Part 6: Transmission formats and laser control

Stabilizing CW laser to an absolute reference

- Using an atomic or molecular absorption or emission line as reference
- Several examples for ~1550nm, providing different stability
  - Side lock to molecular absorption (e.g. C2H2, HCN, CO)
  - PDH lock to molecular absorption
  - Doppler-free lock to atomic absorption (Rb)
  - Two-photon lock to atomic absorption

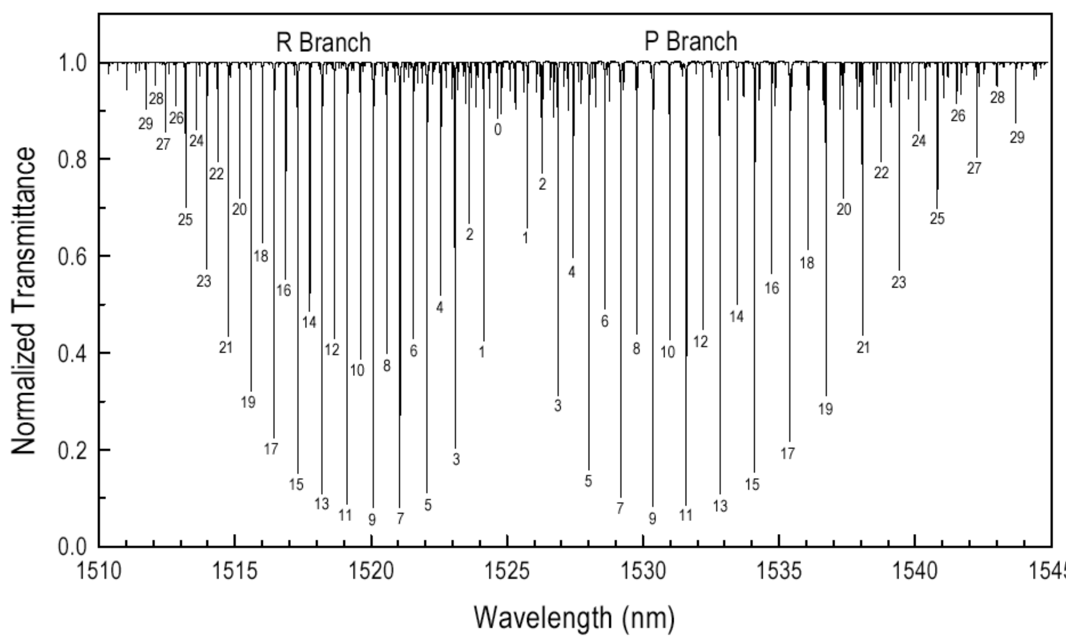
C2H2 molecular frequency standard

- Used as calibration for optical spectrum analyzers, reference for transmitters
- HCN and CO are also well-documented, for longer wavelengths in C-band

NIST Special Publication 260-133
2001 Edition
Standard Reference Materials®

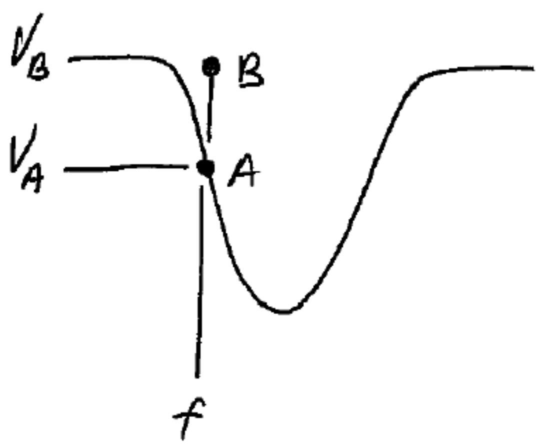
Acetylene $^{12}C_2H_2$ Absorption Reference for 1510 nm to 1540 nm Wavelength Calibration—SRM 2517a

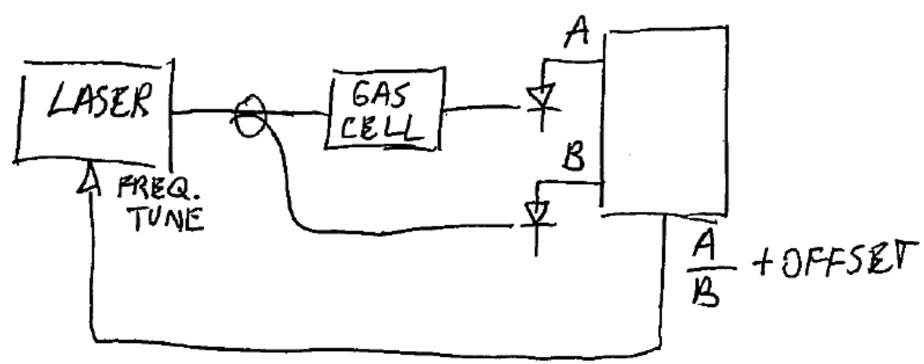
R Branch	Wavelength (nm)	P Branch	Wavelength (nm)
29	1511.7304(3)	1	1525.7599(6)
28	1512.0884(3)	2	1526.3140(3)
27	**1512.45273(12)**	**3**	**1526.87435(10)**
26	1512.8232(3)	**4**	**1527.44114(10)**
25	1513.2000(3)	**5**	**1528.01432(10)**
24	1513.5832(3)	**6**	**1528.59390(10)**
23	1513.9726(3)	7	1529.1799(3)
22	1514.3683(3)	8	1529.7723(3)
21	1514.7703(3)	9	1530.3711(3)
20	1515.1786(3)	**10**	**1530.97627(10)**
19	1515.5932(3)	11	1531.5879(3)
18	1516.0141(3)	12	1532.2060(3)
17	**1516.44130(11)**	**13**	**1532.83045(10)**
16	1516.8747(3)	**14**	**1533.46136(10)**
15	1517.3145(3)	15	1534.0987(3)
14	1517.7606(3)	16	1534.7425(3)
13	1518.2131(3)	17	1535.3928(3)
12	1518.6718(3)	18	1536.0495(6)
11	**1519.13686(11)**	19	1536.7126(3)
10	1519.6083(3)	20	1537.3822(3)
9	1520.0860(3)	21	1538.0583(3)
8	1520.5700(3)	22	1538.7409(3)
7	**1521.06040(10)**	**23**	**1539.42992(11)**
6	1521.5572(3)	**24**	**1540.12544(11)**
5	1522.0603(3)	**25**	**1540.82744(11)**
4	1522.5697(3)	26	1541.5359(3)
3	1523.0855(3)	27	1542.2508(3)
2	1523.6077(3)		
1	**1524.13609(10)**		



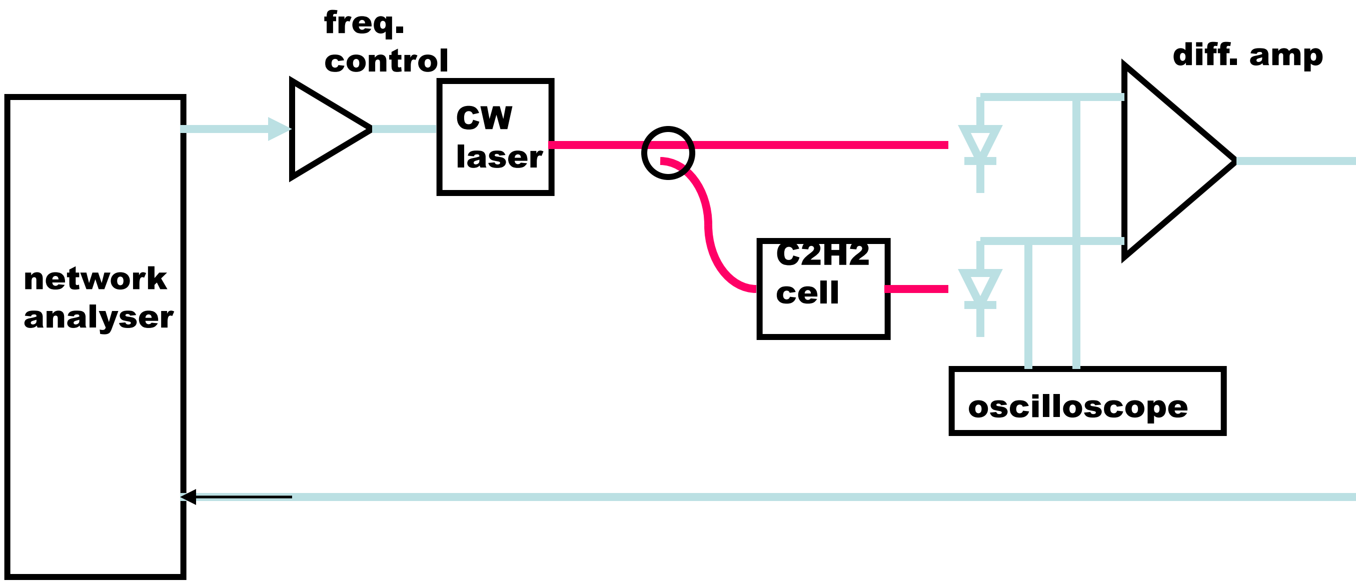
Side lock to absorption line

- Maintain percent absorption through reference cell
- Simple to do
- Stability depends on linearity of photodiodes and electronics
  - Not a preferred scheme for high stability





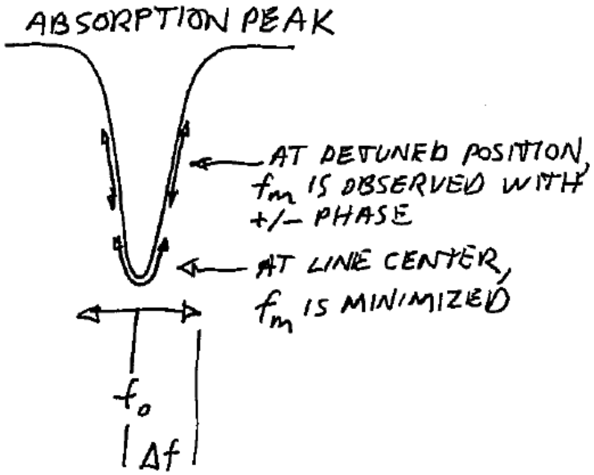
Experiment to measure laser freq. control

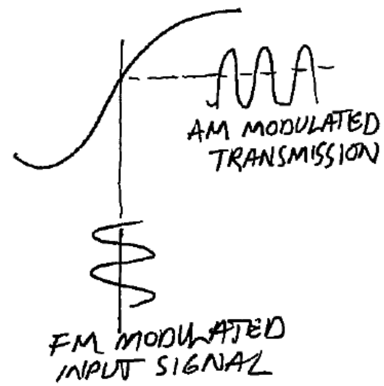


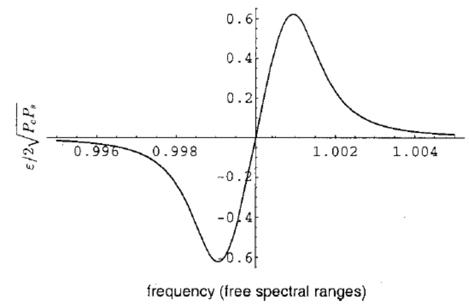
- Want wavelength control transfer function of CW laser, for control loop design
- Sweep frequency of wavelength control signal and observe transmission through cell
  - Center wavelength is adjusted to be on side of absorption line, at 50% point
  - Variations in wavelength appear as changes to transmission
- Measure S21 on network analyzer, in amplitude and phase

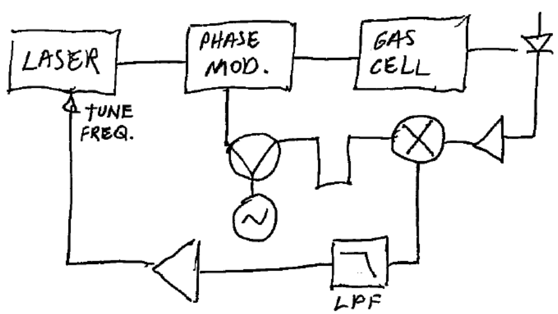
Line center lock (Pound-Drever-Hall)

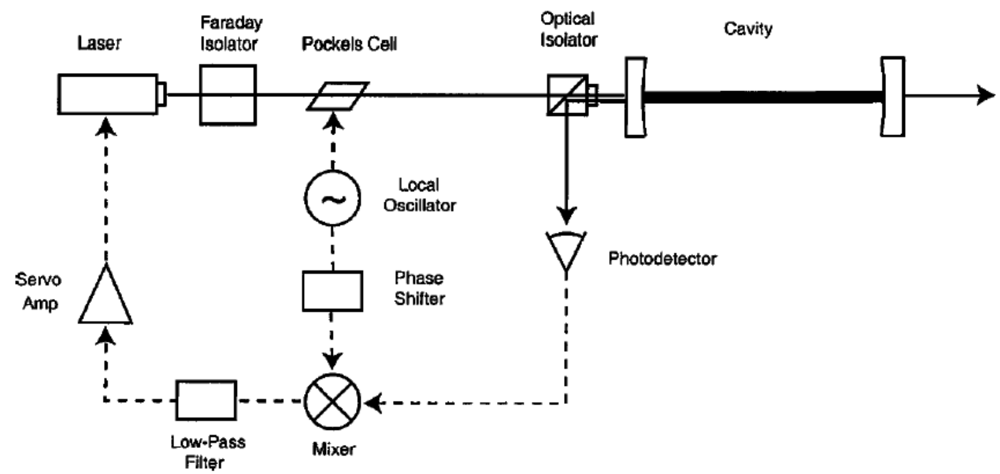
- Stability is a few % of line width









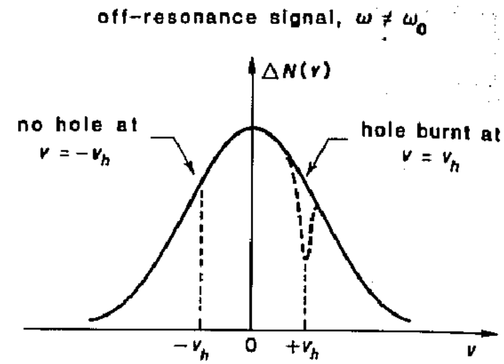


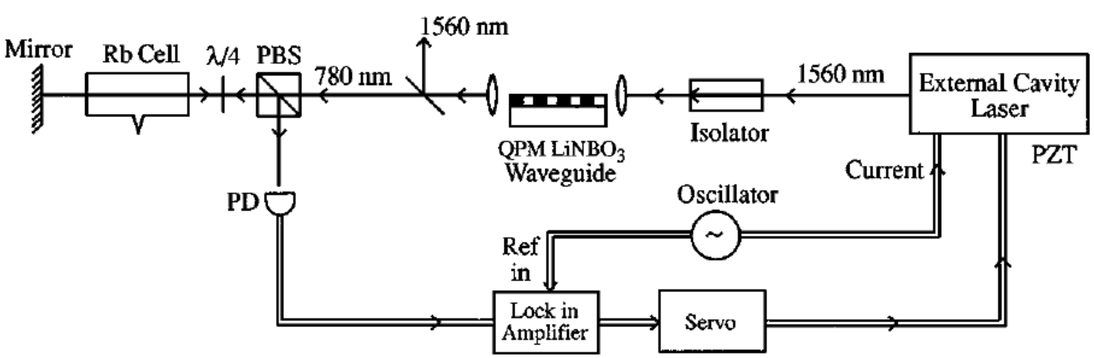
Doppler-free line center lock

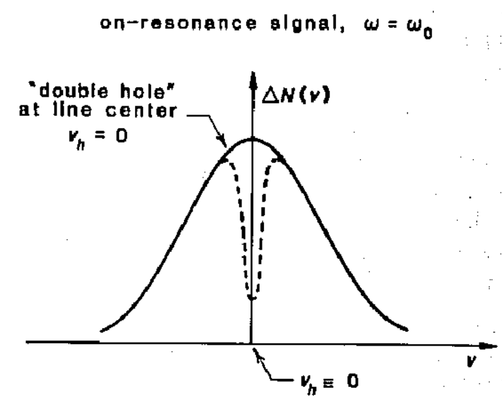
- Called “saturation spectroscopy”
- Optical frequency at line center will “double dip” the saturating atoms
  - Saturation reduces the absorption, by reducing (N0-N1)
  - Only the atoms at zero relative velocity will be hit by both counterpropagating beams

$$\chi''(\nu) = \frac{c^3}{16\pi^2\nu^3} n'^2 \frac{1}{\tau_{\text{radiative}}} f(\nu)(N_0 - N_1)$$

$$\Delta\omega_d = \sqrt{8\ln 2}\frac{\omega_0\sigma_v}{c} = \omega_0 \times \sqrt{8\ln 2\frac{kT}{Mc^2}}.$$

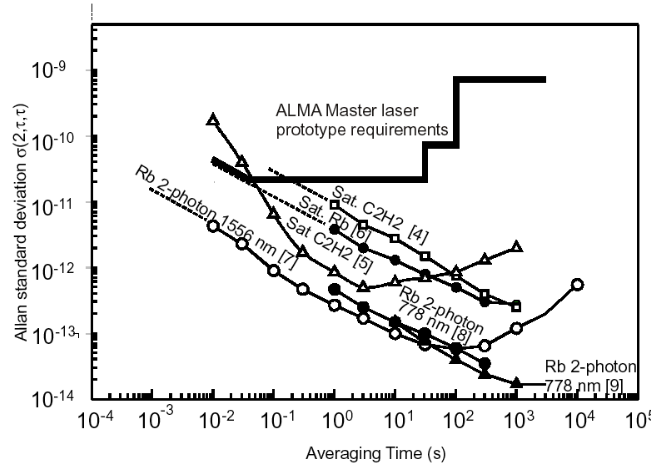


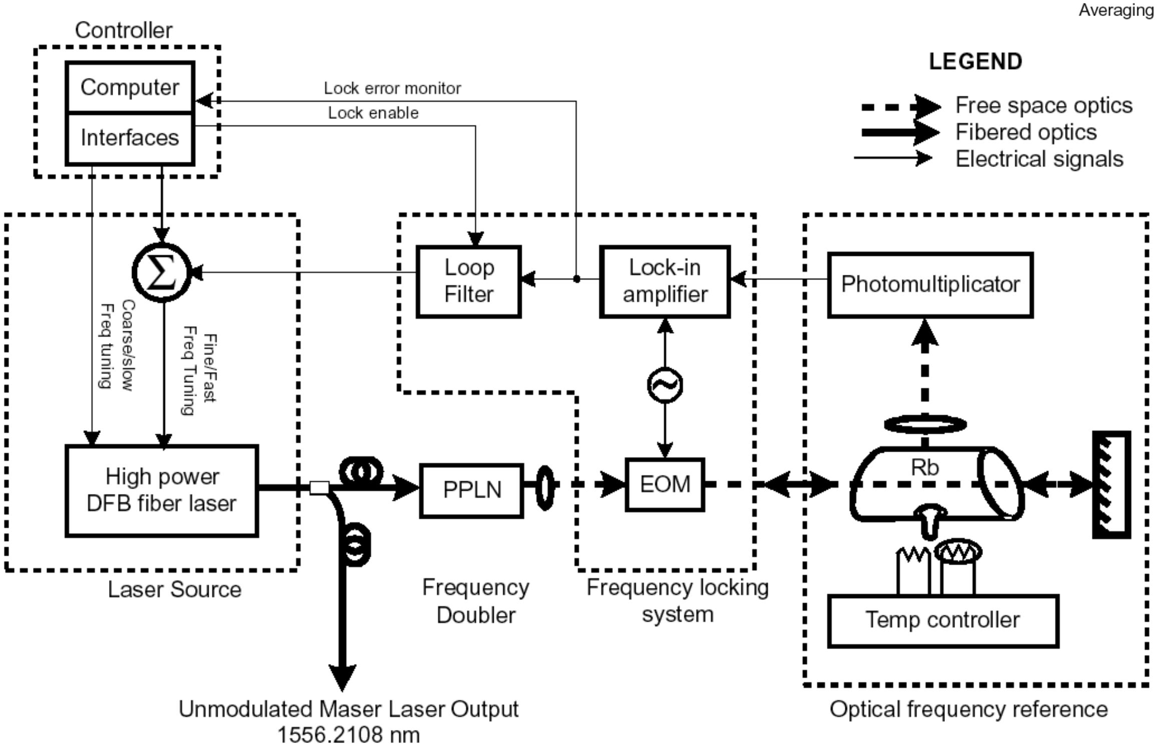




Two-photon atomic center lock

- **Good to 10^-13 after 10 second averaging**



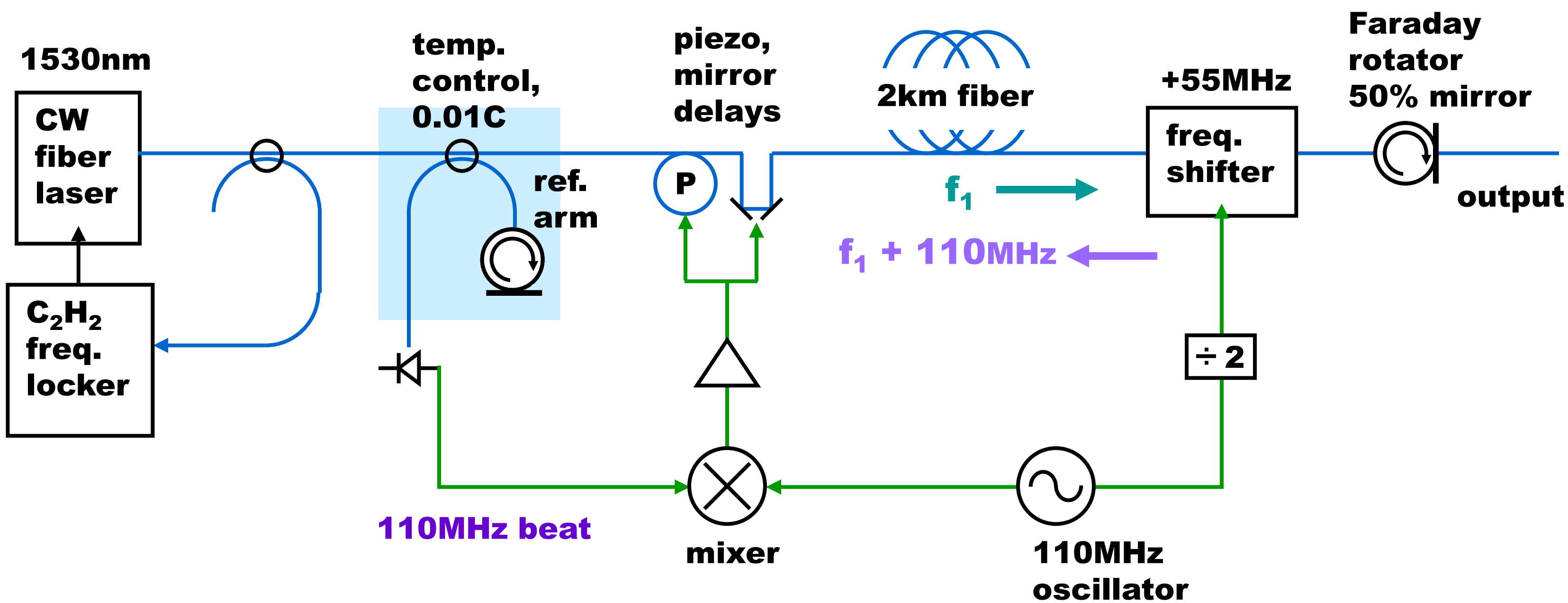


Transmit modulated CW

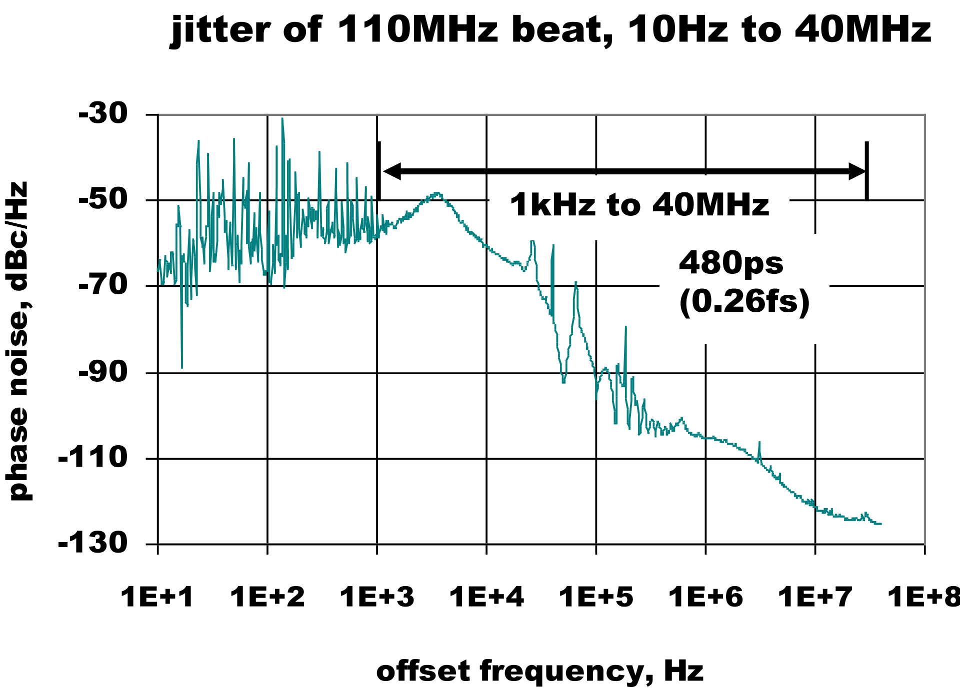
- AM or PM of CW signal
  - AM commonly used by cable TV industry
  - PM used in some communications (DPSK)
- Detection of AM via photodiode
  - Be wary of AM-to-PM in diode
- PM can be detected by interferometer and photodiode
- Modulation frequency is arbitrary. Multiple frequencies can be transmitted
- Stabilize fiber via RF or interferometery
- Issues
  - Group and phase delay changes with temperature are not the same
  - Brillouin scattering nonlinear limit
  - Modulation frequency is limited by modulator technology and electronics (~100GHz)
    - But not limited if "AM sidebands" are actually two independent laser frequencies (suppressed carrier, double sideband). They will beat on the detector at arbitrarily high frequencies

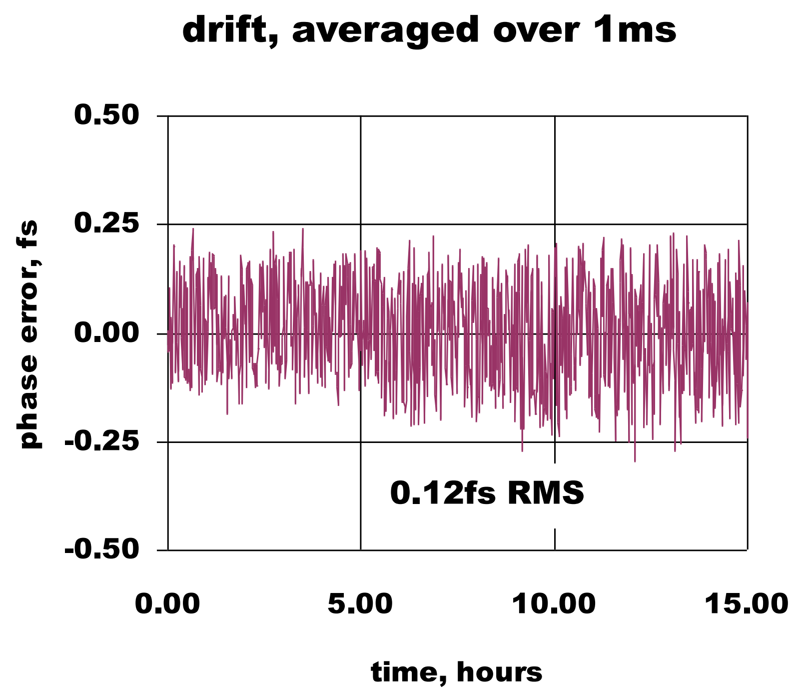
Line stabilization using CW interferometer

- Frequency shifting, or heterodyne interferometer
- Same scheme as commercial, distance measuring interferometers
- Maintain constant phase of heterodyne signal with respect to local oscillator



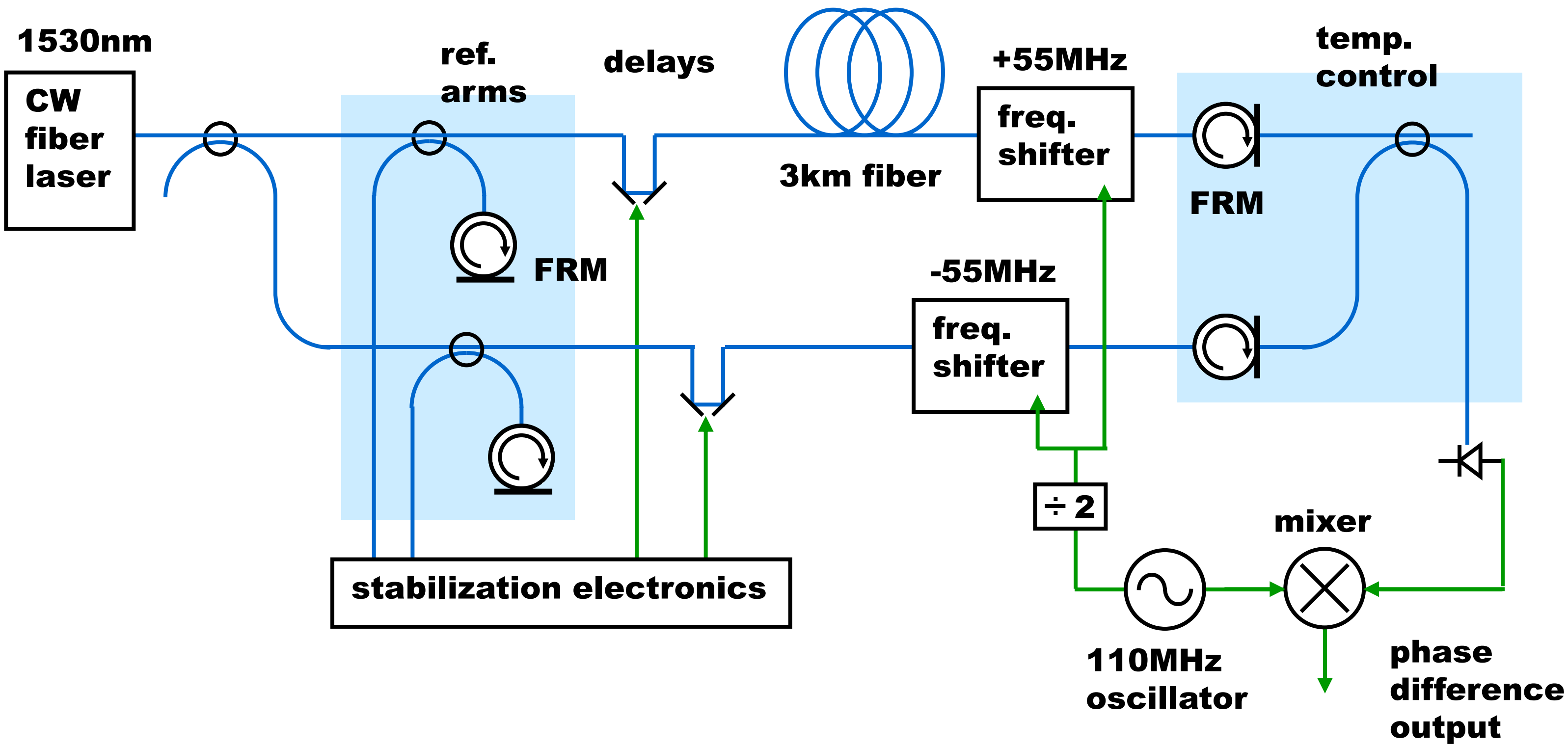
Performance of interferometer





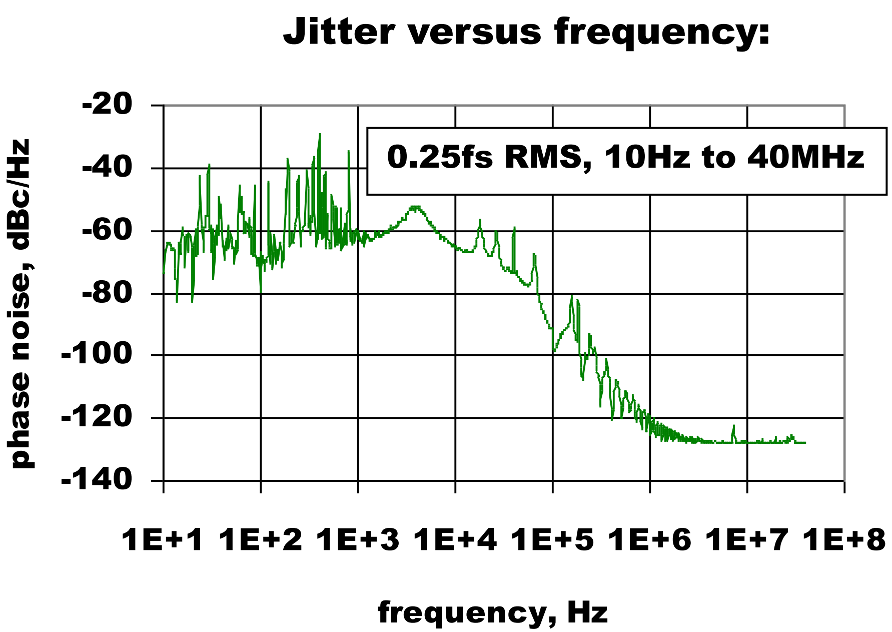
- Phase jitter of 110MHz = phase jitter of 200THz
- Time jitter is divided by frequency ratio
  - 480ps RMS at 110MHz = 0.26fs RMS at optical
  - Loop bandwidth is ~1kHz
- Lasers are typically ~10fs RMS above 1kHz

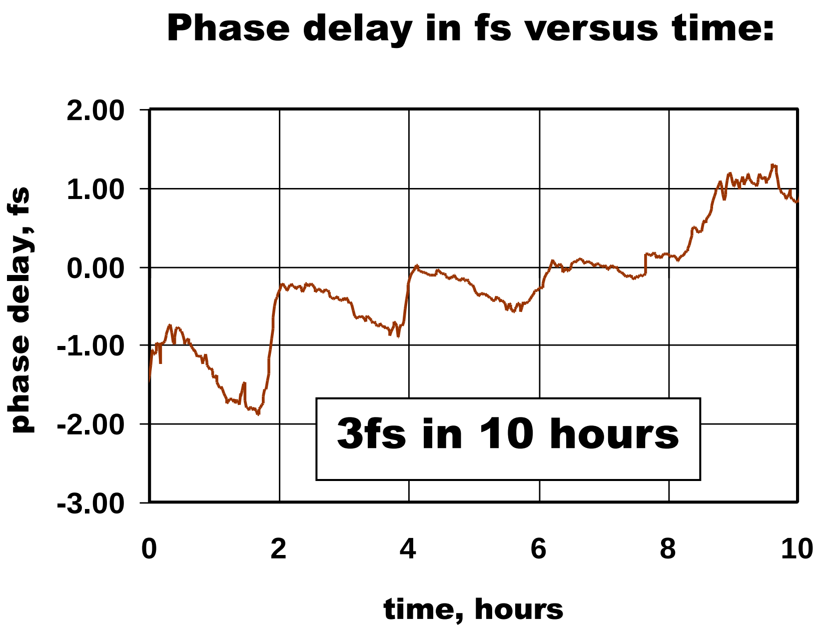
Mach-Zehnder interferometer test



- Mach-Zehnder made of two stabilized arms of Michelson interferometers

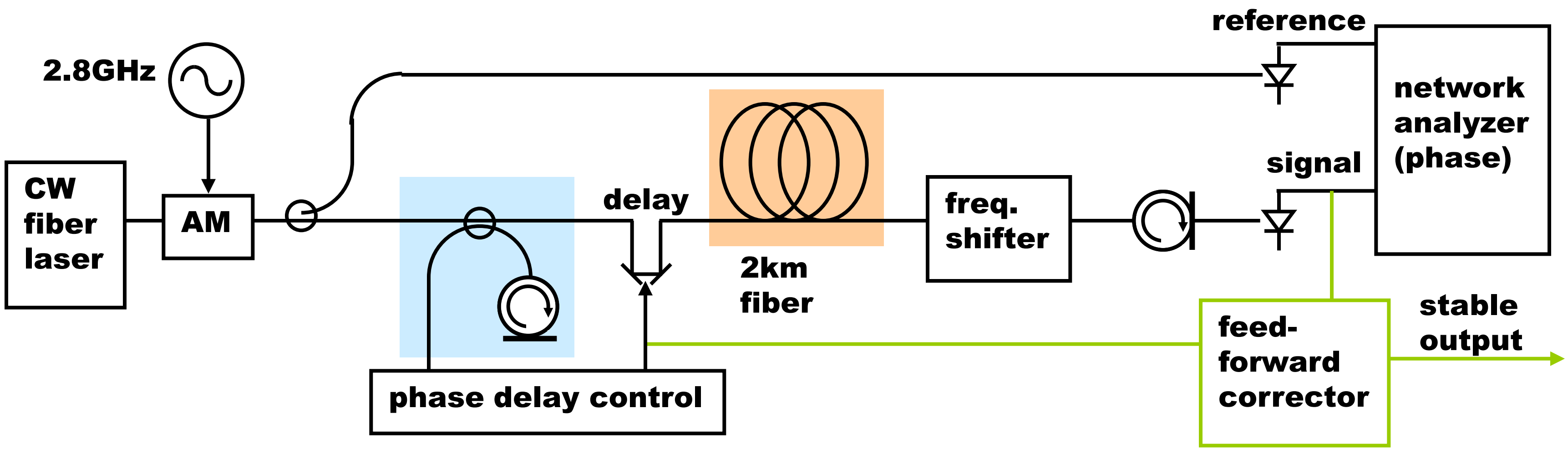
Mach-Zehnder test results

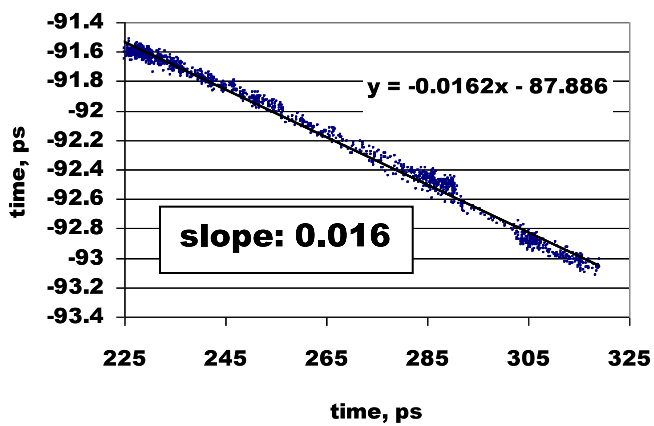


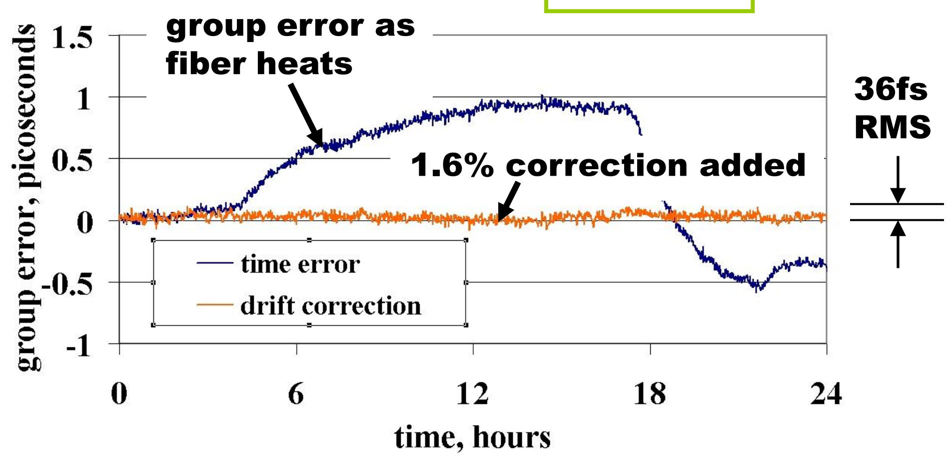


- Drift from room and outside temperature
- Total correction is ~100ps per day
- Drift is ~1fs p-p when arms are equal

Experiment to measure group/phase coefficients







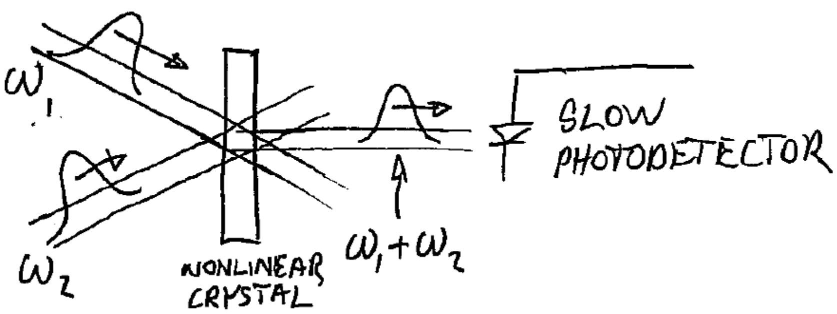
- Optical and RF interferometers share an arm
  - 2km fiber, 36fs over 24 hours (predicted from data)

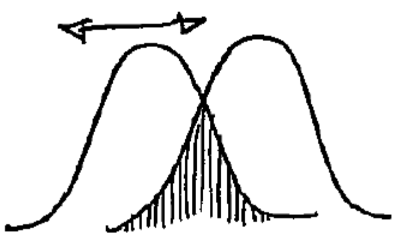
Timing transmission formats, pulse train

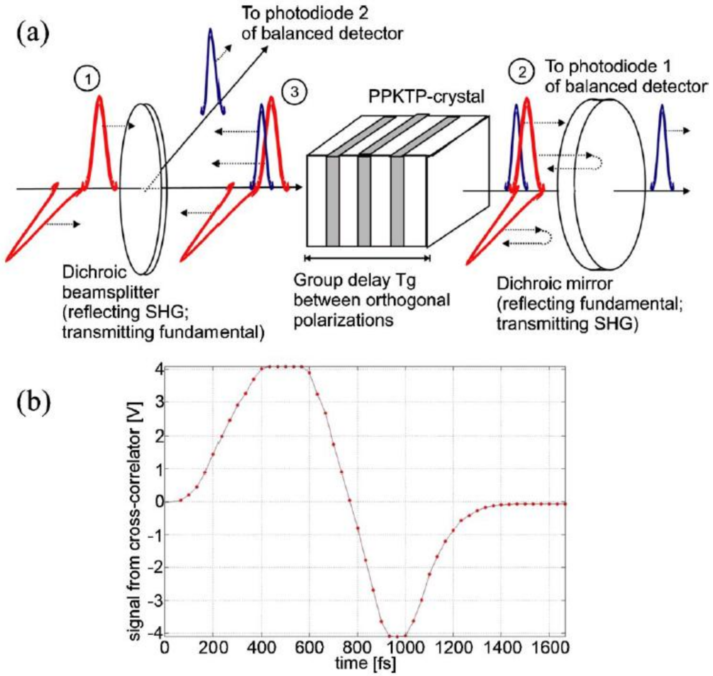
- From modelocked laser
- RF can be extracted via photodiode, at harmonics of reprate
- Detection by electro-optic sampling (mixing)
- Detection by cross-correlation
- Stabilize fiber by cross-correlation or detection of high harmonic
- Issues
  - Need to maintain short pulse over long fiber by dispersion management
  - Other nonlinear effects may be a problem
  - Transmitted frequencies are only harmonics of reprate

Cross-correlation

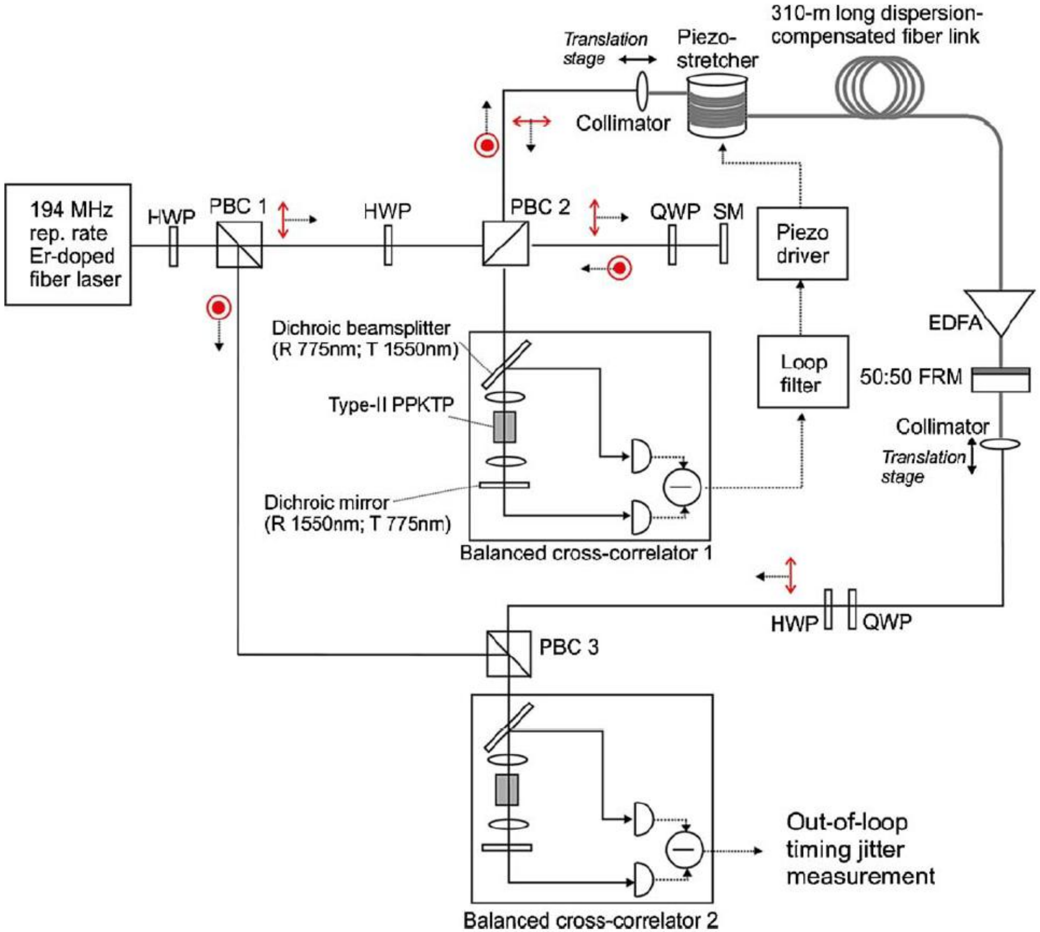
- Nonlinear crystal produces sum frequency of carriers (see RWV p. 696), when two pulses overlap
- Autocorrelation when one pulse is split and delayed
  - Typical measurement of ultrashort pulses
- If two pulses half-overlap, small variations in relative timing are observable as changes in second harmonic signal
  - Sensitivity is a function of the pulse widths, but can be a percent of the FWHM

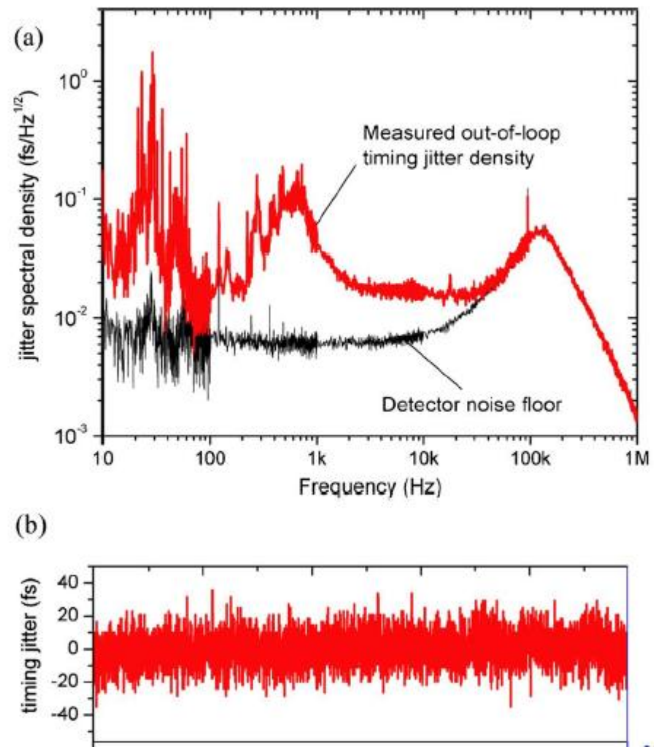






Line stabilization via cross-correlation

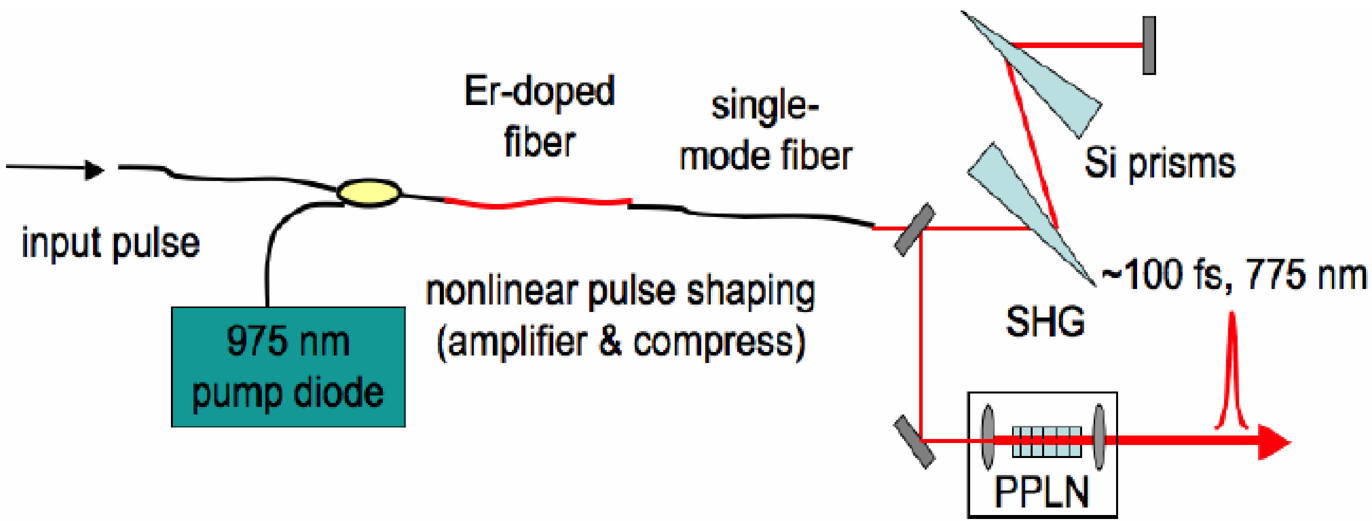




RMS jitter 9.7fs

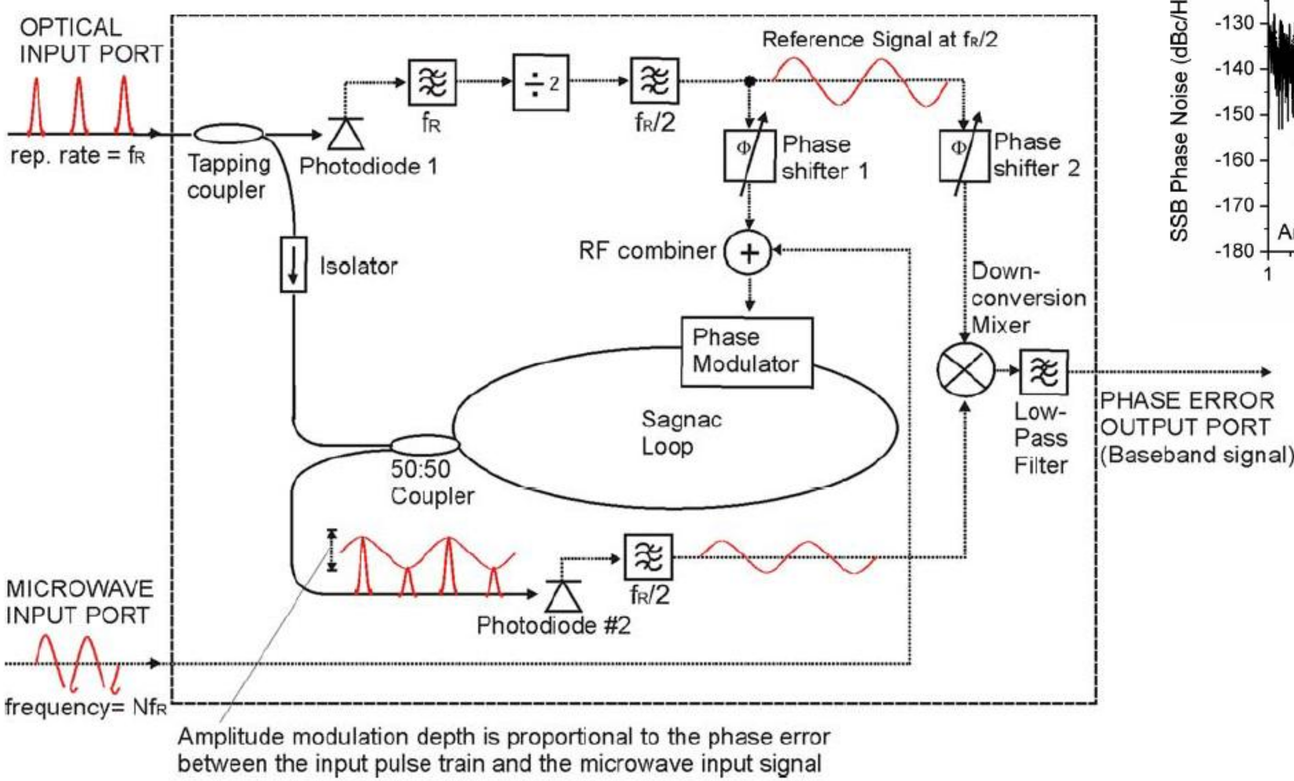
Direct use of pulse train

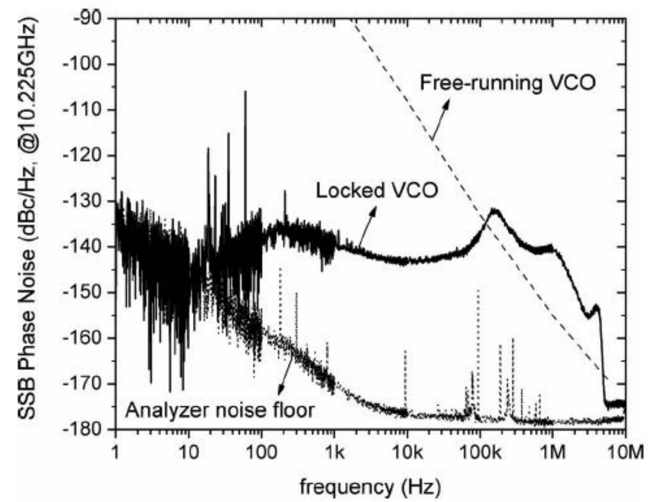
- Fiber-transmitted pulse is recompressed to be short
- Can be frequency converted to match titanium sapphire laser wavelength for subsequent amplification
- Frequency conversion cleans up “wings” from dispersion mismatch



Synching RF to a pulse train

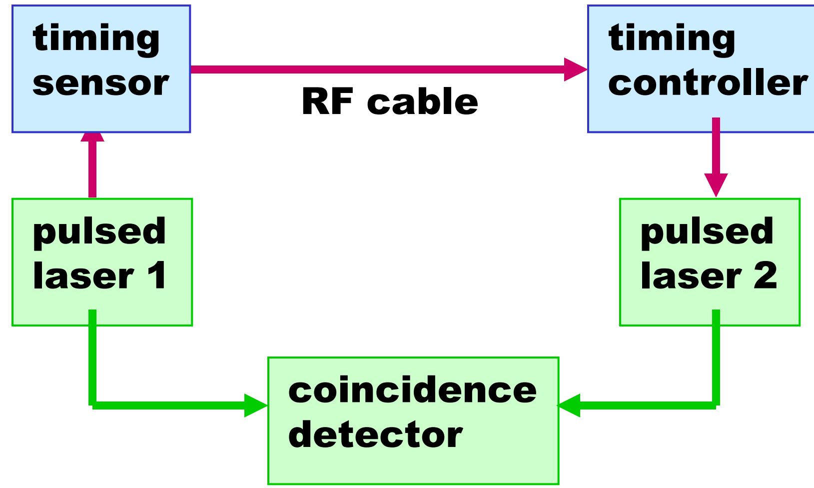
- **Electro-optic sampling of the RF phase**
- **Similar to a double-balanced mixer**
  - **Think of a mixer as sampling the RF at two points and finding the difference**
  - **Optical signal samples RF at two points and then difference is found**





Lock ML laser to RF

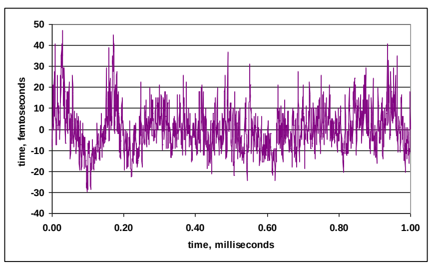
- High harmonics have more “leverage”, but leave ambiguity
  - Solution: coarse lock to fundamental, then fine lock to harmonic
- Can achieve few fs stability under ideal conditions, with difficulty
  - With good lasers, ~10fs is easily achievable with few GHz harmonic



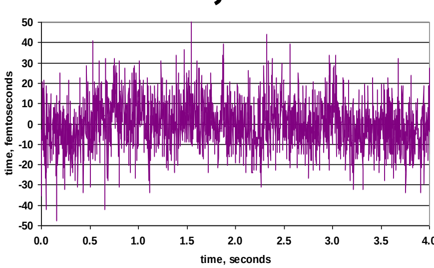
•Repetition rate is 100MHz.

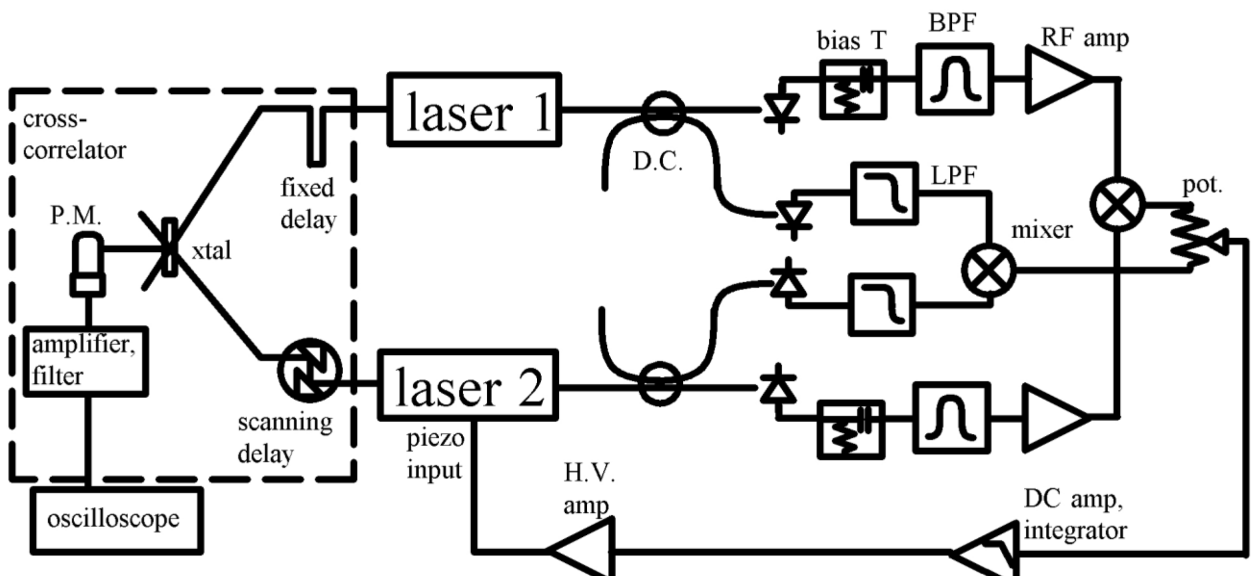
•2.2GHz harmonic extracted from the pulse train of each laser and compared in a mixer

11fs RMS, 1kHz-1.25MHz



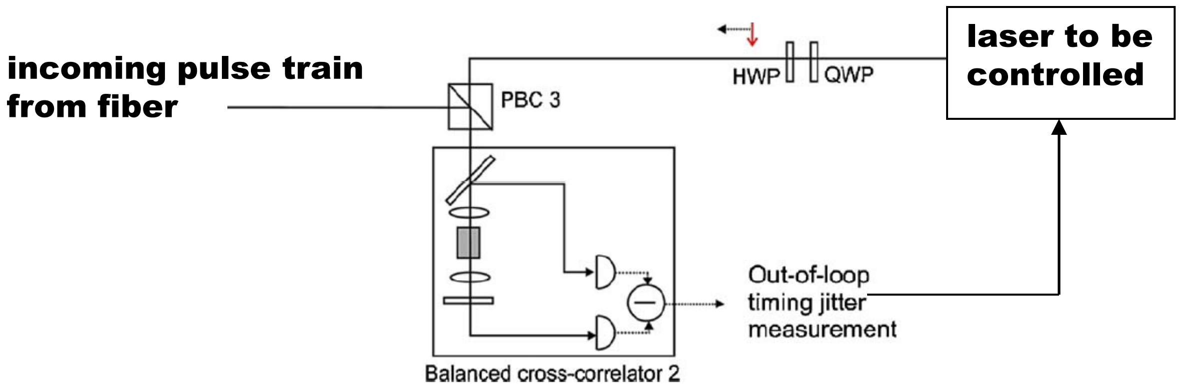
12fs RMS, 4 seconds





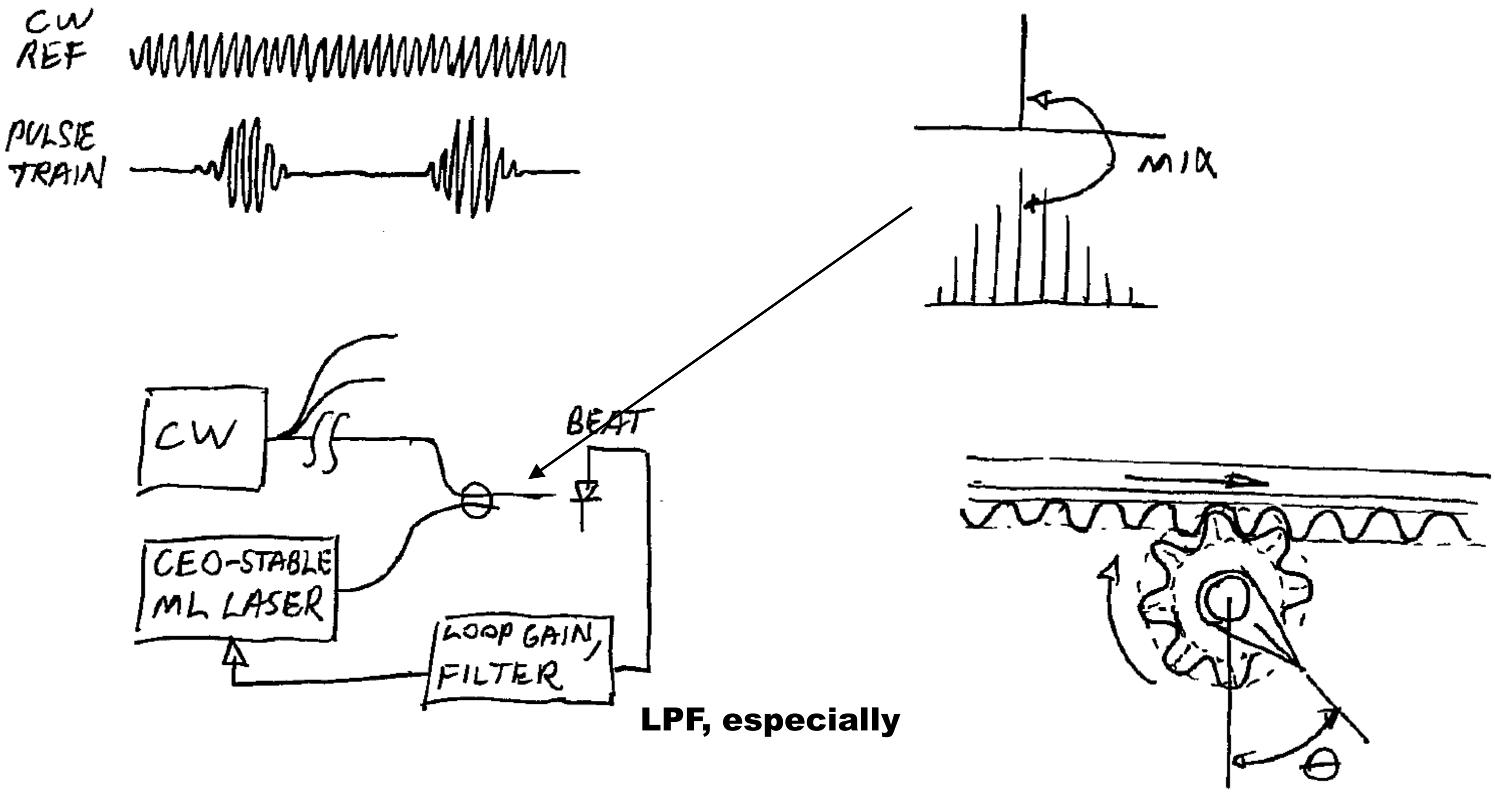
Lock ML laser to pulse train

- Compare pulse timing with cross-correlation
- Two different wavelength lasers can be used
- Repetition rates can be different if they have some common sub-multiple
- Cross correlation provides high sensitivity to timing error (mV/fs)



Lock ML laser to CW

- CEO stabilized laser locks envelope to carrier
  - Lock carrier to some reference and you are done
- Like a rack and pinion gear arrangement. All locked pinions will be in synch

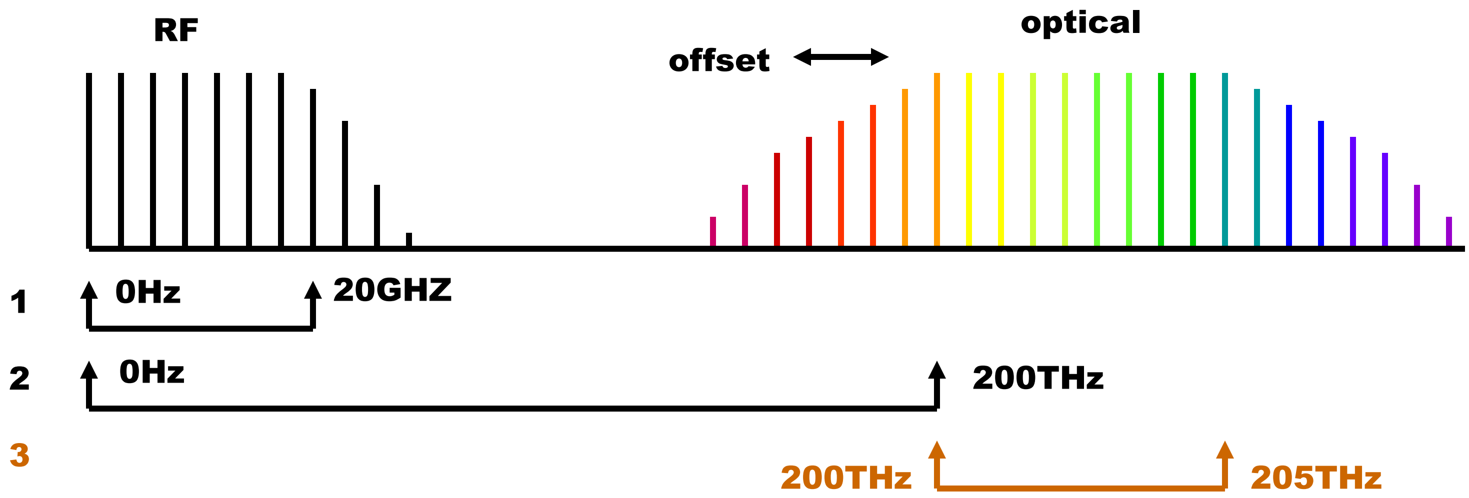


LPF, especially

Stabilization of ML laser combs at two points

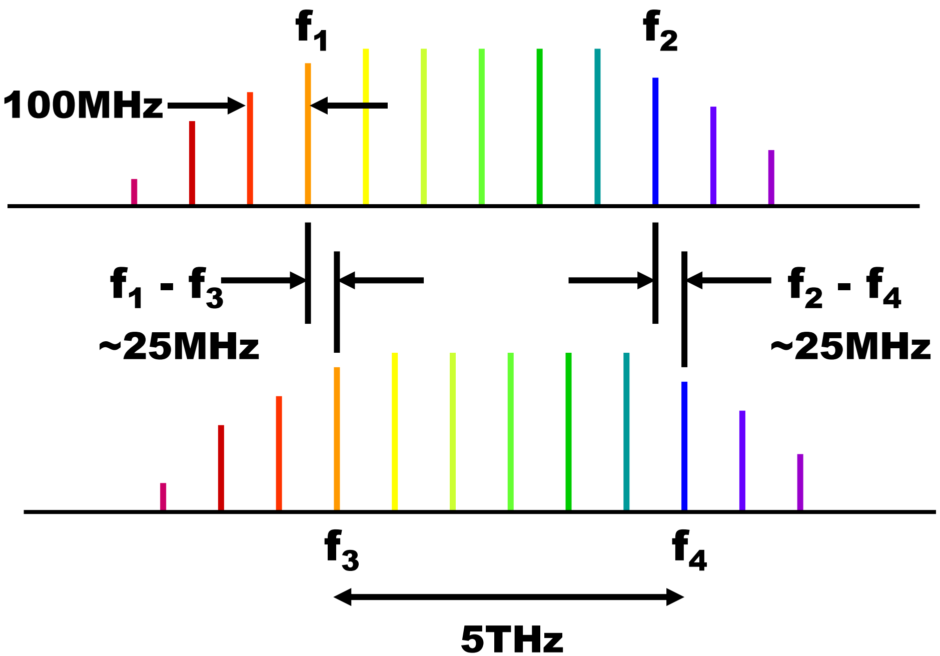
- **Two degrees of freedom for a comb**
  - **Repetition rate and offset frequency**

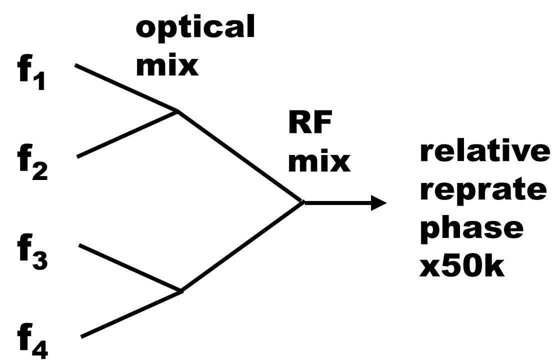
$$f_n = n f_{\mathrm{rep}} + \delta,$$



	Signal frequencies	Offset frequencies	1° in time
1	0, 20GHz	not measured	140fs
2	0, 200THz (400THz)	fixed absolute	0.014fs
3	200THz, 205THz	fixed relative	0.6fs

Comparing comb lines from two lasers





$$\frac{f_1 - f_2}{f_{rep}} = 5 \times 10^4$$

But, also

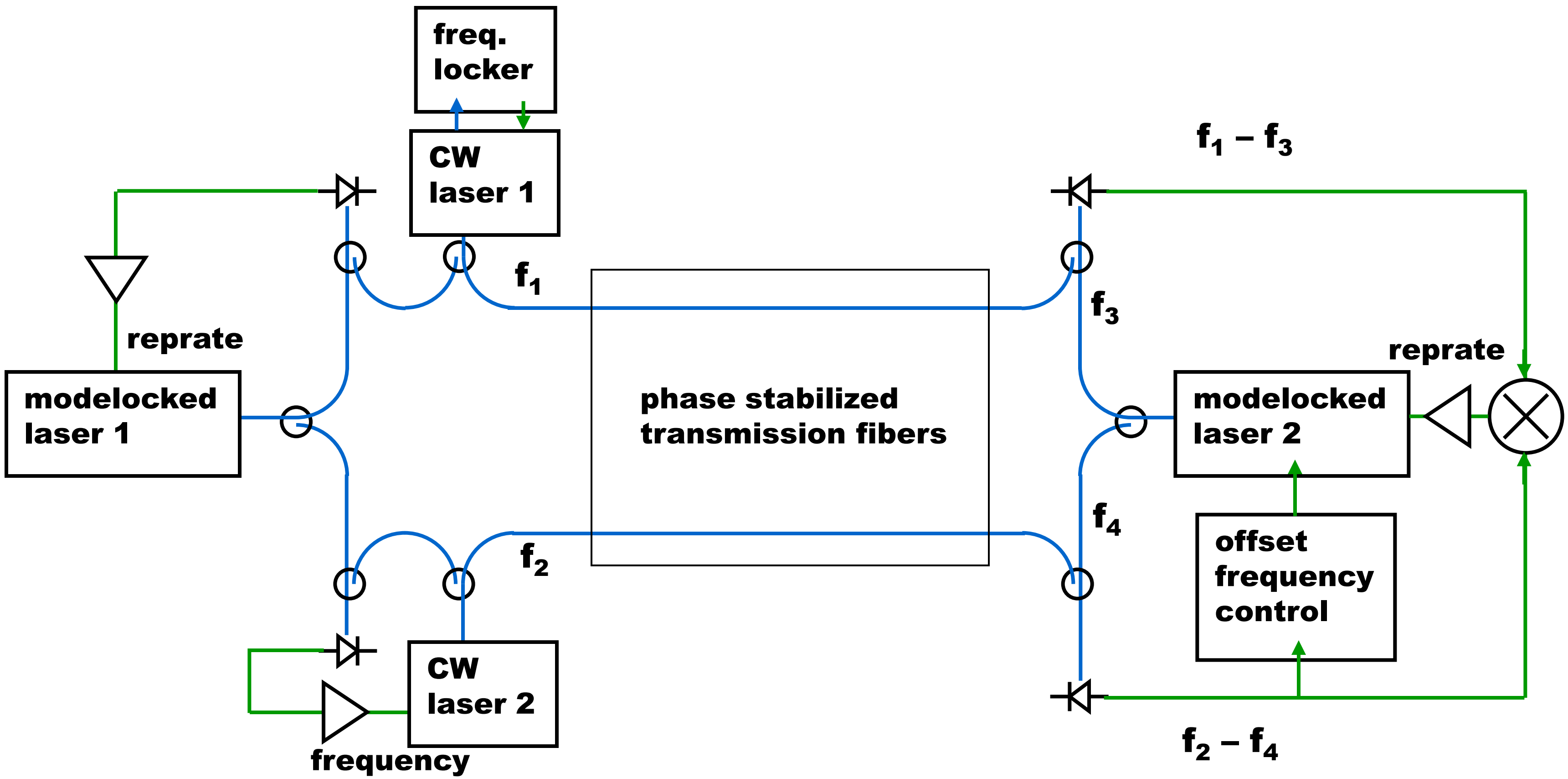
$$\frac{f_1 - f_2}{f_{optical}} = \frac{1}{40}$$

Thus, relative optical phase < 0.25fs for < 10fs timing

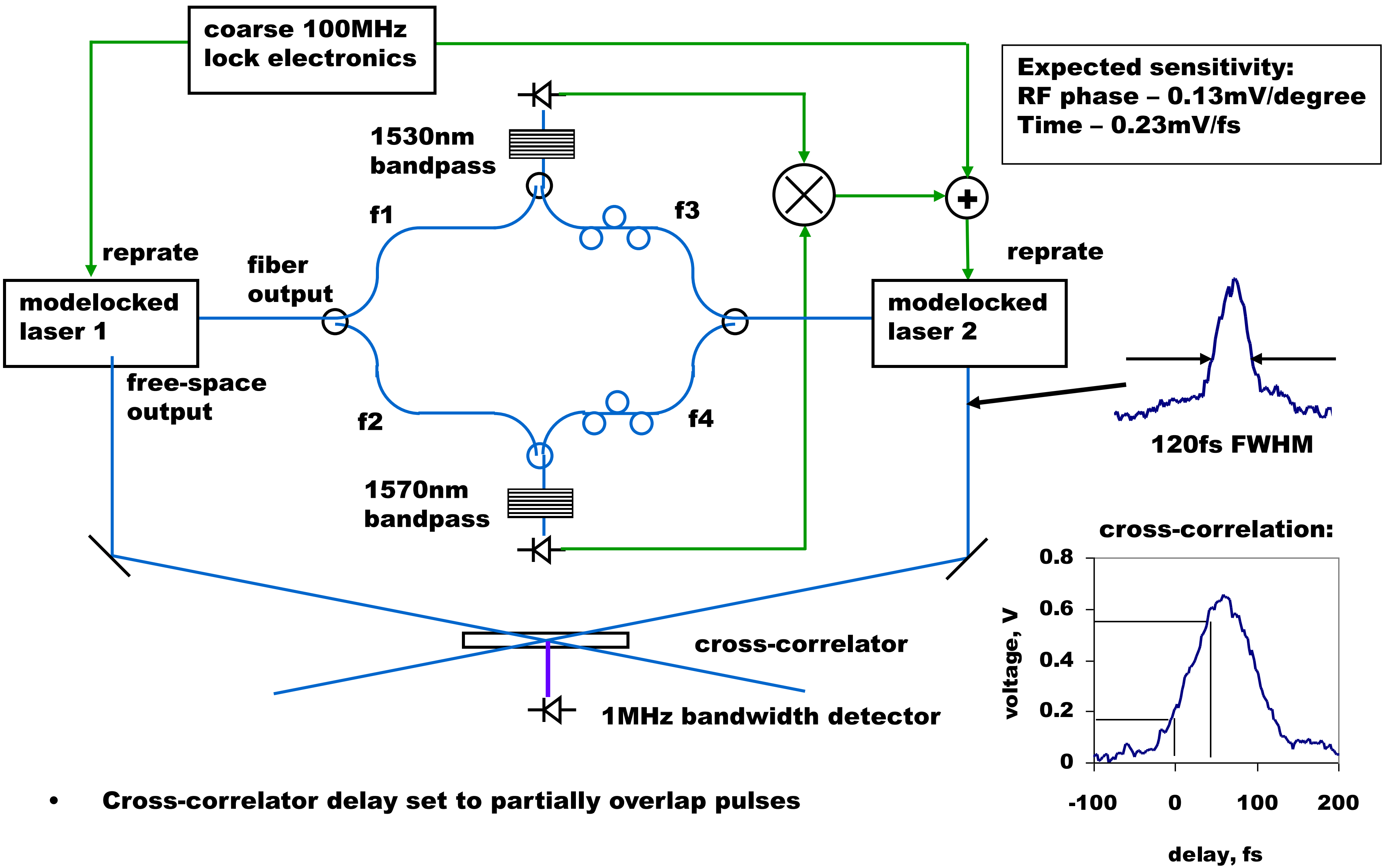
- **$(f_1 - f_3) - (f_2 - f_4)$ = error signal**
- **Equivalent to difference of two THz signals**
- **Offset frequency is cancelled**
- **Can be used with carrier-unstabilized lasers**

Two-freq. lock scheme

- **Enough information is transmitted in two CW frequencies to lock a second laser in time**
- **Interferometric line stabilization delivers constant phase for each frequency**



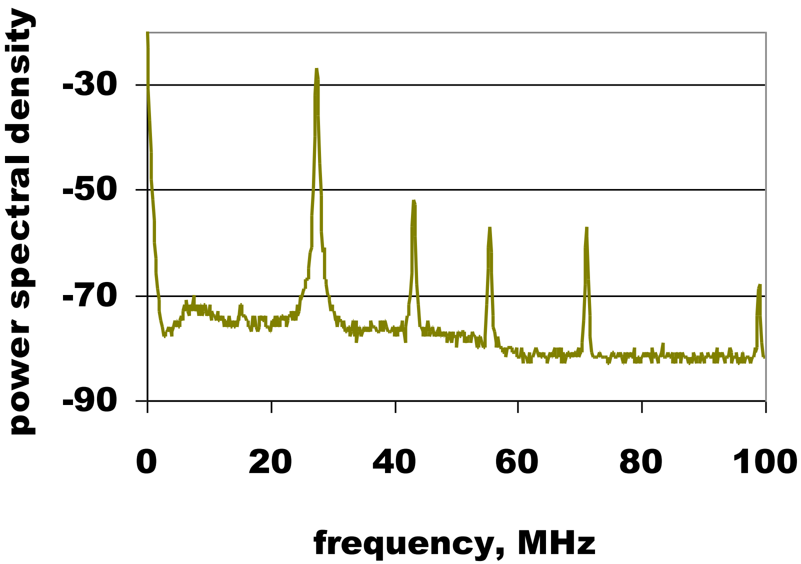
A simplified experiment



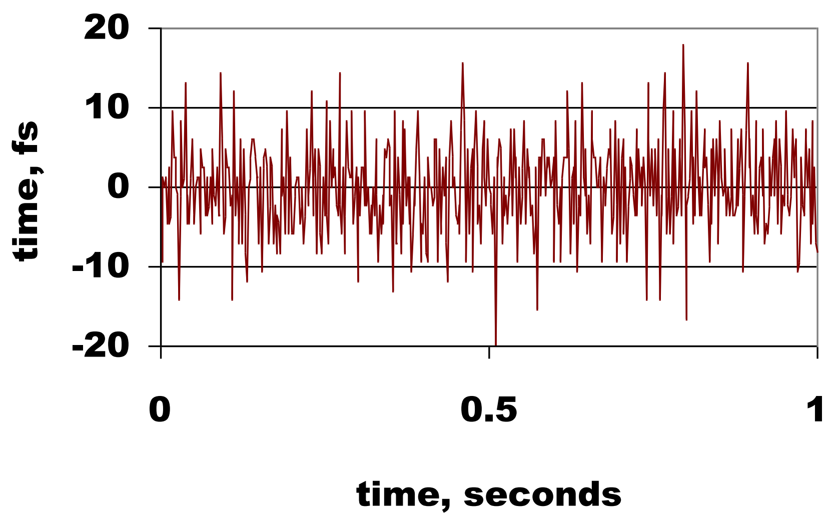
- Cross-correlator delay set to partially overlap pulses

Results

Spectrum of beats between groups of comb lines at 1530nm:



Cross-correlation of output pulses:



5.7fs RMS from 1Hz to 100kHz

Error signal sensitivity is 0.13mV/fs