Progress in femtosecond timing distribution and synchronization for ultrafast light sources

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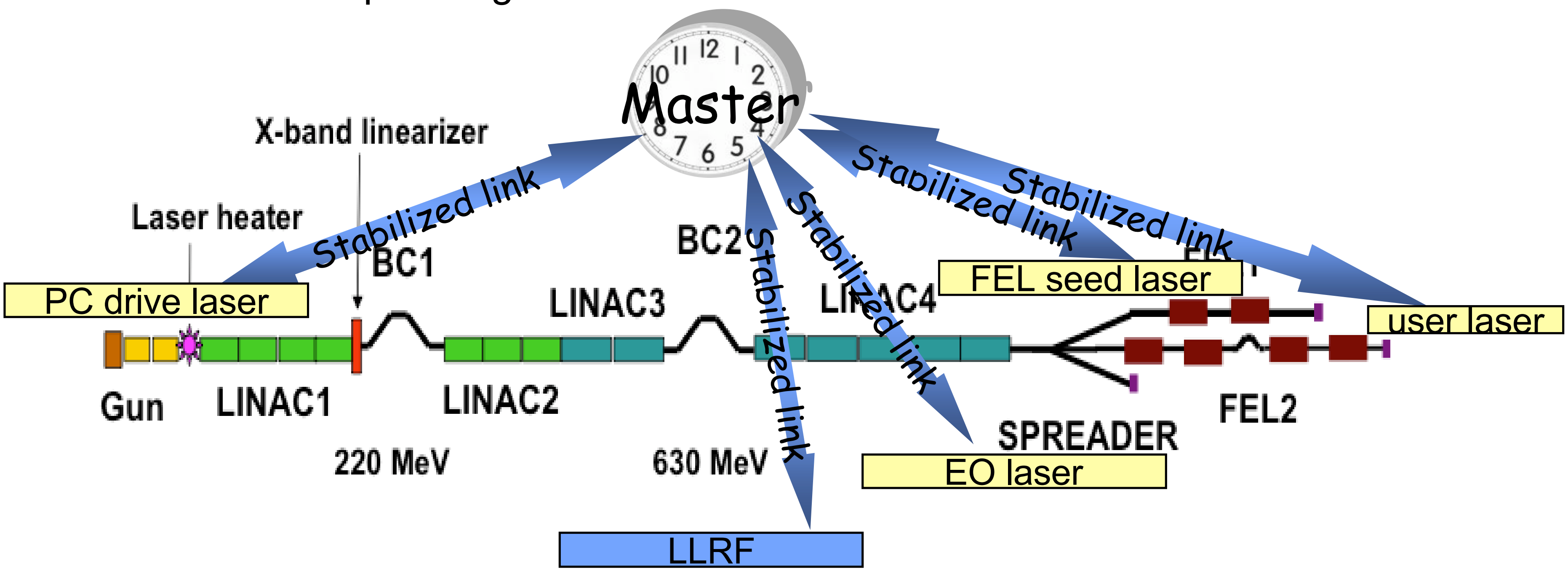
Synchronicity

- Next generation light sources require an unprecedented level of *remote* synchronization between x-rays, lasers, and RF accelerators to allow pump-probe experiments of fsec dynamics.
  - Photocathode laser to gun RF
  - FEL seed laser to user laser
  - Relative klystron phase
  - Electro-optic diagnostic laser to user laser



Stabilized fiber link

Frequency-offset Optical Interferometry

Technique used at ALMA

64 dishes over 25 km

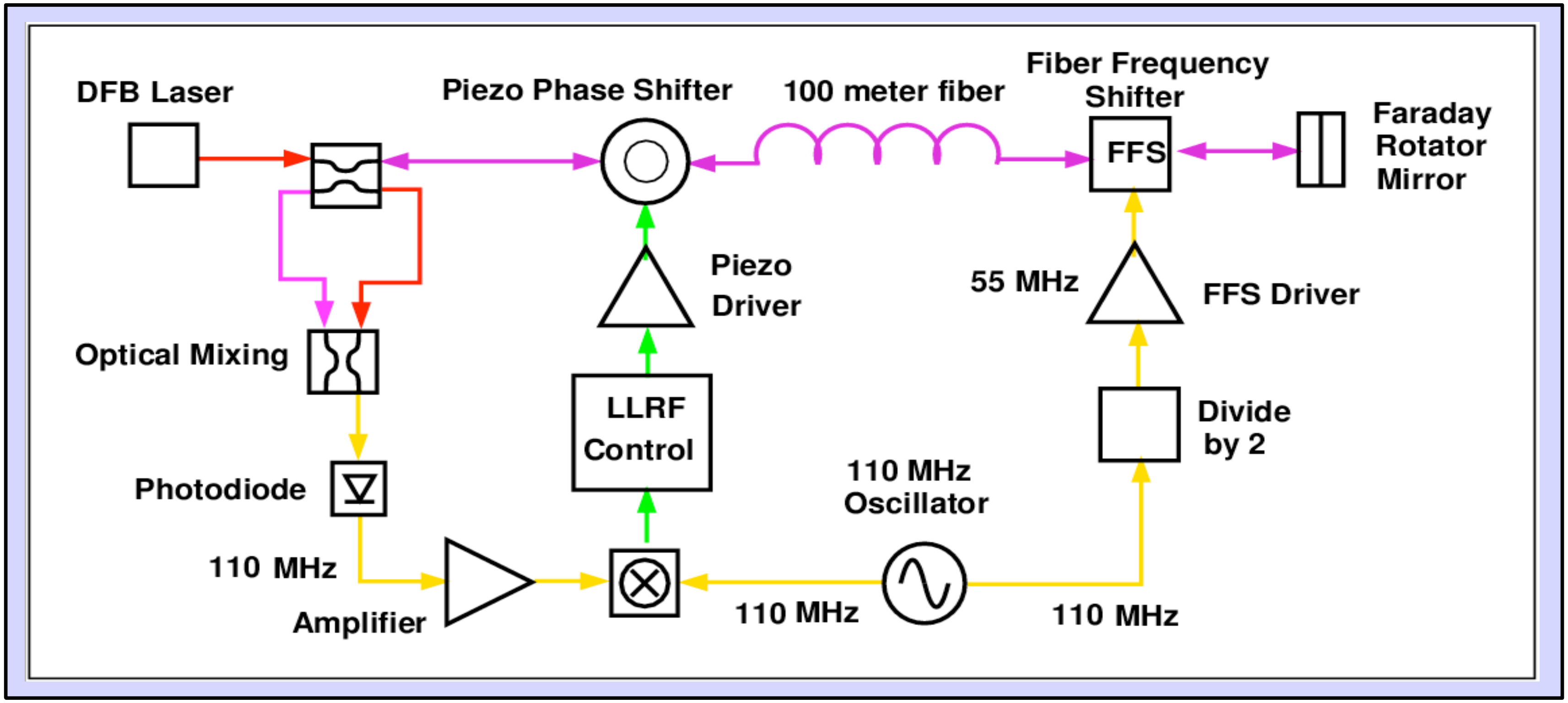
footprint, 37 fsec requirement

Principle: Heterodyning preserves phase relationships

1 degree at optical = 1 degree RF

1 degree at 110 MHz = 0.014 fsec at optical

Gain 10^5 leverage over RF-based systems in phase sensitivity



Detailed configuration

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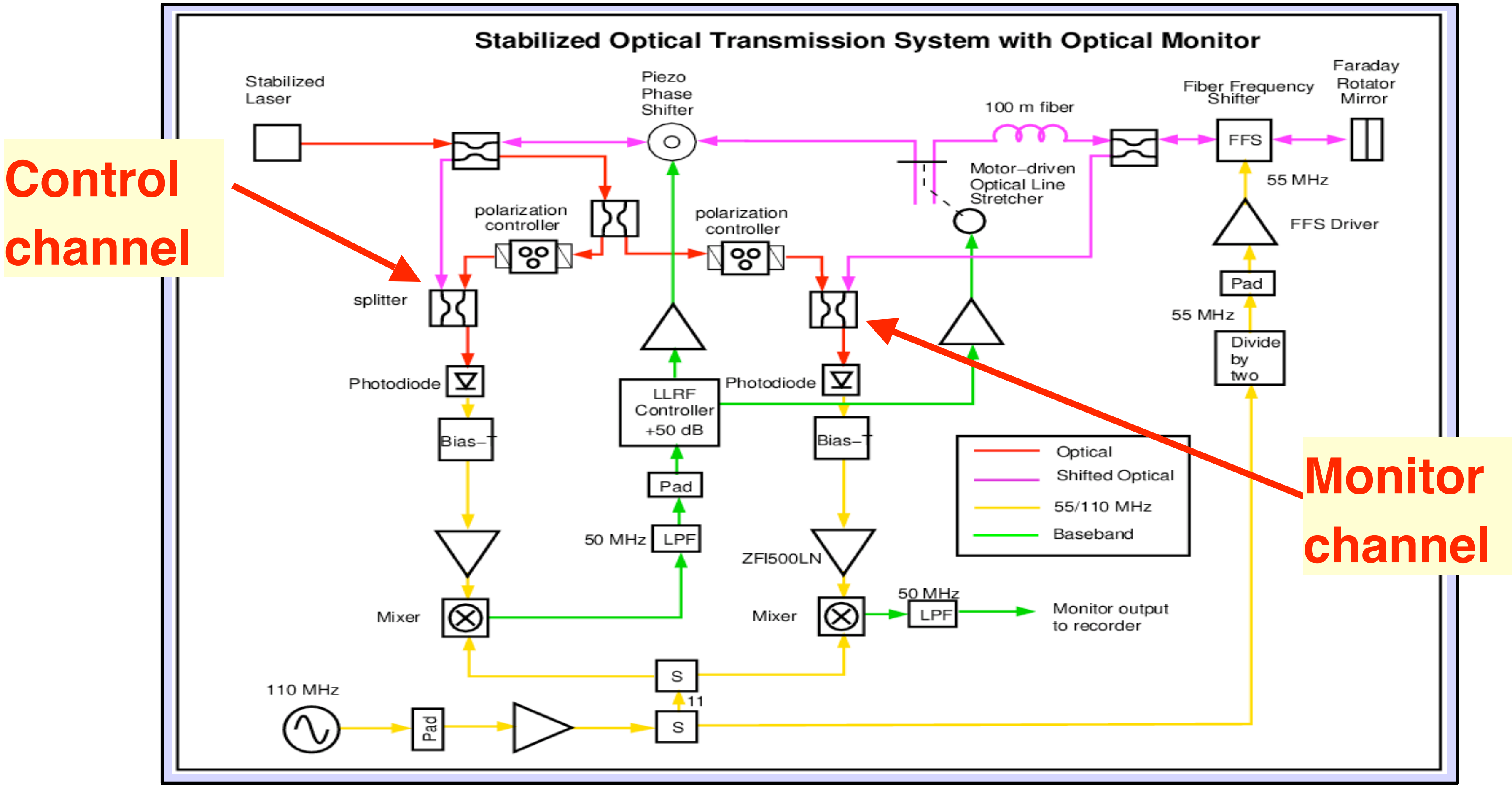


•Phase errors,drifts in 110 MHz RF circuits insignificant

•Reflections along fiber don't contribute: only frequency-shifted reflection beats with outgoing laser line to produce error signal

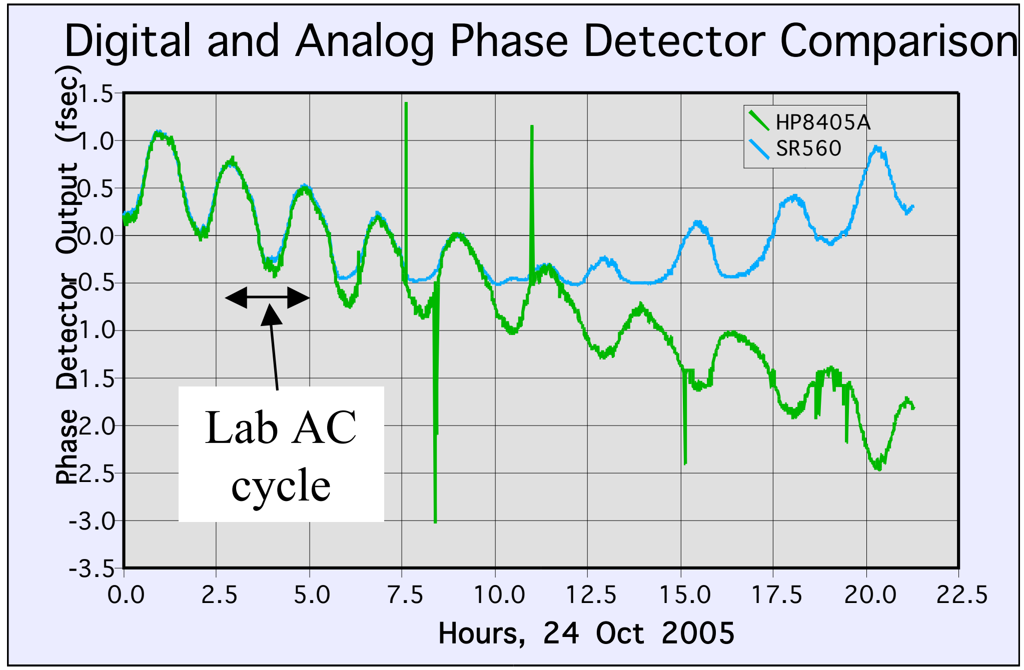
•Low power cw signals, linear system, commodity hardware

Drift Results

Compare phase at the end of fiber with reference to establish stability.

Measure slow drift (<1 Hz) of fiber under laboratory conditions

Compensation for several environmental effects results in a linear drift of 0.13 fsec/hour and a residual temperature drift of 1 fsec/deg C.

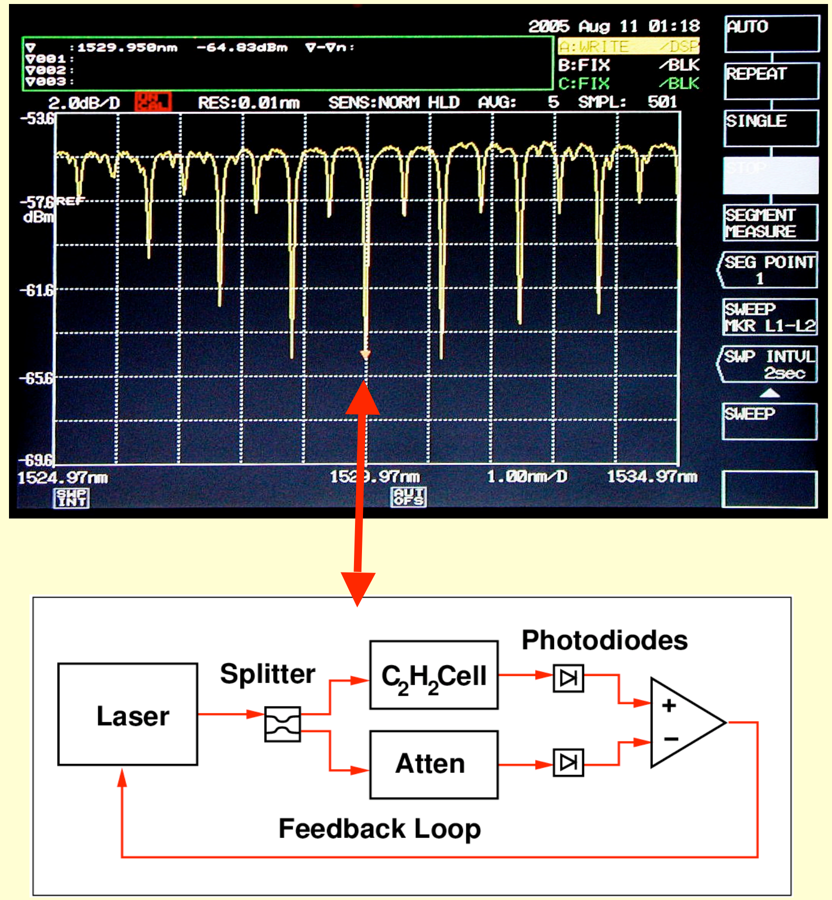


Environmental factors

- Temperature: 0.5-1 fsec/deg C
- Atmospheric pressure: none found
- Humidity: significant correlation
- Laser Wavelength Stabilizer: none
- Human activity: femtosecond noise in the data

Laser Standard Clock

- Laser provides absolute standard for length of transmission line
    - Narrow-line (2 kHz) Koheras Laser (coherence length > 25 km)
    - For single fringe stabilization over 150 m, laser frequency must be stabilized to better than 1:10^8
    - Use frequency lock with acetylene cell



Frequency lock loop on acetylene (C_2H_2) 1530.3714 nm absorption line

Thermal control of critical components

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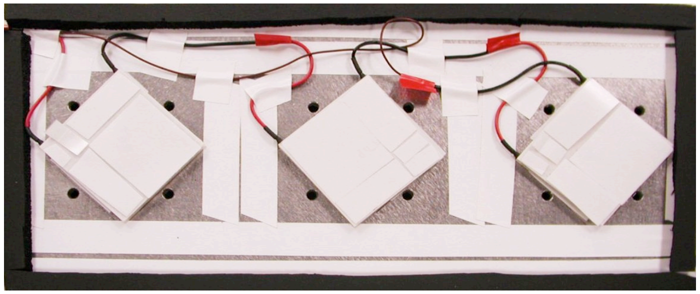
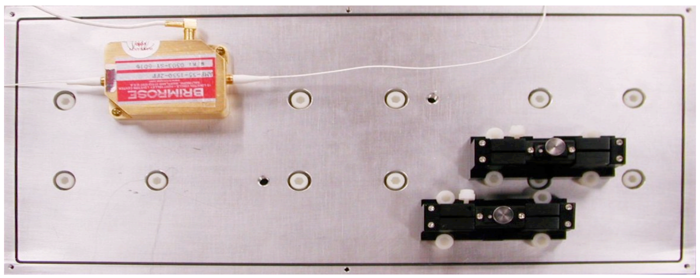
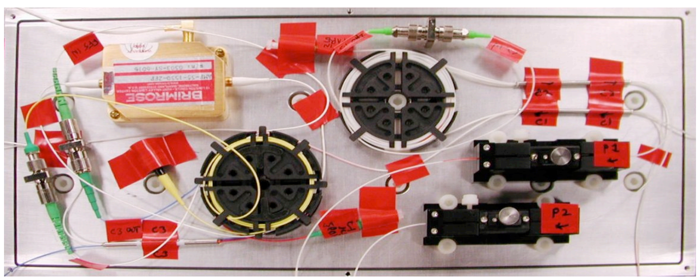


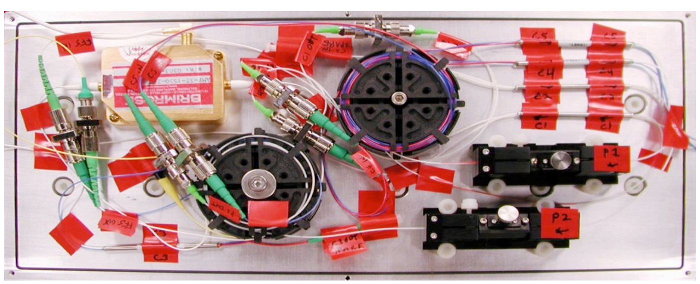
Peltier Coolers



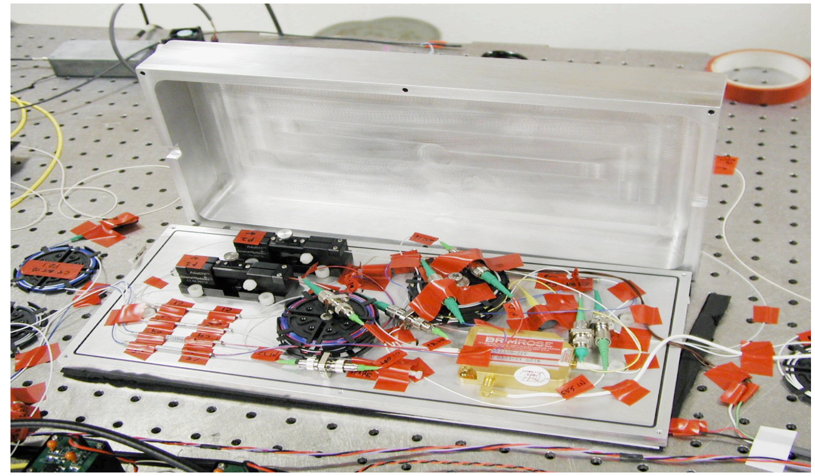
Baseplate



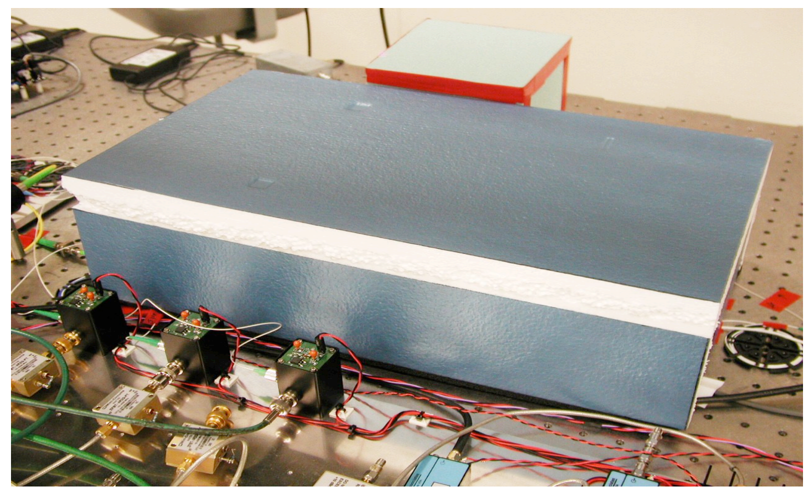
Some components



Complete



Aluminum Chamber



Insulating Jacket

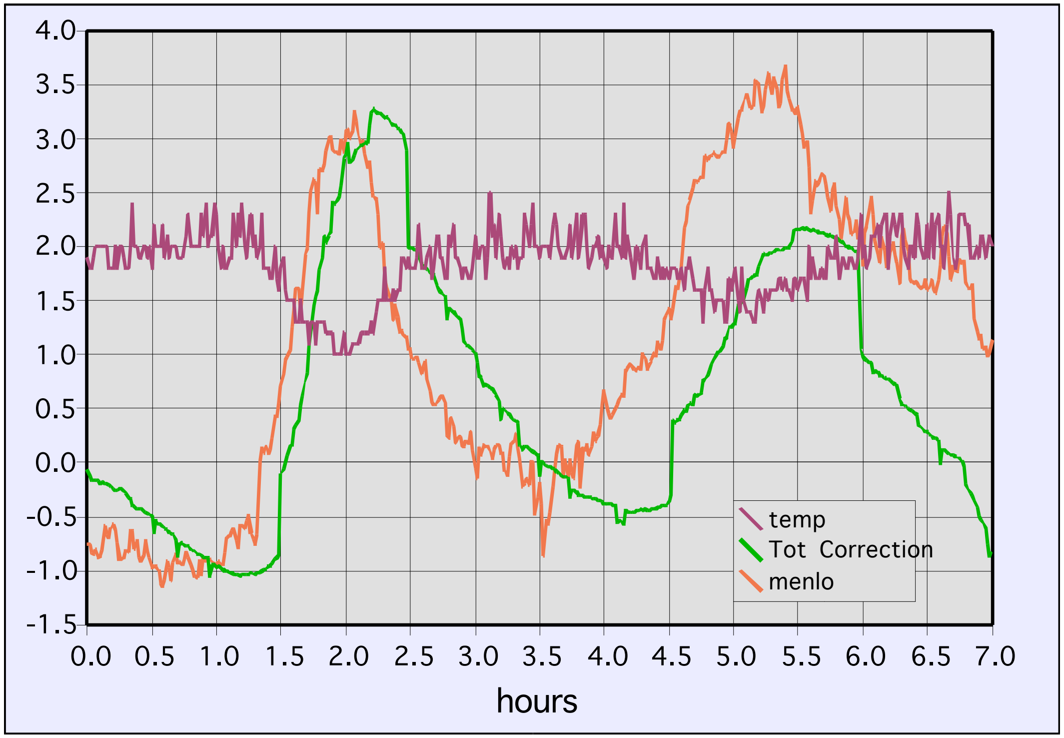
Group and Phase Velocity Correction

Interferometric technique corrects single frequency phase velocity.

To correct for group velocity variations, we can derive the group velocity from the differential phase velocity at two frequencies.

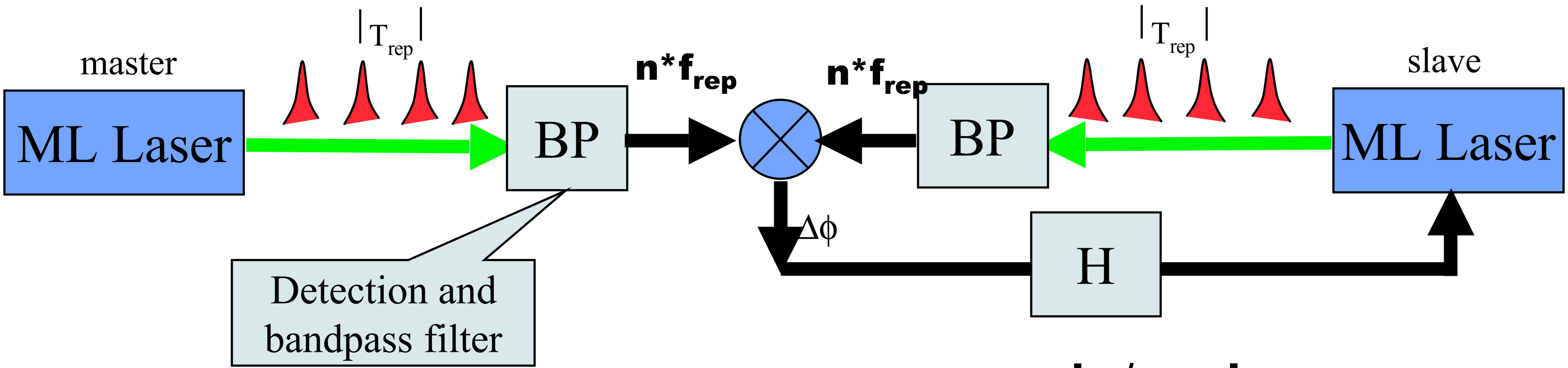
Correction can be applied dynamically or via a feedforward scheme.

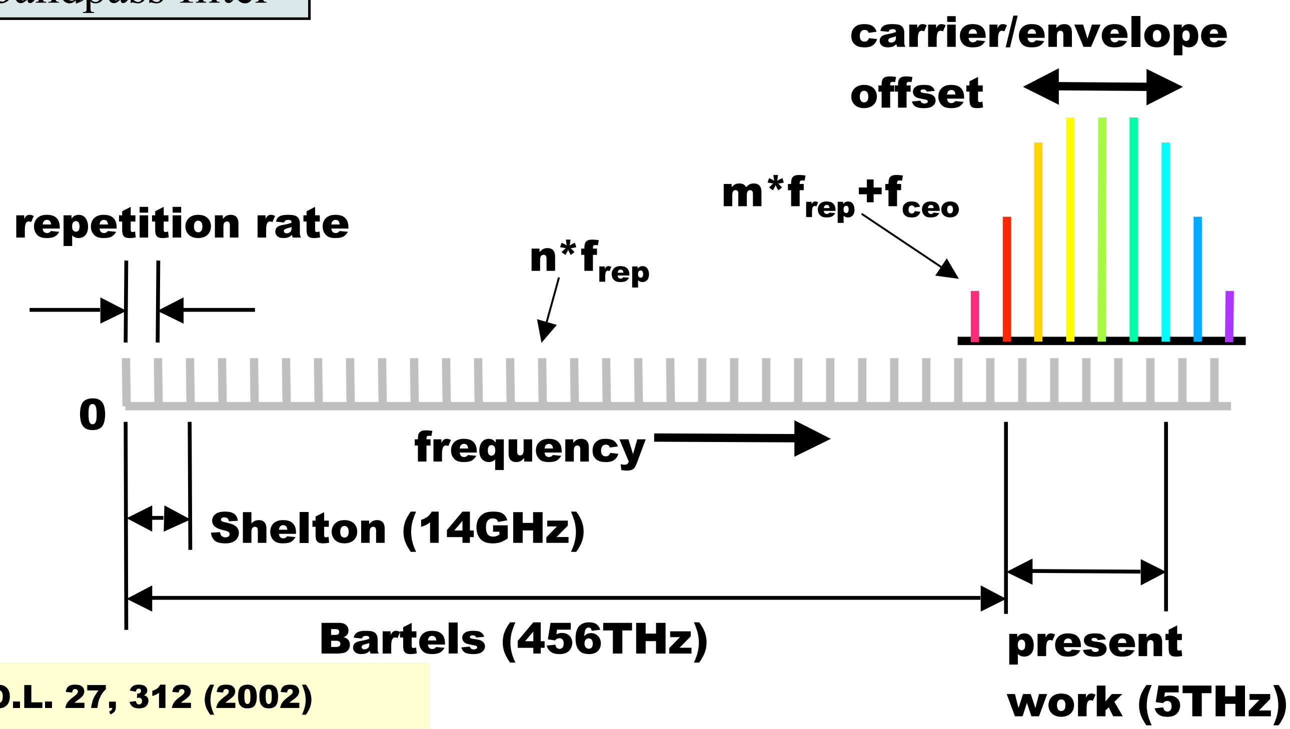
Study presently underway.



Correction applied to 1530 nm wavelength in psec as a function of temperature and the measured 1570 nm phase variation divided by 1.92%.

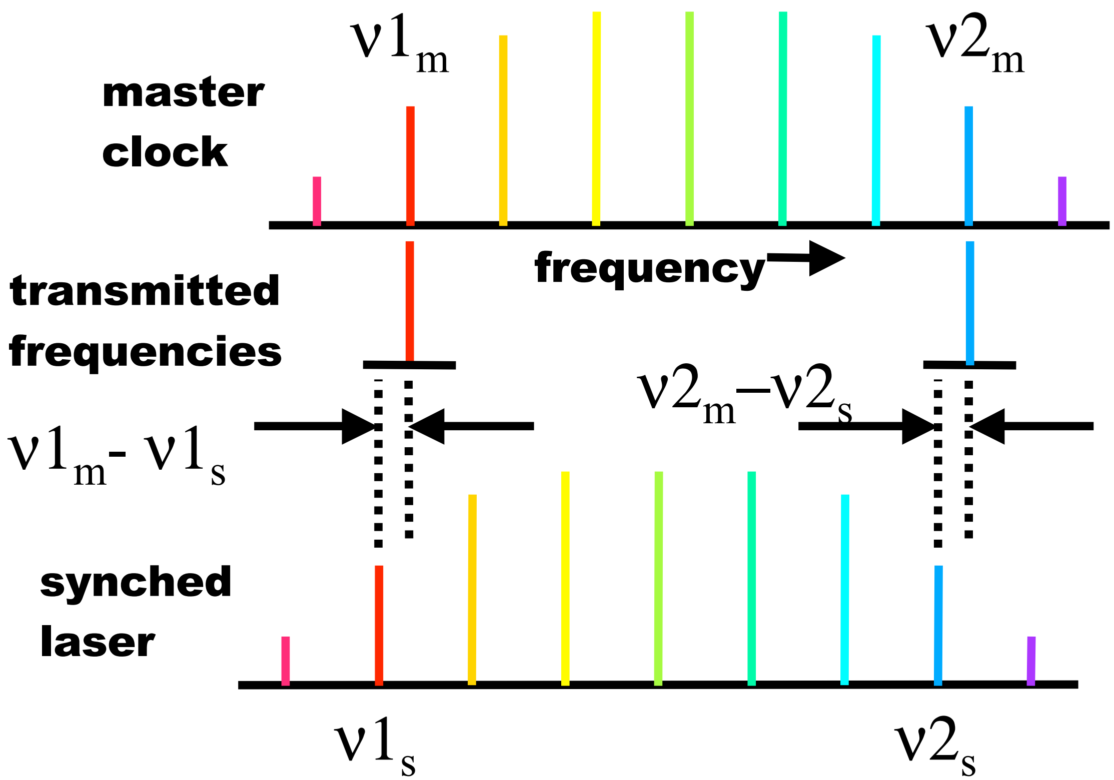
Synching mode-locked lasers





Shelton et al, O.L. 27, 312 (2002)
Bartels et al, O.L. 28, 663 (2003)

Two-frequency synch scheme



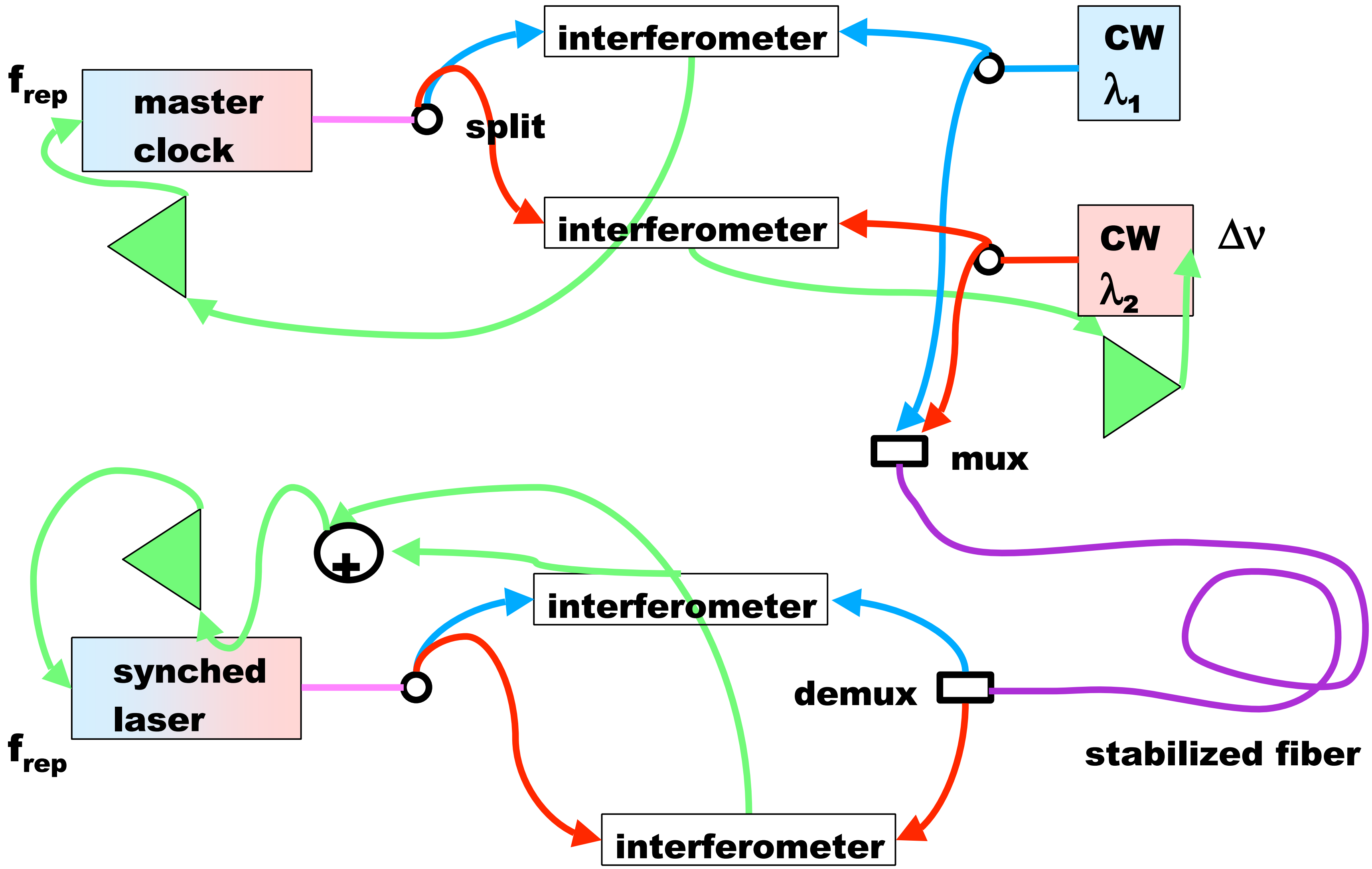
Lock two frequencies within the frequency comb separated by 5 THz.

For a 1 **degree** error in phase detection, temporal error is <0.6 fsec

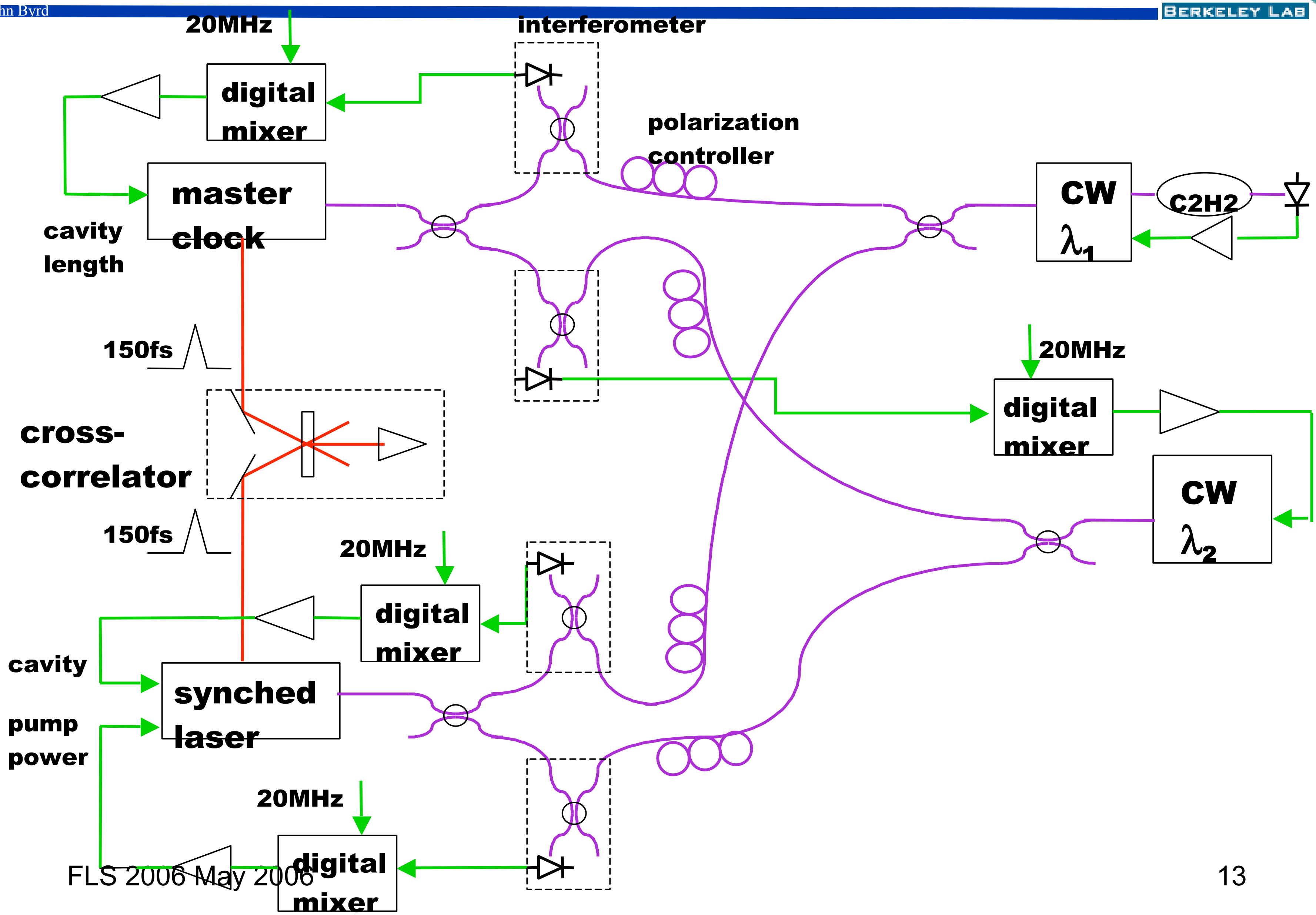
$$(\nu 1_m - \nu 1_s) - (\nu 2_m - \nu 2_s) = 0$$

$$\underbrace{(\nu 1_m - \nu 2_m)}_{5\mathrm{THz}} - \underbrace{(\nu 1_s - \nu 2_s)}_{5\mathrm{THz}} = 0$$

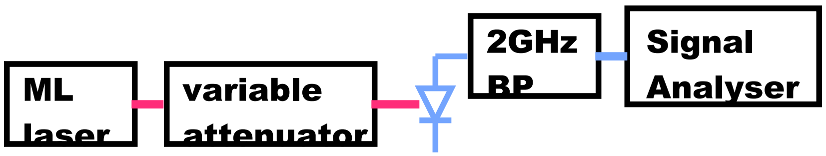
Two-frequency synch layout

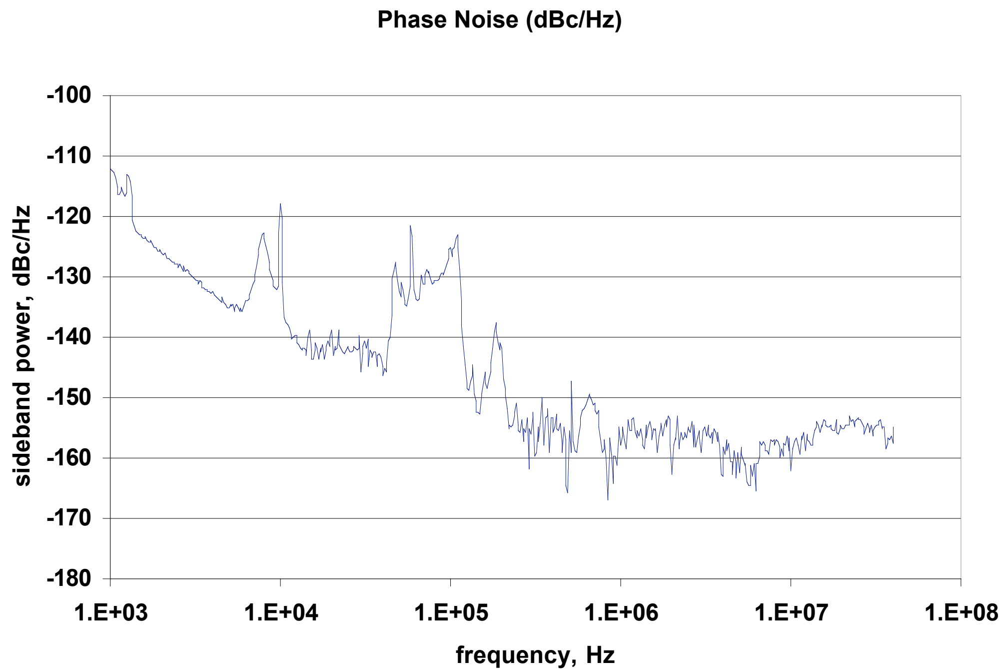


Experimental setup



Fiber laser transfer function





- Measured using 15GHz diode at around 1mW input power (maximizing high harmonic power, -15dBm at 2GHz)
- Harmonic at 2GHz was analysed, showing 18fs RMS jitter from 1kHz to 40MHz
- Results are ~2x higher than MIT laser, but power level on diode was lower, and a different diode used, so not truly comparable
  - A higher power diode might yield lower noise, as our result is shot noise limited at ~156dBc

Noise in the laser lock loops

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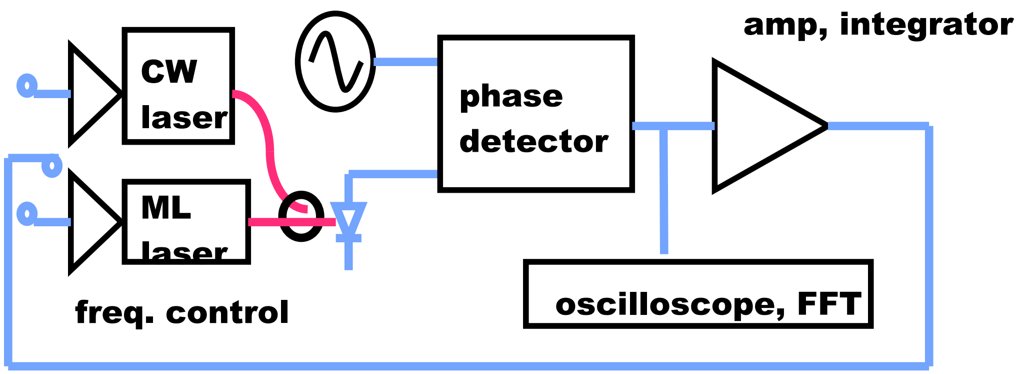
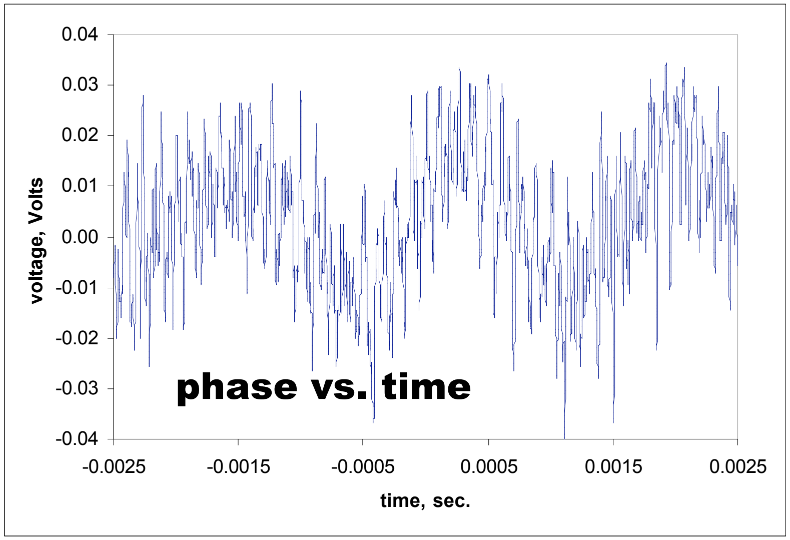
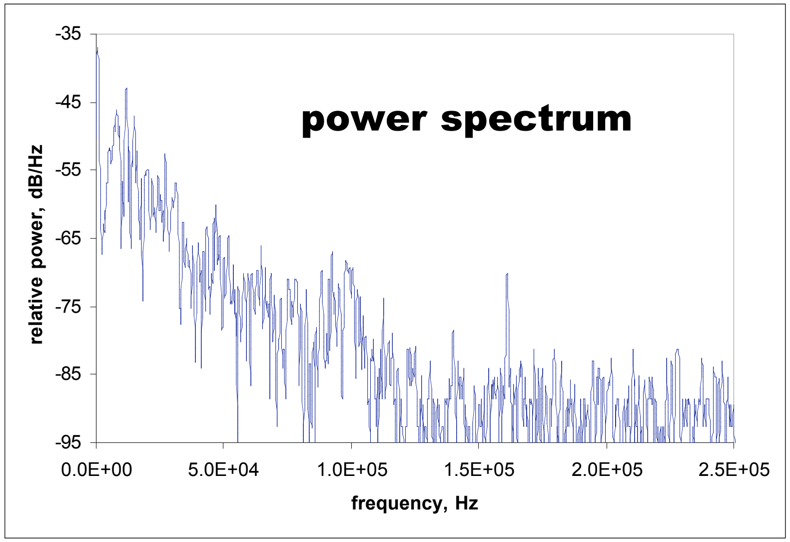
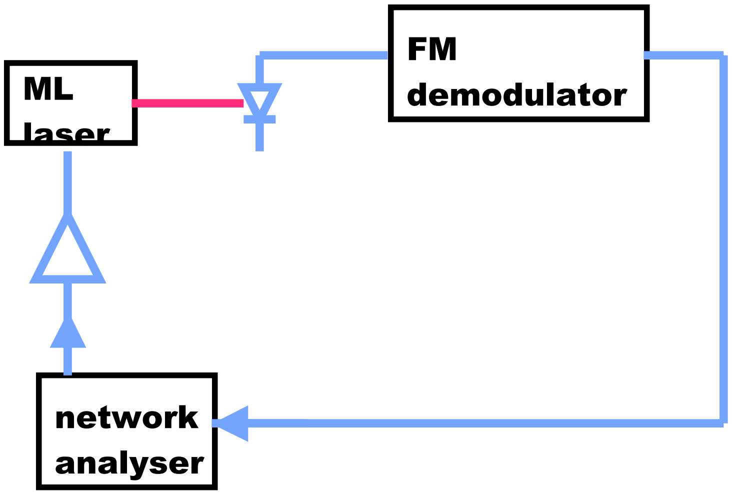


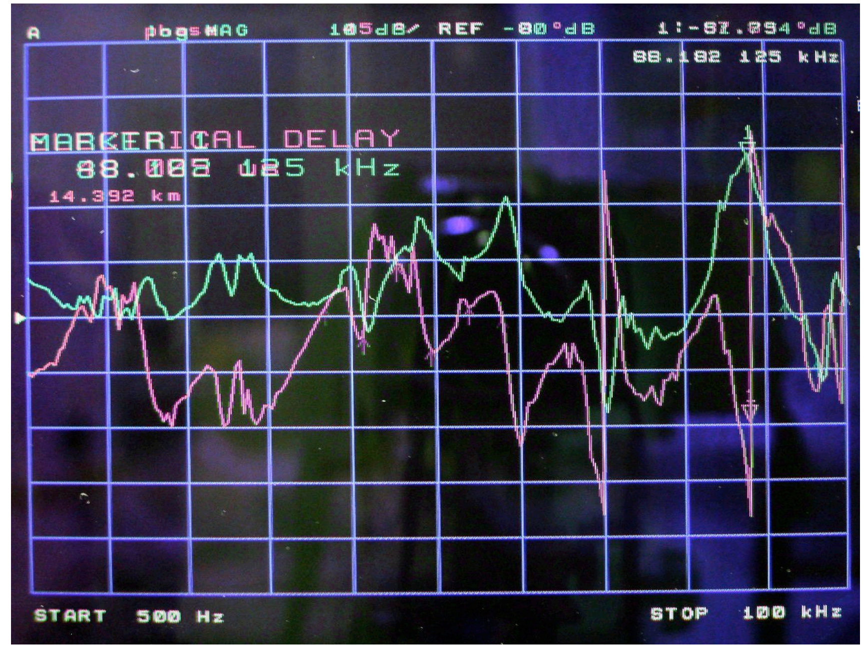


- Both configurations tested
- Based on phase detector calibration, about 250fs p-p jitter
- Mainly at 650Hz and 8kHz
- Need about 18x reduction in jitter
- PLLs limited by oscillation
  - Fix: design better loop filters
  - Use improved lasers
    - Second Menlo is better
    - Koheras has improved design



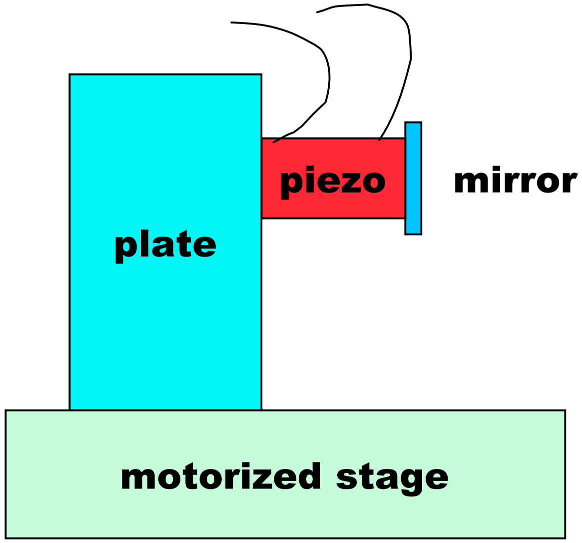
Fiber laser transfer function



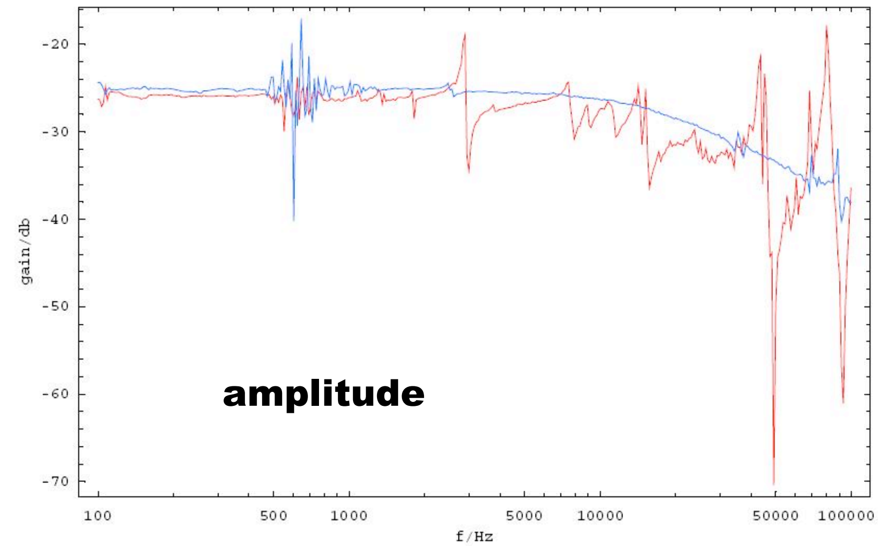


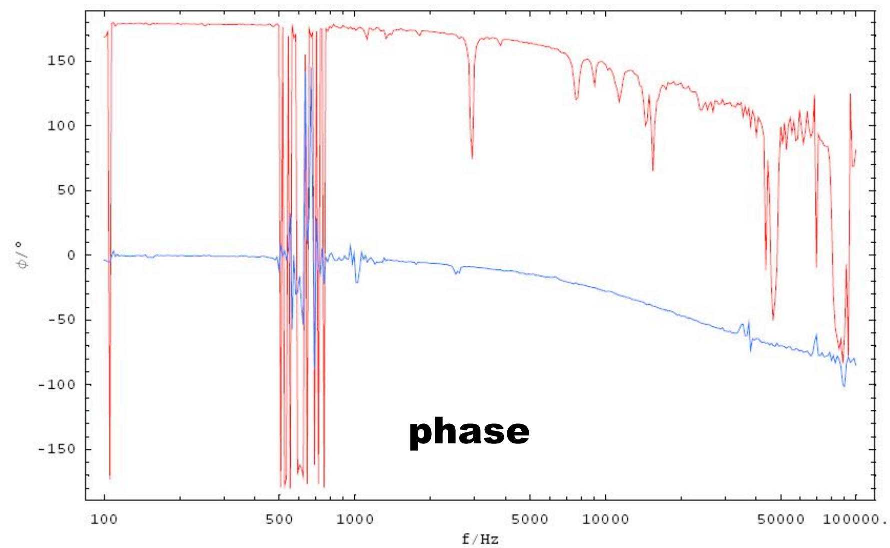
- **Modelocked laser reprate was frequency modulated, detected at a high harmonic (2GHz) and demodulated**
- **Indicates several resonances at high frequencies (67kHz, 88kHz), which are also observed in the error signals of the optical phase lock loops**

EDFL Transfer function

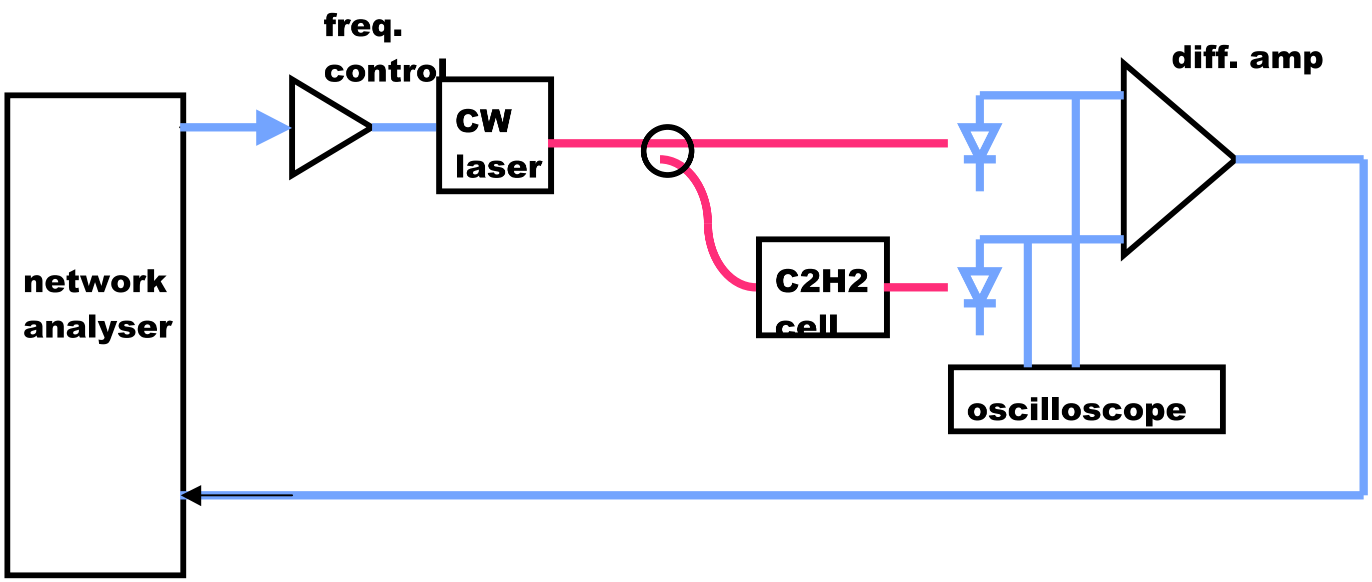


- Piezo driven cavity end mirror controls reprate
- Was a 10mm long piezo on a light Al plate
- Replaced with 2mm piezo on steel plate
- Control loops should be easier to stabilize
  - New laser will arrive soon



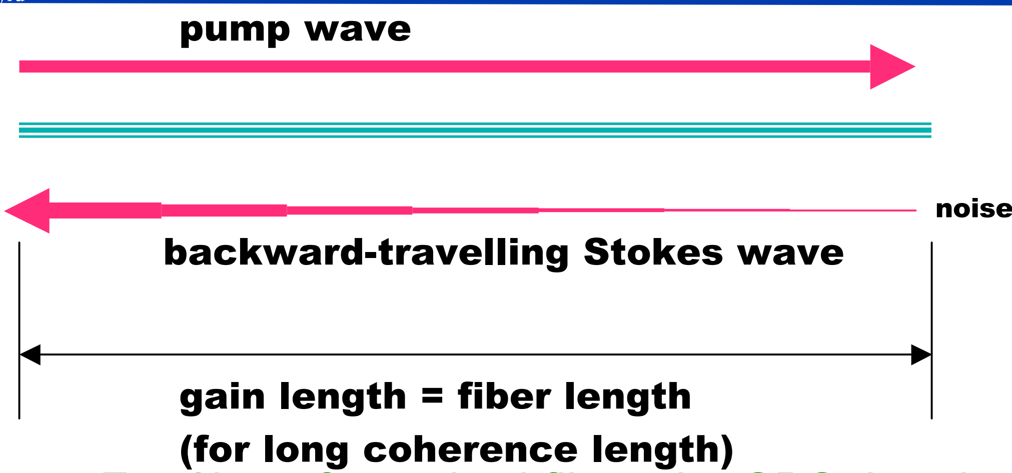


CW laser piezo TF



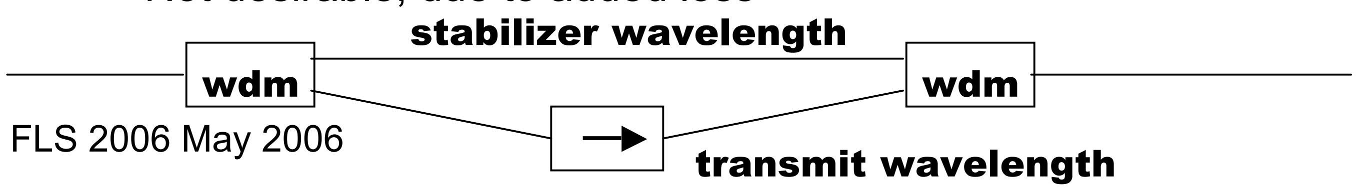
- **CW laser was optical frequency modulated and demodulated by tuning to edge of C_2H_2 absorption line. AM signal was analysed**
- **CW laser has high frequency resonances (26kHz at +22dB, 65kHz at 32dB), also observed in its loop error signal**
- **Overall conclusion: need to design the phase lock electronics to avoid oscillation due to excess phase from resonances**
  - **New Koheras design has better mechanical characteristics, should help**

Brillouin scattering

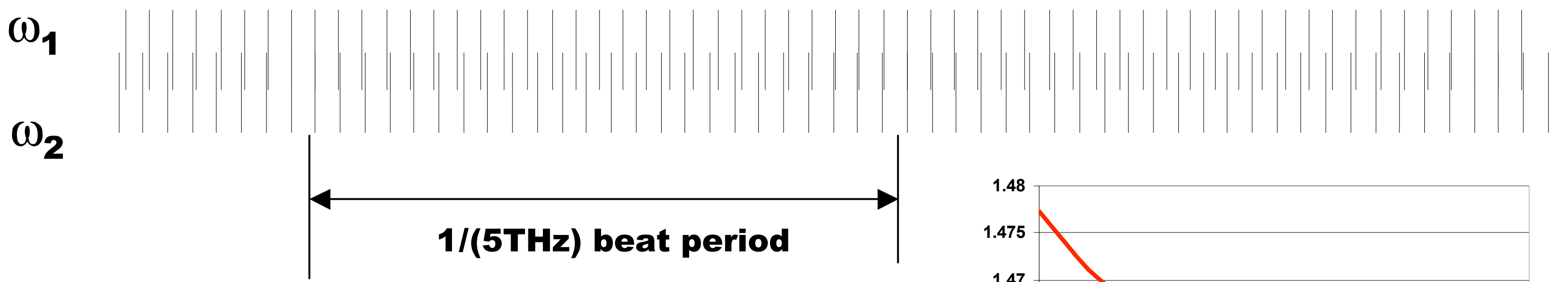


$$P_0^{cr} \cong 21 \frac{A_{eff}}{L_{eff}\, g_a}$$

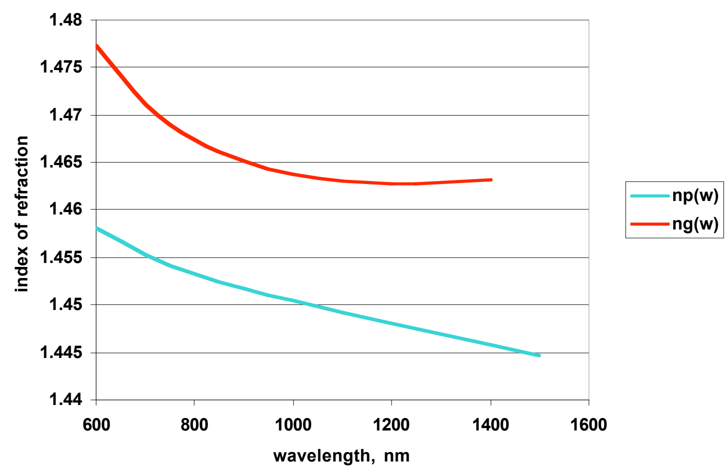
- For 2km of standard fiber, the SBS threshold is ~15mW
  - Larger mode area fibers exist, with higher threshold
  - Actual length may be ~1km, if clock is in center
- We have not yet measured the jitter vs. transmitted optical power for the system, but initial tests will be <20mW per wavelength due to limited laser power
- A receiver-end fiber amp might not add appreciable jitter (?)
- Backscatter blockers could be placed along the fiber, with the stabilization signal at a different wavelength
  - Not desirable, due to added loss



Dispersion correction



$$n_g = n_p + \omega \frac{dn_p}{d\omega}$$

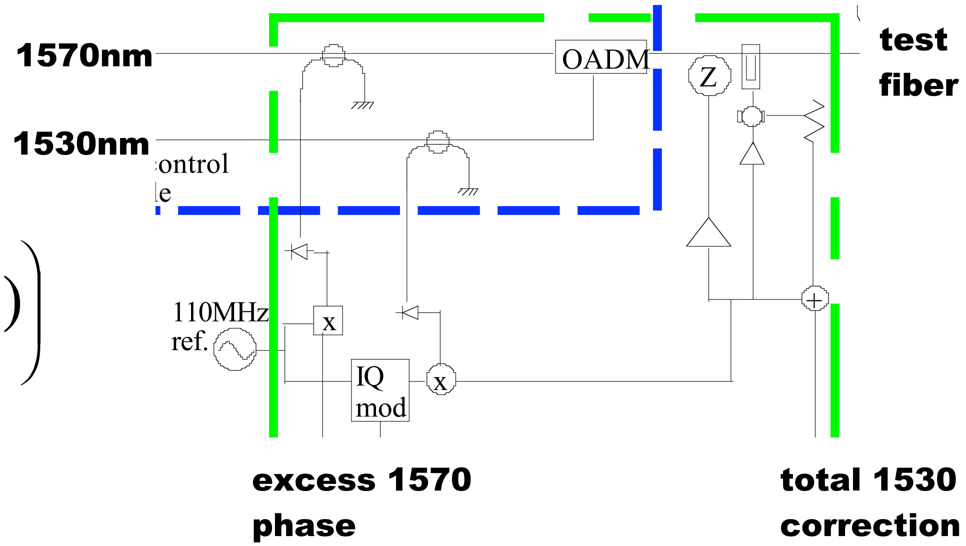


- Due to dispersion, phase and group delay are different. This would be OK, but
  - Due to temperature coefficient of dispersion, phase and group delays won’t change equally with temperature
- Need to correct!

Phase vs. group velocicty, continued

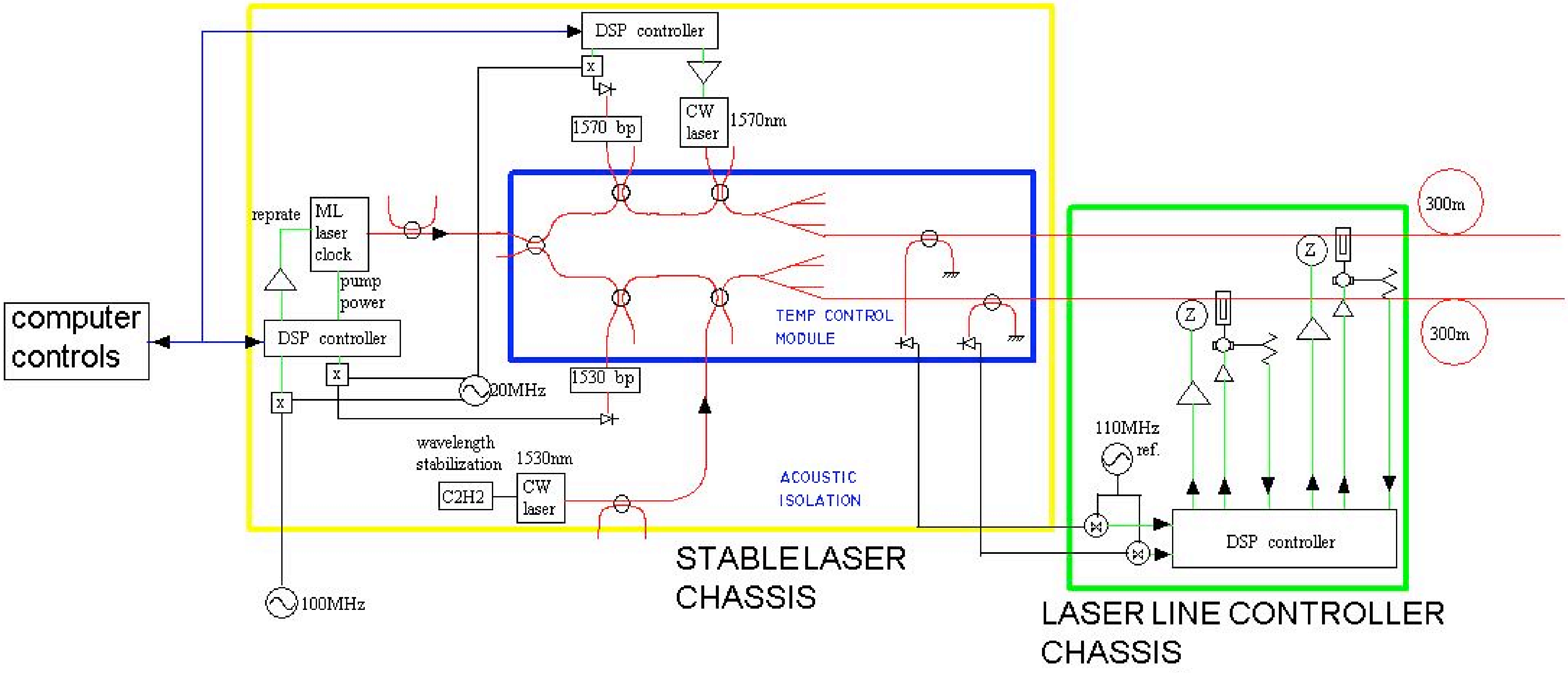
$$n_g = n_p + \omega \frac{dn_p}{d\omega}$$

$$\Delta n_g = \frac{1}{2}\left((\Delta n_2 + \Delta n_1) + \frac{f_2 + f_1}{f_2 - f_1}(\Delta n_2 - \Delta n_1) \right)$$



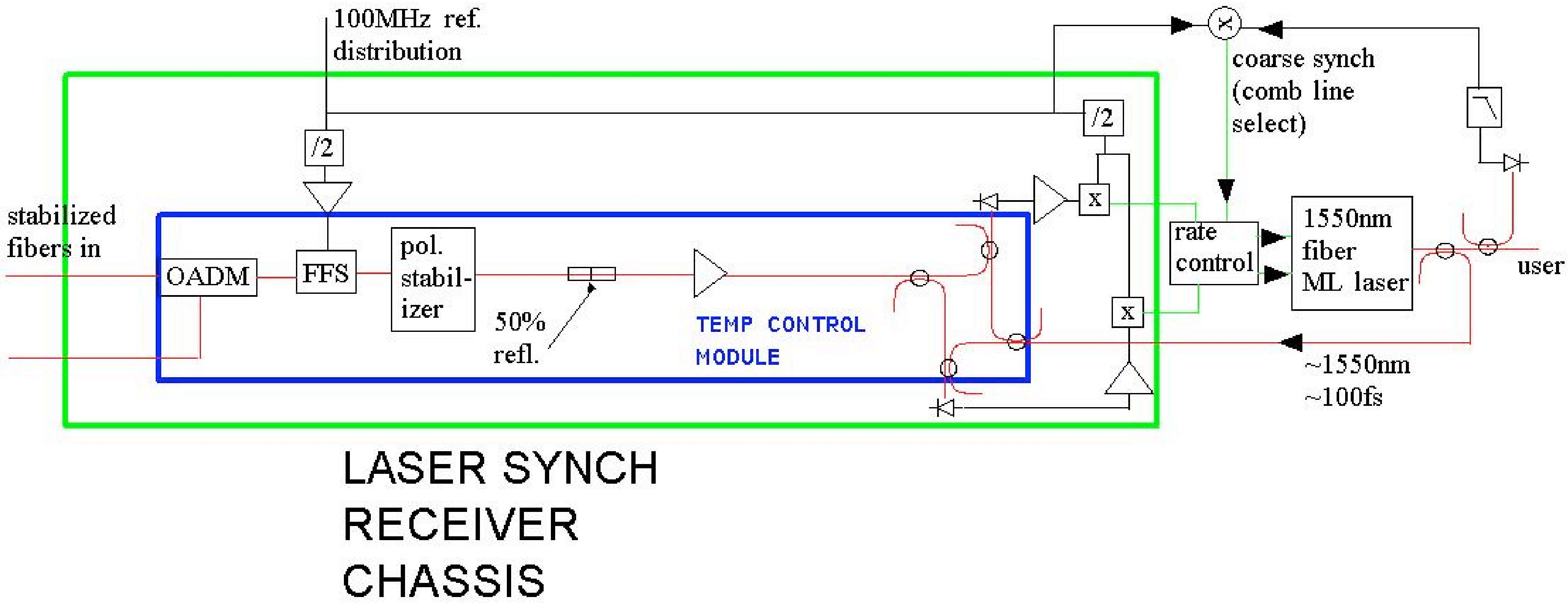
- Three fixes
  - With two wavelengths transmitted, measure phase change for each, calculate correct delay change
  - Measure total phase delay change and add delay correction based on previous measurements
  - Transmit two wavelengths on two fibers, just deliver phase of each
- We are currently measuring the group/phase difference
  - Two-frequency interferometer
  - RF transmission over phase-stabilized fiber
- Different fibers have different coefficients

Laser synchronization Xmitter



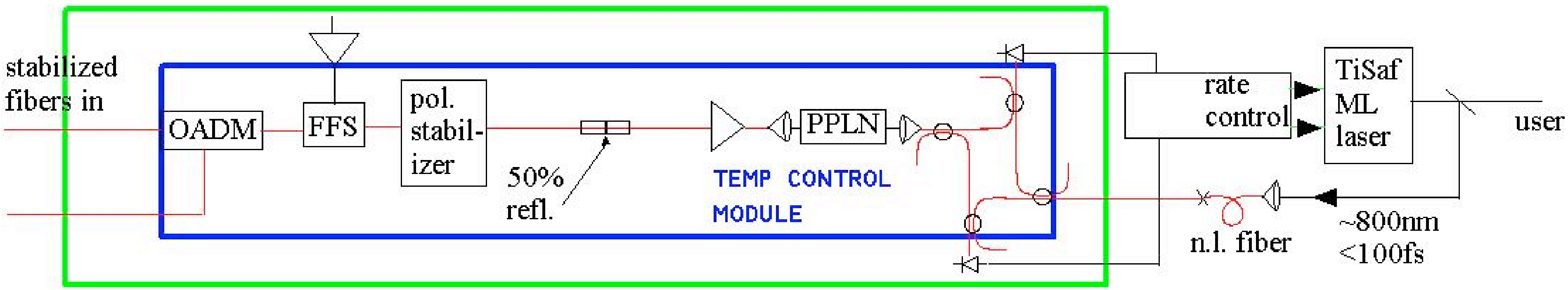
- Two fibers are used, to solve group/phase velocity problem
- Fibers would be in duplex cable, with common mode temperature and acoustic perturbations

Locking EDFL to EDFL



- Correct comb line is selected by beating user laser reprate and reference frequency
  - 100MHz is distributed for this and to drive frequency shifters

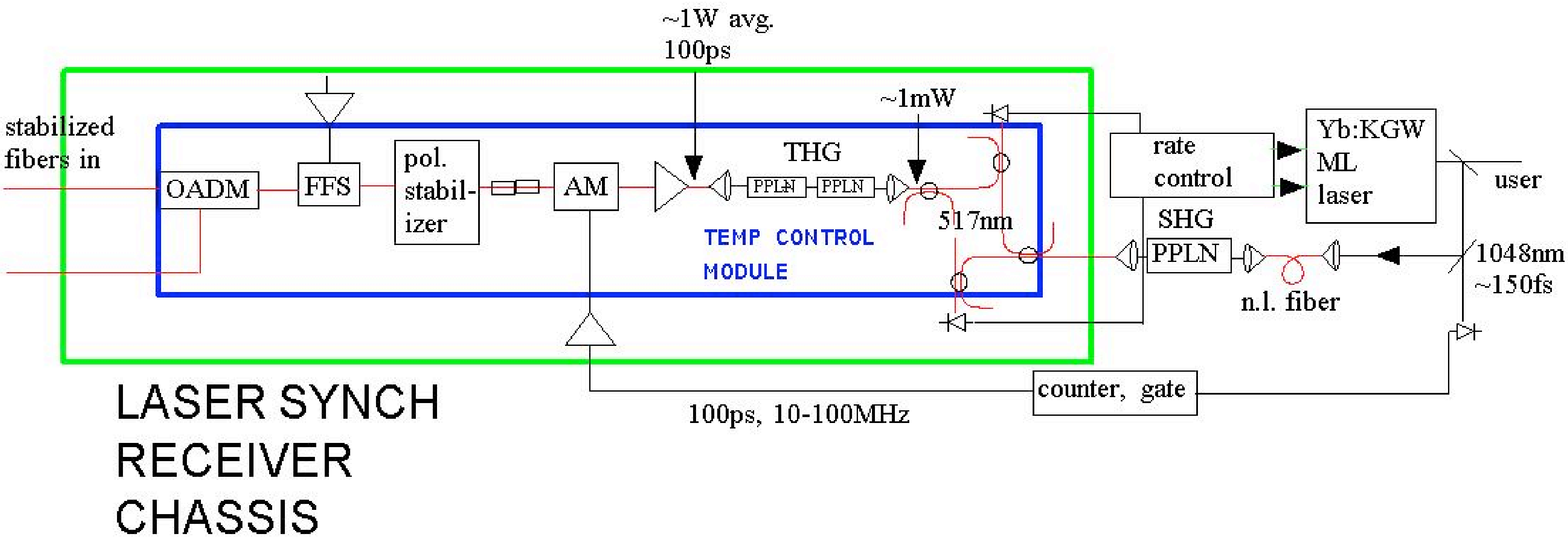
Locking a TiSaf to EDFL



LASER SYNCH
RECEIVER
CHASSIS

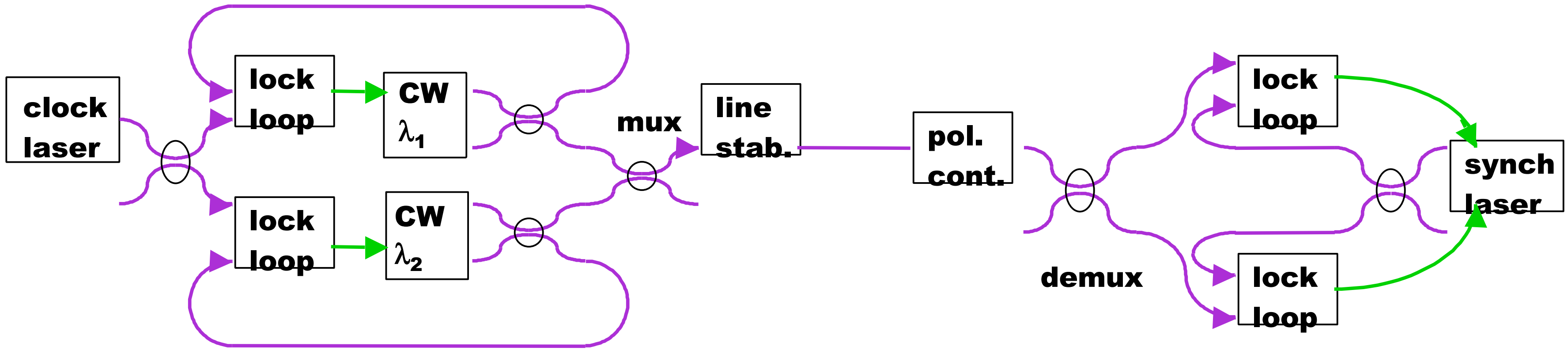
- Interferometer operates at 2nd harmonic of 1550nm laser
- Nonlinear fiber provides frequencies to cover gaps

Locking a Yb:KGW to EDFL



- Interferes 2nd harmonic of 1048 with 3rd harmonic of 1550
- Directly diode pumped modelocked lasers are cheaper and more reliable (in principle)
- Other lasers use Nd or Yb in different hosts, covering a range of wavelengths from 1030 to 1064nm
  - Should be able to use this technique

Error estimate



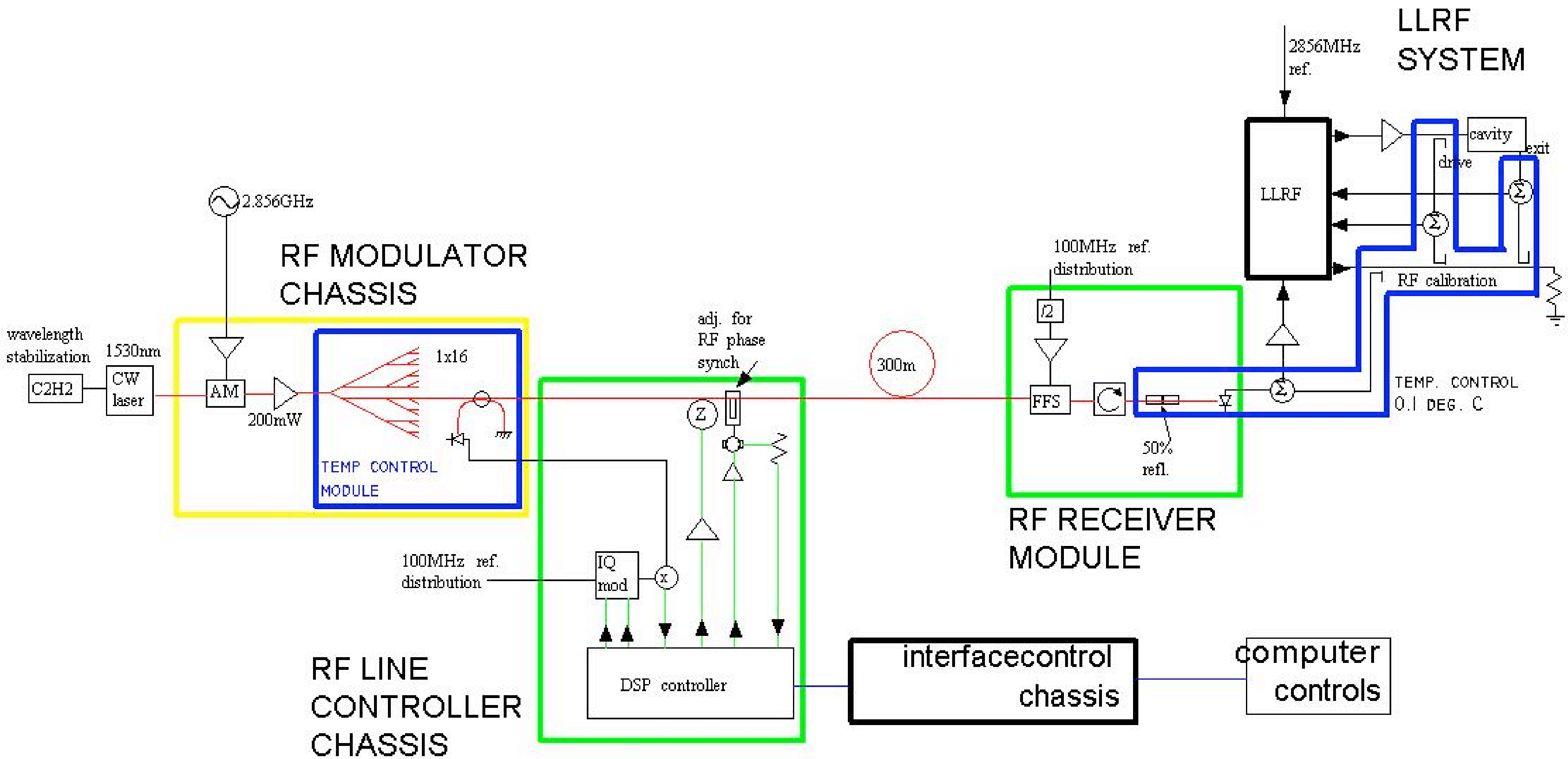
clok	fiber	loop	CW	fiber	stabl fiber	pol. cont.	fiber	disp. cmp	loop	fiber	laser
3	1	3	3	1	3	5	1	4	3	1	3

Assumptions:

- **Interferometrically stabilized main line**
- **Thermally stabilize all other fibers to 0.01 deg C**
- **Dispersion variation compensation**
- **Low noise lasers**
- **Uncorrelated slow noise dominates, adds in quadrature**
    - **Although, air conditioning is probably correlated**
- **High freq. noise is filtered by limited bandwitdh control loops**

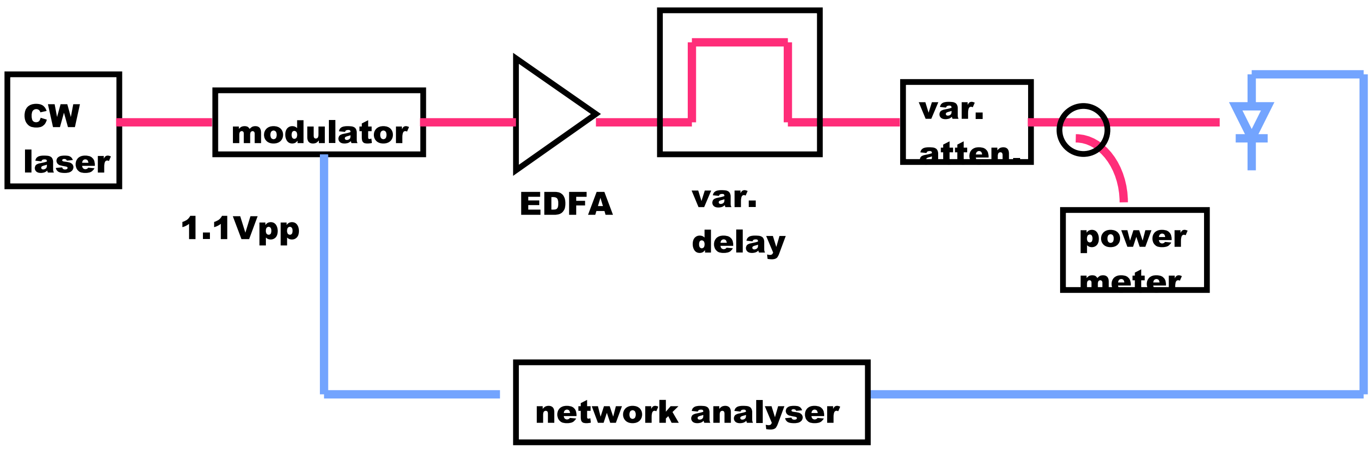
$$\sqrt{\sum \Delta t_i^2} = 10\ fs$$

RF transmission method



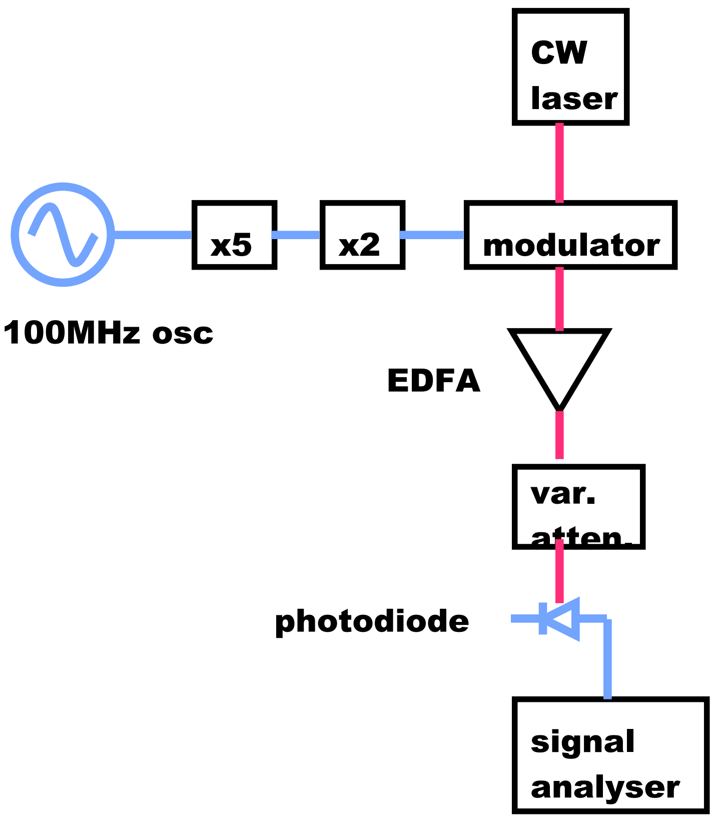
- RF transmission has looser requirements on jitter
- LLRF system can integrate between shots to reduce high frequency jitter

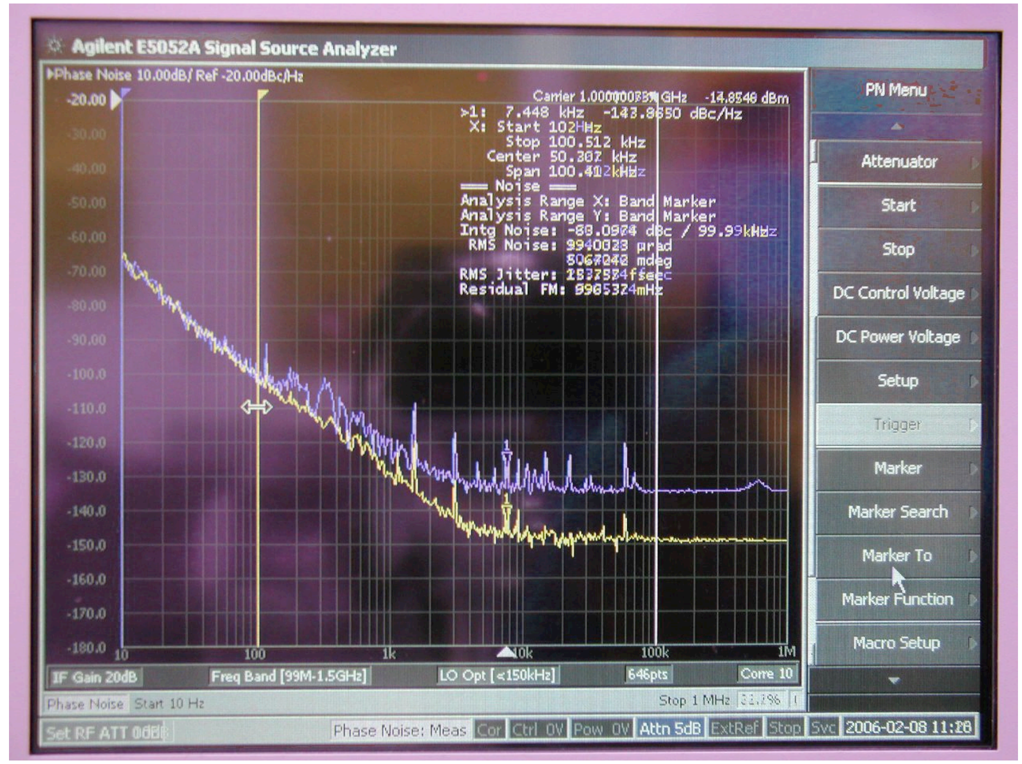
AM/PM conversion in a PD



- **Measured at 3GHz using a network analyser**
- **Modulation was 100% AM on 1530nm CW carrier**
- **From 1mW to 0.5mW on a 15GHz photodiode, phase shift was 87fs/mW**
- **In this test, phase noise from 10Hz to 3kHz was 92fs p-p. The noise was averaged over 100ms to determine AM/PM shift**
- **CW power stability through 100m fiber <10% p-p variation over 16h (low polarization dependent loss)**
  - **This variation results in 8.7fs p-p**
- **Conclusion: for RF transmission, AM-to-PM is not an issue**

Initial RF Xmission results





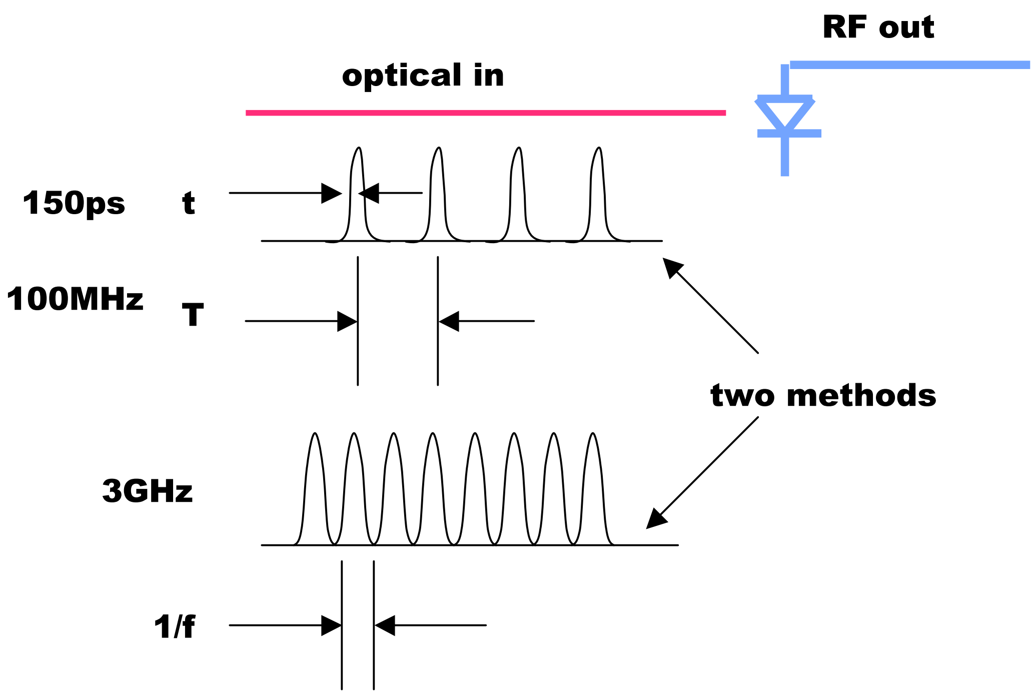
- **Note relaxation oscillation peak around 600kHz.**
- **Typical AM feature for fiber DFB lasers, varies between the two we have**

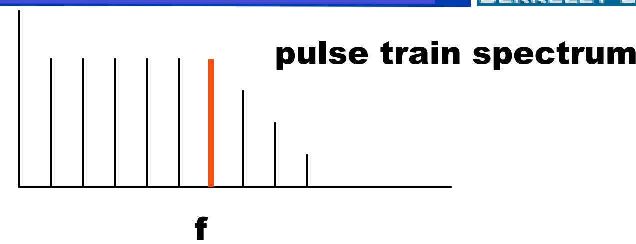
Initial RF transmission results

- When transmitted, measured “phase noise” is the same as 1GHz oscillator up to 100Hz, but limits at –130dBc/Hz above 3KHz
- When baseband amplitude noise is observed on a spectrum analyser, the noise level (sideband power) is the same (scaled to 1GHz), indicating the noise is actually AM.
  - The E5052 shows relaxation oscillation feature of the DFB laser, (too low in AM to be converted to PM in the diode), indicating 5052 can’t tell the difference
- Consistent with RIN noise and optical SNR reported in the literature*
  - Us: -130dBc/Hz RIN, 48dB OSNR. Them: -130dBc/Hz, 53dB
- Thus the transmitter adds AM noise due to laser noise
  - LLRF system ignores low level AM noise
  - Would be common mode
  - LBL’s LLRF system can average phase measurement over 1ms, eliminating noise above 1kHz
  - Therefore, the added CW laser noise is not a system issue
- This measurement indicates that an absolute measurement is misleading, so we need to do differential measurement with two receivers

***IEEE Phot. Tech. Lett. 15, p.191 (2003)**

SNR for CW vs pulsed





$$P_n = \frac{t}{T} P_{av}$$

- Diode has an average current limit before saturation
  - At saturation, high frequencies drop in power
- Diode bandwidth is chosen to be equal to RF frequency, and pulse width is 1/bandwidth
- For t=150ps, T=10ns and f=3GHz, AM has 15db more power in the transmitted frequency

Integrated system

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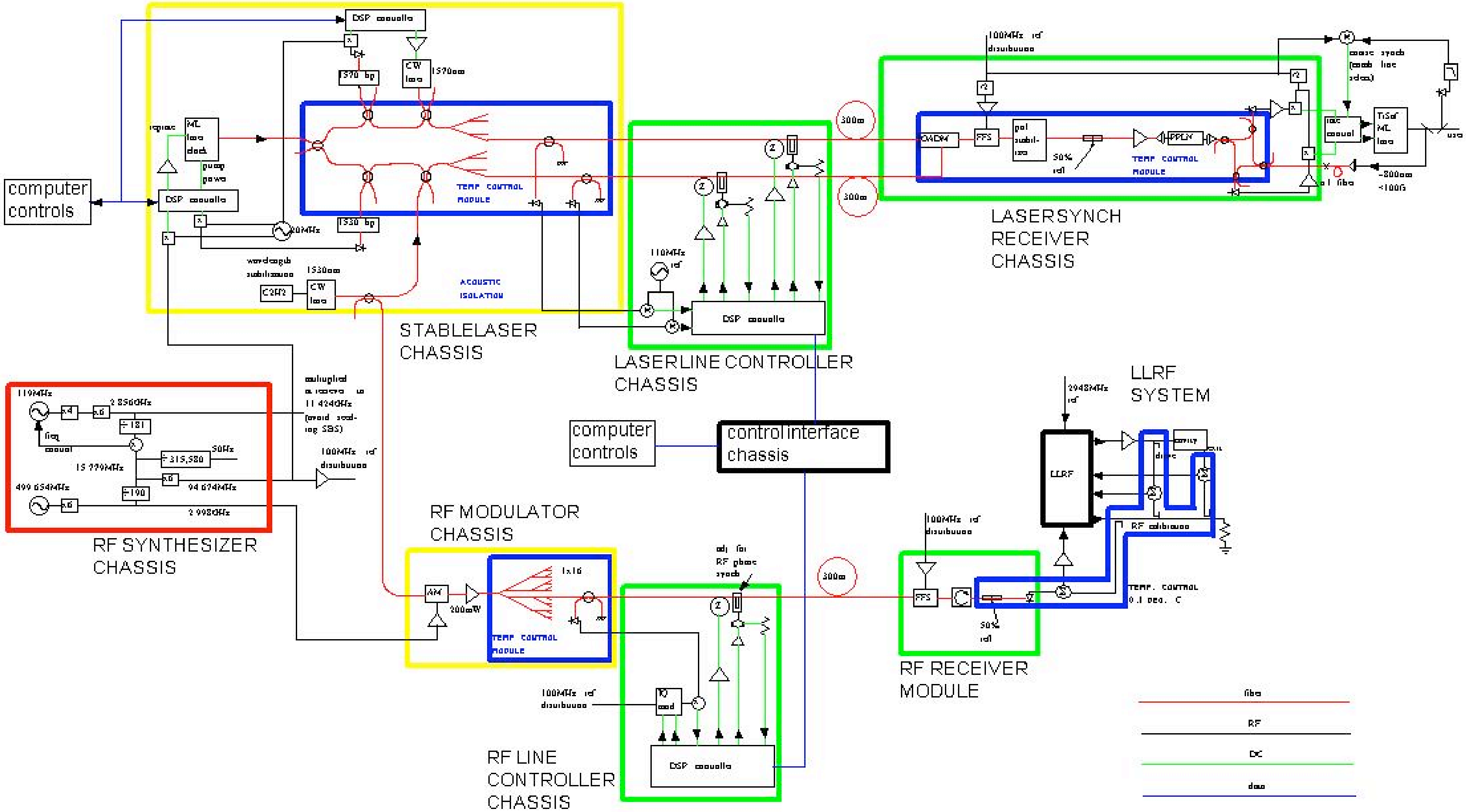

- Laser synch for any popular modelocked laser
- RF transmission via modulated CW, and interferometric line stabilization
- RF receiver is integrated with low level RF electronics design
- All functions separated into chassis blocks for estimation of costs

Summary

- Stabilized link
  - achieved drift of 0.13 fsec/hour and wideband jitter (55 MHz) of 0.2 fsec rms. Jitter within stabilization bandwidth at attosecond level.
  - dual link ready for ready for RF transmission expt
  - Setup being prepared for test in SLAC tunnel/KG
  - Radiation hardness study in progress
- Synchronizing lasers
  - achieved 150 fsec rms lock over 1 hour at 2 GHz
  - present studies aimed at locking under 100 fsec over 24 hours
  - optical beat lock still under development