LX Spider

Pulse Measurement System

User Manual

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Content

1. Introduction

The acronym LX SPIDER stands for “Long Crystal Spectral Phase Interferometry for Direct Electric-field Reconstruction” [1]. It is a patented technology which was born from the idea of simplifying the SPIDER concept – a standard technique for the measurement and characterization of ultrashort laser pulses. With this technique the laser pulse is measured completely in the spectral domain by analyzing the fringe structure of a spectral interferogram. The result allows for the reconstruction of the temporal pulse structure. In contrast to autocorrelation based techniques (e.g. FROG) SPIDER is an intrinsic single-shot method that delivers both the amplitude and phase of the ultrashort pulse without the need for an iterative reconstruction algorithm [2, 3]. This makes SPIDER the method of choice for real-time pulse characterization or the real-time alignment of laser systems.

2. Description

The LX SPIDER is an interferometer with a nonlinear conversion step and an internal spectrometer, all enclosed in the upper part of the optics unit (Fig. 1). The input beam height is 70 mm.

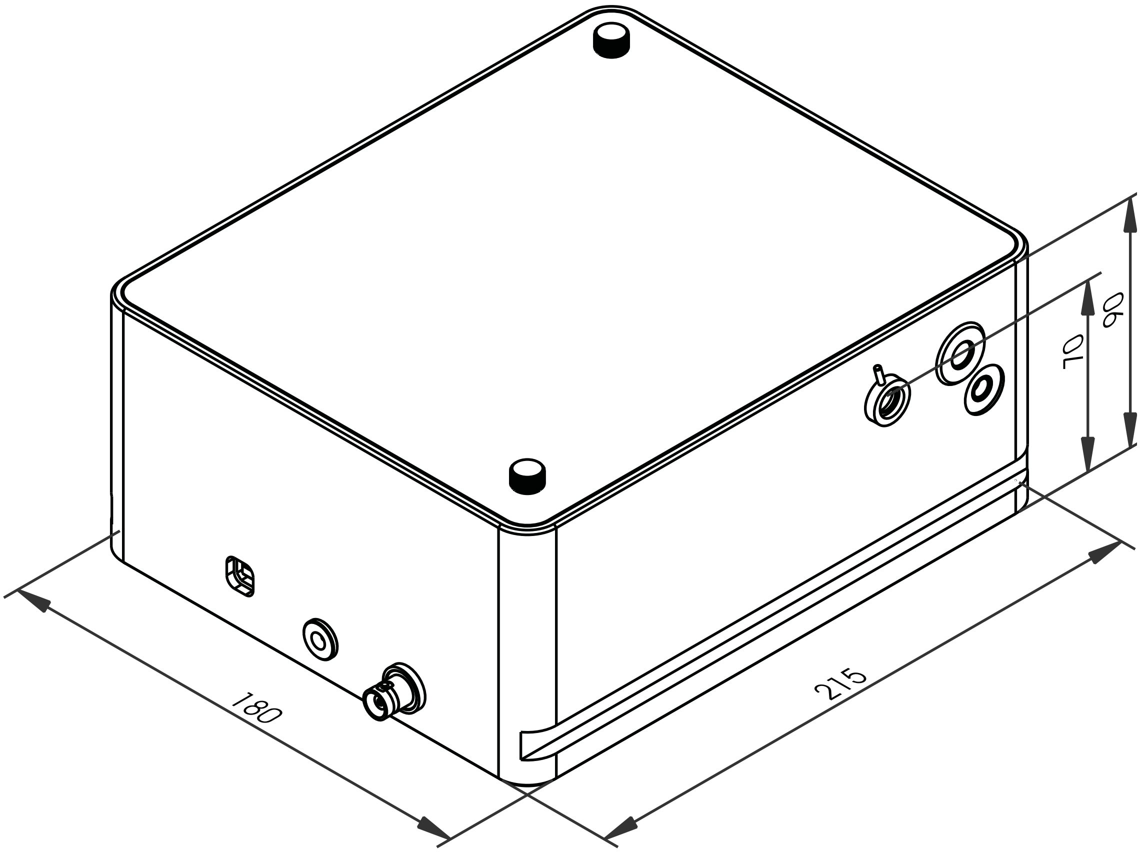


Fig. 1 Optics Unit

A measurement can only be done computer controlled after installation of the LX SPIDER software on a computer.

Attention: Do not connect the LX SPIDER device to a computer prior to the installation of the LX SPIDER software!

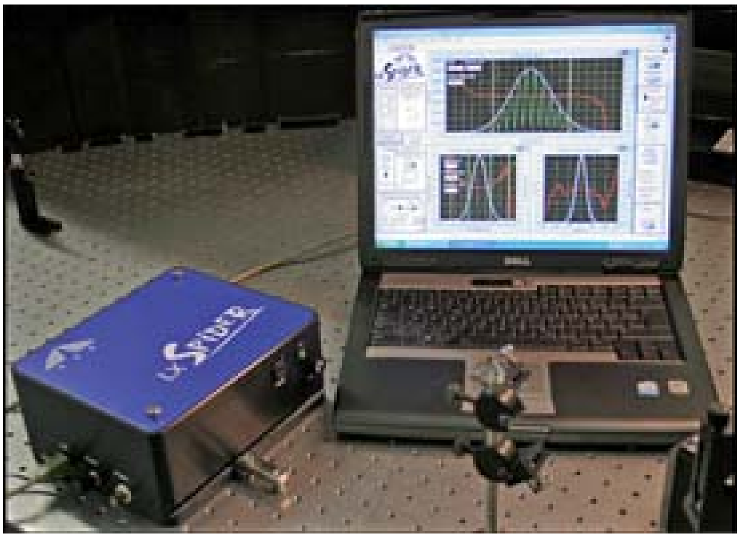


Fig. 2 LX SPIDER measurement setup

Electronics of the LX SPIDER is located in the bottom part of the optics unit and allows to handle one spectrometer, 5 servo motors and one stepper motor via a common USB 2.0 port. The whole, fully functional measurement setup is shown in Fig. 2.

2.1 Schematic Setup

APE's LX SPIDER is a compact device that uses the left and the right hand side of the entering beam profile to generate the necessary double pulse for Spectral Interferometry. The implementation of the patented LX SPIDER technique is shown in Figure 3 as a scheme of the optical setup. The functionality of the successive optical components that follow the input beam path is listed below.

After entering the input aperture (1) the linear polarized laser beam is turned to horizontal or 45° polarization by a waveplate (2). Depending on what has to be measured - a fundamental or a second harmonic (SHG) signal - an attenuator (3) is inserted into the beam path. The quartz block (4) separates horizontal polarized components from vertical polarized ones of the input laser pulse in time. As a next step, the left and the right hand side of the input beam is divided by the splitting mirror (6) that reflects these two beams under slightly different angles and introduces a time delay between the two beams of ~1 ps. If both, vertical and horizontal polarized components of the input laser pulse are present, Type II phase-matching inside the nonlinear crystal (7) leads to the generation of a SHG signal in each of the two beams that transmit through the crystal. A steering mirror (8) reflects these two beams onto a focusing mirror (11). The latter is needed to overlap both beams on the entrance slit of the spectrometer (14). Fundamental spectral components can be suppressed by insertion of a color filter (13) in front of the spectrometer. To measure the pure fundamental spectrum a reflective diffuser (5) can be turned into the beam path behind the quartz block. For initial alignment, an alignment mirror (9) is moved in the beam path in front of the focusing mirror reflecting the two partial beams onto an alignment window. Again, a color filter (10) enables discrimination of fundamental and SHG signal. The shutter (12) in front of the focusing mirror allows to measure the up-converted spectrum of each partial beam separately.

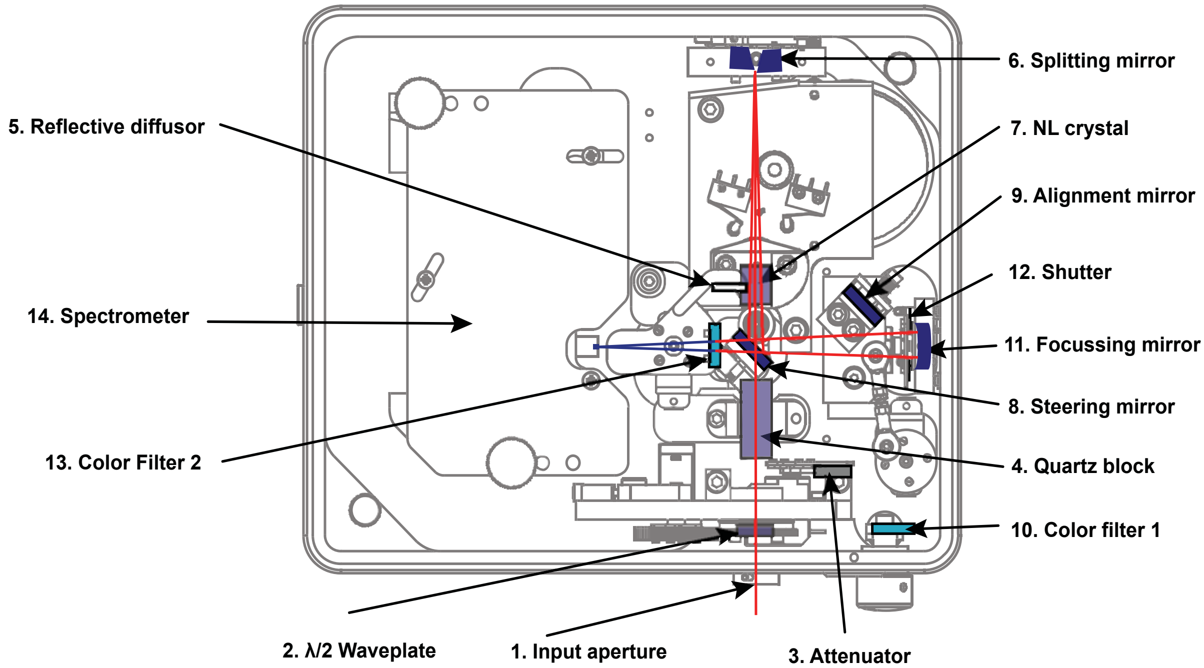


Fig. 3 Schematic setup of LX SPIDER including beamline

Successive optics in the beam path / functionality:

1. Input aperture	Sets the beam height to 70mm and limits the input beam diameter by 4 mm
2. λ/2-waveplate (motorized)	Turns polarization of input beam to horizontal for calibration measurement and to 45° for SPIDER-measurement
3. Attenuator insertion (motorized)	Levels intensities between measurements in the fundamental and second harmonic frequency range
4. Quartz block	Positive uniaxial crystal: Horizontal or e-polarized component of the pulse is pre-delayed with respect to the vertical or o-polarized one.

5. Reflective diffusor (motorized)	For optional measurement of the fundamental pulse spectrum
6. Splitting mirror	Separates left and right hand side of the beam profile; Introduces a divergence and a time delay between both beams
7. Nonlinear crystal (motorized)	Nonlinear negative uniaxial crystal: In each beam the o-polarized pulse is up-converted by a narrowband frequency component of the co-propagating e-polarized pulse while the pre-delayed e-pulse overtakes the o-pulse. A spectral shear is generated between the two beams due to different propagation angles.
8. Steering mirror:	Turns the two beams onto a focusing mirror
9. Alignment mirror (motorized)	Traversable steering mirror to project double beam onto alignment window
10. Color filter 1	Blocks the fundamental signal for optional check of phase matching: Up-converted signal becomes visible on fluorescent window.
11. Focussing mirror	Overlaps both beams on the entrance slit of the spectrometer
12. Shutter (motorized)	Allows for blocking each beam separately to enable spectral shear measurement between the two independently up-converted beams
13. Color filter 2 (motorized)	blocks / unblocks the fundamental signal for discrimination between calibration measurement in the fundamental and SPIDER measurement in the second harmonic spectral range
14. Spectrometer:	Optical Multi-channel Analyzer

3. Specifications

Wavelength range	750...900 nm	
	Optics set 1	Optics set 2
Pulse bandwidth	13 nm - 40 nm	5 nm - 15 nm
Pulse duration[1)]	80 fs - 25 fs[2)] (with reduced accuracy down to 16 fs/65 nm bandwidth)[3)]	200 fs - 70 fs
Maximum pulse duration	150 fs	300 fs
Input polarisation	linear	
Input beam height	70 mm	

1) Transform limited duration of Gaussian pulses
2) theorethical reconstruction error < 1%
3) theoretical reconstruction error < 10%

Minimum power operation: Pave*P0 = 20 W2 (not for alignment):

Repetition rate	Pulse duration	Average power P_{ave}	Peak Power P_0	Pulse energy
75 MHz	100 fs	12 mW	1700 W	0.15 nJ

Optimum operation (examples):

Repetition rate	Pulse duration	Average power P_{ave}	Peak Power P_0	Pulse energy
75 MHz	100 fs	100 mW	10000 W	1.3 nJ
5 kHz	35 fs	20 mW	115 MW	4 µJ
10 Hz (single shot)	50fs	130 µW	260 MW	13µJ

Electrical parameters:

Power supply	Input:	100 – 240 V AC, 50 – 60 Hz, max. 0.9A
	Output:	13.2 V DC, 3 A/40W

Use only the delivered power supply!

Interface	USB 2.0
Trigger input	TTL, for repetition rates < 1 kHz
Size (L xW x H)	180 x 215 x 90 mm^3

4. Installation and Alignment

The LX SPIDER comes ready to use with the requested optics set installed. However, before connecting the LX SPIDER to your computer via the USB cord software installation is necessary!

Attention: Do not connect the LX SPIDER device to a computer prior to the installation of the APE LX SPIDER software!

4.1 Contents of Delivery

The following components are delivered with the LX SPIDER:

1. LX SPIDER optical unit:
   - Optical Unit (with one USB4000 spectrometer and one optics set installed)
   - Optional: one additional optics set

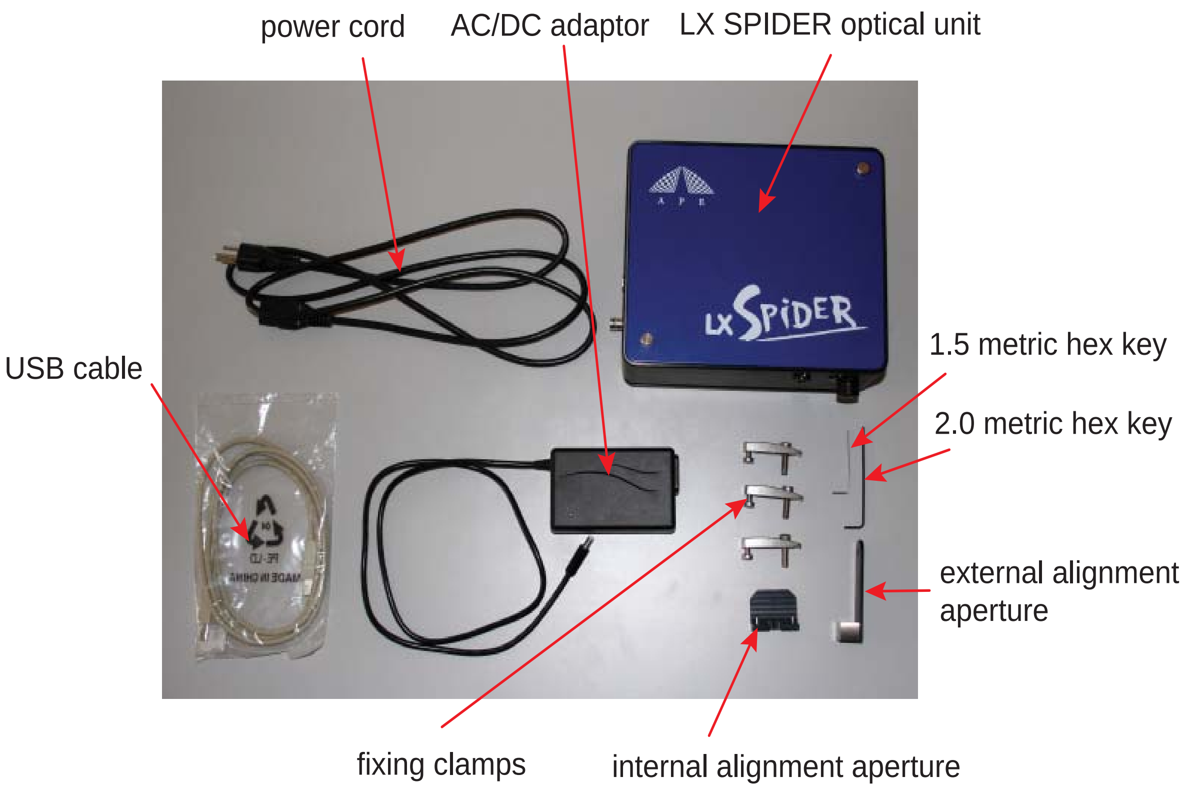


Fig 4 Contents of Delivery

2. Tools [compare with Fig. 4)]:
   - 3 clamps to fix the optical unit on a laser table
   - 1 hex key (1.5 metric)
   - 1 hex key (2.0 metric)
   - Internal alignment aperture
   - External alignment aperture
3. Cables:
   - Power cord (to connect with the AC/DC adaptor)
   - AC/DC adaptor [to connect with the device´s “Power” connector]
   - USB cable [to connect the computer with the device´s “USB” connector]
4. Software on CD
   - LX SPIDER software
   - OOIBase32
   - driver
5. LX SPIDER manual

4.2 Mounting of the LX SPIDER device

In case an input beam height of 70 mm can be provided, mounting of the LX SPIDER device can be done directly on the table with the delivered clamps. For larger input beam heights the device can be screwed on three posts. For this purpose, three metric (M4) and three imperial (UNC 8-32) tapped holes are located at the bottom side of the device (See fig. 5).

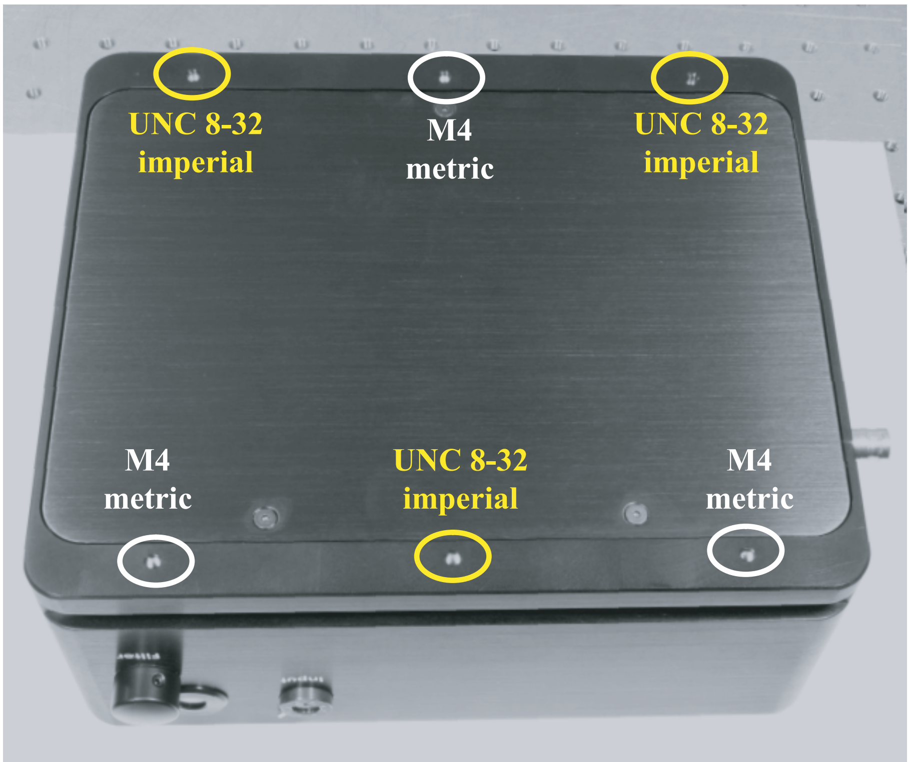


Fig. 5: Bottom side of the LX SPIDER device. Different tapped holes for mounting the device are marked.

4.3 Software Installation

1. Put the delivered LX SPIDER software CD in the CD-ROM drive of your computer.
2. The setup of the LX SPIDER software starts automatically (if not, double click on the “setup. exe” icon).
3. Choose destination directory and accept the license agreement.
4. After complete installation of the LX SPIDER software the setup of the “OOIBase32” software starts automatically (if not, double click on the “OOISetup.exe” icon).
5. When asked for a password, click OK for Standard Edition.
6. Restart your computer after complete installation.
7. Leave the LX SPIDER software CD in the CD-ROM drive.
8. Connect the LX SPIDER optics unit to the computer via the delivered USB 2.0 cable.
9. Connect the delivered power supply to the LX SPIDER optics unit.
10. Open the “hardware update wizard” and choose “no connection to windows update”
11. Two USB devices will be installed subsequently, the Ocean Optics USB4000 and the LX SPIDER.
12. After complete installation of the two USB devices, please check the “device manager” for them (See Fig. 6). If one is still missing, unplug the power supply cable, then reconnect the power supply and have the missing USB device be installed.
13. If both devices are recognized by the device manager, the LX SPIDER software can be

started by double click on the LX SPIDER icon (or the “LX SPIDER.exe”).

Fig. 6 The „Ocean Optics USB4000“ and the „APE-LX-SPIDER“ should be recognized by the device manager.

4.4 Laser Safety

For the application of lasers or laser radiation you have to pay attention to safety rules according to the used laser class! Incorrect handling and operation of lasers can be hazardous to your health. Take care! There might be back-reflected laser radiation of the laser beam that enters the LX SPIDER optical unit!

Protect the LX SPIDER from humidity, because the SHG crystals are slightly hygroscopic.

4.5 Alignment

Status:

- The LX SPIDER is connected to the computer via the delivered USB 2.0 cable.
- Power is supplied to the LX SPIDER via the delivered AC/DC adaptor.
- The two USB devices "Ocean Optics USB4000" and "APE-LX-Spider" are recognized by the device manager of the computer.

4.5.1 Preparation (Software)

1. Start the LX SPIDER software (APE LX SPIDER 1.1.exe).
2. A window opens: "Choose file to read". Please select the delivered LX SPIDER parameter file, e.g. "S01905-OS1 parameters hpol.txt", and press "OK".
3. The indicator "Motors initialized" should show green for proper operation of the motors (See Fig. 7).
4. (In case of an initial phase-matching calibration procedure: A calibration procedure of the phase-matching angle of the device starts that can last for up to 40 seconds. During this period the software appears frozen. After this calibration, noise of the spectrometer camera produces fluctuating curves in the "Measurement" window of the software: The spectrometer is running!)
5. Press the software button "Alignment" in the upper right corner of the LX SPIDER software (See Fig. 7). A steering mirror is placed automatically reflecting the beam onto the alignment window adjacent to the entrance aperture.

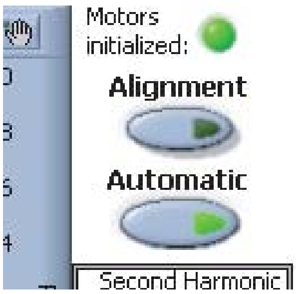


Fig. 7 Alignment button is deactivated. Press Alignment button to move alignment mirror in the beam path for monitoring the two partial beams on the alignment window (See Fig. 8)

4.5.2 Preparation (Laser Beam)

6. Attenuate the laser power to below ~100 mW (@ ~ 80 MHz repetition rates; See chapter 3, Specifications: optimum operation). Keep in mind that depending on the method of attenuation the laser pulse might be changed due to dispersive or nonlinear effects.

7. The laser beam has to be pre-aligned to travel under constant height (70 mm) above the table. It is advisable to use at least two steering mirrors in the beam path to the LX SPIDER optical unit with one of the mirrors directly in front of the input aperture of the unit to enable beam walking alignment. Use the delivered external alignment aperture to monitor the correct height of the laser beam. It has to be assured that the beam is properly collimated (minimum divergence). Because of the spatial beam splitting the beam diameter should be at least 1 mm.

4.5.3 LX SPIDER Alignment / Signal Optimization

8. Place the LX-SPIDER on the table with the beam entering the input aperture of the device centrally and perpendicularly.

Make sure that the color filter is not in front of the alignment window! For this, see figure 8: The mark on the Knob may not point to the alignment window.

9. Slightly turn the device on the table or align the horizontal angle of the steering mirror in front of the input aperture until a double spot appears on the alignment window (See Fig. 8). Fasten the device on the laser table with the delivered clamps.

Fig. 8 Front side of the LX SPIDER device. If the software “Alignment” button is activated a centered double spot should be visible on the alignment window. In case of proper phase-matching and sufficient input power the up-converted signal becomes visible as a green fluorescent double spot on the alignment window. For this, a color filter has to be placed in the beam path by turning the “Filter” knob to the left with the arrow on the knob pointing to the alignment window.

10. In case of being unsuccessful: Open the device and place the internal alignment aperture in front of the splitting mirror [See Fig. 9 b)]. Align the beam to pass through the input and the internal alignment aperture.

a) b)

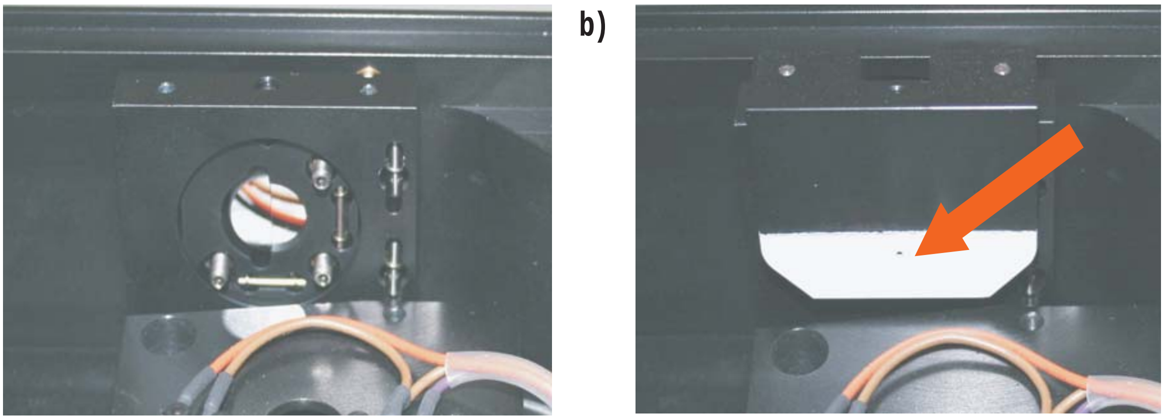


Fig. 9 a) Beam splitting mirror, b) Internal alignment aperture in front of the beam splitting mirror.

11. Walk the laser beam until it is centered both on the input aperture and on the crosshairs of the alignment window. Make sure the input aperture is opened to an operation diameter of ~ 4mm. In this case a double spot should be visible on the window. Fine adjust the mirror in front of the LX SPIDER to show equal intensity in both spots. They should lie on the horizontal line of the crosshairs with the vertical line in between both spots (See Fig. 8). Increase laser power if the visibility of the double spot is too weak in a darkened room.
12. Make sure laser power is attenuated according to step 6 (See Subsection 4.4.2).
13. Deactivate the software button "Alignment" (Compare Fig. 7)
14. Activate the "Measure spectrum" function by setting a checkmark in the software (left mouse click on the box) according to:

15. Monitor the spectral signal in the software's "Measurement" window (green graph) and optimize the input laser intensity for use of maximum dynamic range of the spectrometer camera at a short exposure time (<100 ms for online operation). Avoid detector saturation: Make use of the software's "Auto Exposure" operation mode.
16. Store the laser spectrum by pressing the software button "Save Spectrum" (See step 14).
17. Insert the center wavelength (COG: "Center Of Gravity") of the laser spectrum in the "Go to (nm)" control and press "Tune":

18. Deactivate the “Measure spectrum” function by removing the checkmark (See step 14). An interferogram of the fundamental signal should become visible in the “Measurement” window.

19. Maximize the signal of this fundamental interferogram by adjusting the horizontal (H) and vertical (V) tilt of the focusing mirror (See Fig. 10). (The V-adjustment is less critical and quite insensitive. In addition to maximum intensity, one important alignment criterion is the fringe visibility and high, symmetric modulation depth of the interferogram.) Make sure that the “Auto Exposure” operation mode is offline during signal optimization adjustments.

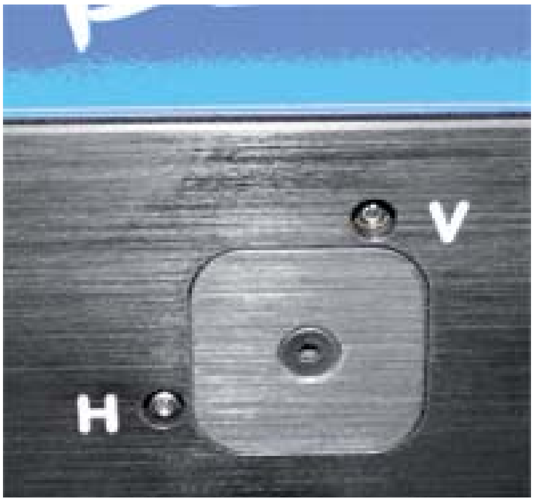
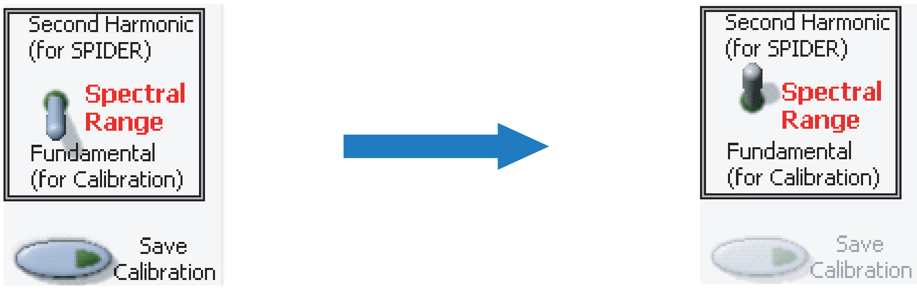


Fig. 10 At the right side of the device: Alignment screws of the focusing mirror are accessible from the outside.

20. Activate the “Auto Exposure” function. Save the fundamental interferogram as calibration by pressing the “Save Calibration” software button and choose “Replace Spectrum?”: “No”. Then switch the “Spectral Range” from “Fundamental” to “Second Harmonic”:



21. A SPIDER interferogram should become visible in the “Measurement” window. Pulse reconstruction in the “Pulse: Spectral Domain” window starts.

22. Further signal optimization of the SPIDER interferogram is advisable:

- Deactivate “Auto Exposure” function.
- Maximize the signal according to step 19.

- Maximize the signal by fine tuning the phase-matching angle with the + / - software buttons in the “Phase matching” window. The optimum should be reached when the “COG” value and the “COG to set” value of the indicators inside the “Measurement” window are alike.
- Maximize the signal by adapting the “Waveplate: Polarization Rotation” in the “Phase matching” window: Removing the checkmark there gives access to the +/- buttons to correct for a deviation of the input polarization from horizontal orientation.

23. Only to be done once after shipment / transportation or exchange of the splitting mirror:
Only in case of poor modulation depth of the interferogram after carriage (For an example of proper modulation, see fig. 12):
First check for other reasons of poor modulation and correct for them:

- Misalignment (repeat step 19) and phase-matching (recheck step 22)
- The two SHG-spots show unequal intensities (compare fig. 8, step 11)

Open the device and maximize modulation depth by slightly adjusting the upper screw (see arrow) of the splitting mirror. This will optimize beam overlap at the spectrometer’s entrance slit.

Do not try the two other screws below the splitting mirror!

The device calibration will be lost!

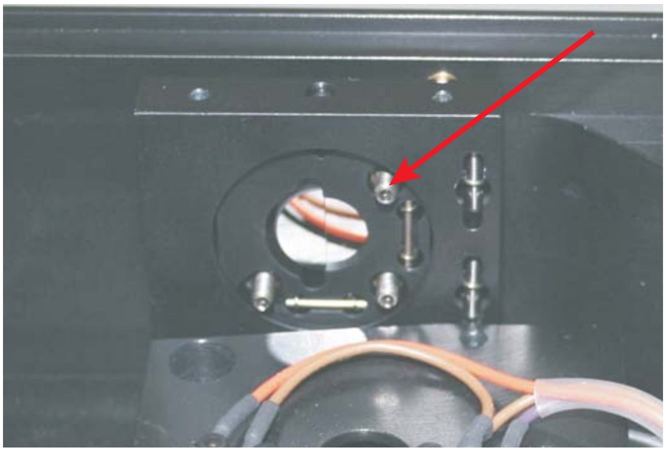


Fig. 11 Splitting mirror adjusting screw

24. After optimization of the SPIDER interferogram a fundamental calibration interferogram has to be taken again:

- Switch the “Spectral Range” from “Second Harmonic” to “Fundamental”.
- Repeat step 20.

5. Description of the LX SPIDER Software (Version 1.1)

Except the positioning of the LX SPIDER device on the table and alignment of the focusing mirror according to Fig. 10 all other operations of the device are done with the control software that is explained in this chapter. Figure 12 shows the main display of the LX SPIDER software. The panel is dominated by two graphs: the “Measurement” and the “Pulse: Spectral Domain” window.

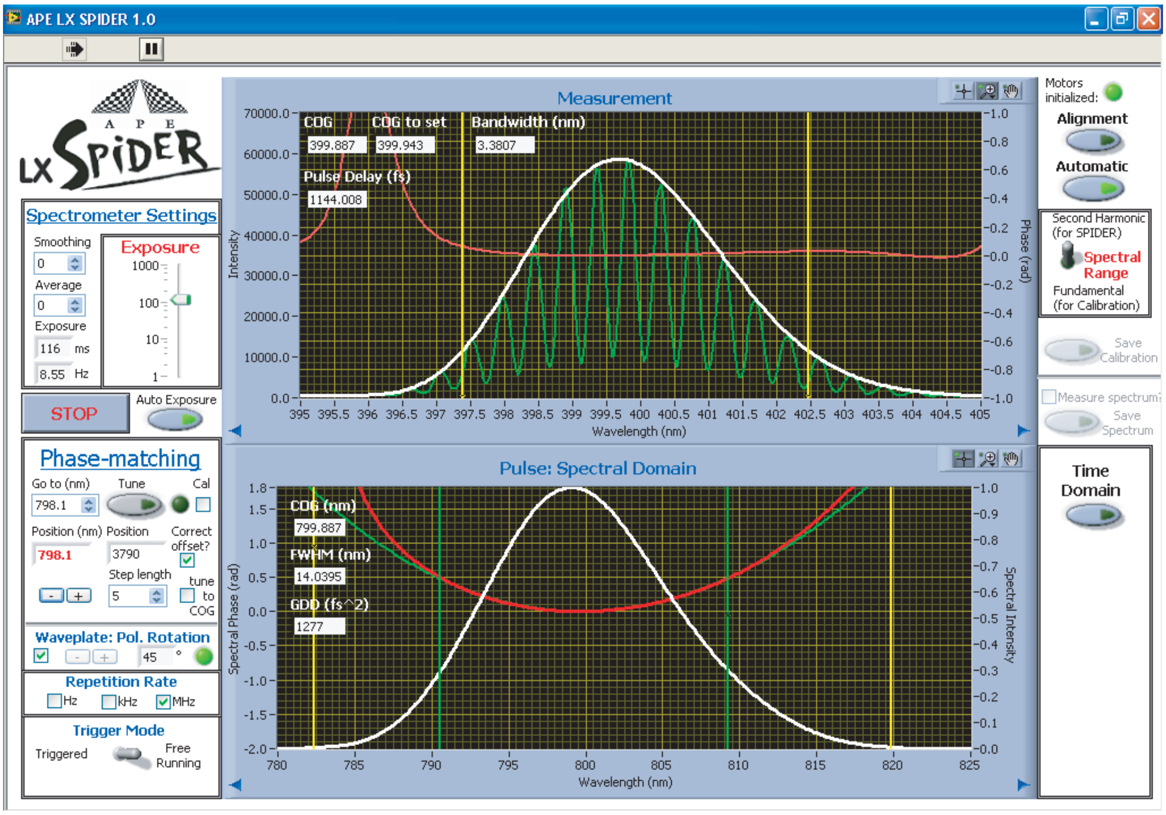


Fig. 12 Display of the LX SPIDER control, measurement and pulse reconstruction software. For device configuration refer to Appendix D.

5.1 The “Measurement” window

The upper graph (“Measurement”) displays the raw spectrometer data (green curve) which is automatically decomposed into amplitude (white curve) and phase (red curve). This decomposition only makes sense when dealing with interferograms. Here, the amplitude is the intensity envelope of the interferogram whereas the local slope of the phase encodes the spectral dependence of the temporal distance between the two pulses. Between the two yellow cursors the mean slope of the phase has been derived and is displayed as “Pulse Delay (fs)” inside the “Measurement” window. For reasons of presentation this slope and a phase offset at the COG (“Center Of Gravity” of the pulse spectrum) have already been subtracted from the phase yielding the red curve. Its deviation from a constant value along the wavelength axis will lead to higher orders of the chirp in the reconstruction. In the case of poor fringe visibility or high noise, inspection of this interferogram phase is most reliable for the detection of measurement artifacts. As soon as this phase shows up jumps at wavelengths with poor fringe contrast the measurement is assumed to be corrupted. There are three additional indicators inside the "Measurement" window: The one labeled as "COG" displays the center of gravity (or center wavelength in nm) of the actual spectrum in the "Measurement" window. As soon as a fundamental measurement is stored by pressing the "Save Calibration" button the indicator labeled as "COG to set" displays the center wavelength of this specific measurement divided by two. The "Bandwidth (nm)" indicator displays the FWHM of the shown spectrum.

Left hand side of the "Measurement" window: Spectrometer Settings

Smoothing:	Averages the signal over (the neighboring) 2N+1 pixels along the wavelength axis.
Average:	Averages the spectrum over N+1 exposure cycles.
Exposure:	Sliding controller to set the exposure time of the spectrometer camera manually (4 ms – 1000 ms).
Exposure:	Displays the chosen exposure time (in ms) and the actual refresh rate of the software (in Hz).
Auto Exposure:	Activation sets the exposure time automatically for optimal use of dynamic range.
Stop:	Stops the software

Right hand side of the "Measurement" window:

Motors initialized:	Indicator is green if internal motor control is initialized. Please restart the LX SPIDER software if indicator is off.
Alignment:	Activation moves a steering mirror in the beam path to reflect the double beam onto the alignment window next to the entrance aperture (For device configuration,refer to Appendix A.). Deactivate for LX SPIDER measurement!
Automatic:	Activated by default: All parameter and filter settings are done automatically. Deactivation enables manual handling of the cursors in all windows. An additional panel opens giving accessto advanced options (See chapter 5.4. Advanced Options).
Spectral Range:	Switches between calibration measurement in the fundamental spectral range (~750 nm – 900 nm; for device configuration, refer to Appendix B), measured in first order of the spectrometer grating diffraction, and SPIDER measurement taken in the second order (~375 nm – 450 nm; for device configuration, refer to Appendix D).

Both measurements are needed for retrieving the spectral phase of the pulse and for pulse reconstruction in the time.

Save Calibration: This button below the “Spectral Range” switch is activated if the switch is set to “Fundamental”.

Push the button to save the fundamental measurement displayed in the “Measurement” window to the software memory.

Two curves of the fundamental calibration measurement are important: The envelope of the fundamental interferogram can be taken as the spectral amplitude of the pulse by choosing “Replace Spectrum?”: “Yes”. (This envelope deviates significantly from the actual pulse spectrum for pulse bandwidths exceeding ~20 nm. The “Measure Spectrum” option is chosen to avoid this deviation influencing the pulse reconstruction.)

The phase of the fundamental interferogram calibrates the device, i.e. it contains the information about the temporal separation of the two fundamental replica pulses.

A flat phase (on a +/-1 radian phase scale) of the fundamental calibration interferogram over the wavelength range that exhibit spectral content is crucial. A curved calibration phase or kinks in the phase are hints for misalignment, and the pulse reconstruction is not reliable any more.

Measure Spectrum: Use this option to replace the envelope of the prior saved fundamental calibration interferogram by the pure pulse spectrum for further online analysis (advisable for precise pulse reconstruction at bandwidths exceeding 20 nm):

Activate the “Measure spectrum” function by setting a checkmark in “Measure spectrum?” box (left mouse click on the box):

This turns a diffuser in the beam path behind the quartz block (See Appendix C). Press the “Save Spectrum” button to store the pulse spectrum that is displayed in the “Measurement” window. Figure 13 shows the appearance of the LX SPIDER software in the “Measure Spectrum” mode. Again, the green curve is the raw data from the spectrometer, whereas the white curve is the smoothed spectrum due to short pass filtering in the Fourier domain.

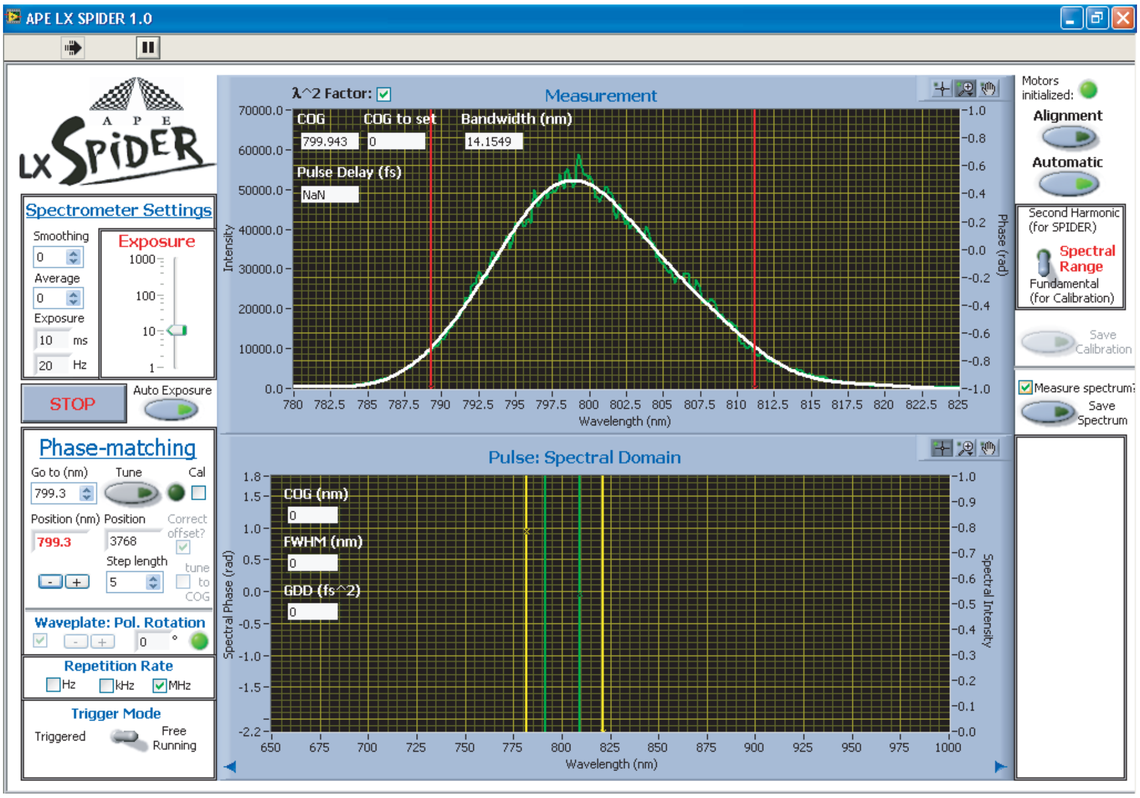


Fig. 13 LX SPIDER software in the “Measure spectrum” mode. For device configuration refer to appendix C.

5.2 The “Pulse: Spectral Domain” window

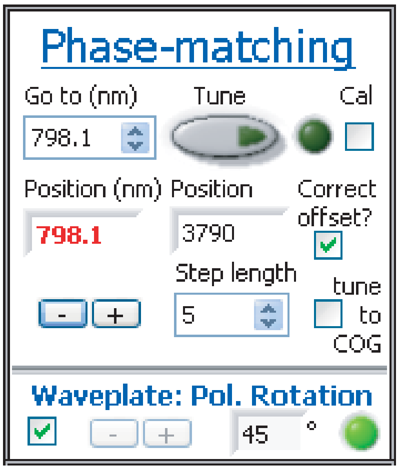
The lower graph (“Pulse: Spectral Domain”) of Fig. 12 already displays the measured pulse in its frequency representation. It comes to life as soon as a fundamental calibration trace is saved by pressing the “Save Calibration” button and the “Spectral Range” switch is turned to “Second Harmonic (for SPIDER)”.

The white curve is the pulse spectrum which is only updated if a new fundamental spectrum / calibration measurement has been saved. Two yellow cursors set the borders for (super-Gaussian) apodization of the spectrum. The reconstructed spectral phase of the pulse is shown as a red line. This curve is updated with each measured SPIDER interferogram. Two green cursors frame the range for a quadratic fit of the spectral phase. The result is plotted as a thin green line that gives an estimate of the residual linear chirp on the pulse. The respective Group-Delay-Dispersion (GDD / in fs^2) value is printed inside the window below the indicators for the Center Of Gravity (COG) of the pulse spectrum and the spectral bandwidth (FWHM / in nm) of the pulse.

Left hand side of the "Pulse: Spectral Domain" window: Phase-matching

The phase-matching panel allows the user to turn the nonlinear crystal to the phase matching angle of a certain wavelength via a stepper motor. The user can choose between three possible operator modi:

1. Insert the wavelength in the "Go to (nm)" control and press the "Tune" button. The crystal is turned directly to the calibrated position relying upon a former calibration of the initial position.
or
2. Insert the wavelength in the "Go to (nm)" control, set a checkmark in the "Cal" box and press the "Tune" button. The crystal is turned in the calibration mode to the desired position. This mode is time consuming (~ 40 sec) because the stepper motor first turns to a mechanical end stop feeler, and then counts to the desired position.
or
3. In case the COG (nm) indicator inside the "Pulse: Spectral Domain" window already shows the desired wavelength for phase-matching, setting a checkmark in the "tune to



COG" box activates the tuning to this wavelength value.

Crystal turning in the second (calibration) mode is necessary for correct positioning if the software was not stopped or closed properly or if there was a power cut during operation. It is advisable to use this second mode for an initial crystal tuning if the LX SPIDER is set up for the first time.

While moving the nonlinear crystal, the green indicator lamp next to the "Tune" button is on and all servo controls are offline until the crystal is positioned. This could take several seconds. The "Position" of the stepper motor (in step units) and the wavelength calibrated "Position (nm)" is updated once the motor stops.

For signal optimization around the correct phase-matching position use the plus / minus buttons (- / +). This turns the crystal in single steps with a given step length. The user can change this step length with the adjacent control "Step length" that is set to 5 by default (corresponds to steps of ~0.4 nm).

Correct offset?

The check mark indicates a given conversion between stepper motor position ["Position"] and the phase-matching position ["Position (nm)"]. If this calibration is off (e.g. due to an exchange of

the nonlinear crystal), i.e. the proper phase-matching position does not resemble the "COG (nm)" value, an offset correction of the stepper motor position is possible:
- Remove the check mark in the "Correct offset?" box.
- Find the proper phase-matching position by maximizing the SPIDER signal with the +/- tuning buttons.
- Insert the check mark again and save a new parameter file with the new stepper motor offset.

Waveplate Pol. Rotation: (only active if "Spectral Range" switch is set to "Second Harmonic")

This option allows software controlled manual correction for deviation of the input polarization from the horizontal. The polarization of the input laser beam is presumed to be horizontal if a parameter file containing the abbreviation "hpol" was initially chosen.

- Remove the checkmark at "Waveplate Pol. Rotation" by left mouse click on the box to activate the adjacent +/- buttons.
- Maximize the intensity of the SPIDER interferogram with the +/- buttons. Wait for the measurement signal to respond! The green indicator lamp turns to red as soon as the left or right turning limit is reached.
- Deactivate the +/- buttons by setting the checkmark again and save a new parameter file containing the new optimal orientation of the waveplate for this special measurement configuration. It can be used further instead of the delivered parameter file.

The polarization rotation indicator next to the +/- buttons displays the angle of polarization rotation introduced by the actual orientation of the waveplate. For horizontal (vertical) input polarization it should show 0° (90°) if the "Spectral Range" switch is set to "Fundamental" and 45° (135°) for "Second Harmonic".

Repetition Rate:

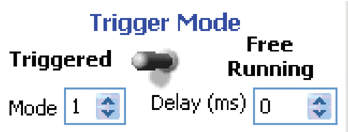
Set a checkmark in the "Hz", "kHz" or "MHz" box according to the repetition rate of the laser's pulse train. An appropriate attenuator is chosen to balance the intensity levels between the "Fundamental" and "Second Harmonic" measurement modi. Please, be careful in case of choosing the "Hz" option. No or week attenuation is introduced for a fundamental calibration measurement that could cause damage of the spectrometer's detector especially at higher repetition rates of the laser.

Trigger Mode:

Free Running (Default):	The spectrometer camera is not synchronized with the laser repetition rate. Choose this mode down to repetition rates below 1 kHz (3 to 4 laser pulses lay within the shortest exposure cycle of 4 ms).

Triggered: The spectrometer camera only starts a measurement once a TTL trigger signal is applied. Without a trigger signal the spectrometer is waiting, and the software is inactive. It is advisable to choose this measurement mode for repetition rates below 500 Hz. The exposure time of the spectrometer camera is initially set to 4 ms.

To find a signal an appropriate delay between the trigger pulse and the laser pulse has to be introduced, e.g. by a delay generator! The control “Delay (ms)” of an internal delay generator appears in the trigger mode. It allows for delay values up to 32 ms. For higher delay values an external delay generator has to be used.



The “Triggered” operation mode itself has three different modi:

Mode 1: The spectrometer camera is set to “Free Running” as long as the TTL trigger level is high, whereas the measurement and the software are frozen during TTL trigger level low. (This means for example if the TTL trigger level high period length is 12 ms and the exposure time of the spectrometer is set to 4 ms there will be 3 successive exposure cycles at each trigger pulse.)

Mode 2: Only one exposure cycle is started at each TTL trigger pulse. However, the exposure time is not software controlled but is given by the length of the TTL pulse (the duration of the TTL trigger level high signal).

Mode 3: Only one exposure cycle is started at each TTL trigger pulse with a software controlled exposure time.

Right hand side of the “Pulse: Spectral Domain” window: Time Domain

Press “Time Domain” button to open “Pulse: Time Domain” window and start pulse reconstruction in the time (See Fig. 14).

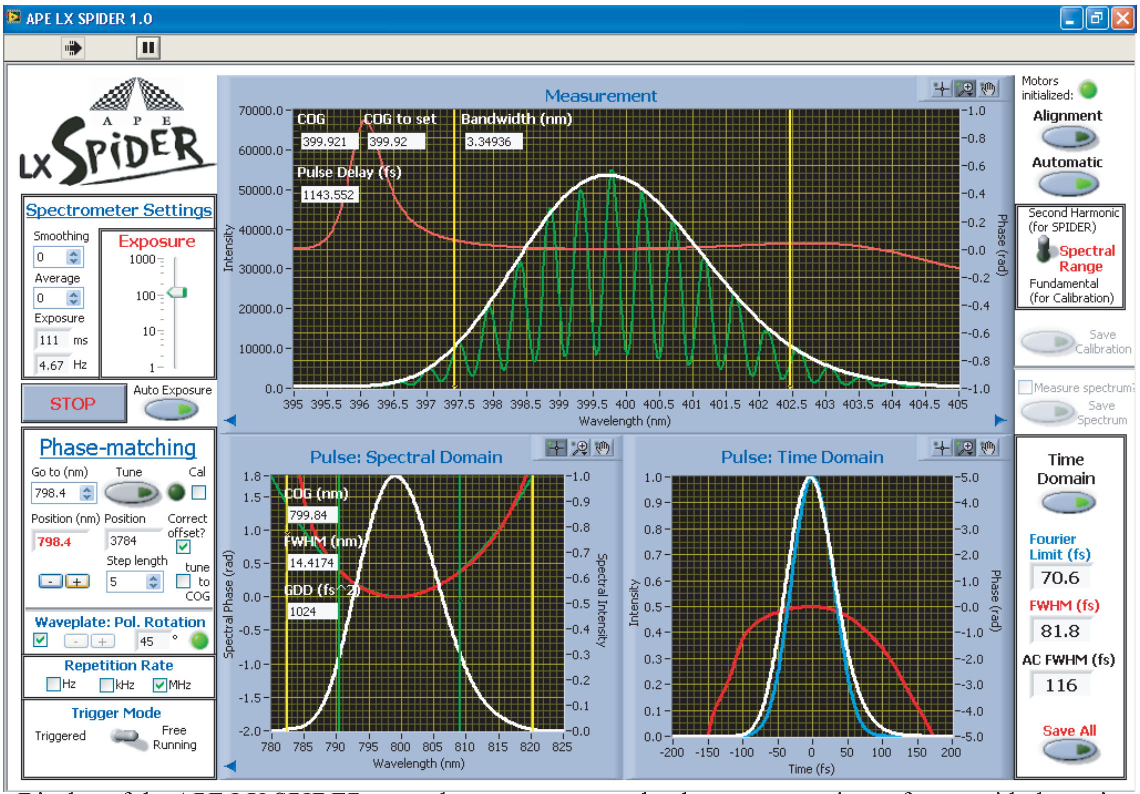


Fig. 14: Display of the APE LX SPIDER control, measurement and pulse reconstruction software with the activated “Pulse: Time Domain” window.

Figure 14 shows an additional display: the reconstructed pulse in the time domain in which negative times arrive first and positive later. In this “Pulse: Time Domain” window the blue curve indicates the shape of the Fourier limited pulse, i.e. a pulse with the given spectrum and a flat spectral phase. Its FWHM (Full Width at Half Maximum) pulse duration is depicted as the indicator “Fourier Limit (fs)” on the right hand side next to the graph. Again, the white curve is the intensity envelope of the electric field of the pulse with its FWHM duration indicated as “FWHM (fs)”. For reasons of convenience the FWHM duration of a calculated intensity autocorrelation function (not shown) can be monitored as well: “AC FWHM (fs)”. The red curve shows the temporal phase of the pulse that encodes the chirp [the time dependent center frequency $\omega(t)$] of the pulse according to: $\omega(t) = \omega_0 - d\varphi/dt$, with ω_0=center of gravity in rad/s.

Save All:

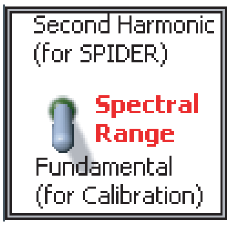
- Press this button to save the current data. Choose a name for the data and a directory. Then, five additional files are created named:
- “name_freq.txt” for the frequency domain representation of the pulse,
- “name_time.txt” for the pulse in the time domain,
- “name_calib.txt” as fundamental calibration file,
- “name_spider.txt” as SPIDER raw data,
- “name_values.txt” for the fitted or extracted values.

5.3 Measurement Procedure

After proper alignment (see chapter 4) pulse measurement is done in an instant:
(Pre-check: “Alignment” button has to be de-activated, “Automatic” button is activated)

1. Activate the “Auto Exposure” function.

2. Set the “Spectral Range” switch to “Fundamental (for Calibration)”

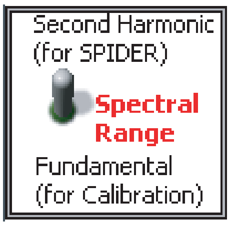


3. Push button: “Save Calibration”.
Choose “Replace spectrum”: “Yes” to take the envelope of the fundamental interferogram as the spectral amplitude (and possibly skip step 4) or click on “No” to work with a previously saved spectrum. (Pay attention that there is no saturation and all the dynamic range is used at short exposure times.)

4. Set checkmark in the “Measure spectrum” box and save the spectrum by pressing the adjacent button.

(Pay attention that there is no saturation and all the dynamic range is used at short exposure times.)

5. Set the “Spectral Range” switch to “Second Harmonic (for SPIDER)”
(Pay attention that there is no saturation and all the dynamic range is used at short exposure times.)



6. Check if both values are alike (within ~0.5 nm)

If they are not alike:
- Set a checkmark at “tune to COG” and / or optimize with [- / +] buttons.
- Contingently check optimum horizontal (H) alignment of the focusing mirror (See Fig. 10).
- Repeat steps 2 and 3.

7. Activate the “Time Domain” button.

For the online monitoring of pulse compressor alignments, deactivate the “Time Domain” button. This speeds up the software. The influence of dispersive effects on the pulse can be detected by observing the bending of the spectral phase.

Notice: The overall behavior of the spectral phase is always meaningful. However, a quantitative reliable reconstruction of the spectral phase and the temporal pulse shape is warranted only if all the features of the electric field of the pulse lie within the time window defined by the optics and the shear (See specifications).

Notice: A new calibration / spectrum measurement has to be taken, if:
- there are any changes in the beam pointing
- there were any alignments done on the LX-SPIDER (e.g. to optimize the SPIDER interferogram or crystal tuning)
- the pulse spectrum did change (e.g. due to laser tuning or nonlinear effects)

In this case repeat steps 2 through 5.

Notice: Concerning Attenuation

Do not attenuate via closing the entrance aperture (“input”)! The aperture should be kept open with a diameter of at least ~1 mm. **Exception:** In the “Measure spectrum?” mode the entrance aperture can be used for attenuation.

5.4 Advanced Options (for experienced users)

By deactivating the “Automatic” button manual adjustment of the cursors in all windows is possible. An additional panel opens giving access to advanced options (See Fig. 15).

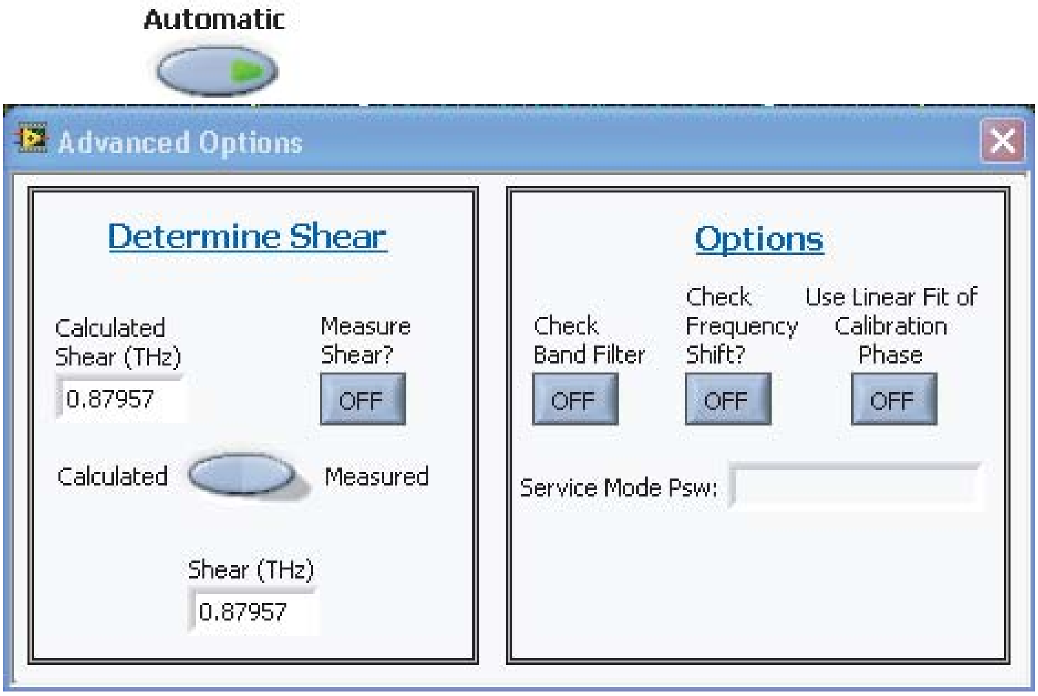


Fig. 15: Advanced Options: Window opens when software button “Automatic” is deactivated.

Determine Shear

Calculated Shear (THz)

(default setting) shows the spectral shear value between the two up-converted pulses. This value is calculated from the known, calibrated divergence angle of the two partial beams inside the nonlinear crystal and the currently measured fundamental center wavelength.

Measure Shear

- Press button: on
- Opens an additional window for shear measurement (See Fig. 16)

a)

b)

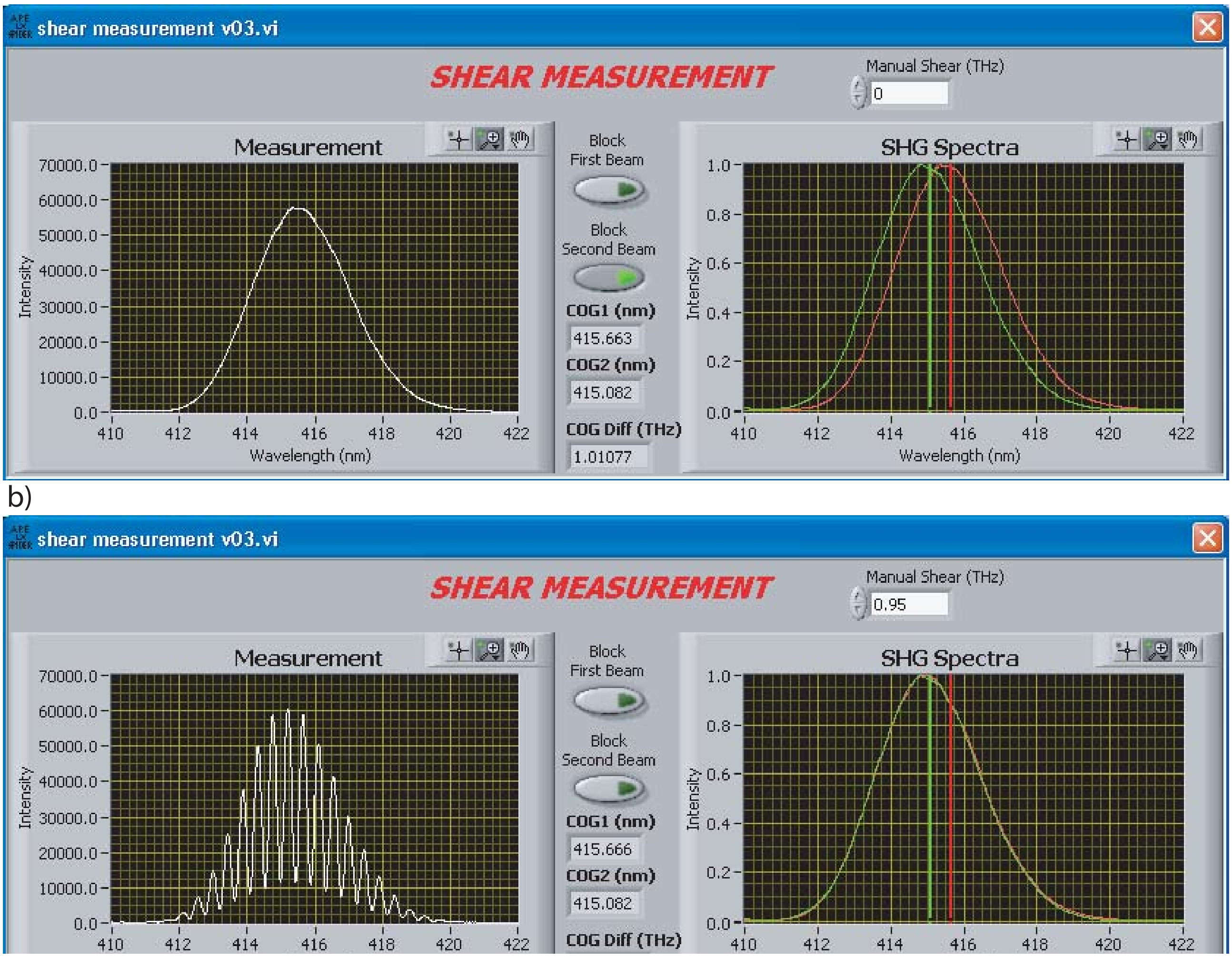


Fig. 16 Shear measurement window: a) Measurement of the two SHG spectra which refer to the two beams of the internal interferometer. b) Using the “Manual Shear (THz)” control the user can determine the shear value by shifting one spectrum to match the other. This method is more precise than the calculation of the difference of the two “Center Of Gravity” values (COG Diff = COG1 - COG2).

This option facilitates to close each of the two beams of the internal interferometer separately with the help of the shutter in front of the focusing mirror (See Fig. 3).

Block First Beam

Press button: The interferogram in the “Measurement” window changes to a pure SHG spectrum of the unblocked beam 2 which is saved and updated in the “SHG Spectra” window as a green graph. The corresponding center wavelength of the SHG spectrum shown is displayed at the indicator “COG2 (nm)”.

Block Second Beam

Press button: The interferogram in the “Measurement” window changes to a pure SHG spectrum of the unblocked beam 1 which is saved and updated in the “SHG Spectra” window as a red graph. The corresponding center wavelength of the SHG spectrum shown is displayed at the indicator “COG1 (nm)”.

The difference between the two COG values is shown as the “COG Diff (THz)” indicator and gives an estimate of the spectral shear in THz (10^{12} Hz).

For the measurement of smooth and comparable SHG spectra use the smoothing and averaging tools in the “Camera Settings” as well as the “Auto Exposure” operation.

Manual Shear (THz)

Move the SHG spectrum of the first beam (red line) in steps of 0.5 THz to match the SHG spectrum of the second beam (green line) by left mouse click on the up / down arrows of the “Manual Shear (THz)” control [See Fig. 16 b)]. (Because the shear is spectral dependent, it is the more delicate to define a certain value for a measurement the more broadband the pulse is. For pulse bandwidths below 20 nm the direct shear measurement is a precise tool to determine its value for a given center wavelength.)

Close the “SHEAR MEASUREMENT” window!

Advanced Options

Use the toggle switch of the “Determine Shear” option (See Fig. 15) to choose between the proposal displayed at “Calculated Shear (THz)” and the measured shear that was determined with the “Manual Shear (THz)” control (See Fig. 14). The actual shear that is used for the pulse reconstruction is displayed at the indicator “Shear (THz)” (See Fig. 15).

The shear measurement option is also a tool to check for proper alignment of the LX SPIDER! Both SHG spectra should show approximately the same signal height at a given exposure time. Otherwise, readjustment is necessary to get equal intensity in both beams.

Options

Check Band Filter

- Press button: on
- opens the additional window:

"Measurement: after Fourier Transformation" (See Fig. 17) in which the modulation bands and the Super-Gaussian filter functions for the amplitude and phase reconstruction of the interferogram is shown (See Ref. [5]). The filter settings can be manipulated by moving the cursors that define the filter limits. Activation of the "Automatic" option leaves this additional window active, however, the cursors are reset to default values.

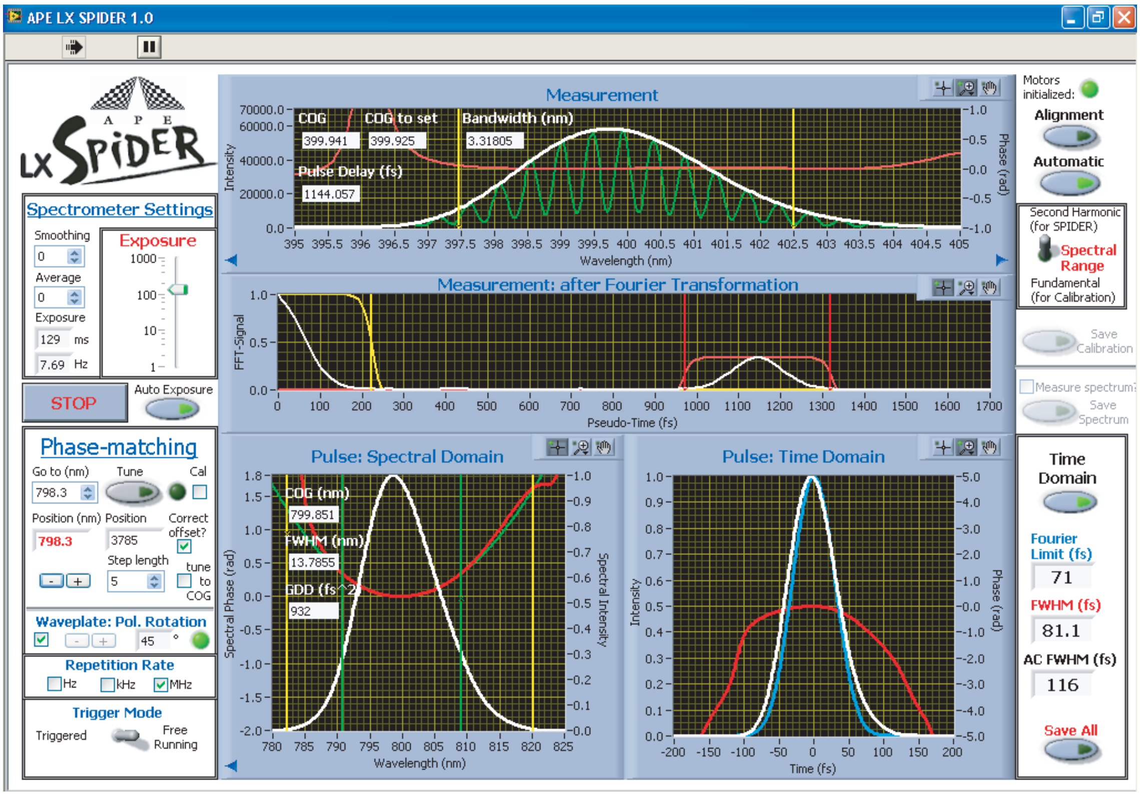


Fig. 17 Display of the LX SPIDER control, measurement and pulse reconstruction software with the additional window: "Measurement: after Fourier Transformation".

Check Frequency Shift

- Press button: on
- opens the window "Check Frequency-Shift".

The pulse reconstruction depends crucial on the correctness of the "Shift (THz)" value depicted in the lower right corner of this window. This value is calculated from the cross correlation between the SPIDER interferogram (green) and its anticipated envelope (white) that is calculated from the measured fundamental spectrum [See Fig. 18 a)].

In case the white curve does not envelope the green SPIDER interferogram the user can manually correct the shift value with the "Shift Correction" control [Compare Fig. 18 b)].

In addition, the “Check Frequency Shift” monitor allows to check whether the whole bandwidth of the pulse is up-converted.

a) b)

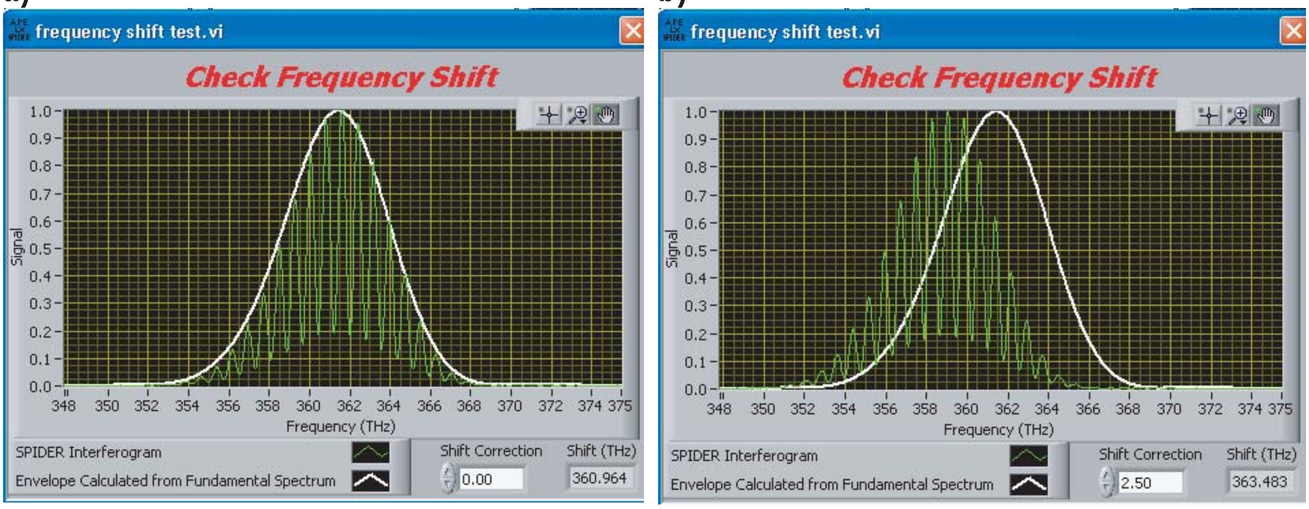


Fig. 18 Monitor for the frequency shift between the SPIDER measurement (green) in the SHG spectral region and the pulse spectrum measurement (white) in the fundamental spectral region. The SPIDER interferogram and its phase respectively have to be shifted by approximately 361 THz to match the spectral region of fundamental intensity.

Use Linear Fit of Calibration Phase

A linear fit of the measured calibration phase is used instead of the fundamental calibration measurement itself. The calibration phase (red curve in the “Measurement” window) is the phase of the interferogram taken in the fundamental spectral range. It contains the information on the temporal delay between the two fundamental pulses of the interferometer. In some cases, a distorted fundamental calibration measurement, yielding a non-constant interferogram phase introduces additional error to the pulse reconstruction. This error can be minimized when using a linear fit of this phase. The two yellow cursors in the “Measurement” window limit the fitting range and can be set manually as long as the “Automatic” option is deactivated.

5.5 Additional Features of Version 1.2

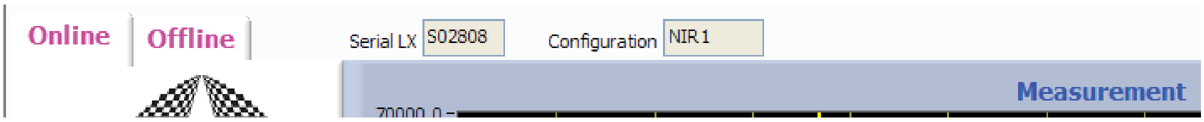
1. An offline software mode is offered to reconstruct the pulse shape from saved raw data. If the LX SPIDER device is not connected to computer the software starts automatically in the offline pulse reconstruction mode. The online software mode for pulse measurement may only be used if the LX SPIDER device is properly connected to the computer and recognized by its device manager. While running the online mode the user can switch between online measurement and offline reconstruction just by mouse click on the respective register. However, one has to keep in mind that all data that is already in the software's memory remains there until it is overwritten. That's why, when switching the register, calibration and spectrum measurement should be saved again. In the offline mode, previously saved data that was taken with the LX SPIDER software using the same parameter file has to be used. Only the fundamental raw data (marked by the abbreviation "_calib") and the second harmonic raw data (marked by the abbreviation "_spider") are needed for offline reconstruction. The latter file is chosen by default once the path to the fundamental raw data is browsed. Use only the pair of files that are saved together! Otherwise, the device might not be calibrated correctly. Concerning the visible software buttons (except the "alignment button"), the reconstruction procedure in the offline mode resemble the online measurement. In spite of loading the necessary data files, saving calibration and spectrum to the software's memory is still necessary.

2. Spectral phase fit including third and fourth order can be activated by setting a check mark in the "Higher Orders" Box inside the "Pulse: Spectral Domain" window. Keep in mind that the additional dispersion values shown (TOD and FOD) are only meaningful if the fit (green curve) follows the spectral phase.

5.6 Additional Features of Version 1.5

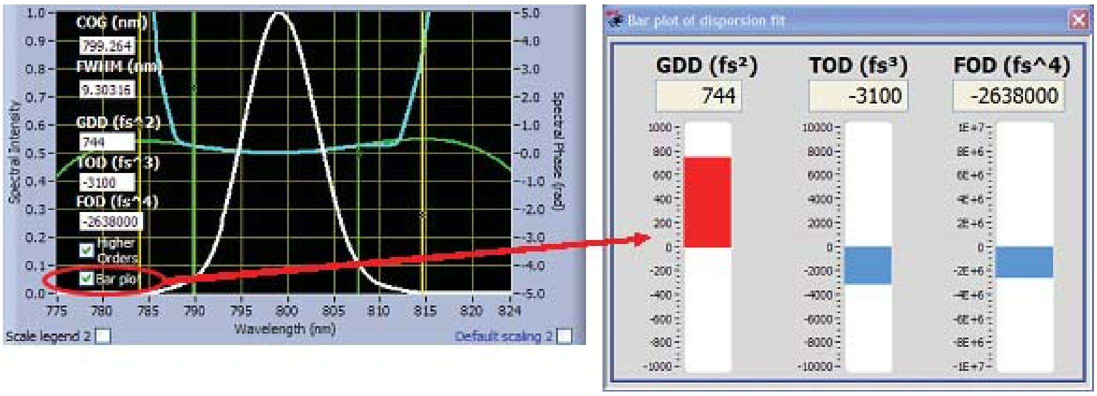
1. The former parameter file "S0****-OS* parameters hpol.txt" is replaced by a configuration file "LX SPIDER.cfg" that is loaded automatically from the same location as the "APE LX SPIDER 1.5.exe". To use a different configuration file (e.g. after a change of the optics set) the user has to copy the appropriate cfg-file into the main folder of the software (e.g. from the folder "Config files\NIR OS2" to the location of the exe-file). To avoid loosing user specific changes to the former cfg-file it is recommended to make a copy before replacing it.

After starting the LX SPIDER software, please check the configuration indicators above the "Measurement" display (they indicate the cfg-file used):

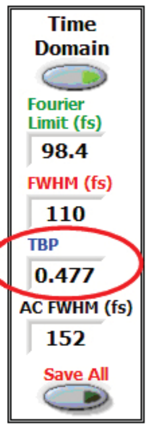


The "Serial LX" indicator should show the serial number of the connected device and the "Configuration" indicator should display a configuration that is conform to the actual optics set installed (NIR1 corresponds to OS1, NIR 2 = OS2, IR1 is infrared configuration).

2. An optional bar plot of the dispersion fit values (GDD, TOD and FOD) can be activated by setting a check mark in the "Bar plot" check box:



3. TBP (Time-Bandwidth Product) indicator is added



6. Optics Set

Two optics sets are available for the LX SPIDER that allows for pulse characterization within different spectral pulse bandwidth intervals (See chapter 3: Specifications). Every optics set consists of 3 parts: one mounted quartz crystal, one nonlinear crystal on an eccentric mount and one splitting mirror (Compare Fig. 19).

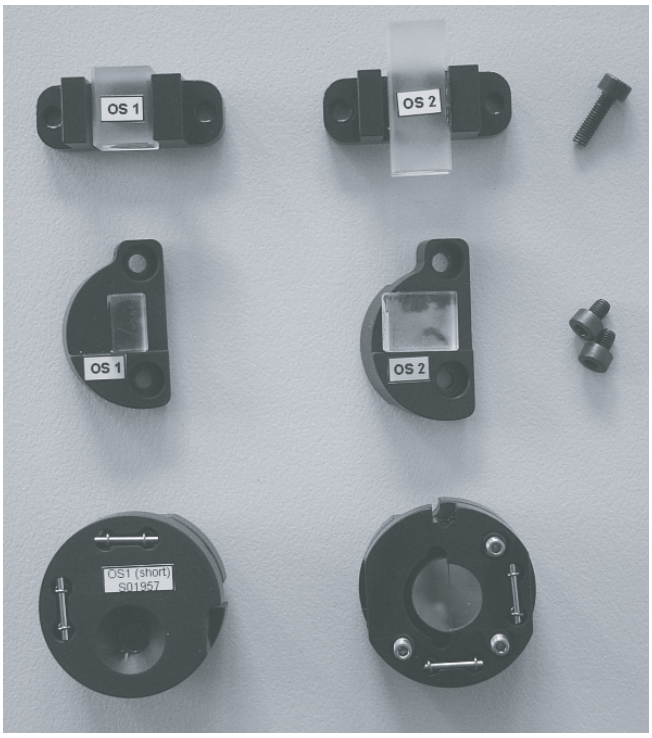


Fig. 19 The two available optics sets OS1 and OS2 for different spectral bandwidth intervals of ultrashort pulses. Left column: Optics set 1 (short), Right column: Optics set 2 (long). Top through bottom: quartz in its holder, nonlinear crystal on eccentric base, splitting mirror element (left: back side; right: front side).

The crystals' lengths determine the time window for the characterization (400 fs for the short and 800 fs for the long crystals optics set) whereas the splitting mirror defines the spectral shear (~1 THz for optics set 1 and ~0.5 THz for optics set 2). One requested optics set is already installed and completes the LX SPIDER optical unit. The second optics set is optional and adds to the contents of delivery if ordered.

6.1. Exchange of Optics Set

For a precise measurement of an ultrashort pulse with FWHM bandwidth of more than 13 nm the Optics Set 1 [OS1 (short)] should be installed. If the bandwidth is less than 13 nm it is necessary to use Optics Set 2 [OS2 (long)] because the resulting longer pulses call for a larger time window and the reduced bandwidth necessitates smaller spectral sampling steps (smaller shear values). Figure 20 shows the two possible configurations of the LX SPIDER optical unit.

a) b)

Fig. 20 Two configurations of the LX SPIDER optical unit. a) Optics set 1 installed; spectrometer in backmost position. b) Optics set 2 installed; spectrometer in front position.

The following steps describe the exchange of the optics sets along with the necessary alignment procedure (One additional 2.5 metric hex key is needed.):

1. Run the LX SPIDER device as in a measurement with an aligned laser beam.

2. Tune the nonlinear crystal to a “Phase-matching” angle for 820 nm (See section 4.4.3, step 17).

3. Align the LX SPIDER as described in section 4.4.3 to the state depicted in Fig. 8.

4. Block the laser beam.

5. Open the cover of the optical unit.

6. Deactivate the “Alignment” software button.

7. Unscrew the quartz mount and remove the mounted crystal. Do not touch or get in contact with the optical surface of the crystal!

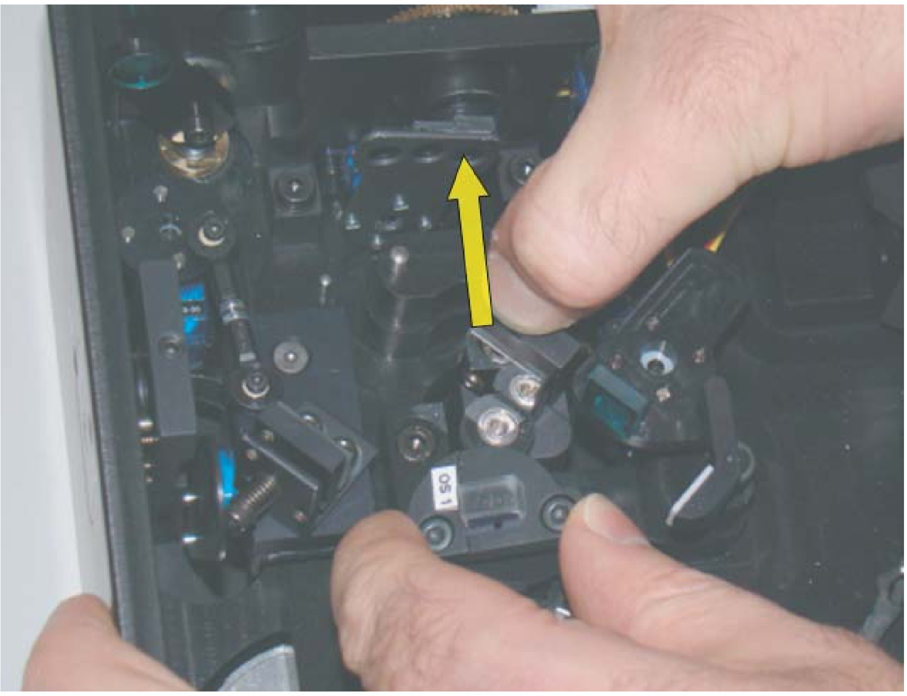


Fig. 21 Exchange of the nonlinear crystal. The quartz holder has to be detached before replacement of the eccentric base with the crystal. Retain the eccentric base with two fingers, unscrew it without turning the stepper motor gear and detach the crystal's holder while pulling the slidable turning mirror away from the eccentric base.

8. Unscrew the eccentric base of the nonlinear crystal while retaining it with two fingers. Do not touch the optical surface of the crystal. Pull the adjacent slidable turning mirror away in the direction to the input aperture and remove the eccentric base. Use the back plate of the mirror holder for pulling (See Fig. 21). Do not push on or touch the optical surface of the mirror!

9. Tighten the eccentric base of the new Optics Set with the two screws while fixing it with two fingers. Take care not turning the stepper motor gear by fastening the crystal's mount. Release the slidable turning mirror: Let the small wheel be pushed against the eccentric base.

10. Screw the quartz mount of the new optics set on its post.

11. Removing the cover plate at the back side of the LX SPIDER optical unit gives access to the alignment screws of the splitting mirror holder. The splitting mirror element is fixed in this holder.

12. Unscrew the fixing screw on top of the holder and pull the splitting mirror element through the opened back side (See Fig. 22). Mount the splitting mirror element of the new optics set. Take care that the splitting mirror is pushed through the back side into the holder till to the end stop. Do not touch the optical surface of the splitting mirror! Do not

change the three alignment screws of the splitting mirror's front side – alignment and shear calibration will be lost!

13. Unscrew the two knurled screws of the spectrometer's mount. Move the internal spectrometer to the designated position of the optics set configuration. (Compare Fig. 20; for Optics Set 1: spectrometer is farthest away from the focusing mirror. For Optics Set 2: spectrometer is in the closest position to the focusing mirror.) Fix the spectrometer again.

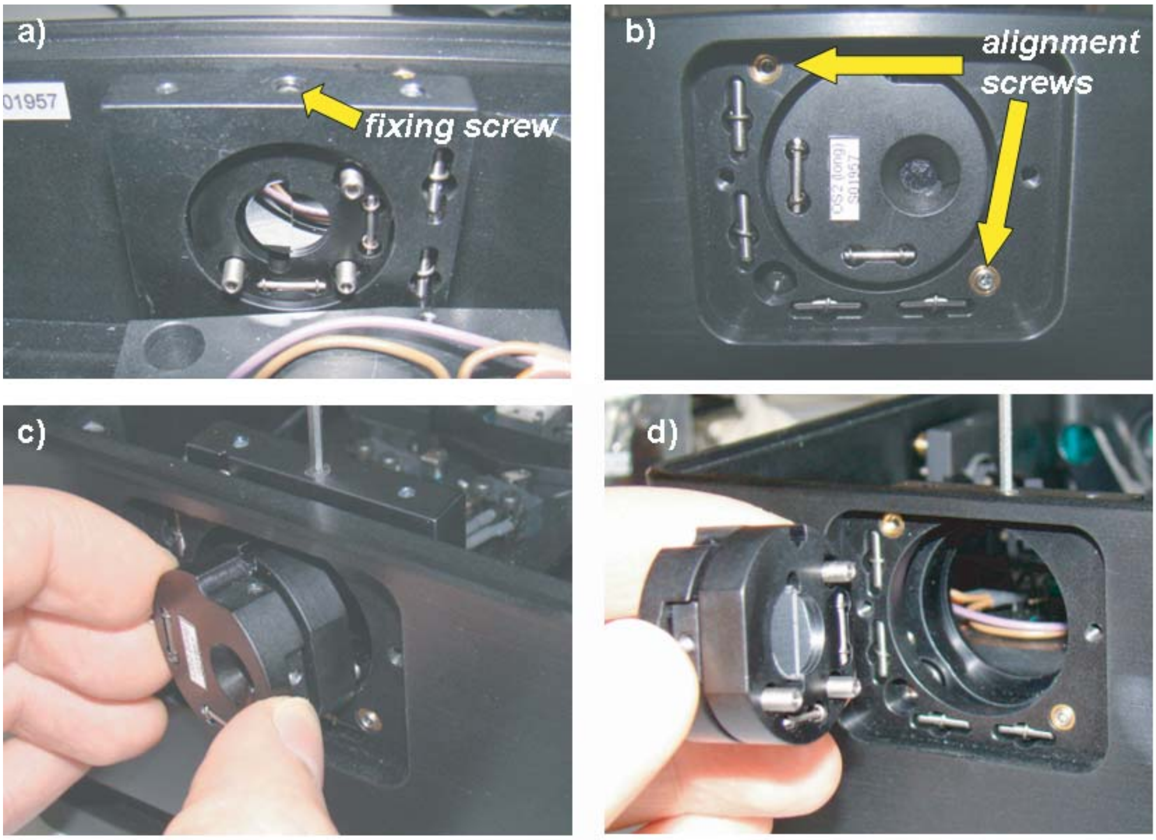


Fig. 22 Splitting mirror. a) Splitting mirror from inside the optical unit: Unscrew the fixing screw. b) Back side of the optical unit after removal of the cover plate: Two screws for alignment of the splitting mirror are exposed. c) and d) Replacement of the splitting mirror element.

14. Activate the "Alignment" software button and unblock the laser beam.

15. Use the two alignment screws in the opened back side of the LX SPIDER [Fig. 22 b)] to center the double spot on the alignment window as shown in Fig. 8. Check if the double spot is also centered on the focusing mirror after deactivation of the "Alignment" software button.

16. Maximize the signal of the fundamental interferogram by adjusting the tilt of the focusing mirror (See Fig. 10).

For further measurements a new configuration file (LX SPIDER.cfg) related to the optics set installed has to be used by the software. To allow this, please stop the software and replace the cfg file in the folder of the “APE LX SPIDER.exe” with the appropriate cfg file of the new optics set.

(E.g. for Optics Set 1 take the cfg-file of the folder “Config files\NIR1”, for OS2 take the cfg-file out of “Config files\NIR2” and for the infrared configuration IR1 take the cfg file out of “Config files\IR1”.)

17. After a restart of the LX SPIDER software the new configuration file is used by the software. To confirm this, please check the configuration indicators above the “Measurement” display (“Serial LX” and “Configuration”).

18. Continue the optimization / measurement procedure at step 14 of section 4.5.3.

19. If no SPIDER signal appears while Spectral Range switch is set to “Second Harmonic”, use the +/- software buttons in the “Phase-matching” box in combination with a big step length (e.g. 50) to find the SHG SPIDER signal at the half wavelength value of the center of gravity of the fundamental spectrum (See section 5.2. “Phase-matching”).

20. Optimize / maximize the SPIDER signal in small steps (e.g. 5) and follow the procedure described in section 5.2 “Correct offset”.

7. Theory of Operation: Principle of SPIDER

7.1. Spectral Interferometry

Spectral Interferometry (SI) is an established method to measure the phase difference between two optical paths in the frequency domain. The appropriate experiment only consists of an interferometer and a spectrometer that detects the spectral intensity of two recombined laser pulses after each one had traveled along a different path. The spectrum of such a double pulse is called a spectral interferogram because - in most cases - it exhibits a strong intensity modulation along the frequency axis. The modulation period of length $\Delta\omega_i$ at a certain frequency ω_i of the spectrum encodes the temporal separation $\tau_i=2\pi/\Delta\omega_i$ between the two pulses at this frequency. If one of the two pulses has been additionally chirped due to a dispersive element in its beam path the spectral interferogram deviates from even periodicity. Now, the change in the period length of the modulation along the frequency axis reveals the spectral dependence of the temporal distance between the "test" pulse and the "reference" pulse: $\tau = \tau(\omega)$. This function arises from the actual measured difference in the spectral group delay (GD) of the two pulses:

$$2\pi/\Delta\omega(\omega)=GD_{pulse1}(\omega)-GD_{pulse2}(\omega)$$

with

$$GD(\omega)= d\varphi/d\omega,$$

with $\varphi(\omega)$ as the spectral phase of the pulse. Integration gives the information about the phase difference between the two beam paths, i.e. the phase added by the additional dispersive element in one interferometer arm. However, the information about the actual spectral characteristic of the group delay of the pulse is lost.

7.2. Spectral shearing interferometry

In 1998 C. Iaconis and I. A. Walmsley introduced "Spectral Phase Interferometry for Direct Electric-field Reconstruction" as a modification of SI [2]. Because they where not interested in the phase difference of two primarily identical pulses but in the phase of a pulse itself they had to use an additional trick. Frequency shifting two identical copies of the input pulse by a small amount Ω (about 10% of the pulse's bandwidth) with respect to each other and analyzing their spectral interferogram gives direct access to the group delay $GD(\omega)$ of the input pulse (See Fig. 23).

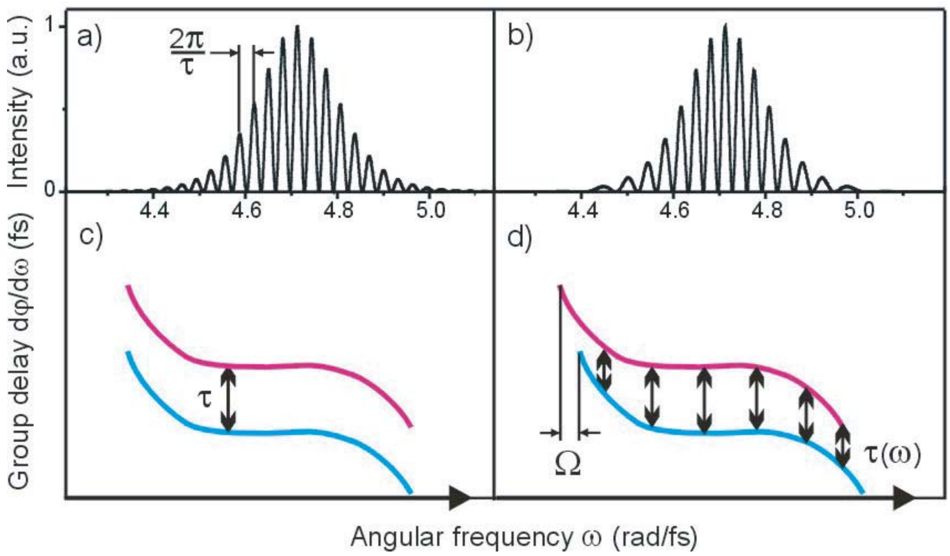


Fig. 23 Principle of spectral shearing interferometry;
a) Delaying two identical replica pulses with respect to each other results in equidistant fringe spacing in their interferogram.
b) Applying a spectral shear between the pulses causes a deviation from the calibration fringe spacing shown in a).
c) Without a shear the temporal separation of the group fronts remains constant along the frequency axis.
d) A spectral shear Ω yields a change or even a spectral dependence of the temporal separation of the group fronts that can be directly retrieved from the spectral interferogram.
This information encodes the change of the spectral pulse phase in steps Ω along the frequency axis.

Full information on the spectral behavior of the group delay is sufficient to reconstruct the spectral phase of the pulse except for a constant offset (the carrier-envelope offset phase). Together with a measured spectrum of the pulse one is able to calculate its electric field in the time domain just by means of Fourier transformation.

The different types of SPIDER mainly vary in the method how the frequency shear Ω is generated. Especially, in case of characterization of ultrashort pulses each of the two replica pulses is up-converted with a different monochromatic frequency component. The traditional way of doing this is to split the incoming pulse in three replica pulses. Whereas two are delayed with respect to each other in some sort of interferometer (Michelson or an etalon) the third one is strongly chirped and stretched. Recombining all three pulses in a thin nonlinear crystal is followed by Sum Frequency Generation (SFG) of the whole spectrum of the two replica pulses with the respective frequency component of the stretched pulse that lies in the time window of the replica. In this way, both pulses are frequency shifted to the second harmonic frequency range by a slightly different amount resulting in the necessary frequency shear (See Fig.24).

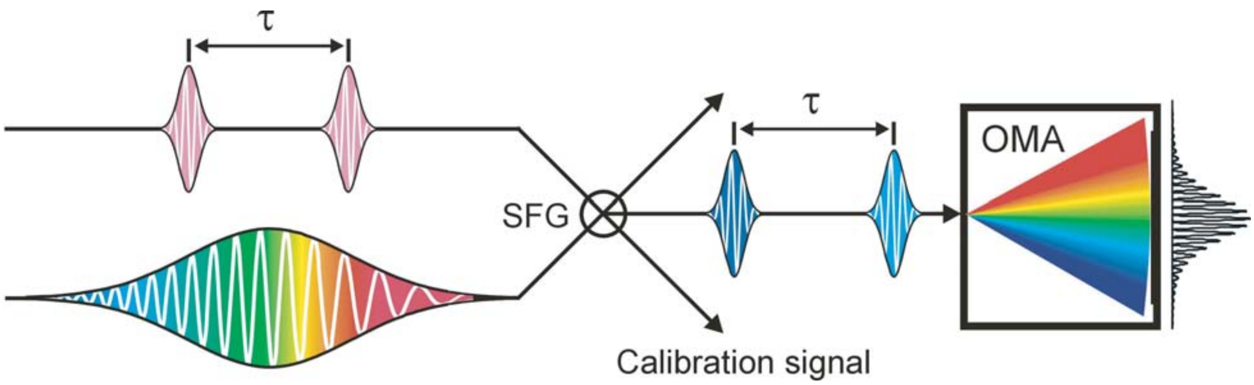


Fig. 24 Schematic setup of traditional SPIDER;
Two identical replica pulses of the input pulse are separated in time by a constant delay τ and spatially / temporally overlapped with a third strongly chirped pulse inside a thin nonlinear crystal. Sum-Frequency Generation (SFG) of the whole spectrum of each pulse replica with different quasi-monochromatic components of the chirped pulse translates the delay τ into a spectral shear Ω between the two up-converted replica pulses. The spectrometer (OMA: Optical Multi-channel Analyzer) signal of these two replica pulses manifests as a spectral interferogram that is spectrally analyzed. The calibration signal gives an interferogram of the two replica pulses without shear. It enables the determination of the delay τ.

7.3. Spectral shearing with a long crystal

A smart and more compact way to generate a spectral shear relies on a specific type-II phase-matching inside a long nonlinear crystal where the pulse interacts with itself [1, 4]. This renders the separation and chirping of a third up-converter pulse unnecessary.

The general idea behind the LX-SPIDER scheme is the fact that the combination of a specific crystal material and a certain wavelength range produces a phase-matching function that has a very broadband acceptance for signals polarized along the ordinary (o) axis of the crystal and is very narrow along the extraordinary (e) axis (See Fig. 25). Therefore, sending two cross polarized pulses collinearly under a certain phase-matching angle θ through such a crystal is followed by the up-conversion of the whole spectrum of the o-polarized pulse with only a spectral slice of the e-polarized pulse. Here, the angle θ defines the frequency selection in the e-plane.

Two of those beams - each traveling under a different angle through the crystal - result in two up-converted but spectrally sheared pulses. By introducing a convenient time delay between these pulses and overlapping them on the entrance slit of a spectrometer a SPIDER interferogram is measurable (See Fig. 26).

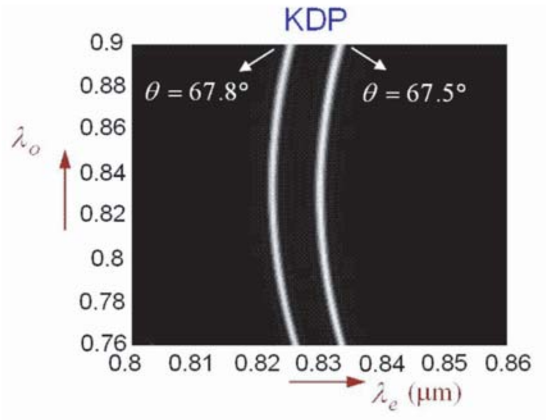


Fig. 25 Phase-matching function of KDP around λ=830nm for two different angles θ of propagation through the crystal.

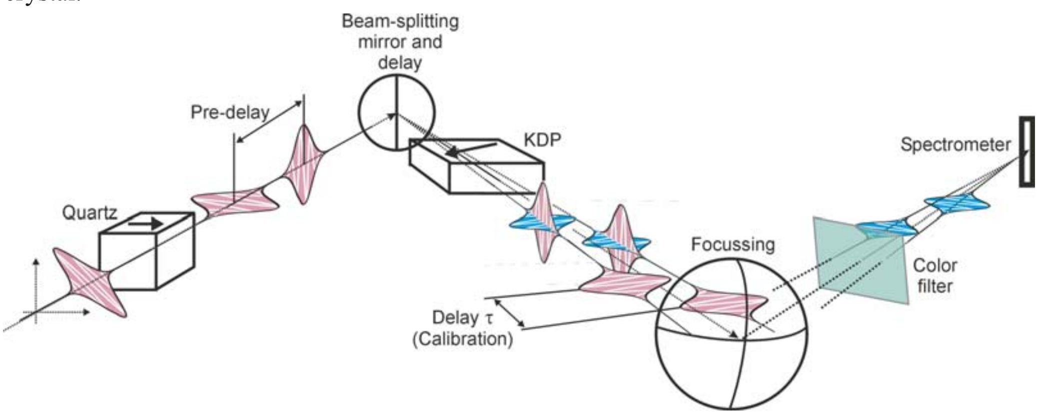


Fig. 26 Schematic setup of the LX-SPIDER; The spectral shear between the two up-converted (blue) pulses is caused by the different propagation angles of the two beams inside the KDP-crystal.

7.4. Long crystal corrections

The prerequisite for an appropriate nonlinear crystal is that the group velocities of the fundamental o-polarized pulse and the up-converted e-polarized pulse are the same. Within the Ti:Sapphire wavelength range this condition is fulfilled for KDP at λ_0~830 nm.

However, inside such a nonlinear crystal type II (oee) Sum-Frequency Generation only takes place if the o-polarized and the e-polarized fundamental pulses coincide. Because in KDP the e-polarized fundamental pulse travels faster than the o-polarized one by an amount of +145 fs/mm, the e-pulse has to be pre-delayed with the help of a prefixed birefringent crystal of opposite sign. In case of crystal quartz the group velocity mismatch of -32 fs/mm between both fundamental pulses call for a crystal length of factor 2.3 of the KDP length to ensure that both pulses coincide in the middle of the KDP crystal. Also, the KDP-crystal should be long enough to allow the e-polarized pulse to completely overtake the o-polarized one.

For phase reconstruction, several effects introduced by these two long crystals have to be taken into account:

- Influence of the quartz crystal: Group-Delay Dispersion
- Influence of the KDP-crystal:

1. effective Group-Delay Dispersion of the fundamental pulse,
2. change in the temporal separation between the two pulses when going from fundamental double pulse to the spectrally sheared second harmonic double pulse,
3. change in the shape of the phase-matching function when detuning away from the ideal wavelength of 830 nm.

The APE LX-SPIDER software corrects for all these influences as suggested and numerically verified in reference [6] (See Fig. 27).

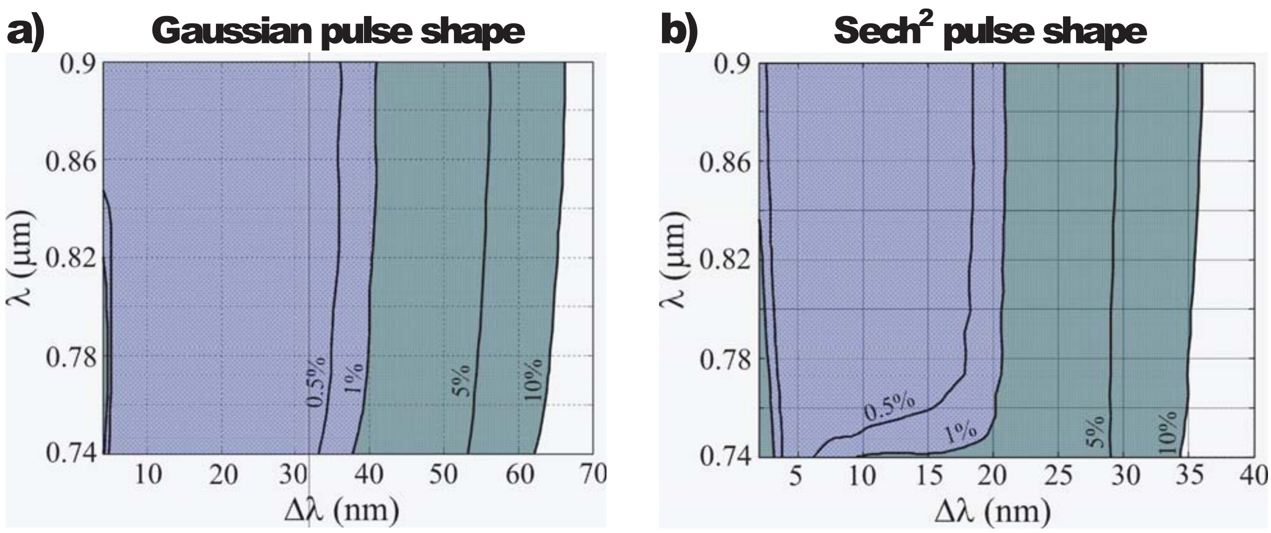
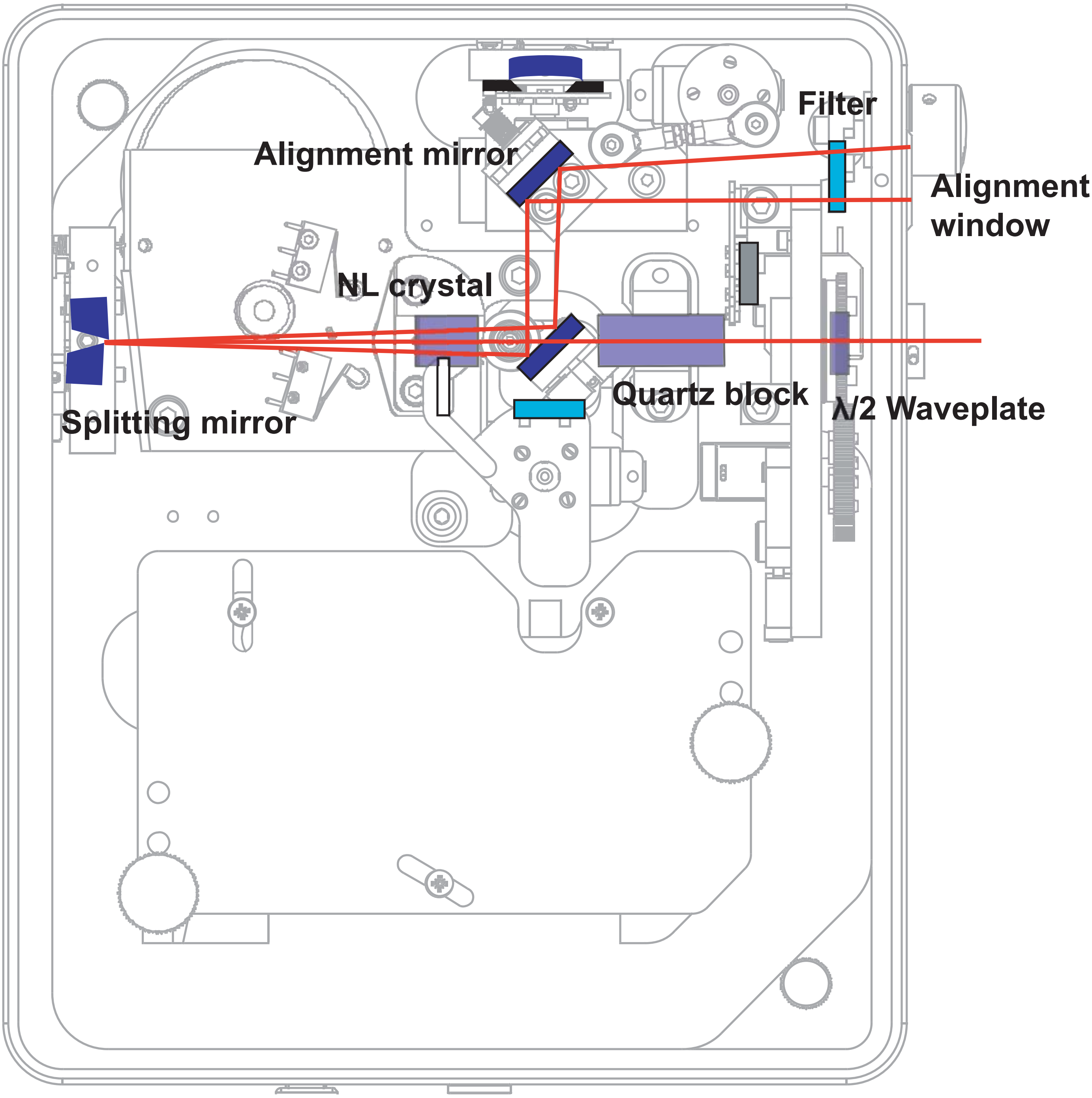
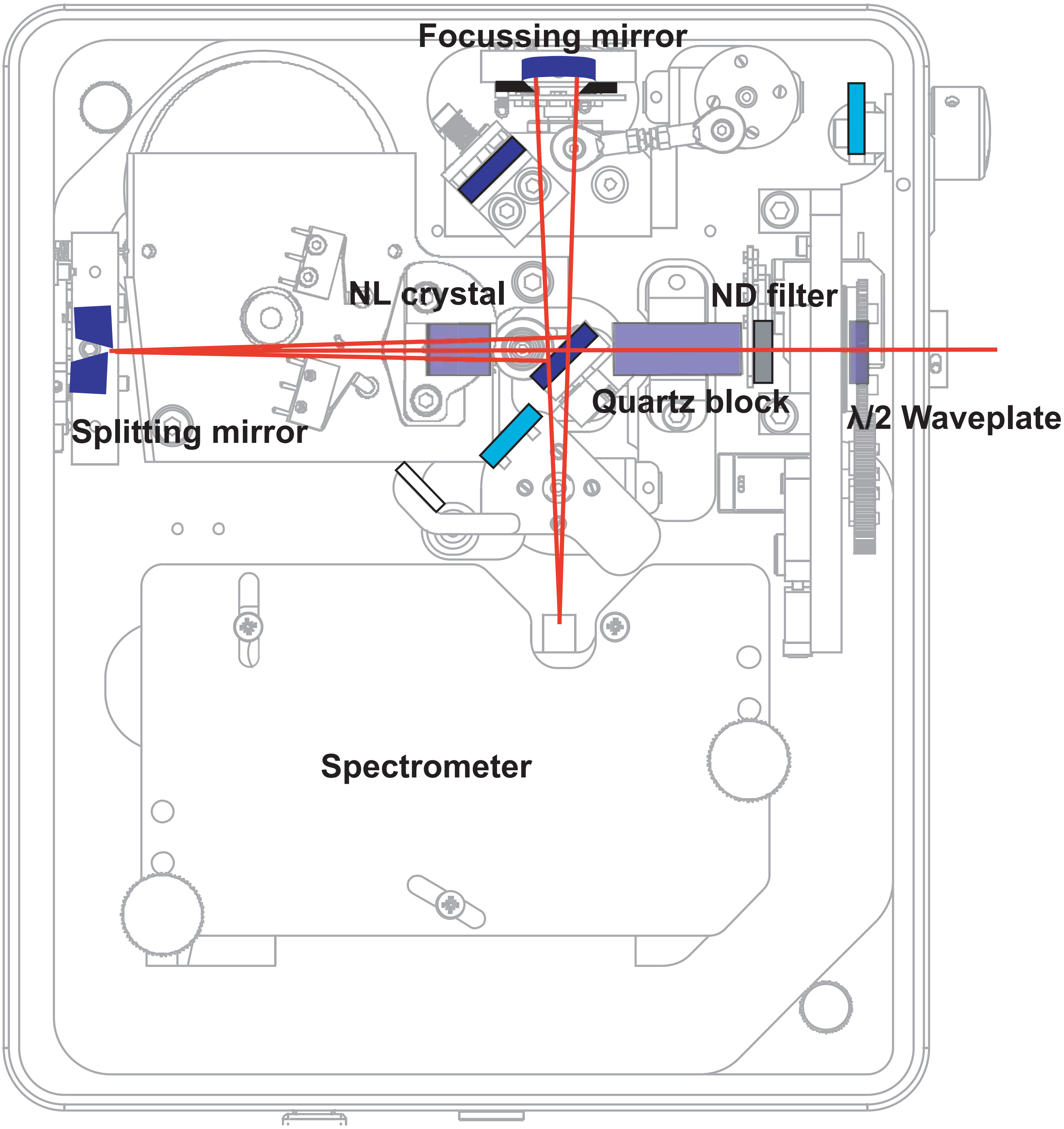


Fig. 27 Influence of the residual phase difference between a simulated LX-SPIDER measurement after phase correction and the input pulse on the temporal intensity envelope for a Gaussian shaped pulse. The contour lines mark constant relative errors in the FWHM value of the reconstructed pulse along the pulse parameters: λ=center wavelength, $\Delta\lambda$=bandwidth. A KDP crystal of 5mm length was used for the calculation.

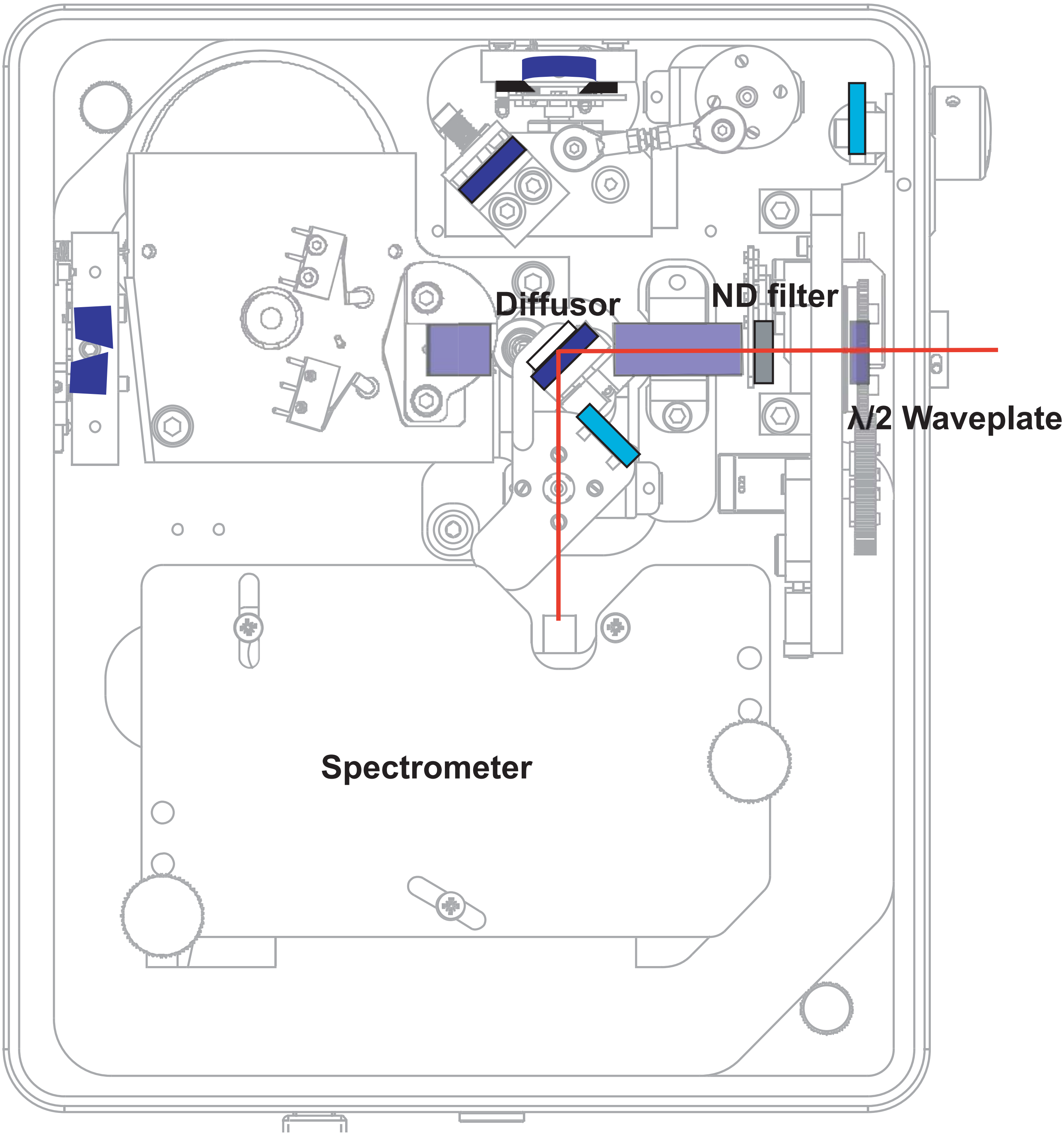
Appendix A: First Step - Alignment



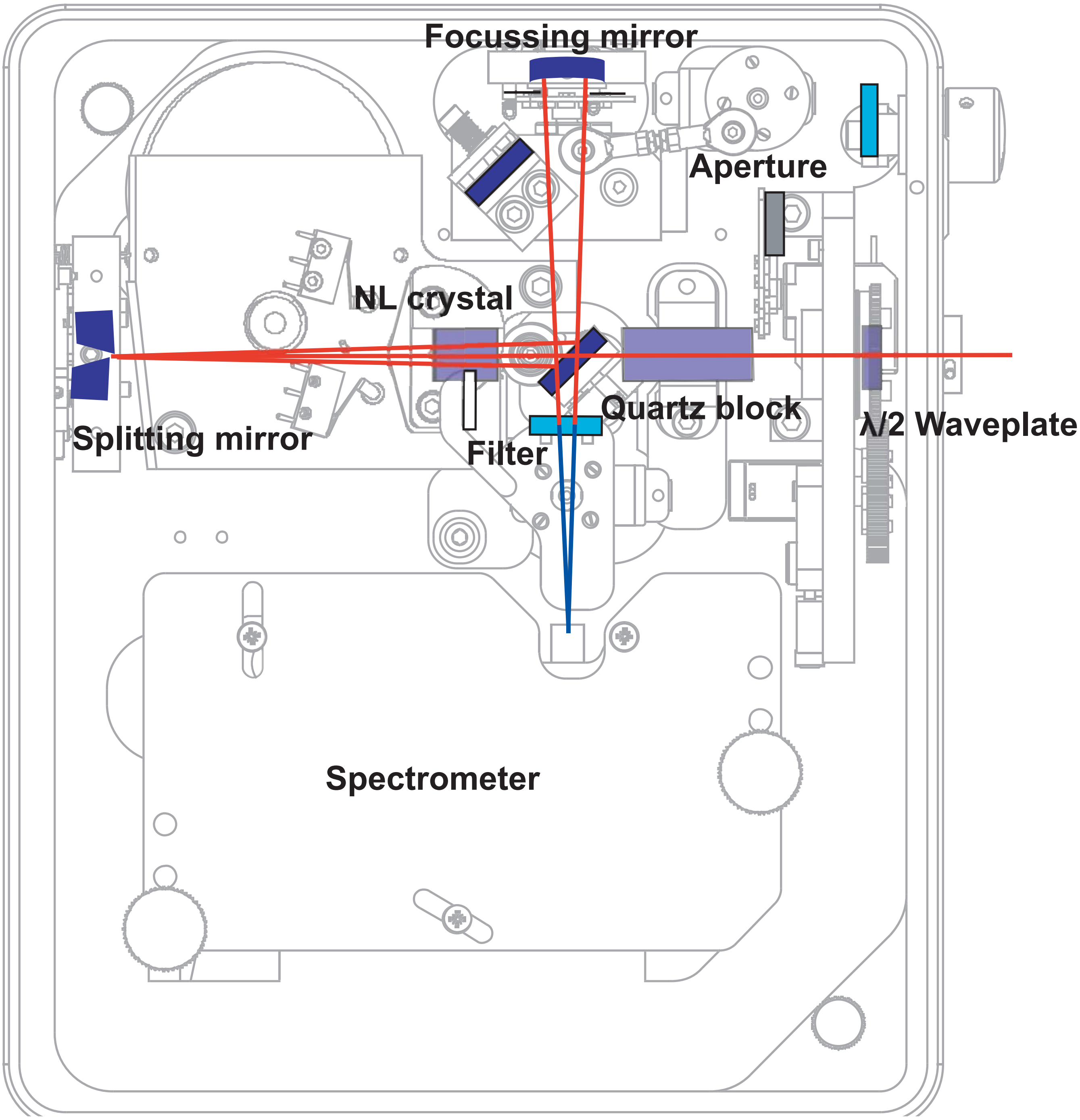
Appendix B: Second Step - Calibration



Appendix C: Third Step - Measurement of Fundamental Spectrum



Appendix D: Fourth Step - SPIDER Measurement



Appendix E: CLEO/QUELS 2008: CThK3, Thursday, May, 2008

Fully Automated, Phase Corrected Long Crystal SPIDER for the Characterization of Broadband Pulses

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Abstract: We present an optimized and automated implementation of the compact Long-Crystal-SPIDER design. The integrated phase-corrections allow for precise pulse reconstruction up to bandwidths of 17 THz and linear chirp detection at bandwidths exceeding 40 THz.

OCIS codes: (320.7100) Ultrafast measurements; (320.7160) Ultrafast technology; (190.4360) Nonlinear optics, devices

The widespread use of Ti:Sapphire laser systems to steadily generate ultrashort pulses with durations below 100 fs calls for realtime pulse measurement schemes that are reliable and easy to handle. Monitoring the proper operation of the laser, control of pulse compression and dispersive influence on the pulse shape are crucial for most ultrashort experiments. Beside other techniques that allow for complete reconstruction of ultrashort laser pulses, spectral phase interferometry for direct electric-field reconstruction (SPIDER) rapidly delivers the spectral phase of the pulse under test without any prior assumptions [1]. For this, a spectral interferogram of two identical replicas of the input pulse which exhibit a temporal delay and a small spectral shift with respect to each other is measured. To generate this spectral shear in the most compact way type-II phase-matching inside a long nonlinear crystal (LX) was proposed [2]. The combination of a specific crystal material and a certain wavelength range results in a phase-matching function that has a very broadband acceptance for signals polarized along the ordinary (o) axis of the crystal and is very narrow along the extraordinary (e) axis [See inset of fig. 1a)]. By the propagation of two beams of crossed polarized pulses under different angles through such a crystal the two required up-converted and spectrally sheared pulses are generated [fig. 1a)]. However, due to the amount of dispersive material and the curvature of the phase-matching function, additional phase corrections are necessary.

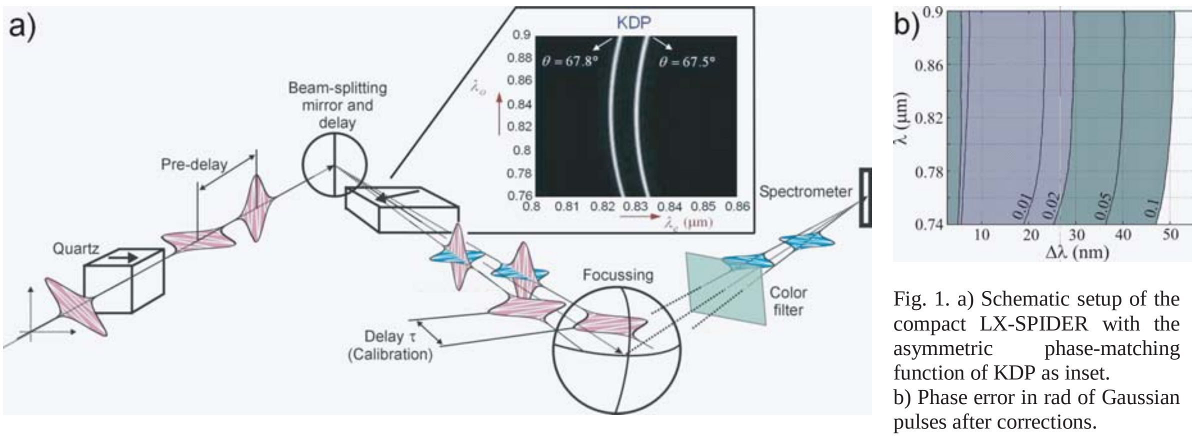

Fig. 1. a) Schematic setup of the compact LX-SPIDER with the asymmetric phase-matching function of KDP as inset.
b) Phase error in rad of Gaussian pulses after corrections.

In this work we present the implementation of the introduced LX-SPIDER scheme as an automated measurement device with software integrated phase corrections. Because phase-matching and precise phase reconstruction can be achieved by wavelength and shear calibration with respect to the crystal angle θ, these parameters are set automatically only by knowledge of the center wavelength of the laser. Also, taking a calibration measurement to determine the pulse delay τ is implemented by fast and automatic polarization rotation combined with switching of filters.

The analytic phase corrections are based on the following assumptions. Within the wavelength range shown in the inset of fig. 1a) the LX-SPIDER interferogram can be approximated by

$$S(\omega)=|E_1(\omega)|^2+|E_2(\omega-\Omega)|^2+2|E_1(\omega)||E_2(\omega-\Omega)|\times\cos\left[\varphi\left(\frac{\omega}{s}\right)-\varphi\left(\frac{\omega-\Omega}{s}\right)+\delta\varphi(\omega)+\omega\tau\right], \quad (1)$$

where Ω is the directly measurable spectral shear [3]. The frequency scaling factor s corrects for the tilt of the phase-matching function while $\delta\varphi(\omega)$ includes the effective dispersion of the nonlinear crystal and a change in the temporal separation of the two up-converted pulses inside the crystal. A calibration measurement for the delay τ in the fundamental spectral region of the pulse delivers the contribution $\omega\tau$ plus an additional phase term due to the different propagation angles inside the crystal. In the integration method for phase reconstruction additional dispersion as well as corrections of the temporal delay between the pulses can be merged into a single correction term for phase curvature $\varphi_{corr} \sim a_{corr}\omega^2$ with a_{corr} only depending on crystal parameters. The validity and limits of such an analytic approach to correct the measured spectral phase are tested by numerical simulations of the up-conversion process in presence of dispersion. Figure 1b) shows the amplitude weighted phase deviation between the initial Gaussian pulse and the reconstructed pulse from a simulated LX-SPIDER measurement with a 5mm long KDP crystal after phase correction. The influence of this phase error on the FWHM pulse duration strongly depends on the pulse shape. While for a Gaussian pulse the relative deviation in pulse duration is below 1% near a Fourier-limit of 25fs, the error is already at 5% in case of a *sech*^{2}-pulse. Thus, to demonstrate the reliability of the LX-SPIDER phase reconstruction procedure, comparing measurements with a second independent characterization method are necessary. Therefore, test pulses with different bandwidths were characterized with LX-SPIDER and conventional SPIDER (APE GmbH).

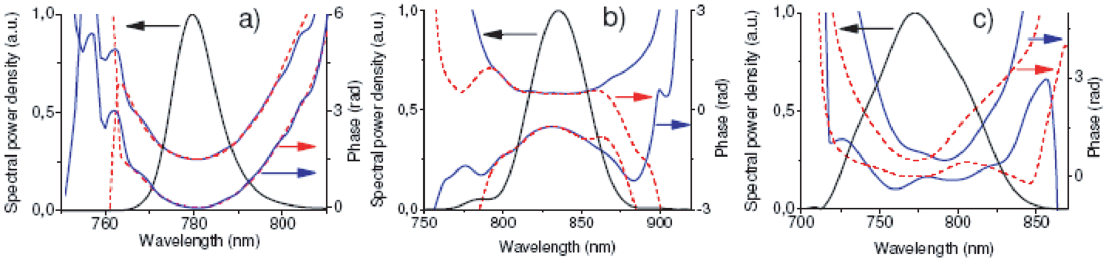

Fig.2. Comparing phase measurements with LX SPIDER (dotted) and conventional SPIDER (solid) for three different bandwidths [a) 13nm, b) 45nm, c) 85nm] with (upper curves) and without (lower curves) additional dispersion of 5mm BK7.

To check for quantitative dispersion detection, additional amount of 5mm BK7 was introduced (upper phase curves in fig. 2). The spectral amplitude weighted phase difference of the representative examples of Figure 2 were determined to $\varepsilon_\varphi < 0.1$rad for bandwidths $\Delta\nu < 8$THz [fig. 2a)] and $\varepsilon_\varphi < 0.3$rad for $\Delta\nu < 20$THz [fig. 2b)]. In both cases the additional group-delay dispersion of 210fs^2 was reproduced within a deviation of 5%. Because experimental errors from both characterization methods contribute to the phase difference there is a mean factor of 5 between the experimental and theoretical phase deviation. Nevertheless, values up to $\varepsilon_\varphi \sim 0.5$rad are common in comparing pulse characterization measurements. One characteristic of the LX-SPIDER scheme is the broadband up-conversion inside the long nonlinear crystal. Therefore, limits for proper characterization of broadband pulses are only set by raising error bars of the phase correction. Figure 2c) demonstrates the applicability of this method to pulse compression experiments even for pulse spectra spanning more than 70THz.

In conclusion, an optimized and automated long crystal SPIDER device for the characterization of ultrashort Ti:Sapphire laser pulses is presented. Due to an analytical and numerically verified phase correction procedure, the limits for precise phase reconstruction are pushed to bandwidths of more than 40nm. Future inclusion of higher order phase correction terms is expected to expand the applicability of this compact SPIDER scheme to pulses with even broader bandwidths.

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