6.977 ULTRAFAST OPTICS

Spring 2005

Problem Set 10

Issued: April 28, 2005.   **Due:** 11am, May 10, 2005.

Problem 10.1: Interferometric Autocorrelation (IAC)

To characterize the output pulses from the Ti:sapphire mode-locked laser designed in Problem Sets 8 and 9, an interferometric autocorrelation setup is used. Figure 10.2 in the class note shows the setup (the lens will be replaced by a curved silver mirror to avoid dispersion from lens material).

(a) The measured optical spectrum showed a sech^2-shape with a FWHM-bandwidth of 40 THz centered at 800 nm. What is the transform-limited FWHM-pulsewidth?

(b) By use of your favorite math package, plot the ideal interferometric autocorrelation (IAC) result for the pulses with the optical spectrum in part (a), assuming zero phase for the entire optical spectral range. For the plot, use delay range from -50 fs to +50 fs, and normalize the IAC trace to a 0-to-8 scale.

(c) In a real experiment, the pulses from the laser resonator experience dispersion from output coupler substrate, air path and the beam splitter in the IAC setup, and are not transform-limited pulses at the NL-crystal anymore. Suppose the ideal pulse in part (b) propagates through 1-mm thick fused silica and 1 meter of air path. Plot the IAC trace for the pulse after these dispersive elements. Can you clearly see the difference between IAC traces in part (b) and (c)?

Use the following equations and coefficients.

Fused silica:

$$n^2 = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1^2} + \frac{B_2\lambda^2}{\lambda^2 - C_2^2} + \frac{B_3\lambda^2}{\lambda^2 - C_3^2} \tag{1}$$

where λ is a wavelength in μm unit, and $B_1 = 0.696, B_2 = 0.408, B_3 = 0.897, C_1 = 0.0684, C_2 = 0.116, C_3 = 9.90$.

Air:

$$n = 1 + 10^{-8}\left\{26445.9 + \frac{148.7}{\lambda^2} + \frac{1.205}{\lambda^4} + \frac{0.02712}{\lambda^6}\right\} \tag{2}$$

where λ is a wavelength in μm unit.

The group delay T_g is defined as

$$T_g = -\frac{\partial \Phi}{\partial \omega} = \frac{L}{c}\left(n - \lambda\frac{dn}{d\lambda}\right) \tag{3}$$

where L is length of the material, c is the speed of light in vacuum, n is the refractive index, and λ is the wavelength.

(d) Can you fix the pulse distortion from the dispersive elements in part (c)?

(e) Suppose the optical spectrum from laser has a rectangular shape from 590 nm to 1200 nm. Can you still use IAC for characterization of this laser? If not, what is the reason?

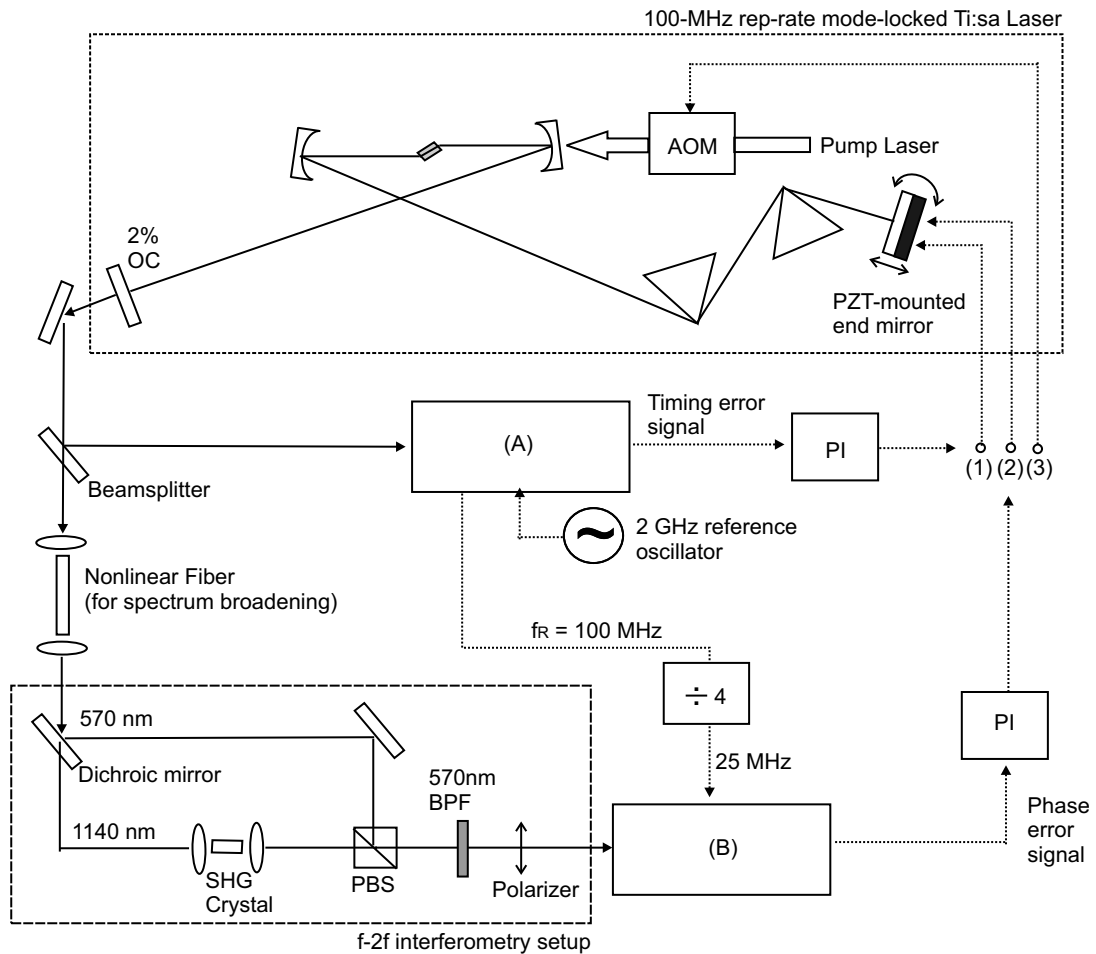## Problem 10.2: Frequency Metrology with Mode-Locked Lasers

Figure 1: Experimental setup for frequency comb stabilization. AOM: Acousto-Optic Modulator, OC: Output Coupler, PZT: Piezoelectric Transducer, PI: Proportional-Integral Controller, SHG: Second Harmonic Generation, PBS: Polarization Beam Splitter, BPF: Bandpass Filter. Note that PZT is 3-axis PZT which can translate (by control signal (1)) and tilt (by control signal (2)) the end mirror. Control signal (3) modulates the intensity of pump beam. Nonlinear fiber can broaden the optical spectrum from Ti:sapphire laser over octave to enable $f - 2f$ interferometry. Solid and dotted lines indicate optical and electric signal paths respectively. The repetition rate of the laser is 100 MHz.

In the frequency domain, the pulse train from mode-locked lasers can provide millions of frequency modes with equal spacing in the optical frequency range (that is the reason why it is also called optical frequency mode "comb"). Each comb line can be expressed as $f_m = f_{CE} + m f_R$. To get a fully stabilized mode comb, we need to control the repetition rate f_R (the spacing of comb lines) and the carrier-envelope offset frequency f_{CE} (the offset frequency of the whole comb) by proper feedback loops. Figure 1 shows the scheme for such frequency comb stabilization based on mode-locked Ti:sapphire laser designed in Problem Sets 8 and 9.

(a) The first step is to stabilize the repetition rate f_R by locking one of its harmonic frequency components to a reference microwave oscillator. In this experiment, suppose we have a very stable 2 GHz microwave oscillator. Complete box (A) with 10 GHz photodiode, proper bandpass filters, and frequency mixer for this purpose. Among control signal ports (1),(2) and (3), which one will you use to close repetition rate locking loop? What is the reason?

(b) The next step is to lock the carrier-envelope frequency f_{CE} to a stable reference oscillator or a fraction of the repetition rate of the laser. In this problem, since we already stabilized the repetition rate, we want to lock f_{CE} to the 1/4th sub-harmonic of the fundamental repetition rate, 25 MHz. A standard $f - 2f$ interferometry is used to detect f_{CE}. Complete box (B) with photomultiplier tube, proper bandpass filters, and frequency mixer to close carrier-envelope phase lock. Among control signal ports (1), (2) and (3), which one will you use to close the loop? What is the physical mechanism for tuning carrier-envelope phase (if you chose multiple ports, give the reason for each case and compare their advantage/disadvantage)? To initiate locking, one should move f_{CE} as close as possible to the target frequency, 25 MHz. How can you first tune f_{CE} of the laser to put it in the locking range?

(c) With two feedback control loops in part (a) and (b), you can get a fully stabilized frequency mode comb, $f_m = (m + 1/4) f_R$, in optical frequency range. If you want to make a mode comb with exact multiples of repetition rate, that is, $f_m = m f_R$, how can you change the $f - 2f$ interferometry setup?

(d) You want to use the output from this stabilized mode-locked laser to measure an unknown optical frequency. Before that experiment, you need to evaluate how much phase noise and corresponding phase jitter you have in your frequency mode. You can easily measure the phase noise of the signal labelled "Phase error signal" in Figure 1. The measured result shows phase noise of 0.1 rad from 2.5 mHz to 10 MHz, corresponding to 45 attosecond phase jitter at 800 nm. Is this measurement sufficient for evaluating carrier-envelope phase noise of the laser output? If not, which additional experiment do you need to perform?