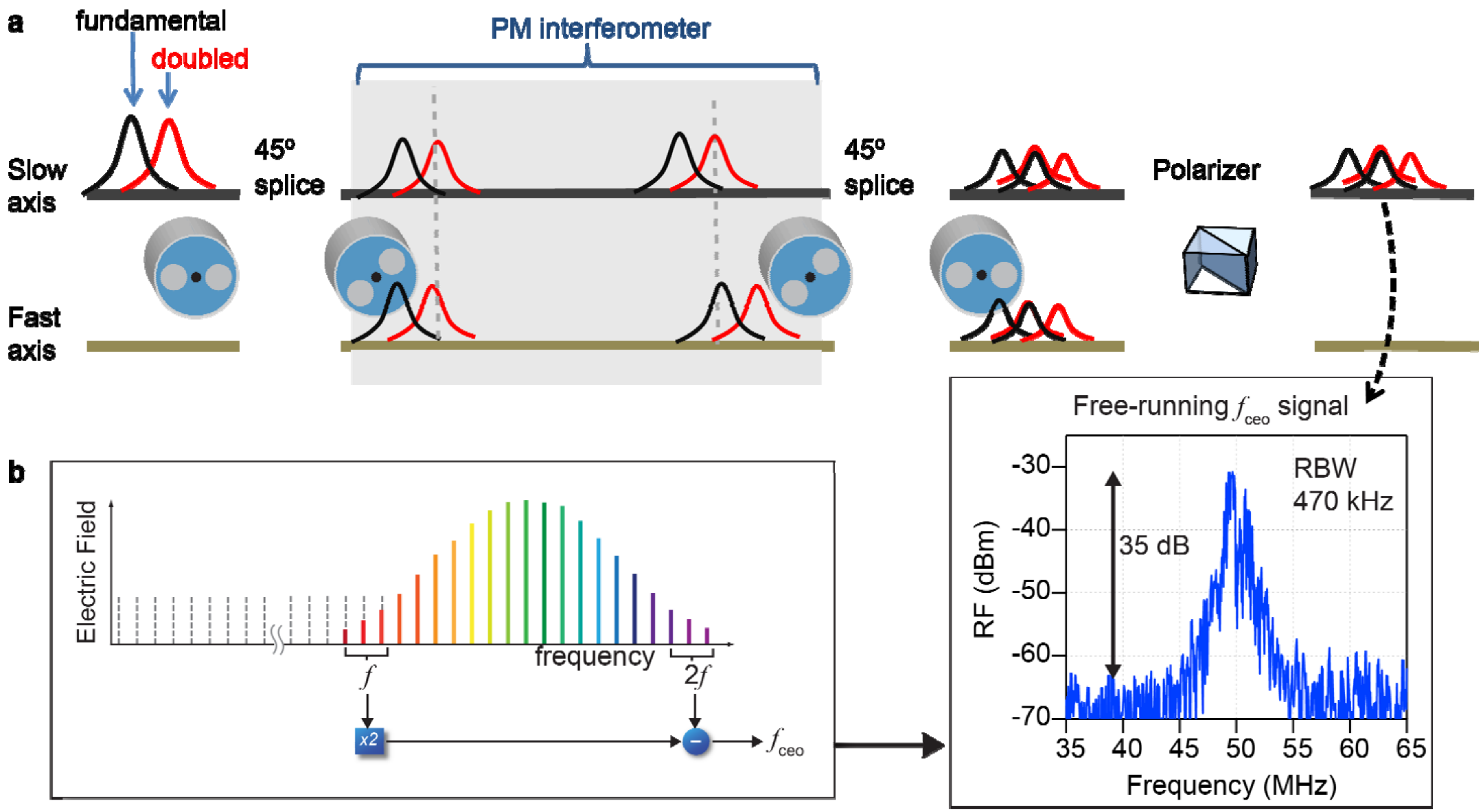


“In-line” Interferometer

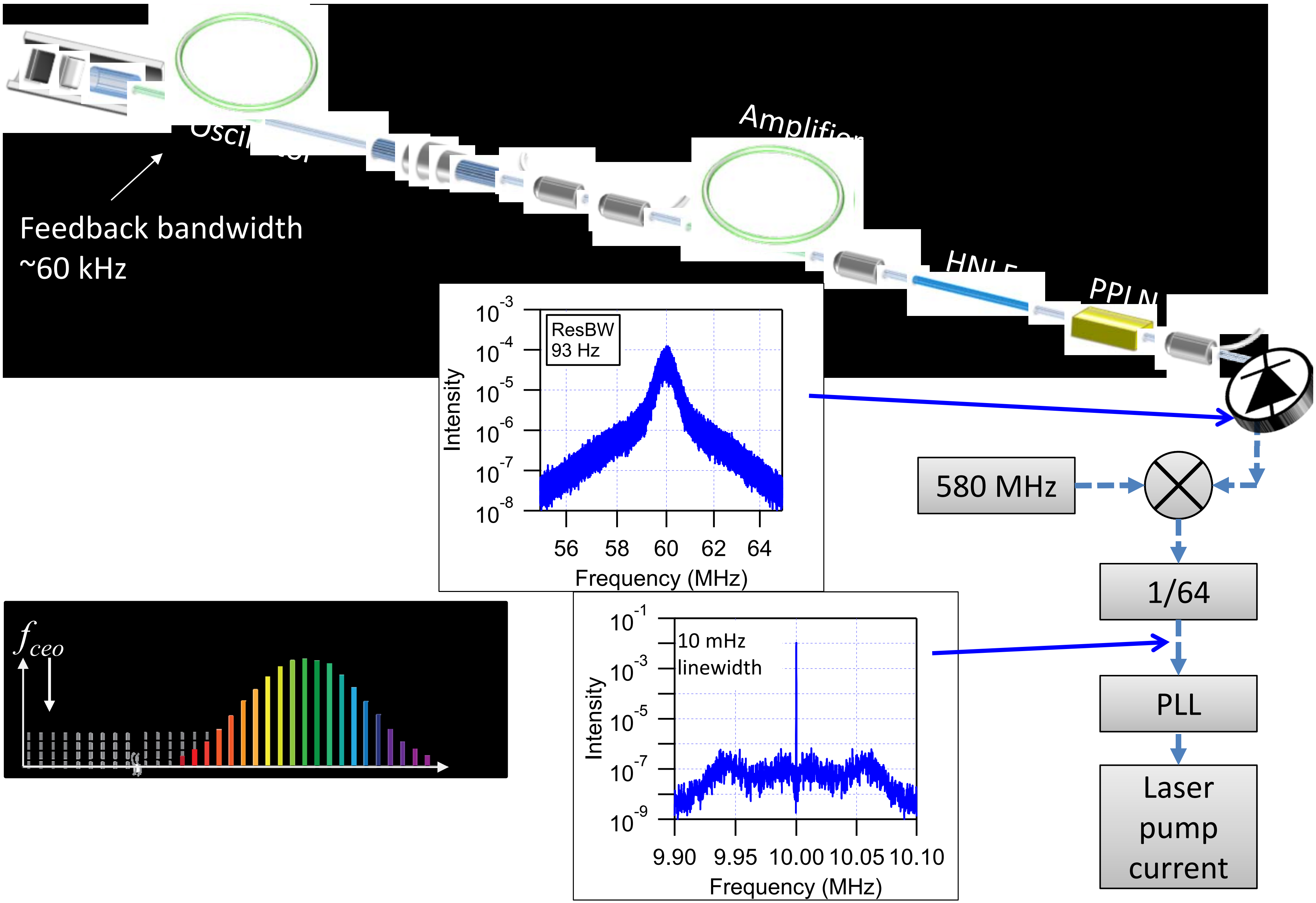
- Overlap f and $2f$ signals
- Removes need for free-space interferometer

* I. Hartl et al, *Opt. Express*, **13**, 6490, (2005)

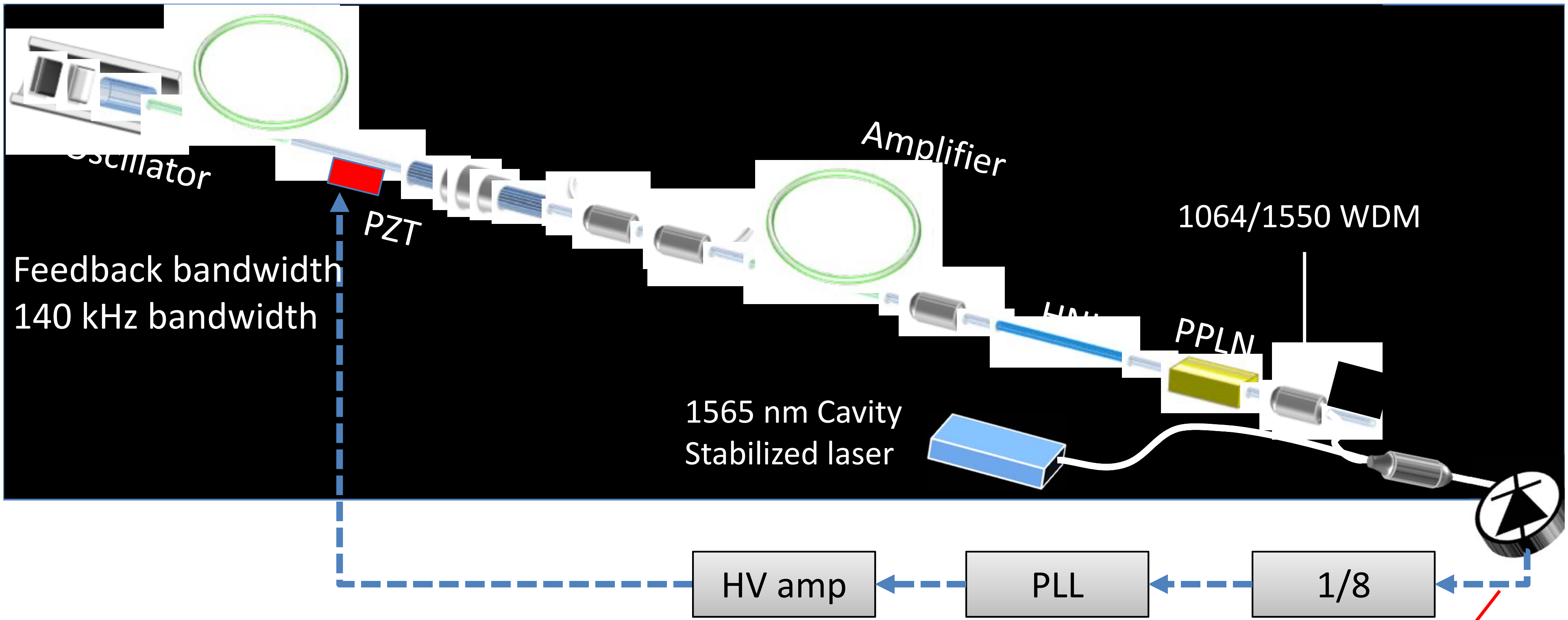
f_{ceo} Detection and "In-Line" Interferometer

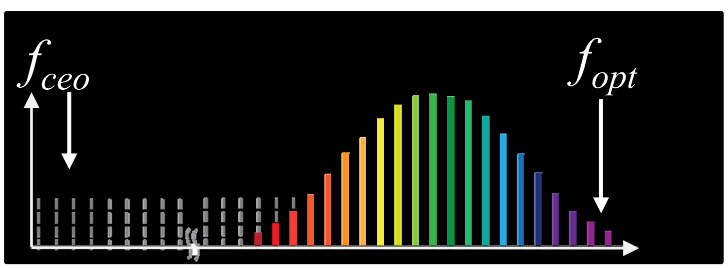


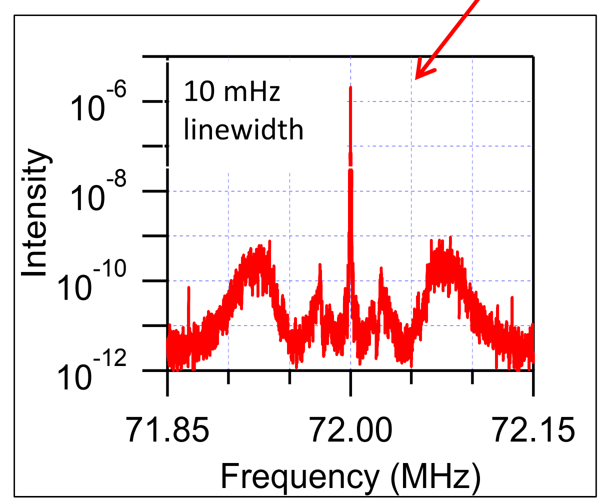
Stabilization of f_{ceo}



Carrier Stabilization

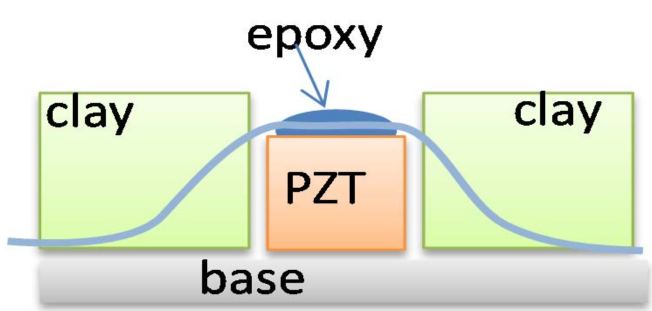




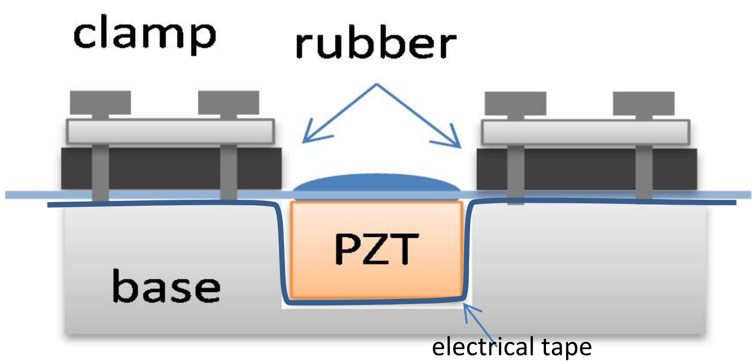


PZT mounting critical for high bandwidth feedback

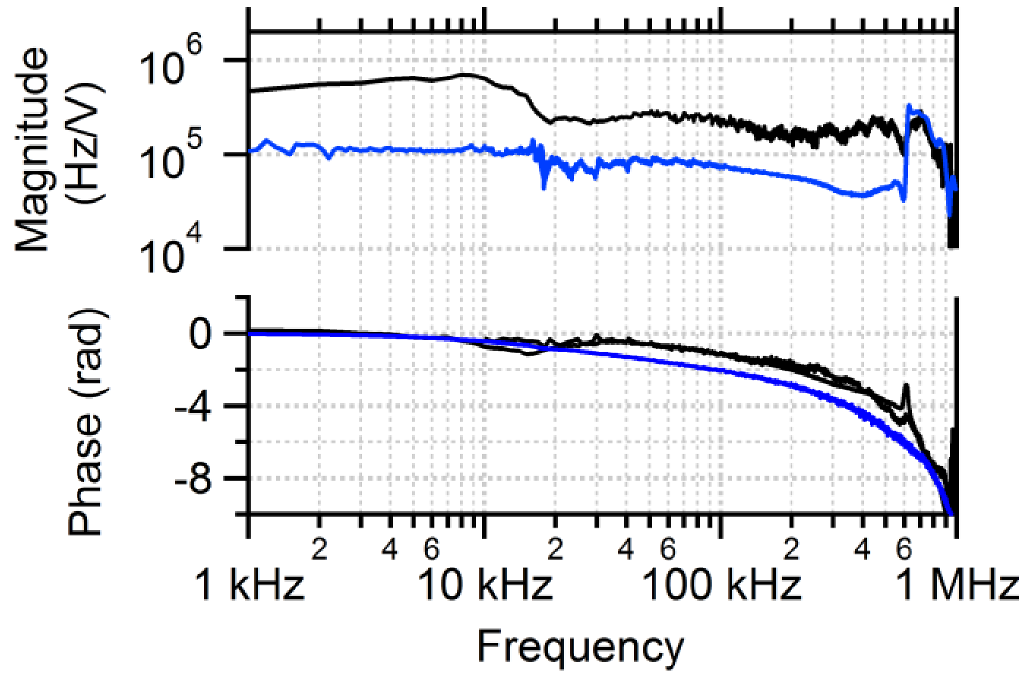
Free-standing



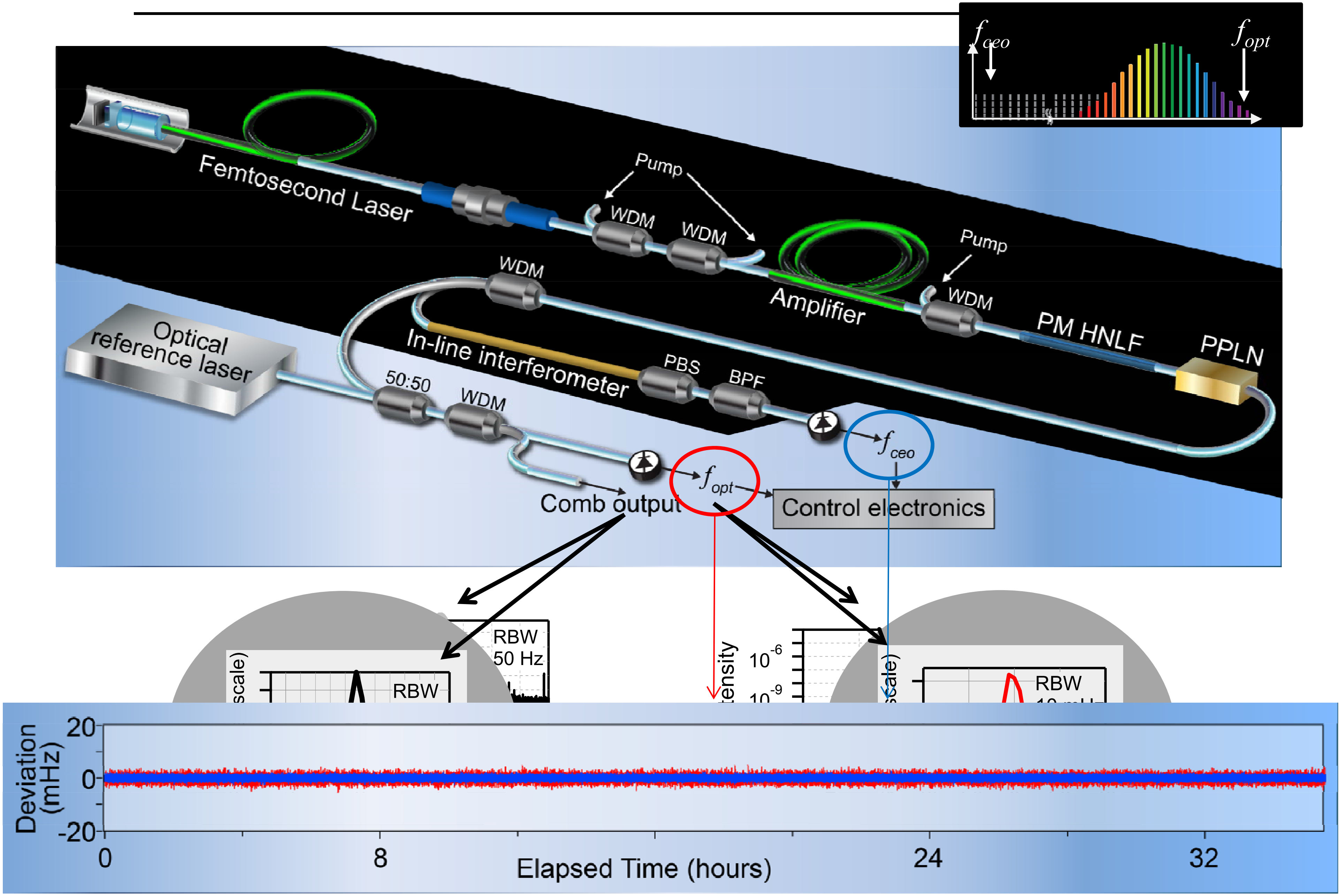
Pocket



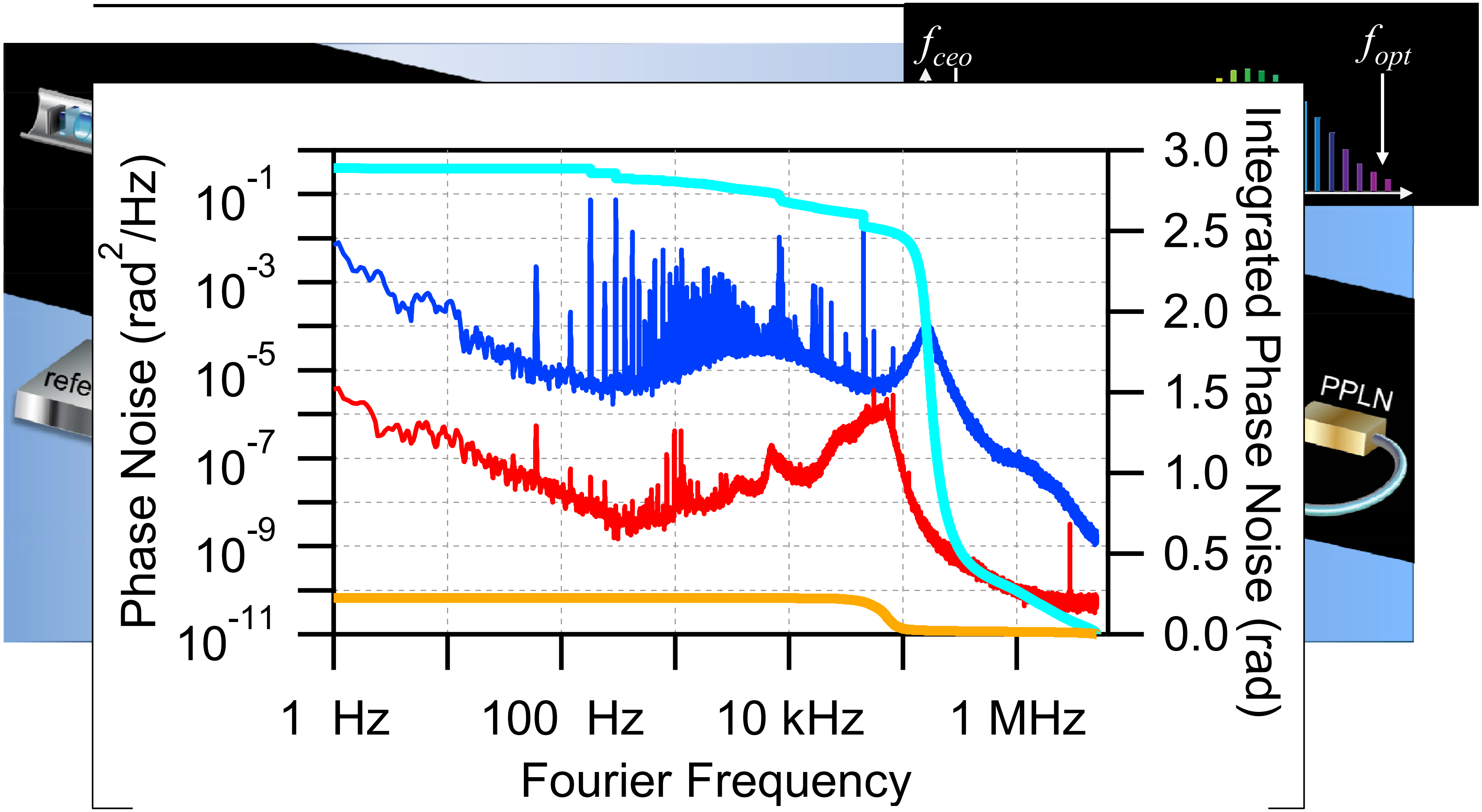
PZT response: 140 kHz feedback



Performance

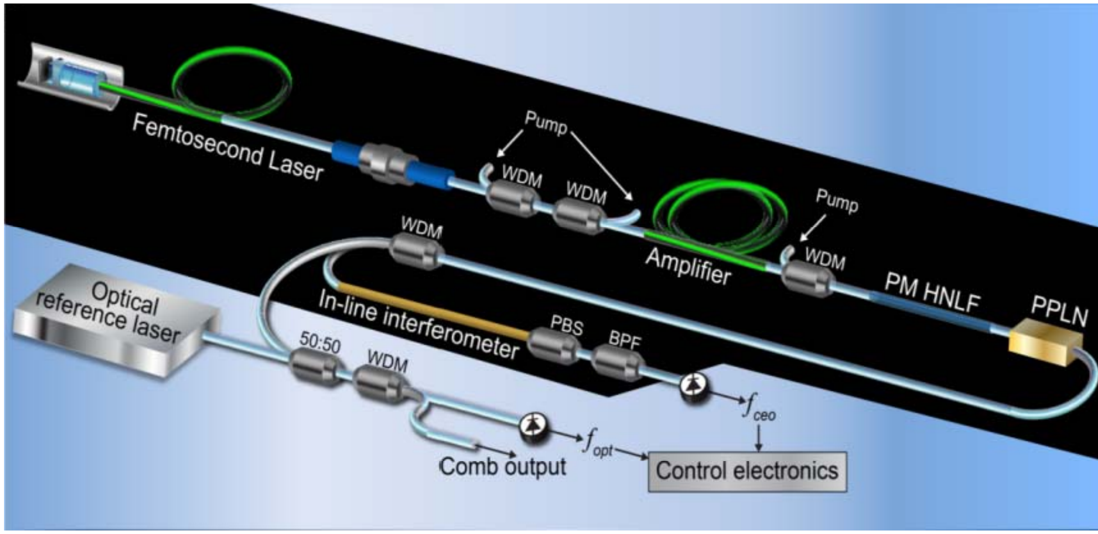


Performance

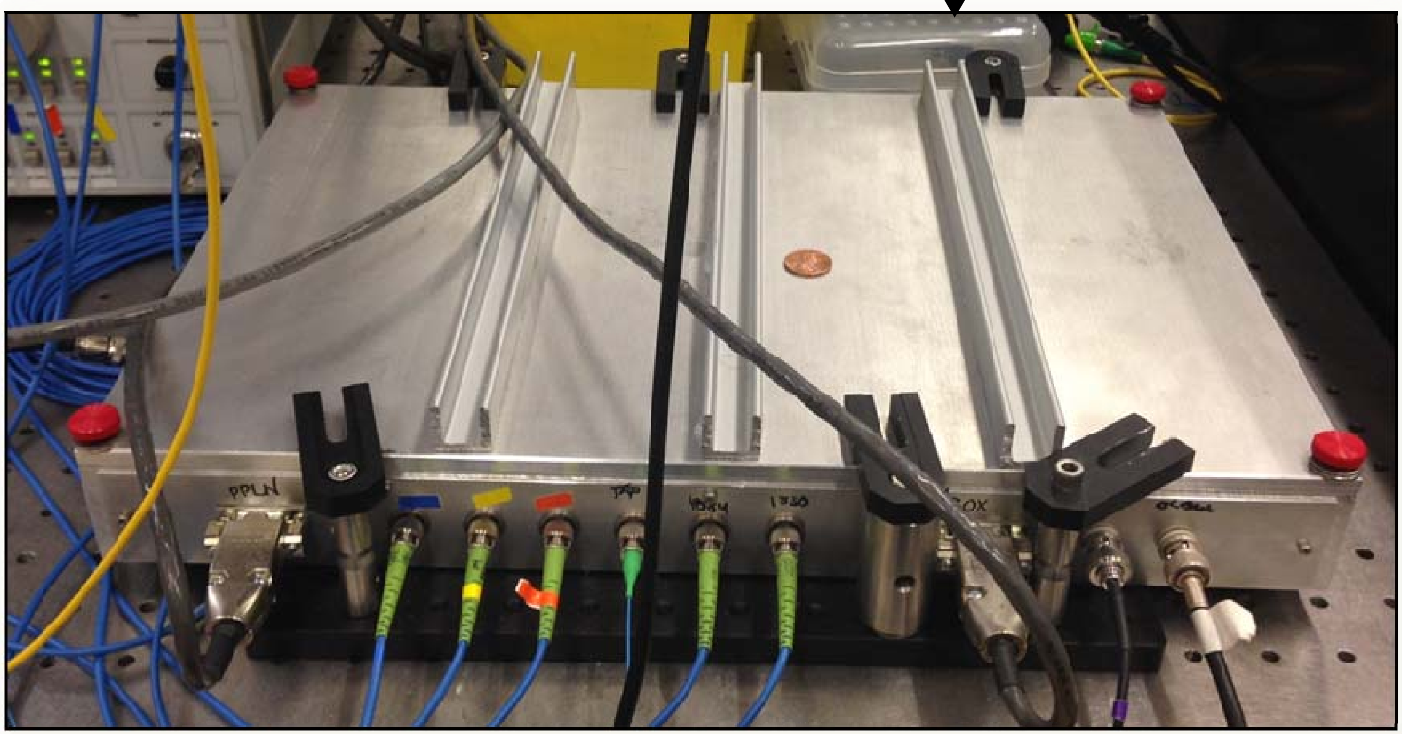


- 2.9 rad integrated CEO phase noise
- 0.23 radian optical phase noise
- Equivalent pulse-to-pulse timing jitter ~ 2.4 fs
- ~100 kHz feedback bandwidth on both locks

First Generation Robust PM Frequency Comb



6 liters
Mostly Aluminum and Air

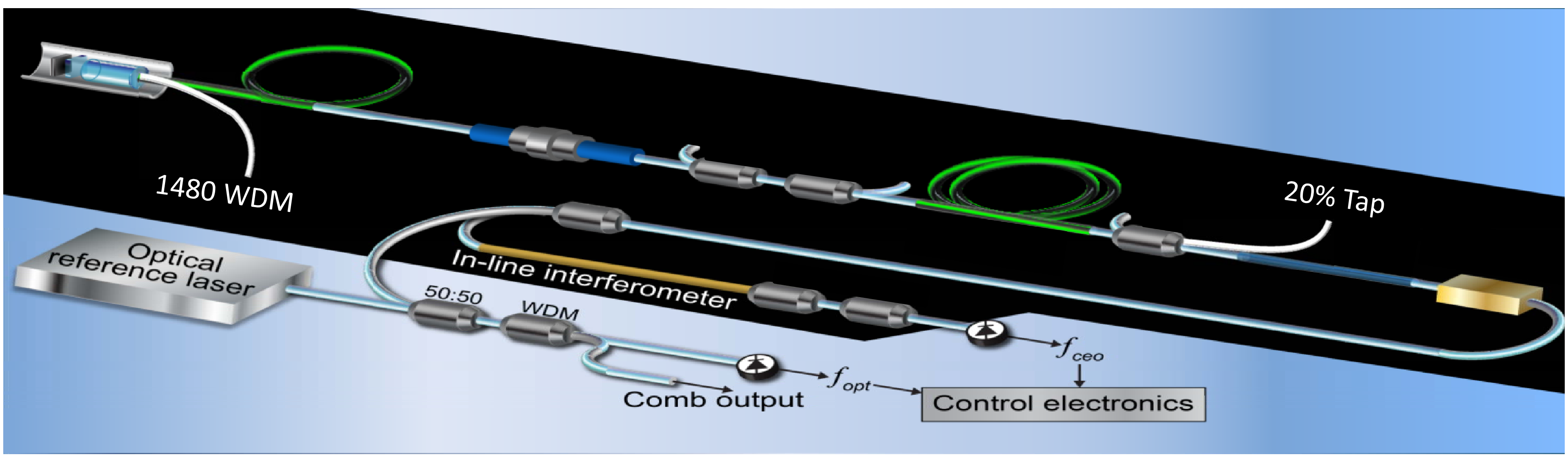


Outline

- Motivation
- Development of a Robust Frequency Comb:
  - The First Generation Comb
  - Version 2
- Environmental Testing of the First Generation Comb:
  - Mobile Van Testing
  - Vibration Testing on an Industrial Shaker
- Applications :
  - Free-Space Time and Frequency Transfer
  - Dual Comb Spectroscopy

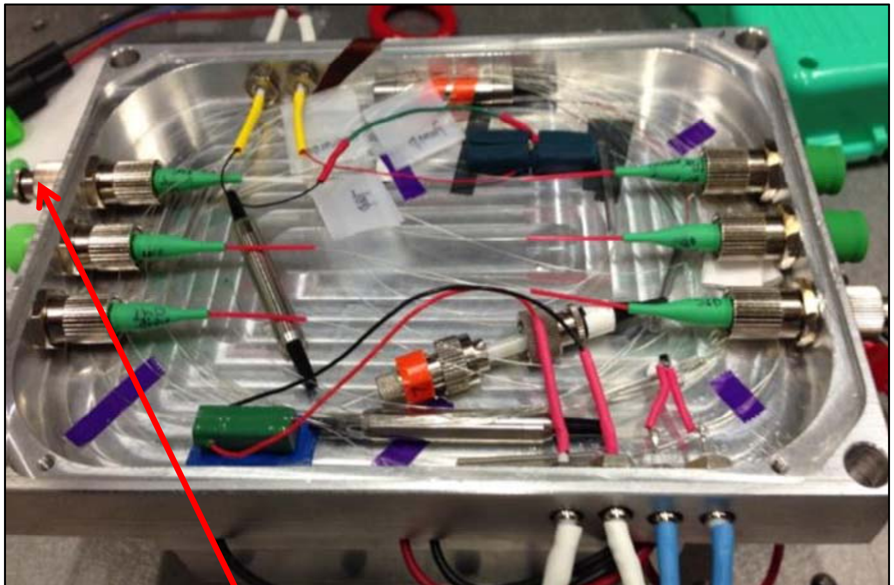
Modified Frequency Comb -> Version 2.0

- **<1 liter package for each comb (Down from 6 liter)**
- **Control repetition rate precisely (through fabrication and temperature)**
  - → Δf_r =5kHz at room temp (+/- 2kHz/°C)
- **Integrated WDM/SESAM for 1480 pumping**
  - → Lower noise pumps
  - → Pump isolator is 10x cheaper and 10 more compact
  - → No pump light on the SESAM (lifetime?)
- **20% Tap after the amplifier**
  - → 70mW, 100 fs output

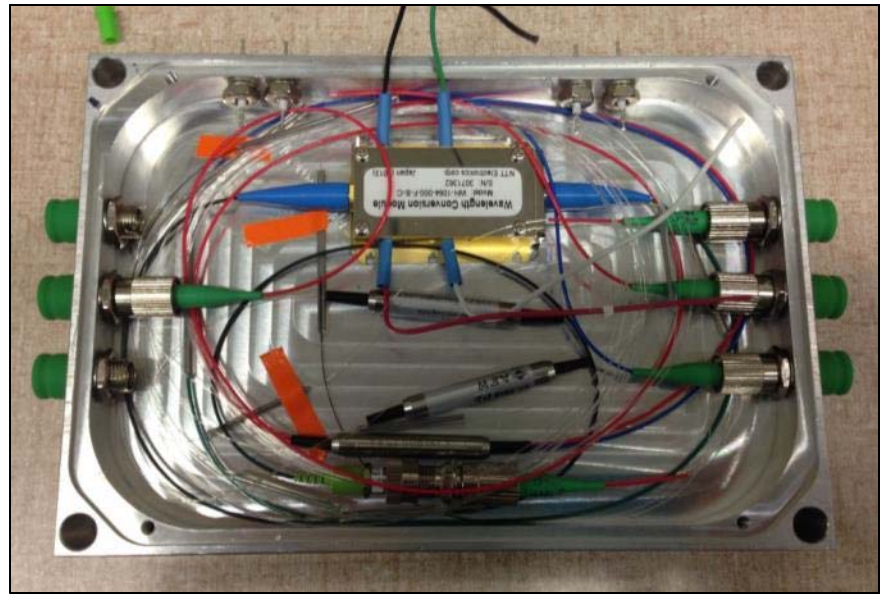


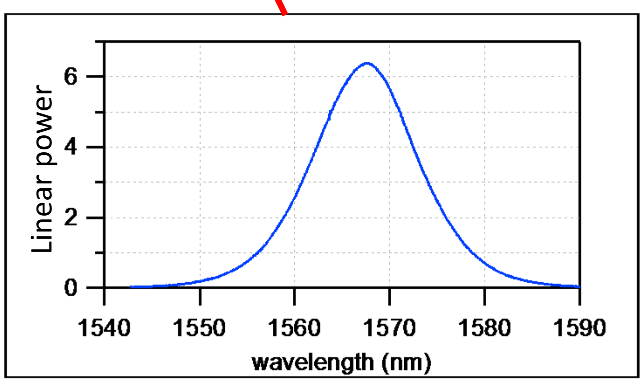
Version 2.0 Fieldable Frequency Comb

Laser and amplifier



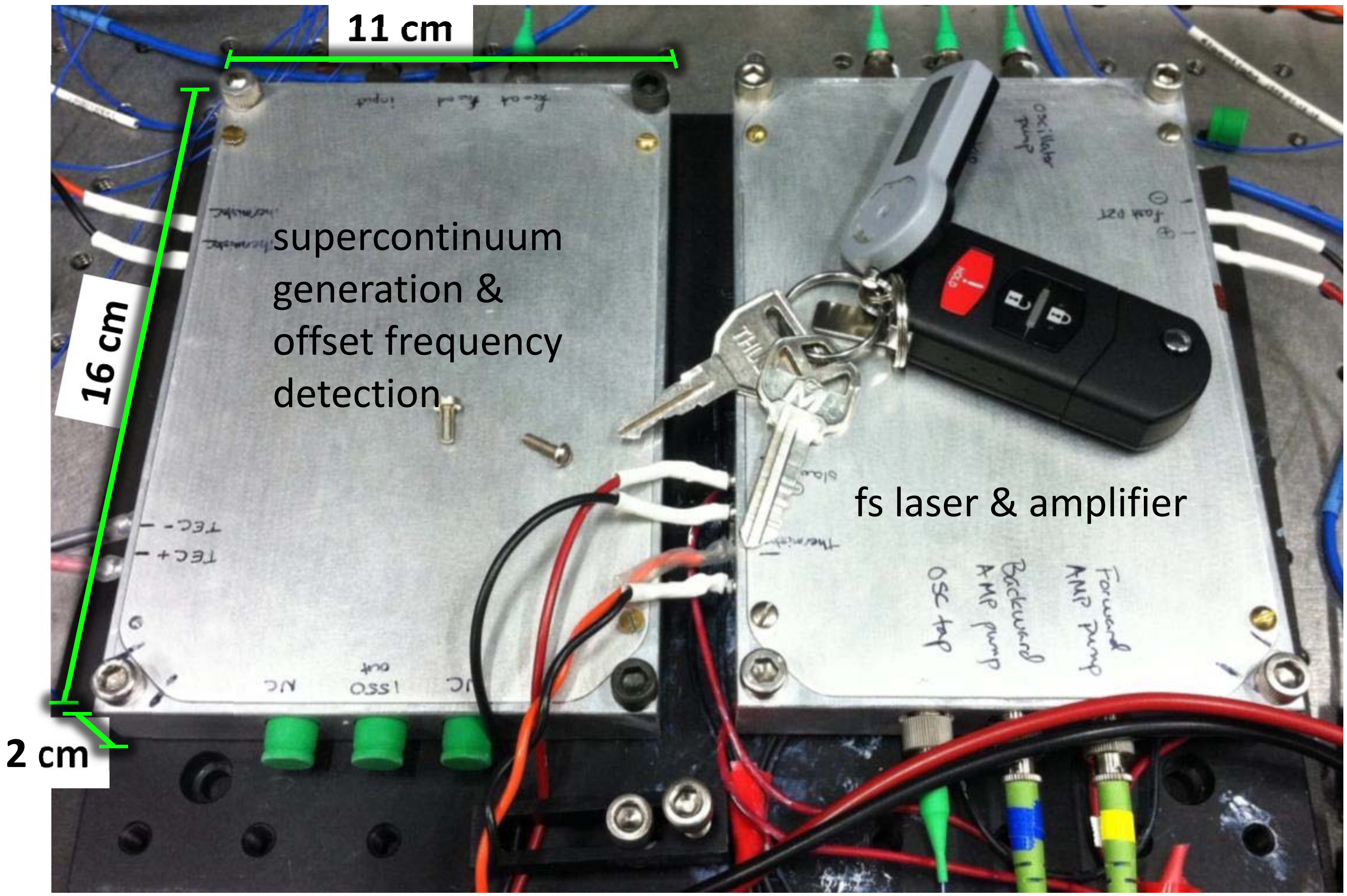
HNLF, PPLN and CEO detection





1. Similar spectra between lasers, interchangeable amplifiers/HNLF sections
   - Cavity dispersion dominated by material dispersion (insensitive)
2. Temperature control of the amplifier
3. Separate case for HNLF and PPLN
   - Thermal isolation between cavity and PPLN heater

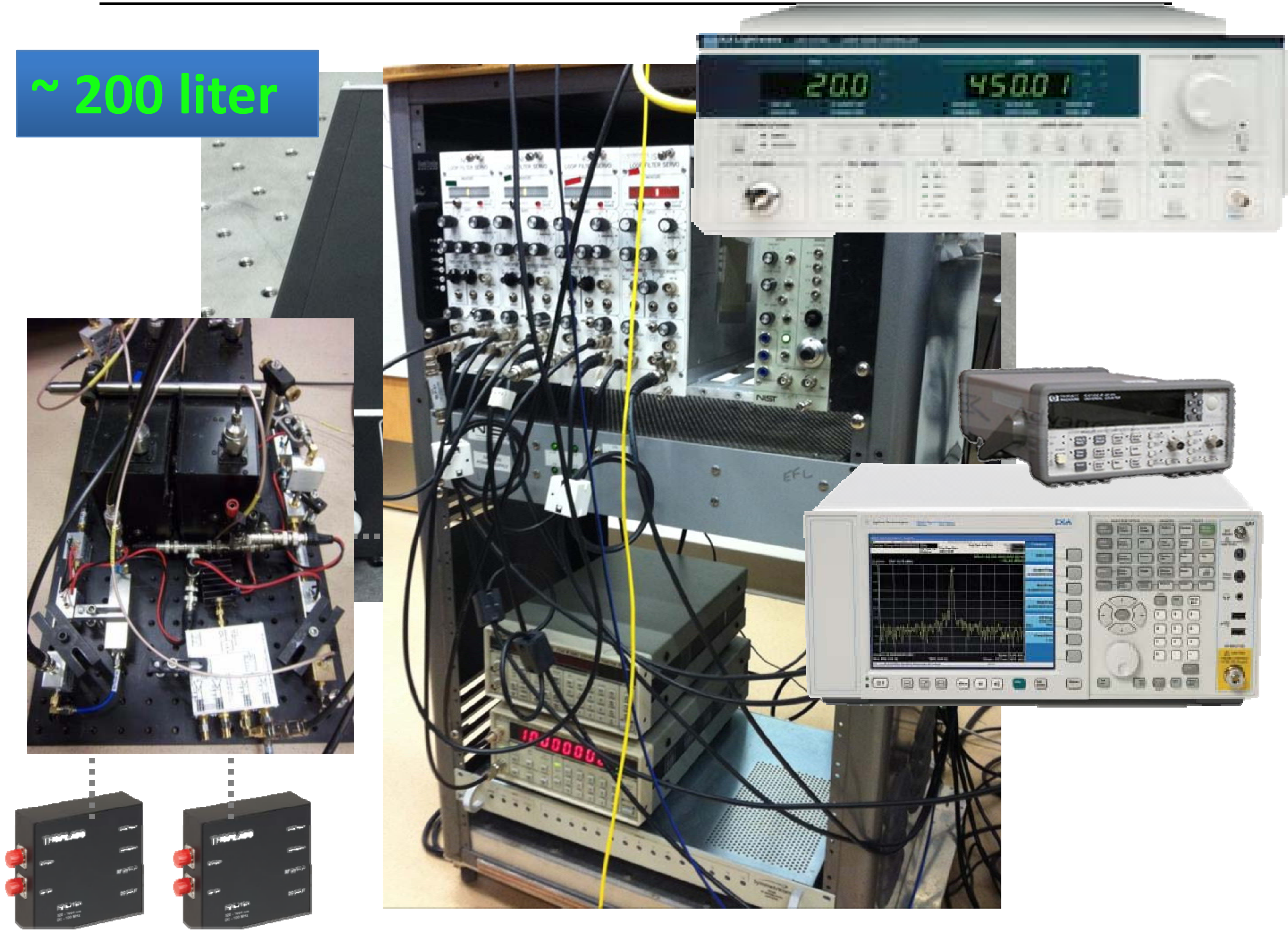
Version 2.0 Fieldable Frequency Comb



- 0.7 liter package (.35 L for laser and amp, 0.35 L for HNLF and PPLN)*

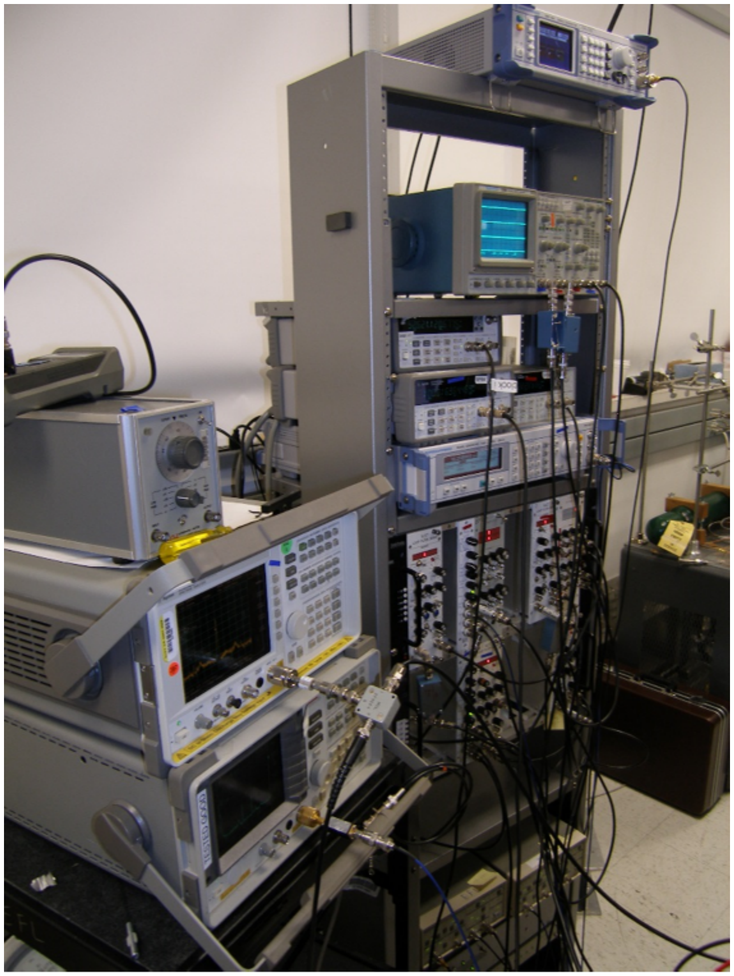
* excludes three butterfly packaged pump diodes

Analog control electronics-> FPGA & OEM based system



Analog vs Digital Control Electronics

Analog

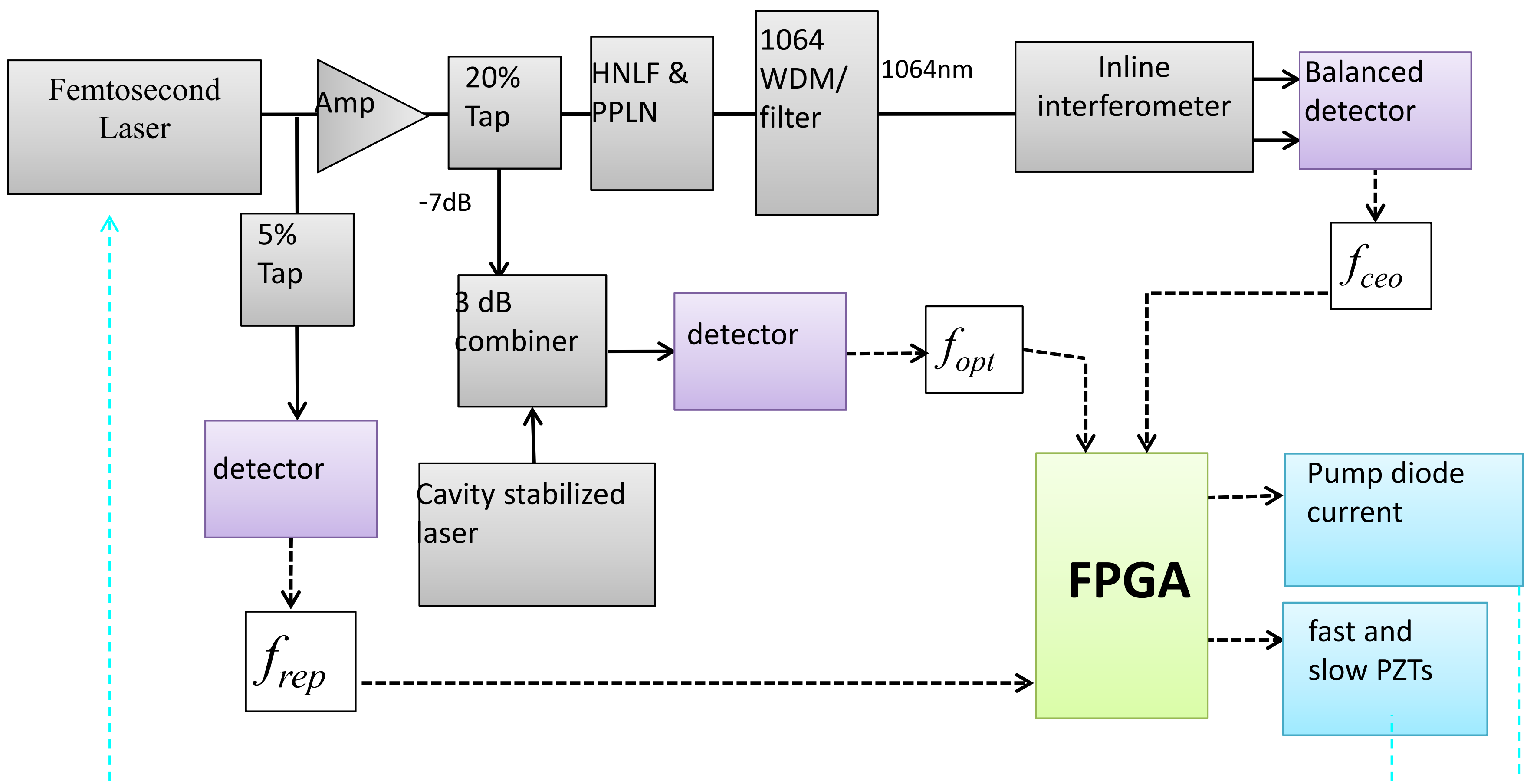


Digital

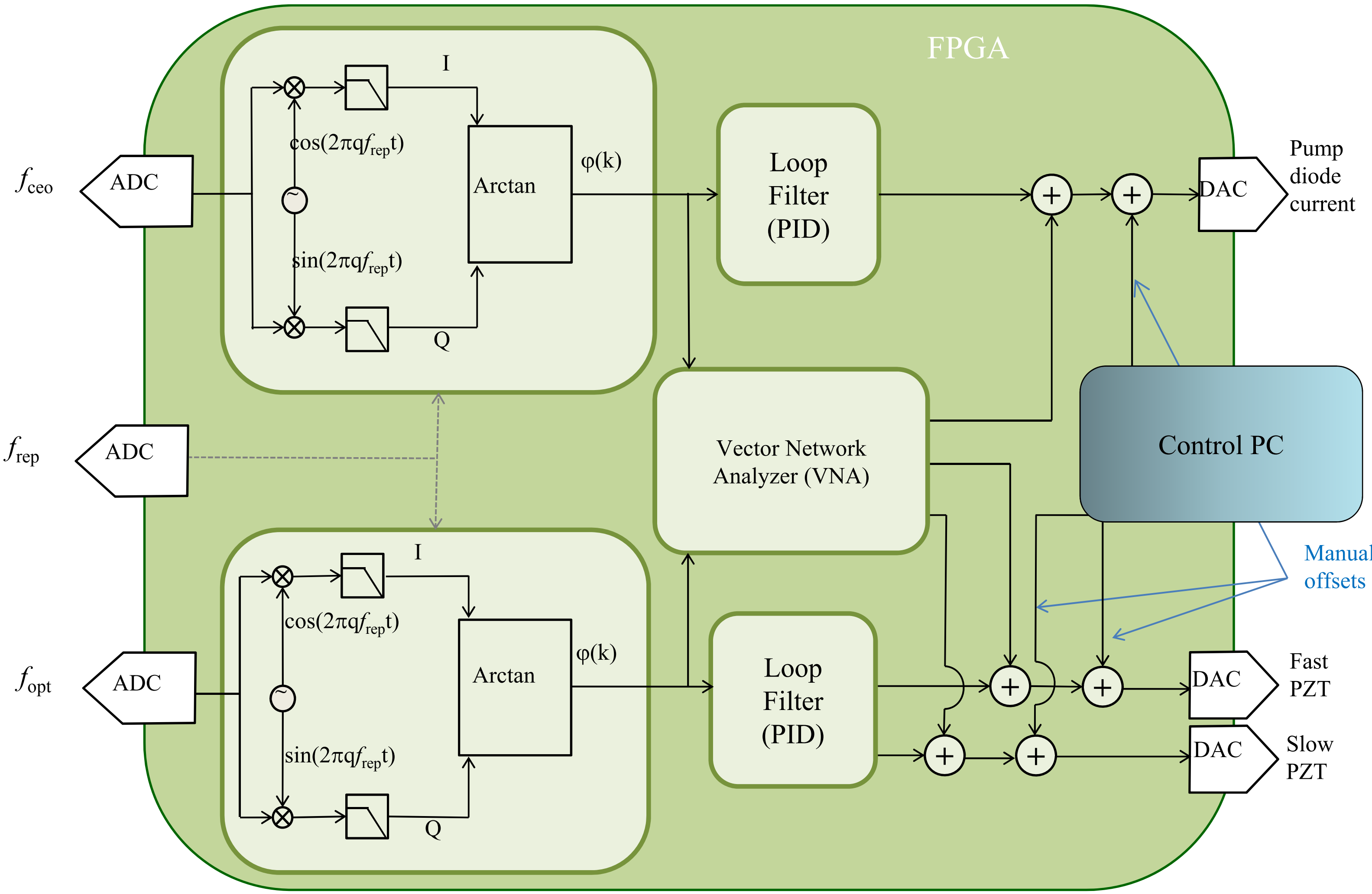
Jean-Daniel Deschenes (VHDL)
Dave Leibrandt (hardware)

- Xilinx Spartan 6 FPGA + ADC
- Clock of 10 MHz or comb (self-referenced)
- Control of both optical lock and offset frequency lock
- Digital phase unwrapping
- 20 x smaller, much cheaper
- Built-in comb diagnostics
- Feedback optimization

FPGA-based Digital Controller

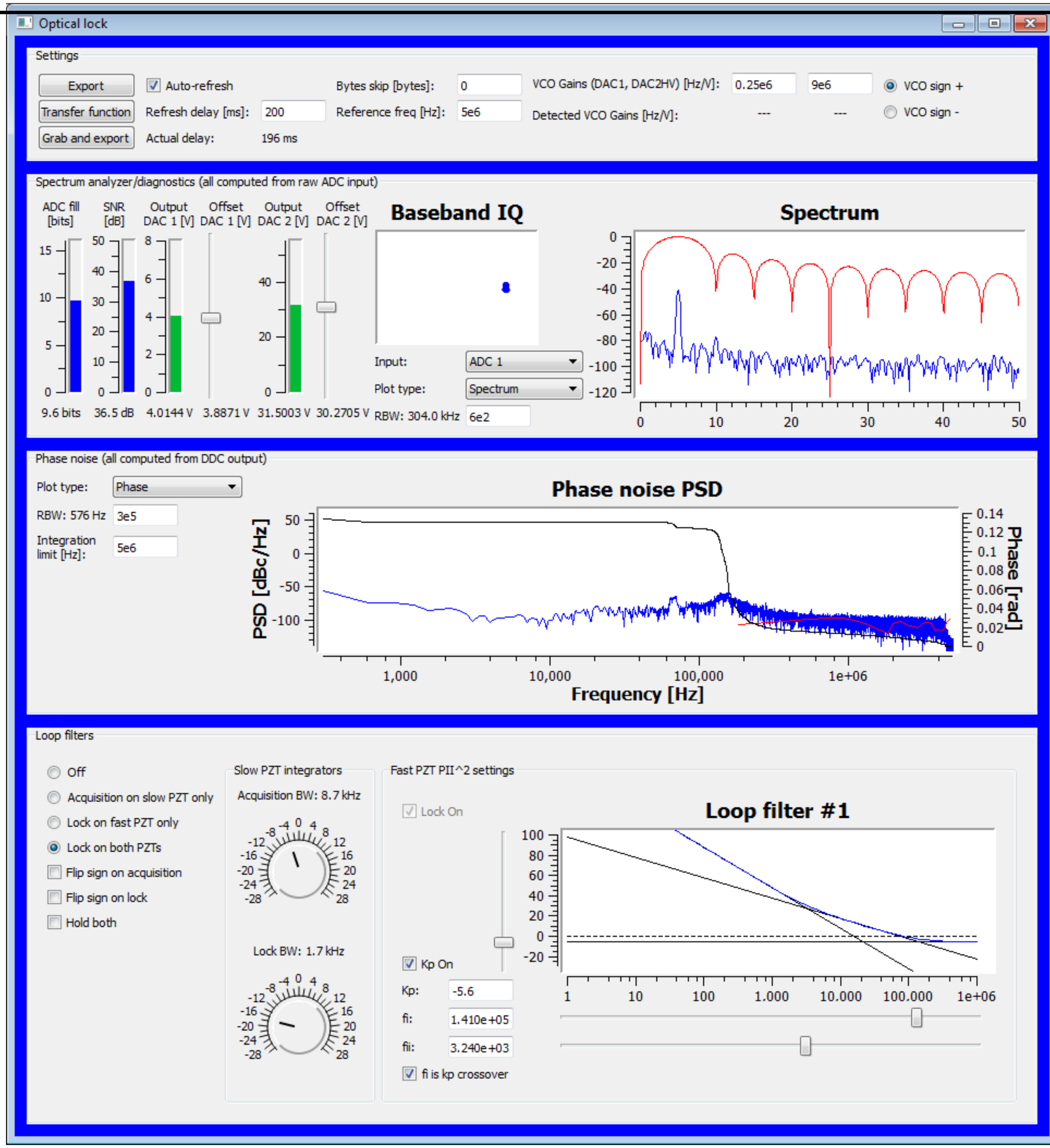


FPGA-based Digital Controller



http://www.nist.gov/pml/div686/grp07/fpga-based-digital-control-box-phase-stablization-frequency-comb.cfm

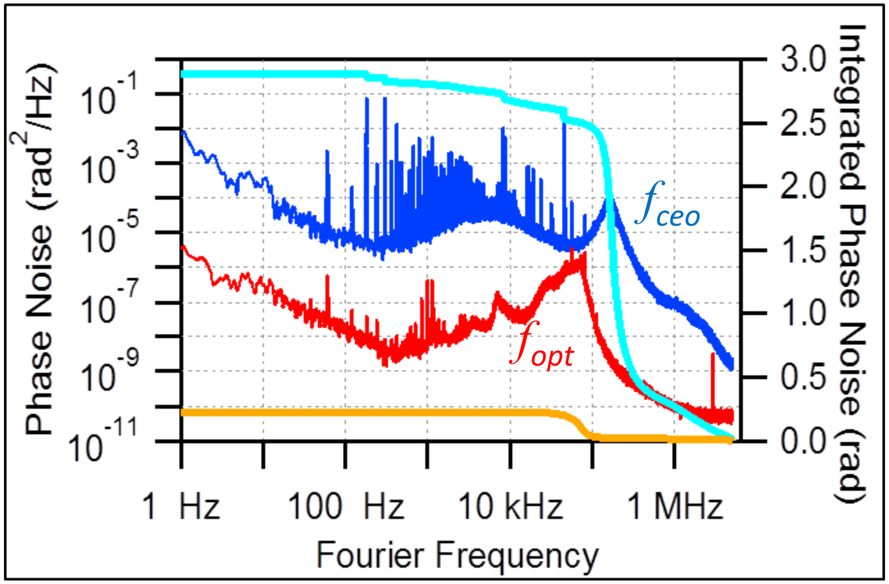
Screenshot of Comb Control Software



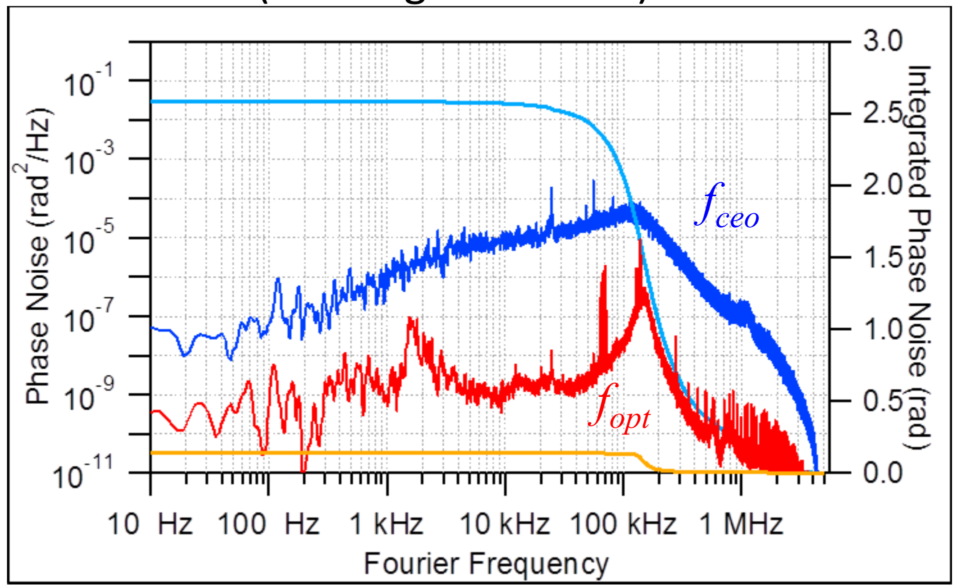
Version 2.0 Frequency comb: Laboratory Phase Noise PSD

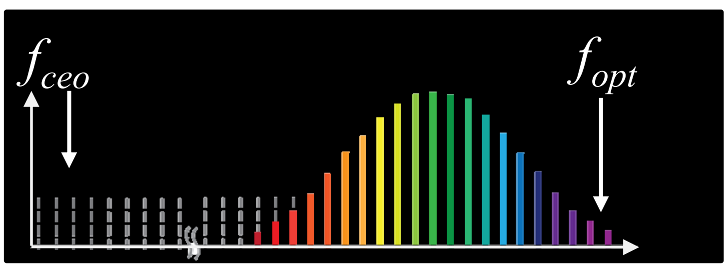
- Feedback bandwidths >100kHz optical and CEO

Old phase noise
(with analog electronics)



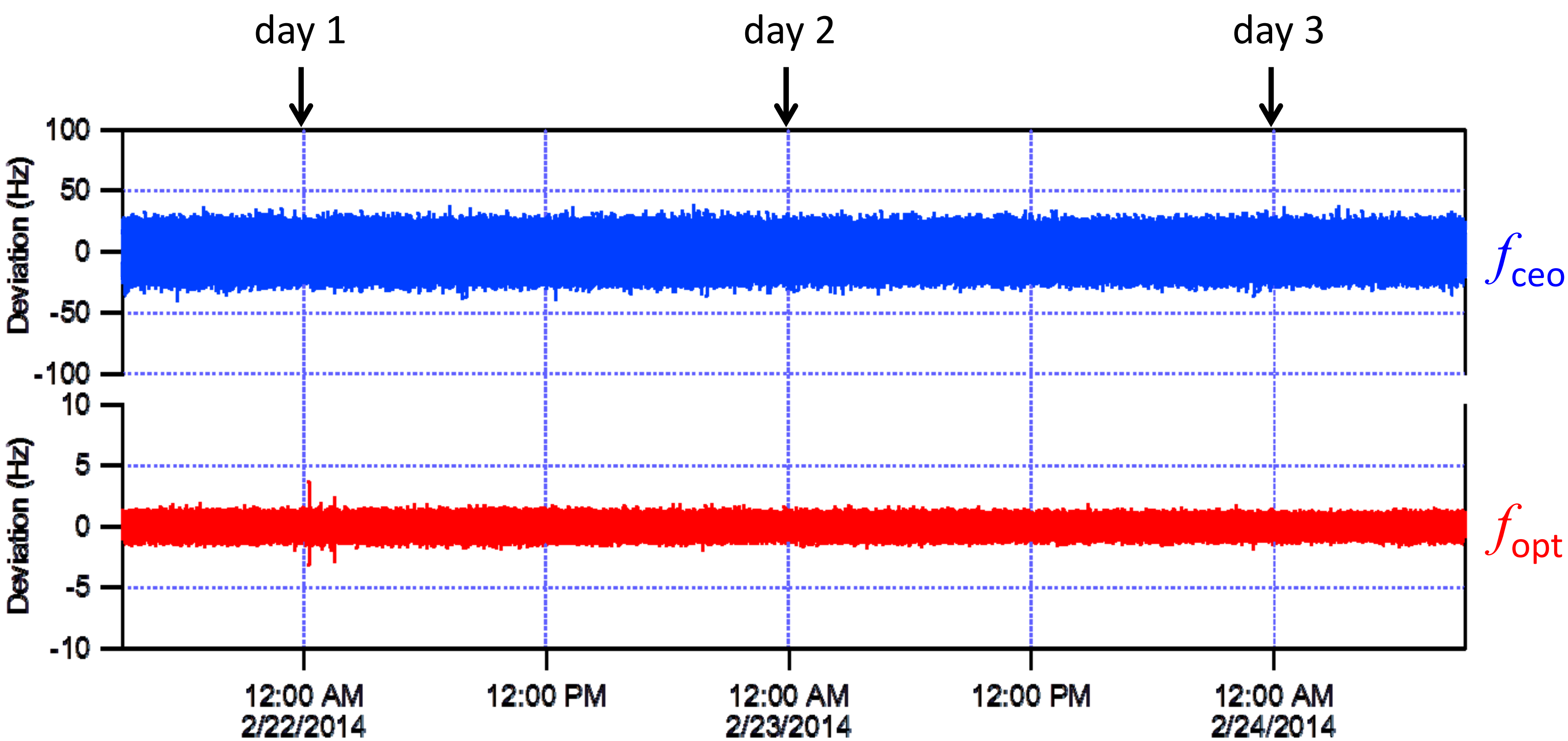
New phase noise
(with digital control)

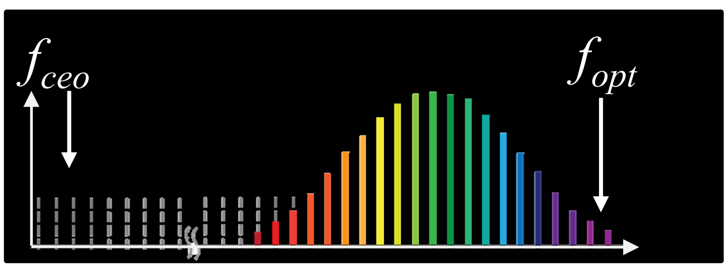




Integrated CEO phase noise: 2.9 rad-> 2.6 rad
Integrated optical phase noise: 0.2rad-> 0.14 rad
Equivalent pulse-to-pulse timing jitter ~ 2.1 fs

Long term phase locking

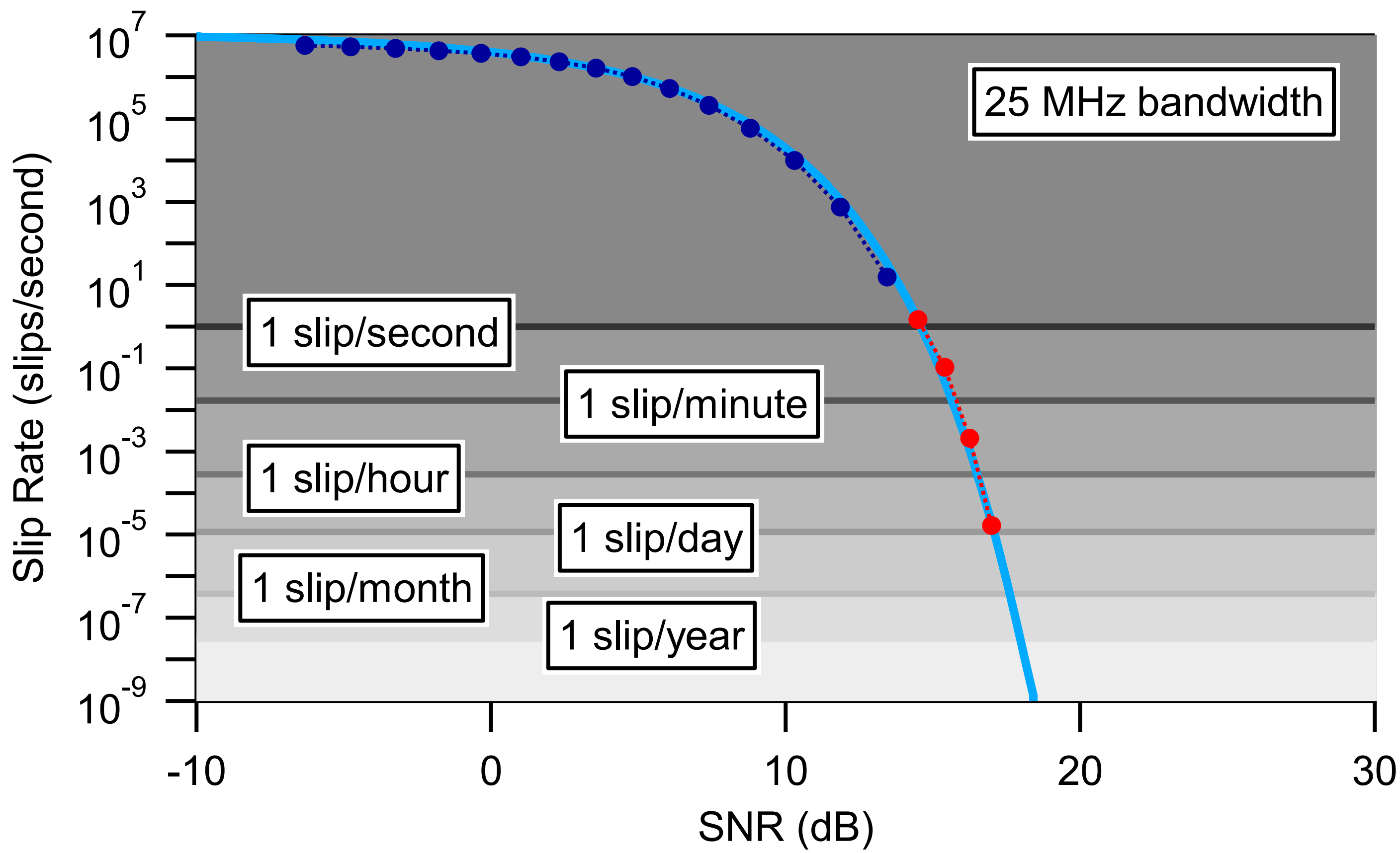




100 ms gate time

Phase-slip free operation up to theoretical SNR limit

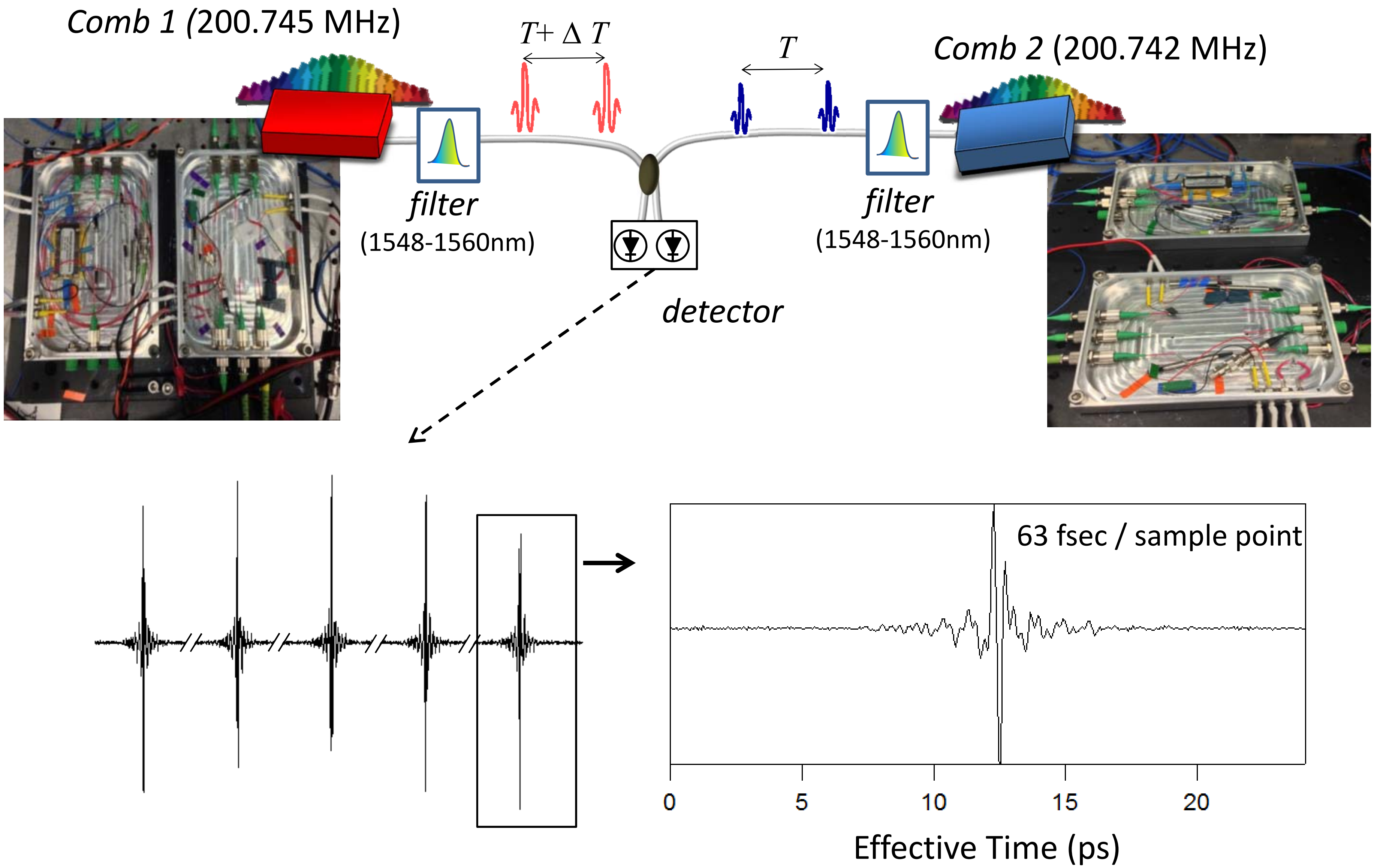
Important for future optical clock timekeeping



- Analogous to bit error rate (BER) in Binary Phase Shift Keying Communication
- Both the simulation and analytical calculation assume gaussian noise

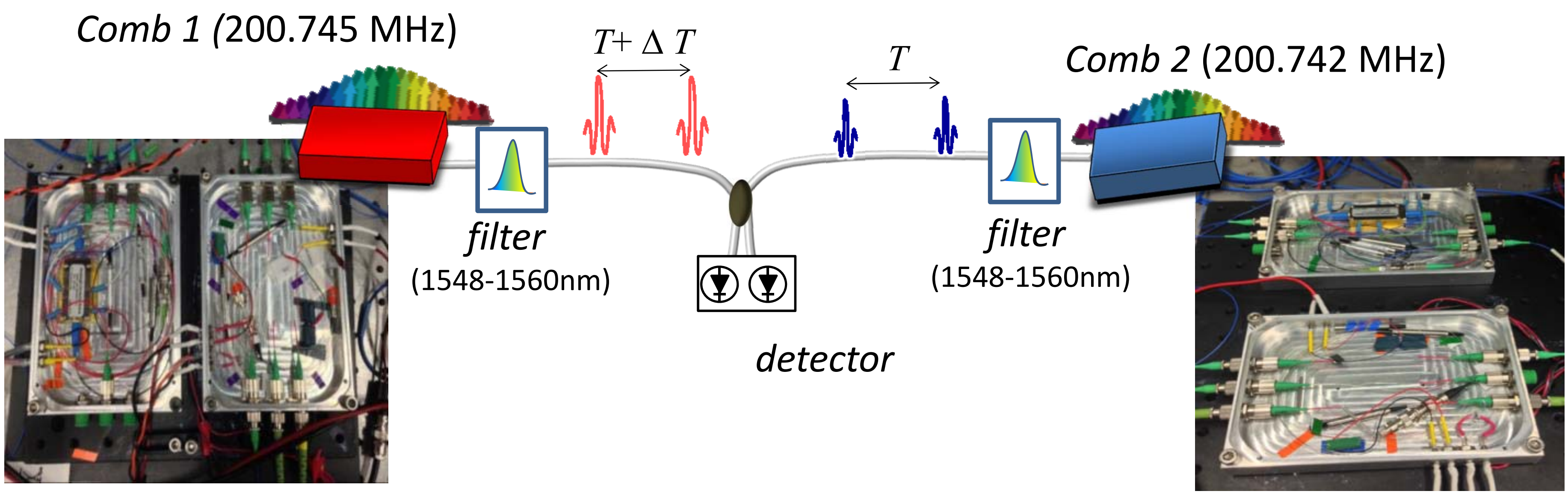
Operation of dual Frequency combs

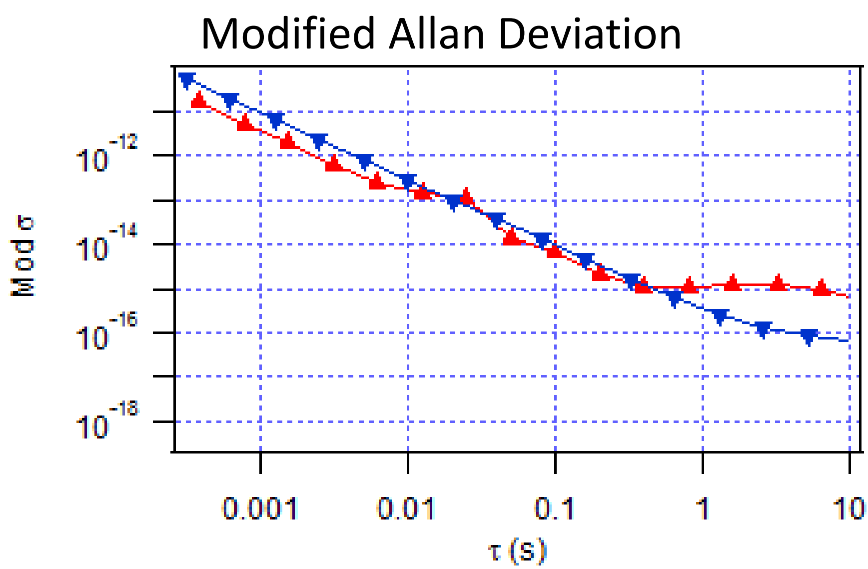
Initial timing measurements (cross-correlation)

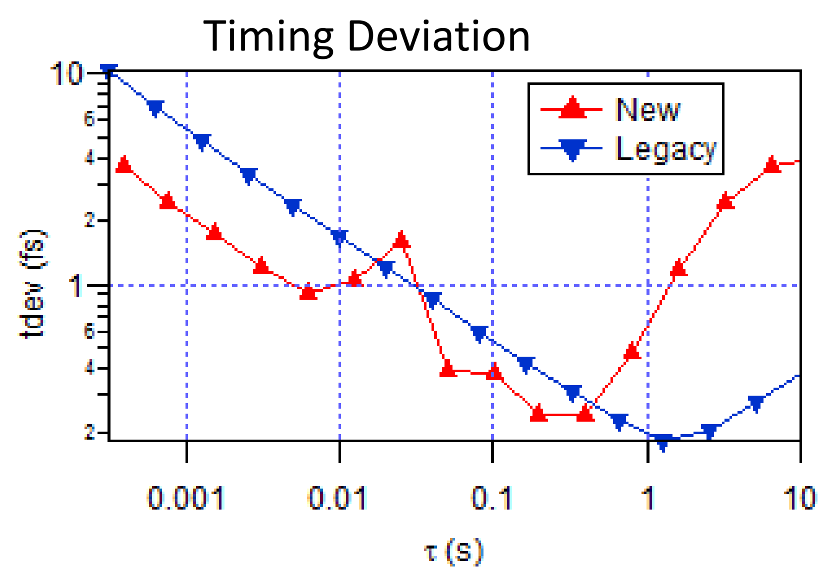


Operation of dual Frequency combs (v2.0)

Initial timing measurements (cross-correlation)





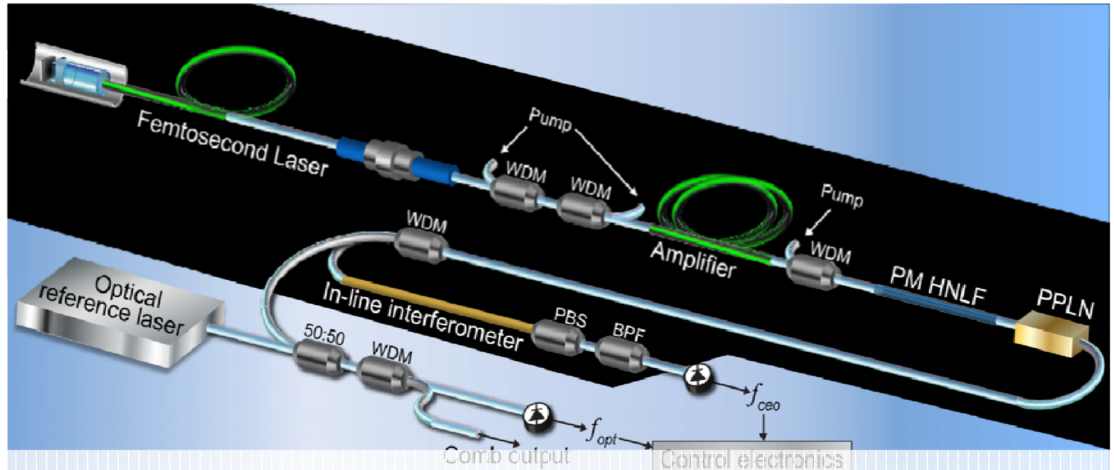


Better performance at short times

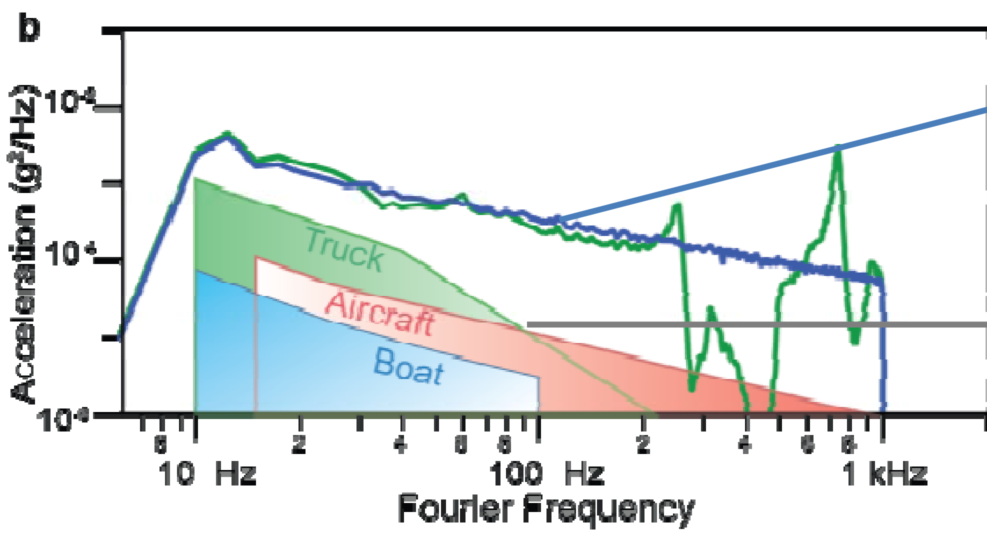
Outline

- Motivation
- Development of a Robust Frequency Comb:
  - The First Generation Comb
  - Version 2
- Environmental Testing of the First Generation Comb:
  - Vibration Testing on an Industrial ShakerMobile Van Testing

Operation under Strong Vibrations: Frequency Comb on a Shaker Table



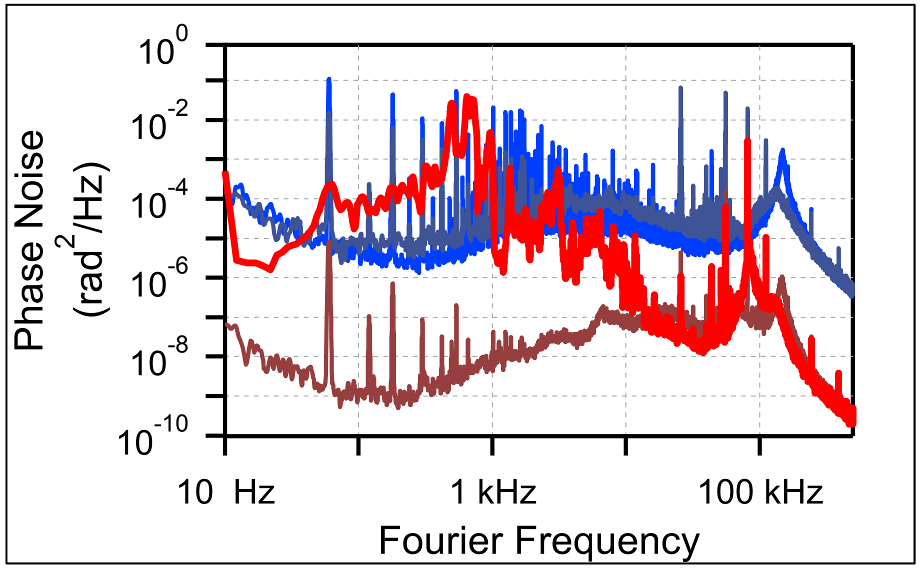
Black region = “optics package” that was shaken

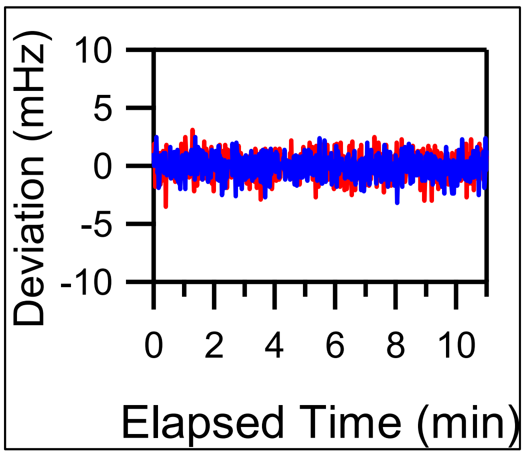


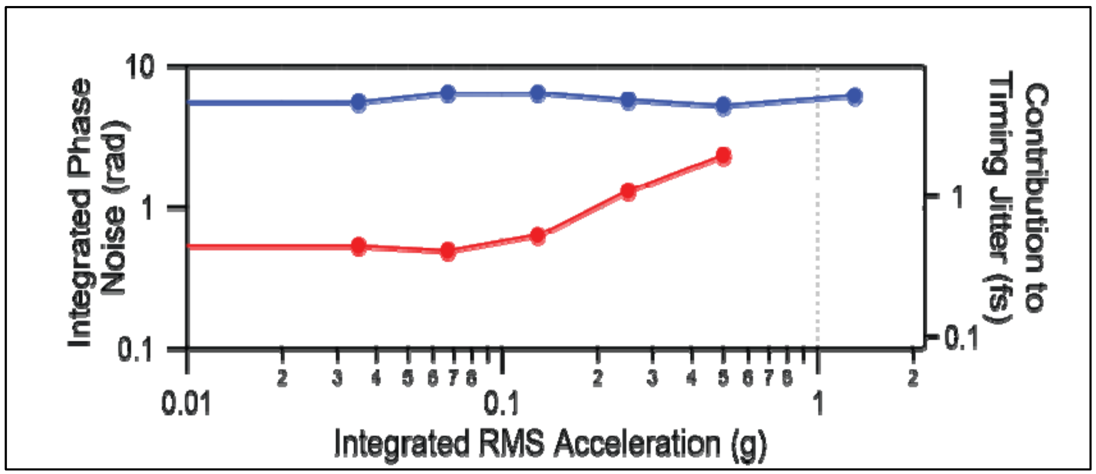
0.05g rms integrated acceleration

US DoD, "MIL-STD-810G: Environmental Engineering Considerations and Laboratory Tests," (2008). **Assuming pneumatic isolator with a natural frequency at 2.5Hz and a 6% damping ratio**

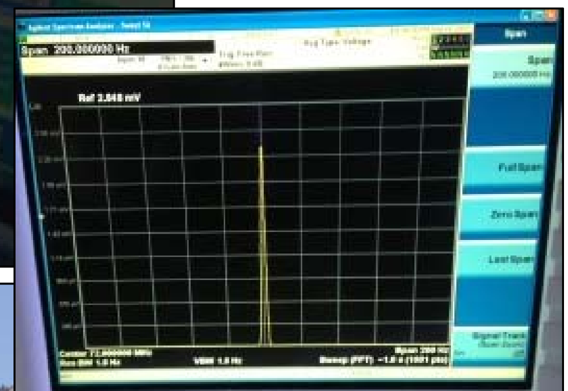
Operation under Strong Vibrations: Frequency Comb on a Shaker Table







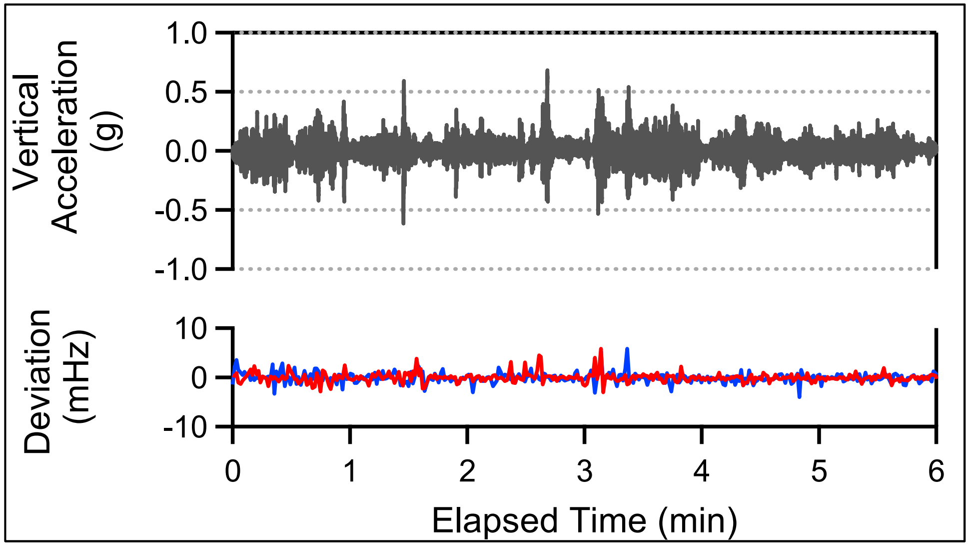
Operation in a Moving Vehicle

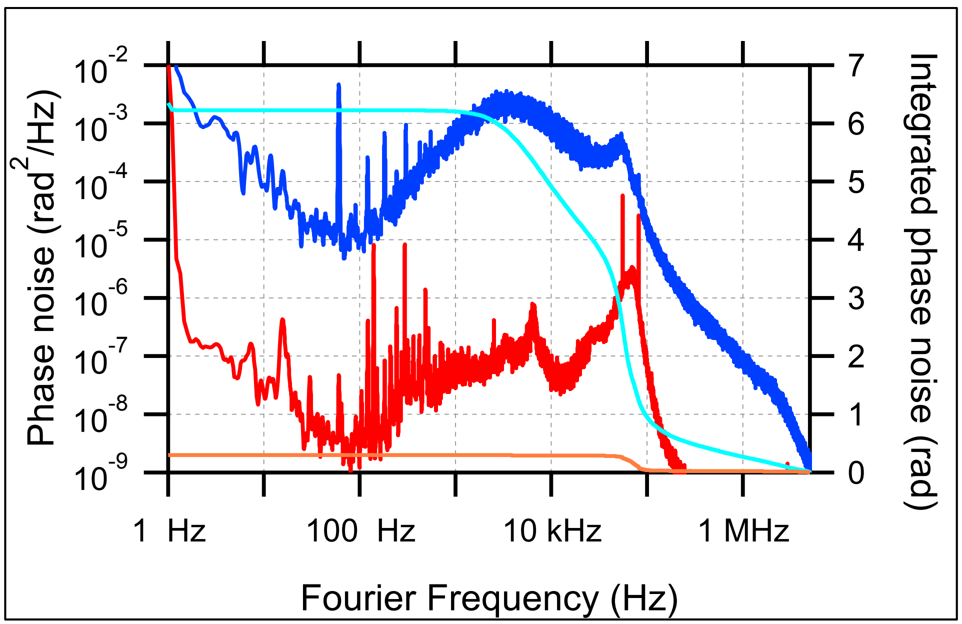


Operation in a Moving Vehicle: movie

Phase-locks and optical coherence maintained while
- the vehicle was operated at up to 20 mph
- over significant dips
- over speed bumps
- and on a gravel road

Operation in a Moving Vehicle: summary of performance





Conclusion

- Frequency combs can support a wide variety of applications
- Applications have a corresponding wide range of requirements
  - On frequency comb stabilization
  - On many other parameters – spectral flatness, robustness etc.
- Fiber frequency combs are currently the most “common” frequency comb because of their lower cost, flexibility, and greater robustness
- Noise on frequency combs best understood in fixed point model
- Fiber frequency combs continue to evolve
  - Field operation becoming a reality