Development of a fast wavelength tuning system for OPO-based lidar measurements

Master's thesis
by
Fredrik Nordin

Lund Reports on Atomic Physics,
LRAP-243
Lund, April 1999

Abstract

Differential absorption lidar (DIAL) is an excellent method of monitoring different emissions. It is an optical and non-intrusive on-line measurement that can be used for a number of gases over a great distance. The limitation is the need for an isolated spectral structure of the monitored gas. In the case of gases with an overlapping spectral structure, standard DIAL measurements are not suitable. A solution is to record a spectral structure and compare the data collected with a reference database. If multiple species are present it can be possible to use principal component analysis techniques, which enables to mathematically calculate the amount of the different gases in the emission. An optical parametric oscillator (OPO) system can be used to scan the structure, but since it is too slow for practical measurements, there is a need for a faster system. This thesis describes the development of a fast wavelength tuning system for OPO-based lidar measurements. The high speed was achieved by using piezoelements, which allow the quick change in wavelength necessary for the process. The programming language LabVIEW was used to control the process.

TABLE OF CONTENTS

1 Introduction

1.1 Background

The principle of lidar (**li**ght **d**etection **a**nd **r**anging) is the same as the principle of radar. A short pulse of light is sent out and the backscattered light is collected in a sensor and analysed. Because of the short pulse length, it is very easy to calculate the range to an object detected, just by measuring the time it takes for the backscattered light to arrive.

The invention of laser has increased the possibilities and applications of lidar. Especially lasers with both short pulses and high output energy is suitable for lidar measurements, for example the Nd:YAG laser. Other characteristics of a suitable laser are high repetition rate, stable operation, low divergence and preferably eyesafe operation.

One method of measuring the concentration of a gas in a medium is DIAL (**di**fferential **a**bsorption **li**dar). The principle of the method is shown in Figure 1-1. The first picture shows a situation, where the laser beam is directed through two smokestacks containing the gas being measured. The laser is alternated between two wavelengths, one where the wavelength is on an absorption peak (λ_{on}) and one where it is tuned off the peak (λ_{off}). The λ_{off} wavelength acts as a

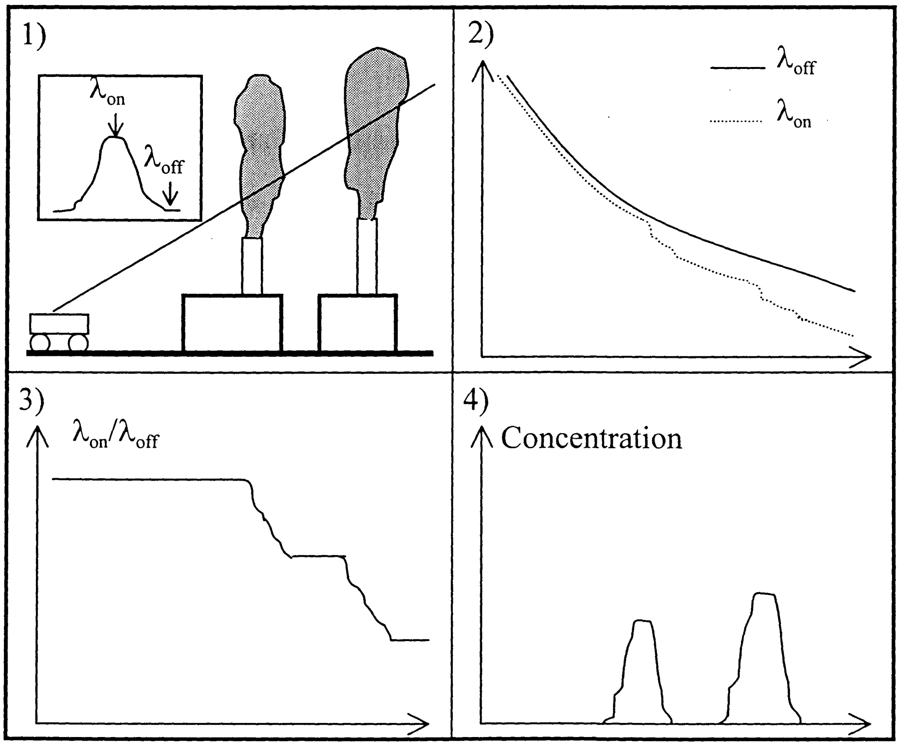


Figure 1-1 Description of the DIAL technique

reference signal, showing the absorption of the surrounding medium, since the gas has a minimum absorption at this wavelength. This is the top curve in the second picture. The λ_{on} wavelength has the same attenuation as the λ_{off} wavelength until the first smokestack is reached, where the signal is decreased because of the absorption in the gas. After the smokestack the signal again follows the same λ_{off} attenuation behaviour until the second smokestack is reached. The signal is then decreased further. This is shown in the lower curve in the picture. The two signals are then divided by each other ($\lambda_{on}/\lambda_{off}$), which gives the third picture. Finally, to get the concentration of the gas at the different locations, the DIAL formula[1] is used on the third picture, which gives the fourth picture. This picture clearly shows both the concentration and the locations of the gas, namely at the location of the smokestacks. The location is in this case the distance to the gas from where the laser is being emitted.

The department of Atomic Physics in Lund have a mobile DIAL system. This is very suitable for field measurements, since it is easy to move to a new location. The system is placed in a Volvo truck with a cargo department, which have been modified to house the laser system and electronics. The laser system is made up by a Nd:YAG pump laser and a dye laser system. The laser light is sent out from the system via a tiltable mirror on the top of the bus. The backscattered light is collected by a 40cm lidar telescope and sent into a photo multiplier tube. The data is read by a high-speed digitizer and finally processed in a computer with a LabVIEW program, which evaluates the data and displays the concentration and location of the measured gas for different locations on the monitor screen.

This method works very well when the gas has an isolated absorption structure, i.e. the gas has one or many absorption peaks where the other gases in the medium do not absorb. When the measured gas does not have an isolated absorption structure in the present medium, DIAL is not preferable. This is because of the difficulties in finding λ_{on} and λ_{off} wavelengths when the other gases in the medium have interfering structures.

---

[1] DIAL formula : $\dfrac{P(\lambda_{on},t)}{P(\lambda_{off},t)} = \dfrac{\xi(\lambda_{on})\times\beta(\lambda_{on},R)}{\xi(\lambda_{off})\times\beta(\lambda_{off},R)}\times e^{-2\int_0^R \{\kappa(\lambda_{on},r)-\kappa(\lambda_{off},r)\}dr}$

$P(\lambda,t)$: signal power received from the backscattered light corresponding to the transmitted wavelength

$\xi(\lambda)$: the spectral transmission factor of the receiver

$\beta(\lambda,R)$: the volume backscattered coefficient

$\kappa(\lambda,r)$: the atmospheric attenuation coefficient

One way of overcoming this problem is to scan the absorption structure of the mixture at multiple wavelengths and then, by using an absorption structure of the measured gas from a database, mathematically calculate the concentration of the gas in the mixture by a principal component analysis technique. This method allows us to get the concentration of one or more gases with overlapping structures in a mixture, which normally can't be done with DIAL techniques.

The system we use to achieve a rapid wavelength tuning is an OPO (Optical Parametric Oscillator) laser system. It is an all-solid state system, which uses crystals instead of dyes for wavelength tuning. The advantages with this system is that it is an all-solid state system, i.e. no need for dyes, covering a large wavelength region (220nm to 1800nm) and with a fast wavelength tuning capability. Limitations are, however, the speed of the wavelength tuning, since it is to slow for our purposes. Tuning is controlled by step motors and in a DIAL measurement, for example, the time it takes to alternate between the λ_{on} and λ_{off} wavelength is simply too long. To decrease the tuning time, a set of piezoelements were added to the system to support the step motors. This increases the speed of system, so it exceeds the repetition rate of the laser, i.e. the laser can be tuned over the full range of the piezos between every laser shot. This enables us to have a method capable of fast and accurate wavelength tuning in a large wavelength region, reaching far into the IR region with difference frequency generation and with nothing but solid state materials.

1.2 Project overview

A schematic view of the total system is shown in Figure 1-2. It displays the system set-up described in the report.

As described in chapter 1.1, a set of piezoelements has to be added to the system to achieve the desired speed for fast wavelength tuning. The needed modifications to the system were made at three points. The first two were made in the OPO system, where the original design of the tuning mirror and the crystal housing were modified to house the piezoelements. The third were made at the IR mixing unit, where the mixing crystal housing were modified to house the last piezoelement.

To control the behaviour of the piezoelements a piezo position control unit was added to the system referred to as PI system in the figure. The unit monitors the position of the piezoelements and applies the correct voltage to reach the desired position.

A linewidth unit was constructed to monitor the linewidth of the laser beam. Two delay units were added to supply the equipment with the necessary trigger pulses. Finally a Burleigh wavemeter was added to allow diagnostics of the system.

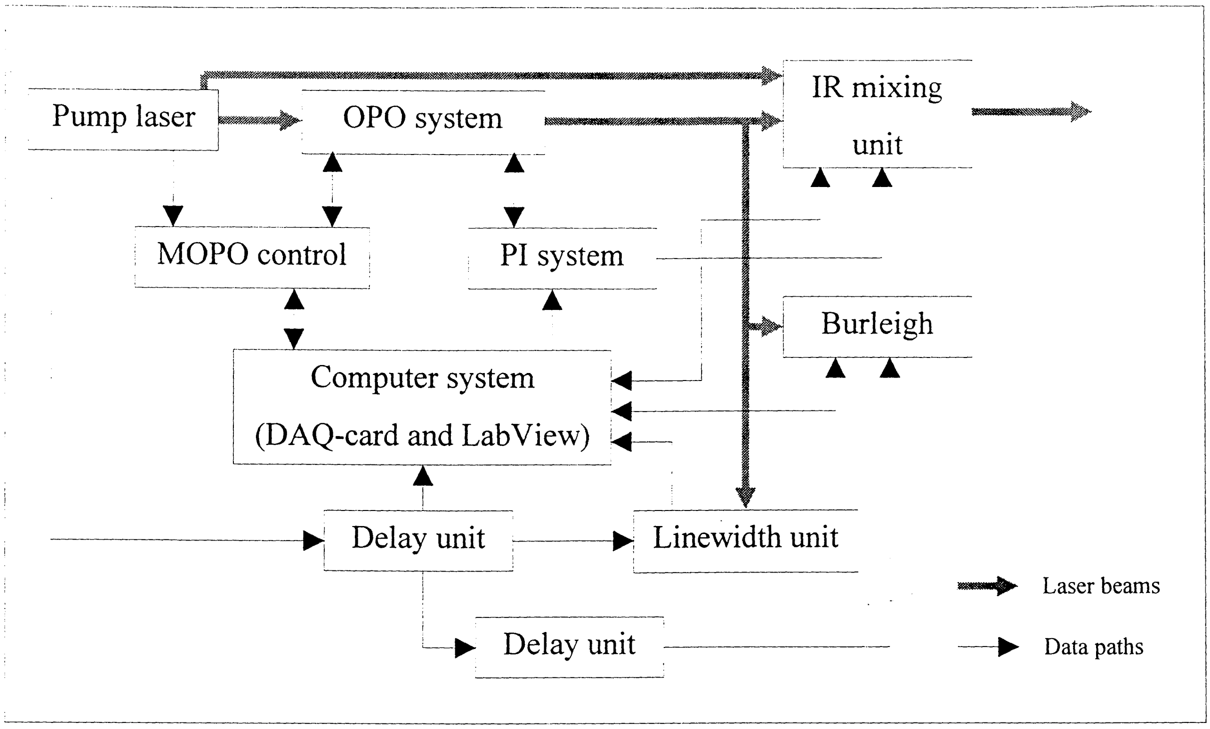


Figure 1-2 Schematic view of the total system

A computer system controls the entire system, including wavelength positioning, laser calibration, linewidth measurement, and system diagnostics. The computer system uses a multifunction I/O board (DAQ-board) and the LabVIEW programming language to perform all of these actions.

Chapter 2 describes the equipment used in the system, i.e. OPO system, PI system, Burleigh system, delay unit, data acquisition board, and LabVIEW programming language.

Chapter 3 describes the modified system, i.e. the modification of the OPO system and IR mixing unit. It includes the mechanical construction, interface between computer and mechanics, and software of the wavelength control system. It also includes description of the linewidth unit, the wavelength positioning and data acquisition software, and the validation software.

Chapter 4 describes the test procedures and results of the system validation. The validation is performed to measure the impact of the new design compared to the original design.

Chapter 5 includes the conclusions and future ideas of the project.

Finally a user manual for the system is included in chapter 6.

2 Equipment

2.1 OPO system

2.1.1 OPO principle

Operation of the OPO (Optical Parametric Oscillator) system can be understood as the inverse of the non-linear frequency mixing process used to generate odd harmonics from a wavelength. For example, to generate the third harmonic of a wavelength, the fundamental wavelength is mixed with the second harmonic, thus generating the third harmonic. This can be done with a non-linear material such as BBO or KDP, as shown in Figure 2-1. As mentioned, the OPO works in the reverse fashion. The pump photon at frequency ω_p is converted to the two photons ω_s (signal wave) and ω_i (idler wave), thus satisfying the conversion law:

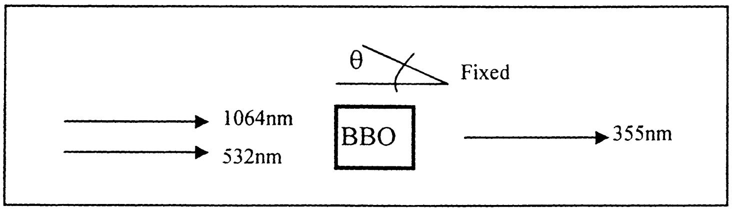


Figure 2-1 Frequency mixing to generate third harmonic

$$\omega_p = \omega_s + \omega_i \qquad \text{(frequency)}$$

$$1/\lambda_p = 1/\lambda_s + 1/\lambda_i \qquad \text{(wavelength)}$$

If the on-linear material, for example BBO, is placed in an appropriate resonant cavity, oscillation at the signal and/or idler wavelength can be obtained. The output of the OPO has the same characteristics as a laser, but the OPO generates wavelengths from non-linear conversions rather than atomic transitions, thus only operating when a pump wave is present. Wavelength tuning is accomplished by rotating the angle of the crystal, thus changing the resonated wavelength in the cavity. This is true only if the pump wavelength and the beam path are fixed. Any variations in these parameters will also affect the wavelength in the cavity. For further information on OPO theory, see [1].

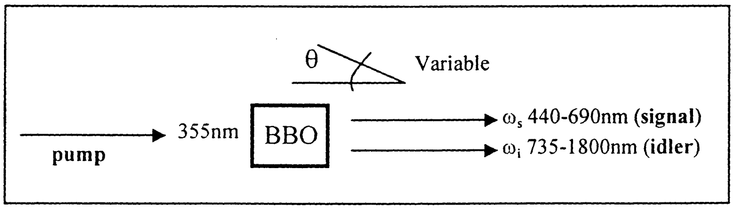


Figure 2-2 Generation of signal and idler wavelength

2.1.2 OPO operation

The OPO system used is a Quanta-Ray MOPO-730 Optical Parametric Oscillator from Spectra Physics [2]. The name MOPO (Master Oscillator/Power Oscillator) is derived from the design of the system. A high energy Power Oscillator is seeded with a narrow bandwidth Master Oscillator. This enables the system to emit high energy, narrow bandwidth and tuneable coherent radiation. The active non-linear material used is Beta Barium Borate (BBO) crystal. The two BBO crystals for the Power Oscillator and the Master Oscillator are placed on the opposite ends of a rotational crystal housing, ensuring simultaneous tuning of the two cavities.

The Master Oscillator uses a grating placed in grazing incidence geometry, thus producing a narrow linewidth output wavelength. The MO optical cavity is made up by a broadband high reflector, a high modulation holographic grating with a suitable diffraction efficiency over the whole tuning range and a broadband reflecting tuning mirror mounted on a high resolution sine bar. By placing the mirror on the sine bar, a linear scanning capability is provided. In addition, two 355nm dichroics are used in the cavity to route the pump beam into the cavity, through the BBO crystal and then out of the cavity. The Grazing Incidence Cavity, also called a Littman Oscillator, produces a narrow linewidth output by a high dispersion and high incidence angle. This results in high wavelength selectivity, but it also results in increased cavity losses. The incidence angle and the grating parameters in the MOPO-730 were chosen to minimize the losses and to still achieve the linewidth specifications ($<0.2\text{cm}^{-1}$). The signal and idler wavelengths produced in the BBO crystal interact with the grating in the grazing incident angle, diffracting off the grating described by the diffraction theory:

$$\alpha \sin\theta = \lambda$$

where α is the grating groove spacing and λ is the wavelength.

The signal will reflect off the grating in a number of orders (the idler reflects out of the cavity in the zeroth order (mirror) reflection). By orientating the mirror so it reflects the photons at the peak of the crystal bandwidth, a spectrally narrowed beam is reflected back into the cavity. The beam is then reflected back again into the cavity by the broadband high reflector and the gain of these photons dominates the gain at other wavelengths. This will continue until oscillation threshold is reached. The large number of interactions with the grating will result in a further narrowing of the wavelength.

The Power Oscillator is a two mirror linear cavity including another BBO crystal, a broadband high reflector, two 355nm dichroics, a crystal compensator and an output coupler. The rotation of the BBO crystal results in a beam displacement and is corrected by the compensator crystal. The signal and idler wavelengths transmitted from the Power Oscillator are separated by two dichroics before exiting the system. One dichroic transmits the idler beam through an output port and reflects the signal beam onto the other dichroic, which transmits the remaining idler and reflects the signal beam through an output port.

The output from the Master Oscillator is directed through the Power Oscillator broadband back reflector. Even though the energy levels that leak through the mirror is low, it is enough to achieve seeded operation of the Power Oscillator. To achieve seeded operation, the phase match angle between Master Oscillator and Power Oscillator is necessary. The frequency overlap is achieved by independently adjusting the angle of the Power Oscillator. Only when frequency overlap occurs, seeded operation will be achieved. A result of seeded operation is the increase of output power, since the injected photons will decrease the oscillation threshold. Another result is the decrease in linewidth of the Power Oscillator, since the injected photons have a lower linewidth (a $10cm^{-1}$ unseeded Power Oscillator seeded with a $0.2cm^{-1}$ source will result in an output linewidth of $0.2cm^{-1}$).

A MOPO control unit [3] controls the MOPO-730. Operation includes scan parameters, position control, energy readout and diagnostics of the system. A number of ports are also available for connection to laboratory and data acquisition equipment.

The OPO is pumped by a Quanta-Ray GCR-230 pulsed Nd:YAG laser [4] with a pulse repetition frequency of 20 Hz and three output wavelengths: the fundamental 1064nm, the frequency doubled second harmonic at 532nm and the third harmonic at 335nm, generated by mixing of 1064nm and 532nm in a KDP crystal. The design of the laser consists of an oscillator part and an amplifier part, each with two Nd:YAG rods pumped by a set of flashlamps. The produced wavelength of 1064nm is sent through two mixing crystals to generate the harmonic wavelengths of 532nm and 335nm. Two mirrors reflect the beams through two output ports, one transmitting the 1064nm and the 532nm and reflecting the 335nm onto the second mirror, which reflects the beam through the second output port.

2.2 PI system

The piezo system from Physik Instrumente (PI) consists of three major parts: macroblock translators used for fast movements, LVDT (Linear Variable Differential Transformer) sensors for monitoring of the movement, and a unit with amplifier and sensor modules used for movement control.

The piezoelement we used was a P-287.30 macroblock translator [5]. It is constructed as a rectangular stainless steel casing with stacked piezo blocks located in the centre. One side of the casing acts as a lever arm and when a voltage is applied, the piezo expands and pushes the side of the casing outwards, thereby increasing the angle. Nominal expansion is 300 μm, which corresponds to an angle of 0.3°.

Since the control unit needs to know the expansion of the macroblock translators, an E-115K001.SM1 LVDT sensor [5] is used to monitor the expansion. The LVDT is a small toroid housing with a movable core inside. As the core is moved back and forth inside the toroid, the inductance of the toroid is changed. By reading the phase shift, the position of the LVDT core can be measured. If the LVDT is attached to the piezoelement, we have an easy way of monitoring the expansion.

Control electronics is necessary in order to control the macroblock translators. An E-500.00 basic module carrier 19" rack with E-530.00 multi function power supply module, three E-507.00 amplifier modules (one for each macroblock translator) and one E-509.L3 sensor/control module with three channels are included in the unit [6].

The sensor/control module is a displacement sensor module with an integrated servo controller. The position servo control part is an analog P-I (Proportional Integral) controller and proportional and integral gain can be set internally by trimmers to individually match each of the channels. A notch filter is also included to allow the system to operate closer to the resonant frequency. To achieve optimum performance each sensor/control channel must be calibrated individually with the specific macroblock translator for displacement range, frequency response, settling time, optimum match with the LVDT and load of the system. The sensor/control module generates the input signal for the amplifier module according to the difference of target and actual position, by reading the position from the LVDT. Drift and hysteresis of the macroblock translators are compensated and it also increases the stiffness of a macroblock translator by quickly adjusting the operating voltage as soon as a change in force or load occurs.

The amplifier module generates the driving voltage for the macroblock translator by amplifying the signal from the sensor/control module. The driving voltage ranges from 0 to –1000V.

2.3 Burleigh system

The Burleigh Pulsed Wavemeter [7] is a wavelength-measuring unit for pulsed or CW lasers. The laser light is directed through two Fabry-Perot interferometers (etalons) that are wavelength calibrated against an internal HeNe reference laser. Two CCD arrays collect the interferograms and the data is sent to a computer via an A/D converter board for processing and presentation.

Two shutters control the source of laser light to reach the etalons. The internal shutter determines if to use the internal HeNe beam, which is used to periodically calibrate the system against thermal drift. The external shutter determines if to let the incoming laser light to pass onto the etalons. The external shutter is closed when an internal calibration is performed and opened, with the internal shutter closed, when making a measurement of the external laser. With both shutters opened, the HeNe beam is sent out from the unit and can be used for alignment of the external laser beam.

The program, running under Windows, is capable of presenting wavelength, linewidth, shift and other parameters of the measured laser light by acquisition of a single or multiple spectra. In continuous mode only the wavelength is presentable and then only for one of the etalons.

2.4 Delay unit

The DG535 Digital Delay and Pulse Generator [8] is used for delaying the Q-switch trigger pulse from the pump laser and provides the positioning system and the Burleigh unit with trigger pulses. The unit has an accuracy of 1ppm, precision of 5ps, and a wide range of 0 to 1000s. The unit provides four logic transitions or two logic pulses with BNC contacts located on the front panel. The front panel also features LCD display, menu keys, data entry keys and trigger status.

The LCD display is the programming operation interface for the user.

The menu keys allow entry to the different menus. Menus included are trigger (define trigger source), delay (adjust the four delays), output (set output levels), GPIB (operation of GPIB data and functionality), store and recall (used for storage of instrument settings).

The data entry keys are used for entry and modification of data displayed on the LCD. The data is entered by using the numerical buttons or the cursor buttons.

The trigger status displays information concerning trigger operation, for example when trigger occurs, if the unit is performing a timing cycle or if a trigger occurs during a timing cycle.

There are five delay outputs (BNC) on the unit, marked T0, A, B, C, and D. T0 is the start of the timing interval. The other four delay outputs can be set from 0 to 1000s in 5ps increments with respect to T0. The output level may be set to TTL, NIM, ECL or adjustable and can drive 50Ω or high impedance loads.

There are four delay outputs (BNC) on the unit, marked AB, -AB, CD and -CD. The AB and CD pulse interval is set by the time interval between channels A and B and between channels C and D. The -AB and -CD outputs are the complementary pulses of AB and CD.

2.5 Data acquisition board (DAQ-card)

The DAQ-card used is a Plug and Play National Instruments PCI-MIO-16E-4 multifunction I/O board [9]. It features 12-bit ADCs with 16 analog inputs and 250kS/s maximum sampling rate, 12-bit DACs with 2 voltage outputs, eight lines of TTL-compatible digital I/O and two 24-bit counter/timers for timing I/O operation. Either one of the analog inputs or the PFI0/TRIG1 pin can be used for hardware triggered operation.

The board can be fully controlled by the LabVIEW programming language. Therefor, no extra programming for board control is called for, since all the necessary libraries are included in LabVIEW.

2.6 LabVIEW programming language

LabVIEW is a program development tool suited specifically for data acquisition and instrument control. It uses a graphical programming language called G to create program in block diagram form. Little programming knowledge is needed, since familiar graphical symbols are used, instead of text based programming. LabVIEW features a large number of functions, routines and libraries for both simple and advanced programming, for example standard numeric functions, libraries for data acquisition, GPIB and serial instrument control, data analysis, data presentation and data storage. It also features easy debugging using breakpoints, animation of the execution and single step through functions.

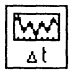
LabVIEW programs are called virtual instruments (VIs) because of their similarity to actual instruments, but they are analogous to conventional language program subroutines. The VIs features an interactive user interface, a source code equivalent and the capability of accepting parameters from higher level VIs. The interactive user interface is called the front panel (similar to the panel of a physical instrument). It contains buttons, knobs, graphs and other controls and indicators. The input is controlled using the mouse or keyboard and the results are shown on the computer screen.

The block diagram contains the graphical program code in which you do your actual programming. The VIs are hierarchical and modular, which means they can be used as a top-level program or a subprogram within other program (they are then called subVIs). Connection between VIs is done using a connector pane, where inputs and outputs are defined.

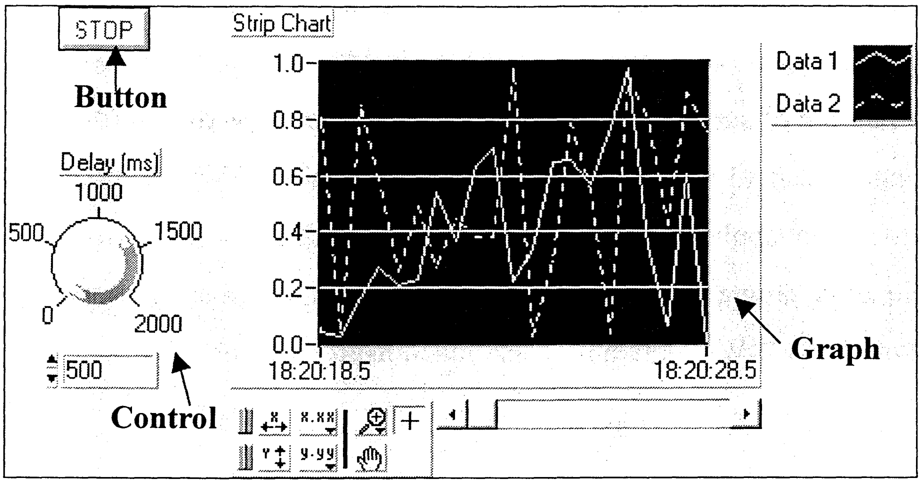
The concept of modular programming simplifies programming and debugging. A problem can be divided into a number of subVIs controlled by a top VI and since each subVI can be executed by itself, debugging of each VI is much easier. Furthermore, each subVI can be specialised to perform task common to several applications and thereby be used in different programs.

An example of a program with front panel and block diagram is shown below. For more information about LabVIEW programming and functionality see [10].

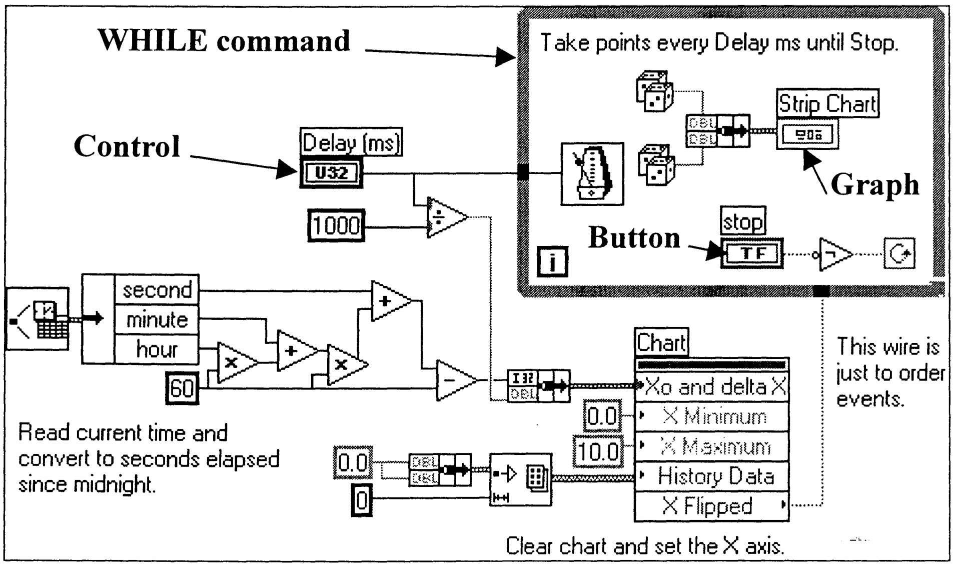
Connector Pane



Front Panel



Block Diagram



3 System description

3.1 Wavelength control

The wavelength control consists of three major parts; the mechanical modification of the system, the interface between mechanics and computer and the software to control the wavelength position and system calibration.

3.1.1 Mechanical construction

In order for the system both to work over the desired wavelength range and to have the ability to change wavelengths at the desired speed, some modifications and additions to the existing system had to be made. The key points to modify are the tuning mirror in the Littman Oscillator along with the crystal housing in the OPO system and the mixing crystal in the IR mixing system. They are normally tuned by servo motors. To achieve the desired speed, piezoelements were added to the system. The advantage of piezoelements is the ability to quickly move to a new position and to very accurately reach this position.

3.1.1.1 Mirror mechanics

The original mirror construction was designed with the mirror placed in a mirror mount, which was placed on a turnable sine bar. A stepper motor moves the sine bar arm and thereby changes the angle of the mirror as the construction moves around the turning point, which also changes the wavelength in the Littman Oscillator.

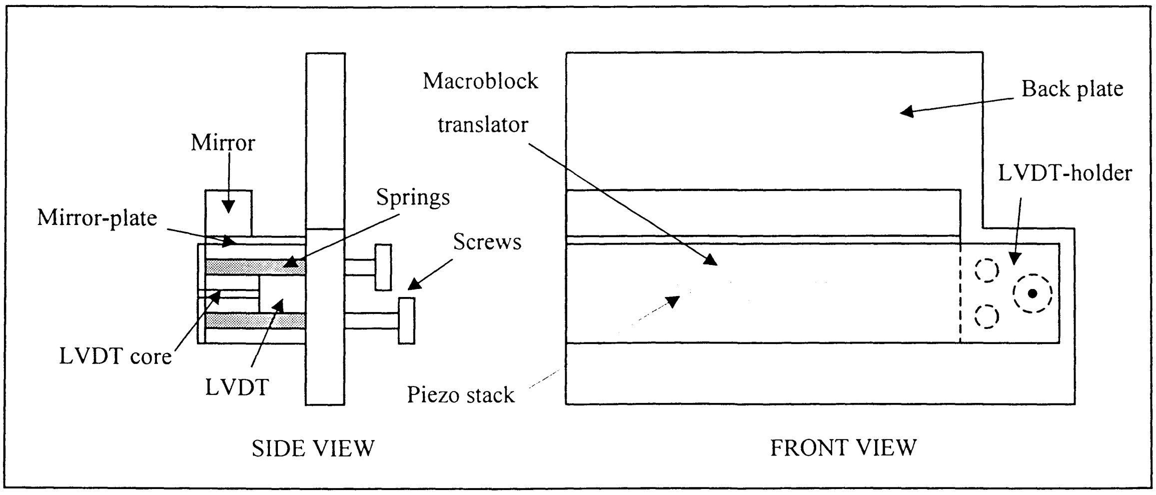


Figure 3-1 Mirror construction with macroblock translator

In the new mirror construction the mirror mount had to be removed and replaced with a new mount, shown in Figure 3-1. The mount is made up by a back plate, a macroblock translator, a LVDT, a mirrorplate, a LVDT-holder and two springs. The mirror is glued onto the mirrorplate and the plate is then screwed onto the piezoelement. The LVDT-plate is screwed onto the front of the macroblock translator and the LVDT is placed on the back plate, with the core placed on the LVDT-plate. Thereby the expansion of the macroblock translator can be monitored. To preload the macroblock translator and thereby increase the resonance frequency of the construction, two springs are placed between the back plate and the LVDT-plate (a more rigid construction has a higher resonance frequency). Screws on the back plate are used to tighten the springs, so that the construction doesn't resonate at the operating frequency of 10 Hz.

The new mount is then placed on the sine bar and can now be used just like the original mirror construction, but with the additional ability to rapidly change wavelength by using the macroblock translator. A wavelength tuning range of up to 1.6nm can be achieved with the macroblock translators.

3.1.1.2 Crystal housing mechanics

A servo motor pushing a lever arm on the rotational crystal housing controls the angle of the housing in the original design. A potentiometer is used by the MOPO control box to read the angle

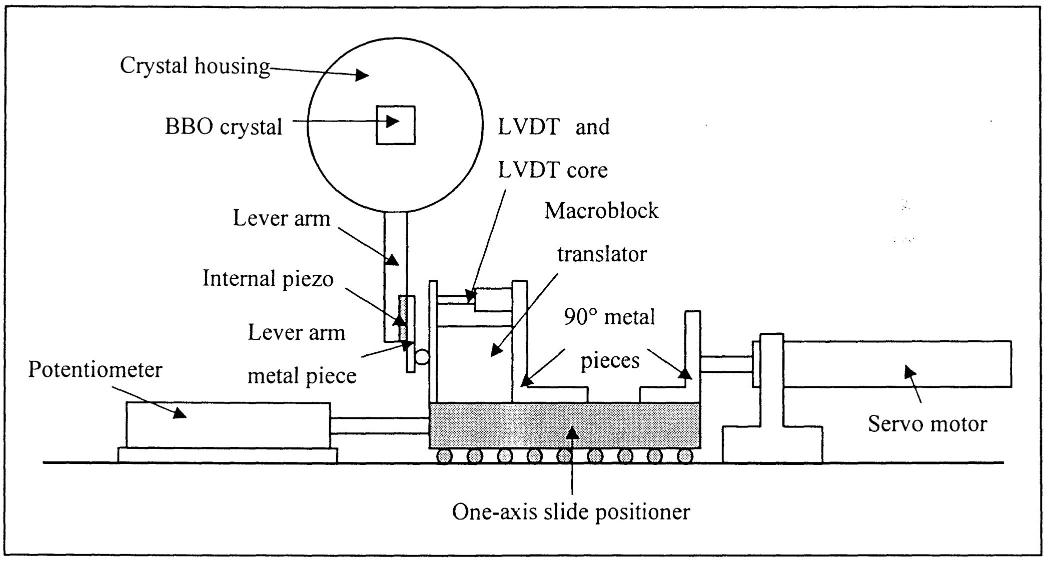


Figure 3-2 New crystal mechanics with macroblock translator

of the crystal, by reading the position of the lever arm.

Only a few modifications and addition had to be made in the new design, shown in Figure 3-2. The macroblock translator was placed on a one-axis slide positioner, placed between the motor and the lever arm. The motor had to be moved away from the lever arm to fit the slide positioner. The macroblock translator and the LVDT were placed on a metal plate screwed onto the slide positioner. The LVDT core was placed on a metal piece on the lever arm of the macroblock translator, thus allowing the expansion of the macroblock translator to be monitored. Another metal plate was screwed on the opposite side of the sleigh, acting as a pushing plate for motor. This allows the system to use, independently of each other, the motor and the macroblock translator to change the angle of the housing.

An internal piezo is located between the flat metal piece on the lever arm and the lever arm itself. The piezo is used by the MOPO system to fine-tune the angle of the crystal housing to reach maximum energy, by pushing or pulling the metal piece. This metal piece is also where the potentiometer reads the location of the lever arm. This works for the original design, but will not work for the new design. As the macroblock translator pushes the lever arm, the potentiometer will detect the change in position and try to compensate the change by using the motor. Shortening the metal piece eliminated this error, so that the potentiometer reaches the slide positioner instead of the metal piece. This means that the potentiometer reads the location of the slide positioner instead of the lever arm, thus allowing the macroblock translator to move freely without the motor trying to compensate. This design allows to motor pushing point and the potentiometer reading point to maintain their original vertical positions, which is important for the system to operate as before.

3.1.1.3 Mixing crystal mechanics

The construction of the mixing unit is almost the same as for the OPO crystals. The resulting wavelength is achieved by mixing the idler wavelength with 1064nm from the Nd:YAG laser in a

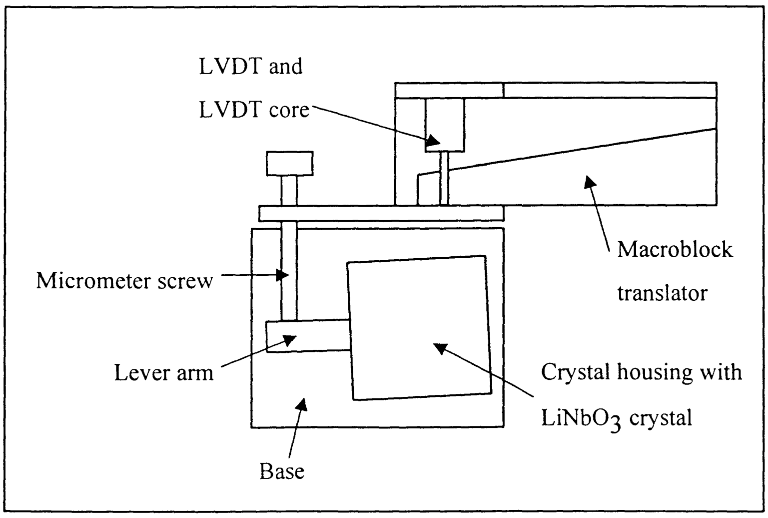


Figure 3-3 Mixing crystal mechanics

$LiNbO_3$ mixing crystal. A mirror located after the mixing crystal reflects the idler and 1064nm wavelength into a beam dump and transmits the resulting wavelength out of the unit.

The mixing crystal is placed in a crystal housing, which is placed on a turnable base. A micrometer screw is used to change the angle of the housing, by pushing a lever arm on the turnable base. The base and housing are placed vertically on a metal construction. The macroblock translator and the LVDT are placed on this construction and a metal plate is screwed onto the macroblock translator, where both the LVDT core and the micrometer screw are located. This design will allow the micrometer screw to push the lever arm of the turnable base as the macroblock translator expands. The micrometer screw has to be turned by hand to pre-set the mixing crystal angle for the desired wavelength, but this is no practical problem since the mixing crystal has a wide acceptance angle. Therefor is it only necessary to adjust the angle of the crystal to the starting wavelength by hand and then use the piezo to move to a new wavelength.

3.1.2 Interface between computer and mechanics

The control unit monitors and controls the expansion of the macroblock translators. The voltage to be applied to the macroblock translators is sent to the control unit from the DAQ-card in the computer. To get a smooth change in output voltages, a low pass filter is added to each of the outputs. The filter both filters out any unwanted high frequency noise and also dampens the voltage step applied to the outputs (a smoother increase or decrease in voltage is better for the macroblock translators, to prevent any unnecessary damage). Because of the card's limitation to two outputs and the fact that we need three outputs, is it necessary to use a multiplexer to apply two voltages from one source. A sample and hold circuit is connected to each of the two outputs of the multiplexer and the second output from the DAQ-card is connected to the input of the multiplexer. The two voltages are generated by applying the first voltage to the DAQ-card output with the multiplexer set to output one. The multiplexer is then changed to the second output. The first S&H-circuit is set to hold and the second S&H-circuit is set to sample. The second voltage is applied to the DAQ-card output and the second output is updated with the new voltage. When a new set of voltages are to be applied, the multiplexer is changed to the original state. Again, the first S&H-circuit is set to sample and the second S&H-circuit is set to hold. We now have a way of applying two voltages from one output.

3.1.3 Software

In order for the system to work properly and reach the desired wavelength, control software was developed. Functions needed in the program are the output of the voltage to the three macroblock translator channels, determination whether to use the MOPO control unit or the macroblock translator for wavelength change and transformation of the desired wavelength to the corresponding voltage for each channel. A program called *Position Control.vi* incorporates all of these functions. Block diagram is shown in Figure 3-4.

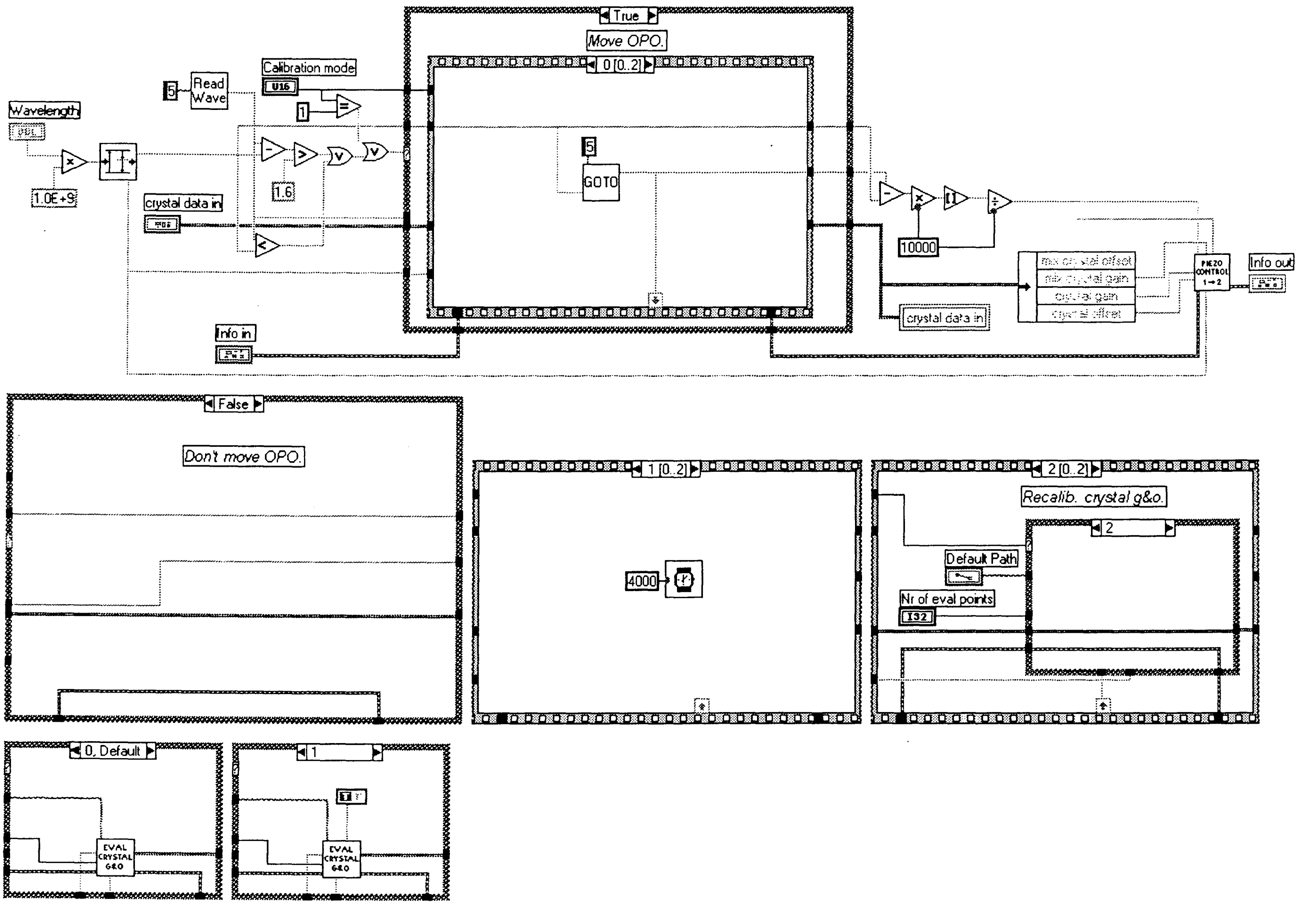
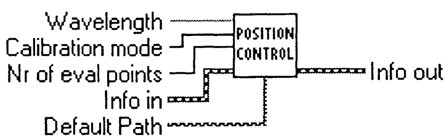


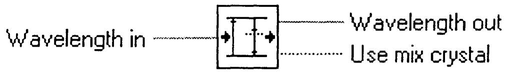
Figure 3-4 Block diagram of Position Control.vi

Inputs needed are desired wavelength, calibration mode, number of evaluation points used for calibration, and default path for calibration output data storage. Info in and info out include data



passed on to every VI, for example error-handling data.

The left part of figure 3-4, before the first case structure, transforms the input wavelength to the signal wavelength used by the MOPO system and then determines whether to move the wavelength by using the stepper motors or by the macroblock translators. Transformation to signal wavelength is done in *Transform wavelength.vi*. If the wavelength is in the signal region no transformation is made. If it is in the idler wavelength, transformation from idler to signal is made. If it is above idler



wavelength, transformation is first made to idler and then from idler to signal. The *Use mix crystal* boolean output is true only when input wavelength is above idler range, i.e. only when mixing crystal operation is needed.

The transformed wavelength is then compared with the wavelength position of the MOPO system, by reading the wavelength from the MOPO control unit using *Read Wave.vi*. MOPO wavelength is subtracted with the desired wavelength and the result determines whether to move the wavelength by stepper motors or to use the macroblock translators. The stepper motors is used if the desired wavelength is greater than the actual wavelength or the desired wavelength is out of range for the macroblock translators. The macroblock translators are used if the desired wavelength is less than the actual wavelength no more than 1.6nm.

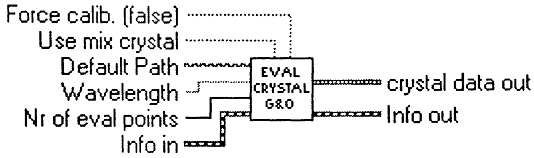
The outer case structure of the centre section determines what actions to take for the two movement options. Nothing is done in the case of macroblock translator movement; data is simply passed on. More is done in the case of MOPO movement. First the MOPO system is set to the desired wavelength with the stepper motors and then the crystal data parameters is calculated. The crystal data consists of voltage gain and offset for the OPO crystal and IR mixing crystal. These are the constants used for calculating the output voltage from the wavelength, described by the following formula:

$$V = gain \times \lambda + offset$$

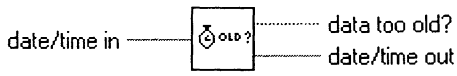
Mirror voltage is calculated by the same formula as with the crystals, but with the offset set to zero. The gain of the mirror is calculated by measuring the wavelength change between 0 and 10V applied to the mirror. The voltage range (10V) is the divided by the resulting wavelength, which gives the mirror gain:

$$gain = \frac{\Delta V}{\Delta \lambda}$$

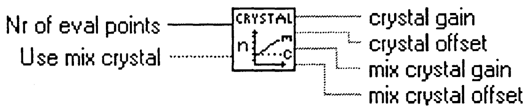
Evaluation of crystal gain and offset is controlled by *eval_crystal_gainoffset.vi*. New evaluation of crystal parameters or recalibration of old parameters is performed and the data is saved to disk at the path defined by *Default path*. Parameters saved to disk are gain and offset for the crystals along



with the timestamp of the data. Since the parameters are wavelength dependent, data is saved in the correct location in the data file corresponding to the current wavelength. New parameters are calculated when *Force calib.* is true, when the data is too old or when no prior data has been calculated for that wavelength. Recalibration of old parameters is only performed when none of the above events are true. Data age verification is performed by *check timestamp.vi*, which compares the timestamp of the old data to the current timestamp.



New crystal parameters are calculated by *crystal_gainoffset.vi*. This VI calculates gain and offset by stepping the mirror voltage from 0 to 10V (the number of steps is determined by *Nr of eval*

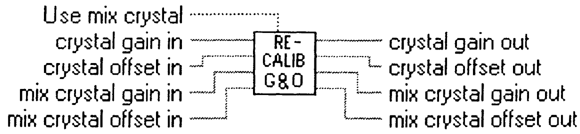


points) and finding the crystal voltage corresponding to maximum energy output from the MOPO system and the IR mixing unit. The *Use mix crystal* input determines if mixing crystal gain and offset should be calculated or not.

The algorithm for finding maximum energy location consists of two steps. First, the peak location is roughly found by stepping the crystal voltage until the peak is passed. Second, the rough peak location is fine scanned to locate the correct peak location. This algorithm is performed for each of the evaluation points. Linear fit is then used on the crystal voltages along with the corresponding mirror voltages to get the gain and offset of the crystal voltages. The algorithm for calculating mixing crystal gain and offset is almost the same as for the above, but instead of stepping the mirror voltage the wavelength of the OPO signal is stepped from 0 to 1nm.

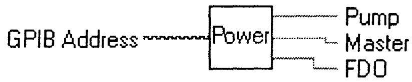
When estimating the MOPO crystal parameters, linear fit gain corresponds to the crystal gain with respect to mirror voltage. The correct crystal gain can be calculated by multiplying the linear fit gain with the mirror gain. The linear fit offset corresponds directly to the crystal offset and therefore no extra calculations are needed. Since the mixing crystal voltages corresponds directly to wavelength, linear gain and offset is in this case mixing crystal gain and offset.

Recalibration of crystal parameters is done by *recalib_g&o.vi*. The algorithm used is somewhat different from that used by *crystal_gainoffset.vi*. Instead of roughly finding the peak and then using

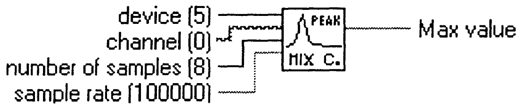


fine scanning, only fine scanning is used. The new offset value is calculated by using the old value at 0nm expansion and fine scanning the offset to find the new peak location, thus giving the new offset value. The new gain value is calculated by using the new offset value and the old gain value at 1nm expansion and fine scanning the gain to find the new peak location, thus giving the new gain value. This method is used for the evaluation of MOPO crystal parameters and mixing crystal parameters, with the difference that the new MOPO crystal parameters are also used in the evaluation of the mixing crystal parameters.

Two different VIs are used to read the energy from the laser. The first is called *Power.vi* and reads the power of the Master and Power Oscillator in the MOPO system. The data is sent via GPIB



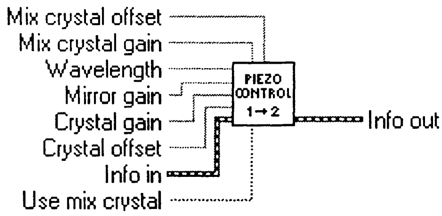
from the MOPO control box to the computer and this can be used for the evaluation of MOPO crystal parameters by reading the Master output energy from the VI. The second VI is called *mix crystal power.vi*. This VI reads the signal of a detector monitoring the power from the IR mixing unit, by connecting one of the analog inputs of the DAQ-card to the detector output. The VI scans



the signal from the detector and calculates the maximum of the laser pulse. This value can be used for evaluating mixing crystal parameters.

The inner case structure of the centre section of *Position control.vi* determines which type of evaluation mode for crystal parameters to use. This is selected by the *Calibration mode* control, which is an integer value ranging from 0 to 2. Calibration mode 0 tells *eval_crystal_gainoffset.vi* to automatically choose which type of evaluation method to use (new parameters or recalibration of old parameters on the basis of the results from *check timestamp.vi*). Calibration mode 1 forces *eval_crystal_gainoffset.vi* to evaluate new parameters, which for example is very useful at the start of a new measurement series. Calibration mode 2 uses none of the evaluation methods. This can be used if there is no need to evaluate new parameters.

The section to the right of the outer case structure outputs the correct voltages to the three channels. It uses the wavelength from the case structure (either the unmodified wavelength or the new MOPO wavelength) and changes the precision to 4 digits before it is sent to *piezo control.vi*. Voltages to the three channels are calculated by using the wavelength and crystal gain and offset as described above. The first thing the program does is to change the digital output that controls the



multiplexer unit (to use three outputs with the two outputs on the DAQ-card), so that the MOPO crystal is selected. Next the program does a triggered output of MOPO mirror and crystal voltages. The program waits until the trigger occurs and then the two channels are updated with the new voltages. The multiplexer is then changed to mixing crystal output by changing the digital channel. Finally the mixing crystal is updated with the new voltage. This is only executed if the *Use mix crystal* input is true.

3.2 Linewidth unit

In absorption measurements the laser linewidth can be a critical parameter. In order to determine whether or not the laserpulse has the desired linewidth, a linewidth-measuring unit is included in the system. The basic idea of the unit is shown in Figure 3-5. The laser light is directed through a

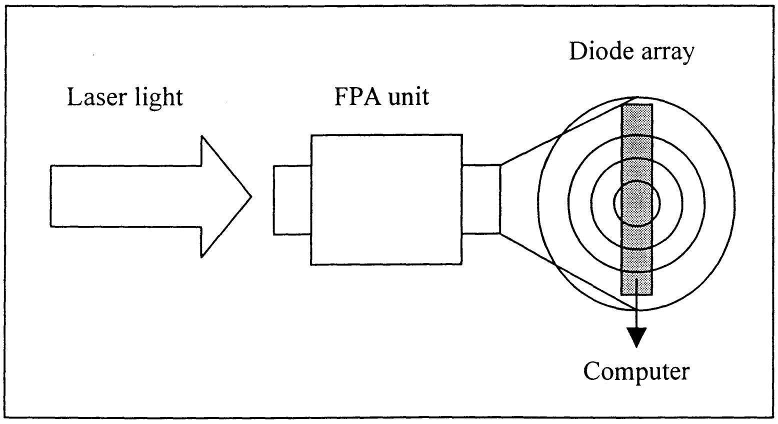


Figure 3-5 Principle of linewidth unit

Fabry-Perot analyser (FPA) and a linear diode array is placed a focal length away from the FPA. The linewidth is then calculated as the product of the free spectral range of the etalon and the ratio of the Full-Width-Half-Maximum (FWHM) and fringe to fringe spacing of the diffraction pattern.

The data from the diode array is read out using an A/D-card and the resulting linewidth is calculated in a LabVIEW program. The unit also consists of other components for signal processing and interface between the laser and the linewidth unit.

3.2.1 Hardware

The hardware consists of an S3923-1024Q linear image sensor, a C4074 driver/amplifier circuit and a C4091 pulse generator, all from Hamamatsu Photonics [11]. The image sensor is an integrated signal processing circuit, which provides boxcar output waveform[2] for simple readout through a single video line. The total sensor area is made up by 1024 pixels in a single line. The circuit also features high UV sensitivity with good stability, low dark current and high saturation charge, wide dynamic range, low power consumption and CMOS logic compatible control signals. Since the sensor needs power supply and different clock pulses as well as components for signal processing, a driver/amplifier circuit and a pulse generator are included in the unit.

The driver/amplifier supplies the sensor with the necessary signals and also offers a number of outputs. These are the trigger output, the end of scan (EOS) output and the video output. The trigger output is set every time new data is presented on the video line and can be used as a trigger for example for an A/D-card. The only input signals required are a master start pulse, a master clock pulse, a reset pulse, +5V and ±15V. The master start pulse controls the start of the data readout from the image sensor. The master clock pulse is the clock frequency used for data readout (a higher clock frequency gives a shorter readout time). The reset pulse controls when to reset the image sensor. The reset pulse is applied directly onto the image sensor chip, onto the saturation control gate. This isn't normally used, but since we have a very short laserpulse, we need to block out as much background light as possible by resetting the sensor just before the lasershot and applying the master start pulse just after. This way we read out only the light detected by the sensor during this short period of time, thus blocking out as much background light as possible.

The pulse generator supplies the driver/amplifier circuit with a master start pulse and a master clock pulse. These signals are digitally presetable by a slide switch and rotary switches. The master clock pulse is set to 1.5 MHz. It takes 6 clock pulses to generate one data pulse, so the data flow has a frequency of 250 kHz at 1.5 MHz clock frequency and 250 kHz is a suitable sample frequency for

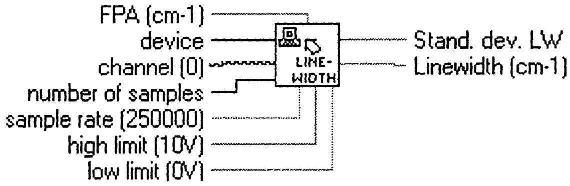
[2] Similar to a square waveform, but the pulses have variable amplitude.

the DAQ-card. The master start pulse from pulse generator is not used, since it is generated externally.

In the hardware is also included a sample-and-hold circuit. The reason for this is a need to expand the pulsewidth of the output signal from the sensor, since the frequency of the output signal and the sample frequency of the DAQ-card might not be the same. By expanding the pulsewidth any problems with differences in frequencies is eliminated. The trigger output from the driver/amplifier circuit mentioned above is used as a clock pulse for the S&H-circuit.

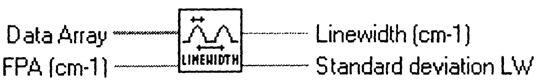
3.2.2 Software

The linewidth evaluation program is called *Linewidth.vi*. It includes data collection from the array sensor and calculation of the linewidth. The data collection is controlled by a function called AI Waveform Scan. It controls the sample rate, number of samples (in this case preferably set to



1024 to read all of the pixels of the array), type of trigger and other parameters needed to operate the DAQ-card in a desirable way. The VI collects the data from the array sensor and sends the data to a subVI called *Linewidth Calc.vi* for linewidth calculation.

The subVI called *Linewidth Calc.vi* is where the linewidth is calculated from the data collected in the *Linewidth.vi* program. Inputs needed are an array of data and the value of the FPA (e.g. 1



cm^{-1}). Outputs given are the linewidth and its standard deviation. The block diagram of the VI is presented in Figure 3-6.

Subtraction of the minimum intensity value is done to eliminate the offset. An advanced peak detector determines the peak locations of the data. This VI uses a number of filter functions for finding the correct peaks. Taking the maximum value in the data array and dividing by three sets the threshold level for the peak detector.

The for-loop calculates the free spectral range and the FWHM for all of the peaks except the first and the last, due to the method being used (this means at least three number of peaks must be present). This means the program starts with the second peak and ends with the second last. The top section of the for-loop calculates the free spectral range of the second peak by subtracting the

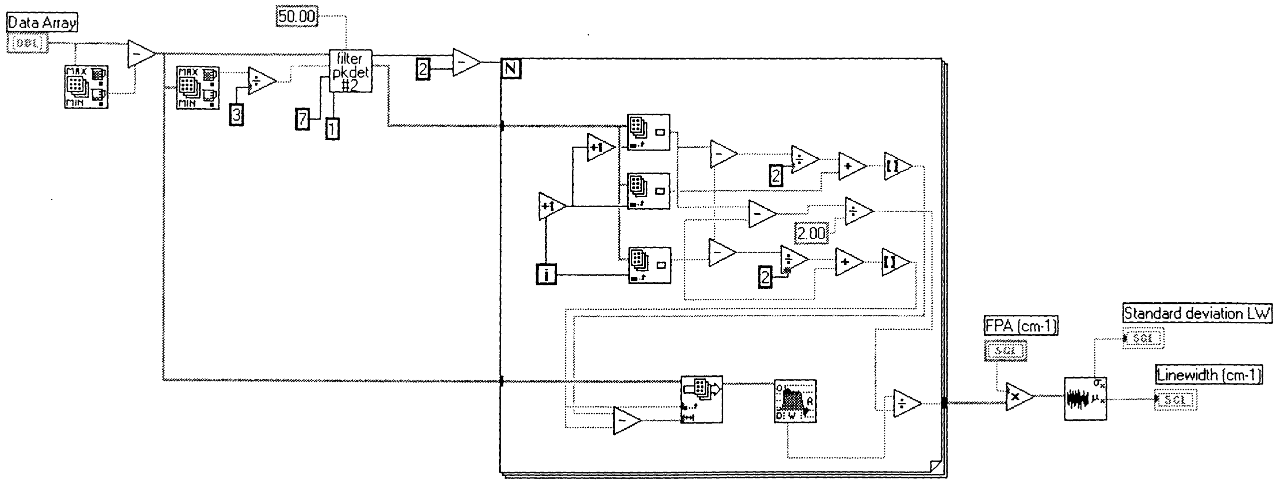


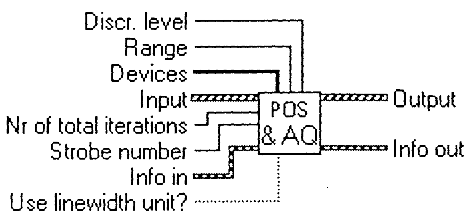
Figure 3-6 Block diagram of Linewidth Calc.vi

location of the first and the third peak and dividing with two. The result is a normalised value of free spectral range, thus compensating for the varying fringe separations caused by the Fabry-Perot analyser. FWHM for the second peak is calculated by extracting the data for the second peak and using a pulse parameter function (the VI at the bottom of the for-loop) to get the pulse width at half of the maximum, i.e. FWHM. The beginning position and length of the second peak must be calculated to extract the second peak data. The beginning position is calculated by taking the first peak location added with half of the distance between the first and second peak (position 1). The second position is calculated by taking the second peak location and adding half of the distance between the second and third peak (position 2). The length of the second peak is calculated by subtracting position 2 with position 1. Thereby the intensity values of the peak are extracted from the data array and FWHM can easily be calculated in the pulse parameter function.

Finally, FWHM is divided by free spectral range. The for-loop executes until all of the peaks have been used and the FPA value is multiplied to the data from the loop. The final thing produced is the mean value of the linewidth and its standard deviation for every shot.

3.3 Position and Acquire software

The wavelength positioning and data acquisition program is called *Pos and Aq.vi*. The program features wavelength positioning, data collection for each of the wavelengths using a digitizer and



calculation of output values.

The *Input* array contains the desired measurement wavelengths and the number of samples for each wavelength. The *Nr of total iterations* input determines the number of executions of the wavelength measurement series. The *Strobe number* input selects number of values collected for each wavelength. Digitizer parameters are set by the *Devices*, *Range* and *Discr. level* inputs. The *Use linewidth unit?* input determines whether to use the linewidth unit in the data collection process or not. *Info in* and *Info out* are cluster of general parameters and data, for example error handling. Finally, the *Output* array contains the collected measurement values for each of the wavelengths.

The block diagram of the program is shown in Figure 3-7. The program code before the outer for-loop initialises the digitizer and performs an evaluation of crystal gain and offset for the first wavelength. The outer for-loop runs the measurement series the number of times determined by the

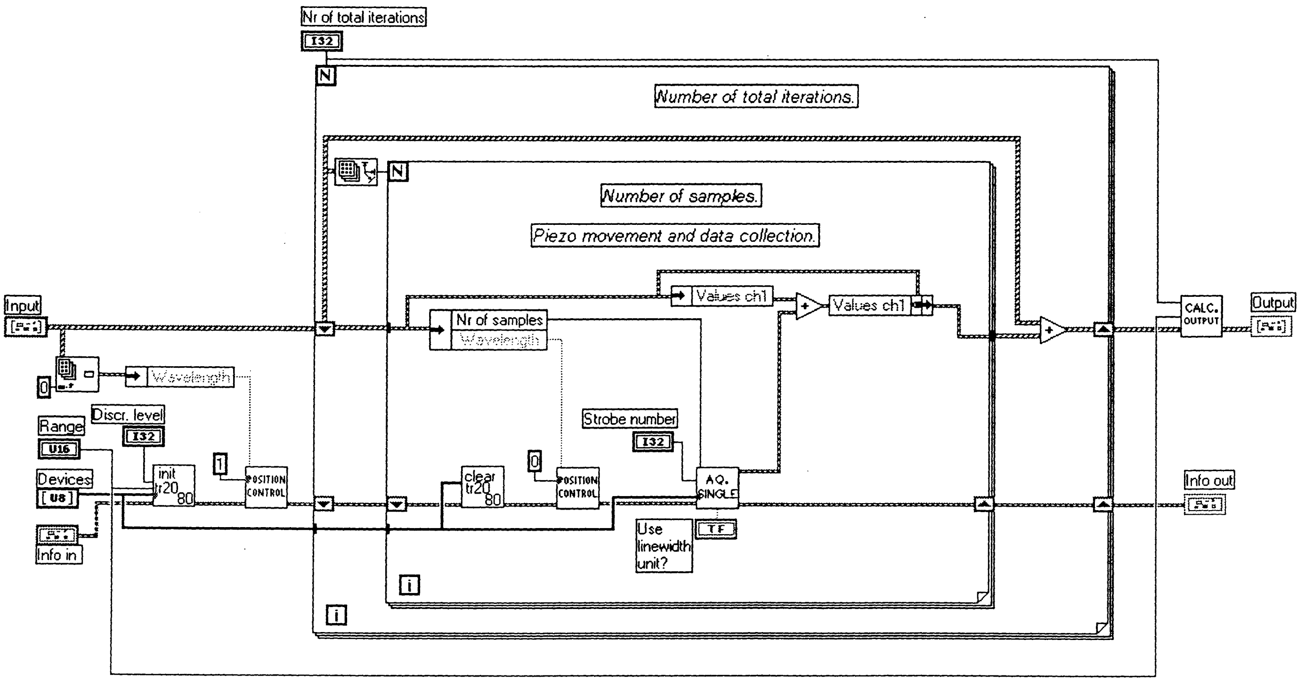
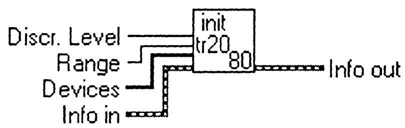


Figure 3-7 Block diagram of Pos and Aq.vi

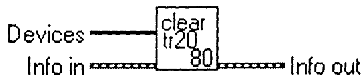
Nr of total iterations control. The inner for-loop steps through each of the wavelengths and collects the values from the digitizer. The part to the right of the outer for-loop calculates the correct output values, by scaling the values with respect to the range used by the digitizer and dividing the values with the total number of measurement iteration and the number of samples for each wavelength.

A program called *InitTR20-80.vi* performs the initialisation of the digitizer. The program resets



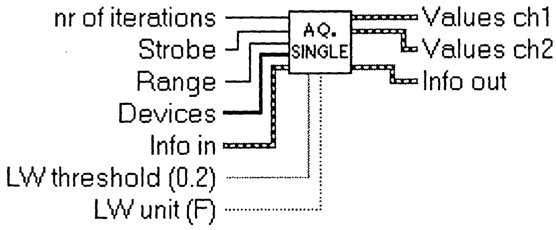
the digitizer cards and configures the digital I/O buffer. It also sets the card number, the voltage range, and discriminator value for the digitizer.

It is necessary to clear the digitizer memories prior to a new wavelength measurement. This is controlled by the *ClearMemoryTR20-80.vi.* The program fills the digitizer memories with a zero value, thus erasing all of the old data.



The wavelength positioning and the crystal gain and offset evaluation is controlled by *Position control.vi.* The functionality of the program is discussed in chapter 3.1.3. The program is present at two locations in the main program. The first is located before the outer for-loop and the second is inside the inner for-loop. The first location of the program moves the positioning system to the first wavelength in the input array and performs a forced evaluation of crystal parameters. A forced evaluation means that the program evaluates entirely new parameters and ignores the possibility of recalibration of old crystal parameters (see chapter 3.1.3 for more information). The second location of the program moves the positioning system to the next wavelength in the measurement series and sets the program to work in auto evaluation mode. Auto evaluation mode means that the program decides whether to evaluate entirely new crystal parameters or to recalibrate old crystal parameters (see chapter 3.1.3 for more information).

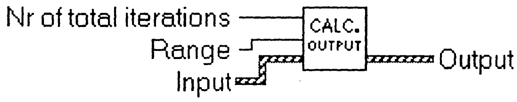
The values of the wavelength are collected by a program called *Aqcuire SS Multiple.vi.*



The *nr of iterations* input is used to set the number of samples for the wavelength. The *Strobe* input indicates the number of values collected by the digitizer for each wavelength and the *Range* input sets the voltage range of the digitizer. The *LW unit* input is true if the linewidth unit is to be used in the measurement and the linewidth discriminator value is set by the *LW threshold* input. *Values ch1* and *Values ch2* are the values collected by the digitizer cards.

The output value is generated by summarising the value of each sample, controlled by the *nr of iterations* number. If the linewidth unit is used and the linewidth value is above the threshold, the collected value for that sample will be discarded and a new value will be collected until the linewidth value is below threshold. The linewidth program discussed in chapter 3.2.2 collects the linewidth value.

The *Calc output.vi* program is used to calculate the correct output values, since the output values from the *Aqcuire SS Multiple.vi* program are a function of voltage range of the digitizer, number of



samples for each wavelength, and the total number of measurement iterations. The values are scaled from bytes to voltage by multiplying the values with the voltage range of the digitizer and the resolution of the digitizer, described by the formula below:

$$V = x \cdot Range(V) \cdot \frac{1}{4096}$$

where x is the byte values and the resolution is described by the inverse of the maximum number of bytes. The scaled values is then divided by the number of samples for each wavelength and the total number of measurement iterations, which gives the correct output values.

3.4 Validation software

The validation software for energy data collection was implemented using a LabVIEW program. The program feature energy readout from the MOPO system and the IR mixing unit, voltage output to the macroblock translators, calibration of crystal gain and offset, calculation and presentation of interesting parameters and storage of data parameters onto disk.

The front panel of the MOPO system and IR mixing unit energy diagnostic software are shown in Figure 3-7. The top left box controls if to start or stop the measurement and which macroblock translator wavelengths to use. The middle left box controls the calibration of crystal parameters. The bottom left box indicates the path for data storage, which is selected at the start of the measurement.

The top graph displays the Master Oscillator (MO), Pump laser, and IR mixing unit energy for each wavelength (currently only two wavelengths are used, but more wavelengths can easily be implemented). The shot to shot change in energy of the energy readouts and the energy ratio of the Master Oscillator and the IR mixing unit for the different wavelengths are displayed in the bottom graph. The mean value and the standard deviation of the shot to shot change and ratio are shown in the bottom right box.

The *average points* control on the right is used to choose the number of energy values to average. The total number of measurement points are determined by the *Nr to collect* control. *Nr collected* indicates the progress of the measurement. *Update rate* controls how often the program should update the data file and the graphs with new data.

The data shown in the graphs are saved to file in a spreadsheet format along with the timestamp of each measurement point, file path and the date of the measurement. This enables future diagnostics and data calculation by using an appropriate spreadsheet program, e.g. Microsoft Excel.

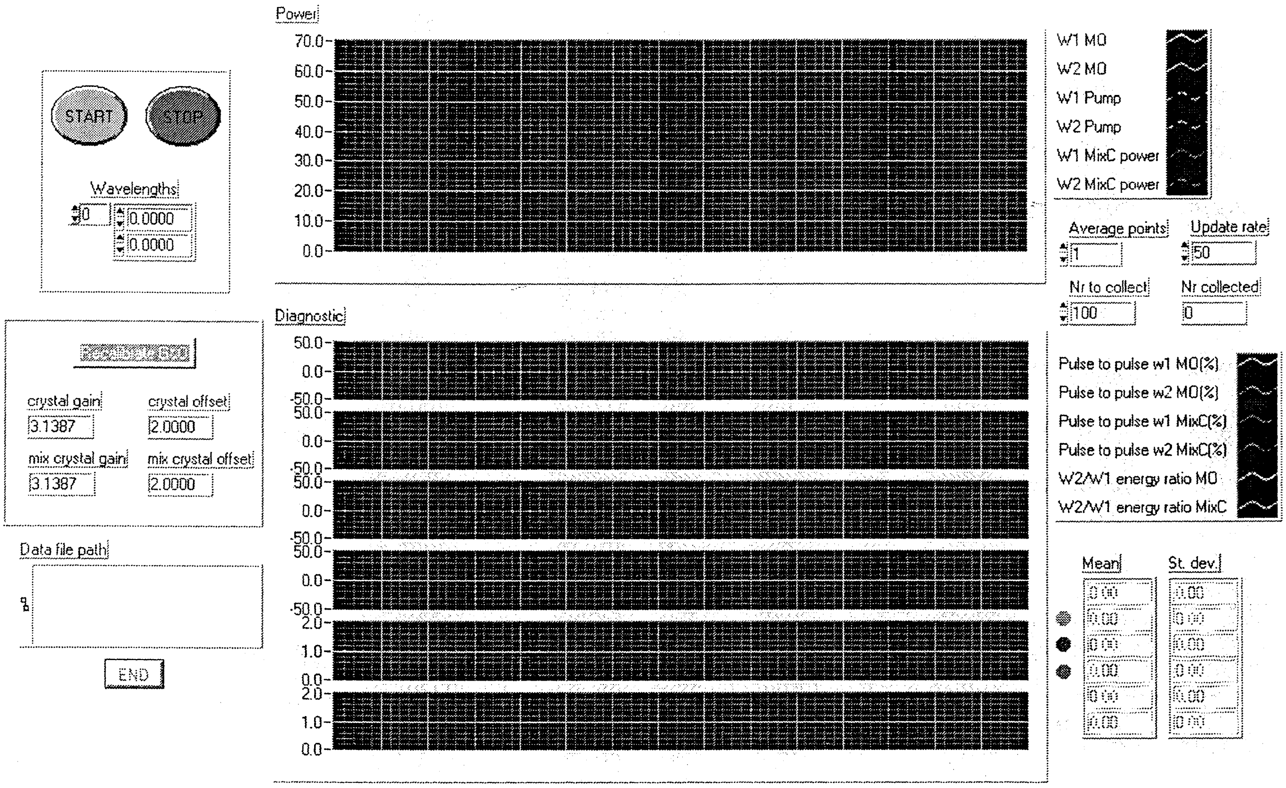


Figure 3-7 Energy diagnostic program for multiple wavelengths

Finally, another LabVIEW program controls the data collection from the Burleigh wavemeter and is to be run in parallel with the original Burleigh program and the energy diagnostic program. It collects the raw data of the diode arrays from the Burleigh instrument and the calculated wavelength from the original Burleigh program. The program features presentation of the wavelength (either one or two is presented depending on the test being performed), calculation and presentation of the wavelength shift, calculation and presentation of linewidth A and B, presentation of the output energy, and histogram graphs of the data. It also calculates the average and standard deviation of the data (wavelength, linewidth, shift, and energy).

The wavelength, linewidth, shift, and energy data along with the timestamp of each measurement point are saved to file in spreadsheet format. As with the energy diagnostic programs, the data can be used by a spreadsheet program for future diagnostics and data calculation.

4 System validation

4.1 Procedures

It is required that the modifications made to the system, i.e. macroblock translators tuning system, don't cause any deterioration in behaviour compared with the original design. The diagnostic tests that were performed to the modified MOPO system were wavelength, energy and linewidth stability (with and without wavelength change), and repeatability of wavelength change of the modified system compared with the original design. All of these parameters are to be validated in the blue, green and red wavelength region to examine the wavelength dependence and over a 5-minute period of time to examine time dependent variations. Finally the mixing unit is validated for energy stability with and without wavelength change and repeatability of wavelength change. There is no need to validate wavelength and linewidth for the IR mixing unit, because the incoming laser beam has already been validated in the diagnostics tests of the modified MOPO system.

The diagnostic test procedures regarding wavelength, energy and linewidth of the modified MOPO system were:

System run with:

- PI system and positioning control system disconnected (similar to the original system design)
- PI system connected and positioning control system disconnected
- PI system and positioning control system connected with no wavelength change
- 1nm wavelength change between each laser shot

The diagnostic test procedures regarding energy stability of the mixing unit were:

System run with:

- no wavelength change at 0nm expansion of the macroblock translator
- no wavelength change at 1nm expansion of the macroblock translator
- 1nm wavelength change between each laser shot

The interesting parameters are modified MOPO system output energy, mixing unit energy, relative change in output energy between shots and, if wavelength change is performed, the ratio between the energy output of the two wavelengths. By examining the relative change in energy between shot, energy fluctuations can be compared with the specifications of the MOPO system.

The ratio gives a good value of how well the crystal gain and offset calibration was made. If the ratio consistently is above or below one, the system has to be recalibrated.

The validation programs discussed in chapter 3.3.2 collected wavelength, linewidth, and energy parameters of the MOPO system. All of the data were saved to disk in spreadsheet format for later analysis and calculations.

4.2 Results

4.2.1 MOPO system

All of the values collected in the *macroblock translators and computer disconnected* measurement were used as reference values in the later measurements, to compare the new design with the original design. In this way the impact of the modifications could be examined.

Blue region

The measurements in the blue region were done at a wavelength of 454.3nm. The change in wavelength average between different set-ups is due to difficulties reaching the previous wavelength when changing between set-ups.

PI system and positioning control system disconnected

The wavelength data over a 5-minute period of time is presented in the Figure 4-1a (data is displayed with a 50 point sliding average function). The rising of the curve is probably caused by a change of laser modes in the Master Oscillator, but the change is below one linewidth. Figure 4-1b shows 100 points from the measurement of the wavelength in the original design. Each point in the figure represents one laser shot and this is, if nothing else is mentioned, the case for all of the following figures. The average of the wavelength is 454.3397nm and standard deviation is 0.0012nm. The total wavelength span is 0.0080nm.

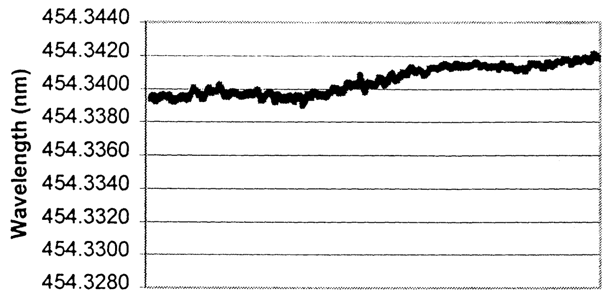


Figure 4-1a 5-minute wavelength measurement

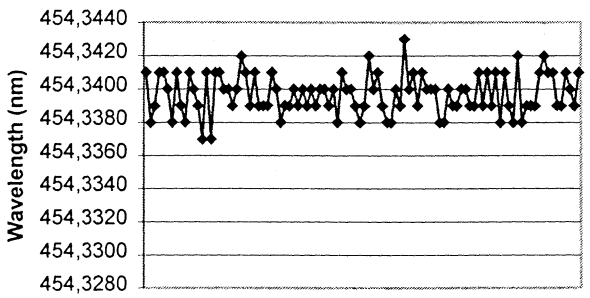


Figure 4-1b 100 points wavelength measurement

Figure 4-1c-d shows the linewidth for the same points. The average is 0.192cm^{-1} and the standard deviation is 0.067cm^{-1}. Finally, the output energy is displayed in Figure 4-1e-f. Figure 4-1e shows the whole energy measurement with a 50-point sliding average. The periodical variation in the output energy is due to periodical variations in the pump laser output. Figure 4-1f shows 100-point data of the energy measurement. The average is 146.51 and the standard deviation is 17.93. The average of the shot to shot change is 9.1%.

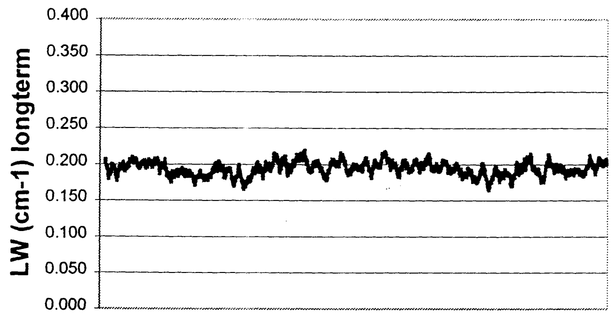


Figure 4-1c 5-minute linewidth measurement

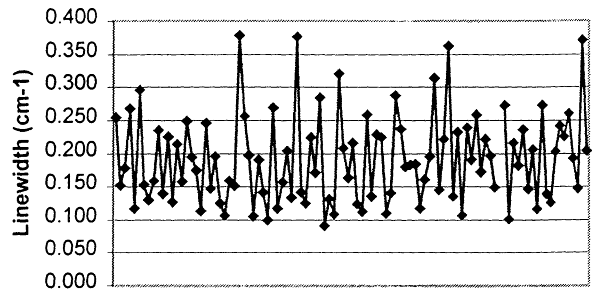


Figure 4-1d 100-point linewidth measurement

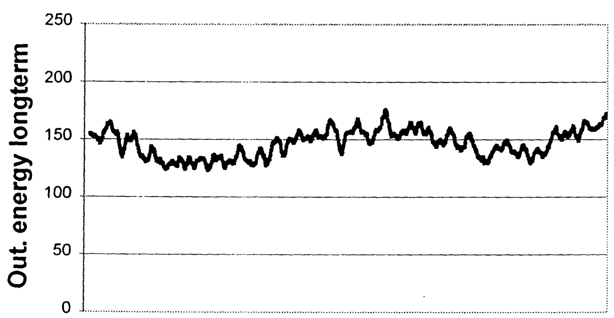


Figure 4-1e 5-minute energy measurement

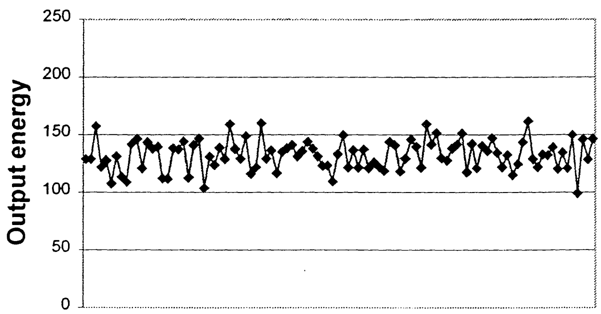


Figure 4-1f 100-point energy measurement

PI system connected and positioning control system disconnected

The wavelength data over a 5-minute period of time is presented in Figure 4-2a and of the linewidth in Figure 4-2b(data is displayed with a 50 point sliding average function). 100 points from the measurement of the wavelength is presented in Figure 4-2c and of the linewidth in Figure 4-2d. The average and the standard deviation of the wavelength is 454.3322nm and 0.0009 nm, and of the linewidth it is 0.210cm^{-1} and 0.055cm^{-1}. The total wavelength span is 0.0050nm. This corresponds well to the values of the original design. A small difference in the linewidth average can be observed, but can be explained by the fact that the linewidth might change between different wavelengths. Since the wavelength average is different in the two measurements, the linewidth can be affected.

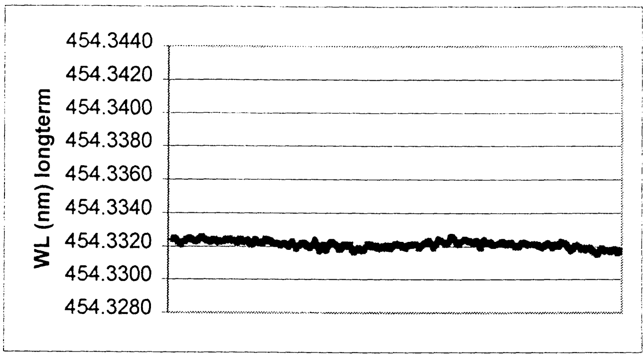


Figure 4-2a 5-minute wavelength measurement

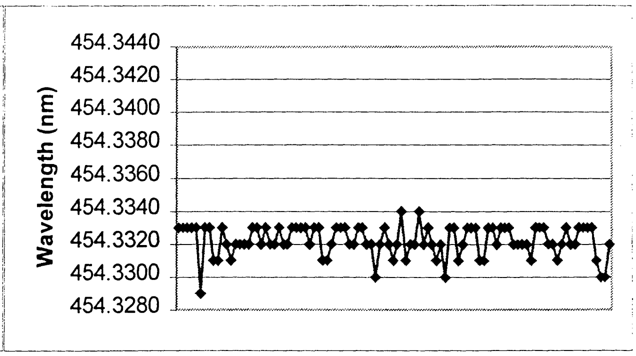


Figure 4-2b 100-point wavelength measurement

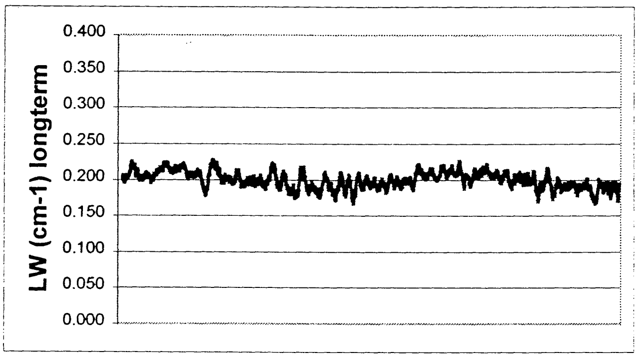


Figure 4-2c 5-minute linewidth measurement

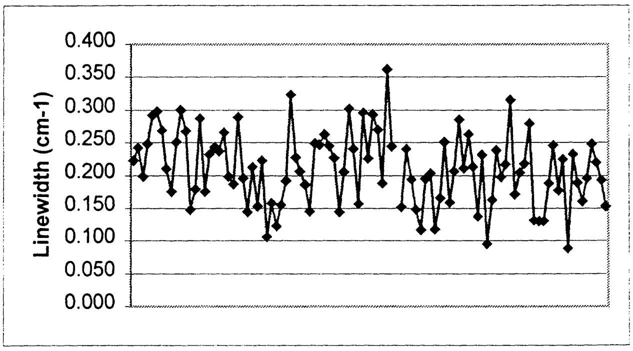


Figure 4-2d 100-point linewidth measurement

The 5-minute energy measurement with a 50-point sliding average is presented in Figure 4-2e. Figure 4-2f shows 100-point data of the energy measurement. The energy average and standard deviation is 153.87 and 18.52. The average of the shot to shot change is 8.2%. This corresponds quite well to the original design.

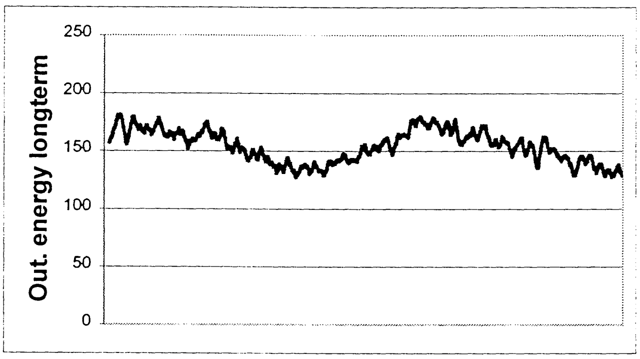


Figure 4-2e 5-minute energy measurement

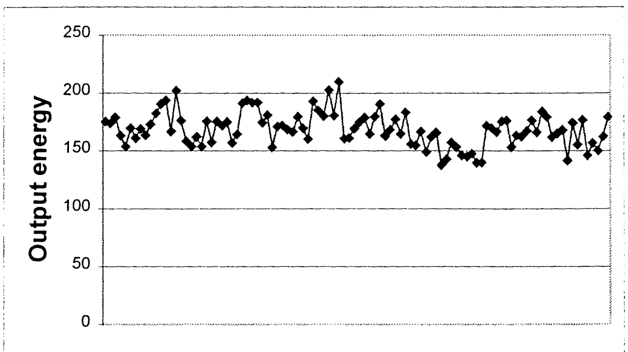


Figure 4-2f 100-point energy measurement

PI system and positioning control system connected with no wavelength change

The wavelength and linewidth data over a 5-minute period of time is presented in Figure 4-3a and Figure 4-3c(data is displayed with a 50 point sliding average function). 100 points from the measurement of the wavelength is presented in Figure 4-3b and of the linewidth in Figure 4-3d. The average and standard deviation of the wavelength is 454.3342nm and 0.0010nm. The corresponding values for the linewidth is 0.161cm^{-1} and 0.048cm^{-1}. The total wavelength span is 0.0060nm. The wavelength values show no differences compared with the original design values, but the linewidth is in this case much better. The reason for this is probably because of a change in wavelength mode, affecting the linewidth. Another reason for the lower linewidth can be a lower gain profile of the Master Oscillator. A lower gain profile will allow fewer cavity modes to reach laser threshold, thus lowering the linewidth of the emitted laser light. This will show up on the energy graph as a decrease in energy.

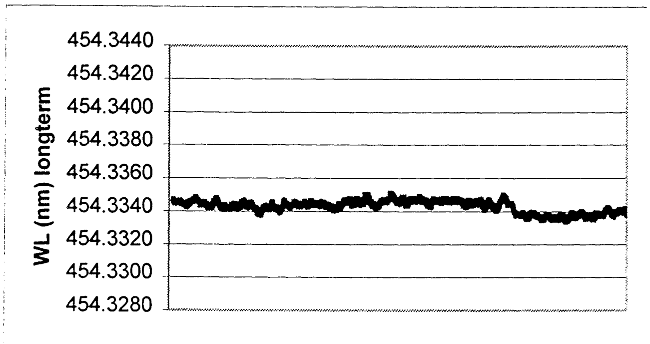


Figure 4-3a 5-minute wavelength measurement

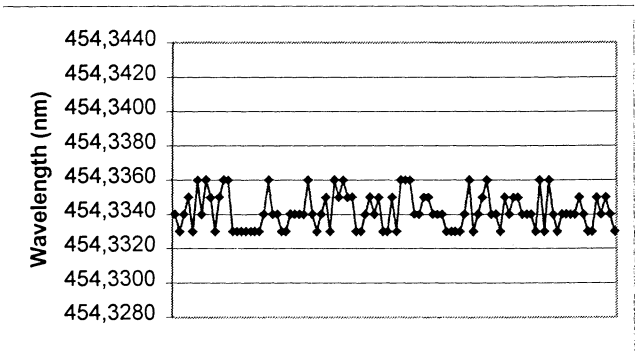


Figure 4-3b 100-point wavelength measurement

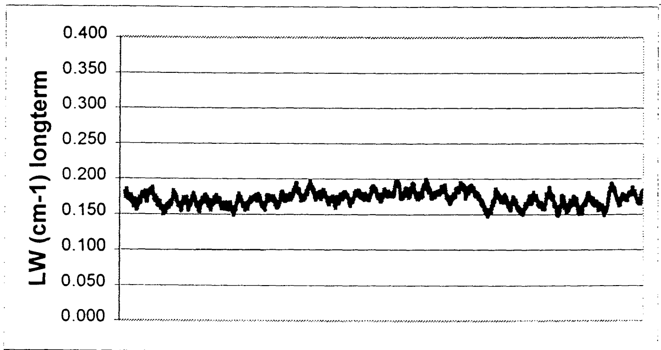


Figure 4-3c 5-minute linewidth measurement

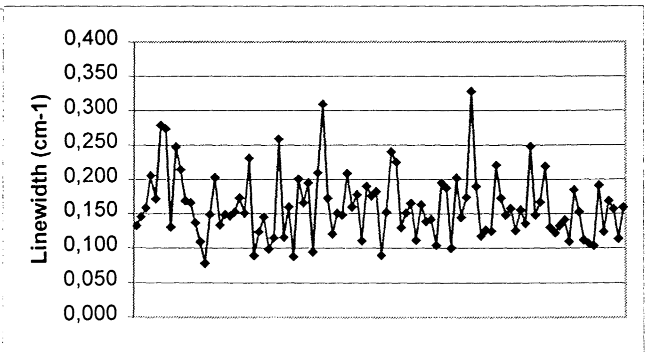


Figure 4-3d 100-point linewidth measurement

The 5-minute energy measurement with a 50-point sliding average is presented in Figure 4-3e. Figure 4-3f shows 100-point data of the energy measurement. The energy average and standard deviation is 116.71 and 19.37 with an average of the shot to shot change of 14.4%. As can be seen from the results the energy decreased, so the reason for the lower linewidth is probably a lower gain profile.

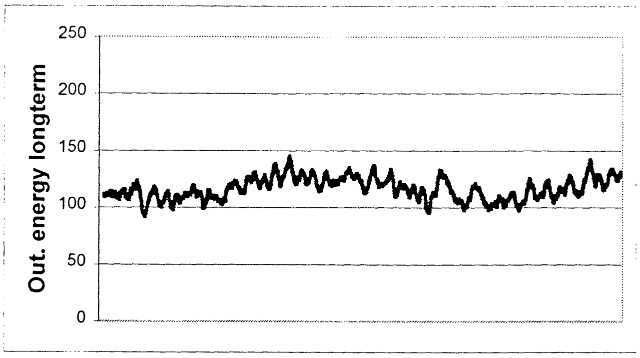


Figure 4-3e 5-minute energy measurement

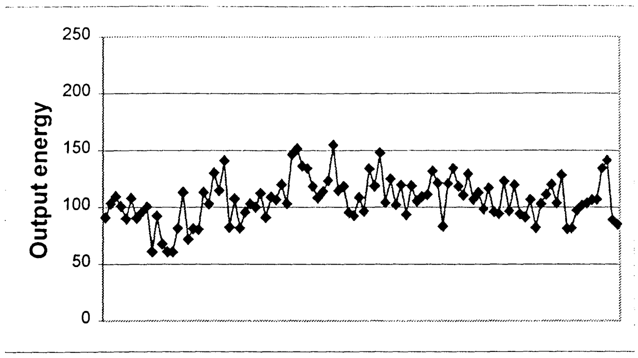


Figure 4-3f 100-point energy measurement

1nm wavelength change (0nm to 1nm) between each laser shot

The wavelength data over a 5-minute period of time for the two wavelengths is presented in the Figure 4-4a and Figure 4-4b. Figure 4-4c shows 100 points from the first wavelength measurement and Figure 4-4d shows 100 points from the second wavelength measurement. The average and standard deviation of wavelength1 (0nm) is 454.2904nm and 0.0010nm. The same for wavelength2 (1nm) is 453.2374nm and 0.0012nm. The total wavelength span for wavelength1 is 0.0060nm and

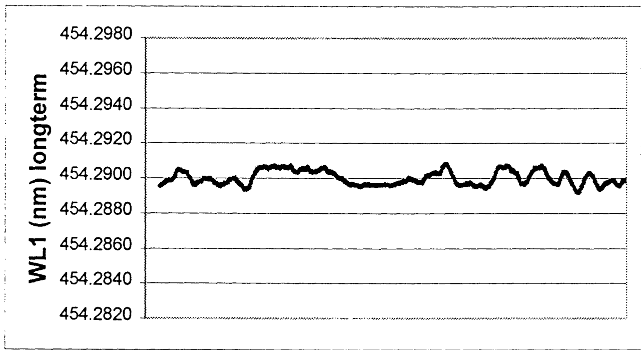


Figure 4-4a 5minute wavelength1 measurement

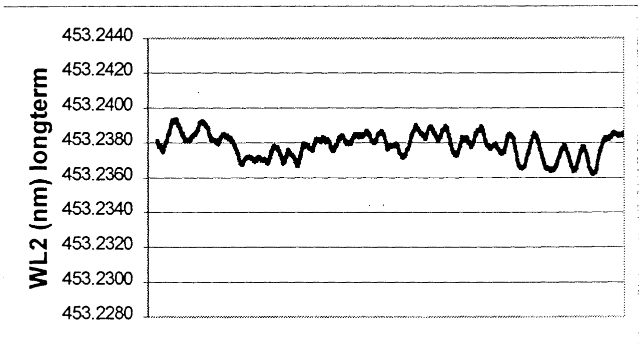


Figure 4-4b 5-minute wavelength2 measurement

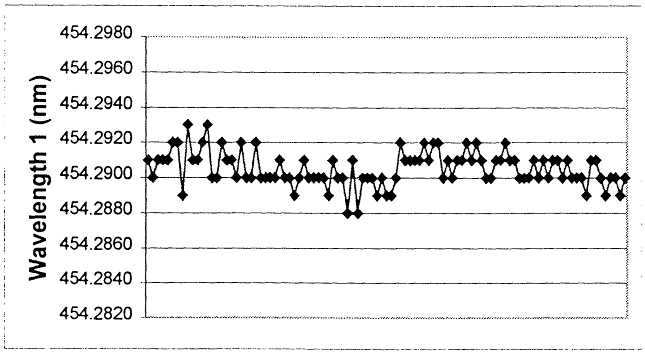


Figure 4-4c 100-point wavelength1 measurement

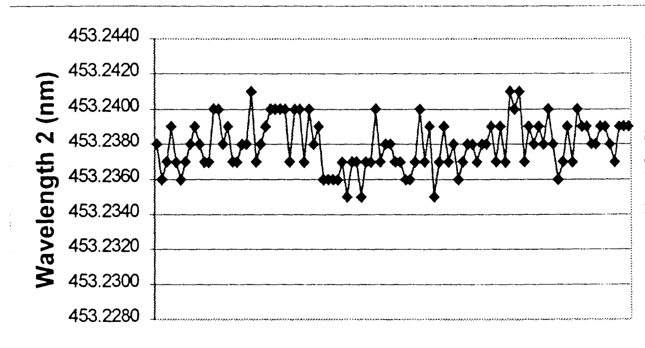


Figure 4-4d 100-point wavelength2 measurement

the total span for wavelength2 is 0.0090nm. Subtraction of the wavelength averages gives the value 1.067nm instead of the desired 1nm. This can be explained by an incorrect calibration of the piezo controlled tuning mirror expansion.

The wavelength data over a 5-minute period of time for the two wavelengths is presented in the Figure 4-4e and Figure 4-4f. The 100 point linewidth values for wavelength1 is shown in Figure 4-4g and the linewidth points for wavelength2 is shown in Figure 4-4h. The average and standard deviation of the linewidth is for wavelength1 0.187cm^{-1} and 0.065cm^{-1}, and for wavelength2 0.186cm^{-1} and 0.063cm^{-1}. These values correspond well with the values from the original design.

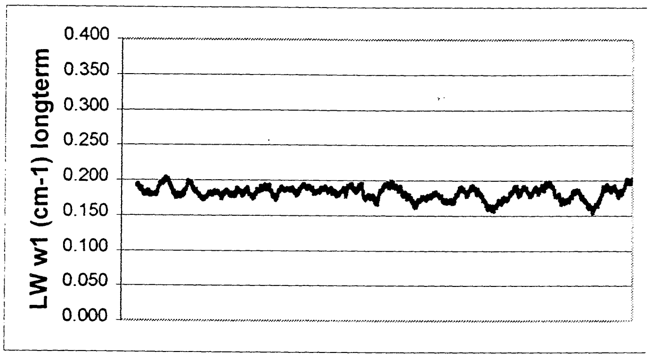


Figure 4-4e 5-minute linewidth (WL1) measurement

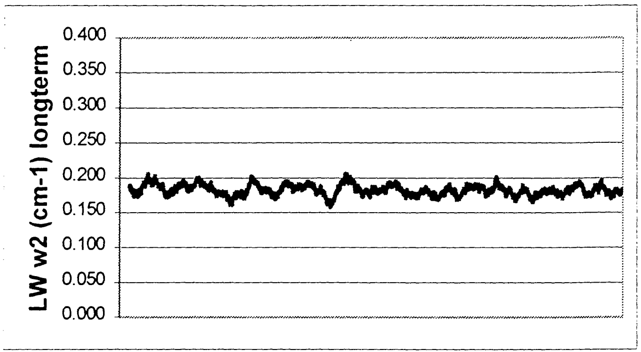


Figure 4-4f 5-minute linewidth (WL2) measurement

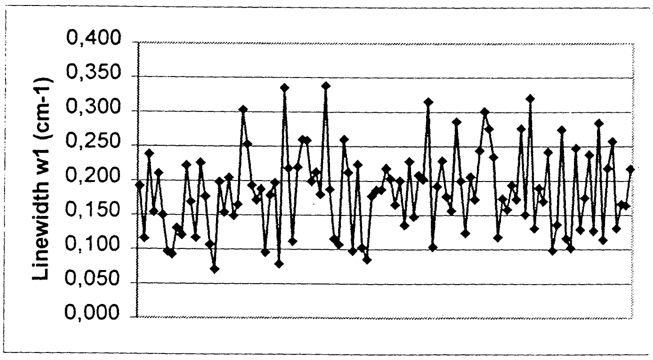


Figure 4-4g 100-point linewidth (WL1) measurement

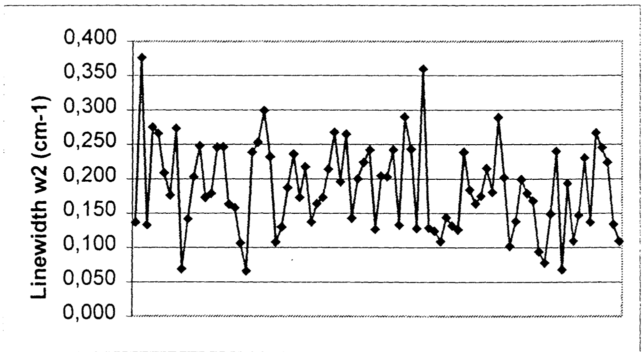


Figure 4-4h 100-point linewidth (WL2) measurement

Figure 4-4i displays the 100-point output energy of the two wavelengths (dots for wavelength1 and boxes for wavelength2) and Figure 4-4j shows the ratio between the two energy graphs, to show how well the system is calibrated with respect to crystal gain and offset. The 5-minute period of time measurement for the output energy and energy ratio is displayed in Figure 4-4k and Figure 4-4l (data is displayed with a 50 point sliding average function). The energy average and standard deviation for wavelength1 is 118.80 and 11.90 with a standard deviation of the shot to shot change of 8.9%. The energy average and standard deviation for wavelength2 is 119.78 and 10.63 with a standard deviation of the shot to shot change of 8.4%. The relative energy W2/W1 average and standard deviation is 1.02 and 0.13, which tells us that the crystal gain and offset evaluation was adequate. The energy values for this measurement are in comparison with the original design values and thus satisfactory.

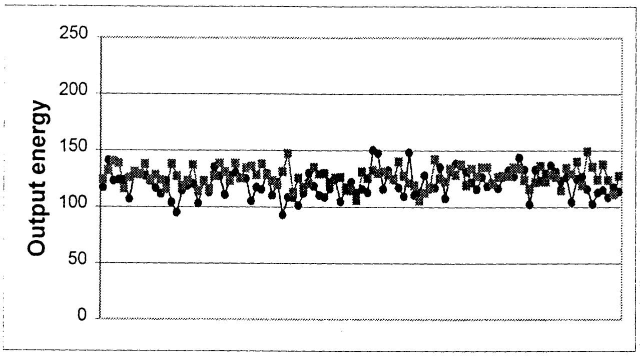


Figure 4-4i 100-point energy measurement of wavelength1 (•) and wavelength2 (♦)

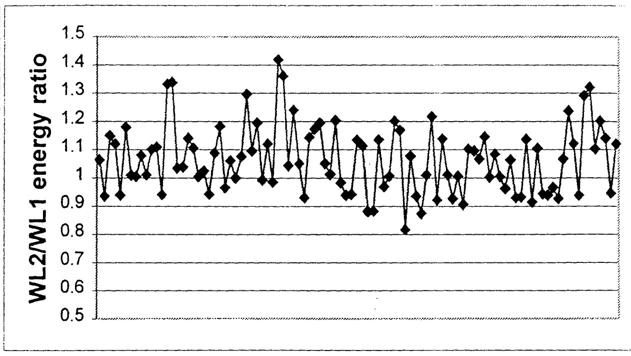


Figure 4-4j 100-point energy ratio

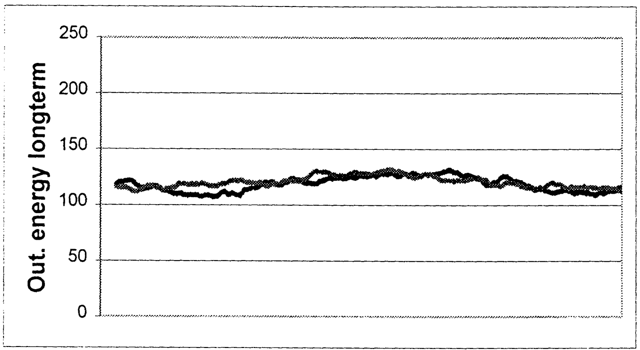


Figure 4-4k 5-minute energy measurement of wavelength1 and wavelength2

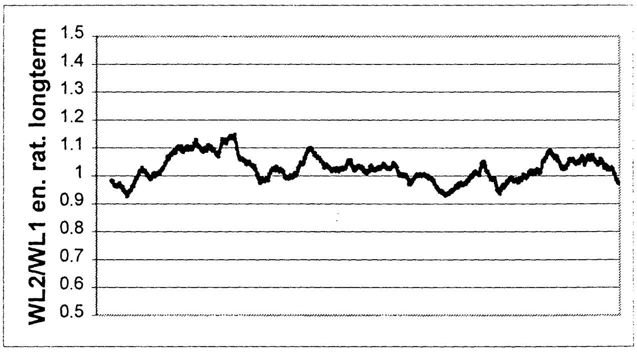


Figure 4-4l 5-minute energy ratio

Green region

The validation of the system in the green region was performed using the wavelength of 494.7nm. The results are presented without graphs in this chapter, since the appearance of the graphs are very similar to the ones in the blue region. The comparison between the original design and the new design were done in the same manner as in the blue region.

PI system and positioning control system disconnected

As in the blue region, this set-up acts as the original design. The results given here are to be compared with the results in the following validations, to check for differences in the two designs.

The average and standard deviation of:

- the wavelength is 494.7312nm and 0.0017nm

- the linewidth is $0.150cm^{-1}$ and $0.065cm^{-1}$
- the relative energy is 219.93 and 19.60, with a standard deviation of the shot to shot change of 12.5%

PI system connected and positioning control system disconnected

The average and standard deviation of:

- the wavelength is 494.7289nm and 0.0022nm
- the linewidth is $0.149cm^{-1}$ and $0.070cm^{-1}$
- the output energy is 195.36 and 12.93, with a standard deviation of the shot to shot change of 6.9%

PI system and positioning control system connected with no wavelength change

The average and standard deviation of:

- the wavelength is 494.7286nm and 0.0022nm
- the linewidth is $0.143cm^{-1}$ and $0.071cm^{-1}$
- the output energy is 176.79 and 13.60, with a standard deviation of the shot to shot change of 7.3%

1nm wavelength change (0nm to 1nm) between each laser shot

The average and standard deviation of:

- the wavelength1 is 494.9219nm and 0.0011nm
- the wavelength2 is 493.9040nm and 0.0017nm
- the linewidth of wavelength1 is $0.150cm^{-1}$ and $0.061cm^{-1}$
- the linewidth of wavelength2 is $0.134cm^{-1}$ and $0.055cm^{-1}$
- the output energy of wavelength1 is 279.81 and 25.44, with a standard deviation of the shot to shot change of 10.9%
- the output energy of wavelength2 is 221.02 and 27.74, with a standard deviation of the shot to shot change of 14.7%
- the output energy W2/W1 is 0.81 and 0.13

A correct calibration of the mirror gain would result in a difference of the two wavelengths equal to 1nm, instead of the 1.02nm in this measurement. The rest of the values show a good correspondence with the values of the original design.

Red region

The validation of the system in the red region was performed using the wavelength of 659.1nm. The presentation of the results is done in the same manner as in the green region, but with the difference that *Macroblock translators connected and computer disconnected* is not included. The reason for this is the very low impact of this set-up on the system behaviour, as can be seen by comparing the data of the previous regions. Therefor, only the new design (*Everything connected with no wavelength change*) are compared with the original design.

PI system and positioning control system disconnected

As in the previous regions, this set-up acts as the original design. The results given here are to be compared with the results in the following validations, to check for differences in the two designs.

The average and standard deviation of:

- the wavelength is 659.0633nm and 0.0019nm
- the linewidth is 0.123cm^{-1} and 0.045cm^{-1}
- the relative energy is 121.09 and 19.10, with a standard deviation of the shot to shot change of 13.3%

PI system and positioning control system connected with no wavelength change

The average and standard deviation of:

- the wavelength is 659.0636nm and 0.0019nm
- the linewidth is 0.122cm^{-1} and 0.048cm^{-1}
- the output energy is 101.82 and 18.67, with a standard deviation of the shot to shot change of 15.9%

All of the values are almost equal to the ones in the original design, indicating a very low impact of the new design on the system parameters in the red region.

1nm wavelength change (0nm to 1nm) between each laser shot

The average and standard deviation of:

- the wavelength1 is 659.0619nm and 0.0020nm
- the wavelength2 is 658.3853nm and 0.0021nm
- the linewidth of wavelength1 is 0.107cm^{-1} and 0.052cm^{-1}
- the linewidth of wavelength2 is 0.111cm^{-1} and 0.058cm^{-1}

- the output energy of wavelength1 is 121.23 and 15.61, with a standard deviation of the shot to shot change of 17.0%
- the output energy of wavelength2 is 85.40 and 18.11, with a standard deviation of the shot to shot change of 15.3%
- the output energy W2/W1 is 0.72 and 0.21

It can be noticed that the difference between the two wavelengths is not equal to 1nm. The reason for this is, as explained before, that the mirror gain was not correctly calibrated, i.e. the macroblock translator is not fully expanded when 10V is applied from the computer. Otherwise, we have got very good values compared with the ones in the original design, especially the linewidth that is very low. Only the energy values are somewhat unsatisfactory, but can be explained by a bad crystal gain and offset parameter evaluation. This is clearly shown by the energy ratio values.

4.2.2 IR mixing unit

The validation of the IR mixing unit was done at signal wavelength of 458nm. This corresponds to a wavelength of about 3.3μm in the IR region, where future measurements of hydrocarbons are to be performed. Another reason to use this wavelength region is that the sensitivity of the MOPO system are higher in the blue region. Therefore the IR mixing unit will also have higher sensitivity in the same region, since the idler beam from the MOPO system very much determines the operation of the IR mixing unit.

No wavelength change at 0nm expansion

The 5-minute energy measurement is presented in Figure 4-5a (data is displayed with a 50 point sliding average function). A 100-point presentation of the IR mixing unit energy is shown in Figure 4-5b. The average and standard deviation of the IR mixing unit energy is 0.44 and 0.08, with an average of the energy shot to shot change of 12.07%.

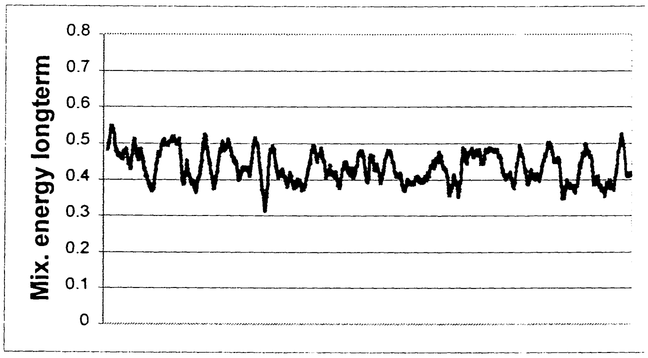


Figure 4-5a 5-minute energy measurement

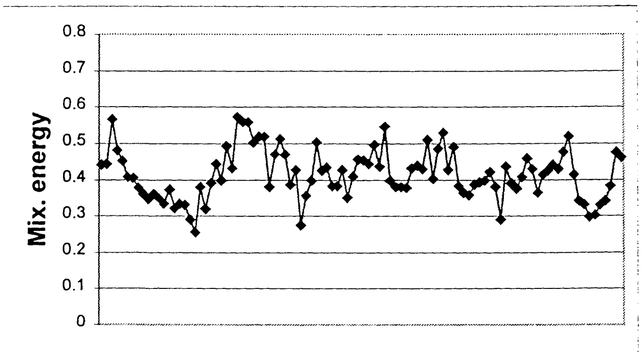


Figure 4-5b 100-point Mix. energy measurement

No wavelength change at 1nm expansion

The 5-minute energy measurement is presented in Figure 4-6a. A 100-point presentation of the IR mixing unit energy is shown in Figure 4-6b. The average and standard deviation of the IR mixing unit energy is 0.40 and 0.07, with an average of the energy shot to shot change of 12.70%. The average and standard deviation corresponds well with the value from the previous section.

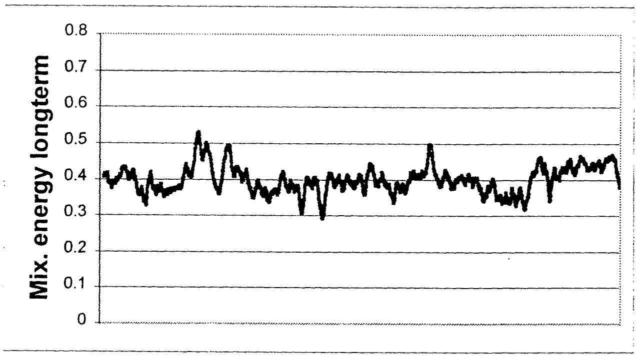


Figure 4-6a 5-minute energy measurement

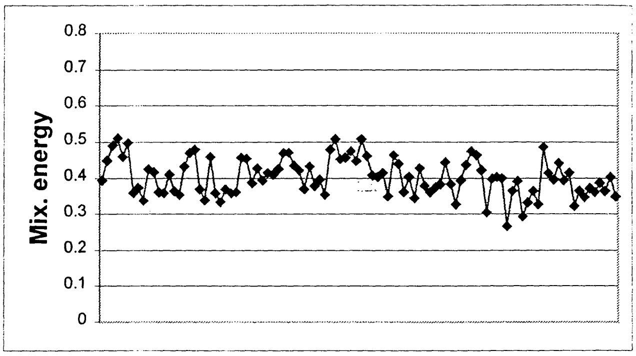


Figure 4-6b 100-point Mix. energy measurement

1nm wavelength change between each laser shot

The 5-minute energy measurement of wavelength1 is presented in Figure 4-7a and the 5-minute energy measurement of wavelength2 is presented in Figure 4-7b. A 100-point presentation of the IR mixing unit energy for wavelength1 and wavelength2 is shown in Figure 4-7c and Figure4-7d.

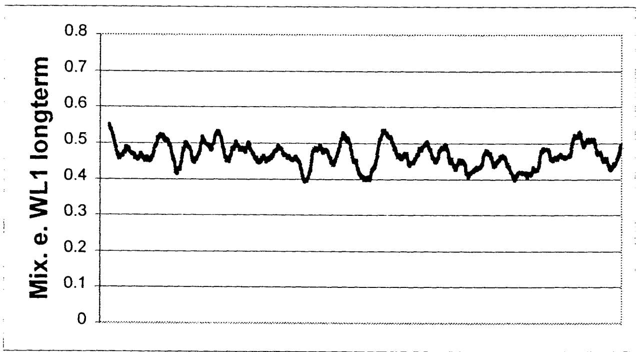


Figure 4-7a 5-minute energy measurement (WL1)

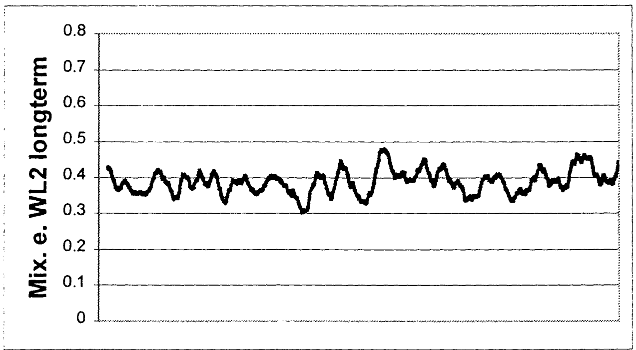


Figure 4-7b 5-minute energy measurement (WL2)

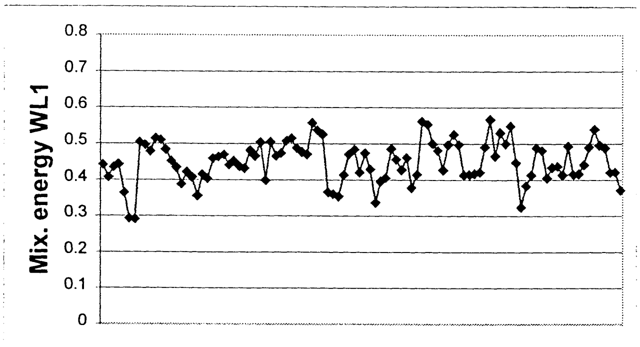


Figure 4-7c 100-point Mix. energy measurement of wavelength1

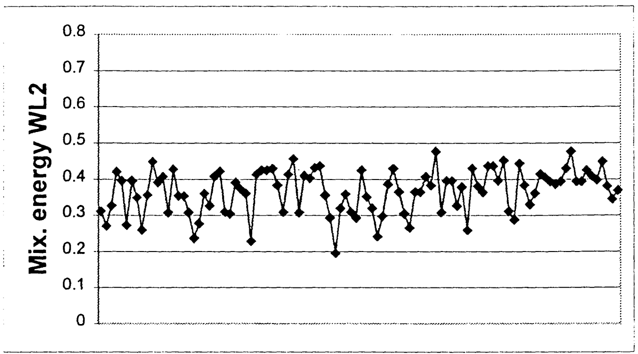


Figure 4-7d 100-point Mix. energy measurement of wavelength2

The average and standard deviation of:

- the IR mixing unit energy of wavelength1 is 0.45 and 0.11, with an average of the shot to shot change of 14.67%
- the IR mixing unit energy of wavelength2 is 0.38 and 0.09, with an average of the shot to shot change of 15.30%

The average, the standard deviation, and the average of the shot to shot change values from this test corresponds well with the values from the previous sections. Any long-term fluctuations of the energy can be explained by long-term fluctuations in the pump laser output energy.

4.3 Discussion

4.3.1 MOPO system

The data from the three wavelength regions are summarised in the table shown below. The tests ranging from 1 to 4, is system run with:

1. PI system and positioning control system disconnected
2. PI system connected and positioning control system disconnected
3. PI system and positioning control system connected with no wavelength change
4. 1nm wavelength change between each laser shot

	WAVELENGTH		LINEWIDTH		ENERGY		
TEST	Average (nm)	St. dev. (nm)	Average (cm^{-1})	St. dev. (cm^{-1})	Average	St. dev.	Shot to shot (%)
1	454.3397	0.0012	0.192	0.067	146.51	17.93	9.1
2	454.3322	0.0009	0.210	0.055	153.87	18.52	8.2
3	454.3342	0.0010	0.161	0.048	116.71	19.37	14.4
4 (WL1)	454.2904	0.0010	0.187	0.065	118.80	11.90	8.9
4 (WL2)	453.2374	0.0012	0.186	0.063	119.78	10.63	8.4
1	494.7312	0.0017	0.150	0.065	219.93	19.60	12.5
2	494.7289	0.0022	0.149	0.070	195.36	12.93	6.9
3	494.7286	0.0022	0.143	0.071	176.79	13.60	7.3
4 (WL1)	494.9219	0.0011	0.150	0.061	279.81	25.44	10.9
4 (WL2)	493.9040	0.0017	0.134	0.055	221.02	27.74	14.7
1	659.0633	0.0019	0.123	0.045	121.09	19.10	13.3
3	659.0636	0.0019	0.122	0.048	101.82	18.67	15.9
4 (WL1)	659.0619	0.0020	0.107	0.052	121.23	15.61	17.0
4 (WL2)	658.3853	0.0021	0.111	0.058	85.40	18.11	15.3

The changes in wavelength averages are merely due to difficulties reaching the previous wavelength when changing between set-ups, for example when changing from the original set-up to macroblock translators connected. When connecting the macroblock translators the PI control unit applies an initial voltage to the translators, thereby changing the wavelength a small amount. This change had to be compensated by changing the wavelength on the MOPO control unit.

Analysing the standard deviation of the wavelength shows good coherence for the new design compared with the original design over the whole wavelength range.

The linewidth shows a small change in averages and standard deviations between set-ups, but this can be explained by the change in wavelength average between set-ups. The linewidth is different in one wavelength compared with another wavelength, so this is one possible explanation. A second explanation is a change in crystal gain and offset parameters for the different set-ups. The parameters affect the energy output and thereby the gain profile of the Master Oscillator. A lower gain profile will for example lower the linewidth of the laser light, by allowing fewer laser modes reach laser threshold.

Another interesting result is that the linewidth is higher in the blue region compared with the other regions. Theoretically this should be the other way around. The energy output in the blue region is lower than in higher wavelengths and this should give a lower linewidth, as explained above. The reason for this is the fact that the laser beam path of the MOPO system was realigned between the different wavelength regions. An incorrect alignment of the laser beam path may cause the linewidth to decrease. This seems to be the reason for the decreased linewidth in the green and red region.

The energy values are consistent for the different set-ups and wavelength regions. Differences in crystal gain and offset parameters and long-term changes in pump laser energy output can explain any differences between set-ups. Also the fact that the Burleigh wavemeter had to be realigned from time to time between set-up can explain some differences. It is very difficult to get the same amount of laser light to enter the wavemeter for the different set-ups.

4.3.2 IR mixing unit

The results from the tests of the IR mixing unit are presented in the table shown below.

	ENERGY		
TEST	Average	St. dev.	Shot to shot (%)
No wavelength change at 0nm expansion	0.44	0.08	12.07
No wavelength change at 1nm expansion	0.40	0.07	12.70
1nm wavelength change (WL1)	0.45	0.11	14.67
1nm wavelength change (WL2)	0.38	0.09	15.30

All of the values from the 1nm wavelength change test corresponds well with the values from the two no wavelength change tests. It can be noticed that the shot to shot change in energy when performing no wavelength change is slightly increased compared to the values for the modified MOPO system in the blue wavelength region. This is expected, since the IR wavelength is generated through a mixing process, where two fluctuating sources are mixed to generate the output. The increase of the shot to shot change when performing a wavelength change compared to the no wavelength change tests, can be explained by a slight hysteresis in the movement of the crystal housing lever arm in the IR mixing unit. This indicates that the mechanical construction of the IR mixing unit is not optimal.

5 Conclusions

The purpose of the project was to develop a fast wavelength tuning system for OPO-based lidar measurements. This was achieved using macroblock translators located at the wavelength tuning points, i.e. the tuning mirror and the crystal housing in the MOPO system and the mixing crystal housing in the IR mixing unit. The control of the wavelength positioning and data acquisition was implemented in a LabVIEW program.

The modified MOPO system was validated for wavelength, linewidth and energy parameters compared with the parameters of the original MOPO system, as described in chapter 4. The results of this chapter show that the new design has a very low impact of the system parameters. Especially the standard deviation of the wavelength, the linewidth and the energy values show good coherence with the values of the original design, both with and without wavelength change. This is important, since a stable wavelength and linewidth between shots are necessary in a DIAL measurement. The IR mixing unit was validated for energy stability when performing a wavelength change compared with the values for a non-wavelength change. The results show that only a small difference can be detected. Hysteresis in the movement of the lever arm in the IR mixing unit crystal housing can explain the differences and can be corrected by a better mechanical construction.

Finally, the modified MOPO system and the IR mixing unit works well compared with the original system and the system is capable of moving to a new wavelength between each laser shot.

Future modifications are to use macroblock translators with a larger expansion, to cover a wider wavelength range. An increased ability to use the macroblock translators means a faster system, since the stepper motors of the MOPO system do not need to be used as often. Another important addition to the system would be to use a pump laser with a beam lock and divergence lock, which eliminates time-consuming realignment of the beam path of the MOPO system. A beam lock and divergence lock system would also eliminate much of the start-up time and allow easier operation of the system.

A faster and more reliable crystal gain and offset evaluation program is desired. A new algorithm featuring faster and more accurate evaluation would increase the performance and speed of the system.

A future feature of the evaluation program is an automatic evaluation of the tuning mirror gain with respect to wavelength. Currently the tuning mirror gain has to be calculated by hand, by measuring the wavelength change a certain voltage applied to the mirror causes. This can easily be implemented in the program.

6 System manual

The purpose of the user manual is to give an easy reference of system set-up and operation, including hardware and software components. Information on the operation of the equipment not discussed in this manual can be found in the operation manuals listed in the reference list. Information on the operation of the laser and the alignment of laser beams are not discussed here, since this is assumed to have been done prior to reading this manual. Information concerning the laser system and alignment process can be found in the laser operation manuals [2-4].

6.1 Hardware set-up

PI system

1. Make sure the macroblock translators are mounted in the system.
2. Adjust the LVDT cores to the zero position, i.e. place them inside the LVDTs leaving 12.5mm of the core outside. Also make sure the cores are placed in the centre of the LVDTs, not touching the inner surface of the LVDTs.
3. The screws on the back of the tuning mirror construction should be tightened to about two turns and secured with the locking nuts, to prevent the resonance frequency of 10Hz.
4. Connect the macroblock translators to the amplifier modules in the PI system (the amplifier for the tuning mirror is to the right, the OPO crystal is in the middle and the mixing crystal is on the left) and the LVDTs to the sensor/control module (tuning mirror on the top, OPO crystal in the middle and the mixing unit on the bottom).
5. Follow the calibration instructions in the calibration manual for the sensor/control module [12]. This is performed in order to calibrate the operation of the macroblock translators, with respect to drift, hysteresis, load, displacement range, frequency response, settling time, and optimum match with the LVDT sensors.
6. Make sure the sensor/control module is in use for the three channels, by changing the switches on the sensor/control module to the top position. Also verify that the potentiometers on the amplifiers is set to zero.

Linewidth unit

1. Place the Fabry-Perot analyser in the laser beam path.

2. Place the linewidth unit a focal length away from the FPA. Make sure the centre of the diffraction pattern is placed above the top or below the bottom of the diode array.
3. Connect the power supply.
4. Connect the reset input to output CD on the delay unit.
5. Connect the start input to output AB on the delay unit.

Computer connection

1. Connect pin 22 to the tuning mirror amplifier on the PI system.
2. Connect pin 21 to the input of the multiplexer circuit. Connect output one of the multiplexer circuit to the OPO crystal amplifier and output two of the multiplexer circuit to the mix crystal amplifier on the PI system. Connect pin 52 to the channel select input on the multiplexer circuit.
3. Connect pin 11 to the T0 output on the delay unit.
4. Connect pin 33 to the photo diode on the IR mixing unit.
5. Connect pin 68 to the output of the linewidth unit.
6. Connect the GPIB cable from the computer to the MOPO control unit.

Delay unit

1. Connect the trigger input of the delay unit to the q-switch advance synch on the pump laser.
2. Adjust output A to 0s, output B to 8μs, output C to 49.990ms, and output D to 49.995ms.
3. Make sure the outputs uses TTL output, 50Ω coupling, and no inverted pulses.

6.2 Software operation

Start the program called *Main program.vi* for measurement set-up and execution. The front panel is shown in Figure 6-1. By pressing the first button, called **Wavelength selection**, the measurement wavelengths and parameters are determined. The second button, called **Calibrate laser**, determines the wavelength error of the laser and compensates the selected measurement wavelengths with the error. By pressing the third button, called **Start measurement**, the measurement with the wavelengths and parameters selected in Wavelength selection is executed. The last button is used to end the program. The data collected is then output from the VI for analysing and presentation

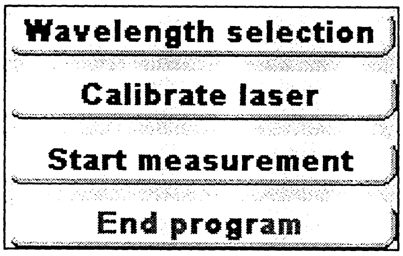


Figure 6-1 Front panel of Main program.vi

in another program.

The program executed when pressing the **Wavelength selection** button is called *Wavelength select.vi*. The front panel is shown in Figure 6-2.

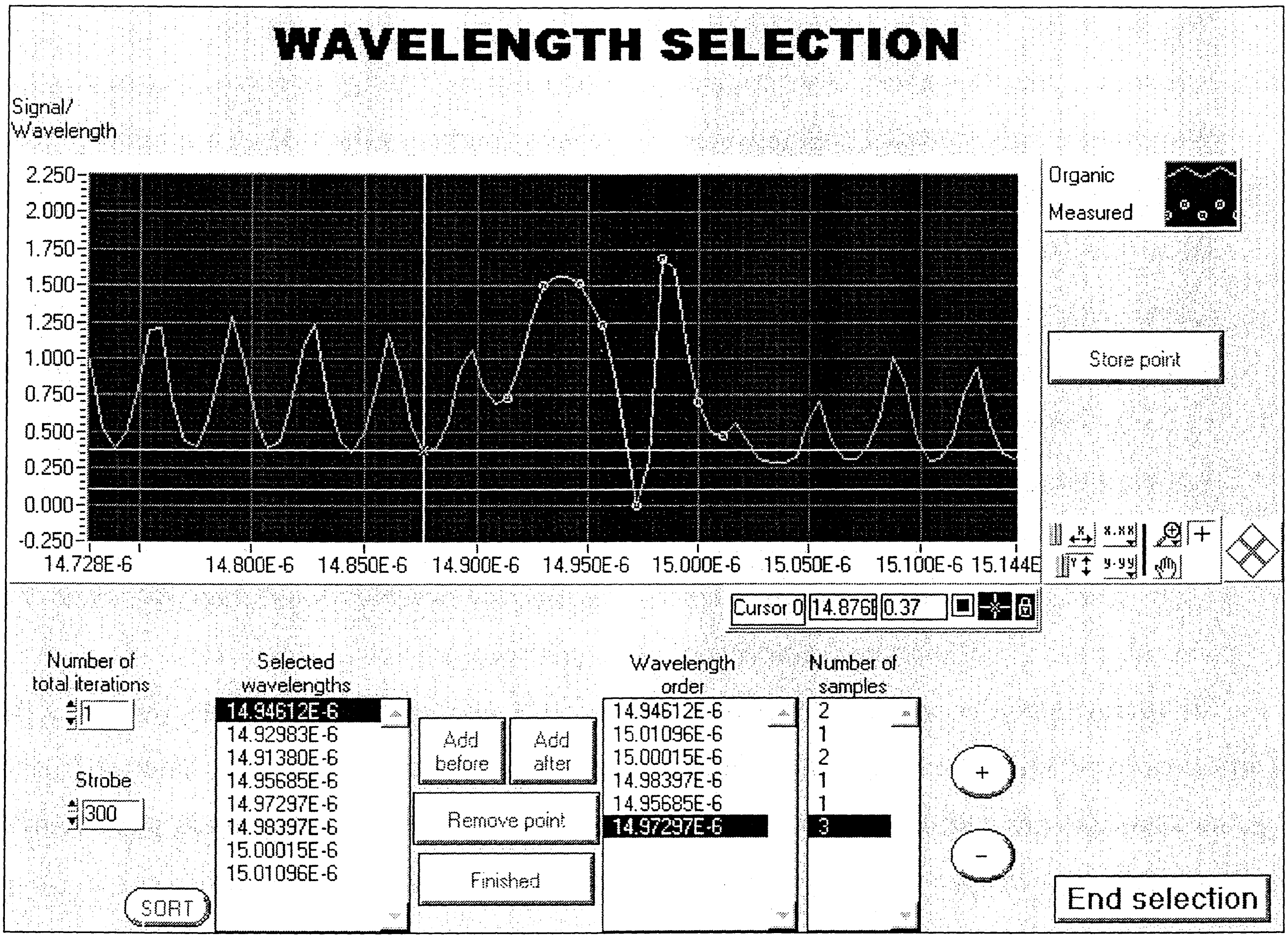


Figure 6-2 Front panel of Wavelength select.vi

Choose the desired measurement wavelengths and parameters in the following manner:

1. Select the absorption spectrum of the desired gas or mixture of gases when prompted to do so at the start of the program. The spectrum will show up in the graph.
2. Mark the desired measurement wavelengths in the graph by moving the cursor and pressing the **Store point** button for each point. Each of the marked wavelengths will show up as a white circle in the spectrum. Use the cursor buttons on the right of the graph to zoom and move the spectrum. The selected wavelengths will be listed in the **Selected wavelengths** box. The selected wavelengths will be sorted in ascending order, if the **Sort** button is pressed.
3. The order of the wavelengths is selected by moving the cursor to one of the marked wavelengths in the graph (the selected wavelength will be highlighted in the **Selected wavelenghts** box) and pressing either the **Add before** or the **Add after** button. The marked wavelength will be inserted

before or after the highlighted position of the **Wavelength order** box. Change highlighted position of the **Wavelength order** box by clicking on the desired position in the box. To remove a wavelength from the **Wavelength order** box simply select the wavelength and press **Remove point**. When the order of the wavelengths is complete, press **Finished**.

4. Select the number of samples for each measurement point by highlighting the wavelength in the **Wavelength order** box and pressing either the + button or the – button. The cursor in the graph will move to the selected wavelength, thereby visualising the selected wavelength. The number of samples for each measurement point is shown in the **Number of samples** box.
5. Change the number of times the measurement series will execute by changing the **Number of total iterations** control. Change the number of collected values for each measurement point by changing the **Strobe** button.
6. End the wavelength selection process by pressing the **End selection** button.

If the wavelength selection process for some reason was not satisfactory, simply restart the wavelength selection program and redo the process described above.

The laser calibration process, initiated by pressing the **Calibrate laser** button, calculates the difference between the desired wavelength and the actual wavelength from the laser. The value given from this program is subtracted (added if negative value) from the selected measurement wavelengths, thus compensating for the laser wavelength error. The actual wavelength is now equal to the selected measurement wavelength.

Finally, the position and acquire program discussed in chapter 3.3 is launched when the **Start measurement** button is pressed. The results from the program are located in an array, containing the values for each of the selected wavelengths.

Some of the subVIs can also be used for stand alone purposes.

- Use *Position control.vi* to move the system to a new wavelength and to evaluate new crystal parameters. The functionality of the program is discussed in chapter 3.1.3.
- Use *crystal_gainoffset.vi* or *recalib_g&o.vi* along with *piezo control.vi* to evaluate new crystal parameters and update the macroblock translators with the new voltages. This is useful when only maximum energy is desired and no wavelength change is necessary. R*ecalib_g&o.vi* is only useful when old crystal parameters is available. If not, use *crystal_gainoffset.vi* first.

7 References

[1] Steven E Harris, "Tuneable Optical Parametric Oscillators", *Proceedings of the IEEE*, vol. 57, no. 12, p. 2096-2113, December 1969

[2] Spectra-Physics Lasers Inc., "Quanta-Ray MOPO-730 Optical Parametric Oscillator", Instruction manual, January 1995

[3] Spectra-Physics Lasers Inc., "Quanta-Ray MOPO-730 Optical Parametric Oscillator", Instruction manual, p.19 29-37 85-91, January 1995

[4] Spectra-Physics Lasers Inc., "Pulsed Nd:YAG Lasers GCR-200 series", User's manual rev. B, May 1995

[5] Physik Instrumente, "Products for micropositioning", Catalogue edition E, p. 5.89 5.41, May 1995

[6] Physik Instrumente, "Operating manual PZ 62E", Operating and handling manual for E-500 series PZT control electronics, Release 2.20, 6 October 1997

[7] Burleigh Instruments Inc., "Pulsed Wavemeter operating manual", Operating manual rev. E, 1997

[8] Stanford Research Systems Inc., "Model DG535 Digital Delay/Pulse Generator", Revision 2.4, November 1997

[9] National Instruments Corporation, "DAQ PCI E Series User Manual", July 1997

[10] National Instruments Corporation, "LabVIEW for Windows Tutorial", August 1993

[11] Hamamatsu Photonics K.K., "MOS Linear Image Sensors", Product catalogue, December 1995

[12] Physik Instrumente, "Operating manual PZ 77E", Calibration procedures for the E-509 Position Servo Control Module, Release 1.0, 25 July 1997