Development of a Dispersion Scan Device for the Characterization of Femtosecond Laser Pulses

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Abstract

This work represents the study and implementation of dispersion scan technique, used to characterize temporal properties of ultrafast laser pulses. The optical setup was based on the original dispersion scan paper [1]. Retrieval of pulse properties was performed using differential evolution algorithm [2]. Moreover, a user interface was created for the control of retrieval algorithm and optical setup. The device was tested on STARLIGHT laser system located in DESY, Hamburg and maintained by attosecond science group. The retrieval results were found to be within an appropriate range of values. Performance of the device was discussed and key changes for further development were suggested.

Contents

1 Introduction

Influenced by technological breakthroughs in the field of arbitrary pulse shaping few-cycle femtosecond pulses and complex shaped pulses can be synthesized in various spectral regions. Such pulses are widely used in biological imaging [3], optical communications [4] and coherent control [5]. With some pulses reaching attosecond time scales it becomes crucial to be able to determine pulse properties as accurately as possible.
All the information concerning an ultrashort pulse is contained in its electric field or equivalently in both its spectral phase and spectral amplitude. However, for a femtosecond pulse a direct measurement of the electric field is not possible due to a requirement of a detector with a time response shorter than the optical cycle of the pulse to characterize. The fastest detectors typically have a time response of around hundreds of femtoseconds [6]. Thus, ultrashort pulse characterization uses indirect methods to access spectral phase and amplitude.
One technique of such indirect methods is the use of a reference pulse whose spectral phase and amplitude are perfectly known. However, the reference pulse and the test pulse need to have similar spectral properties, such as central frequency and bandwidth. This leads to the same initial problem of inability to characterise ultrashort pulses. The solution to this issue is to use the test pulse as a reference for its own measurement [7]. This technique does not require any prior knowledge to achieve the reconstruction of the test pulse. Nonetheless, self-referenced characterisation involves complex experimental setup consisting of nonlinear and non-stationary optics. Examples of most widely used self-referenced characterisation systems are FROG [8], SPIDER [9] and DSCAN [1]. This report focuses on DSCAN technique and its performance compared to other systems.

2 Theory

An ultrashort laser pulse can be described by its complex spectral amplitude $\tilde{E}$ as:

$$E(\omega) = |\tilde{E}(\omega)|e^{i\phi(\omega)} \tag{1}$$

where ϕ is spectral phase and ω is angular frequency. If a pulse passes through a piece of transparent glass and then a SHG crystal, the measured SHG spectral power S can be expressed as:

$$S(\omega, z) = |\int(\int Ee^{izk(\omega)}e^{i\omega t}d\omega)^2e^{-i\omega t}dt|^2 \tag{2}$$

where z is the thickness of the glass and k is the wavenumber. In equation 2 phase is applied to the original spectrum and a Fourier transform is applied to obtain the electric field in the time domain. Second harmonic generation is approximated by taking a square of the electric field and the spectrum is obtained by an inverse Fourier transform. This assumes an instantaneous and wavelength-independent nonlinearity. A dispersion scan is obtained by introducing different thicknesses of glass and measuring the SHG spectra. Such a scan provides a two-dimensional trace, where the phase function is simply the one introduced by a piece of glass. The introduced phase can be calculated by knowing the material of the glass and using corresponding Sellmeier equation. The glass wedges used in this experimental setup consisted of fused silica whose Sellmeier equation is as follows:

$$n^2 = 1 + \frac{0.6961663\lambda^2}{\lambda^2 - 0.0684043^2} + \frac{0.4079426\lambda^2}{\lambda^2 - 0.1162414^2} + \frac{0.8974794\lambda^2}{\lambda^2 - 9.896161^2} \tag{3}$$

Using the whole trace's information and a numerical iterative algorithm the spectral phase can be found in a robust and precise way.

2.1 Retrieval Algorithm

The method used to retrieve the phase was based on a differential evolution (DE) algorithm [2]. DE does not use the gradient of the problem being optimized, thus it makes few or no assumptions and can search very large spaces of candidate solutions. However, such a matheuristic approach does not guarantee an optimal solution is ever found and is prone to divergences into local minimas. The working principle of a DE algorithm starts with creating a population of candidate solutions. This population is moved around in search-space by combining the positions of existing solutions from the population. There are many simple mathematical formulae for the combination, however this project uses rand/1/bin variant due to the best results presented in the paper reviewing the retrieval techniques [10].

The DE algorithm can be described by using two parameters: population size N and crossover probability CP. The algorithm can be separated into distinct steps:

- An appropriate value for N is selected and the population is initialised with random positions.
- For each member of the population mutation is carried out with three randomly selected members of the remaining population, which are arranged by decreasing fitness. Mathematically a mutant is expressed as:

$$\phi_m = \phi_1 + rand(1)(\phi_2 - \phi_3). \tag{4}$$

- The mutant then undergoes a crossover process with a primary parent and an offspring is generated according to the following rule:

$$\phi_o = \begin{cases} \phi_m, & rand(1) \le CP \\ \phi_p, & else \end{cases} \tag{5}$$

- The process of mutation and crossover is repeated for each member and then the fitness of all offsprings is evaluated by an error function.
- The parents and offsprings are combined and sorted by fitness, and those whose ranks are beyond the population size N are discarded.

- The whole process is repeated for a given number of iterations or until a convergence criterion is met.

For dispersion scan technique, the mentioned error function is given as:

$$G = \sqrt{\frac{1}{N_i N_j}\sum_{i,j}(S_{meas}(\omega_i, z_j) - \mu_i S_{sim}(\omega_i, z_j))^2} \tag{6}$$

where S_{sim} and S_{meas} correspond to simulated and measured dispersion scan traces respectively. N_i indicates the number of frequencies in the trace whereas N_j is the total number of traces. μ accounts for the spectrometer response and the SHG conversion efficiency. It is calculated and updated every iteration using:

$$\mu_i = \frac{\sum_j S_{meas}(\omega_i, z_j) S_{sim}(\omega_i, z_j)}{\sum_j S_{sim}(\omega_i, z_j)^2} \tag{7}$$

By using this error function, the algorithm works on matching the trace's features instead of simply matching the trace as a whole. Remarkably, this approach allows the identification of phase for a certain frequency even if there is no signal at the corresponding SHG frequency.
To make the algorithm converge faster two additional features were introduced: sensible initial guess and non-fixed number of generated phase points. The initial guess was modelled on the third and fourth order dispersion within the frequency range of interest. Moreover, the number of generated phase points were increasing throughout the retrieval process. At the start the phase points were mostly acquired through interpolation and thus the points had more influence on the whole retrieval. Once those points found appropriate positions, the number of points were further increased to obtain an even better result. Lastly, to decrease the possibility of converging into a local minima, random noise was introduced to primary parents which did not satisfy crossover probability condition.

3 Experimental Setup

A schematic diagram of the experimental setup is shown in Figure 1. STARLIGHT laser system provided ultrafast laser pulses with a duration of 4-5 fs and central wavelength of around 750 nm. Negative dispersion was then introduced by placing two broadband chirped mirrors, providing -80fs^2 dispersion in total. The beam was then steered towards an insertable and a stationary glass wedges with a 4° angle. The insertion of the glass wedge was controlled by a translational stage which has a range of 50 mm and a smallest step of 100 nm. After passing the wedges, the beam was focused by an off-axis parabolic mirror (10 cm focal length) into a BBO crystal (100μm thick) which was used as a second harmonic generator. After the SHG, beam was collimated by a lens and any non-SHG signal was filtered out by a linear polariser. Finally, the dispersion scan traces were recorded by an OceanInsight spectrometer. Communication between spectrometer and translational stage allowed to obtain dispersion traces at different values of insertion of glass which were then used by the retrieval algorithm. However, before any retrieval processes could take place a measurement of the fundamental spectrum was taken by removing the BBO crystal.

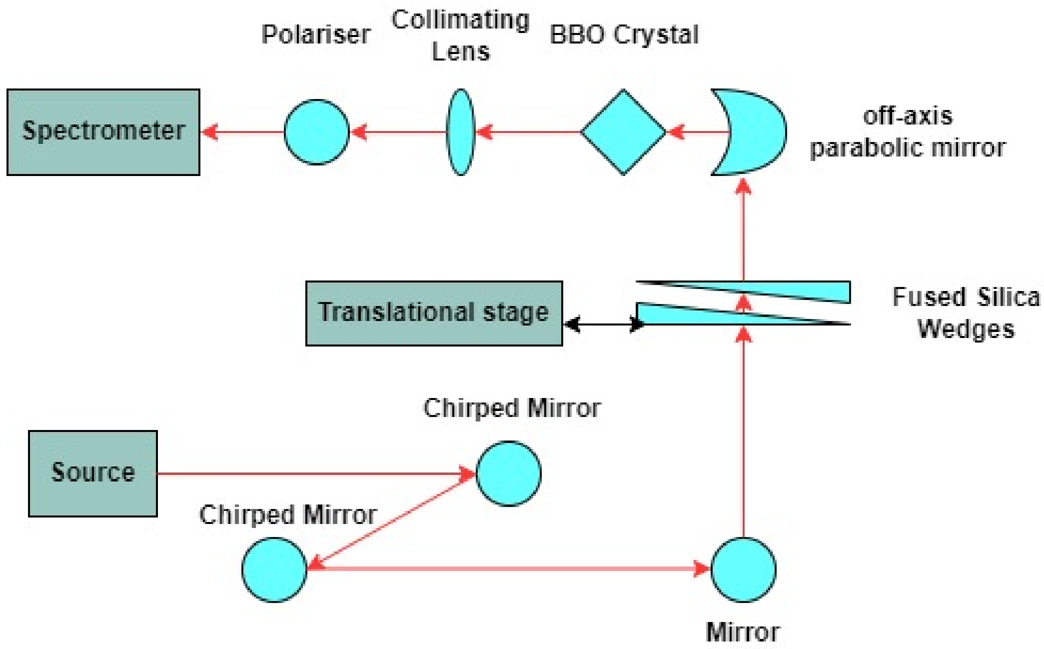

Figure 1: Experimental setup used to obtain dispersion scan traces. The distances between different components are not exact and only used for visualisation.

4 User Interface

In order to effectively communicate between translational stage, spectrometer and retrieval algorithm user interface was created. The interface allows to control the parameters of stage movement and specify the number of dispersion traces to obtain. The user has to specify the number of chirped mirrors (each assumed to introduce $-40fs^2$) used in the optical setup and any additional glass placed before the wedges. Additional glass may be required since the wedges have limited thickness which might not be enough to fully compress the pulse. The scan can be either performed around the reference thickness (2 mm) or within an exact range of thicknesses. This is controlled by 'Automatic Bounds' check box and is presented in Figure 2.

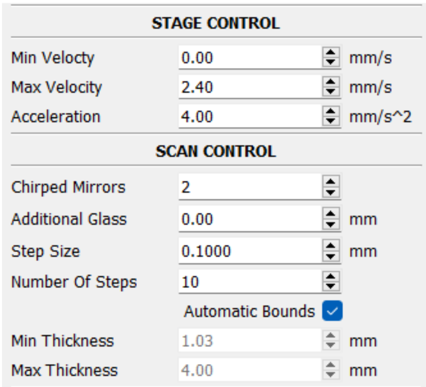

Figure 2: User interface section used to control stage movement and dispersion scan trace acquisition parameters.

However, before the scan can be started a file containing dark spectrum needs to be uploaded for correction. Dark spectrum can also be obtained by pressing 'GET DARK SPECTRUM' button. Then, similarly the user uploads or acquires the fundamental spectrum. Once the fundamental spectrum is read the user can specify the bounds of interest by adjusting the values of 'Min wavelength' and 'Max wavelength' boxes. The green and red lines indicate the central frequency as a weighted average and middle of the frequency array respectively. Ideally, the user needs to align the two lines, however, before the scan is performed only the appropriate limits of wavelength need to be specified. 'Shrinking Factor' is used to downsample the frequency points to make the retrieval faster. If a factor of 2 is selected the number of points in the fundamental spectrum is halved. This parameter can be adjusted both before and after the scan is performed. After the measurement of dispersion scan is obtained, the red and green lines can be adjusted by 'Padding Left' and 'Padding Right' buttons. The buttons add zeros around the specified limits of wavelength, thus shifting the middle of the frequency array. This alignment is important for the proper use of fast Fourier transform features. Nevertheless, the padding can be reversed by 'Deleting Left' and 'Deleting Right' buttons. The described features are shown in Figure 3.

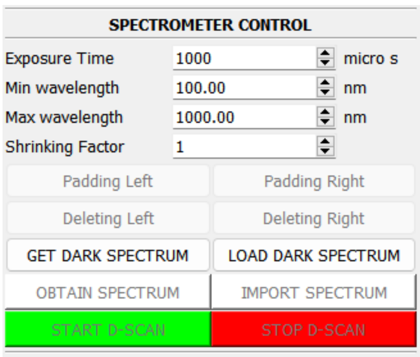

Figure 3: User interface section used to control spectrometer parameters and adjust the fundamental spectrum.

The user can also control the parameters of the algorithm and select two different modes of retrieval. The first mode retrieves the fully compressed pulse, whereas the second one retrieves the initial pulse. The modes are controlled by the 'Dispersion Offset' check box. Moreover, there are two additional controllable parameters: point increase and phase points. Point increase controls the increase of generated phase points throughout the retrieval. Smaller value corresponds to higher initial number of phase points and bigger steps of increase, whereas a bigger value acts the opposite. The phase point parameter allows to set an upper limit for the number of generated phase points by the algorithm. 'Max' check box next to it allows to set this number equal to the number of data points in the fundamental spectrum (region of interest). If a compressed pulse is being retrieved, the interface also shows a value for dispersion offset which includes the effect of chirped mirrors within the setup and required glass to compress the pulse. Thus, if the shown amount of glass was placed before the setup the pulse would be fully compressed.

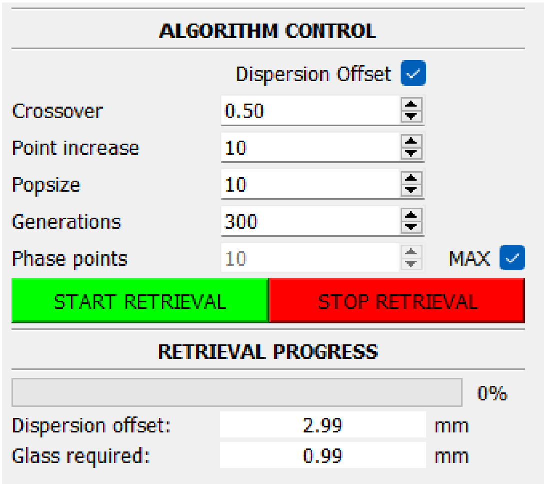

Figure 4: User interface section used to control spectrometer parameters and adjust the fundamental spectrum.

Since the duration of scan and retrieval is of the order of minutes multithreading and timers were necessary for a positive user experience. The user is guided towards the proper use of the program by enabling and disabling buttons at different stages of dispersion scan process. The interface also provides live updates during the scan and retrieval, as well as allows you to stop the processes at any time. As part of the live features there are 6 plots illustrating: measured dispersion scan, fundamental spectrum with retrieved phase, retrieval algorithm error, retrieved dispersion scan, second harmonic spectrum and retrieved pulse along with a Fourier limited one. Second harmonic spectrum is presented along with the fundamental one and ideally, they should have maximum overlap. The whole user interface is presented in Figure 5.

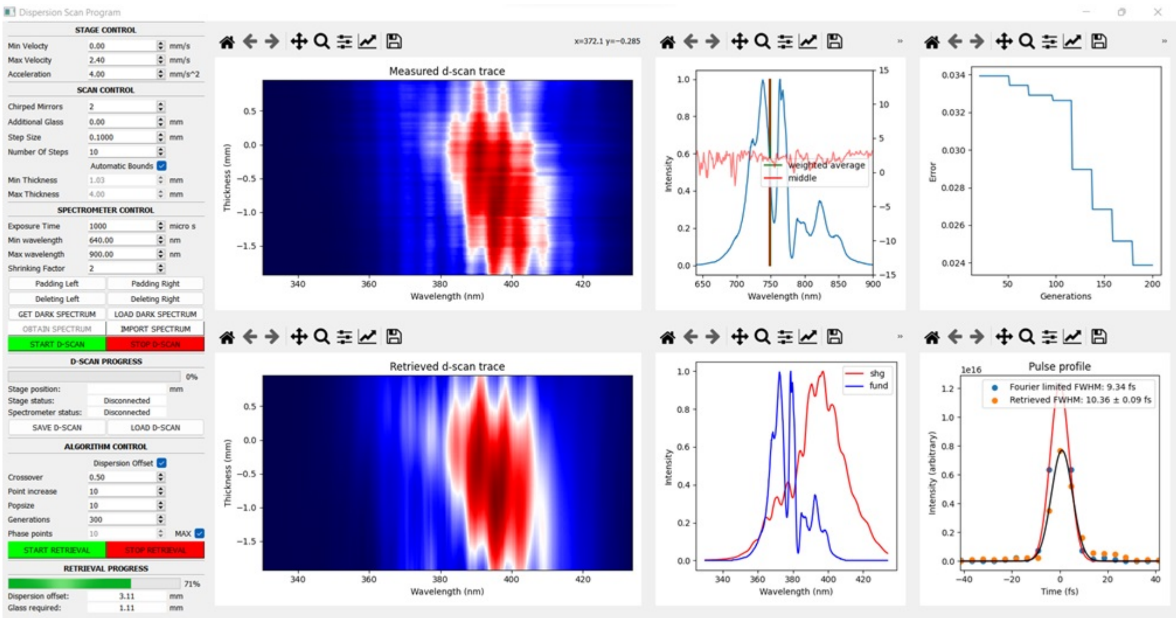

Figure 5: The version of user interface which includes manual zero padding and wavelength selection.

However, the main flaw of this program is that the best overlap does not result in the best pulse retrieval. This inspired to look for another version of a program which would be more automated and would not rely on matching the second harmonic with fundamental spectrum by hand. This version of program differs from above described one by not having manual minimum wavelength and maximum wavelength as well as zero padding features. Instead it finds the appropriate range of the fundamental spectrum by selecting a noise threshold and then zero pads everything outside it. The part of fundamental spectrum that is used for reconstruction is selected by finding the central frequency within the data above the threshold value and extending the width twice compared to the data above the threshold. This includes some data which has already been zero padded. Thus, the only requirement to start the retrieval once dispersion scan is finished is to select an appropriate threshold value. Such method proved to be more efficient, which is further discussed in the results section.

5 Results

5.1 Munich data

The retrieval algorithm was first tested on the data acquired by attosecond imaging group at the Max Planck institute of quantum optics. During this stage, both versions of the retrieval were used. Dispersion scan traces along with the retrieved ones are presented in Figure 6.

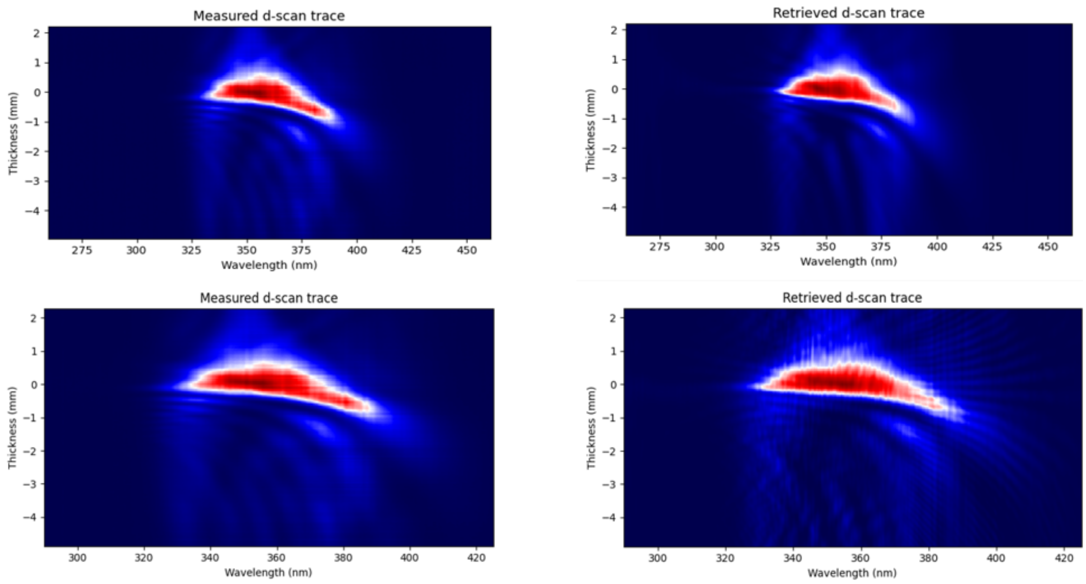

Figure 6: Dispersion scan retrieval using the data acquired by the attosecond imaging group at the Max Planck institute of quantum optics. The top row uses bounds approach whereas the bottom row utilises noise threshold.

As can be seen in Figure 6, both approaches manage to visually retrieve the dispersion scan traces. However, the use of threshold approach introduces more noise into the retrieval result. To test the algorithm properly, algorithm parameters were varied and the spectral phase was observed. The difference between using maximum and 90 phase points in the algorithm is presented in Figure 7.

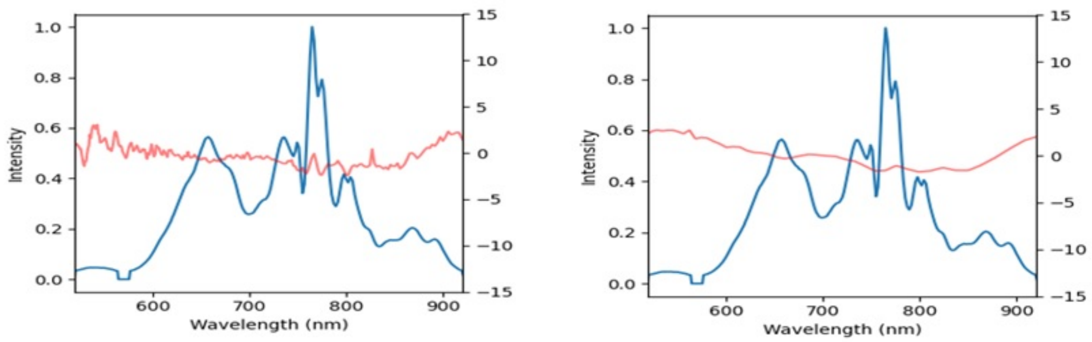

Figure 7: Retrieved spectral phases using the data acquired by the attosecond imaging group at the Max Planck institute of quantum optics. The figure on the left uses maximum number of phase points available, whereas the right one uses 90 points.

Figure 7 indicates that the retrieval process can converge into similar results. Also, it is evident that by reducing the number of generated phase points, the noise in the retrieved spectral phase decreases. The obtained spectral phase is relatively flat, which indicates that the pulse duration should be close to the Fourier limit. The retrieved pulse had a

FWHM value of 4.89 ± 0.04 fs whereas the Fourier limit was found to be 4.28 fs. This approves that the results obtained by the retrieval algorithm are of the correct order.

5.2 DESY data

Once the initial testing was finished, dispersion scan was performed on STARLIGHT laser system located in DESY, Hamburg and maintained by the attosecond science group. The fundamental spectrum of the compressed pulse had a range from 500 nm to 1000 nm which could be narrowed by adjusting the pressure of He gas inside the hollow fiber. Initially, the second harmonic generation was obtained by using a 100 μm thick BBO crystal. The generated second harmonic only had a bandwidth of 30 nm which suggested that the phase matching bandwidth of the crystal was too small. Thus, the 100 μm crystal got replaced by a 10 μm one. However, this resulted in a fringe pattern being present in dispersion scan traces. After measuring the spacing between fringes it was confirmed that the 10 μm BBO crystal caused interference between the main pulse and its pedestal. Nevertheless, the bandwidth of the generated second harmonic signal increased significantly. These results are shown in Figure 8.

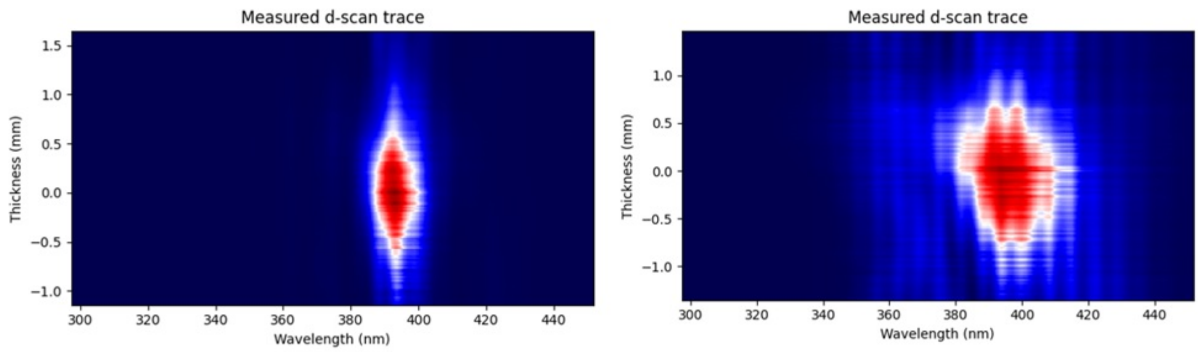

Figure 8: Dispersion scan traces resulting from the use of different thickness BBO crystals. The plots on the left and right were generated by using a thickness of 100 and 10 μm respectively.

First set of measurements were taken by filling the fiber with a 1.8 bar pressure He gas. This produced a fundamental spectrum spanning from 550 to 900 nm. Even though the dispersion scan was strongly affected by the interference fringes, the retrieval algorithm managed to retrieve the key features of the trace. However, the second harmonic spectrum was asymmetric, in particular having higher intensity towards increasing wavelength. The assymetry of the second harmonic signal is shown in Figure 9.

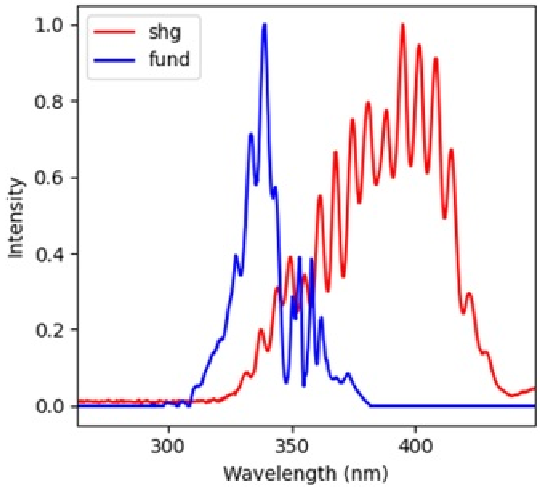

Figure 9: Second harmonic spectrum alongside the shifted fundamental spectrum of a laser pulse compressed by 1.8 bar He gas.

This can be explained by the lower limit of chirped mirror bandwidth at 600 nm. Wavelengths of the input pulse close to this limit were not being affected by the chirped mirrors properly, which suggested that the pressure of He gas needed to be lowered to narrow down the fundamental spectrum.
Another set of measurements were taken by changing the He pressure to 1.6 bar. This shifted the lower limit of fundamental spectrum to around 650 nm. Even though the intensity of second harmonic signal increased at lower wavelengths, the overall shape of the second harmonic signal was still asymmetric. To solve this issue He pressure was lowered to 1.2 bar. At this pressure, the bandwidth of chirped mirrors was not causing any issues, however the pulse duration increased significantly. This meant that the dispersion output from the wedges became weaker and the range of applied glass thickness was not sufficient to generate a full dispersion trace. With the available amount of glass insertion range, only the central part of the trace could be obtained. Retrieval algorithm was applied to both sets of measurements and pulse durations were found. The results are shown in Figure 10 and Table 1.

Pressure (bar)	Fourier limited (fs)	Retrieved (fs)
1.8	5.7	6.0 – 7.5
1.6	6.6	8.5 – 9.7
1.2	10.2	11.7 – 12.0

Table 1: Retrieval algorithm results from data acquired at different He gas pressure. Retrieved pulse duration range originates from 5 different algorithm runs with different parameters.

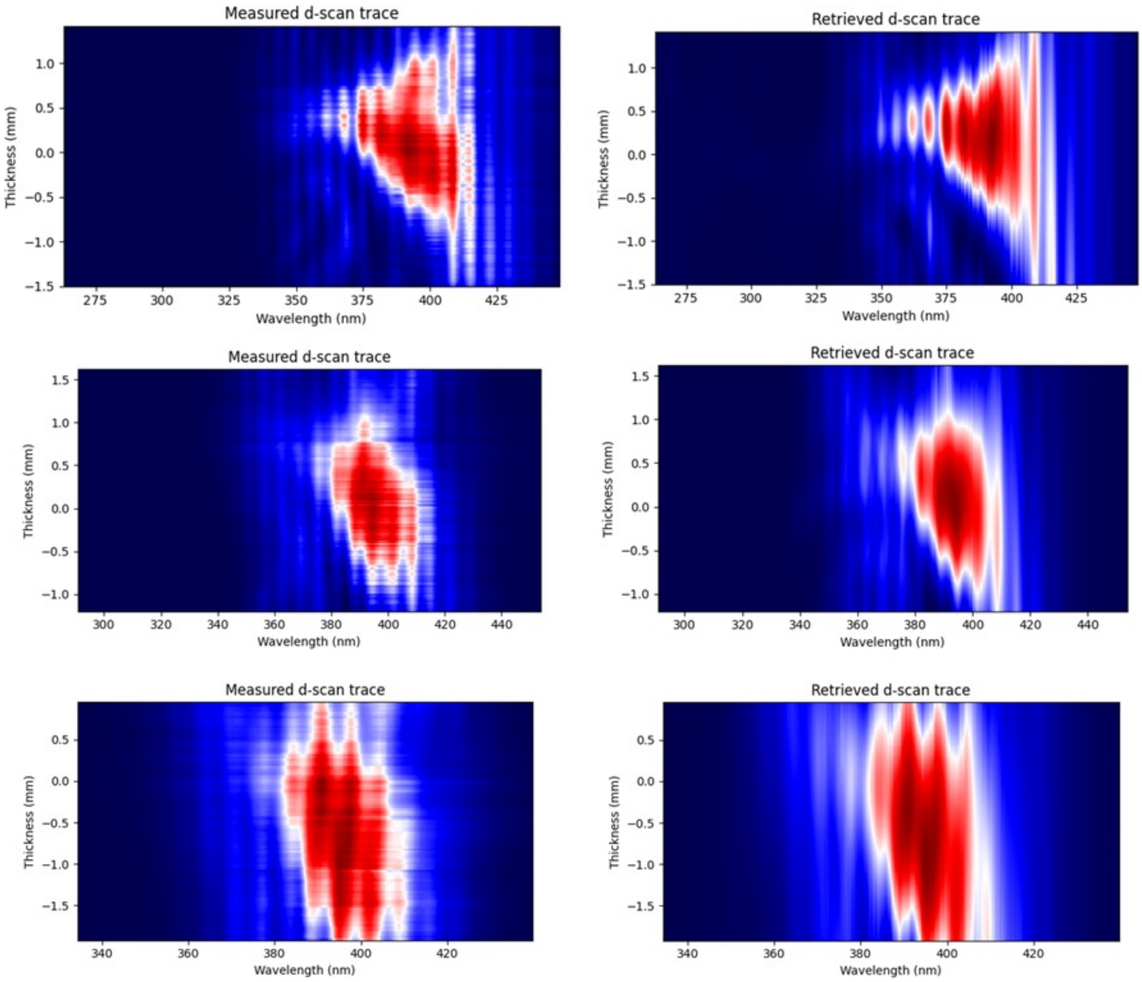

Figure 10: Measured and retrieved dispersion scan traces at 1.8, 1.6 and 1.4 bar He pressure. Top row represents the measurements at highest pressure, whereas the bottom row corresponds to the lowest one.

6 Conclusion

The results in Table 1 are within the expected order of magnitude. Moreover, as the pressure of He gas is decreased the pulse duration increases which agrees with theoretical expectations. Nevertheless, the optical setup requires changes to improve the accuracy of the dispersion scan. Firstly, for proper use of the device the lower limit of chirped mirror bandwidth needs to be lowered to around 400 nm to cover the full fundamental spectrum of STARLIGHT laser pulses. Currently, it is only possible to obtain the central region of dispersion traces. By replacing the glass wedges with longer or thicker ones it would be possible to obtain full information from the traces. The interference fringes within the data could be suppressed or filtered out, since their origin has been identified as the 10 μm BBO crystal. Furthermore, OceanInsight spectrometer is less sensitive to signals at higher wavelengths, thus distorting the fundamental spectrum. This can be overcome

by correcting the data according to the spectrometer's response curve. Another problem arises due to the inability of the polariser to filter out the fundamental spectrum after second harmonic generation. Rotation of the polariser not only changes the intensity of the spectrum but also its shape. This effect is undesirable which indicates that the polariser needs to be changed to a filter.
Similarly to the optical setup, retrieval algorithm's performance can be enhanced significantly. In its current state the algorithm does not always converge to the same results. A thorough parameter exploration, as well as further testing with other laser systems could be one of a few solutions to such problem. Ideally, the retrieved phase could be compared with the results of other self-referenced characterisation system, for example FROG [9], to fully evaluate the performance of the algorithm. Nevertheless, the current version of the device allows the acquisition of dispersion scan traces as well as provides results within an appropriate range.

References

[1] Miranda and Miguel. Simultaneous compression and characterization of ultrashort laser pulses using chirped mirrors and glass wedges. *Optics express*, 20.1:688–697, 2012.

[2] Liu, Junhong, and Jouni Lampinen. A fuzzy adaptive differential evolution algorithm. *Soft Computing*, 9.6:448–462, 2005.

[3] Y. Silberberg. 2009 quantum coherent control for nonlinear spectroscopy and microscopy. *Rev. Phys. Chem.*

[4] H. P. Sardesai, C. C. Chang, and A. M. Weiner. A femtosecond code division multiple-access communication system test bed. *Lightwave Technol*, 16:1953, 1998.

[5] Goswami and Debabrata. Optical pulse shaping approaches to coherent control. *Physics Reports*, 374.6:385–481, 2003.

[6] A. M. Weiner. Femtosecond pulse shaping using spatial light modulators. *Rev. Sci.*, 71:1929–60, 2000.

[7] Oksenhendler and Thomas. Self-referenced spectral interferometry. *Applied Physics B*, 99.1:7–12, 2010.

[8] Shuman and M. Timothy. Real-time spider: ultrashort pulse characterization at 20 hz. *Optics Express*, 5.6:134–143, 1999.

[9] Gagnon, Justin, Eleftherios, Goulielmakis, and Vladislav S. Yakovlev. The accurate frog characterization of attosecond pulses from streaking measurements. *Applied Physics B*, 92.1:25–32, 2008.

[10] Escoto and Esmerando. Advanced phase retrieval for dispersion scan: a comparative study. *JOSA B*, 35.1:8–19, 2018.