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Large group delay dispersion for medium-wavelength infrared optical signals

Bachelor's thesis
in the field of PHYSICS

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Summary

In this thesis, I introduce the reader to the world of optics, explaining basics and providing isight into a currently available dispersion obtaining methods. Finally I introduce the reader to a less-known solution for obtaining a easy-tunable way of achieving large group delay for medium-wave infrared optical signals called the Free-Space Angular-Chirp-Enhanced Delay, shortly FACED. This work extensively explains the set up process and encountered obstacles thus can be used as a guide for those who are eager to build this system. Finally I present gathered data that proves that this technology can indeed fulfill its purpose of generating tunable group delay dispersion.

Keywords

infrared, group delay, FACED, pulse reconstruction, phase reconstruction, ultra-short pulses, chirp

Title of the thesis in Polish language

Dyspersja opóźnienia grupowego dla sygnałów optycznych z zakresu średniej podczerwieni

Contents

Introduction

The shaping of light signals by introducing dispersion is an inseparable element of modern optics. Currently, the most popular methods of achieving this are the use of: a dispersive medium (for example, optical fiber spools), chirped bragg Gratings and pairs of prisms or diffraction gratings. The FACED system discussed in this work, inspired by the work presented in the publications [6] and [5] has an advantage over current systems in several areas. Among other things, it is possible to modify the dispersion using only a few actuators.

Initially, it was planned to build a system operating at the mid-infrared wavelength, hence the name of the work. As an introduction and familiarization with the FACED technology, it was decided to first build a system at the telecommunication wavelength (1550 nm), which is easier to work with. It turned out that such a system already creates many problems, overcoming of which required significant time resources. Nevertheless, the built system provides a significant insight into the FACED approach from a theoretical and a technical point of view, useful in the future setup at medium infrared wavelengths.

Chapter 1

Theoretical Background

In this chapter I will explain the core concepts that are needed to understand how my system works. The chapter briefly explains theoretical notions such as electromagnetic waves and group delay dispersion as well as presents the general principle of operation of the optical elements used to build the system.

1.1. Electromagnetic waves and pulses

First of all let's define electromagnetic waves in three dimensions. Where we can assume that **E** – the electric field and **B** – the magnetic field, where boldface symbols denote vectors. Vectors defining the fields for a monochromatic plane wave:

$$\mathbf{E}(\tilde{\mathbf{r}}, \mathbf{t}) = \tilde{E_0} exp[j(\vec{k} \cdot \vec{r} - \omega t)], \tag{1.1}$$

$$\mathbf{B}(\tilde{\mathbf{r}}, \mathbf{t}) = \tilde{B_0} exp[j(\vec{k} \cdot \vec{r} - \omega t)]. \tag{1.2}$$

Further $\vec{r} = x\hat{x} + y\hat{y} + z\hat{z}$ is a distance vector. $\tilde{B_0}$ and $\tilde{E_0}$ are the complex vector amplitudes of the electric and the magnetic field. The behavior of light or magnetic and electric field is governed by a wave equation. We can define it as:

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial z^2} = \frac{1}{v^2} \frac{\partial^2 \psi}{\partial t^2}. \tag{1.3}$$

Provided that $v = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$, where ϵ_0 is the electric constant and μ_0 is the vacuum magnetic permeability.

In my case I am not interested in the spatial distribution of the field, moreover it is enough to focus only on the electric field as the magnetic field is strictly connected to it. By removing the mentioned elements I get the pulse equation (1.4).

$$E(t) = \sqrt{I(t)} \exp\{\omega_0 t - i\phi(t)\}, \tag{1.4}$$

where $I(t) = |E(t)^2|$ means intensity in time, ω_0 denotes the angular frequency of the pulse that corresponds to the central wavelength of the pulse and $\phi(t)$ temporal phase. The same electric field can be presented in terms of frequency.

$$E(\omega) = F(E(t)), \tag{1.5}$$

where F denotes Fourier transformation. Finally after the transformation, $E(\omega)$ can be expressed as:

$$E(\omega) = \sqrt{S(\omega)} exp\{i\phi(\omega)\}, \tag{1.6}$$

$S(\omega)$ denotes the power spectral density, in other words–the spectrum. Whereas $\phi(\omega)$ is the spectral phase.

1.2. Pulsed Lasers

In the case of my project main kind of used laser are pulsed lasers. This refers to any laser that does not produce continuous wave and the optical output appears with some repetition frequency. There are a few reasons why one would want to use that kind of laser. Firstly, in the case of pulsed lasers it is possible to create much greater energy than with continuous wave laser. This is simply because, in the case of pulsed lasers if one distributes the same energy as in continuous wave lasers in packets one can create higher energy per time. Some applications rely on peak pulse power, notably when one wants to obtain nonlinear optical effects. Secondly, in some cases it is just necessary to create pulses, where by definition it is impossible to do with continuous wave lasers. Contrary to the continuous wave lasers that have a narrow spectrum, pulsed lasers have spectrum spread over considerable bandwidth due to a short temporal length and the Fourier transform relationship between the pulse duration and its frequency spectrum.

1.3. Group delay

The group delay of an optical element is the time delay experienced by a light pulse propagating through that element. That time delay depends on the optical frequency, or correspondingly, the wavelength. The group delay is defined as a derivative of the spectral phase with respect to the angular optical frequency. More precisely:

$$T_g = \frac{\partial \phi(\omega)}{\partial \omega}, \tag{1.7}$$

where ϕ denotes a spectral phase and ω angular optical frequency. The unit of the group delay is the unit of time (e.g nanosecond).

1.4. Group delay dispersion

The group delay dispersion – often called the second order dispersion is defined as:

$$D_2(\omega) = \frac{\partial T_g}{\partial \omega} = \frac{\partial^2 \phi(\omega)}{\partial \omega^2} \tag{1.8}$$

D_2 is a quantitative measure of a chromatic dispersion of an element, that is, the dependency of the phase velocity and the group velocity on the angular frequency. The derivative of spectral phase over angular frequency can by understood as a way to find a behaviour of phase shift between the frequencies in the pulse. Moreover the group delay dispersion is closely related to the group velocity dispersion, the first one always relates to a particular optical element, since its unit is s^2, whereas the second one is the group delay dispersion experienced by a unit of length, which yileds the unit of $\frac{\mathrm{s}^2}{\mathrm{m}}$.

1.5. Dielectric materials

A dielectric is a material that is electrically an insulator which can by polarised while an electric field is applied to it. The electric susceptibility $\chi_e(\omega)$ is a measure of how easily a given dielectric get polarised in an electric field. That parameter generally is dependent on the frequency and this defines the dispersion properties of the dielectric. The refractive index is related to the electric susceptibility $n = \sqrt{1 + \chi_e}$, thus when a pulse of white light enters a dielectric, the different colors it is made up of will travel at different speeds due to the varying refractive index, and the initial beam will be stretched into a multi-color pulse.

1.6. 4f with diffraction gratings

In Figure (1.1), a 4f system with optical gratings, similar to the one used in my experiment, is presented.

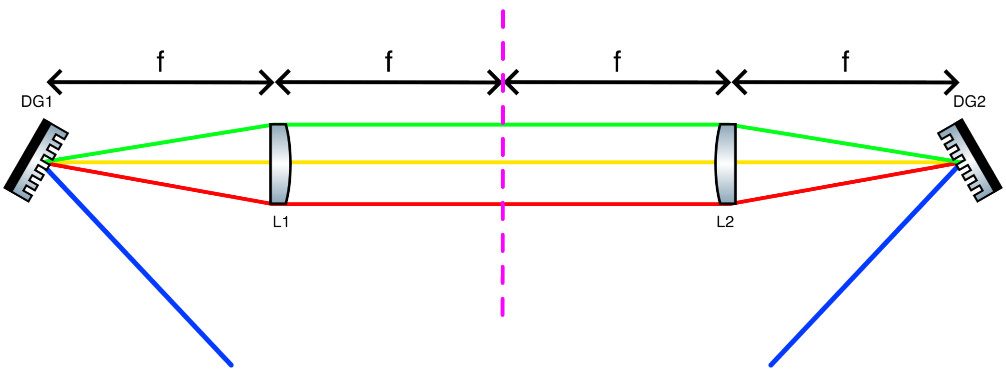


Figure 1.1: The layout of a standard 4f system.

The colors of the beams between the diffraction gratings denote different wavelengths, chosen only as the representation of the different wavelengths and do not represent the color of the light they have. The blue beam represents wide wavelength beam that enters and exits device. The red beam can be understood as light with the longest wavelength in the blue beam and the green as one with the shortest one. The yellow denotes the beam with a wavelength equal to the central wavelength of the blue beam. The system consists of two diffraction gratings (DG1, DG2) and two lenses (L1, L2). Those four components are mounted at the distance of the focal length of the lenses (f) from each other. When the light hits the first diffraction grating (DG1), it introduces angular dispersion. Next, the beam is collimated with the lens (L1) and then focused with the lens (L2). The beam aimed at diffraction grating (DG2) has once again angular dispersion but mirrored in the plane denoted by Fourier plane — the pink dashed line in Figure. The diffraction grating eliminates angular dispersion and puts together the beam to the state it was initially at. Between the lenses the light is in the Fourier domain. That allows the manipulation of the optical spectrum in the terms of phase and amplitude. For further manipulation of the phase it is common to mount a spatial light modulator between the lenses in the Fourier plane

1.7. Faraday circulator

A Faraday circulator is an non-reciprocal optical device utilising the Faraday effect, typically equipped with three or four ports. In this instance, a circulator with three outputs was used. Its basic function can be described as directing input light from one port to the next one sequentially. The another application involves signal splitting when unpolarized light is introduced at the input. By placing a polarization controller between the laser's output and the first port, the power ratio between the 2nd and the 3rd port can be adjusted, also enabling the control over the separation of polarization.

1.8. Telescope

Telescopes are typically recognized as optical instruments used for observing objects located at a long distance. A basic telescope consists of two lenses with different focal lengths. In the simplest form, known as a Kepler telescope, the lenses are positioned at a distance equal to the combined focal lengths of the both lenses. It is worth noting that, in my case, the telescope is used in reverse. Typically, a telescope reduces the size of the light beam, but here it expands the beam instead. The construction remains the same; the only difference is the direction from which the light enters the telescope. The necessity to expand the beam arises from the fact that it is far easier to spot a waist in a wider beam than in a narrow one. Finding a waist is a common action performed multiple times while setting lenses and collimating beams in my system.

In my case, I chose a Galilean telescope because of its compact design. In this setup, the spacing between the lenses is $f_1 - f_2$. The diagram below shows the layout of the Galilean telescope used in the system.

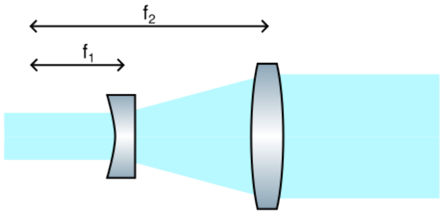


Figure 1.2: The layout of the Galilean telescope type used in my system. The left-most lens has negative focal length — f_1 and the right-most positive — f_2

1.9. Wave plates

A wave plate, also known as a retarder, is an optical device used to manipulate polarization of light. The two most common types are a quarter-wave plate and a half-wave plate as the one being used in my system. A half-wave plate flips the polarization direction of linearly polarized light. In my application, I use it to precisely adjust the polarization to minimize the reflections from a diffraction grating. These wave plates are made from a birefringent materials such as quartz, used in my system. In these materials, the refractive index varies along different axes, thus introducing a phase shift causing the polarization of light to change.

1.10. Fibre polarization controller

Fibre polarization controllers rely on, similar to wave plates, befringence of a material. In this device the befringence is created by introducing mechanical stresses into fiber spools. One can say that every spool creates an independent wave plate that is able to transform the polarization by adjusting their rotation. Generally 2 spools should be enough in principle, unfortunately the retardation change is not precise, so having a 3rd spool helps obtaining the desired retardation. Below in Figure (1.3), the layout of a typical fibre polarization controller is presented.

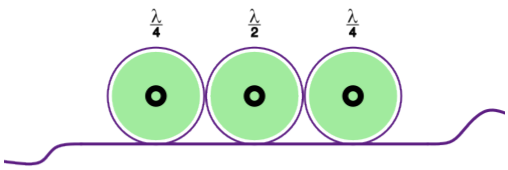


Figure 1.3: The layout of a fibre polarization controller, where $\frac{\lambda}{4}$ denotes a transformation equivalent to a quater-wave plate and $\frac{\lambda}{2}$ - a half-waveplate. The purple elements symbolize a optical fiber.

1.11. Cross correlation – time delay calculation

To estimate the time shift between two signals, I used the cross correlation method in my work, also known as sliding dot product or sliding inner-product. It is used in pattern recognition, tomography, cryptanalysis, and neurophysiology. In the calculating delay between two signals case, after computing the cross-correlation between two signals, the peak of the cross-correlation function identifies the point in time where signals are the most aligned. In a mathematical way, the delay is given by:

$$\tau = \operatorname{argmax}((f \star g)(\tau)), \quad \tau \in \mathbb{R}, \tag{1.9}$$

where f and g are signals and $\star$ means a cross correlation defined as:

$$(f \star g)(\tau) = \sum_{t=0}^{N-1} f(t)g(t+\tau), \tag{1.10}$$

where t denotes time.

Chapter 2

Overview of methods to achieve group delay dispersion

2.1. Dielectric materials and optical fibres

The simplest method of obtaining group delay dispersion is to use a dielectric medium. One that has the refractive index dependent on wavelength and a non zero second derivative of the spectral phase: $\frac{\partial^2\phi(\omega)}{\partial\omega^2} \neq 0$. A simple example of such a medium is silica used to construct optical fibers. In the case of glass refractive index changes with wavelength and introduces a difference of velocity between wavelength components of a pulse, thus stretching or squeezing it in time, depending on the wavelength. The exception to that is for wavelengths around 1300 nm, where the group velocity dispersion is close to zero.

2.2. Prism pairs

The prism pair approach is quite different from the other methods. For wavelengths $\lambda < 1300$ nm prism pairs allow to introduce negative dispersion into system, often used as counterbalance to unwanted positive dispersion introduced by optical mediums. The prism pairs works by refracting light in such a way that shorter wavelengths travel longer paths, while longer wavelengths take shorter paths, thus compressing a pulse.

2.3. Chirped Bragg Gratings

Bragg gratings are usually constructed in the form of a fiber where in some part of it the refractive index varies periodically along the structure. Depending on the specific variation pattern, it is possible to obtain numerous optical effects like a reflection of specific wavelengths or introducing group delay dispersion. To obtain group delay dispersion with that approach, it is required to use chirped Bragg gratings. Inside that kind of a fiber, the period of refractive index modulation increases with the length, thus broadening reflected, spectrum and introducing group delay dispersion.

2.4. FACED

FACED (Free-Space Angular-Chirp-Enhanced Delay) is a novel approach for obtaining group delay dispersion, designed for time-stretch imaging and mainly tested in the short-wavelength regime. FACED employs a diffraction grating and two slightly misaligned (10^{-3} rad) mirrors to create different optical paths for different wavelengths, thus introducing temporal delay dependent on the wavelength. It operates in free space, which minimises optical losses associated with material dispersion such as a silica in optical fibres, additionally it is theoretically possible to actively reconfigure the system achieving continuous modification of group delay dispersion. This is in contrast to combining discrete values of group delay dispersion obtained with optical fibre patch cords and chirped fibre Bragg gratings. On the other hand, the device splits its output signal spectrum into a discrete signal due to its principle of operation. A more thorough explanation is provided in chapter 3.1.

Chapter 3

FACED – implementation

3.1. Detailed principle of operation

FACED harnesses the slight misalignment angle α (typically $\approx 10^{-3}$ rad) between a pair of highly reflective dielectric plane mirrors, separated by the distance S, which results in the change of the light-path, thus streching the input signal. The light entering the FACED device is required to be a converging and angle chirped pulsed beam focused at the entrance of the device, located at the edge of one of the mirrors. The angle chirp and the convergence is achieved using an 2F-2F (or 4F with lenses with different focal lengths) system and an angular disperser, a diffraction grating in this case. The layout of the whole system used in the experiment is presented in Figure (3.1).

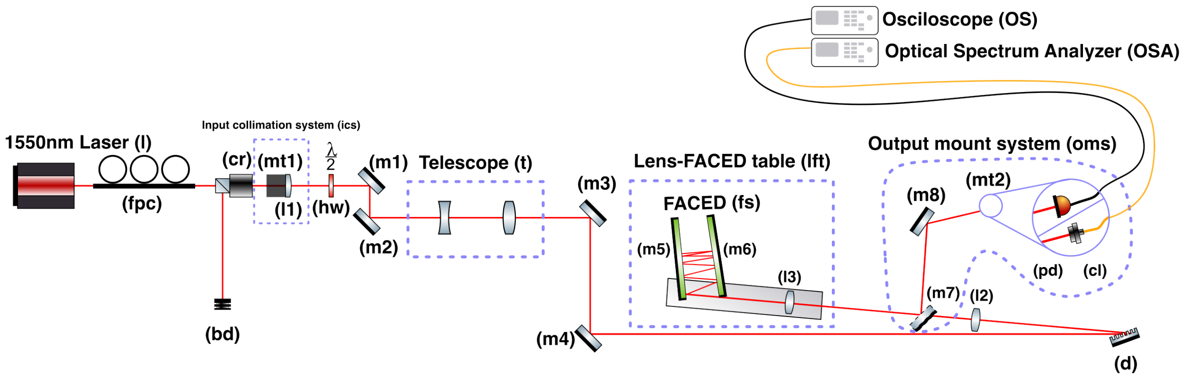


Figure 3.1: The layout of the system used in the experiment, where the following symbols mean: (l) – Laser, (fpc) – fibre polarization controller, (cr) – Faraday circulator, (bd) – beam dump, (mt1) – first precision mount, (l1) – lens $f = 4$ mm, (l2) – lens $f = 200$ mm, (l3) – lens $f = 150$ mm, (hw) – half waveplate, (m1)–(m8) – mirrors, where (m5) and (m6) are dielectric mirrors integrated in FACED (fs) device. (d)–diffraction grating, (pd) – photodiode, (cl) – collimator. The system can also be divided into the device systems marked as: (t) – telescope, (fs) – FACED device, (lft) – lens-FACED table, (isc) – input collimation system, (oms) – output mount system. The measurements were performed with: (OS) – oscilloscope, (OSA) – optical spectrum analyzer

The output beam from the device has a discrete structure. It is created due to the geometry of the device. The principle of that is well explained in paper [5]. I highly suggest reading it before proceeding with mine. The layout of the ray paths from that publication is presented in Figure (3.2), briefly explains how the beams behaviour inside of the FACED device.

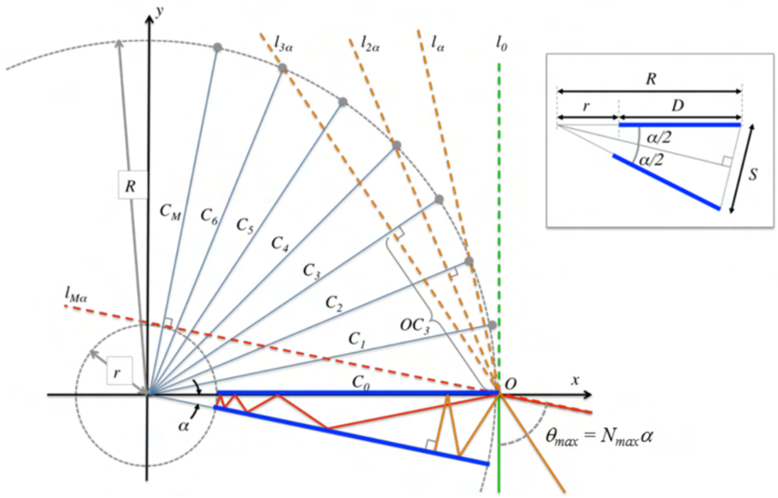


Figure 3.2: Figure from the publication [5], explaining the light ray's behaviour inside the FACED device. Where blue lines represent the mirrors inside the FACED device, equivalent to the (m8) and (m9) mirrors in my system. The green line and the red line denote the borders of the converging and angle chirped pulsed beam focused at the entrance of the device. α denotes the angle between the mirrors, θ_{max} is the divergence angle of the initial beam, N_max i the number of generated spots in the output beam, D is the length of the mirrors and l_0-$l_{3\alpha}$ represent the rays that are returned back inside the FACED device.

After entering the device, because of the slight misalignment of the mirrors, the beam changes the angle of incidence with every reflection. For angles of incidence that are multiples of α the beam stops inside the device and is reflected back, other angles are not reflected and exit at the other side.

For different angles (or wavelengths as the input beam is angular chirped) a stopping position (the position when the beam is turned and returns by the same path) in FACED is different, thus the output beam consists of spots of different spectra that have different times of flight. Those two effects in total create the effective group delay dispersion. Figure (3.3) shows the diagram of a typical output beam form the FACED device.

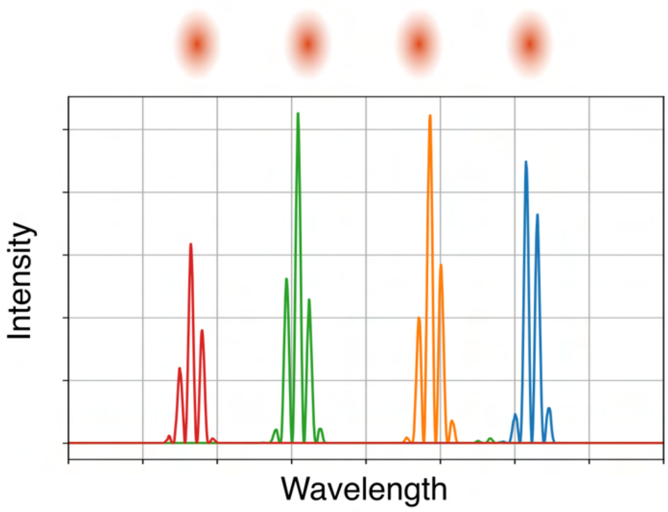


Figure 3.3: Spots appearing in the output beam. The lower part shows spectras measured in my experiment

The figure (3.4) shows the location of the position axis(green) in relation to the system and the output beam. The measurements were conducted along that axis.

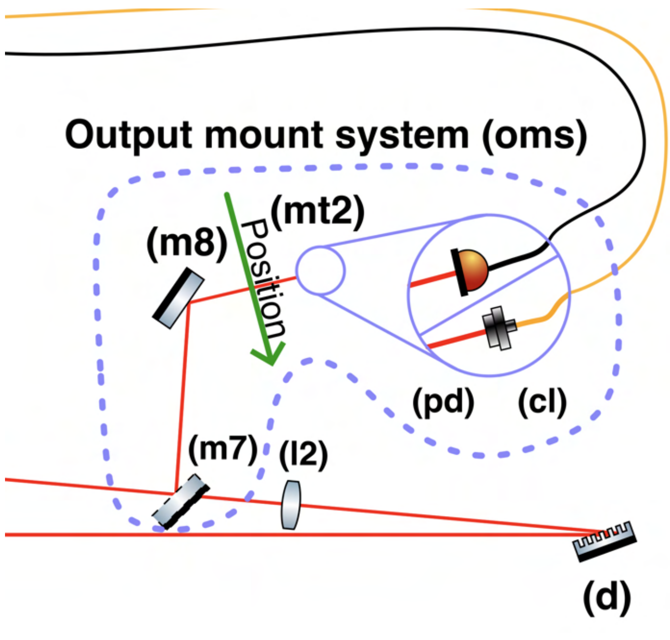


Figure 3.4: The location of the position axis, denoted as the green arrow, in relation to the system and the output beam (the red line).

3.2. Set up procedure and obstacles

3.2.1. Auxiliary systems

For understanding how systems mentioned in this section are connected, the simplified layout of the system is presented in Figure (3.5).

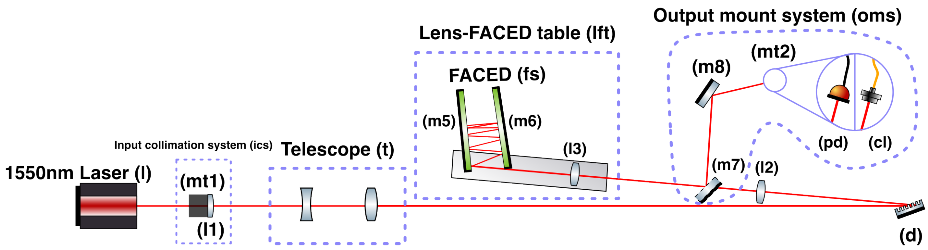


Figure 3.5: The layout of the simplified system, some elements were omitted. The full layout is presented in Figure (3.1).

Telescope – (t)

In Figure (3.6) I present a photo of the telescope that was constructed for the calibration of my system. Its primary goal is to enlarge the beam so that any changes to its diameter are more visible. That way setting up lenses in the correct positions is much easier and faster. In this case the telescope system consists of two lenses with focal lengths 1000 mm and 750 mm mounted in the Thorlabs cage system for a ease of adjustment and stability.

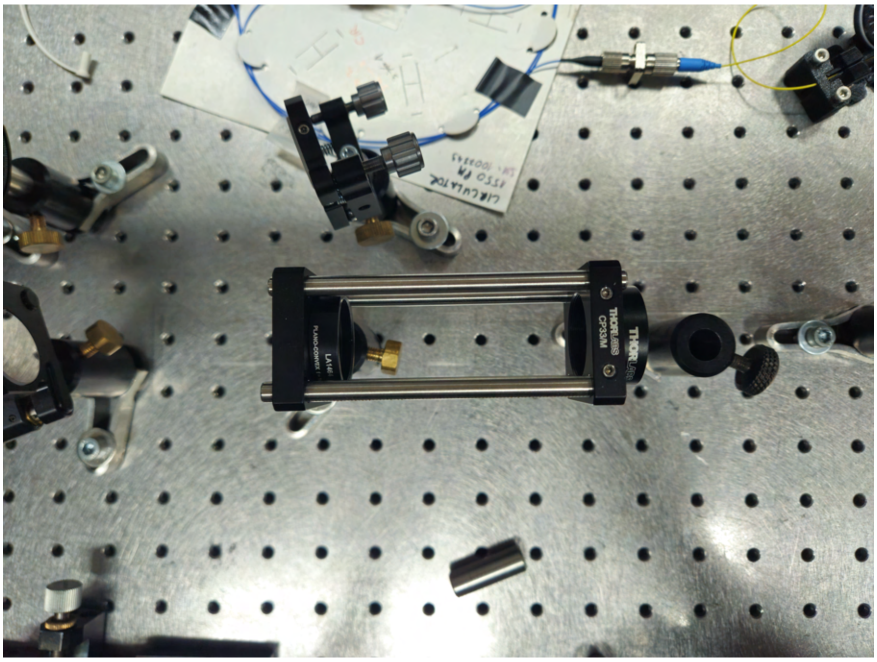


Figure 3.6: A photo of the telescope constructed for use in my system.

The final magnification of that telescope is $\frac{4}{3}$. That ensures better visibility of a waist, provided it is not at infinity. To calibrate the telescope follow the steps listed below:

1. Mount lenses in the cage system.

2. Direct a laser beam at the center of the telescope and perpendicular to the plane of the left-most lens, so that it incomes from the left side.

3. Loosen the screws holding one of the mounts.

4. Observe the beam in the far field, at least a few meters. By moving the right-most lens, find a position where the beam is collimated–there is no visible waist.

5. Tighten the screws.

Lens-FACED table – (lft)

In Figure (3.7) I present the layout of the mount connecting the lens (l3) and the FACED device (fs). This kind of mount allows the movement of both the elements while fixing the distance between them.

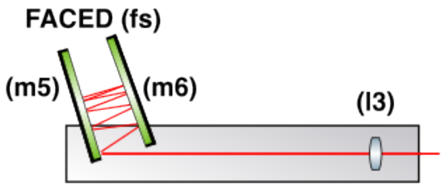


Figure 3.7: The layout of the FACED-lens mount system constructed used in the experiment.

To calibrate the mount follow the steps listed below:

1. Mount the lens (l3) and the FACED device (fs) in approximately the focal length of the lens.

2. Turn the FACED device so that the mirror (m5) is perpendicular to the incoming beam and reflects it straight back. Tilt the mirror (m5) slightly downwards so that the returning beam goes under the incoming beam.

3. Measure the diameter of the incoming beam before the lens (l3) — for easier callibration or if the initial beam from laser is very thin, use the telescope (t) to enlarge it.

4. Using reflection method set up the lens (l3) perpendicular and so that the beam hits the center of it.

5. By observing the far field of the outgoing beam compare its diameter to the initial beam. By moving lens the find position where the outgoing and the initial diameters are the same.

6. Correct rotation of the lens (l3) in the axis perpendicular to the optical table by observing the reflected light.

FACED device–(fs)

In Figures (3.8)–(3.10) photos of built FACED device are presented.

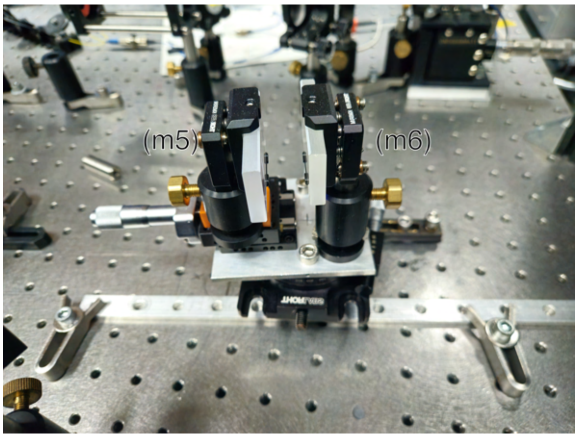


Figure 3.8: Side view of the constructed FACED device system used in my experiment.

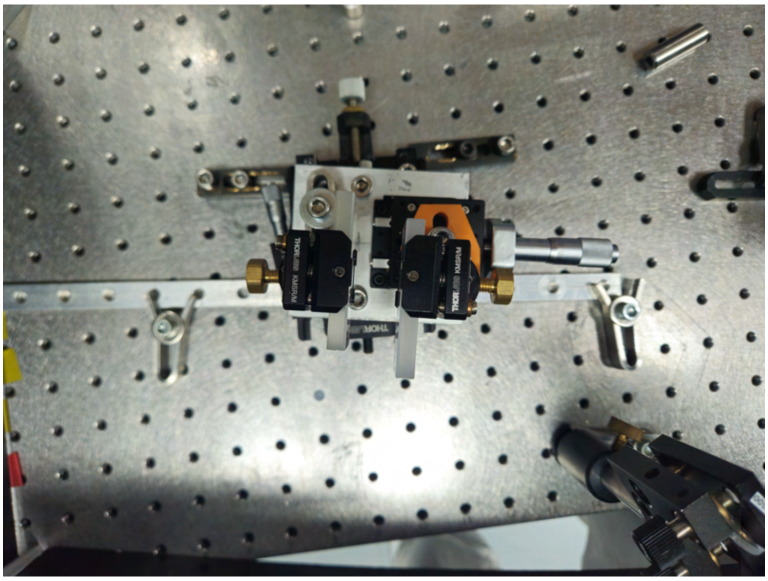


Figure 3.9: Top view of the constructed FACED device system used in my experiment.

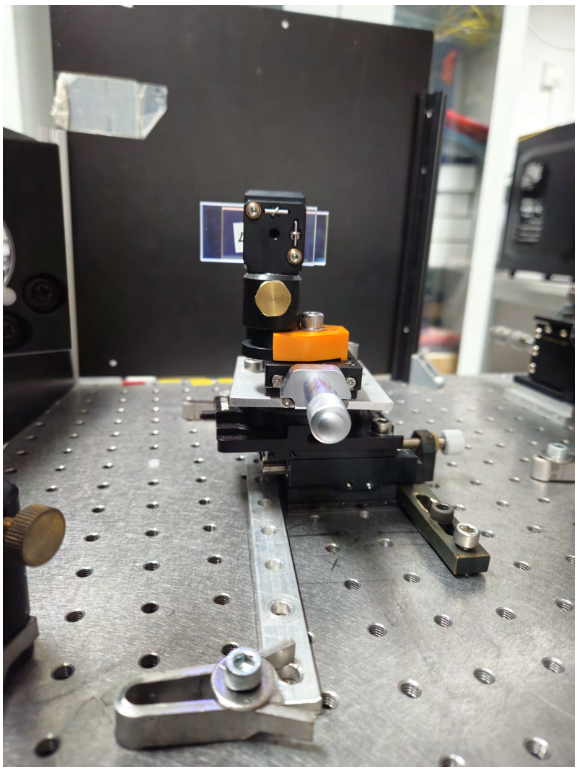


Figure 3.10: Front view of the constructed FACED device system used in my experiment.

The separation between the mirrors (m5) and (m6), in the axis perpendicular to the plane of the mirrors should be just enough that the beam can enter the device when the FACED device is in its final position – it is slightly rotated relative to the beam. In my case Displacement is around 0.5 cm.

Input collimation system – (ics)

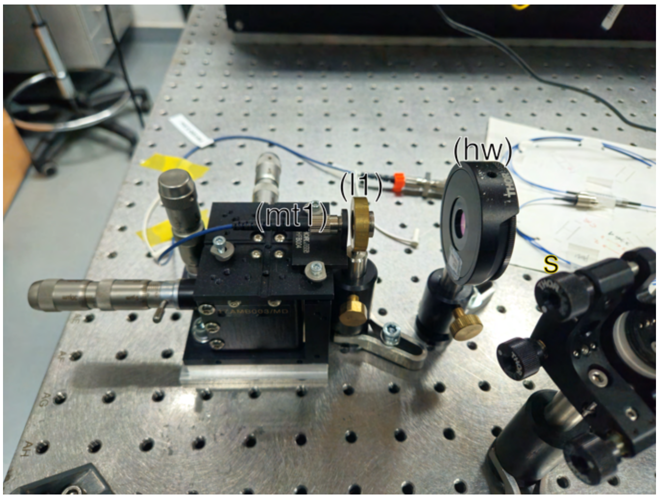


Figure 3.11: A photo of the first collimator system constructed for generating the beam used in the experiment.

I mounted the lens (l1) in front of the laser output placed on the 3-axis precision mount (mt1). This system is basically a manual collimator. By using that kind of setup I have more control over the collimation process, thus that allows me to achieve the best possible collimated beam.

Output mount system – (oms)

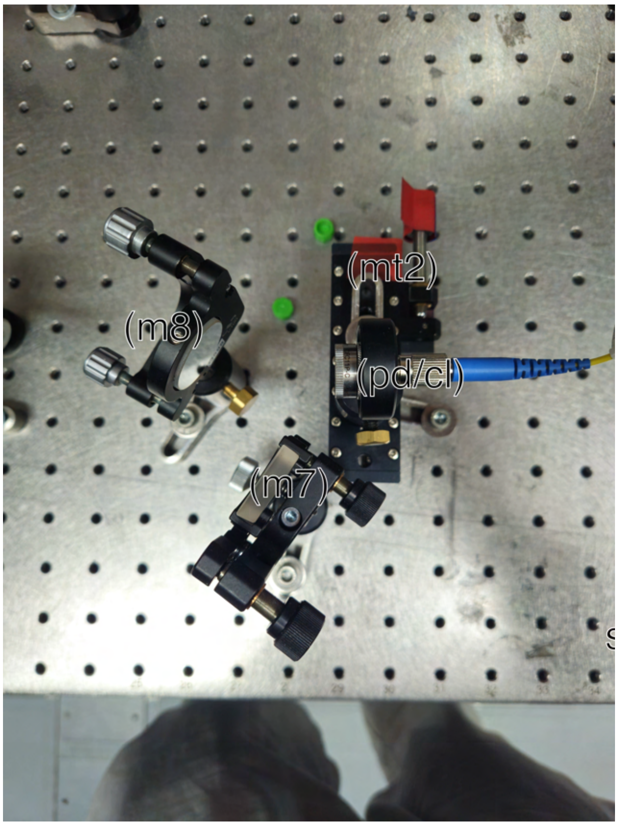


Figure 3.12: A photo of the second output system constructed for measurements.

The output system consists of: the D-shaped mirror (m7) which allows to redirect the outcoming beam, the mirror (m8) and the collimator (cl) or the photodiode (cl) for 1550 nm mounted in the precision mount (mt2) in a way that allows moving it smoothly in one direction — green arrow in Figure (3.4). That one axis is where the beam outcoming from the FACED is going to spread, the movement across that axis allows to scan the beam and perform measurements of different spots.

3.2.2. Set up procedure

Detailed steps followed to set up and calibrate the system are stated bellow. For setting up use a short bandwidth continuous wave laser until instructed to switch to a wide bandwidth pulsed laser – the one used in the final measurements.

1. Build the Telescope – (t).

2. Build the lens-FACED table – (lft).

3. Build the FACED device – (fs).
4. Build the output mount system – (oms).
5. Build the input collimation system – (icm).
6. Connect, in this order; the fibre polarization controller(fpc) and the Faraday circulator (cr) to the output of the laser.
7. Connect the output from the circulator and mount the other end in the collimator system(ics).
8. Mount the half-wave plate(hw) in front of the constructed collimator (isc). I am using the half-wave plate (hw) to control the polarization of the light because the intensity of the light diffracted by the diffraction grating that is going to be mounted in the set up depends on the polarization.
9. For ease of use I mounted two mirrors; (m1) and (m2). That allows me to control the further path of the light and level out the beam with a optical table.
10. Reserve a space between those two mirrors and the next one for mounting the telescope (t) in the future steps
11. Mount the mirrors (m3) and (m4).
12. Mount the diffraction grating (d). It should be mounted on a precision 3 axis table with the ability to control a rotation around its vertical axis.
13. Using the mirror (m4), position the beam so that it hits the center of the diffraction grating.
14. Set up the half-wave plate (hw) to the position where the beam reflected from diffraction grating has the maximum intensity.
15. By observing the beam reflected form the diffraction grating and the diffraction beam set up the diffraction grating so that the diffraction grating lines are vertical.
16. Rotate the diffraction grating until you find a position where the reflected beam has minimum intensity.
17. Set up the half-wave plate to the position where the beam on the diffraction grating has maximum intensity(if easier find minimum of the beam intensity reflected from the the diffraction grating).
18. Find a optical axis after the diffraction.
19. Mount the telescope (t) in the reserved space and check the collimation of the outgoing beam.

20. On the side or after the mirror (m4) set up the lens (l2), if on the side, redirect the output from the telescope. After the lens (l2) mount a mirror of any kind so that it reflects back. Set the mirror in the focal length of the lens (l2) by observing the reflected beam. Move the mirror until the reflected beam has the same size as the initial beam from the telescope and is collimated. That step it to find the real focal length of the lens (l2)

21. Fix distance between the lens (l2) and the mirror used for the calibration, for example with rods or plates.

22. Move the lens (l2) with the connected mirror and mount it in the designated place on the optical axis after the diffraction grating in the system. Mirror should be placed in the way that the beam from the diffraction grating goes through the lens (l2) and is reflected straight back.

23. To mount the lens (l2) in the focal length distance from the diffraction grating measure diameter of incoming beam before the diffraction grating and by moving the lens (l2) and the attached mirror find a place where the diameter of the reflected beam is the same. Using the reflection method set up the lens perpendicular and so that the beam hits the center of it. If the lens is flat-convex type, mount the flat part towards the diffraction grating.

24. Remove the mirror attached to lens (l2), used for calibration.

25. In the approximately distance of the sum of the focal lengths of the lenses (l2) and (l3) from the lens (l2) mount the lens-FACED table (lft). Turn the FACED device so that the mirror (m5) is perpendicular to the incoming beam and reflects it straight back. Tilt the mirror (m5) slightly downwards so that the returning beam goes under the incoming beam.

26. By moving lens-FACED table find place where, between lenses (l2) and (l3), outgoing beam has the same diameter as incoming. That allows to mount the lens-FACED table in the exact distance of the sum of the focal lenghts of the lenses (l2) and (l3).

27. Set the mirror (m5) in the approximately parallel position to the mirror (m6).

28. Turn the FACED device so that the beam enters it and exit on the other site. Device should be rotated approximately few degrees around its vertical axis.

29. Tilt the mirror (m6), so that the beam stops inside the FACED device.

30. By repeating those steps correct the outgoing beam so it returns straight bellow the incoming beam and few millimeters under it. There are 4 parameters to control while calibrating, the angle of whole FACED device, the distance between the mirrors (m5) and (m6) and angle of mirror (m6) in x and y. Perform steps in a very small increments;

- Set the distance between the mirrors to about 1.5 cm.
- Check the position of outgoing the beam.
- Turn the FACED device to move outgoing the beam to the desired position.
- If the beam disappears during the previous step correct the mirror (m6). Look at the pattern that the light creates between the FACED mirrors. By finding if the light exits at the bottom/upper or the end part of the device one can find out in which direction to move the mirror (m6).
- Repeat the last 3 steps if the spots in the output beam are not visible.

31. Correct the vertical position of the outgoing beam by moving the mirror (m5).
32. Lock the mirrors movement in the FACED device and the whole FACED device if possible.
33. Between the lenses (l2) and (l3) place the D-shaped mirror (m7) to redirect the outgoing beam without disturbing the incoming beam.
34. Mount the two-mirror system of the mirrors (m7) and (m8).
35. Calibrating measurement systems can be done in two ways, for observing the signal in a domain of wavelength using an Optical Spectrum Analyzer and for observing in a domain of time using an Oscilloscope.
    - Wavelength domain–In the output mount system (oms) connect collimator (cl) to fiber–ideally use a multi-mode fiber, it is easier to collimate into a multimode fiber than a single mode fiber. Using connected on the other end of fiber power meter, mirrors (m7) and (m8) couple beam into the fiber.
    - Time domain–instead of collimator (cl) from previous step mount photodiode(pd) into the output mount system (oms). Perform the same collimation procedure as in previous step. When collimated, trigger oscilloscope on the second output from the Faraday circulator (cr), and measure signal from beam outgoing from FACED device.

3.2.3. Performing the measurements

The wide bandwidth laser I used for the measurements is the Menlo Systems C-Fibre HP. Central wavelength of beam is 1550 nm and full spectral width at half maximum power of the signal (FWHM) is ≈ 20 nm. In my case power at the input to the system was approximately 100 mW, that amount is necessary as the system has a lot of elements that introduce losses. More about it in section (3.3).

Spectral measurements

The steps followed by me to conduct the measurements of output signal in wavelength domain are stated below.

1. Follow the steps necessary for callibration of the system output (35), mentioned in section (3.2.2). calibrate measurement for wavelength domain.

2. Switch to wide spectrum pulsed laser.

3. Confirm that spots like in figure (3.3) are visible between after last mirror (m8), preferably using light sensitive card detector or infra red sensitive camera.

4. By using the mount (mt2), move the collimator (cl) into position of spot that you desire to measure.

5. Couple into the collimator using the mirrors (m7), (m8) and a power meter connected to the output from collimator (cl).

6. Disconnect the power meter and connect the optical spectum analyzer (OSA).

7. Conduct the measurement

8. Repeat the steps (4),(5), (6) and (7).

Time delay measurements

The steps followed by me to conduct the measurements of output signal in time domain are stated below.

1. Follow the steps necessary for the callibration of the system output (oms). Calibrate the mesurement for the time domain system as mentioned in step (35) of the setup procedure.

2. Switch to the wide spectrum pulsed laser.

3. Confirm that the spots, like in Figure (3.3), are visible between after the last mirror (m8), preferably using a light sensitive card detector or a infra red sensitive camera.

4. By using the mount (mt2), move the photodiode (pd) into the position of the spot that you desire to measure.

5. Using the mirrors (m7) and (m8) maximize an output from the photodiode (pd).

6. Conduct the measurement.

7. Repeat the steps (4), (5) and (6).

3.3. Problem of instability, complexity and losses

The FACED system has many degrees of freedom, moreover some of them are correlated. It is very hard, if even possible, to change the entry angle of the beam to the FACED system, without changing the position of the outgoing beam. As for now rotating the FACED device requires changing the position of the outgoing beam to again aim it into the collimator, that causes change of the parameters influencing the value of generated group delay dispersion, thus it is impossible to perform dispersion measurements only for the change of one parameter, e.g. the angle of the incidence beam going into the FACED device.

Another, not insignificant obstacle, are losses. Even ignoring the losses of my system until the beam enters the FACED, the device itself generates significant losses that are rising exponentially due to its design. The beam bounces hundreds of times and each bounce absorbs about 0.2% of the energy – for the dielectric mirror used in system. For example for 200 bounces the final intensity is $0.998^{200} \approx 0.67$, as a result of which transmission = 67% of the initial beam. In addition, another source of loss is the obstruction of the beam coming out of the FACED by the lens (l3), because for some configurations of the FACED, outgoing beam is wider than the size of the lens (l3).

Taking into account the above circumstances, the system requires using the best available mirrors and lenses in terms of reflection and transmission coefficients. However, even so, it is necessary to use a high power input beam of $P \approx 100$ mW.

3.4. Measurements

Firstly, i built and calibrated the system shown in Figure (3.1) using the instructions provided in section (3.2). Next, following the procedures from the section (3.2.3) I performed, firstly, the time delay measurement and then the spectral measurements.

The time delay analysis allowed me to measure the delays between the signals, whereas the spectral measurements, the spectra of the observed signals. Those two element when combined together allowed me to determine the occurrence of a group delay dispersion.

Unfortunately due to the complexity and instability of the constructed system, as detailed in section (3.3), during the change of the measurement type, changes to the system are introduced. The signal wave forms and the spectra presented below cannot be assumed to come from the same measurement series.

3.4.1. Time delay analysis

For time analysis I used the photodiode (pd) mounted in the output mount system (oms).The signal from it was connected to the oscilloscope (OS). The device was triggered on a rising edge of the signal registered on the photodiode connected to the second output from the Faraday circulator (fc). Both photodiodes are of the same type. Technical details of the measurement are stated in section (3.1). In Figure below dependence of voltage registered by the photodiode on time has been presented.

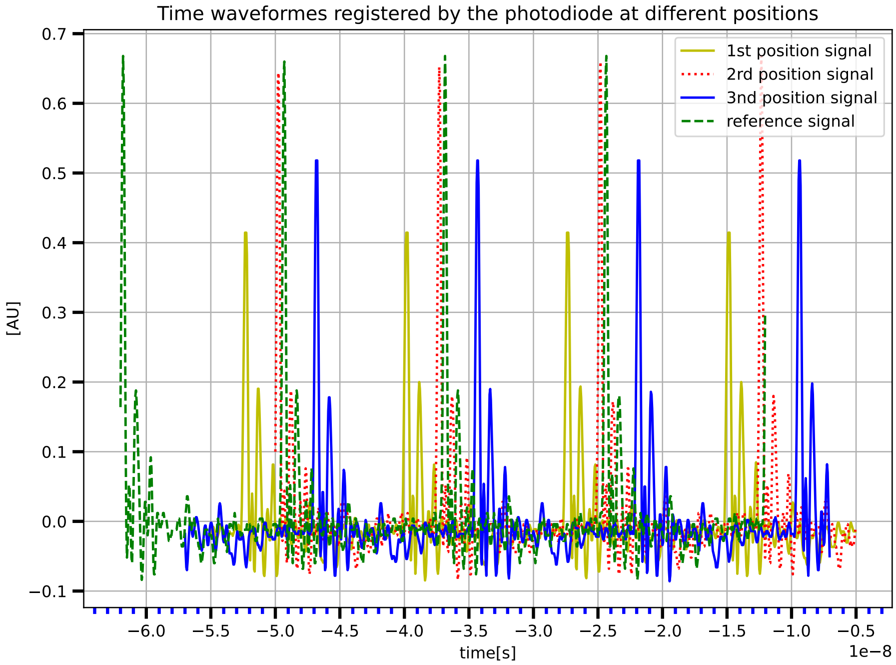
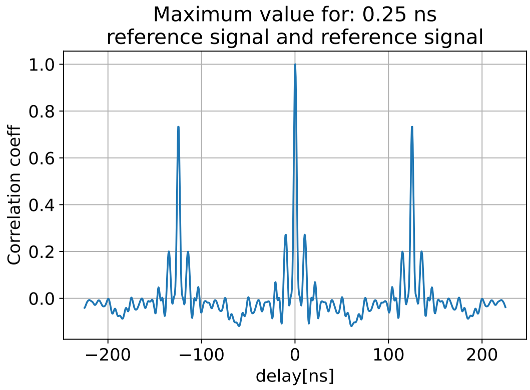
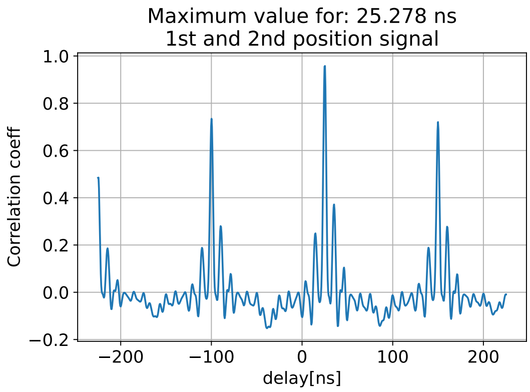


Figure 3.13: The registered time waveform from the oscilloscope of the four spots observed in the output beam.

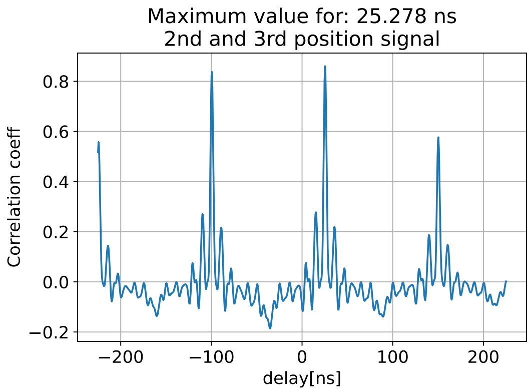
To properly asses time delay of the impulses, I calculated the cross correlation between the signals measured at the FACED device output — or to be precise, the spots appearing in the output beam, more in section (3.1). In Figures (3.14a – 3.14c) the dependence of the correlation coefficient on the time delay has been presented:



(a) cross correlation value for 3rd position signal with itself



(b) cross correlation value for 1st and 2nd position signal.



(c) cross correlation value for 2nd and 3rd position signal.

Figure 3.14

Using the calculated cross correlation maximum for each pair, the time delay between the signals was determined. The cross correlation of the 3rd signal with itself has been provided as a way of calculating the uncertainty of this method, it has been assumed as $u_c = 0.25$ ns. The reference signal plotted in Figure (3.13), was only used for triggering, time delay between the output signals and the reference signals is not important so it was not calculated. From the figures (3.14a – 3.14c) I can tell that time delay achieved between the spots in the output beam is equal (25.278 ± 0.25) ns. Uncertainty of the oscilloscope and other sources of it were omitted as they turned out to not be that significant compared to the value of 0.25 nm. Furthermore, this measurement is intended to be a proof of concept only, where precise estimation of uncertainty is not needed.

3.4.2. Spectral analysis

To properly asses that the signals were measured for different wavelengths, I conducted spectral analysis of the output signals. For that measurement I coupled the spots in the output beam into the collimator using system (oms). The fiber was connected to the optical spectrum analyser (OSA) that I used to perform the spectral analysis. Technical details of the measurement are stated in section (3.2.3). It is important to note that due to the complexity of system or changing type of measurements some changes to the system were introduced during the recalibration process and that spectral analysis and the previous time delay analysis cannot be recognized to come from the same measurement series. Different number of observed spots (3 in time delay analysis and 4 in spectral analysis) unfortunately prove that idea. The spectra of the measured signals are presented in Figure (3.15).

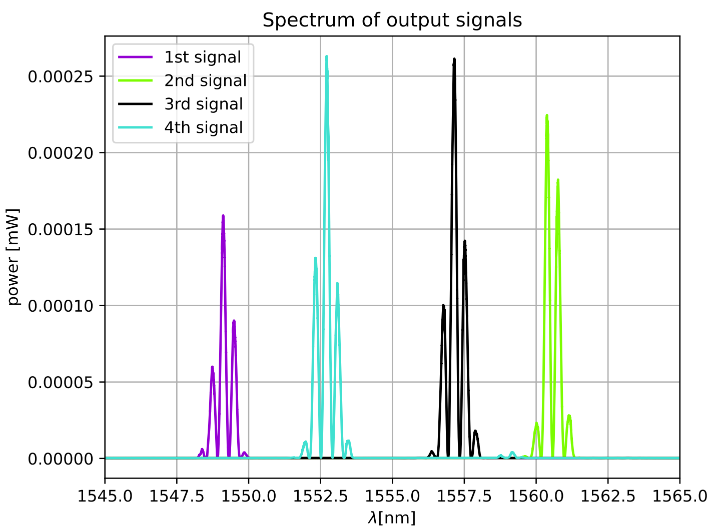


Figure 3.15: The spectras of the spots in the output beam registered by the Optical Spectrum Analyser

As we can observe, the spectral distance between the neighbouring signals is approximately 3 nm. This and the considerations from the previous subsection allows me to believe that I indeed achieved group dispersion, even though the fact that the measurements does not come from the same measurement series.

3.4.3. Approximation of number of bounces between mirrors

Using the known parameters, the time delay and the distance between the mirrors it is possible to estimate the number of reflections between the mirrors. This cannot be considered a perfect calculation because I neglected the change of the distance between the mirrors resulting from their misalignment angle. Using a simple distance formula I estimated the difference in the optical path that generates the measured time delay $\Delta d = 3 \cdot 10^8 \frac{\mathrm{m}}{\mathrm{s}} \cdot 25.278 \cdot 10^{-9} = 7.58$ m. Then dividing this value by the distance between the mirrors gives an estimate of the number of reflections equal to $N \approx \frac{7.58 \text{ m}}{0.015 \text{ cm}} \approx 505$.

3.5. Applications

The FACED device can be effectively utilized in various fields:

Ultra-Fast Imaging: By distributing a signal over time, detection of the signal can be achieved using a single photodetector. This capability enables the observation of extremely fast processes, such as movement of blood cells, which would be challenging or impossible to capture with a standard camera due to the speed limitations of CCD matrices. For more details, see the publication [6].

Real-Time Spectroscopy: This technology facilitates the analysis of spectroscopic signals from events that are either unique or occur at the exceptionally high speeds. Further information can be found in [2].

Signal Shaping: The device functions as a pulse stretcher, making it a crucial component in many optical systems. With its potential ability to adjust dispersion, it is applicable in the scenarios where standard methods, like those discussed in the chapter (2), do not cope.

Further research

I anticipate further research on the technology and the system itself in the following areas:

Minimization of losses: There are numerous components that currently introduce losses, which could likely be minimized. For instance, using a larger lens or one with a shorter focal length might help reduce losses introduced by obstruction of the ougoing part of the beam.

Exploration of the system's applications: As outlined in the chapter (3.5), it would be beneficial to fully explore the potential of the FACED technology, particularly in an applications such as ultra fast spectroscopy and pulse shaping.

Miniaturization: Currently, the system occupies a considerable amount of space on a optical table. I believe it can be made more compact without compromising performance.

Simplification of the calibration process: At present, the experiment is highly sensitive to any changes made to the optical components, making a recalibration complex and time-consuming process. It would be advantageous to develop elements or methods that simplify the calibration and operation of the system.

Expansion to medium wavelengths infrared signals: In this work I managed to implement the part that was to be an introduction to the initial plan for this project. This turned out to be more than difficult and overcoming technical problems required significant time resources. The next step is the implementation of the initial goal, which is to expand the FACED method to work with medium wavelengths infrared signals. Such a change brings with itself difficulties, such as the need to change the lenses, the mirrors and the diffraction grating to the elements specially created for this wavelength. In addition, medium infrared wavelength is difficult to work with, because it is impossible to observe the beam path using detection cards, instead the best solution is to use a camera with a sensor sensitive to medium infrared waves.

Chapter 4

Summary

In this work I proved that the FACED approach has a future and can be successfully used to achieve group delay dispersion as an alternative to the more conventional methods. The system still requires a lot of work, especially from the technical side because the setup process itself is quite complicated. The biggest advantage of this system is the potential ability to change the generated dispersion on the fly, allowing for fine tuning this parameter to the desirable value in the system. However, this remains yet to be proven in the further research. Moreover, it would be interesting to test the system in applications where it can show its advantage, such as time spectroscopy, ultrafast imaging and extend its functionality into medium wavelengths infrared signals.

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Chapter 5

Appendix

5.1. Finding optimal diffraction grating angle

To find the optimal incidence angle for a diffraction grating I measured dependence of the relative diffracted power on the incidence angle for the diffraction grating (d) used in the system. The diffraction grating used in the experiment has 1200 lines/mm. The data from that measurement is presented in Figure (5.1).

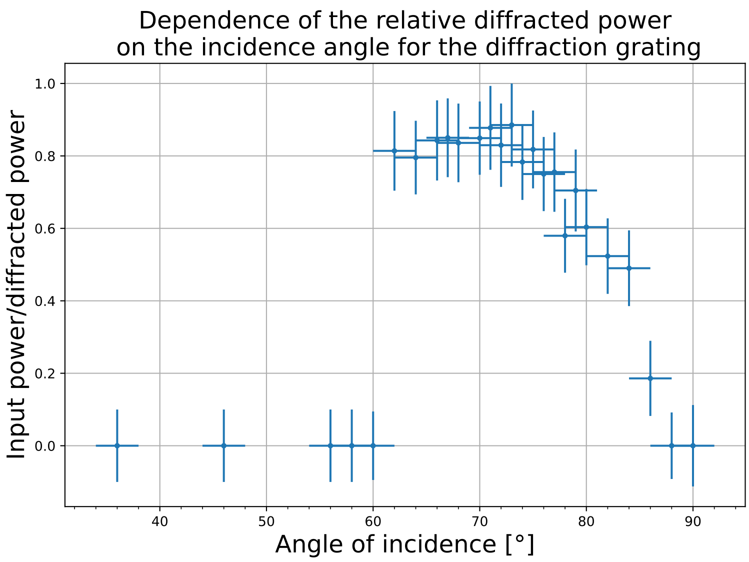

Figure 5.1: From data of dependence of relative power on the incidence angle for the diffraction grating in the system, I can expect to get the maximum diffracted power at around 72°.

To conduct the measurements I used the thorlabs power meter mounted 10 cm from the diffraction grating. The angles of the incidence and the outcoming beam were calculated by tracing the paths of the beams on the optical table to construct triangles in reference to the diffraction grating. Next, the angles were calculated using inverse tangent of the constructed triangles. Uncertainties were estimated based on the uncertainty of: the tape measure used to measure traced paths, the precision mount used for the diffraction grating and the stability of the power meter.