Characterization of optical components of a laser amplifier via spectral interferometry

Bachelor thesis

Martin Beyer

supervisors: Prof. Dr. Malte Kaluza, Dr. Sebastian Keppler

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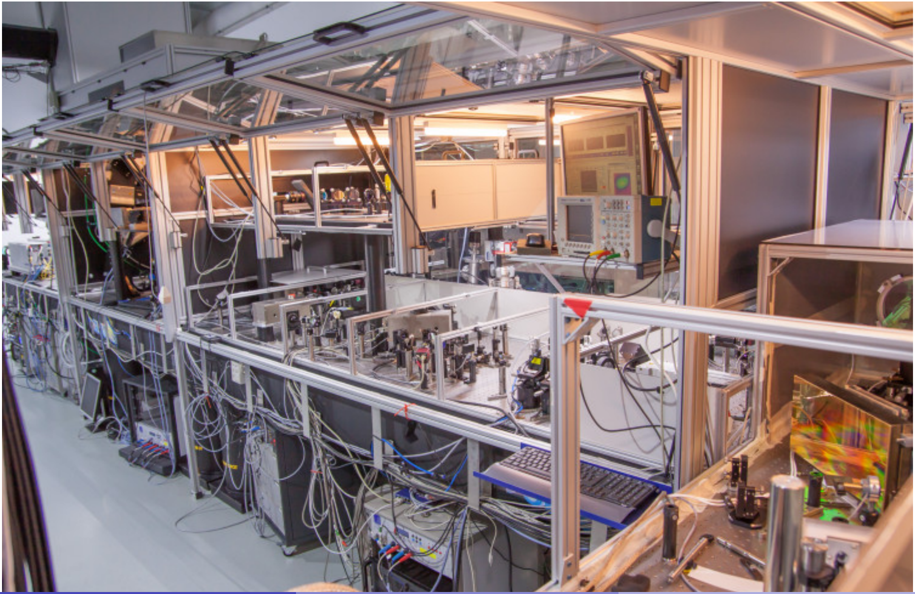
IOQ JENA
Friedrich-Schiller-Universität

The POLARIS laser



Spectral phase and dispersion

Electric field of the GAUSSIAN shaped optical pulse:

$$\boldsymbol{E}(t) = \boldsymbol{E}_0 \cos(\phi(t)) \cdot \exp\left[-\left(\frac{t}{\tau}\right)^2\right] \tag{1}$$

$$\text{Fourier transform } \Rightarrow E(\omega) = \sqrt{S(\omega)}\exp(\mathrm{i}\varphi(\omega)). \tag{2}$$

TAYLOR-Series expansion of the spectral phase

$$\varphi(\omega) = \varphi(\omega_0) + \underbrace{\left.\frac{\mathrm{d}\varphi(\omega)}{\mathrm{d}\omega}\right|_{\omega_0}}_{\text{Group delay}}(\omega - \omega_0) + \frac{1}{2}\underbrace{\left.\frac{\mathrm{d}^2\varphi(\omega)}{\mathrm{d}\omega^2}\right|_{\omega_0}}_{\text{GDD}}(\omega - \omega_0)^2 + \ldots .$$

GDD = Group delay dispersion, [GDD]= fs^2

Spectral phase and dispersion

Similarly the effects of a dispersive medium can be characterized by the wave number $k(\omega)$.

$$\text{Group velocity dispersion: GVD } = \left.\frac{\mathrm{d}^2 k(\omega)}{\mathrm{d}\omega^2}\right|_{\omega_0}. \tag{3}$$

Accumulated phase of a pulse travelling through a medium of length L:

$$\begin{aligned} \varphi(\omega) &= k(\omega) \cdot L \\ \Rightarrow \mathrm{GDD}(\omega) &= \mathrm{GVD}(\omega) \cdot L \end{aligned} \tag{4}$$

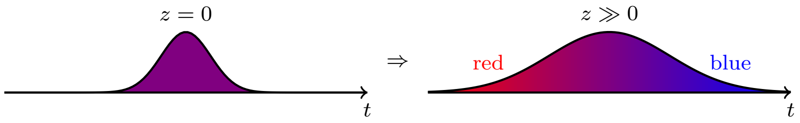


Figure: Schematic representation of the pulse stretching during the propagation in a dispersive medium.

Spectral interferometry

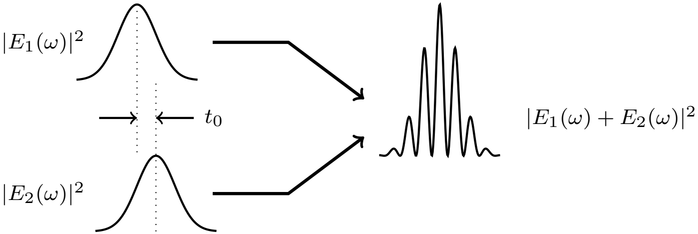


Figure: Sketch of spectral interference between two laser pulses with a GAUSSIAN spectrum, one of which is delayed by t_0.

$$\begin{aligned} \tilde{S}(\omega) &= |E_1(\omega) + E_2(\omega)|^2 \\ &= 2S(\omega) \cdot [1 + \cos(\varphi_1(\omega) - \varphi_2(\omega))] \\ &= 2 \exp\left(-\frac{\omega^2\tau^2}{2}\right) \cdot [1 + \cos(\Delta\varphi(\omega) + \omega t_0)] \end{aligned} \tag{5}$$

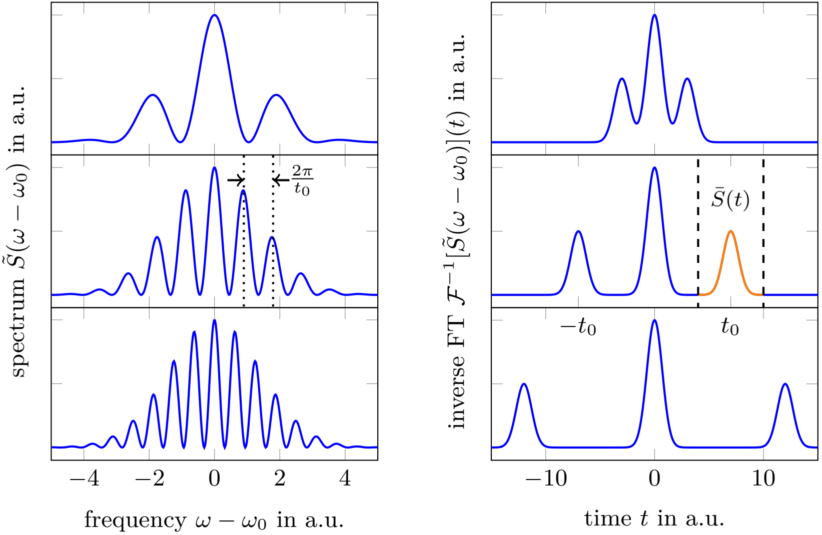


Figure: Left: Simulated spectrum of two interfering Gaussian pulses for different delays t_0. Right: Absolute value of the Fourier transform of the spectrum.

GDD estimation

There are three different methods for the determination of the GDD:

- Numerical phase differentiation
- Fitting a high order polynomial to the phase and differentiate analytically.
- Using the cubic phase function

$$E(\omega) = \sqrt{S(\omega)}\exp(-\mathrm{i}\varphi(\omega)) \\ = \exp\left(-\frac{\omega^2\tau^2}{4}\right)\exp\Big[-\mathrm{i}(\varphi_0 + \varphi_1\omega + \varphi_2\omega^2 + \varphi_3\omega^3)\Big] \tag{6}$$

Cubic phase function [1]

$$\mathrm{CPF}(\omega,T) = \int_0^\infty E(\omega+\omega')E(\omega-\omega')\exp\left(\mathrm{i}T\omega'^2\right)\mathrm{d}\omega'$$
$$= S(\omega)\mathrm{e}^{2\varphi(\omega)}\frac{\sqrt{\pi}}{2}\left\{\frac{\tau^2}{2} + \mathrm{i}[2(\varphi_2 + 3\varphi_3\omega) - T]\right\}^{-\frac{1}{2}} \quad (7)$$

- The absolute value of $\mathrm{CPF}(\omega,T)$ peaks along the curve $T = 2(\varphi_2 + 3\varphi_3\omega) = \dfrac{\mathrm{d}^2\varphi(\omega)}{\mathrm{d}\omega^2} = \mathrm{GDD}(\omega)$.
- Therefore: $\mathrm{GDD}(\omega) = \arg\max_T |\mathrm{CPF}(\omega,T)|$.

[1] Zeng et. al: *Group delay dispersion measurement from a spectral interferogram based on the cubic phase function.*

Michelson interferometer setup

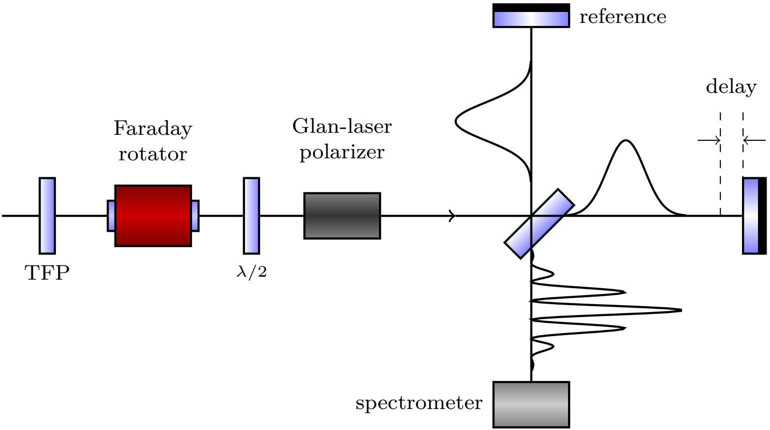
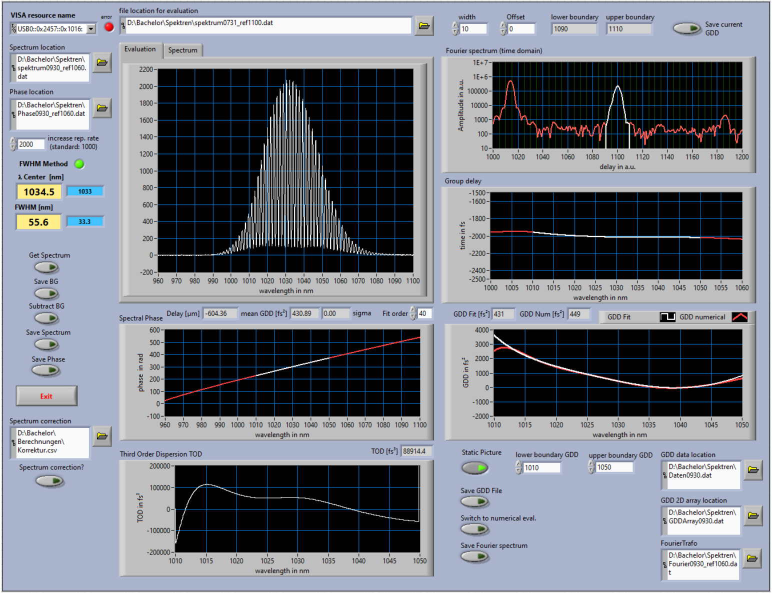


Figure: Experimental setup: A Michelson interferometer is used to create a second pulse, which interferes with the first pulse leading to fringes in the spectral domain due to the delay between the two pulses.

LabVIEW application



Measurement referencing

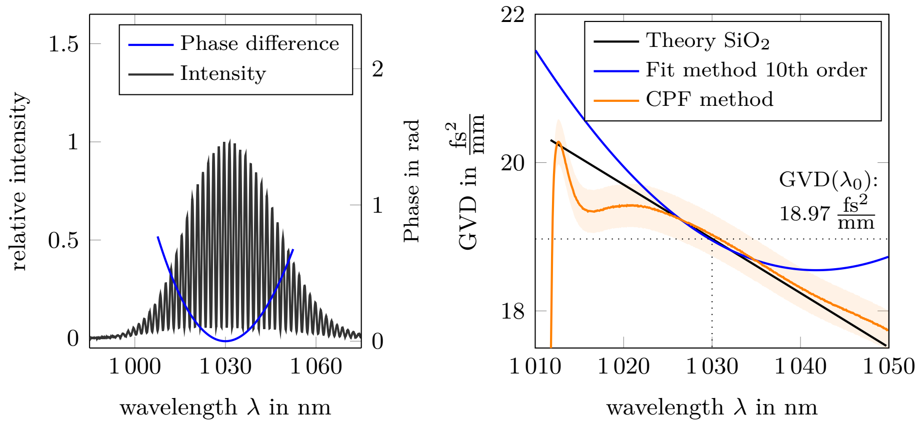


Figure: GDD measurement of a fused silica for the phase differentiation and CPF method. The shaded area represents a $\pm 1.5\,\%$ deviation from the measured value.

Experimental issues - Spectral calibration

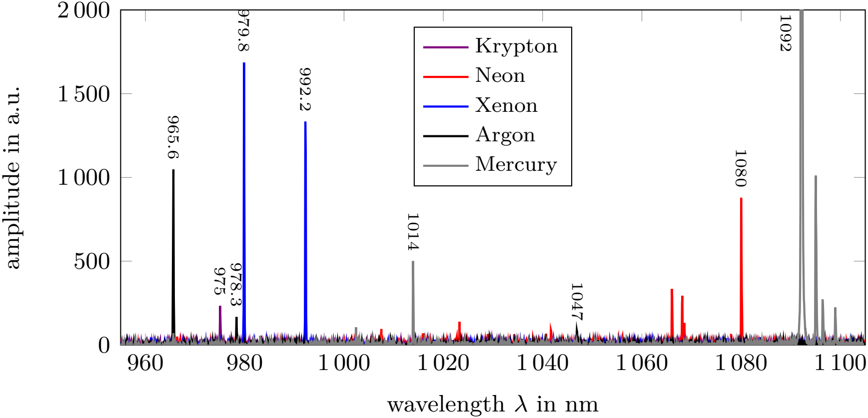


Figure: Spectral lines of several elements measured with the high-resolution spectrometer *Ocean Optics HR2000+*.

Experimental issues - Spectral resolution

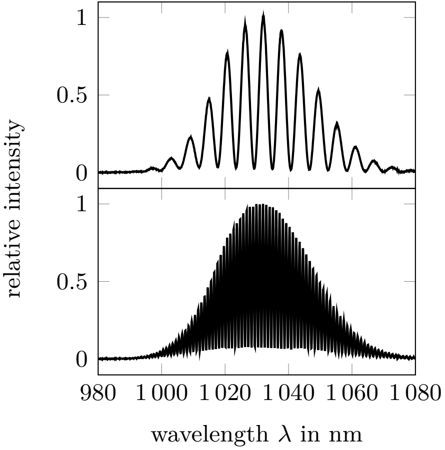


Figure: Comparison of the density of fringes for different pulse delays t_0.

Experimental issues - Spectral resolution

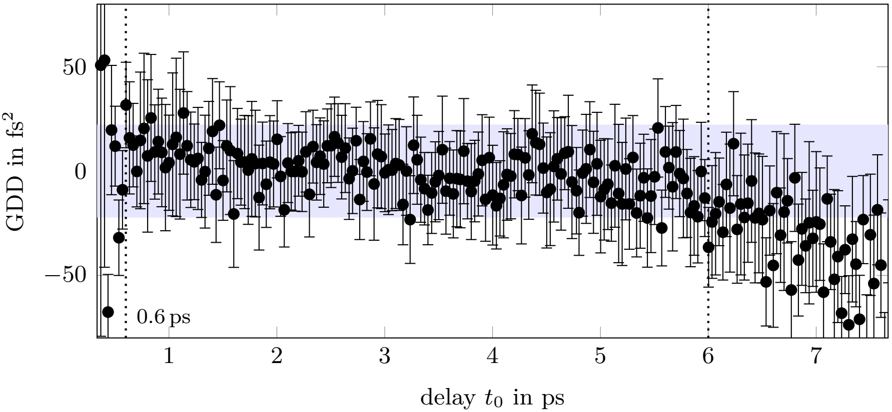


Figure: GDD difference measurement of two pulses as a function of the delay at $\lambda_0 = 1030\,\text{nm}$. Each value is averaged over 50 individual measurements. The blue shaded area represents two times the standard deviation.

Experimental issues - Noise sensitivity

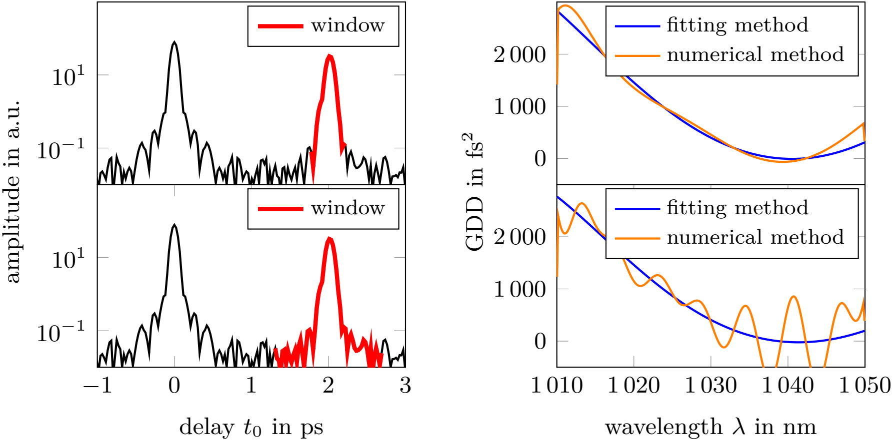
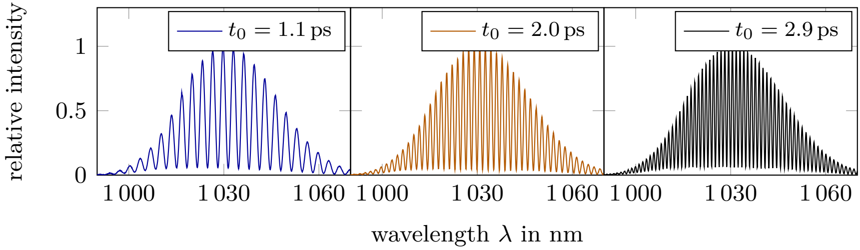
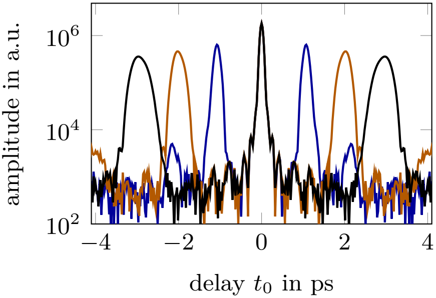
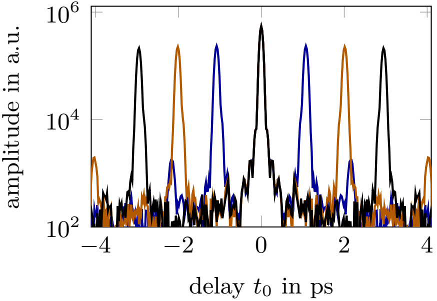


Figure: Sensitivity of the retrieved GDD on the window width for different phase differentiation methods.

Experimental issues - Frequency sampling

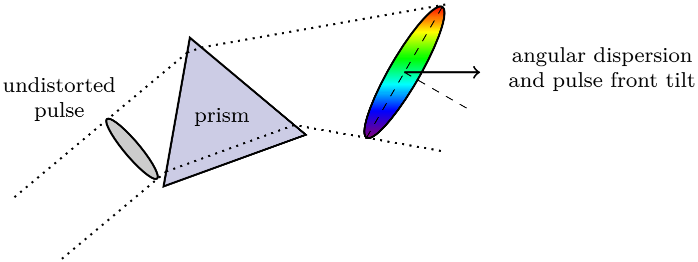






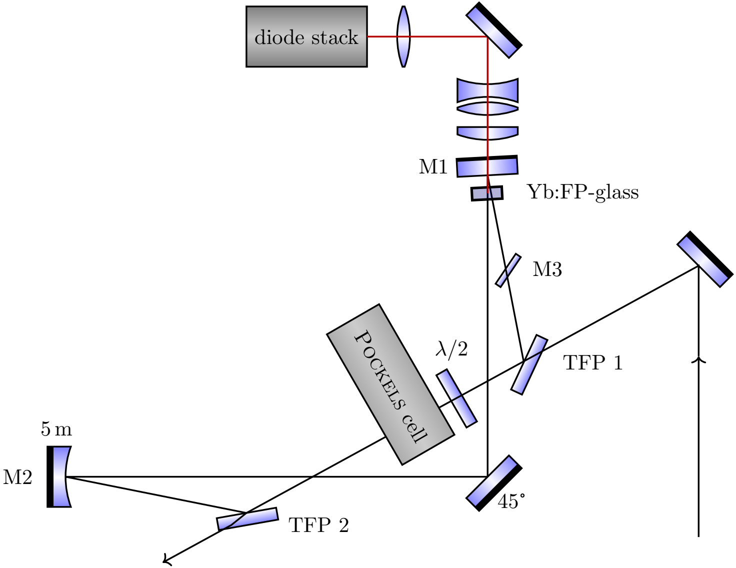
Experimental issues - Angular dispersion [2]

- can be described by the dispersion of the propagation angle θ_0 of the ω-component of the beam.
- Angular dispersion: $\frac{\mathrm{d}^2\varphi}{\mathrm{d}\omega^2} = \left.\frac{\mathrm{d}^2\varphi}{\mathrm{d}\omega^2}\right|_{z=0} - k_0\beta^2 z, \qquad \beta = \frac{\mathrm{d}\theta_0}{\mathrm{d}\omega}.$



[2] Akturk et. al: *Pulse-front tilt caused by spatial and temporal chirp.*

Setup of the laser amplifier



Short pass filter (pump mirror)

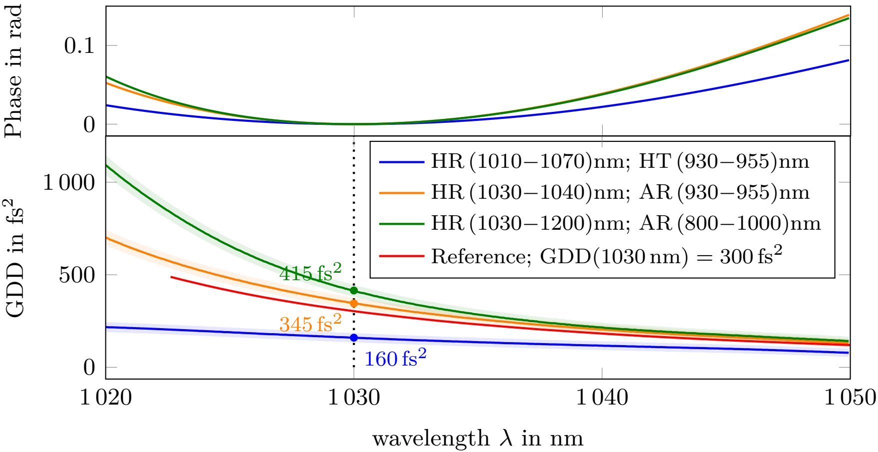


Figure: Phase (top) and GDD measurement (bottom) of three different short pass filters which are high reflective (HR), high transmissive (HT) or anti reflective (AR) in certain wavelength ranges.

Laser mirror, Yb:FP, and Pockels cell

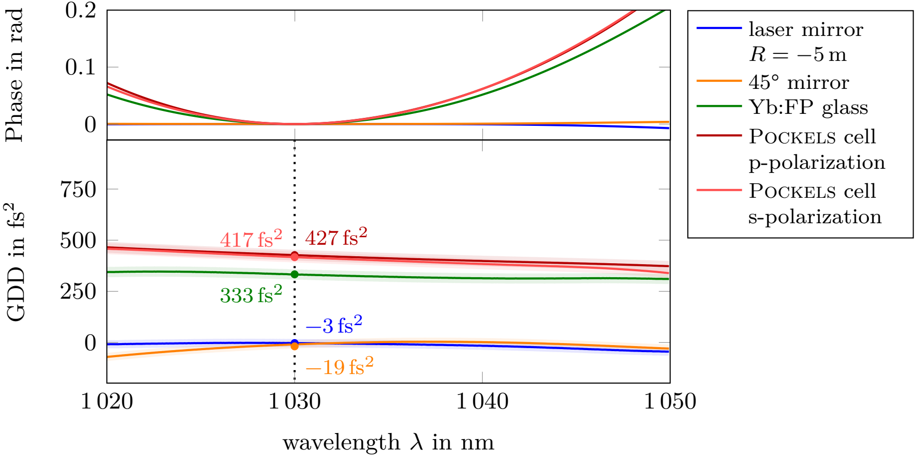


Figure: Phase difference (top) and GDD measurement (bottom) of a curved laser mirror with $R = 5$ m, a 45° deflection mirror, the Yb:FP glass and the POCKELS cell in p-polarization and s-polarization.

TFP, spectral mirror, half wave plate

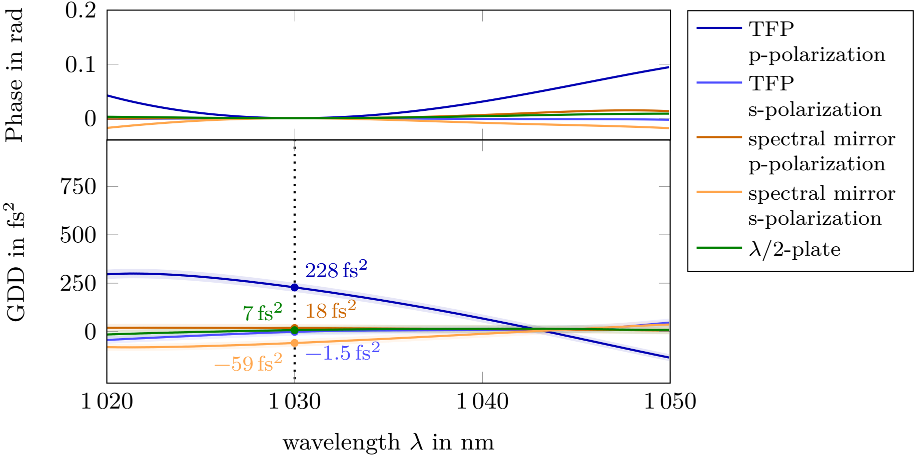


Figure: GDD measurement of a TFP, spectral mirror FP15 with a Gaussian reflexion profile in p-polarization and s-polarization and a $\lambda/2$-half wave plate.

Phase dispersion after a whole resonator cycle

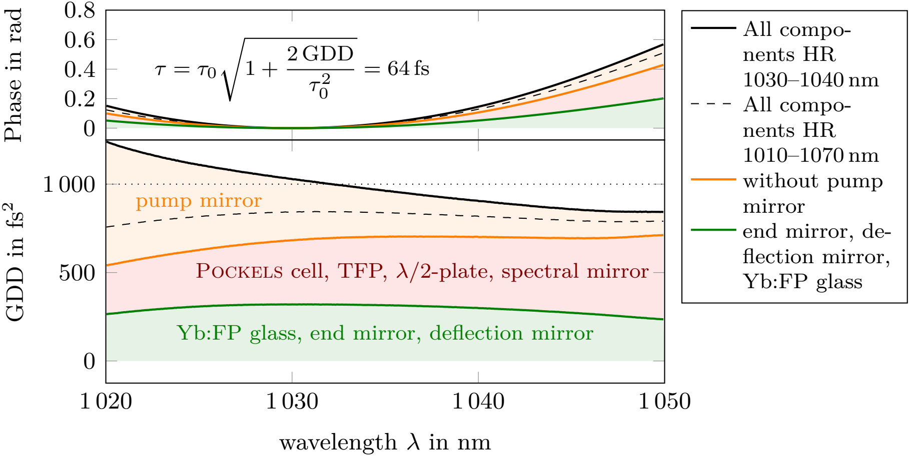


Figure: Summation of the spectral phase difference (top) and GDD (bottom) of all components (with pump mirror HR 1030–1040 nm) of the laser amplifier for a single cycle.

Phase dispersion after 40 resonator cycles

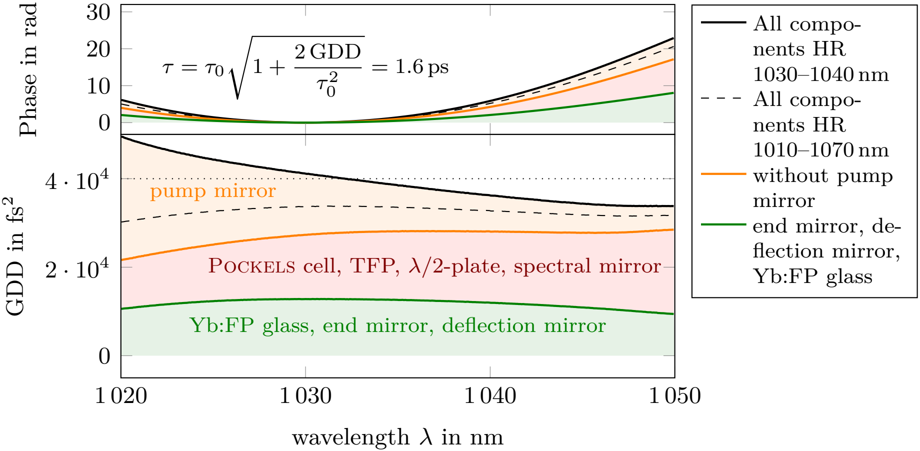


Figure: Spectral phase difference (top) and GDD (bottom) of all components (pump mirror HR 1030–1040 nm) of the laser amplifier for the whole amplification (40 resonator cycles, input and output coupling).

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