

Bachelor Thesis

Temperature measurements using spectroscopy

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Abstract

This project helps to reach the end goal of doing long distance measurements. Long distance measurements depends on the refractive index of air. The refractive index depends on temperature, pressure, humidity and gas mixture. The biggest uncertainty of calculating the refractive index is the temperature, as ambient fluctuations are non-uniform across space. Measuring the temperature optically using spectroscopy is a method that can be used to accurately detect temperature fluctuations, when looking at the absorption profile of in this specific case two gases, oxygen and carbon dioxide. Two gases were selected to be able to compare the measurements with each other when performed in air. The absorption spectra of O_2 and CO_2 were detected with two different spectrometers. The two different spectrometers operate in different wavelength ranges. Both the setups use the same frequency comb laser as an illumination source.

The spectrometer to detect O_2 lines was built as a part of this project and a first O_2 spectral measurement was demonstrated. The CO_2 spectrometer was also realigned and a CO_2 measurement was performed. Both the beams were also made to co-propagate through the same gas cell so that simultaneous measurements could be performed on the same gas volume using the two spectrometers.

To obtain an absorption spectrum two measurements are done. First a measurement is done with a reference gas, during this project nitrogen is used. The gas cavity is then evacuated with a vacuum pump and then filled with a gas(mixture) of choice. Using a MATLAB program the ratio between the reference and measurement is converted to an absorption spectrum. This thesis presents measurements of the absorption spectra of O_2 and CO_2 . The measured absorption spectra are then compared with spectra from the HITRAN database. At the end of the project the absorption spectra only need be optimised to perform temperature measurements.

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Chapter 1

Introduction

This bachelor project was conducted at the Optics Research Group of Delft University of Technology. One of the research projects done at this group is long distance measurements, in collaboration with VSL. The topic discussed in this thesis will help to reach this end goal. The topic of this thesis is temperature measurements using spectroscopy in the same beam path as being measured. Section 1.1 explains why long distance measurements are done and what the dependency of long distance measurements is with respect to measuring the temperature. Section 1.2 focuses on the present work that is done during this bachelor project.

1.1 Background

High accuracy long distance measurements are important in many different fields, for example surveying and spacebased interferometry. For space applications the ability to accurately determine the distance to an object is important in future tight formation-flying satellite missions, where precise measurements of the absolute distance are critical for maintaining the relative position of the individual satellites [1]. On earth the accuracy of long distance measurements depends on the refractive index of air. Though the refractive index is known to a high degree, namely $1 \cdot 10^{-7}$ [2,3] it still limits the final accuracy that can be reached. The refractive index depends on temperature, pressure, humidity and gas mixture. The biggest uncertainty of calculating the refractive index is the temperature, as ambient fluctuations are non-uniform across space. Even in a well controlled lab environment the temperature can vary by half of a degree. There are several techniques to measure the temperature, most of them are non optical. There is a technique used in the chemical industry [4] to measure the temperature optically using spectroscopy. At present temperature measurements are done locally, this would mean that many detectors are needed to measure the temperature along the propagation direction. The great advantages of measuring the temperature optically is that the relevant path is measured and the measurements are done with the beam used for the measurements itself. Therefore it is important to be able to measure the temperature for the path for which the distance is being measured. Not until recently this method was only done for high temperature (above 500 K) measurements with an accuracy of a few degrees. In 2010 researchers were able to do temperature measurements using spectroscopy at room temperatures with an accuracy of 7 mK [5,6]. This project uses the same idea of measuring the temperature optically using spectroscopy but the approach is different. Section 1.2 explains the approach of the present work.

1.2 Assignment

As explained in Section 1.1 the main task in this thesis was the measurement of temperature using spectroscopy. The specific method used during this project is absorption spectroscopy. When

light of a certain spectral band passes through a sample, some of it gets absorbed. Analysing the absorbed light gives information about the sample. In this project the aim is to measure the temperature of a gas by analysing its absorption spectrum. When the temperature of the gas changes the effect of this can be seen on the absorption spectrum. The temperature change, changes the level population according to the Boltzmann distribution [7]. Thus the absorption spectrum which is measured at different temperatures is different. The temperature can be determined by comparing the absorption spectra. Air mainly consists of three gases, namely nitrogen (N_2), oxygen (O_2) and carbon dioxide (CO_2), besides some trace gases, with N_2 as the most dominant gas. In this project the aim to measure the temperature of air using absorption spectroscopy of O_2 and CO_2 . The laser available for this project has a spectral range of 1400-1600 nm which makes this feasible. N_2 is not used because its characteristic absorption lines lie in the UV-region. The absorption spectra will be obtained with two different spectrometers, namely a spectrometer that detects the characteristic lines of O_2 and a spectrometer that detects the characteristic lines of CO_2 . These spectrometers measure the transmitted spectrum in different wavelength ranges. The spectrometer used is a Virtually Imaged Phased Array (VIPA) spectrometer.

Both setups use a frequency comb laser as a source because of its broad spectrum. The frequency comb laser has originally a wavelength range between 1400 and 1600 nm. For the O_2 VIPA the initial beam needs to be frequency doubled in order to detect the absorption spectrum in the wavelength range around the 750 nm.

After doing several temperature measurements a MATLAB program converts the obtained images from the spectrometer into spectra. The change between these spectra is then compared with the change in the predicted spectra at these different temperatures from the HITRAN database [8]. During this project the HITRAN database is used as a reference.

Thus if spectroscopy is performed in the same beam path as the distance is being measured, the ambient temperature of the beam path can be determined. This then helps in knowing the refractive index better.

1.3 Thesis Outline

This thesis starts with giving an introduction about the background of the research and with a brief description of the project. Chapter 2 will explain the theory behind the optical elements needed for absorption spectroscopy. It will also discuss briefly the behaviour of a molecular spectrum and spectral lines. Chapter 3 gives the specifications of both spectrometers and it will give details of the approach of this bachelor project. Chapter 4 presents the obtained results and discusses these results. It also gives the associated inaccuracies of the obtained results. Chapter 5 reports the conclusions and will present recommendations for further investigation.

Chapter 2

Absorption Spectroscopy

Absorption spectroscopy is a technique that measures the absorption of light, while travelling through a medium, as a function of frequency. The absorption varies as a function of frequency and this can be obtained with a spectrum over a range of frequencies.

The basic principles of absorption can be understood with the Beer-Lambert law [9, 10]. The Beer-Lambert law explains the relation between absorption and the interaction distance in a certain medium. If a beam with initial intensity I_0 travels through a medium with an interaction distance of x it will have a decreased intensity that is given by

$$I = I_0 e^{-\alpha(\nu)x} \quad (2.1)$$

where:

I : intensity of the beam after travelling through the medium [W/m²]
 I_0 : initial intensity of the beam [W/m²]
 $\alpha(\nu)$: absorption coefficient of the medium [cm⁻¹]
 x : interaction distance [cm]

Equation 2.1 can also be written as

$$I = I_0 e^{-\epsilon cx} \quad (2.2)$$

where:

$\epsilon(\nu)$: molar absorptivity [l/mol·cm]
 c : concentration of the medium [mol/l]

The fraction of the initial intensity that is absorbed at specific frequencies can also be written in a term called absorbance. The absorbance is given as a logarithmic ratio of the transmission of the medium as given in Equation 2.3

$$A = -\ln(T) \quad (2.3)$$

where:

A : absorbance of the medium
 T : transmission of the medium

The absorbance can also be written in terms of the absorption coefficient, interaction distance and the concentration as given in Equation 2.4

$$A = \epsilon cx \quad (2.4)$$

Equation 2.4 shows that the absorbance is linear with the concentration.

There are several contributions that determine the structure of the absorption spectrum. One of the environmental contributions is the temperature. The shape of some spectral bands in the spectrum will change if the temperature changes. This phenomenon can be detected due to

the change in level population of molecules. The change in the absorption spectrum will give information how the temperature varies.

This chapter will cover the theory behind absorption spectroscopy. It will explain the theory behind spectral lines and a molecular spectrum and it discusses the components needed for a spectroscopic measurement.

2.1 Spectral Lines

The manner in which light is absorbed and emitted by atoms can be explained by using a part of the quantum theory introduced by Bohr [11, 12]. This quantum-mechanical model was able to predict the wavelengths of its emission spectrum. This theory is a well explained starting point to understand the transition between different energy levels. This idea of transition between two allowed states can also be used for the absorption process.

Beside the electronic states there are other smaller transitions between states, namely the vibrational and the rotational states.

2.1.1 Molecular Spectrum

Atomic spectra are essentially determined by the different electronic states. For a molecular spectrum there are additional states and the spectrum is therefore not only determined by the electronic states.

To fully understand the molecular spectrum and the behaviour of this spectrum the Born-Oppenheimer [13] approximation is used. This approximation makes the assumption that the nuclei are much heavier than the electrons. Due to this assumption the wavefunction can be divided into an electronic component and additional degrees of freedom that are determined by the electron cloud but also by the nuclei and its movements. The additional degrees of freedom can be divided in a rotational component and a vibrational component of the molecule. This is given by Equation 2.5.

$$E_{tot} = E_{elec} + E_{vibr} + E_{rot} \quad (2.5)$$

where:

E_{tot} : total energy of the molecule [eV]

E_{elec} : electronic energy of the molecule [eV]

E_{vibr} : vibrational energy of the molecule [eV]

E_{rot} : rotational energy of the molecule [eV]

The different energies shown in Equation 2.5 are for the behaviour of diatomic molecules. The contributions in Equation 2.5 and shown in Figure 2.1 all have different ranges in the electromagnetic spectrum.

When a transition occurs between different rotational levels for the same vibrational and electronic state it will lead to a pure rotational spectrum with wavelengths in the microwave region ($\lambda \approx 1$ mm to 1 m).

When a transition occurs between rotational levels of a different vibrational level it will lead to a vibration-rotation spectrum with wavelengths in the mid-infrared region ($\lambda \approx 2$ μ m to 20 μ m).

The transitions between two different electronic states will lead to a spectrum with wavelengths from the UV to the near infrared region ($\lambda \approx 0.1$ μ m to 2 μ m) [14].

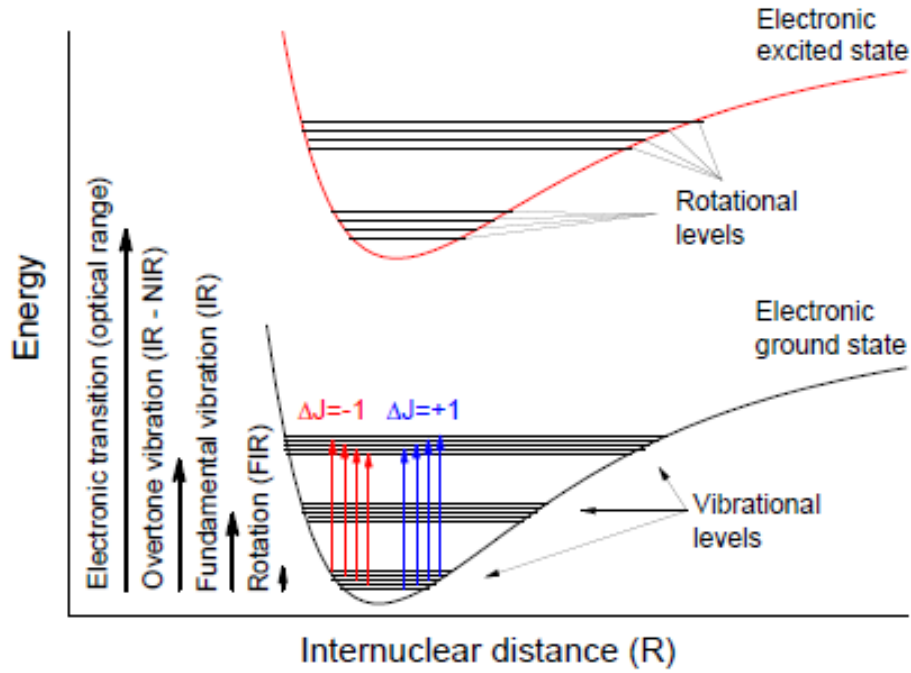


Figure 2.1: Different transitions of the energy levels of the vibrational, rotational and the electric energy [15].

As shown in Equation 2.5 the energy of a molecule is equal to the sum of all energy contributions. Whereas the temperature of any part of the energy contributions is the same as that of the whole. According to the Boltzmann distribution law [7] the temperature determines the distribution of the molecules over all the possible states. The distribution law for molecules in the quantum states E_m and E_n can be defined as

$$\frac{N_m}{N_n} = e^{-\left(\frac{E_m - E_n}{kT}\right)} \quad (2.6)$$

where:

k : Boltzmann's constant = $1.38 \cdot 10^{-23}$ [J/K]

E_m : energy of the lower state [eV]

E_n : energy of a higher state [eV]

T : temperature [K]

In the next sections the components are described needed to perform the experiments to observe the spectral lines.

2.2 Frequency Comb Laser

As an illumination source to do spectroscopy a frequency comb laser [15–17] is used, because it is a broadband source with highly calibrated frequencies. The broad spectrum of a frequency comb laser consists of spectral lines all equally separated by a period τ as shown in Figure 2.2. The period between the pulses is defined as

$$\tau = \frac{n_r L}{c} \quad (2.7)$$

where:

τ : period between the pulses [s]

n_r : refractive index inside the laser cavity
 L : cavity length of the laser [m]
 c : speed of light $= 3.00 \cdot 10^8$ [m/s]

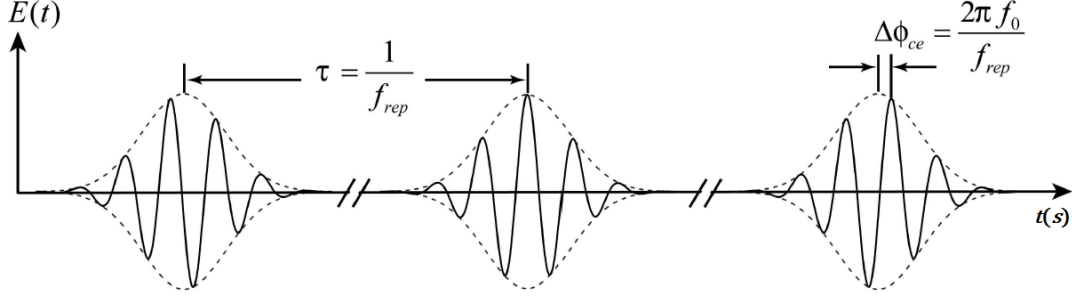


Figure 2.2: Several pulses of a frequency comb laser. The Gaussian envelope is indicated with a black dashed line and a carrier wave of a pulse is indicated with a black line [15].

The repetition rate of the frequency comb laser is defined as

$$f_{rep} = \frac{1}{\tau} \quad (2.8)$$

where:

f_{rep} : repetition rate of the frequency comb laser [Hz]

The spectrum of the frequency comb laser consists of multiple integers of f_{rep} and is defined as

$$\nu_m = m f_{rep} \quad (2.9)$$

where:

ν_m : multiple frequencies of f_{rep} [Hz]

m : positive integer; $m=1,2,3,\dots$

The propagating pulses inside the laser cavity can be described by a Gaussian envelope function times a continuous carrier wave with a frequency of f_c . The dispersion inside the cavity leads to an offset frequency of f_0 . This offset is caused by a difference in velocity between the Gaussian envelope (group velocity) and its carrier wave (phase velocity) as can be seen in Figure 2.2. This figure shows that the carrier wave is lagging behind the Gaussian envelope. Due to this difference a phase shift ϕ_{ce} occurs defined as the carrier-envelope phase. This phase shift can be written as

$$\phi_{ce} = 2\pi f_c L \left(\frac{1}{v_g} - \frac{1}{v_p} \right) \quad (2.10)$$

where:

ϕ_{ce} : carrier-envelope phase

f_c : continuous carrier wave frequency [Hz]

L : length of the laser cavity [m]

v_g : average group velocity [m/s]

v_p : average phase velocity [m/s]

After the carrier-envelope phase is defined Equation 2.9 can now be written as

$$\nu_m = m f_{rep} + f_{rep} \frac{\phi_{ce}}{2\pi} \quad (2.11)$$

As mentioned an offset is introduced due to the velocity mismatch between the Gaussian envelope and the carrier wave. This also can be noticed when comparing Equation 2.9 and Equation 2.11. The offset frequency f_0 can also be written as

$$f_0 = f_{rep} \frac{\phi_{ce}}{2\pi} \quad (2.12)$$

The two different frequencies f_{rep} and f_0 are shown in Figure 2.3. This figure shows that the f_0 provides a shift to the whole spectrum and f_{rep} is the separation between two individual spectral lines.

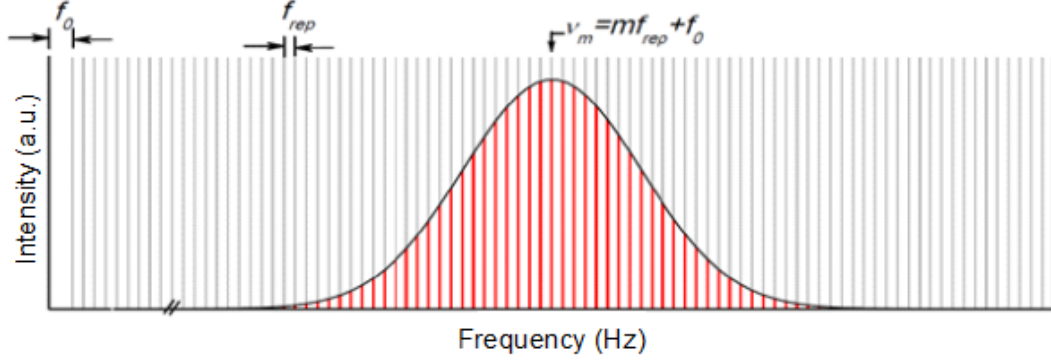


Figure 2.3: Frequency comb spectrum [18].

2.2.1 Mode-Locked Er^{3+} Doped Fiber Laser

The laser used during this project is an Er^{3+} doped fiber laser. The Er^{3+} doped fiber laser consists of a stabilized Er^{3+} fiber ring resonator and two parallel amplifiers. The first amplifier is used to stabilize the f_0 and the second amplifier provides the output of the laser. The laser has a central frequency of 1550 nm with a bandwidth of 1400-1600 nm. Using a highly nonlinear fiber this can be extended to 1000-2000 nm. The repetition rate is 100 MHz with an offset frequency of 10 MHz. The pulse length is 150 fs. For a more specific explanation about the laser and the nonlinear fiber technique Reference documents [19, 20] should be consulted.

2.2.2 Frequency Doubling

The frequency comb laser has a wavelength range between 1.4 and 1.6 μm and in order to detect the absorption spectrum of O_2 laser light at a wavelength of 0.75 μm is needed. To generate this wavelength a nonlinear crystal is used for frequency doubling/second harmonic generation.

When an optical wave in a medium can be described as a linear wave equation, the process is called linear optics. When the light intensity becomes high enough it cannot only be described with linear optics. There are still linear contributions but an extension of nonlinear [21] theory is needed. With nonlinear phenomena, the outer electrons of the atoms are mainly responsible for the polarization of the medium by the beam's E -field. When the beam has a low intensity the polarization is proportional to the E -field. If the beam has a high intensity (the oscillations of the electrons compared to the field are big) the proportionality decreases. As an optical field E propagates through the crystal, it causes a polarization of the medium,

$$P = \epsilon_0 \chi_e E \quad (2.13)$$

where:

P : electric polarization induced by the optical wave $[\text{C}/\text{m}^2]$

ϵ_0 : vacuum permittivity $= 8.85 \cdot 10^{-12} [\text{F}/\text{m}]$

χ_e : electric susceptibility
 E : electric field [V/m]

The electric susceptibility χ_e is now depending on the strength of the incidence field in the case of strong electric fields and therefore needs to be modified for nonlinear optics,

$$\chi_e = \chi^{(1)} + \chi^{(2)}E + \chi^{(3)}E^2 + \dots \quad (2.14)$$

The first term represents the linear optics where the polarization is proportional to the E -field. The nonlinear terms are important when coherent light such as a laser beam is used. When Equation 2.14 is substituted in Equation 2.13 the polarization is written as

$$P = \epsilon_0(\chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \dots) \quad (2.15)$$

Equation 2.15 can also be written in terms of polarization as shown in Equation 2.16

$$P = \underbrace{P_1}_{\text{linear}} + \underbrace{(P_2 + P_3 + \dots)}_{\text{nonlinear}} \quad (2.16)$$

Frequency doubling is caused by the contribution of the second-order term in Equation 2.15 and 2.16. This second-order term is in the form of

$$P_2 = \epsilon_0\chi^{(2)}E^2 \quad (2.17)$$

If a wave has an applied E -field in the form of the mathematical equation given as

$$E = E_0 \cos \omega t, \quad (2.18)$$

where:

ω : frequency of the wave [rad/s]
 t : time [s]

an appearance of a second harmonic in the polarization is expected. For the equation of the polarization of the second-order term with this applied E -field, Equation 2.18 can be substituted in Equation 2.17.

$$P_2 = \epsilon_0\chi^{(2)}E_0^2 \cos^2 \omega t = \epsilon_0\chi^{(2)}E_0^2 \left[\frac{1}{2}(1 + \cos 2\omega t) \right] \quad (2.19)$$

Equation 2.19 shows that the second order polarization has a term of twice the initial frequency of the optical wave.

2.3 VIPA Spectrometer

When choosing a spectrometer, two features are very important. The first one is the spectral resolution and the second one is the spectral bandwidth. These features determine the quality of the information that can be obtained. The O₂ VIPA spectrometer has a spectral resolution of 813 MHz around the 750 nm central wavelength and a spectral bandwidth of 50 nm. The CO₂ VIPA spectrometer has a spectral resolution of 690 MHz around the 1550 nm central wavelength and a spectral bandwidth of 200 nm [15].

The VIPA spectrometer consists of two stages. In the first stage the different frequencies of the beam will get separated by a VIPA, which essentially consists of a cylindrical lens and a Fabry-Perot etalon. In the second stage a diffraction grating will separate the dispersed beam in the horizontal direction. Due to the relation between refractive index and wavelength, all different frequencies will travel at a different angle after being dispersed by the VIPA and the diffraction grating. The spherical lens will then focus the different wavelengths at different positions on the CCD/CMOS camera.

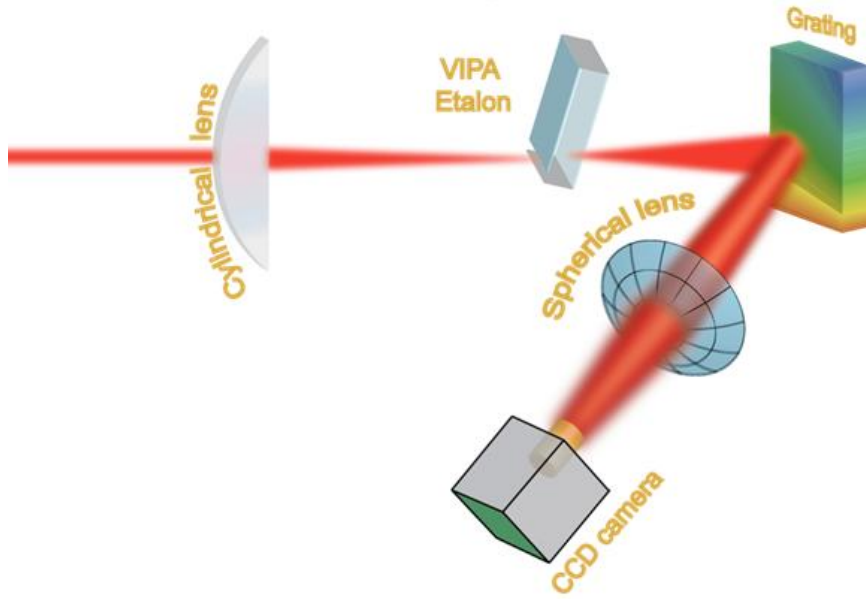


Figure 2.4: Schematic drawing of the CO₂ VIPA spectrometer setup [15].

2.3.1 VIPA

The VIPA [22, 23] is a high resolution disperser and shows large angular dispersion. The angular dispersion is 20 to 30 times higher than of common diffraction gratings. Other benefits from the VIPA are the low costs, low polarization sensitivity, compactness and simple structure [28]. The VIPA consists of a cylindrical lens and a thin glass plate or etalon as shown in Figure 2.5.

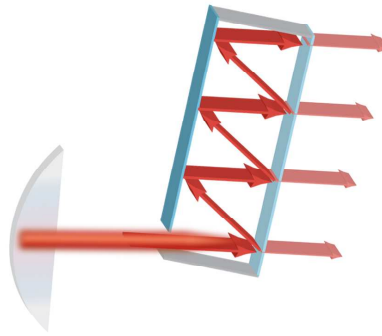


Figure 2.5: Schematic drawing of the VIPA [15].

The cylindrical lens focuses the beam at the rear side of the etalon. The front side of the etalon has a reflectivity of almost 100%, except for a small window on the front side. This small window is coated with an antireflection coating. The rear side of the etalon has a high reflectivity coating. The beam enters the etalon through the small window with the antireflection coating. A small part of the beam will pass through the etalon and a large amount will be reflected by the rear side. The beam makes a small angle (θ) with the normal of the etalon; this creates the multiple Fabry-Perot reflections. The smaller the angle θ , the bigger the amount of reflections. The beams

that pass the etalon will diverge after the beam waist [24] as shown in Figure 2.6. Because of the reflections, each beam coming out of the etalon seems to come from a virtual image as depicted in Figure 2.6b. These virtual images lie along the normal of the etalon. Their interference produces an output beam where the different wavelengths are sent out under different angles. The constant space between the virtual images is $2t$ (t is the thickness of the etalon). The distance in height between two reflections is δh .

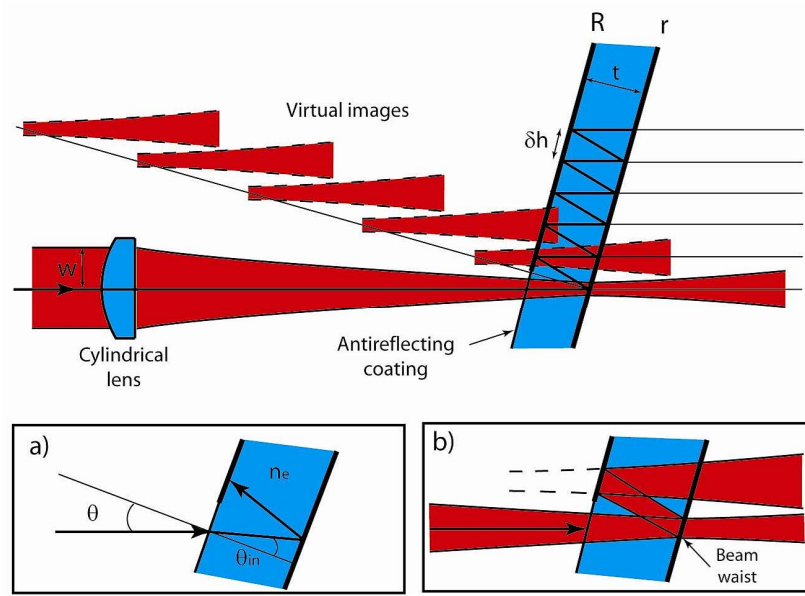


Figure 2.6: Schematic drawing of the different beam paths, a) the entrance angle and the resulting reflection, b) the reflection of the beam, the diverging effect and the origin of the virtual image [18].

The range that is used at the detection plane for this experiment is the Free Spectral Range (*FSR*). The *FSR* is the frequency spacing between adjacent orders, as seen in Figure 2.7 with the two white dots. The approximate value of the *FSR* of the VIPA can be calculated with

$$FSR \approx \frac{c}{2n_e t} \quad (2.20)$$

where:

t : thickness of the etalon [cm]

n_e : refractive index of the etalon=1.81

It is important to know what the size is of the *FSR* at the detection plane, because the detection plane has to be big enough to detect the whole range of the same order in one sweep. The *FSR* of the CO₂ VIPA is shown in Figure 2.7. This figure shows the interference pattern due to the VIPA spectrometer and explains how the frequencies are separated.

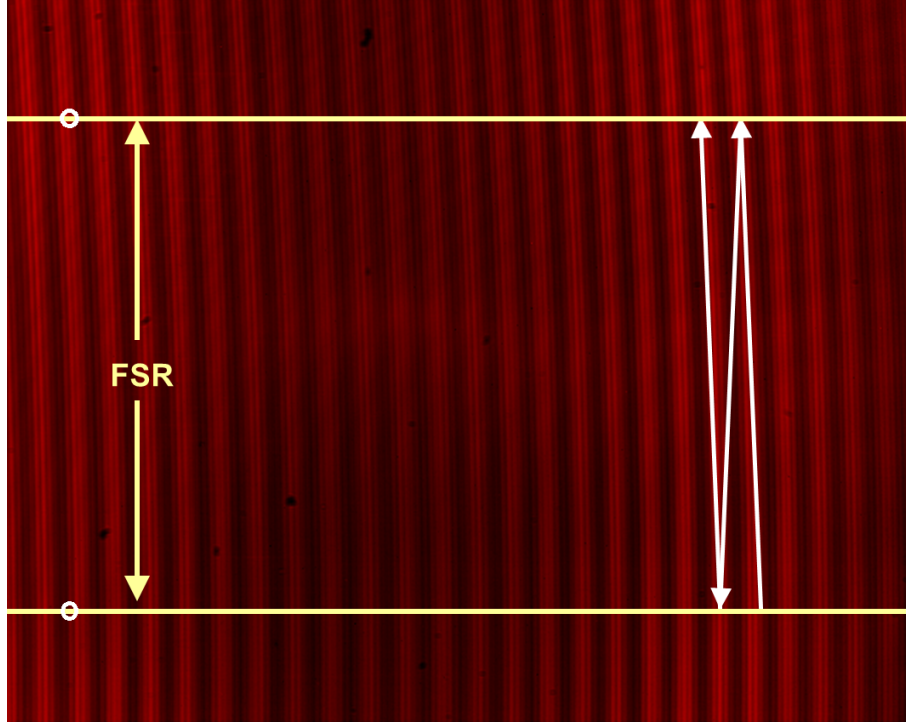


Figure 2.7: The interference pattern at the detection plane due to the VIPA spectrometer. The vertical separation of the FSR is due to the VIPA. It also shows how to identify the separate wavelengths. The horizontal separation is due to the diffraction grating as can be read in Section 2.3.2. [15].

The size of the FSR is calculated with Equation 2.21

$$\Delta y_{FSR} = \frac{mf\lambda_c^2 FSR}{2tc} \left[\tan(\theta_{in}) \cos(\theta) + \frac{\cos(\theta_{in}) \frac{y}{4}}{n_e f} \right]^{-1} \quad (2.21)$$

where:

Δy_{FSR} : size of the FSR in the y-direction [cm]

FSR : Free Spectral Range of the VIPA [GHz]

f : focal length of the spherical lens [cm]

θ_{in} : angle inside the etalon [°]

θ : angle of the incoming beam [°]

y : vertical coordinate on the detection plane [cm]

m : order of the VIPA transmission

To make sure the FSR fits at the detector plane, the interference pattern produced by the VIPA is given as

$$W_y = \frac{\sqrt{2}fw}{f_c} \quad (2.22)$$

where:

W_y : size of the interference pattern [cm]

w : radius of the collimated beam prior to the cylindrical lens [cm]

The spectral resolution of the VIPA can be calculated with

$$\delta\nu_{FWHM} = \frac{c(1 - Rr)}{\pi\Delta\sqrt{Rr}} \quad (2.23)$$

where:

$\delta\nu_{FWHM}$: spectral resolution of the VIPA [Hz]

R : reflectivity of input window coating

r : reflectivity of output window coating

Δ : geometrical intensity distribution factor of the VIPA [cm]

A more detailed explanation of the VIPA theory can be found in Appendix B.

2.3.2 Diffraction Grating

The diffraction grating is used to cover a broad bandwidth. The diffraction grating is covered with equally spaced grooves with a size d as indicated in Figure 2.8. The grating will separate the angular ordered collimated beam in the horizontal direction. A collimated beam that hits the diffraction grating with an angle of α is diffracted into an angle β as shown in Figure 2.8.

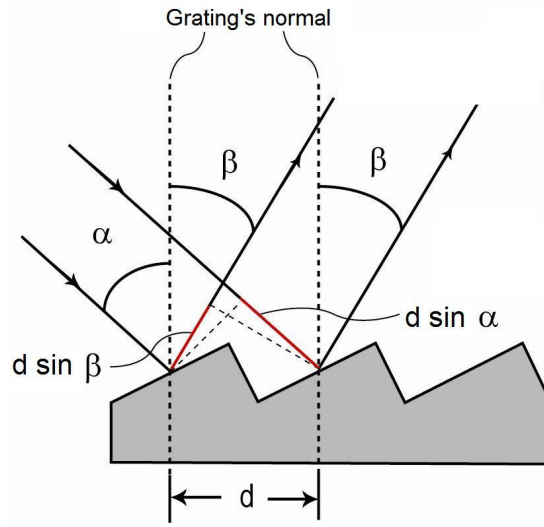


Figure 2.8: Principle of a diffraction grating [15].

The effect shown in Figure 2.8 can also be calculated with Equation 2.24.

$$d(\sin \beta \pm \sin \alpha) = m\lambda \quad (2.24)$$

where:

d : groove size of the diffraction grating [m]

λ : wavelength of light [nm]

m : order of the diffracted light; $m=1,2,3,\dots$

α : incident angle of the beam [°]

β : diffracted angle of the beam [°]

If the diffracted beam and the incident beam are on the same side of the grating's normal then the sign is considered positive. If the diffracted beam is on the opposite side of the grating's normal then the sign is considered negative.

To calculate the diffracted angle it can be written as a function of wavelength as shown in Equation 2.25. It is assumed that the diffracted and the incident beam are on the same side of the grating's normal.

$$\beta = \sin^{-1} \left(\frac{m\lambda - d \sin \alpha}{d} \right) \quad (2.25)$$

For this experiment it is also useful to know what the angular and spatial dispersion is due to the grating. This can be done by calculating the angular separation between two different wavelengths. To know the angular separation, Equation 2.25 has to be differentiated as a function of wavelength.

$$D = \frac{\Delta\beta}{\Delta\lambda} = \frac{1}{\sqrt{1 - \left(\frac{m\lambda - d \sin \alpha}{d}\right)^2}} \frac{m}{d} = \frac{1}{\sqrt{1 - \sin^2 \beta}} \frac{m}{d} \quad (2.26)$$

where:

D : angular dispersion of the grating [rad/nm]

This equation can be simplified by using the goniometric relation $\sin^2 \theta + \cos^2 \theta = 1$

$$D = \frac{\Delta\beta}{\Delta\lambda} = \frac{m}{d \cos(\beta)} \quad (2.27)$$

The spatial separation of the grating can give information about the width of the dispersion at the focal plane of the spherical lens. The spatial dispersion can be calculated by

$$\frac{\Delta x}{\Delta\lambda} = \frac{mf}{d \cos \beta} \quad (2.28)$$

where:

$\frac{\Delta x}{\Delta\lambda}$: spatial dispersion [mm/nm]

Chapter 3

Setup and Analysis

In this chapter the experimental setup is described in detail. Figure 3.1 shows a schematical drawing of the entire experiment including the beam path of the two different beams and the optical components used in the setup.

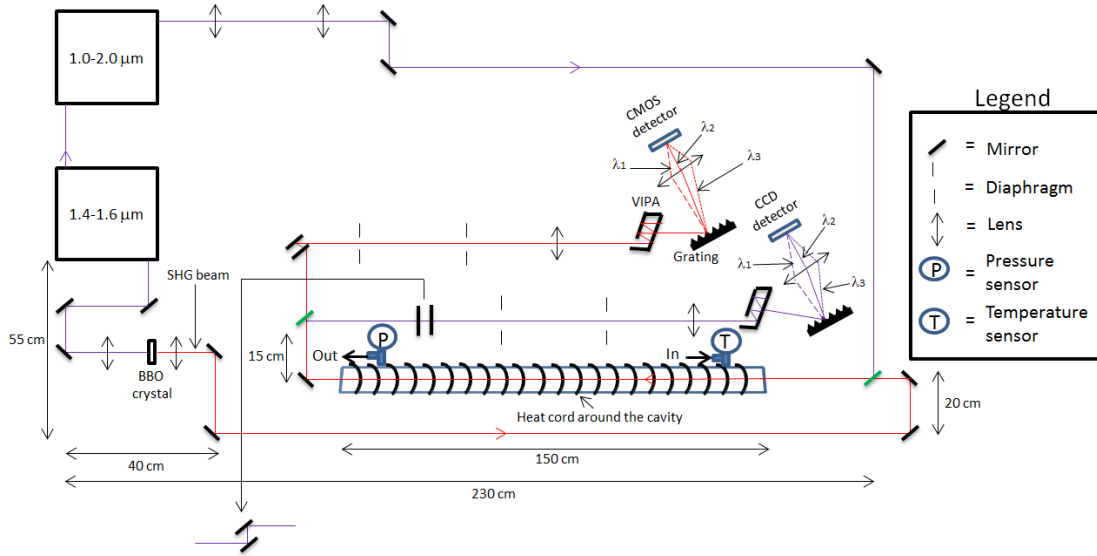


Figure 3.1: Schematic drawing of the experimental setup. The initial beam is indicated with a purple line and the second harmonic beam with a red line. The dichroic mirrors are indicated in green. The path through the cavity is an optical path where the beams are combined. For practical reasons the beam is indicated in the colour of the second harmonic beam. The second dichroic mirror will separate these two beams.

In the figure above the laser can be seen which provides the illumination source for both gases O_2 and CO_2 . For CO_2 the direct beam of the laser is used with a range of 1400-1600 nm broadened by a highly nonlinear fiber to 1000-2000 nm. For O_2 the frequency doubled beam is used. The beam path of the O_2 VIPA is indicated with a red line. The initial beam produces a second harmonic beam due to the nonlinear effect of the crystal (BBO-crystal). The initial beam is indicated with a purple line and has a wavelength range from 1400-1600 nm. After the nonlinear crystal the second harmonic beam is collimated with two lenses and then directed by two mirrors along a straight path. The beam is then directed with three mirrors into the cavity. One of those mirrors is a dichroic mirror, its specifications are shown in Appendix C. There are two dichroic

mirrors used in this setup because there are two different beams at different spectral regions in this setup. The dichroic mirrors reflect the wavelength range of the CO₂ VIPA and it transmit the wavelength range of the O₂ VIPA. The dichroic mirror placed after the cavity will separate the two beams and the second harmonic beam is then directed with two mirrors through two diaphragms into the VIPA spectrometer. In principle it is the same construction as used in the CO₂ VIPA setup. The heat cord around the cavity is to regulate the temperature of the cavity. As a reference a platinum temperature sensor (PT-100) is used with an accuracy of 3 mK. The diaphragms used in the setup are used to define the beam path into the VIPA spectrometer. After passing the two diaphragms the beam travels through the cylindrical lens that focuses the beam on the antireflective window of the etalon. The angular ordered beam at the output of the etalon will then hit the grating and gets dispersed in several orders. The spherical lens after the grating focuses the beam on the detection plane. The different wavelengths will all reach the camera on different positions. The mirrors used for the O₂ VIPA setup are silver mirrors. These mirrors have a broad reflection range. The specifications of the silver mirrors are shown in Appendix C.

The initial beam is first collimated with two lenses and then directed with dielectric mirrors to the dichroic mirror in front of the cavity. The specific properties of the dielectric mirrors are shown in Appendix C. The dichroic mirror after the cavity will reflect the 1550 beam and direct the beam through two diaphragms with the help of two mirrors. The diaphragms implemented in the setup are also used as a pinhole to avoid permanent damage of the camera due to high intensities. The beam is then focused on the antireflection window of the etalon with the cylindrical lens. After the vertical dispersion due to the etalon the beam hits the grating and this causes a dispersion in horizontal direction. The separate wavelengths are then focused with a spherical lens on the detection plane.

After showing the full system used during this bachelor project Section 3.1 and 3.2 will concentrate more on the details of the two different spectrometers. These sections present some specifications of the different components.

3.1 Setup Specifications O₂ VIPA

The components shown in Table 3.1 are used for the detection of the absorption spectra due to O₂.

Component	Parameter		
VIPA	Refractive index	n_e	1.81
	Thickness	t	0.17 mm
	Input reflectivity	R	99.9%
	Output reflectivity	r	95.0%
	Free Spectral Range	FSR	≈ 48.7 GHz
	Spectral resolution	$\delta\nu_{FWHM}$	813 MHz
	Tilt angle	θ	2°
Grating	Height input window (AR)	H	0.3 cm
	Groove's size	d	0.83 μ m
Lenses	Incident angle	α	60°
	Cylindrical	f_c	10 cm
Incident beam	Spherical	f	40 cm
	Diameter	D	0.20 cm
CMOS camera	Central Wavelength	λ_0	750 nm
	Number of pixels	$N_h \times N_v$	2592×1944
	Pixel size	l_p	2.2 μ m

Table 3.1: Parameters for the O₂ VIPA

The frequency comb used during this project produces 150 fs pulses. The frequency doubling for this setup was done with a nonlinear crystal, namely a beta barium borate (BBO) crystal. Figure 3.2 shows the spectrum of the frequency doubled beam obtained with the optical spectrum analyzer (OSA) developed by ANDO with serial number AQ-6315A.

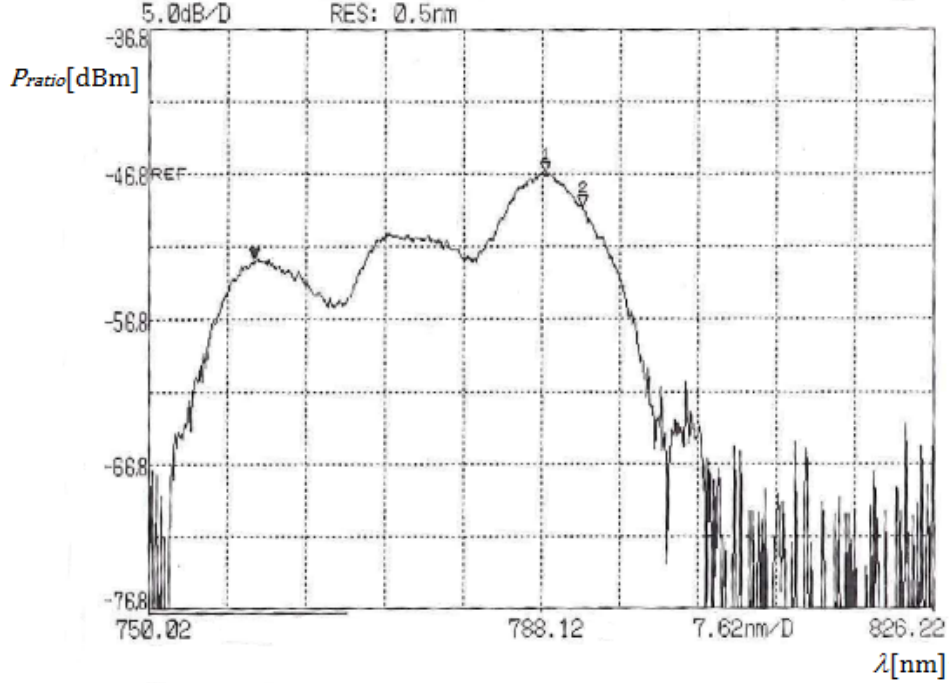


Figure 3.2: Spectrum of the frequency doubled beam used to detect the absorption lines due to O_2 .

This section will calculate some of the VIPA spectrometer properties using the equations from Section 2.2.1. Before calculating the different characteristics of the VIPA, the angle inside the VIPA (θ_{in}) should be known. The angle (θ_{in}) can be calculated with Snell's law as given by

$$n_e \sin(\theta_{in}) = \sin(\theta) \quad (3.1)$$

$$\theta_{in} = \sin^{-1}\left(\frac{\sin(\theta)}{n_e}\right) = \sin^{-1}\left(\frac{\sin(2)}{1.81}\right) = 1.1^\circ$$

An important characteristic of the VIPA is the spectral resolution. The spectral resolution gives information about the ability to resolve features in the electromagnetic spectrum. The spectral resolution can be calculated with Equation B.2 from Appendix B and with Equation 2.23

$$\delta\nu_{FWHM} = \frac{3.00 \cdot 10^8 \cdot (1 - 0.999 \cdot 0.950)}{\pi \cdot 0.615 \cdot 10^{-2} \sqrt{0.999 \cdot 0.950}} = 813 \text{ MHz}$$

To make sure that the FSR covers the detection plane the size of the interference pattern at the detection plane needs to be calculated. From Table 3.1 the beam radius is given and this is used to calculate the size of the interference pattern with Equation 2.22

Given:

$$w = 0.10 \text{ cm}$$

$$W_y = \frac{\sqrt{2} \cdot 0.400 \cdot 0.10 \cdot 10^{-2}}{0.100} = 0.566 \text{ cm}$$

The FSR of the VIPA is given in Table 3.1 and can be calculated with Equation 2.20

$$FSR \approx \frac{3.00 \cdot 10^8}{2 \cdot 1.81 \cdot 0.17 \cdot 10^{-2}} \approx 48.7 \text{ GHz}$$

This is equivalent to a span of $\Delta\lambda=0.091 \text{ nm}$ at $\lambda_0=750 \text{ nm}$. The size of the FSR at the detection plane can be calculated with Equation B.6 from Appendix B that calculates the order of the VIPA transmission and with Equation 2.21

$$\Delta y_{FSR} = \frac{8.2 \cdot 10^3 \cdot 0.4 \cdot (750 \cdot 10^{-9})^2 \cdot 48.7 \cdot 10^9}{2 \cdot 0.17 \cdot 10^{-2} \cdot 3.00 \cdot 10^8} \cdot \left[\tan(1.1) \cos(2) + \frac{\cos(1.1) \cdot 0.107 \cdot 10^{-2}}{1.81 \cdot 0.4} \right]^{-1} = 0.242 \text{ cm}$$

The height of the detection plane is 0.428 cm ($N_v \cdot l_p$), this means that the FSR covers the detection plane for 56.5%. Other orders can also be detected and can be used for calibrating the VIPA spectrometer.

The contributions of the camera and of the diffraction grating are negligible. The resolution of the grating does not affect the resolution to resolve the separate wavelengths because the contribution of the grating is in the x-direction. The resolution of the camera can affect the resolvability of the wavelengths but in this case the effect is proven to be minimum. The equations used to calculate the resolution of the camera can be found in Reference document [15] and in the case of the camera used for the O₂ VIPA the resolution is 29.7 MHz. If these two resolutions are combined by adding their square powers and taking the square root the total resolution is 813.5 MHz. The total resolution shows a small deviation from the resolution of the O₂ VIPA.

3.2 Setup Specifications CO₂ VIPA

The components shown in Table 3.2 are used for the detection of the absorption spectra due to CO₂.

Component	Parameter		
VIPA	Refractive index	n_e	1.81
	Thickness	t	0.175 cm
	Input reflectivity	R	99.5%
	Output reflectivity	r	96.0%
	Free Spectral Range	FSR	$\approx 47.4 \text{ GHz}$
	Spectral resolution	$\delta\nu_{FWHM}$	690 MHz
	Tilt angle	θ	2.5°
Grating	Height input window (AR)	H	0.3 cm
	Groove's size	d	0.83 μm
Lenses	Incident angle	α	80°
	Cylindrical	f_c	6 cm
Incident beam	Spherical	f	40 cm
	Diameter	D	0.20 cm
CCD camera	Central Wavelength	λ_0	1550 nm
	Number of pixels	$N_h \times N_v$	640 $\times$ 512
	Pixel size	l_p	20 μm

Table 3.2: Parameters for the CO₂ VIPA

In this section the properties of the CO₂ VIPA are calculated using the equations from Section 2.2.1. The procedure is the same as for the O₂ VIPA but the parameters for the CO₂ VIPA are

different.

$$\delta\nu_{FWHM} = 690 \text{ MHz}$$

$$W_y = 9.4 \text{ cm}$$

$$FSR \approx 47.4 \text{ GHz}$$

This is equivalent to a span of $\Delta\lambda=0.38 \text{ nm}$ at $\lambda_0=1550 \text{ nm}$.

$$\Delta y_{FSR} = 0.636 \text{ cm}$$

The size of the detection plane of CCD camera is 1.024 cm ($N_v \cdot l_p$). The FSR covers only 62.1% of the detection plane, this means that other orders are also partially detected. These orders contain information to calibrate the VIPA spectrometer.

For the CO_2 VIPA the same applies as for the O_2 VIPA. The effect of the resolution of the camera on the resolvibility of the separate wavelengths is very small. To calculate the resolution of the camera the equations from Reference document [15] are used. The resolution of the CCD camera is 130 MHz and if this is combined with the resolution of the CO_2 VIPA then this results in a total resolution of 703 MHz. This is again a small deviation from the resolution of the CO_2 VIPA.

3.3 Alignment and Measurement Protocol

The goal for this bachelor project is to do temperature measurements using absorption spectroscopy. For this project two spectrometers are required, namely the O_2 and the CO_2 VIPA. The O_2 VIPA spectrometer was built for the experiment and the CO_2 VIPA was realigned. For aligning the VIPA it is recommended to either use a fluorescent card or a power meter in order to see the beam clearly and perfectly align the path.

In order to obtain the most optimized picture at the detection plane a good aligning of the VIPA, grating and spherical lens is required. Figure 3.3 shows this procedure.

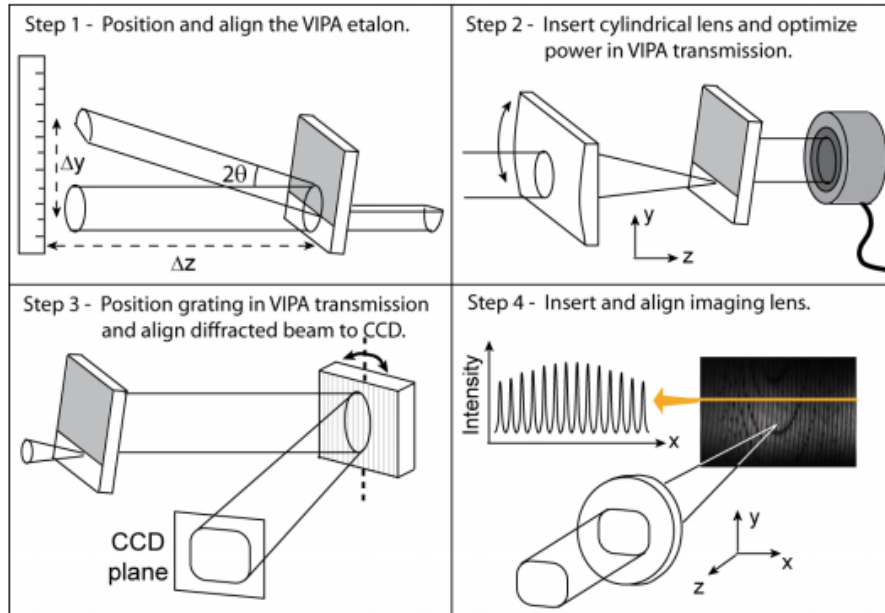


Figure 3.3: Procedure of aligning the VIPA spectrometer [25].

The etalon has a desired tilt angle of typically 1.5° - 3.5° and this can be achieved with using the diaphragm as a reference. The height of the diaphragm is calculated because the angle and

the distance between the etalon and the diaphragm are known. The intensity at the rear window of the etalon is half of the initial intensity at the antireflective window. This means that half of the intensity is reflected and this can be used as a reference. The amount of reflection due to the etalon has not got a restricted value but in order to easily detect the reflected beam a reflection of 50% or even higher is recommended. In the second step the cylindrical lens can be placed one focal length in front of the etalon. The cylindrical lens will create a horizontal focused line on the antireflective window of the etalon. When the VIPA is optimally aligned the transmitted beam is one vertical line that has the same width as the focused beam on the antireflective window.

The third step is to optimize the alignment of the diffraction grating. The grating is mounted on a rotation stage in order to get the required angle regarding to the VIPA. The transmitted beam should hit the grating in the center. Finally, the camera should be positioned at least 1.5 times the focal length of the spherical lens from the grating. The restricted distance between grating and camera is based on the fact that the different frequencies are being dispersed by the grating are parallel beams that will all have a different direction. To reach this difference in position the distance between grating and spherical lens should be at least 0.5 times the focal length of the spherical lens. The distance between the spherical lens and the camera is one focal length. The spherical lens is mounted on a translation stage which allows to control three degrees of freedom, namely the x, y and z position. The mirror mount gives two additional degrees of freedom, it provides tilt control in the vertical and horizontal direction. When aligning the spherical lens it is important to look at the camera image whether the fringes are equally spaced, are in focus and have equal intensity. The intensity of the interference pattern at the detection plane can be visualized with using a line that transects the interference pattern. This option of the camera software shows an intensity cross-section of the interference pattern.

A measurement with the setup shown in Figure 3.1 is done in the following way. The *FSR* at the detection plane and the position of λ_0 for the O₂ VIPA has to be determined in order to do the correct data analysis and obtain a spectrum. The determination of the *FSR* is done with a diode laser operating at a wavelength of 757 nm. Due to the *FSR* of the VIPA etalon a repetition pattern occurs at the detection plane. This can be seen in Figure 2.7. The distance between two repeated points identifies the size of the *FSR*. The λ_0 is determined by placing the repetition pattern at a fixed point and checking the peak wavelength with the OSA. This process needs to be done only once. This procedure was already done for the CO₂ VIPA. Next the cavity can be evacuated to clean the cavity and can be filled with the reference gas. The reference gas used during this project is N₂. N₂ is used as a reference because the characteristic spectral lines of N₂ are in the UV-region and not in the region of interest. The image can be saved with a Labview program (Appendix D) and this writes the images to a text file. The cavity is then again evacuated and filled with the gas (mixture) of choice. The procedure of saving the image is the same as for the reference.

Once the measurement is completed the two text files can be imported in the MATLAB program (Appendix E). The image obtained with the camera is a interference pattern as shown in Figure 2.7 with bright fringes. Essentially these fringes are local maxima and the gaps are local minima. By correctly choosing the size and position of the *FSR* the information outside this region is not used. The program will integrate intensities between two adjacent minima. This results in an intensity distribution for every integrated area. This procedure is done for the reference data and for the measurement data. The next step is to calibrate the wavelength with the number of pixels in the *FSR* region and with the λ_0 . To calculate the absorption the ratio between the reference and measurement is calculated. The calculated spectra are compared with a spectrum from the HITRAN database.

Obtaining the temperature from the spectra is done in the following way. The change in the calculated spectra from different temperature measurements is compared with the predicted change in spectra from the HITRAN database.

Chapter 4

Measurement Results and Error Analysis

This chapter will present the obtained results from the two different VIPA spectrometers. The results are divided in two sections. The first section presents the results of the measurements of O₂ spectra using the O₂ VIPA and the second section presents the results of the measurements of CO₂ spectra using the CO₂ VIPA.

4.1 O₂ VIPA Results

The O₂ VIPA, as described in Section 3.1 uses a camera to detect the dispersed spectra. The camera can only capture a part of the spectrum of the laser.

Due to the broad frequency spectrum of the frequency comb laser it is difficult to determine the position of a specific wavelength at the detection plane. To calibrate the VIPA a reference laser is used to determine the position of the region of interest and to determine the size of the *FSR* as can be seen in Figure 2.7. The reference laser has a narrow bandwidth around the 757 nm. This wavelength is used as a reference to be able to know the position of this wavelength on the detection plane. Then the grating is rotated as such that the region of interest can be obtained. Figure 4.1 shows the spectrum of the reference laser obtained with the optical spectrum analyzer.

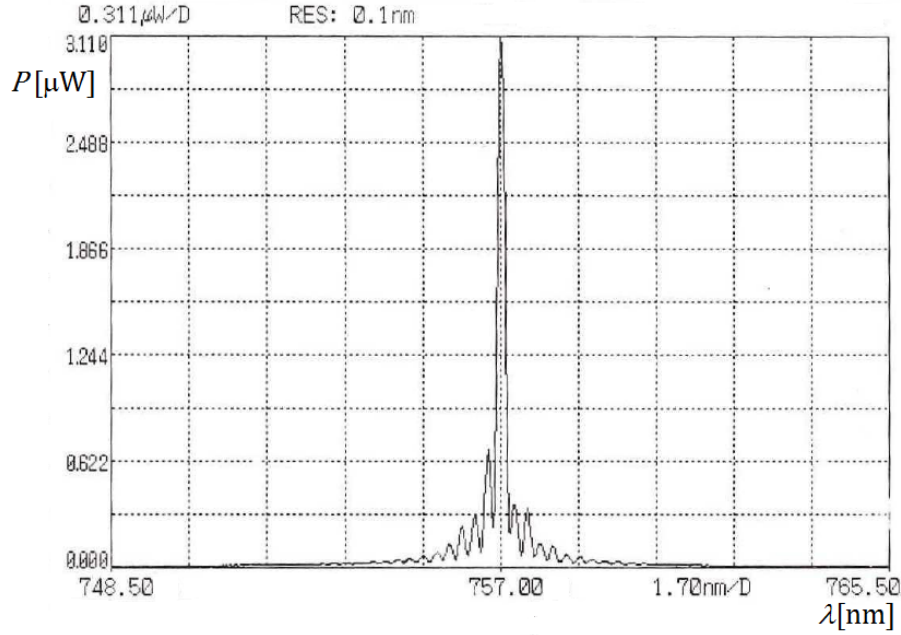


Figure 4.1: Spectrum of the reference laser obtained with the OSA.

The calibration of the VIPA has an inaccuracy of 0.1 nm due to the resolution of the OSA.

The *FSR* of the VIPA etalon causes a repetitive pattern at the detection plane. The distance between two adjacent bright spots is the size of the *FSR*. A picture of the reference laser obtained with the camera of the VIPA is shown in Figure 4.2.

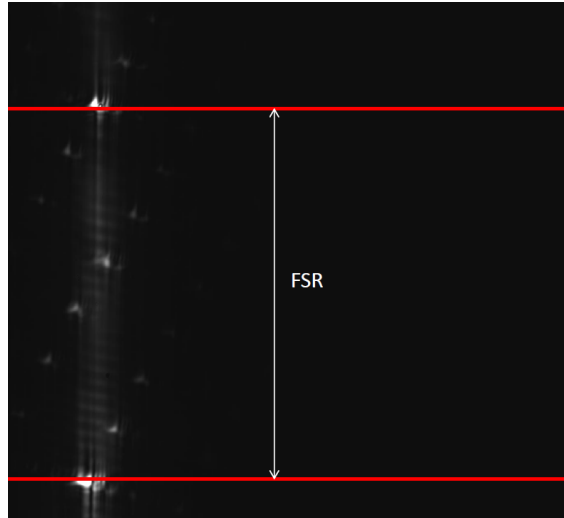


Figure 4.2: Picture taken with the camera of the reference laser that shows the repetition of the pattern of the beam. The distance between the repetition of the beam as indicated in the figure is the size of the *FSR* on the detection plane.

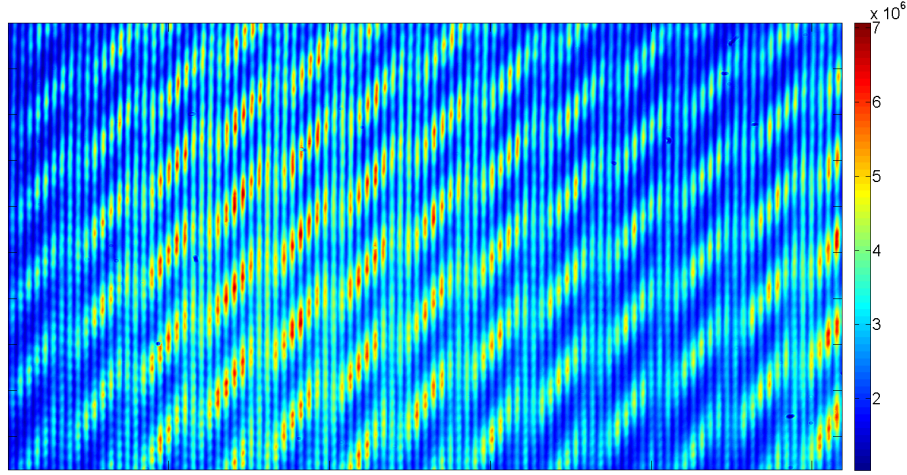
After the width of the *FSR* was determined at the detection plane a measurement with the O₂ VIPA setup was done. The cavity was first filled with N₂ for obtaining a reference image

and afterwards the cavity was filled with O_2 . Between these two measurements the cavity was evacuated using a vacuum pump. This results are shown in Subsection 4.1.1 and 4.1.2.

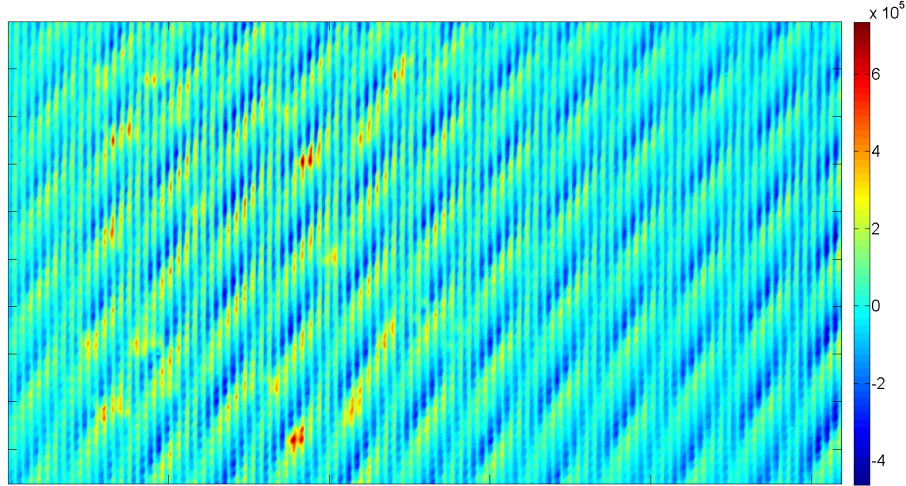
4.1.1 Noise from Vacuum Pump Vibrations

This section shows the results of the first O_2 measurement with the vacuum pump on during the measurements.

Figure 4.3a shows the obtained image when filling the cavity with O_2 and Figure 4.3b shows the obtained spectrum by taking the difference between the images of N_2 and O_2 .



(a) Obtained image when filling the cavity with O_2 . Each vertical line defines a different frequency.



(b) Difference between N_2 and O_2 .

Figure 4.3: The intensity of the image is viewed with the colorbar. The artificial pattern in the image is not due to absorption but is due to the vibrations due to the vacuum pump and because the windows of the cavity are not fixed tightly.

The negative intensity values are due to fluctuations in the cavity, noise of the camera or laser. Most likely, the biggest contribution to this effect is the noise of the camera. This will be further discussed when an absorption spectrum is obtained.

The vertical lines due to the VIPA in Figure 4.3 are clearly visible. The size of the repetition pattern in Figure 4.3b is equivalent to the size of the FSR determined with the reference laser.

Figure 4.3 shows an artificial pattern due to a shift between the reference and the measurement. This shift is caused by two contributions. The vacuum pump causes external vibrations on the optical table and this results in a shift between images. The second contribution is the gas cavity used during the measurements. The windows of the cavity are not fixed tightly to the mirror mount of the cavity. Due to the evacuation between the measurements this causes a small shift of the position of the mirrors.

These contributions that cause this artificial pattern affects both setups. The O₂ VIPA results were used to exemplify the problem.

To calculate an absorption spectrum that can be compared with the HITRAN database an improvement in quality of the measurements was needed.

4.1.2 Measurement with Vacuum Pump Turned Off

In order to be able to neglect these contributions, discussed in Subsection 4.1.1, the vacuum pump was turned off during the measurements. The windows of the cavity are also replaced with new mirrors in a new mirror mount. The mirrors are now fixed to the mount. Figure 4.4a shows an image of the cavity filled with O₂ and Figure 4.4b shows the difference between the N₂ and O₂ measurement.

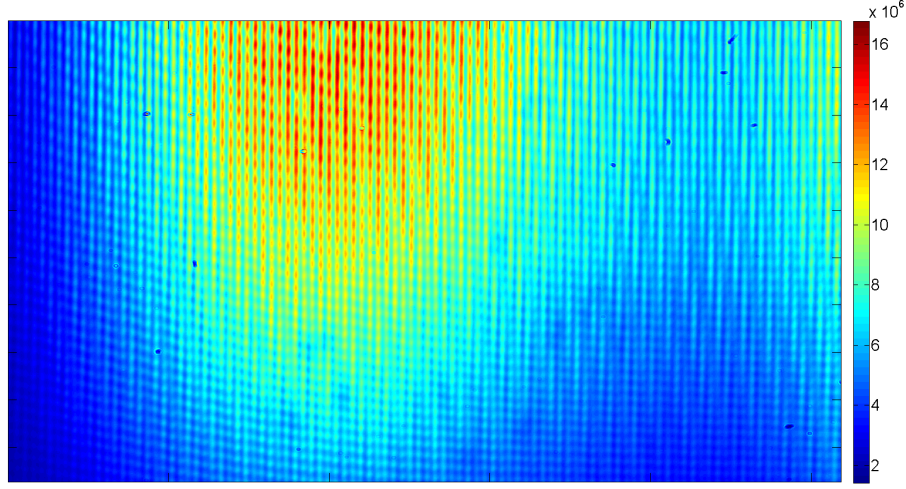
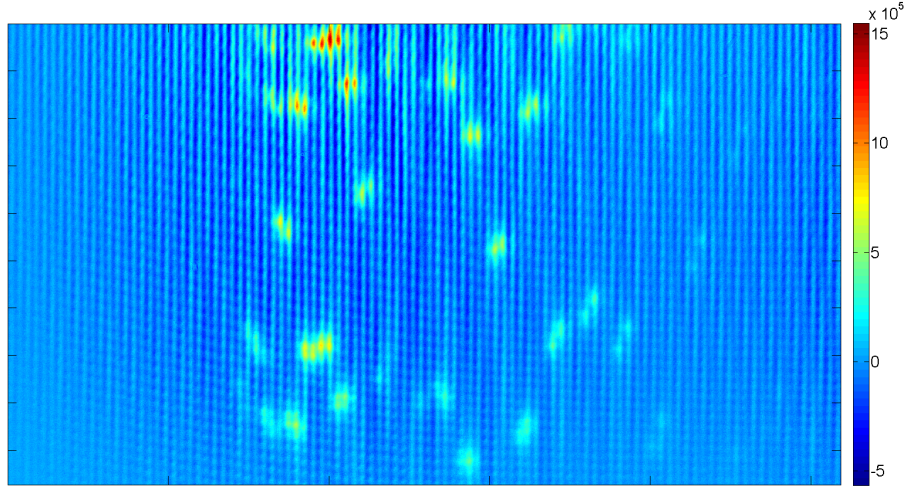
(a) Obtained image when cavity filled with O_2 .(b) Difference between N_2 and O_2 . This image clearly shows a repetition pattern that indicates a FSR .

Figure 4.4: Measurement with turning the vacuum pump off and replacing the windows of the cavity. The absorption is clearly visible in both the images.

The dominant artificial pattern shown in Figure 4.3 cannot be detected when doing measurements following the new procedure. Figure 4.4 shows that in order to improve the image the vacuum pump has to be turned off during the measurements. The envelope of the beam undergoes a minor shift up and to the right due to the change of the windows of the cavity. But that does not affect the quality of the image. The intensity distribution on the obtained camera image shows a non-uniformity due to the Gaussian profile of the illumination source. The intensity distribution in the y -direction is due to the VIPA and the intensity distribution in the x -direction is due to the grating.

Figure 4.4b shows a repetition pattern that indicates the FSR of the VIPA. The size of the FSR is again equivalent to the size of the FSR shown in Figure 4.2. The bright spots visible in the image are due to absorption of several frequencies. To give a clearer view of the absorption the data from the N_2 and O_2 is converted into an absorption spectrum following the procedure explained in Section 3.3. This absorption spectrum is compared with an absorption spectrum from the HITRAN database. The measured absorption spectrum and the spectrum of the HITRAN

database are shown in Figure 4.5.

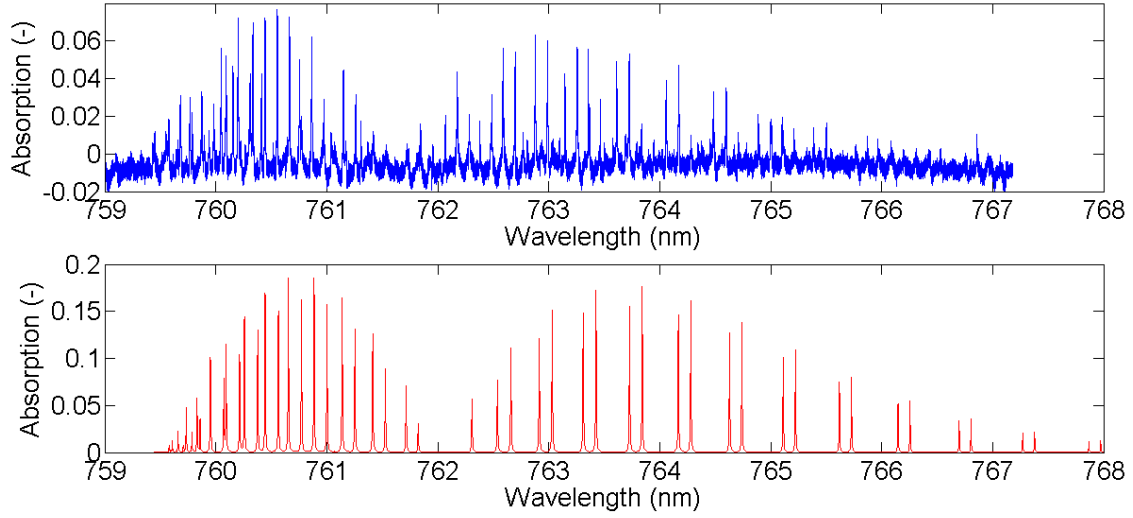


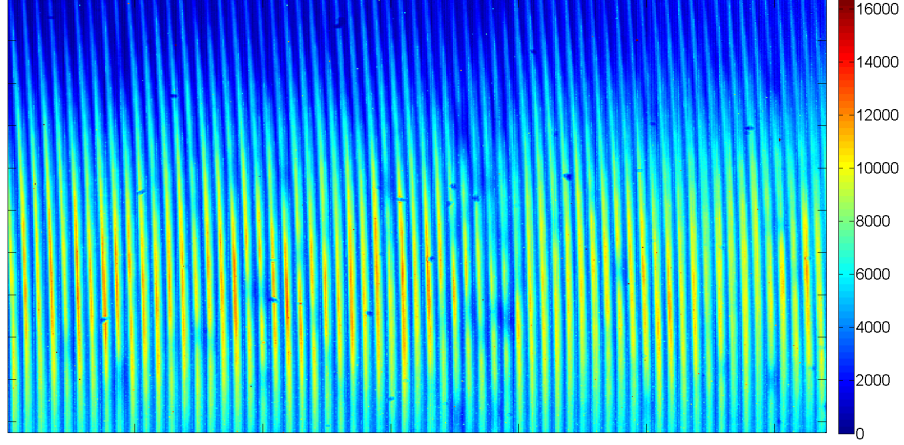
Figure 4.5: The upper spectrum is the measured absorption spectrum and the bottom spectrum is from the HITRAN database.

The structure of the absorption profile shown in Figure 4.5 is similar to the structure of the profile shown in the O₂ spectrum from the HITRAN database. The two branches are due to vibrational transitions and the individual peaks inside each branch are due to rotational transitions in a molecule. The MATLAB code to convert the VIPA camera images into spectra still has to be optimised to identify the lines and match the intensity profiles for a temperature measurement.

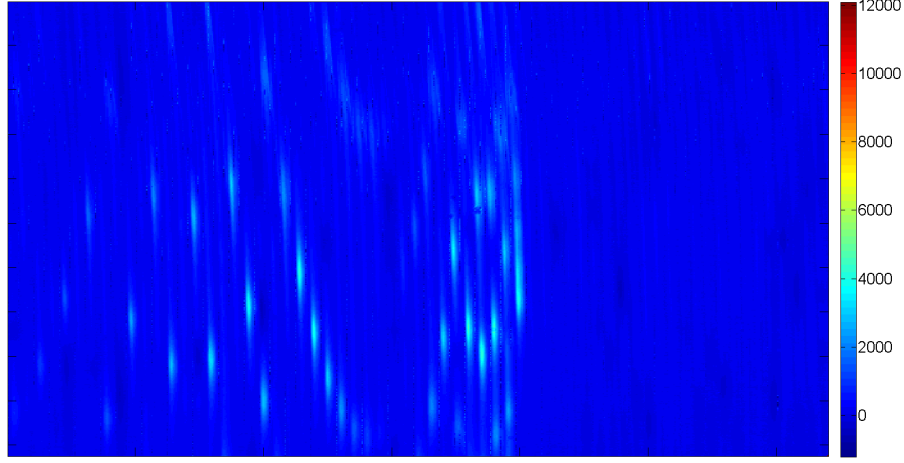
Looking at the measured spectrum one can see that there is a dominant noise level. In order to determine the noise behaviour of the system the standard deviation of the ratio of two reference camera images was calculated and found to be 0.024 and this introduces an intensity offset. The most dominant factor that introduces this noise is the camera used to obtain the images. To get more knowledge about the quality of the obtained results the signal to noise ratio (SNR) can be calculated. The intensity contribution of the camera when the laser is turned off is $7.8 \cdot 10^4$ and the maximum non saturated value when looking at the obtained measurement is $14 \cdot 10^6$. For this specific measurement the SNR is estimated to be 45 dB. This can be further optimised by changing the settings of the camera and the alignment of the VIPA spectrometer.

4.2 CO₂ VIPA Results

The *FSR* determination was previously done for the thesis of Reference document [15] using the same method as for the O₂ VIPA. The absorption lines of CO₂ can be detected with the CO₂ VIPA. This procedure is equivalent to the procedure of the O₂ VIPA. Figure 4.6a shows an image of the cavity filled with CO₂ and Figure 4.6b shows the difference between the reference and the CO₂ measurement.



(a) Obtained image when filling the cavity with CO_2 .



(b) Difference between N_2 and CO_2 . The bright spotted pattern is due to absorption and shows a repetition.

Figure 4.6: Measurement to obtain the CO_2 spectrum.

Figure 4.6b shows a high intensity spot pattern. The repetition of this pattern at the center upper part of the image is due to the *FSR* of the VIPA. This measurement is converted to an absorption spectrum in order to make the characteristic lines of CO_2 visible. Figure 4.7 shows the measured CO_2 spectrum compared with the CO_2 absorption spectrum from the HITRAN database.

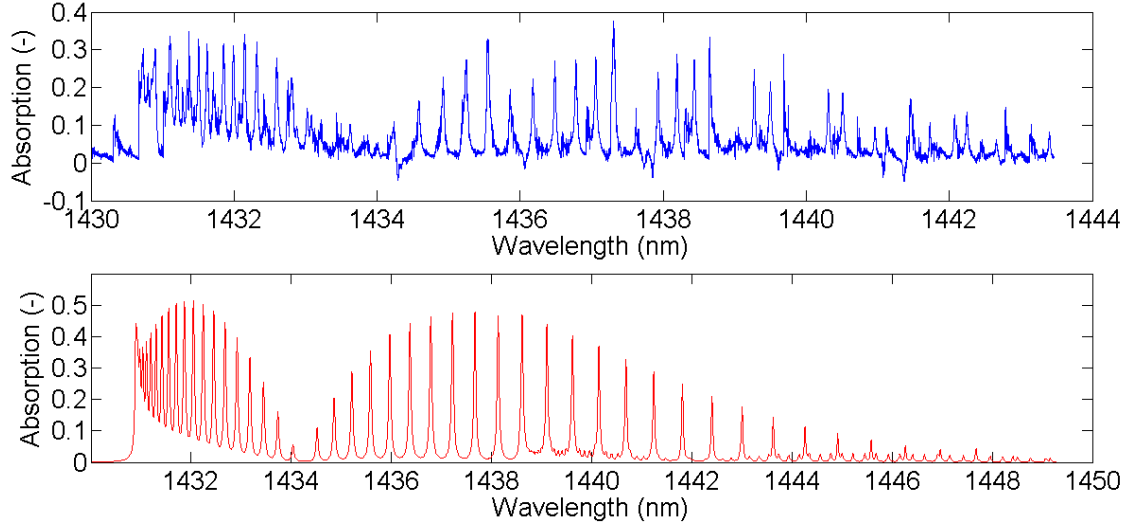


Figure 4.7: The upper spectrum is the measured absorption spectrum and the bottom spectrum is from the HITRAN database.

There are multiple spectral windows in the CO₂ spectrum in the spectral range of the laser and the most dominant one is in the range shown in Figure 4.7. In this region of absorption due to CO₂ there is also the presence of strong water absorption lines around the 1440 nm. These absorption lines are even more dominant than the absorption lines of CO₂. In order to have a realistic measurement a spectrum of other spectral windows should also be obtained. Due to the timespan of this project these measurements have not been done.

The axis of both spectra do not match with each other. This indicates that the CO₂ VIPA need to be recalibrated using the reference laser technique.

The measured spectrum shows a rather dominant noise level where real absorption peaks are difficult to distinguish. The standard deviation of the ratio of two reference measurements was taken to obtain the noise level of the system. The noise level of the CO₂ VIPA is found to be 0.040. This is again contributed by the camera used for this setup. For this particular measurement the SNR can also be calculated. The intensity contribution of the camera is $2.0 \cdot 10^3$ with a maximum intensity of the obtained measurement of $14 \cdot 10^3$. This results in a SNR of roughly 17 dB.

When looking at the quality of both measurements one can conclude that the SNR of the O₂ measurement is higher than the SNR of the CO₂ measurement. In principle this means that the signal of the O₂ measurement can be better detected regarding to the noise of the system than the signal of the CO₂ measurement.

Both the measurements can be optimised further in terms of alignment, camera parameters and analysis programs.

Chapter 5

Conclusion and Recommendations

The aim of this project was to do temperature measurements via spectroscopy of two gases present in air namely O_2 and CO_2 using a frequency comb laser. During the course of the project the setup for the O_2 spectrometer was built and the setup CO_2 was realigned. The two beam paths were aligned as such that the beams could co-propagate through the cavity and the same volume could be sampled by beams from two different wavelength ranges.

Measurements with filling the cavity with O_2 and CO_2 were performed and the absorption spectra were obtained by converting the camera images into spectra with the MATLAB program.

The results shown in Chapter 4 are a good starting point for achieving the goal to accurately determine the temperature using spectroscopy. Some improvements have to be made to optimise the spectra. The spectra can be further improved by optimizing the MATLAB code that converts the images into spectra. Furthermore the SNR of the measurements can be optimised by changing the settings of the camera and by improving the alignment of the VIPA spectrometer. To determine the temperature accurately the measured spectrum needs to be matched with the HITRAN spectrum to identify all individual frequencies.

Due to the timespan of this project temperature measurements could not be done. When these absorption spectra are optimised one can start with changing the temperature of the cavity with the heat cord and obtaining absorption spectra at different temperatures.

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Appendix A

Original Project Description

The assignment will be to develop a temperature sensor using spectroscopy. The level population of the different molecules, e.g. carbon dioxide and oxygen etc. in the atmosphere changes as the temperature changes. So studying the spectral signature of the molecular level populations can offer a very sensitive measurement of temperature. In this assignment we will measure a gas cell with equal amounts of carbon dioxide and oxygen at different temperatures using two different spectrometers called the VIPA (Virtually Imaged Phased Array) at two wavelength ranges. The two spectrometers have already been built. One VIPA spectrometer monitors the region of interest for the characteristic lines of CO_2 and the other spectrometer monitors the region of interest for the characteristic lines of O_2 . This is to calibrate the two thermometers with each other. They will be simultaneously compared to Platinum temperature sensors.

Appendix B

Extended VIPA Theory

This Appendix will discuss the intensity distribution on the camera due to the VIPA and due to the grating. It will also discuss some relevant parameters of the VIPA.

For the theoretical explanation behind the intensity distribution the theoretical work by Xiao, et. al. [28] is used. Xiao uses paraxial wave theory to calculate the total electric field produced by the virtual sources of the VIPA at the detection plane. Using this theoretical work, the intensity distribution can be written as

$$I_{VIPA}(y, \omega) \propto I_{in}(\omega) e^{\frac{-2f_c^2 y^2}{f^2 w^2}} \frac{1}{(1 - Rr)^2 + 4Rr \sin^2(\frac{\Delta}{2}k)} \quad (\text{B.1})$$

where:

I_{VIPA} : power spectral density of the beam at the detection plane [W/Hz]
 I_{in} : power spectral density of the input beam [W/Hz]
 f_c : focal length of the cylindrical lens [cm]
 k : wavenumber [cm^{-1}]

The parameter Δ contains most of the physics that determines the VIPA intensity distribution, the parameter Δ is defined as

$$\Delta = 2tn_e \cos(\theta_{in}) - 2t \frac{\tan(\theta_{in}) \cos(\theta)y}{f} - t \frac{\cos(\theta_{in})y^2}{n_e f^2} \quad (\text{B.2})$$

As shown in Equation B.1 the function $\sin^2(\frac{\Delta}{2}k)$ and the Gaussian profile are causing a non-uniformity in the intensity distribution. The intensity distribution at the detection plane shows an interference pattern that is mainly determined by the parameter Δ . The relevance of the parameter Δ will be shown when the main characteristics of the VIPA are theoretically analyzed.

The intensity distribution in the x-direction is determined by the diffraction grating. This parameter is not as important as the intensity distribution in the y-direction because this gives information about the FSR on the detection plane. Nevertheless the intensity distribution on the detection plane is a 2D distribution and in order to get a complete description of the intensity field at the detection plane the intensity distribution due to the grating is needed. This expression is written as

$$I_g(x) \propto I_{in} e^{\frac{-2(x - A(\omega - \omega_0))^2}{w_0^2}} \quad (\text{B.3})$$

where:

x : horizontal coordinate on the detection plane [cm]
 w_0 : beam waist size at the detection plane [cm]
 A : grating dispersion in frequency domain for the order $m=1$ [$\text{cm} \cdot (\text{rad/s})^{-1}$]
 ω : frequency at the detector array [Hz]
 ω_0 : frequency at the center of the detector array [Hz]

Equation B.4 uses the frequency domain to calculate the intensity distribution. Therefore parameter A is introduced [29]. This is defined as

$$A = \frac{\lambda^2}{2\pi c} \frac{\Delta x}{\Delta \lambda} \quad (\text{B.4})$$

There are three important parameters of the VIPA. The dispersion of light due to the VIPA, the size of the interference pattern and the spectral resolution of the VIPA.

To calculate the dispersion of light at the detection plane, the maxima of the interference pattern have to be found. This relation is given as

$$k\Delta = 2m\pi \quad (\text{B.5})$$

The approximate value of the order of the VIPA transmission can be calculated with

$$m \approx \frac{2tn_e \cos(\theta_{in})}{\lambda_c} \quad (\text{B.6})$$

where:

λ_c : central wavelength of the incoming beam [nm]

The position of the different wavelengths related to the y-position in the detection plane when using Equation B.6 is given by

$$m\lambda = 2tn_e \cos(\theta_{in}) - 2t \frac{\tan(\theta_{in}) \cos(\theta) f}{y} - t \frac{\cos(\theta_{in})}{n_e f^2} y^2 \quad (\text{B.7})$$

Taking the derivative of the relation given in Equation B.7 gives the dispersion of the VIPA

$$\frac{\Delta \lambda}{\Delta y} = \frac{-2t}{mf} \left[\tan(\theta_{in}) \cos(\theta) + \frac{\cos(\theta_{in}) y}{n_e f} \right] \quad (\text{B.8})$$

Appendix C

Specifications Mirrors

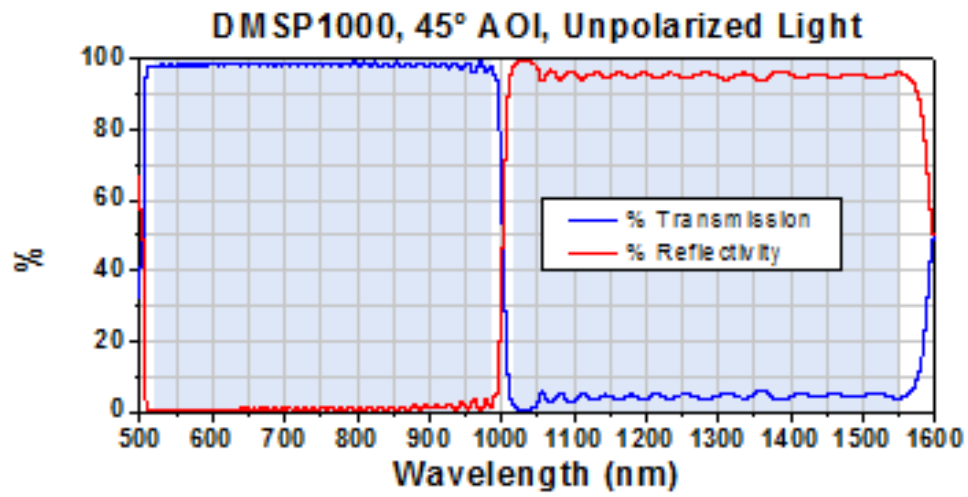


Figure C.1: The graph shows the reflection and transmission range of the dichroic mirrors used in the setup [30].

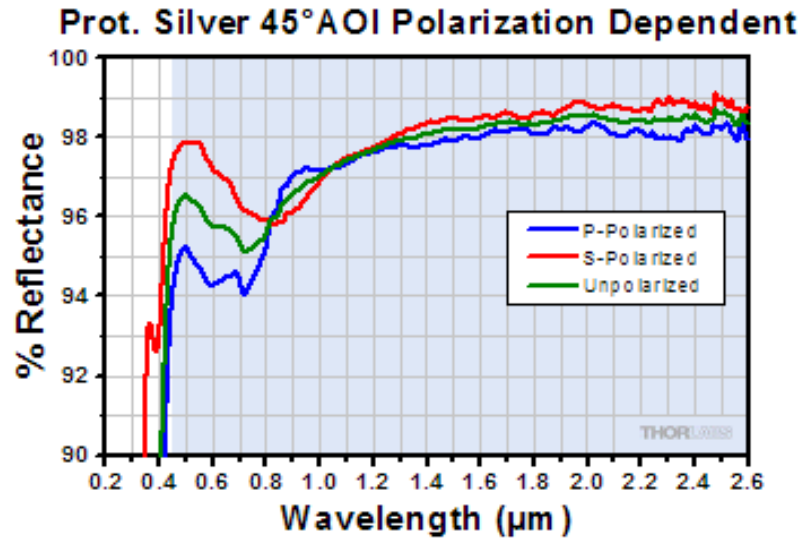


Figure C.2: The reflectivity of a silver mirror used in the O₂ VIPA setup [31]. The source used during this project is unpolarized.

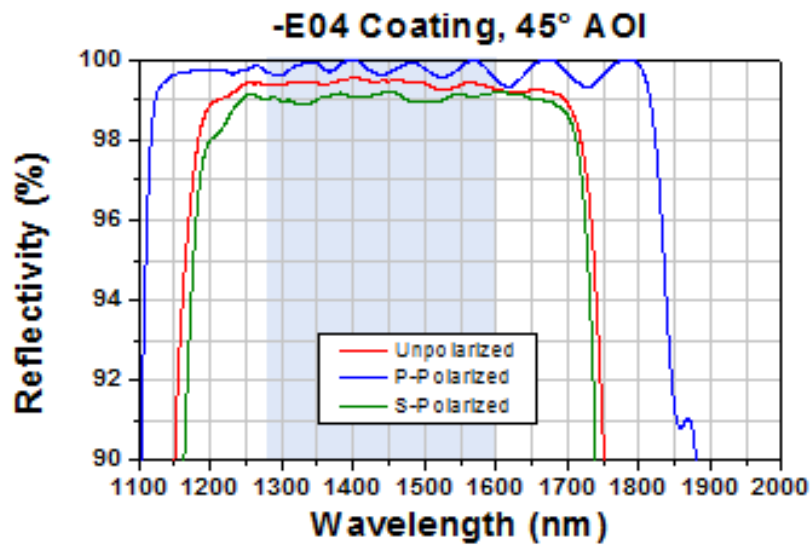
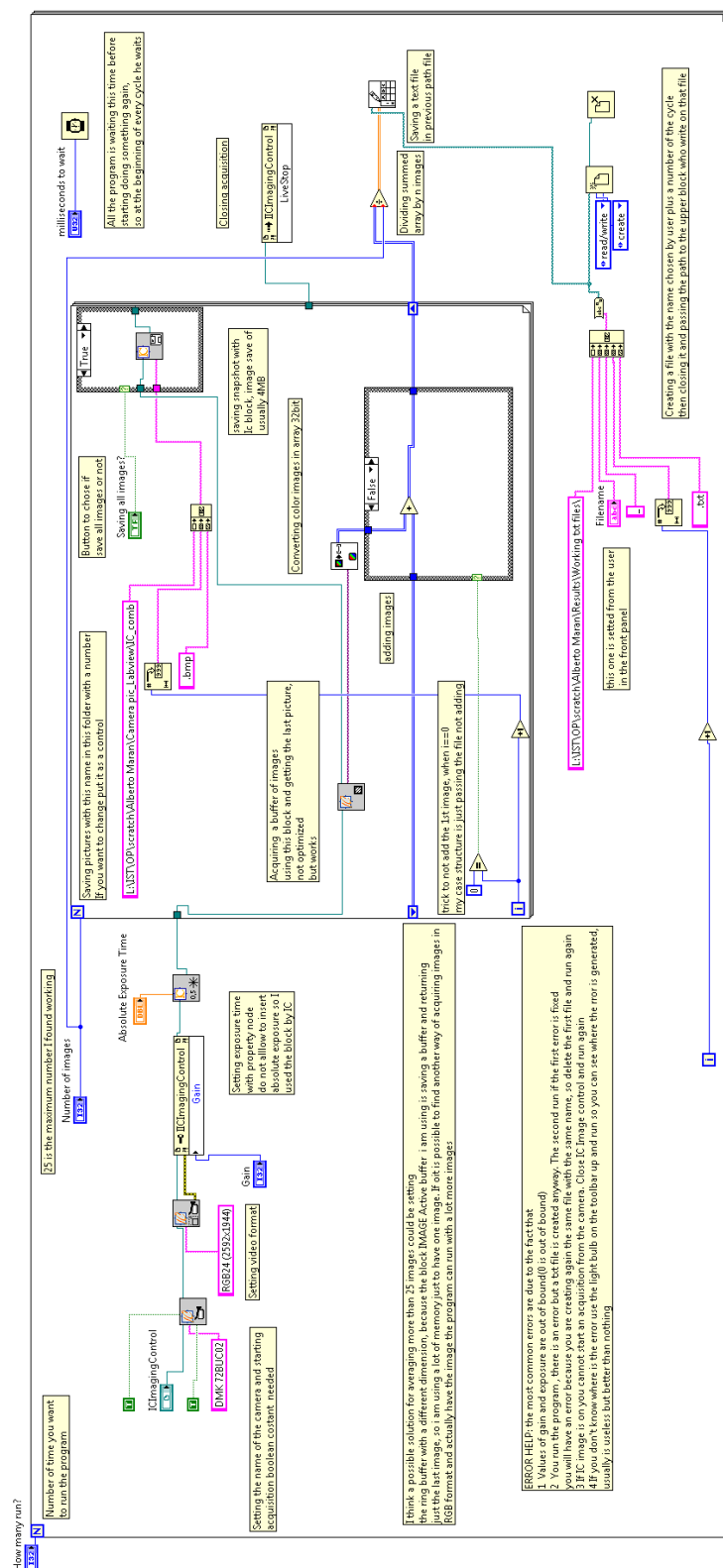


Figure C.3: The reflectivity of a dielectric mirror used in the CO₂ VIPA setup [32].

Appendix D

Labview Program

This labview program obtains images with the subVI's of the camera software. The gain and the exposure time of the camera can be regulated with this program. To improve the images a average of a maximum of 25 can be made. All the functions are commented in the block scheme and will explain why these functions are used.



Appendix E

Matlab Program

The program that is used during this project to calculate the absorption spectra is the Spectrum Generator program. Comments are added to the code and the comments are in the italic font.

```
1 %% SPECTRUM GENERATOR
2 % Calculate the absorption spectrum using a reference and a
   measurement
3 % image taken with a VIPA spectrometer.
4 %
5 % Syntax:
6 %
7 % [spectrum, num_frg, wavelength]=Spectrum_Generator(ref, meas,
   delta)
8 %
9 % Input:
10 %
11 % I = matrix containing the image we want to check the format
12 % (M-by-N or M-by-N-by-3)[No units]
13 %
14 % Output:
15 %
16 % I = matrix containing the Intensity profile image
17 % (M-by-N)[No Units]
18 %
19 % Example(s):
20 %
21 %
22 %
23 % Dependencies: max_min_detector
24 % largest_ocurrence
25 % first_line_corrector
26 % fringe_corrector
27 % fringe_integrator
28 %
29 %
30 % Author: MSc. A. Reyes Reyes
31 % Email: adonisatl@gmail.com
32 %
33 % Project: VIPA Spectroscopy
34 % Keywords:
```

```
35 %
36 %
37 % Version: v1.0 (20-01-2011)
38 %
39
40 %% Change-log
41 %
42 % v1.0 (02-12-2010) Adonis
43 % * First operational version.
44 %
45
46
47 %% Function declaration
48 function [output1, output2, output3]=Spectrum_Generator(input1, input2
    , input3)
49
50 %% Function description
51 %
52
53 %% Input Handling
54 % Assign the computational variables
55
56 ref = input1; %reference image
57 meas = input2; %measurement image
58 delta = input3; %parameter to detect minima and maxima in the images
59
60 %% Function Part1: Find the minima position in each row of the
    reference image and the number of minima per row.
61 % The minima correspond to the vertical fringes produced by the VIPA
    and
62 % the grating.
63
64 num_col = size(ref,2); % determine the number of columns in the
    reference image
65 deltaR=delta*(max(max(ref))-min(min(ref))); %define the parameter to
    detect minima and maxima in the max-min-detector program.
66
67 [pos_max, pos_min, max_frg, min_frg, num_min, num_max] =
    max-min-detector(ref, deltaR);
68
69 %
```

```
70 %% Function Part 2:Determine the number of fringes by taking the value
    with more occurrences in the number of minima per row
71 [num_frg] = largest_occurrence(num_min);
72
73 %
```

```
74 %% Function Part 3: Check and correct the position of the minima in
    the first row of the Free Spectral Range (FSR).
75 %This will be used as a reference to check and correct the position of
    the minima in the rest of the rows.
```

```

76
77 FSR_first = 385;%25;                                %First row of the FSR
78 FSR_last = 1795;%487;                                %Last row of the FSR
79 frg_separation = num_col/num_frg;    %Average number of pixels between
    two adjacent minima
80 first_min = 1;                                        %First minimum we take into account
81
82 [pos_min_ref_row] = first_line_corrector(pos_min, FSR_first,
    frg_separation, first_min);
83
84 %

```

```

85 %% Function Part 4: Check and correct the position of the minima in
    all the rows of the Free Spectral Range.
86 % Takes as reference the corrected positions of the minima in the
    first
87 % row of the FSR.
88 [pos_min_c] = fringe_corrector(pos_min, pos_min_ref_row, FSR_first,
    FSR_last, frg_separation);
89
90 %

```

```

91 %% Function Part 5: Integrate the fringes around the minima position in
    the reference and measurement images.
92 % Integrate the intensity between two adjacent minima in the
    horizontal direction.
93 % Then read column by column the integrated intensity following the
    increase in wavelength and build a vector.
94
95 [ref_integral] = fringe_integrator(ref, pos_min_c, FSR_first, FSR_last
    ); %Integrate the intensity of each fringe in the reference image
96 ref_integral_flipUpDown = flipud(ref_integral); %Flip the integrated
    image to read the columns in the correct order.
97 ref_vector = ref_integral_flipUpDown(:); % Read column by column of
    the integrated intensity and build a vector.
98
99 [meas_integral] = fringe_integrator(meas, pos_min_c, FSR_first,
    FSR_last); %Integrate the intensity of each fringe in the
    measurement image
100 meas_integral_flipUpDown = flipud(meas_integral); %Flip the
    integrated image to read the columns in the correct order.
101 meas_vector = meas_integral_flipUpDown(:); % Read column by column of
    the integrated intensity and build a vector.
102
103 %

```

```

104 %% Function Part 6: Calibrate the wavelength
105
106 wavelength = 0;
107 size_vref = size (ref_vector);
108 index = [1:size_vref]';

```

```
109
110 wavelength = 8e-005* (power(index,1))+0.757e+003;
111 %wavelength = 4.9990e-010 * (power(index,2)) + 9.3063e-004* (power(
    index,1))+1.5664e+003;
112
113 %
```

```
114 %% Function Part 7: Calculate the absorption.
115 % Get the ratio between the measurement and the reference and build
    the
116 % absorption spectrum using the calibrated wavelength
117
118 %Dif_I=(ref_vector-meas_vector)./ref_vector;
119 absorption = 1-(meas_vector./ref_vector);
120 spectrum = [wavelength absorption];
121
122 figure
123 plot (spectrum(:,1),spectrum(:,2));
124
125
126 %% Output handling
127 % The output is
128 output1 = spectrum;
129 output2 = num_frg;
130 output3 = wavelength;
131
132 end
```