Massachusetts Institute of Technology
Department of Electrical Engineering and Computer Science

6.977 Ultrafast Optics

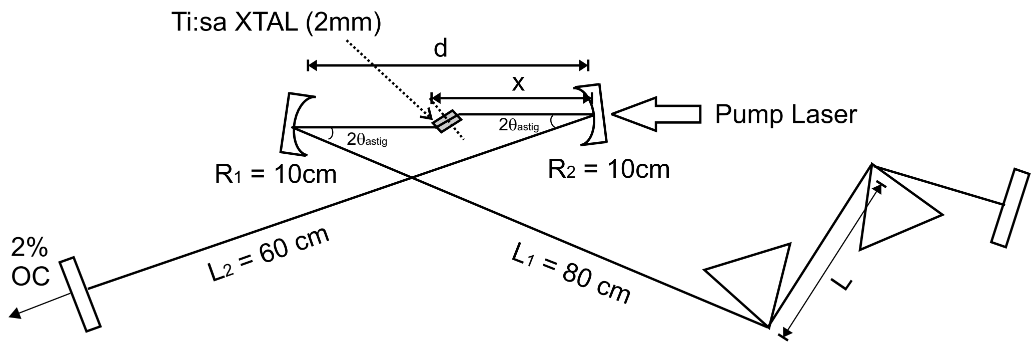
Spring 2005

Problem Set 8

Issued: April 7, 2005. **Due:** 11am, April 14, 2005.
Reminder: April 12 is the term paper proposal due.

Problem 8.1: Fast Saturable Absorber Mode-Locked Ti:sapphire Laser - Part I

For this and next Problem Sets, we want to design a Ti:sapphire laser mode-locked by an artificial fast saturable absorber (Kerr-lens mode-locking). In this Problem, we will design the linear resonator. In the next Problem Set, we will see how the Kerr-lens effect in the laser crystal can change the resonator condition and provide an artificial saturable absorption effect.



Gain Medium: The Ti:sapphire crystal will be used for the gain medium. The gain bandwidth of Ti:sapphire is $\Omega_g = 2\pi \times 43$ THz with a center wavelength of 800 nm. The crystal length is $t = 2$ mm. The refractive index of the crystal is 1.76 at 800 nm. For a rough estimation of the pulsed operation, assume the fast saturable absorber coefficient γ and the self-phase modulation coefficient δ are: $\gamma = 10^{-7}/W$ and $\delta = 10^{-6}/W$.

Resonator: We will use a 4-mirror resonator structure discussed in the class. The radius of curvature of R_1 and R_2 is $R_1 = R_2 = 10$ cm. The arm lengths are $L_1 = 80$ cm and $L_2 = 60$ cm. Assume the mirrors except output coupler have 100 % reflectivity with zero dispersion in the Ti:sapphire gain bandwidth range. The output coupler is 2% one and also has no dispersion.

Dispersion Compensation: To obtain short pulses from this laser the dispersion of the Ti:sapphire crystal has to be compensated. For a dispersion compensation we will put a prism pair (refer to Problem 2.2 again) in the longer arm (L_1). The prisms are cut at Brewster's angle for the center wavelength of 800 nm. The beam at center wavelength 800 nm also defines the prism angle $\beta = 0$.

(a) Determine the astigmatism compensation angle θ_{astig}.

(b) The Ti:sapphire crystal will be placed at the intra-cavity focus between curved mirrors. For 9 cm $\leq d \leq$ 12 cm range, plot the focus size w_0 and the focus position x as a function of d for (i) tangential and (ii) sagittal planes as well as (iii) the case neglecting astigmatism (that is, $f_{1,2} = R_{1,2}/2$). To simplify the calculation, neglect the thickness and refractive index of the Ti:sapphire crystal.

(c) What prism separation, L, would you choose for three different prism materials, (i) quartz, (ii) SF10 and (iii) CaF_2, to compensate the second-order dispersion of Ti:sapphire crystal? The material parameters at $0.8\mu m$ are: Ti:sapphire: $\frac{\partial^2 n}{\partial \lambda^2} = 0.064\frac{1}{\mu m^2}$, Quarz: $\frac{\partial n}{\partial \lambda} = -0.017\frac{1}{\mu m}$, SF10: $\frac{\partial n}{\partial \lambda} = -0.05\frac{1}{\mu m}$, CaF_2: $\frac{\partial n}{\partial \lambda} = -0.01\frac{1}{\mu m}$

(d) How large is the remaining third-order dispersion for the different prism materials? Use the following material parameters for $0.8\mu m$: Ti:sapphire: $\frac{\partial^3 n}{\partial \lambda^3} = -0.377\frac{1}{\mu m^3}$, Quarz: $\frac{\partial^2 n}{\partial \lambda^2} = 0.04\frac{1}{\mu m^2}$, SF10: $\frac{\partial^2 n}{\partial \lambda^2} = 0.18\frac{1}{\mu m^2}$, CaF_2: $\frac{\partial^2 n}{\partial \lambda^2} = 0.031\frac{1}{\mu m^2}$.

Note, for computation of the third-order dispersion use the result for $\frac{\partial^2 P}{\partial \lambda^2}$, where P is the optical path length through the prism pair from Problem 2.2. The term proportional to $\sin\beta$ can be neglected and, therefore, the coefficient $\frac{\partial^3 n}{\partial \lambda^3}$ occurring for the prism pair is not necessary.

(e) The lengthening of the pulse due to third-order dispersion in the absence of second-order dispersion can be approximated by

$$\frac{\tau_{out}}{\tau_{in}} = \sqrt{1 + \left(\frac{8\sqrt{2}\ln 2}{\tau_{in}^3}\frac{\partial^3 \Phi}{\partial \omega^3}\right)^2} \qquad (1)$$

Which prism material would you use to minimize the effects of third-order dispersion?

(f) How much would a 15 fs pulse be stretched within one round-trip in the cavity due to the remaining third-order dispersion?

In the following we neglect third and higher order dispersion. Assume the average output power is 100 mW and the repetition rate is 100 MHz.

(g) Assume that the pulses are soliton like. What is the necessary net intra-cavity dispersion for generating a 10 fs pulse from this laser? How large is then the normalized dispersion, $D_n = D_2/D_g$?

(h) How large is the chirp on the steady-state pulse without assuming a soliton-like pulse?