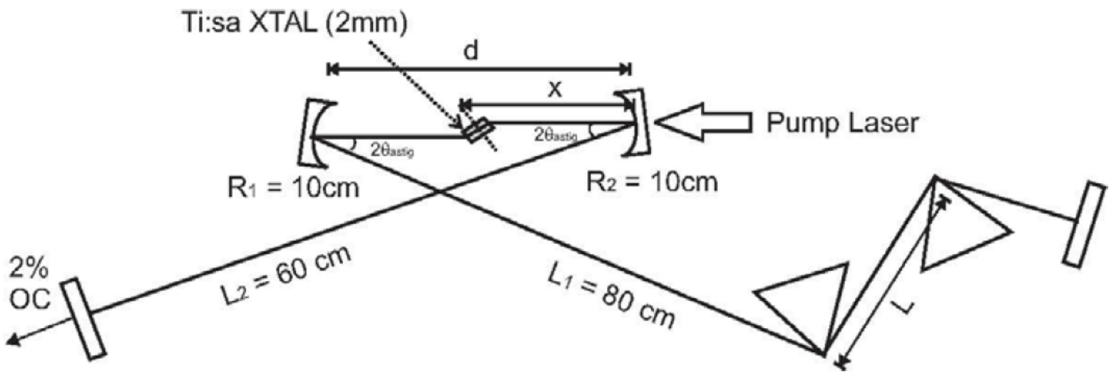
Universität Hamburg
Physics Department

Ultrafast Optical Physics II
SoSe 2019

Problem Set 6

Issued: May 31st, 2019. Due: June 7th, 2019.

Problem 6.1: Mode-Locked Ti:Sapphire Laser and Carrier-Envelope Phase Shift $\Delta\phi_{CE}$



When a pulse propagates through a medium, the relative position between the carrier wave and envelope changes due to dispersion (causing a difference between phase velocity and group velocity) and optical nonlinearities. For an optical pulse circulating inside a mode-locked laser cavity, this leads to the carrier–envelope phase shift in each round-trip.

(a) The Sellmeier equation for the Ti:Sapphire crystal has the following form:

$$n^2 - 1 = \frac{1.4313493\lambda^2}{\lambda^2 - 0.0726631^2} + \frac{0.65054713\lambda^2}{\lambda^2 - 0.1193242^2} + \frac{5.3414021\lambda^2}{\lambda^2 - 18.028251^2}$$

This equation works for the vacuum wavelength between 0.2 um and 5 um. Calculate the $\boldsymbol{\Delta\phi_{CE}}$ for a 800 nm pulse propagating through 4 mm (for a single round trip) Ti:Sapphire crystal.

(b) For a cavity round-trip, the optical pulse travels through 4-m air. The refractive index of dry air under standard condition is written as (where the vacuum wavelength is in um),

$$(n-1)\times 10^8 = 8091.37 + \frac{2333983}{130-\lambda^{-2}} + \frac{15518}{389-\lambda^{-2}}$$

Calculate the corresponding $\boldsymbol{\phi_{CE}}$ caused by air, and compare it with the result in (a). Can they compensate for each other?

(c) The f_{CE} can be altered by varying the intracavity power. Assume the net second-order dispersion inside the cavity is -250 fs^2 and the laser is mode-locked in the soliton regime producing hyperbolic secant pulses with 20 fs pulse duration (τ_0). What is the value of the soliton phase shift (ϕ_0) per roundtrip in the laser cavity? How much change in intracavity power do you need to shift the f_{CE} by 1% of the repetition rate assuming the average output power is 200 mW?

Problem 6.2: Performance of regenerative amplifier

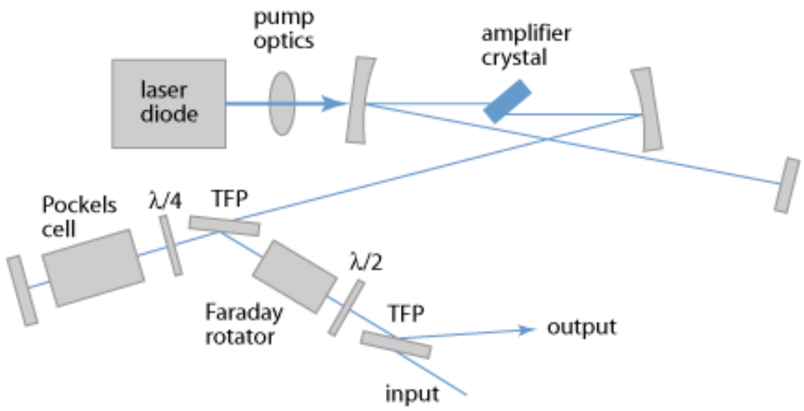


Figure 6.1 Schematic of a regenerative amplifier

A prototype end pumped regenerative Ho:YLF laser amplifier in a resonator configuration as shown in Fig 6.1 produced 1.3 mJ, 3.5 ps output pulses at 1 kHz repetition rate. We want to model the dynamics of this system with the Franz-Nodvik equations, because experience shows that there is only a relatively small parameter interval in terms of pump power and mode size, where the system shows stable output. Here is what we know: The Ho:YLF crystal is pumped by a commercial 19 W CW-Thulium-fiber laser operating at 1938 nm wavelength. The input seed pulse is derived from a broadband Tm-pumped Ho-doped fiber oscillator based on Nonlinear Polarization Evolution (NPE) modelocking with energies of 0.1 nJ at a repetition rate of 33 MHz. At a pump power of 19 W, a single pass small-signal gain coefficient of $g_o = 1.957$ was calculated for the regenerative amplifier. An RTP-based Pockels-cell was employed as a Q-switch with a switching time of 10 ns. The saturation fluence $F_s = h\nu/\sigma$ for Ho:YLF is $4.6\ J/cm^2$ and the upper level lifetime $\tau_l = 15\ ms.$

According to the Franz-Nodvik equations, the fluence in the amplifier develops with the number of passes according to:

$$F_{k+1} = TF_s \ln\{G_k[exp(F_k/F_s) - 1] + 1\},$$

where F_k is the intracavity fluence in the regenerative amplifier at the end of round-trip k, and as such F_0 the initial seed fluence, and G_k is the total round-trip gain during round-trip $k + 1$.

The gain coefficient where $g_k = lnG_k$ during the k+1-round-trip decreases after each pass according to:

$$g_{k+1} = g_k - (p/I_s)\left[\frac{I_{k+1}}{T} - I_k\right]$$

neglecting the pumping during pulse evolution, $p = 0.5$ and $T = \exp(-\delta)$ is passive transfer factor of the cavity including also internal losses in the amplifier per round-trip.

(a) Using the above Franz-Nodvik equations, model the intracavity fluence assuming a total loss δ of 18% in the cavity and initial input energy 0.1nJ focused to a beam radius of 0.5mm.

(b) Plot the intracavity fluence (both in linear and log-scale) as a function of number of passes for different small signal round-trip gains g_o of 1.7, 1.85, 2.1 and 2.3. Also, plot the gain as a function of number of passes.

(c) Determine the total number of passes, $kmax$, required to extract the maximum pulse energy from the regenerative amplifier for the various initial small signal gain values in (b).

(d) In the following, we assume $g_o = 1.95$. The above model is true only when the energy stored in the gain medium is completely restored between two subsequent regenerative cycles, 1ms apart, each time a fresh seed pulse is injected. If the laser is continuously pumped, this is not necessarily the case, especially in Ho:YLF which has a long upper state lifetime of $\tau_L = 15\,ms$, i.e. the energy not extracted after one pulse built-up cycle remains stored in the gain medium. Modify the above model to implement the re-pumping of the gain between two extraction cycles m+1 and m from the gain left in cycle m to the initial small signal gain in cycle (m+1):

$$g_0^{m+1} = g_o + (g_{kmax}^m - g_o)e^{-\frac{t}{\tau_l}}$$

(e) Now assume you switch out the pulse from the regenerative amplifier after $kmax$ round-trips. Simulate for $1 < kmax < 40$ the resulting fluences F_{kmax}^m in units of F_s for $1 < m < 100$. Plot the 100 values for F_{kmax}^m into the same graph for a given $kmax$. Plot the pulse-to pulse noise fluctuation in the output energy for each $kmax$. Explain why there might be fluctuations and not a single value.

The detailed function of a regenerative amplifier is explained in the manuscript in section 11.2.2. It will be also useful to read through the link

http://www.rp-photonics.com/regenerative_amplifiers.html