Determination of femtosecond laser pulse duration using a second-order autocorrelator

Report of Project information technology
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March 2008

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Abstract

The software developed in this experiment makes it possible to obtain an accurate value of the duration of a femtosecond laser pulse. The setup can easily be placed in the path of a laser beam and can be aligned fast. The table, on which a Michelson interferometer is built, is small and can therefore be installed where only limited space is available. A simple audio speaker generates a different path length between the two arms of the interferometer as a function of time, from which an interference pattern can be obtained.

Using a solid-state quasi-monochromatic continuous wave laser beam and applying a continuous sine function with low frequencies to the speaker, a calibration curve is obtained giving a relation between the applied voltage and the displacement from equilibrium position. The absolute zero point of the speaker cannot be determined in this experiment. The error with respect to the relative zero displacement gives a value of only 2 μm at the highest displacement, which corresponds to 6.6 fs. The function generator should be fine-adjusted in a range of ±0.2 Hz for the frequency and ±0.04 V for the amplitude to obtain errors of 1.0 μm in a range of 0.1 V and 1.6 μm in a range of 0.2 V from zero voltage.

The autocorrelation pattern is obtained by using the process of two photon absorption. As a detector, an inexpensive light-emitting diode is used with a bandgap larger than the energy transmitted by a single photon of the incident light beam. Autocorrelation is measured for two different pulse repetition rates: 1 kHz and 80 MHz. The duration of an autocorrelation measurement depends strongly on the choice of the repetition rate. In the software a fit giving the width of the pulse with Gaussian shape gives good results, although it is for some measurements difficult to follow the envelope of the acquired curve. A manual fit function avoids this problem.

1 Introduction

In experiments where pulsed lasers are used, optical devices like mirrors or beam splitters can change properties of the pulse. So even when the characteristics of a pulse are initially known, the characteristics are not known when the pulse reaches its target. The aim of this experiment is to develop a software tool that measures the width of the laser pulse in a short time. It should also be possible to repeat the measurement. By using a Michelson interferometer as an autocorrelator the pulse length is measured.

In a Michelson interferometer the properties of interference are used to obtain a value of the intensity as a function of the displacement in optical path length. When a continuous wave laser (CW laser) is used, the interference pattern can be used to measure the difference in path length. When this displacement is created by moving the coil of a loudspeaker with a mirror glued on top of it, the change in optical path length can be described by a difference in voltage. In the first part of this experiment a relation between these quantities is considered.

Once the difference in optical path length as a function of the input voltage of the loudspeaker is known, it is possible to calibrate the voltage scale of the autocorrelation function of the pulse. Because the length of the pulse is known to be in the regime of hundred femtoseconds, it is not possible to use the real-time properties of a photodiode. As a solution, the non-linear behaviour of the photodiode will be used to create an autocorrelation graph. A width of the curve can then be calculated. Two-photon processes are responsible for the non-linear behaviour.

2 Theory

2.1 Michelson interferometer

In a Michelson interferometer, one beam of light is separated in two beams by a 50/50 beam splitter. Each of these two beams follows a different path with a different path length until they are mixed together again. The optical path length of one or two of the arms may be adjustable, either manually or driven by an electrical-controlled mechanical system. Mixed together, the two beams form an interference pattern according to the phase difference created by the difference in path length [1].

The setup of a Michelson interferometer is shown in the figure below. After the entrance of the beam in the interferometer through an iris diaphragm it reaches the beam splitter. The iris diaphragm can also be used to align the setup. The beam splitter splits the beam into two identical beams with the same intensity (hopefully) and wavelength. The first beam will directly reflect on a mirror, after which it returns to the splitter. The second beam goes through a compensator plate, then also reflects on a mirror, goes again through the compensator plate and again reaches the beam splitter. Finally, the splitter creates a superposition of the two beams which can be projected on a detector. To obtain good results, a lens can be put between the beam splitter and the detector. Also a second iris diaphragm can be placed for alignment purposes.

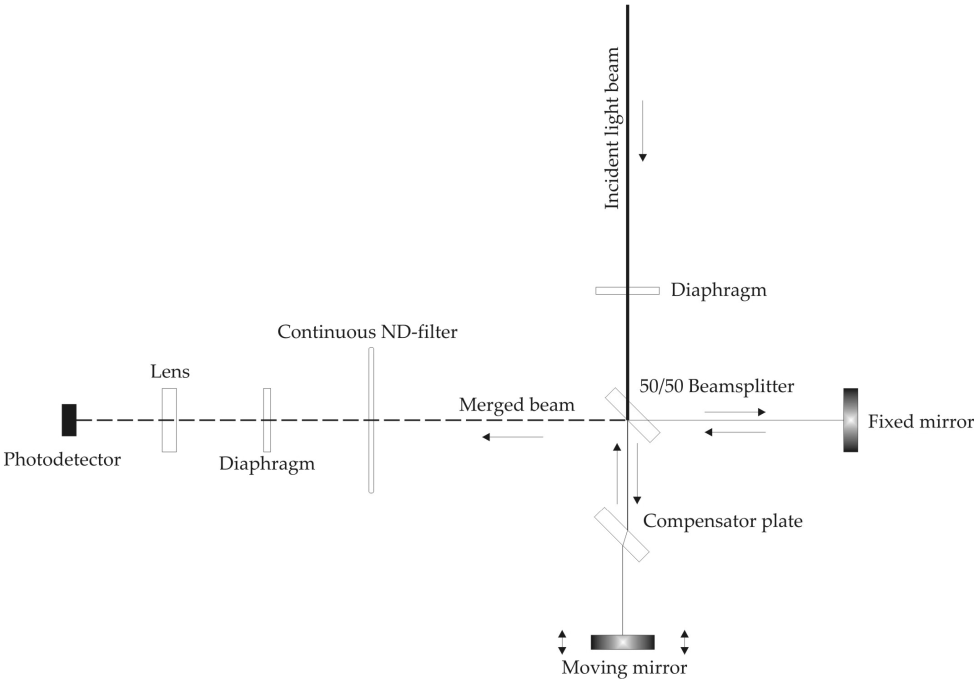


Figure 1: The setup of the Michelson interferometer used in this experiment.

The compensator plate in the second splitted beam is needed because the beam splitter is constructed from a transparent crystal like glass with a half reflecting layer on top of it. When the first splitted beam reaches the lens placed before the photodiode, it will have passed the glass in the splitter three times. When no compensator plate is placed in between, the second splitted beam will go through the same material only once. In case of a monochromatic light beam, this difference will not cause any problem due to dispersive characteristics of light in a material. Ultra short laser pulses have, by definition, wide bandwidths. To avoid dispersion the compensator plate is placed in the optical path and is passed twice by the beam. The second beam has now passed the material equally often as the first beam. The compensator plate is made of the same material and has the same thickness as the beam splitter. The only important difference is the missing half-reflective layer on top of the glass. As a conclusion, the compensator plate ensures equal dispersion in both arms.

2.2 Pulsed laser

To obtain short laser pulses the superposition of a broad spectrum of light frequencies is used. For the generation of pulses the phases of the different frequencies have to be aligned. This principle is called a mode locked laser. By using a laser medium with a high frequency bandwidth, laser pulses can be obtained having a pulse length of only a few femtoseconds. Ti:sapphire lasers are these days very common, having the highest intensity at a wavelength of around 800 nm.

2.3 Gaussian function and autocorrelation

The Gaussian shape which is used in this experiment to characterize the laser pulse can be given by

$$f(x) = a\exp\left(-\frac{(x-b)^2}{2c^2}\right) + d\,, \tag{1}$$

where x is the running variable, a defines the height of the function, b is the displacement from the zero point, c defines the width of the curve and d is a constant. The Gaussian function is needed to make an estimation of the full width half maximum (FWHM) of the pulse. After fitting the curve, the width of the curve at FWHM can after some algebra be easily obtained from the value of c by

$$w_{FWHM} = 2\sqrt{-2c^2\ln(0.5)}\,. \tag{2}$$

The autocorrelation function of a single function with a time delay between two components is defined by [3]

$$R_f(t) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} f(\tau) f(t+\tau) \mathrm{d}\tau \,. \tag{3}$$

It follows that the autocorrelation of a Gaussian function is also a Gaussian function, with a prefactor of $\sqrt{2}$ in the width.

2.4 Second-order autocorrelation

By using the effect caused by the non-linear behaviour of the pulsed laser it is rather easy to obtain a measurement of the pulse duration. This behaviour, which is only seen when light intensities are very high, is described by a Taylor expansion of the polarization **P** of a medium in the presence of an electric field **E** [4]:

$$\mathbf{P} = \Omega_1 \cdot \mathbf{E} + \Omega_2 \cdot \mathbf{EE} + \text{higher order terms} \,. \tag{4}$$

When a beam, built up by the components of this expansion, is directed to a photodiode the influence of this whole expansion is measured. However, when a semiconductor detector is used with intrinsic bandgap energy higher than the energy contained in the photons of the beam, the linear term is minimal. Expressed in wavelengths this means that the wavelength of the laser beam should be larger than the wavelength at which electrons in the semiconductor are excited. When the semiconductor material is now properly chosen, the influence of the second-order term can be measured. In the case of second-order autocorrelation two photons are captured at the same time in the semiconductor material. This results in an excitation with twice the energy of the initial photons. When the bandgap in the semiconductor is below this value, the second order polarization dominates the measurement.

Creating a superposition of two identical electric fields, where one has a phase delay τ, the autocorrelation function is given by (adapted from [4, page 188])

$$I_2(\tau) = \int_{-\infty}^{\infty} \left| \{E(t)\exp(\mathrm{i}[\omega t + \varphi(t)]) + E(t-\tau)\exp(\mathrm{i}[\omega(t-\tau) + \varphi(t-\tau)])\}^2 \right|^2 \mathrm{d}t \,. \tag{5}$$

Using the standard autocorrelation function, T is taken as ∞. Considering two typical phase differences at $\tau = 0$ and $\tau = \infty$, the intensities are given by

$$I_2(\tau = 0) = 2^4 \int E^4(t)\mathrm{d}t \text{ and } I_2(\tau = \infty) = 2\int E^4(t)\mathrm{d}t \,.$$

It follows that the ratio between maximum and minimum intensity is given by a factor of 8.

3 Experiment

The experiment is divided in two parts to obtain an accurate estimation of the pulse width from the laser beam inserted into the Michelson interferometer. First the audio speaker used in the setup has to be calibrated, giving a relation between the applied voltage and the displacement from equilibrium position. Once this relation is known, the results from autocorrelation measurements can be calibrated. Finally, the Gaussian shape found by the autocorrelator has to be fitted. Central in this experiment is the use of the well known Michelson interferometer, which was described in the theory. A Mach-Zehnder setup can also be used [5], but the alignment is harder. By making use of the audio speaker, a high repetition rate for the experiment can be obtained. This gives the advantage of a real-time experiment. The properties of the changing laser pulse can now be determined 'online'. Some pictures of the block diagram in the software are shown here, for the rest the reader is referred to the main programs *Calibration.vi* and *Autocorrelation.vi*. Manuals of the main programs are given in the Appendix, as well as an overview of the subVI's.

3.1 Calibration

To make use of the properties of the Michelson interferometer, the relative phase difference between the two different arms has to be known. Translating the phase difference into a difference in arm length, the moving mirror glued on the audio speaker gives rise to a displacement from equilibrium position.

A calibration of the displacement from the audio speaker as a function of the applied voltage is obtained by inserting a quasi-monochromatic CW laser beam from a conventional helium-neon laser beam supplied by JDS Uniphase with a wavelength of 632.8 nm into the interferometer. A Philips PM5132 function generator is used to apply a sine function with frequencies between 4 Hz and 8 Hz to the audio speaker from a cheap transistor radio. The speaker with the mirror on top of the conus is placed perpendicular to the second arm of the interferometer. In the first arm, a fixed mirror is placed. A standard photodiode with an extern accu pack as a power supply is used to measure the interference pattern. After alignment of the setup, where the two beams are directly overlapped after passing the beam splitter, an interference pattern is seen on the Hameg HM2005 oscilloscope.

The combination of the signals, those from sine generator and photodiode, can now be used to create a calibration curve. For this calibration a software tool is developed, using a National Instruments 6035E DAQ as an analogue to digital converter (ADC). The key principle used in the calibration is setting the zero voltage output of the sine generator as a relative zero point in displacement. In the following text, the software is explained. LabView 7.1 is used as programming and running software tool.

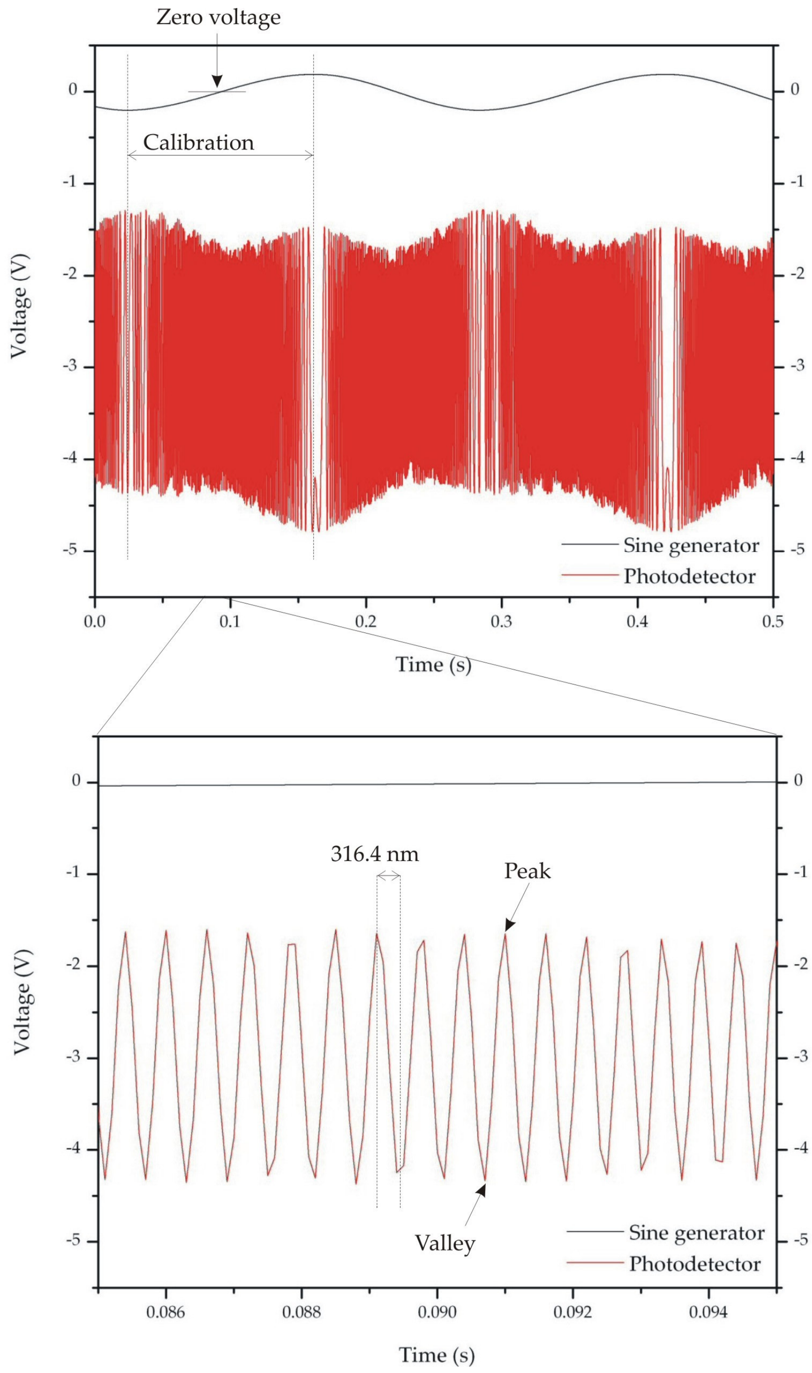


Figure 2: Typical interference pattern from a continuous wave laser beam in a Michelson interferometer. The voltage (V) from the function generator and the photodiode are plotted as a function of time (s). To see the interference pattern, the timescale from the upper graph is zoomed in.

Step 1: Performing measurement

On the front panel the total number of measurements can be controlled, as well as the number of samples per measurement. The ‘number of measurements’ is used to create a reliable calibration, where the average is taken over the different calibration curves. The total number of samples should be high enough to have one part of the curve of the sine generator from a valley to a peak at a rate of 50k samples per second.

Also the frequency and amplitude of the sine function are measured and displayed on the front panel, as well as a graph of the current measurement.

Step 2: Calibration of a single measurement

This step is contained in the subVI *CalibrateMeasurement.vi*. The merged signals from the sine generator and the photodiode are the inputs. These signals are splitted, after which the dynamic data is via a waveform converted into an array. From the sine function, the range from first valley to peak is selected by finding the index numbers of first minimum and first maximum after this point. Also the zero voltage point in between is given, by searching for the first point where the ratio between the current and previous point is smaller than zero. With this set of three index numbers, which correspond to the index numbers of the array with data from the photodiode, the calibration can be performed.

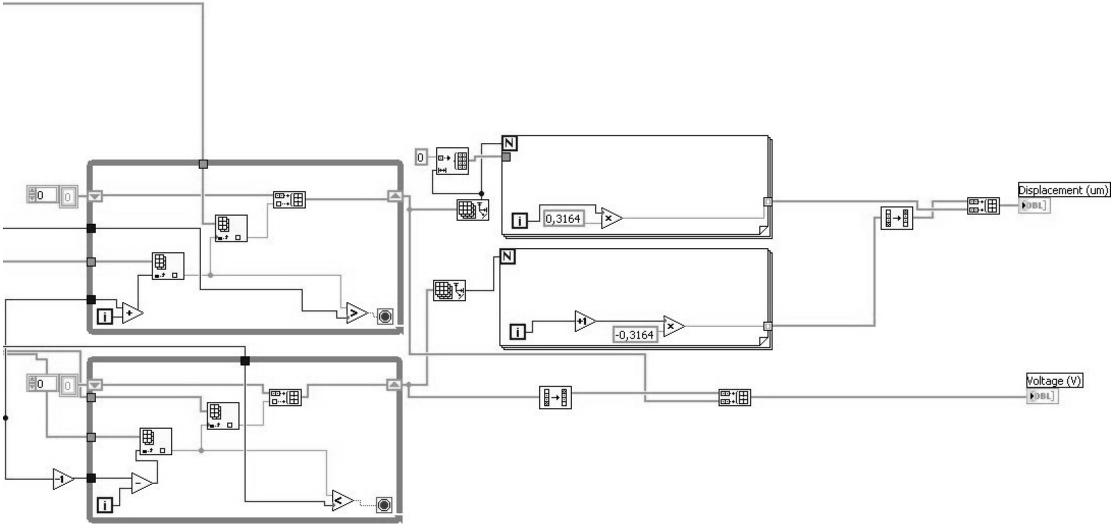


Figure 3: Part of the calibration routine of input voltage versus displacement, using the voltages from function generator and photodiode as inputs.

From the data from the photodiode, the peaks and valleys are selected by the built-in peak detection subVI. It is known from the interference pattern that the distance between a peak and a valley is the displacement difference of half the wavelength of the light beam. This gives in this case a difference of 0.3164 μm. The two arrays of index numbers are merged and sorted in climbing number. The zero voltage point then marks the setting of the relative zero displacement point. Then it is investigated if the previous point in the array with valleys and peaks from the photodiode is closer to the zero point in voltage. If this is the case, this point is taken as a zero point. Hereafter, two parallel while-loops start to run: one is running 'backwards' in voltage and one is running 'forwards'. At the points of the peaks and valleys, the voltage of the sine generator is read out until the minimum and maximum points in index numbers are reached, respectively. These voltages now each correspond to a difference in path length as shown before. The displacements are also calculated in two while-loops, using a constant factor and loop iteration number as a running variable. The two pairs of arrays are mixed together, after reversing the array which was calculated ‘backwards’. Two arrays giving a combination of voltages and displacements are the final result.

Step 3: Averaging the results

Each measurement now gives a single calibration. The length of each calibration is not known; even when the sine generator is not adjusted during the measurements the displacement of the speaker can differ a few micrometers per iteration. For the whole range of measurements, the minimum length of the calibration curve is obtained by looking for the minimum length from the equilibrium point to the maximum displacement in two directions. This minimum length is put in the subVI *Average.vi*, where the average of the calibrated measurements is calculated. Also the calibrations, the number of measurements and the zero indices are inserted.

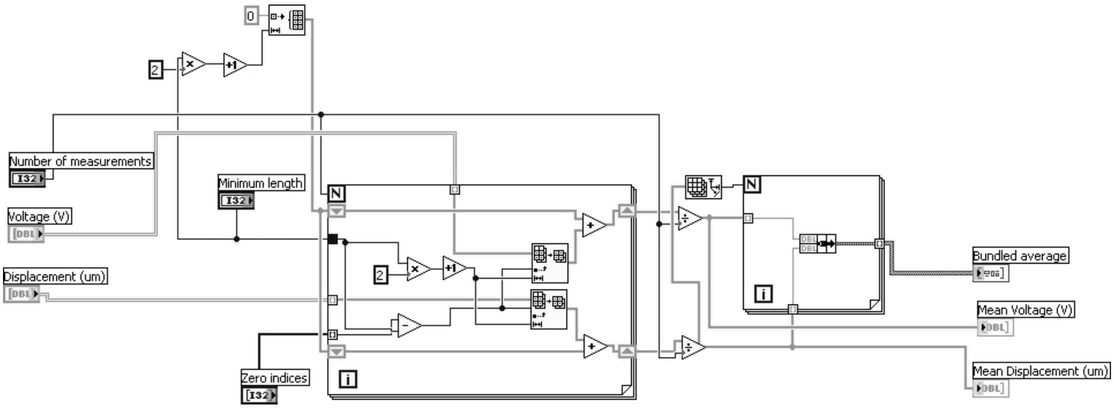


Figure 4: The complete subVI which averages over the total number of measurements.

Because the minimum length of the calibration curve is known, this gives the length of the average curve after multiplying this number with a factor two and adding one for the ‘zero point’. The result will be a symmetric array with respect to the zero voltage from the function generator. Because the zero indices for each of the calibrations are known, the subsets of the arrays can easily be selected from the original ones. Minimum values are given by the point of the zero index minus the minimum length to the boundary value. The length is for each array the same as the length of the average array. In a for-loop, using the number of measurements as the number of times the loop should run, all the subsets of arrays are added. Outside the loop, the array is divided by the number of measurements giving the averages. This process is executed for both the displacements and the voltages. For the latter this is not strict necessary, although it is a good check whether the software works fine. Finally, the two arrays are bundled, so that the bundle can easily be used for interpolation purposes.

Step 4: Saving the results

The results obtained from the calibrations and averaging can be exported to lvm-files, using a button in the main program to enable or disable this function. For this purpose the subVI *FileSave.vi* is developed. In the main program the frequency and amplitude per measurement are obtained from the built-in function 'Tone Measurements'. The results are averaged and inserted into the subVI. Also the preferred file name and directory are put into it, as well as the calibrated series of measurements and the averaged result. In the program, the series of measurements are split up into single measurements, after which they are saved separately. The file names are generated from the program it self using the inserted file name as a basis. For the average results and the information about amplitude and frequency also different files are used to save the results. For future applications for autocorrelation the results are used to convert the voltage into a displacement.

Step 5: Displaying the results

The current measurement, giving the results of the sine generator and the photodiode, is plotted as a function of time. Furthermore, all the calibration curves as well as the averaged calibration are plotted in one XY-graph. Single measurements can be switched off by using the plot legend.

Also a plot is made of the error of the series of calibrations with respect to the averaged calibration. This gives a measure of the error occurring during one series of measurements. To compare with a previous measurement, the path of a previous measurement has also to be inserted. This is obtained by using a case structure. In case of a previous measurement, voltages and displacements from a file are bundled. When the current average is used, the bundled average already exists. For each measurement, each calibration point is compared with the bundled average by using linear interpolation. The voltages in the series of measurements now give a displacement from the bundled average or previous measurement. These values can be compared with the actual displacement by contraction and taking the absolute value. As a function of voltage, displacement errors are now known and plotted in a graph. To obtain the arrays, two for-loops are nested.

3.2 Autocorrelation

Once the calibration curve of the audio speaker is known, it is relatively easy to obtain an absolute value of the curve width of an autocorrelation measurement of a pulsed laser. First of all, the pulsed laser beam has to be aligned in the Michelson interferometer. The beam is assumed to have a Gaussian shape and a peak wavelength of 800 nm. In this experiment, the pulsed laser is used with two different repetition rates, namely 1 kHz and 80 MHz. As will be shown in the discussion, the autocorrelation pattern of the latter one is the easiest to get, even though the intensity of the beam is much lower. Although it is possible to calibrate the displacement in the autocorrelation itself [6], this function is not used here.

The basic principle of showing an autocorrelation pattern on the computer screen is to plot the light intensity on the semiconductor detector as a function of the displacement of the speaker. In the Michelson interferometer, a simple light-emitting diode (LED) is used as a detector [7]. It is connected to an instrumental amplifier of Stanford Research Systems, model SR560. All the other components in the interferometer are the same as in the setup for calibration. During the alignment of the setup a Textronix TDS 3054 oscilloscope was used. In the following text the software developed to acquire data, convert the input voltages to displacements and fit the results is discussed.

Step 1: Acquiring and saving data

In this first step, the voltages from the function generator and the LED are measured as a function of time at a DAQ sample rate of 20 kHz. On the front panel the total number of samples can be adjusted, which is directly linked to the total time in which measurements are performed. In contrary to the calibration, where in one measurement only the subset between the first valley to peak from the sine function was considered, the total measurement time will be used.

As an option, also a previous measurement can be used to perform measurements on autocorrelation. For this purpose a button on the front panel can be switched between a new and a previous measurement. To use this function, a file path must be inserted. After acquiring the data, a tone and amplitude measurement is performed, from which the results are displayed on the front panel. This function can be used to check whether the function generator is tuned in correspondence to the calibration curve. The measurement can be saved to a lvm-file, which is also controlled by a button on the front panel.

Step 2: Converting voltage to displacement

By using a calibration curve, the voltage from the function generator can be converted into a displacement. The calibration curve is loaded in the main program and bundled for interpolation purposes. The conversion is now performed in the subVI *VoltageDisplacementConversion.vi*, where the voltages from the function generator, the LED and the bundled calibration are inserted. Because of hystereses of the speaker between ‘forward’ en ‘backward’ movements, only the first part is considered. A peak detection on the sine function is performed, for both peaks and valleys in the signal. To get only the subsets between the valleys and the peaks, which describe the ‘forward’ moving speaker, the first index in the array of the peaks must be larger than that of the valleys. If it is not, the first index is deleted. Then a test is performed which array is the shortest. The value indicates the number of subsets which can be used. Each subset is then treated in a for-loop. The start-point and end-point of each subset are given, from which the length can be easily obtained. From the initial arrays of voltages all these subsets are mixed together into two separate arrays. For the voltages from the function generator, all the values are converted into displacements, making use of the calibration curve and interpolating software. When the arrays are outside the loop, it is possible to convert the displacement, expressed in μm, into femtoseconds. This is easily obtained by multiplying all the values in the array with a factor of 3.3. Which display mode is considered can be inserted by a boolean.

Step 3: Detecting the peaks in the 1 kHz signal

When the repetition rate of the laser is 1 kHz, there are few measurements in one sweep of the speaker. Therefore, the results on the oscilloscope are seen as small peaks, describing the autocorrelation. These peaks are measured by the computer as pulses, which build up to the maximum voltage and then decay to zero voltage. Only the peak voltages are wanted, so a peak detection is executed on the array of voltages from the LED. At the found index numbers, the displacement is read out.

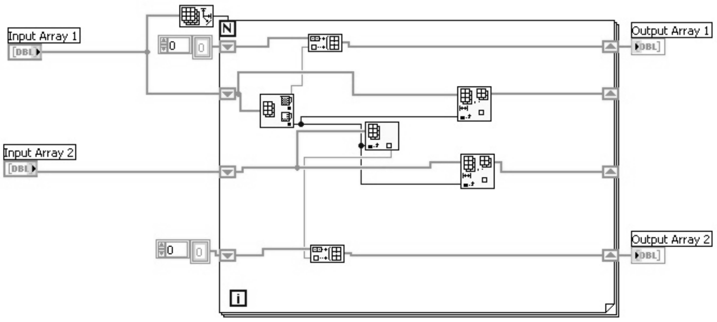


Figure 5: Sorting two arrays with respect to the first.

When several periods from the function generator are used, the result is now an unsorted array containing displacements and an array with corresponding intensities. To calculate maximum intensities over certain intervals, which is needed to fit the results, the array with displacements has to be sorted in climbing number. The intensities however still have to correspond to the displacements. This routine is performed in the subVI *ArraySort.vi*. In this program two arrays are inserted, where each time the minimum value of the first array is searched and both arrays are read out at this point. The operation is performed in a for-loop, using the size of the first array as the number of times the loop should be executed. Once a minimum value is found, this number is deleted from the first array, as well as the element with the same index number from the second array. Finally, the outputs are two arrays sorted with increasing values with respect to the first.

Step 4: Fitting the results

The fit-routine is completely performed in the subVI *GaussianFit.vi*. The inputs are the sorted voltages from the function generator and the LED with respect to the sine function. Also a value for the interval is inserted for determining the maximum value of the photodiode in a small range over which will be fitted. From the zero-point in displacement in each interval the maximum value is determined, making use of two while-loops running in positive and negative displacement direction. The output of each loop is an array containing the values of the displacement and an array with maximum intensities in the interval. The outputs from the loop in negative direction are reversed, after which the arrays of the other loop are placed at the ends. Finally, a fit can be performed using the built-in function in LabView. The coefficients in (1) are now easily obtained. The value of *c* can be used to determine the width at FWHM, see (2). Besides the coefficients a best fit is obtained.

Step 5: Displaying the results

In the main program, the width at FWHM is calculated and displayed on the front panel. The results from the voltage to displacement conversion, the sorted intensity peaks, the maxima over the intervals and the fit result are displayed in one graph, as well as a manual fit. This fit is developed in the subVI *GaussianFunction.vi* and needs the Gaussian coefficients *a*, *b*, *c* and *d* corresponding to (1). These are controlled on the front panel. The graph is contained in a while-loop, to make it possible to switch different graphs on and off through toggle switches, until a stop-button on the front panel is pressed. Controls like these are obtained by using property nodes. These nodes are also used to grey the controls for the manual fit when it is switched off in the graph.

The whole program is contained in a while-loop except the part where the calibration curve is loaded, which has to run only once. When a previous measurement is used, the large while-loop only runs once, while in the case of a new measurement the small loop takes place for one time. This makes it possible to adjust the properties of the graph after the measurement has been performed. Until the stop-button is pressed the while-loops continue.

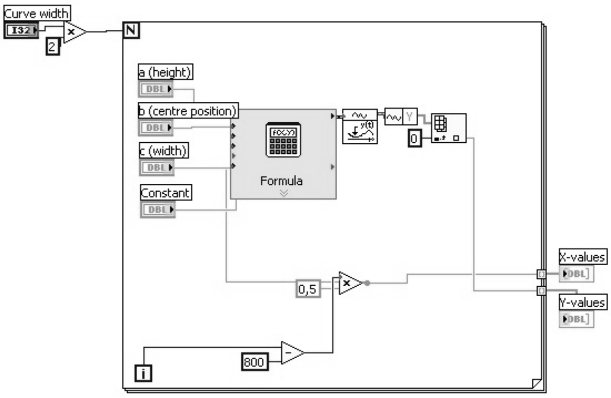


Figure 6: Manual fit routine.

4 Results and discussion

4.1 Calibration

The calibration curve gives for the used audio speaker at different frequencies typical displacements from rest position of around 25 µm at 0.1 V, 50 µm at 0.2 V and 110 µm at 0.4 V in a frequency range from 2 Hz to 10 Hz. This means that at an amplitude of 0.4 V a total displacement of around 700 fs can be measured; enough for laser pulses with a pulse width in the order of 100 fs.

When different calibration curves measured with the same amplitude but with different frequencies are plotted on top of each other, it is seen that they differ in linearity. At 8 Hz, for example, the curve seems to be rather straight, both for positive and negative voltages. When the curve is compared with one measured at 4 Hz, the latter has also non-linear components. At 6 Hz the effect is seen more difficult, but also observable. This does not mean however that errors are higher when certain frequencies are used. As a result, displacements of the speaker are highly predictable by tuning at the same frequency and amplitude as the calibration curve.

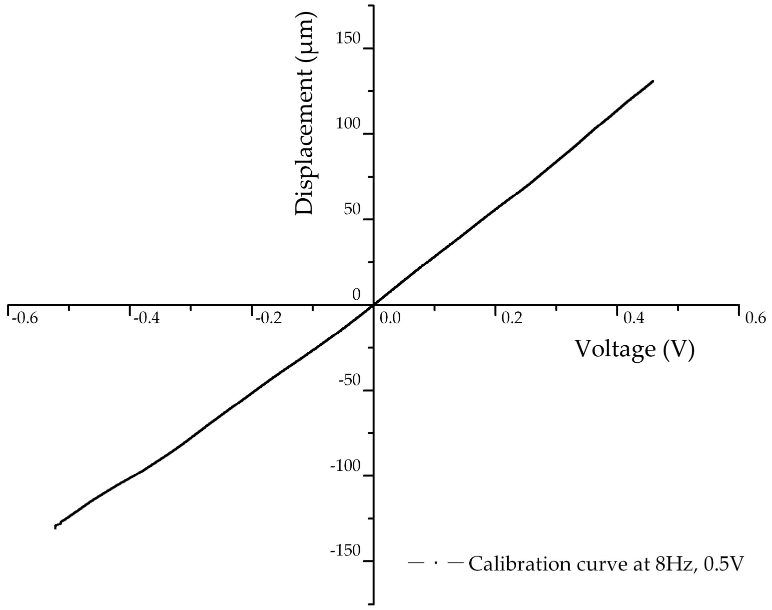


Figure 7: Typical calibration curve of the speaker at a frequency of 8 Hz and an amplitude of 0.5 V. The displacement on the vertical axis is plotted as a function of voltage.

The effect of different amplitudes is even stronger than that of frequencies. It can be easily explained by the non-linear behaviour of the speaker where the voltage reaches it maximum. When the amplitude is set at 0.4 V, the higher perturbation from the previous measurement starts around at 0.3 V. As a reminder, when the laser pulse is well adjusted the boundaries at which the pulse has fallen to its minimum voltages are around 0.1 V.

Another aspect in error which cannot be neglected is the warming up of the equipment, especially for the case of the function generator. The difference in error between a cold and a warm setup is at least a factor of two.

Although all the aspects mentioned above contribute to the error, the influence of the most important factor cannot be easily extracted from measurements. In the software, the point where the displacement is assumed to be zero from equilibrium position is the output of zero voltage from the function generator. All the other displacements are calculated from this point, meaning that a relative displacement is obtained. If one sweep from the sine function is considered, this does not harm the result. However, when more sweeps are contained in one measurement, all the zero points are assumed to be at the same place. This absolute zero though is not known explicitly. A measure could be obtained from the interference pattern by counting the total peaks in one sweep and comparing this number with other calibration curves. Practically, the interference pattern at the end of the sweep is disturbed, making it impossible to give a reasonable result. From the autocorrelation measurements it follows that the error can only be in the order of two micrometers.

The errors for displacements have been determined with respect to calibration curves saved on another day. Frequencies of 4, 5, 6 and 8 Hz have been used, whereas for the amplitudes 0.4 and 0.5 V have been used. Error measurements have now been performed by adjusting frequency and amplitude separately. The error was determined in three ranges: within 0.1, 0.2 and 0.4 V from zero voltage, taking the absolute value. The frequencies and amplitudes were set with an accuracy of ±0.02 Hz and ±0.002 V, respectively.

When the function generator is tuned to the same properties as when the calibration was made, the errors do not differ much. A plot is printed below for the error in displacement as a function of amplitude within a range of 0.1 V from zero voltage, the range in which a 'normal' autocorrelation would fit. As can be concluded from the plot, the error is always smaller than 1.0 μm when a range in input voltage of 0.04 V around the set voltage is considered.

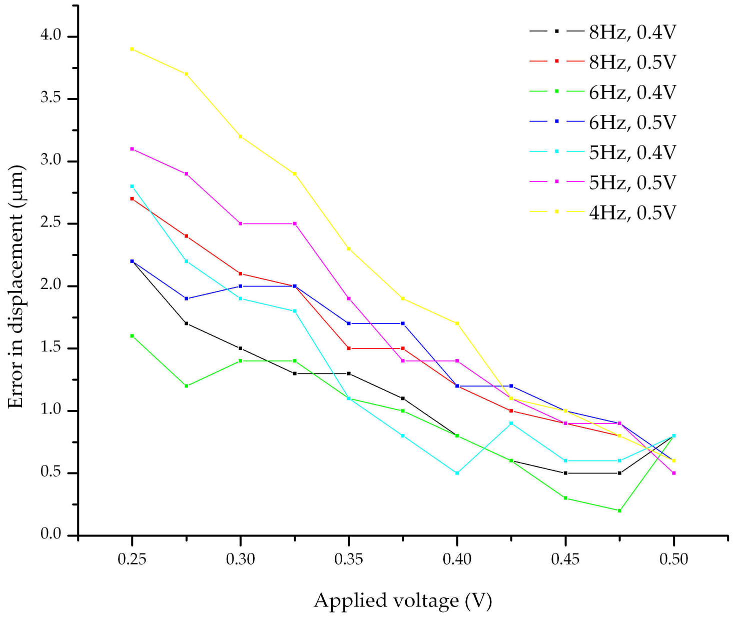


Figure 8: Error in displacement in a range of 0.1 V around rest position plotted as a function of input voltage.

For the frequency dependence a similar plot can be made. It can be seen that the frequency dependence for 5 Hz is a little bit higher than that for 8 Hz, although this also depends on the frequency perturbation itself.

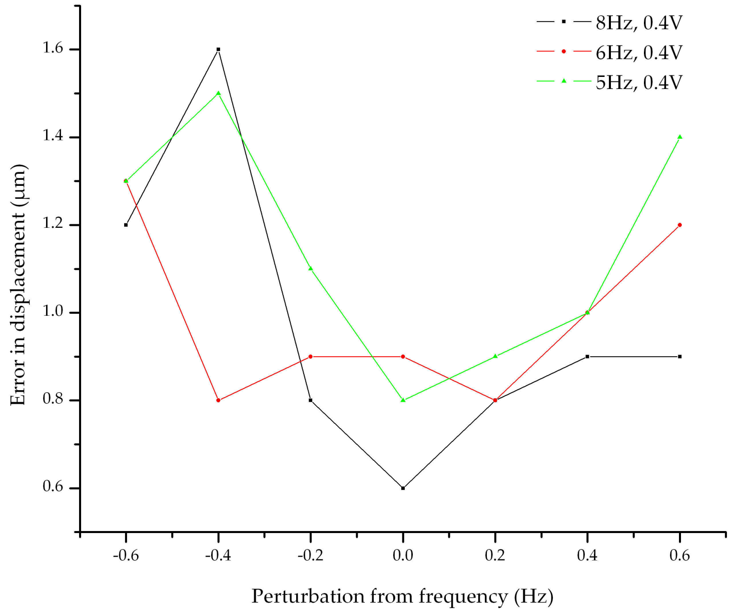


Figure 9: Error in displacement in a range of 0.1 V around rest position as a function of perturbation from frequency.

As a conclusion, to have errors smaller than 1.0 μm in a range of 0.1 V and smaller than 1.6 μm within 0.2 V, the frequency should be fine adjusted in a range of ±0.2 Hz and the amplitude in a range of ±0.04 V. These values should be used with respect to the active calibration curve.

4.2 Autocorrelation

The autocorrelation is measured for two different laser pulses with a repetition rate of 1 kHz and 80 MHz, respectively. As stated before, more sweeps from the function generator should be obtained for the repetition rate of 1 kHz. This can be concluded from the number of useful data points in one sweep, which is around 60 (at 8 Hz and 0.4 V). When a measurement of around 2 seconds is performed, the number of data points can be high enough to approximate a good pulse width, but a measurement of 5 seconds will give better results. The interference pattern in the autocorrelation can then be clearly seen. However, the number of data points is still too low to perform calculations on this pattern. The 1:8 ratio between background intensity and maximum intensity is clearly seen (see also the pattern on the front panel in the appendix).

In the case of the pulsed laser at a rate of 80 MHz one sweep of the sine function is enough to acquire the whole interference pattern. This implies that the LED detector reacts to light intensity at least in the order of 10^{-4} s, which is fast for such a simple and cheap device. In this time the maxima and minima of the interference pattern are acquired. By obtaining a whole measurement from one sweep, the width of the curve should be more accurate to calculate due to the absolute displacement problem. The result of this phenomenon however is not seen in the measurements.

The automatic fit function depends highly on the interval width in the main program in which the maxima of the autocorrelation function are calculated. Minimizing the mean squared error of the fit is not an option, because in practice this almost always leads to an unusable high interval width. In these cases the shape of the fitted function does not follow the envelope of the autocorrelation function at all, so this is not a useful result. By adjusting the width manually on the front panel it can be tuned to the pulse characteristics. The possibility of making a manual fit in the graph gives a reliable solution of determining the width of the curve. Also the built-in cursor in the graph can be used.

The measurement was performed several times, where the properties of the laser pulse and the function generator were not adjusted at all. In this case the pulse widths did not differ more than 6 fs from each other. The maximum range was 10 fs, giving a perturbation of 5 fs around the mean value. In another measurement the pulse width was first calculated manually from the oscilloscope screen, giving a result of 120 fs. The automatically fitted autocorrelation gave a width of 117 fs.

5 Conclusions

A Michelson interferometer used as an autocorrelator can give accurate results in determining the pulse width of a pulsed laser. By using the second-order autocorrelation function, where a two-photon process takes place, a cheap and reliable detector can be used to obtain an autocorrelation pattern on the screen. The light intensity on the LED should however be limited to prevent it from failure.

Two difficulties limit the accuracy in determining the pulse width of the laser. The first one is from mechanical origin, because the absolute zero point in displacement of the audio speaker cannot be determined exactly. Although the relative zero point can be computed very accurate, it is not known whether the speaker shows the same behaviour for repetitive sweeps of a sine function.

The second difficulty arises from the software, where it is not possible to perform an accurate fit on the envelope of the curve. It is necessary to consider maximum values over intervals, but the fit depends very strong on the size of the intervals chosen. Calculating the minimum mean squared error from the fit does not help in this case.

6 Acknowledgements

For me it was really a pleasure to work in the group Optical Condensed Matter Physics of Paul van Loosdrecht during the three months I have been there. I would like to thank Paul van Loosdrecht for the short time in which he could offer me a FIT-stage ('Fysische Informatie Technologie'), helping me in understanding the physics when I arrived and the support during the whole project. I thank Arjen Kamp for all the hours he was busy setting up the Michelson interferometer and teaching me how LabView works. Finally I thank all the other group members for giving advices and helping in doing the measurements.

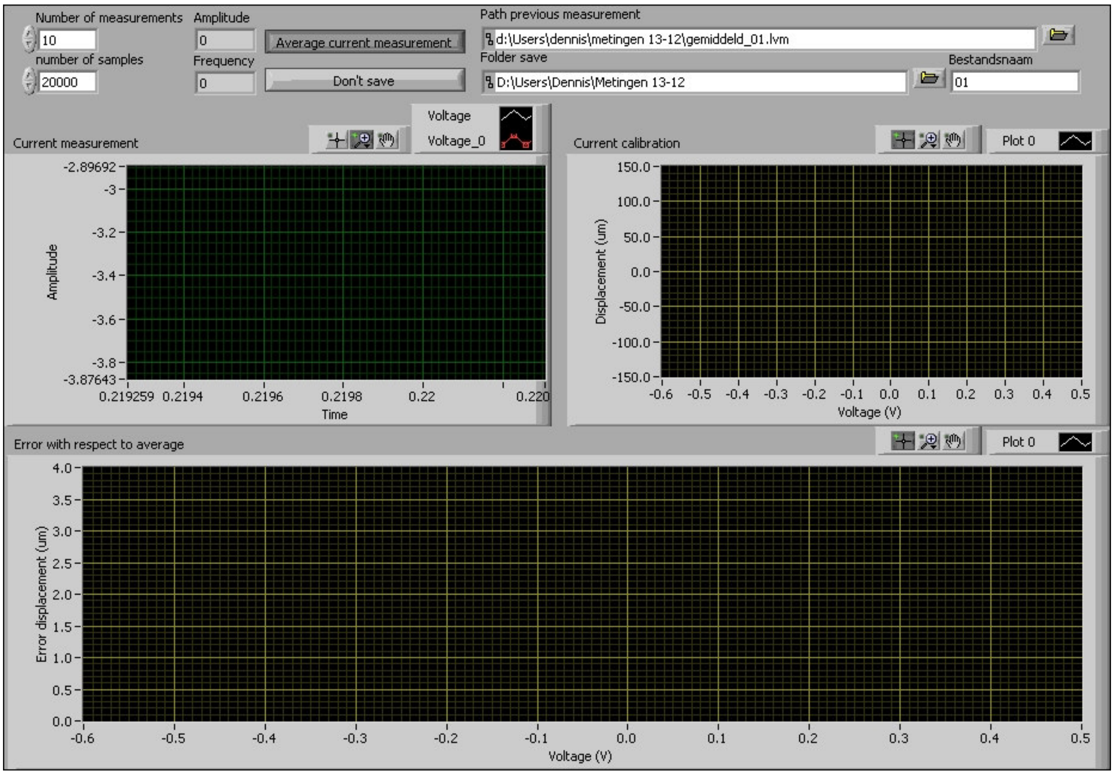
7 References

[1] E. Hecht, *Optics*, Addison Wesley, fourth edition (2002).
[2] A. Baltuška, *Hydrated Electron Dynamics Explored with 5-fs Optical Pulses*, University of Groningen (2000).
[3] Internet: http://mathworld.wolfram.com/autocorrelation.html, retrieved at 14 February 2008.
[4] C. Rullière, *Femtosecond laser pulses*, Springer (1998).
[5] P. Wasylczyk, *Review of Scientific Instruments* **72**, 2221 (2001).
[6] J.A.I. Oksanen, V.M. Helenius, J.E.I. Korppi-Tommola, *Review of Scientific Instruments* **64**, 2706 (1993).
[7] D.T. Reid, M. Padgett, C. McGowan, W.E. Sleat, W. Sibett, *Optics Letters* **22**, 233 (1997).

Appendix 1 – Manual

A1.1 Calibration

The front panel of the main program *Calibration.vi* is built up in this way:



Number of measurements: 10

number of samples: 20000

Amplitude: 0

Frequency: 0

Path previous measurement: d:\Users\dennis\metingen 13-12\gemiddeld_01.lvm

Folder save: D:\Users\Dennis\Metingen 13-12

Bestandsnaam: 01

Figure 10: Front panel of the calibration software.

With the controls in the upper left corner the number of measurements and the number of samples per measurement are controlled. Right to these the measured frequency and amplitude of the current measurement are shown. From the next two buttons the upper controls whether the error should be calculated with respect to the average from the current measurements or a previous measurement (the file path is inserted right next to it). The lower button gives the user the opportunity to save the current measurement into a file. Folder path and file name are inserted in the strings right next to it.

The graph in the upper left corner displays the voltages from the function generator and the photodiode as a function of time. Right next to it, all the calibration curves are shown, as well as the averaged calibration curve. In the graph shown below all the errors of single measurements are shown with respect to the averaged calibration (or previous measurement).

A1.2 Autocorrelation

The fields in the upper left corner control the total number of measurements, as well as the intervals over which maxima should be taken. The autostop-button allows the user to stop measuring when one autocorrelation curve is obtained. The frequency and amplitude from the function generator are shown in the indicators. In the set of three controls placed right next to these, first the choice can be made between a new and a previous measurement. In the latter case, the file path has to be inserted in the dialog right next to it. The second control makes it possible to save the measurement in a file, where the file path has to be given in the lowest text box on the right side. The third control lets the user choose between two different displacement scales: μm or fs. In the middle text box the file path of the calibration curve has to be inserted.

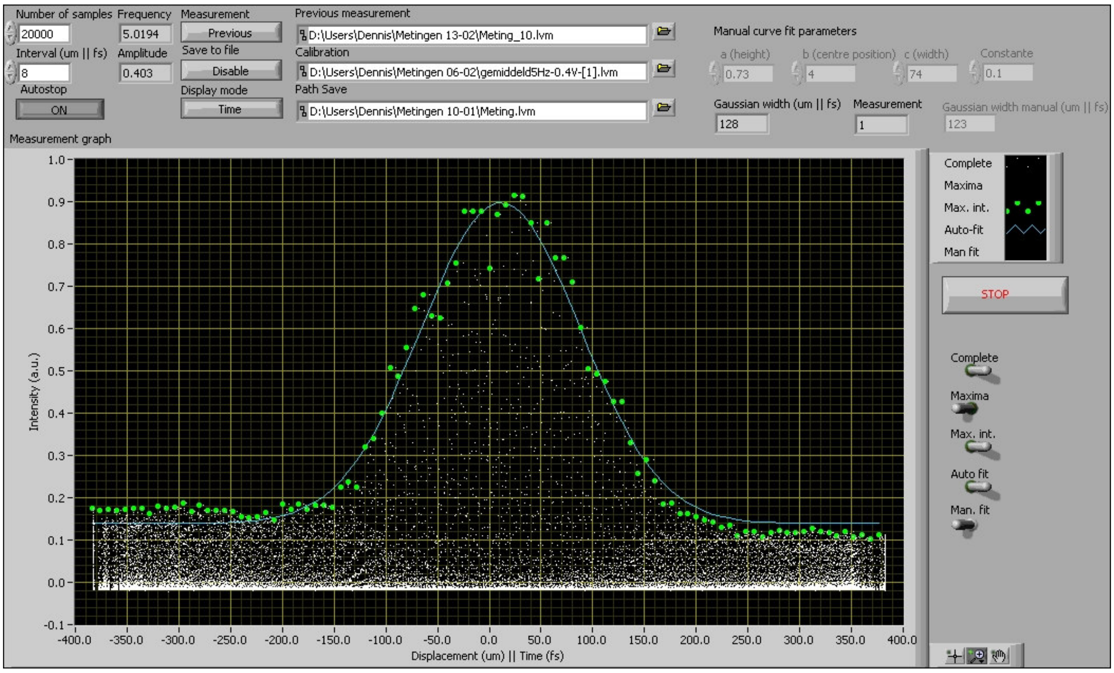

Number of samples: 20000
Frequency: 5.0194
Measurement: Previous
Previous measurement: D:\Users\Dennis\Metingen 13-02\Meting_10.lvm
Interval (um || fs): 8
Amplitude: 0.403
Save to file: Disable
Calibration: D:\Users\Dennis\Metingen 06-02\gemiddeld5Hz-0.4V-[1].lvm
Autostop: ON
Display mode: Time
Path Save: D:\Users\Dennis\Metingen 10-01\Meting.lvm
Manual curve fit parameters
a (height): 0.73
b (centre position): 4
c (width): 74
Constante: 0.1
Gaussian width (um || fs): 128
Measurement: 1
Gaussian width manual (um || fs): 123

Figure 11: Front panel of the autocorrelation software.

In the upper right corner, four controls can be used to obtain a manual fit. To use this function, the toggle switch besides the graph must be turned on. Below the controls, indicators show the width of the curve at FWHM from the automatic fit function, the number of measurements that has been performed and the curve width from the manual fit routine, respectively.

In the graph all the curves can be switched on and off by using toggle switches. The following curves can be shown (not all visible in the figure above):

- Complete (white dots): all the data points from the DAQ
- Maxima (red dots and lines): the peaks from the data points to correct for the slow behaviour of the LED (see also step 3 on page 13).
- Max. int. (green dots): gives the maxima of the data points over intervals
- Auto fit (blue line): shows the best fit from the auto-fit function
- Man. Fit (green line): shows the curve obtained from the Gaussian coefficients inserted in the upper right corner

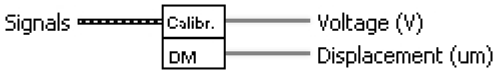
Appendix 2 – Overview subVI's

In this appendix an overview is given of the subVI's explained in the chapter 'Experiment'.

A2.1 Calibration

In the main program *Calibration.vi* the following subVI's are used.

CalibrateMeasurement.vi
Function: converts the signals from function generator and photodiode into a voltage-displacement relation



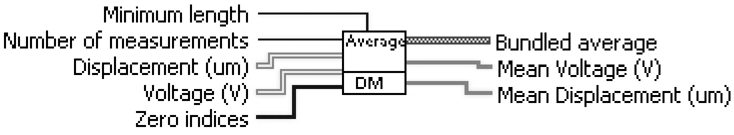
Inputs:

- Signals: dynamic data obtained from DAQ Assistant

Outputs:

- Voltage (V): array of doubles with calibrated voltages
- Displacement (µm): array of doubles containing displacements with respect to equilibrium position corresponding to the voltages

Average.vi
Function: averages over a series of measurements



Inputs:

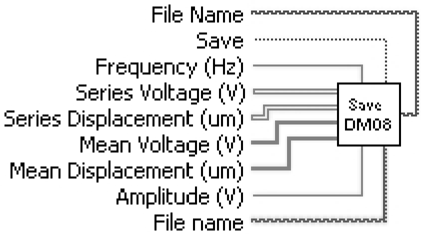
- Minimum length: scalar determining the length of the array of averaged displacements
- Number of measurements: scalar giving the number of measurements over which an average has to be performed
- Displacement (µm): two-dimensional array of doubles containing the displacements from relative equilibrium position
- Voltage (V): two-dimensional array with corresponding voltages to the displacements
- Zero indices: array of scalars giving index numbers where displacement are zero

Outputs:

- Bundled average: contains bundled values for the averaged voltages and displacements
- Mean voltage (V): array of doubles containing the averaged values of voltages
- Mean displacement (μm): array of doubles with averaged displacements

FileSave.vi

Function: saves all the data obtained into lvm-files



Inputs:

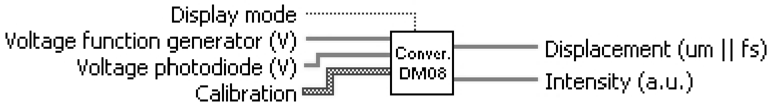
- File Name: directory path of the saved file
- Save: boolean indicating if the data should be saved
- Frequency (Hz): double describing the average frequency of the performed measurements
- Series voltage (V): two-dimensional array of doubles describing the calibrations from all the measurements
- Series displacement (μm): two-dimensional array of doubles with corresponding displacements from equilibrium position
- Mean voltage (V): array of doubles with the averaged voltages
- Mean displacement (μm): array of doubles with the averaged displacements
- Amplitude (V): double describing the average amplitude of the performed measurements
- File name: string with the preferred basis for a file name

A2.2 Autocorrelation

In the main program *Autocorrelation.vi* the following subVI's are used.

VoltageDisplacementConversion.vi

Function: converts voltages from the function generator into displacements, either in micrometers or femtoseconds.



Inputs:

- Display mode: boolean describing whether the displacement scale should be expressed in femtoseconds ('true') or micrometers ('false')
- Voltage function generator (V): array of doubles containing the voltages from the function generator from the performed measurement

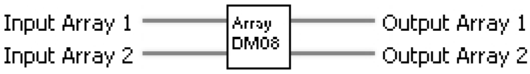
- Voltage photodiode (V): array of doubles describing the voltages from the photodiode from the performed measurement
- Calibration: bundle with doubles describing the correspondence between applied voltage and obtained displacement (µm)

Outputs:

- Displacement (µm || fs): array of doubles containing the calibrated displacements
- Intensity (a.u.): intensities from the photodiode read out at the calibrated displacement points

ArraySort.vi

Function: sorts two arrays with respect to the first with increasing values, needed for determining maximum values over a certain interval



Inputs:

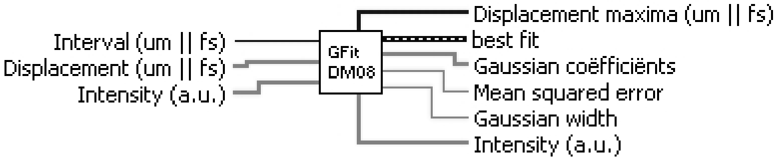
- Input array 1: array of doubles with respect which should be sorted to
- Input array 2: array of doubles with values corresponding to the first array

Outputs:

- Output array 1: sorted array of doubles
- Output array 2: array of doubles sorted with respect to array 1

GaussianFit.vi

Function: fits the input function with a Gaussian shape



Inputs:

- Interval (µm || fs): scalar which determines the interval in which a maximum is calculated
- Displacement (µm || fs): array of doubles containing the displacements on which will be fitted
- Intensity (a.u.): array of doubles in which intensities are stored

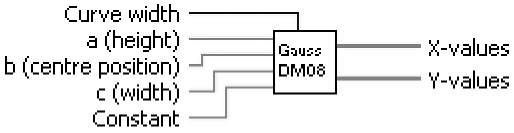
Outputs:

- Displacement maxima (µm || fs): array of scalars describing the displacements in the intervals
- Best fit: dynamic data from the fit-routine
- Gaussian coefficients: array of doubles with the coefficients from (1)
- Mean squared error: describes the error between the fit and the actual data
- Gaussian width: double contains the value of c from the fitted function

- Intensity (a.u.): array of doubles with values of the maximum intensities in the given intervals

GaussianFunction.vi

Function: gives the Gaussian shape for the inserted coefficients



Inputs:

- Curve width: scalar describing the total width of the curve
- a (height): double describing the height of the curve (1)
- b (centre position): double containing the value of the centre position (1)
- c (width): double describing the width of the curve (1)
- Constant: corresponding double to value of *d* in (1)

Outputs:

- X-values: array of doubles describing the displacement values
- Y-values: array of doubles describing the intensities to the corresponding displacements