Doppler free absorption spectroscopy and error signal

Martin Hauden

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1 Introduction

To cool down ytterbium atoms before transporting them into the cavity, one laser needs to be locked at 556nm. We want to perform a saturated Doppler-free absorption spectroscopy on an iodine gas cell. The laser will be locked on an error signal provided by the numerical derivation, using a lock-in amplifier, of the absorption signal.

2 "Theory of Doppler-free spectroscopy and Lock-in"

2.1 Doppler-free spectroscopy

We want to have the frequency of the laser stable. The laser will interact with ytterbium atoms, the atomic line of ytterbium is 180 kHz width. We want to lock the frequency within 20 kHz. To lock the laser, we need to have a stable reference for the frequency. This reference of frequency will be used to see if the frequency of the laser is well set and stable. This frequency reference is provided by an atomic line. Indeed The atomic transition is a very good way to provide this reference because We can find absorption line near the laser frequency easily by choosing the right atoms/molecule. The experimental setup is quite simple, the laser passe through a gas cell (iodine in our case). We could use directly ytterbium as atomic reference but the ytterbium needs to be heat around 500°C to be gaseous. For practical reason the iodine is way more easy to perform. We measure the intensity of the beam with a photodiode at the output of the cell to compare the frequency of the laser to the atomic line Fig.1:

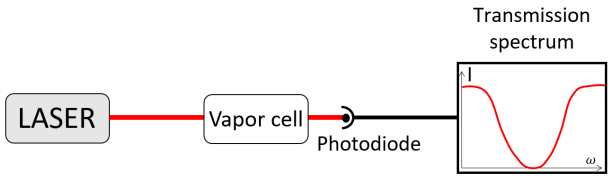

Figure 1: Experimental setup for spectroscopy

If the laser is close to the absorption frequency of the iodine, the iodine molecules will absorb the beam and the intensity of the beam at the output of the beam will decrease. If the frequency of the laser is far from the absorption frequency then all the power will be transmitted trough the gas cell. With this, we are able to compare the frequency of the laser with the atomic transition of the iodine. When the intensity of the beam is minimal, the frequency of the laser is equal to the absorption frequency. If we have variation of intensity, the frequency of the laser is not stable and we need to adjust it. We can adjust the frequency of the laser by tuning the length of the cavity of the laser diode, the electrical intensity or the temperature.

The issue with this setup is that the molecules inside the cell are not stationary. They have a given speed in a random direction. Due to this velocity and the Doppler effect, some molecules will have a different absorption frequency depending of their speed. We recall $f_{atom} = (1 - (v_{atom}/\mathrm{C})) \times f_{laser}$. This phenomena will broad the absorption spectrum (about a GHz). We can't lock the frequency within 20kHz with a GHz width spectrum. The stability of the frequency is limited by this spectrum so we need to get rid of this broadening. We perform a Doppler free spectroscopy. We have now two beams which will interact with the gas, a probe beam and a pump beam. The probe beam is counter-propagating, it will carry the information, we will measure it with a photodiode. The pump beam is needed to get free of Doppler effect. Both beams will interact with atoms inside the cell.

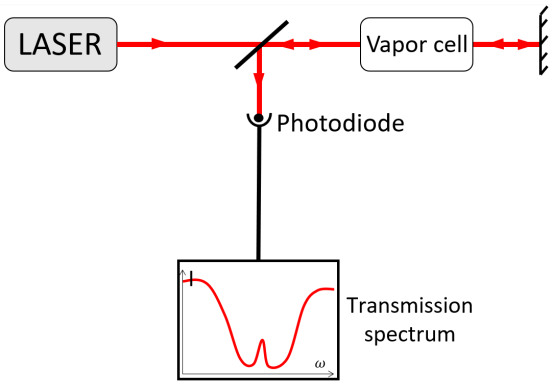

Figure 2: Experimental setup for Doppler free spectroscopy. The pump and the probe are here the same beam. The first trip inside the cell act as the pump and the second trip as the probe

The pump will gives a Doppler broadened absorption of a few GHz width : indeed, even if the laser is not resonant with the molecule at rest, it may interact with a certain velocity class v. The counter-propagating probe, at the same frequency, interacts with molecules with a velocity $-v$. If the laser is resonant with the molecules at rest, that is, interacting with molecules with a velocity $v = 0$, then the pump and the probe simultaneously address the same molecules. If the pump was saturating the transition, then the probe absorption is strongly reduced Fig. 3, and a transmission peak appears in the transmission spectrum. This peak is only few MHz width. This peak will be the frequency reference.

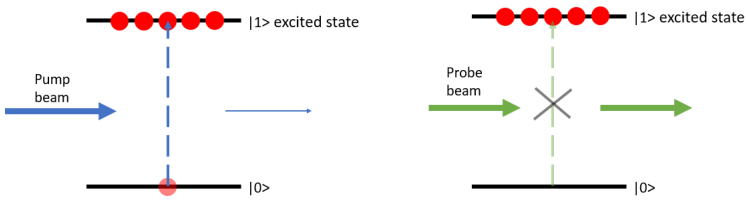

Figure 3: Principle of saturation of the atomic line

2.2 Lock-in amplifier

We have now to compare the frequency of the laser with our reference and to tune it with a feedback loop to make it stable. We don't have directly the frequency of the laser but the intensity of the beam after the cell. With th transmission curve, for a given intensity (doted line Fig. 4), two values are possible for the frequency. We don't know if we need to increase or decrease the frequency.

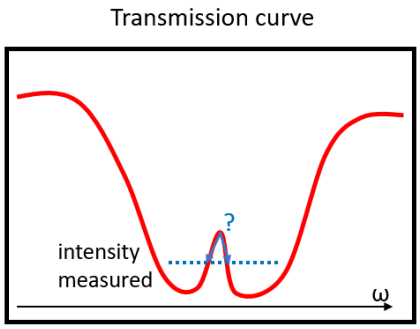

Figure 4: Transmission curve in red function of the frequency of the probe beam. Doted line is the measured intensity for a unknown frequency of the laser.

To know how we need to tune the frequency of the laser, We want a curve without a peak but with a slope. We take the derivative of the transmission spectrum around the peak. This will provide a slope Fig.5.

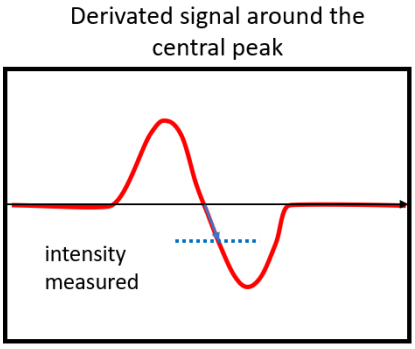

Figure 5: Derivative around the transmission peak. Doted line is the measured intensity for a unknown frequency of the laser.

We have now, for a measured intensity, the information about the frequency. We are able to tell the frequency controller if the frequency is too low or too high. We use a lock-in amplifier to provide the derivative of the transmission spectrum.

To perform that, we modulate the frequency of the probe beam : $\nu_{prob} = \nu_{laser} + \delta\nu_1 \cos(ft)$ where $\delta\nu_1$ is the amplitude of modulation and f the frequency of the modulation. The photodiode will now return a transmission signal, $s_{\mathrm{PhD}}(\nu_{laser}, \delta\nu_1, f)$, depending of $\nu_{laser}, \delta\nu_1$ and f.
The lock in amplifier will demodulate the light. It multiplies s_{PhD} and the modulation signal with a known phase $\cos(ft + \phi)$. We call this signal s.

$$s = s_{\mathrm{PhD}}(\nu_{laser} + \delta\nu_1 \cos ft) \times \cos(ft + \phi). \tag{1}$$

We know that the modulation amplitude is small : $\delta\nu_1 \ll \nu$. We can use the Taylor expansion at first order to make appear the derivative of the signal s_{PhD}.

$$s \simeq [s_{\mathrm{PhD}}(\nu_l) + s'_{\mathrm{PhD}}(\nu_l)\delta\nu_1 \cos(ft)] \times \cos(ft + \phi) \tag{2}$$
$$s = s_{\mathrm{PhD}}(\nu_l)\cos(ft + \phi) + s'_{\mathrm{PhD}}(\nu_l)\delta\nu_1 \cos(ft)\cos(ft + \phi) \tag{3}$$
$$s = s_{\mathrm{PhD}}(\nu_l)\cos(ft + \phi) + \frac{1}{2}s'_{\mathrm{PhD}}(\nu_l)\delta\nu_1(\cos(\phi) + \cos(2ft + \phi)) \tag{4}$$

The lock in amplifier applies a low pass filter to cut off the oscillating terms at frequency f and $2f$ to obtain at the end a signal proportional to the derivative of the input signal s_{PhD}.

$$s = \frac{1}{2}\delta\nu_1 s'_{\mathrm{PhD}}(\nu)\cos(\phi). \tag{5}$$

The amplitude of modulation needs to be big enough to have a clear signal, without noise but if $\delta\nu_1$ is too high, the development we made will not be valid anymore. We chose a fast modulation, not to fast (the photodiode needs to detects the modulation), but fast enough for a good low-pass filter (in practice, ν_{laser} is a function of time and it should not be low-pass filtered).

3 Experiment

3.1 The iodine cell

We use an iodine cell to perform our Doppler free absorption. The iodine have many atomic lines around the laser frequency. The nearest one is about 1 GHz away from the laser frequency. The other advantage of the iodine is that it has a high saturation vapor pressure at room temperature. Due to this high saturation vapor pressure, the iodine is in equilibrium in between gaseous stat and solid stat. We applies heater to maintain the temperature constant over time to keep the saturation vapor pressure high.

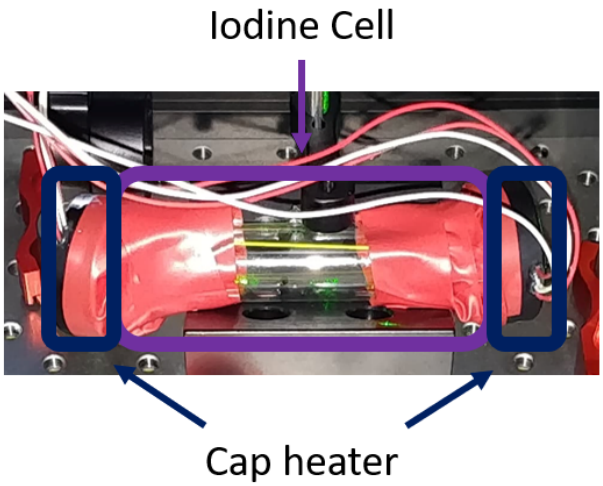

Figure 6: Picture of the iodine cell

The heat caps are driven by a temperature controller via a PID feedback. The cell temperature is set to 27°C. The measured value is 26.8°C, the key point is that the temperature does not fluctuate. The cap heaters were planned for a Ø25mm diameter cell and ours is Ø19mm So we added some thermal paste to make the link between the heater and the cell (under the red tap on Fig.6).

3.2 Experimental setup

To perform our Doppler free absorption, we need first to shift the frequency laser onto an atomic line of the iodine. Then we need to modulate the light to lock-in the absorption signal. We are using acousto-optic modulators (AOM).

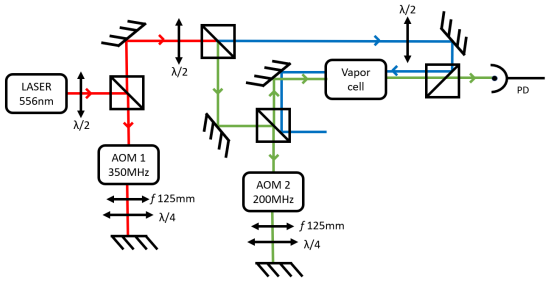

Figure 7: Sketch of the setup

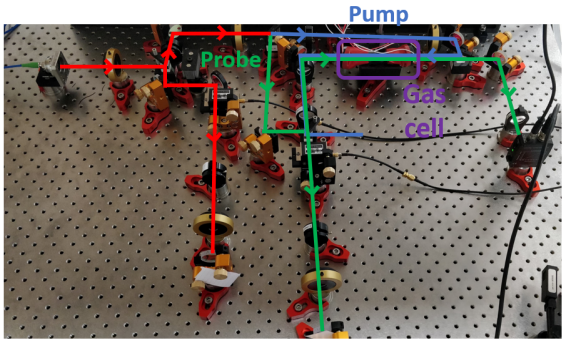

Figure 8: experimental setup

The light emitted by the laser (in red Fig. 7) is linearly polarized, at the polarized beam spliter, the beam will be reflected towards the AOM 1. We using a $\lambda/2$ wave plate to modify the power entering the setup. We use double-pass acousto-optic modulator system to shift twice the frequency. The AOM is changing the direction of the beam depending of the modulation frequency. We use a lens to balance this change of orientation during the modulation.This AOM setup is called cat eye setup. If we are not using the lens, with the frequency shift, the angle will change and the beam won't be well reflected by the mirror into the AOM for the second trip (It will induce high power losses) Fig. 9:

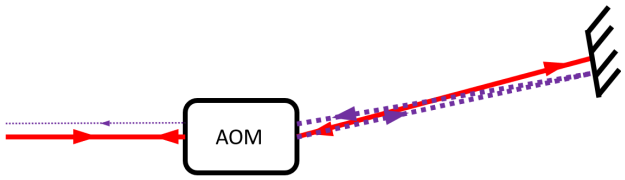

Figure 9: Setup of a classic AOM setup. Red beam is for the "normal" frequency shift of the AOM and the purple one for a different frequency shift.

By adding a lens in between the AOM and the mirror, The AOM and the mirror needs to be at the focal point of the lens, the deviated beam will be focused on the AOM. This setup works for small angles because the lens is working at his center, Fig. 10.

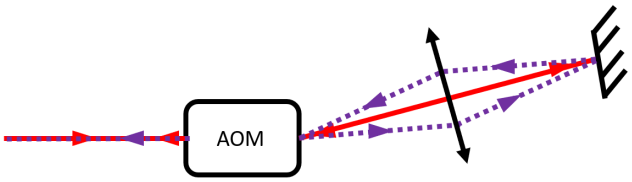

Figure 10: Setup of a AOM Cat eye setup. Red beam is for the "normal" frequency shift of the AOM and the purple one for a different frequency shift.

Alignment is made with adjustable mirrors at the input. After the AOM, we have a $\lambda/4$ wave plate and a mirror. The polarization of the beam, going trough twice the $\lambda/4$ wave plate will turn by 90° allowing the beam to be transmitted by the polarized beam spliter. The AOM 1 is shifting the laser by 700 MHz to match with the atomic line of the diode. The beam passes in another beam spliter to split the beam in the probe beam and the pump beam. We use a $\lambda/2$ wave plate to chose the power distribution between the two beams. The pump beam (in blue Fig.4), is redirected toward the iodine cell. The probe beam (in green Fig.4), is going into another AOM2 to shift again the frequency towards the atomic line but also to make the modulation for the lock-in amplifier. The frequency of the probe can be written :

$$\nu_{probe}(t) = \nu_0(t) + \delta\nu \cos(ft) \tag{6}$$

With ν_0 the frequency of the beam, $\nu_0 = \nu_{laser} + 900$ MHz. $\delta\nu$ is the amplitude of the modulation and f the frequency of the modulation for the lock in amplifier.
The probe beam is sent in the iodine cell, overlapping with the pump beam. The pump and the probe need to interrogate the same molecules. Then it goes on the photodiode. The photodiode needs to be fast enough to measure the oscillation of the modulation.

Both AOMs are driven by high frequency generator(HFG). The radio frequency signal is filtered and amplified. The RF signal at the output of the HFG is about 0dBm We also need to attenuate the RF signal before amplifying it because the amplification is set (+40dBm) and the AOMs can not receive more than 30dBm. We have noise frequency at 30kHz and 160kHz. The 160kHz was induced by the feedback of the doubling cavity inside the laser. Adjusting the cavity suppressed it. The 30kHz is unknown but small enough to be neglected.

3.3 Absorption curve

We can scan the frequencies by a few GHz around 5.4 THz by changing the length of the laser diode cavity. ν_{laser} scan the frequencies around the absorption line. We expected to have the broad absorption line with the transmission peak at the bottom due to the pump beam.The laser frequency is 5 393 872 000Hz $\pm$ 5 GHz.The power of the laser used in the setup is 15 mW. We measure this absorption curve Fig. 11:

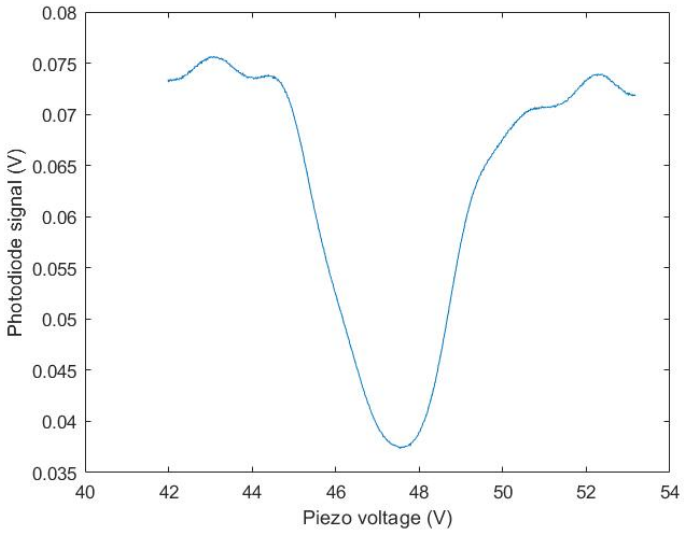

Figure 11: Measured absorption curve of the iodine around 5 393 872 000Hz

We see the simple absorption curve without transmission peaks. We have oscillation at the top of the absorption line. These oscillation are due to interference between the probe and pump beam. Indeed the polarized beam spliter are leaking and a part of the pump is going to th photodiode, making interference with the probe beam. We don't have the expected transmission peaks on the curve with this probe/pump configuration. The issue is that the atomic line is not saturated by the pump beam and so the probe beam is still absorbed by the iodine. This means that the pump and the prob are not interrogating the same molecules (we can adjust the overlap of the two beams inside the cell). The second thing is that the molecules are maybe not excited enough, not saturated and the probe still interact with those molecules. We perform experimental measurements of the power needed for the beam to saturate all the molecules.

3.4 Saturation of the line

We want to know if the atomic line is well saturated by the pump. If the power of the pump is not high enough, the molecules are not saturated and the probe beam will still interact with the molecules. We need to see which pump power we need for the saturation of the atomic line. We make measurements of the output power (before and after the iodine cell). We plot the percentage of absorption function of the input power. Indeed this percentage can be express as :

$$\frac{I_{abs}}{I_{in}} \propto \frac{1}{I_{in}} \times \frac{\frac{I_{in}}{I_{sat}}}{1+\frac{I_{in}}{I_{sat}}} \tag{7}$$

We plot the percentage of power absorbed function of the input power and fit the curve with the eq.7 :

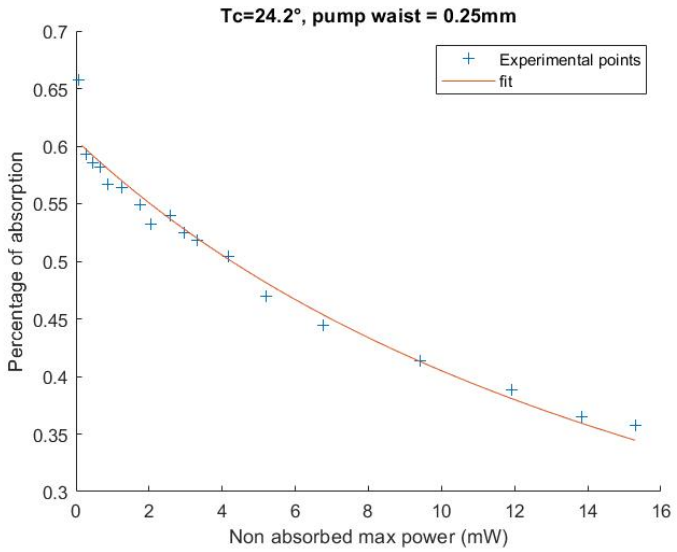

Figure 12: Absorption percentage function of P_{in}

The fit gives us the experimental value for the saturation power.

$$P_{sat} = 20 \pm 2.6 \text{ mW}$$

We can compute I_{sat} knowing the surface of the beam. We measure the beam profile with a beam profiler:

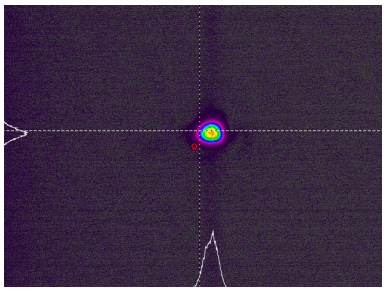

Figure 13: 2D view of the pump beam

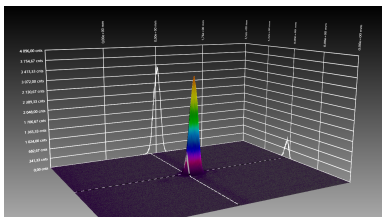

Figure 14: 3D view of the pump beam

We assume that the beam is circular with a Ø0.25mm diameter. we can compute then the saturation intensity :

$$I_{sat} = \frac{P_{sat}}{\pi r^2}$$

$$I_{sat} \simeq 11000 \text{ mW/cm}^2$$

This is quite high value for saturation a intensity. We were not saturating the atomic line with the pump beam. The power was too low and the diameter of the beam was 2mm.

3.5 Absorption curve, high intensity

We want a higher intensity inside the iodine cell for the pump beam. We add up to 20mW of power at the input of the iodine cell. We also decrease the beam size (from Ø2mm to Ø0.25mm) by implementing a telescope. We need to decrease the beam size for both beam, probe and pump, because they need to overlap inside the iodine cell. We perform new absorption curve measurement :

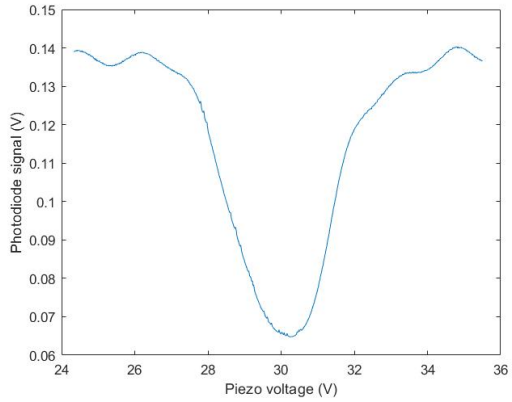

Figure 15: Measured absorption curve of the iodine around 5 393 872 000Hz

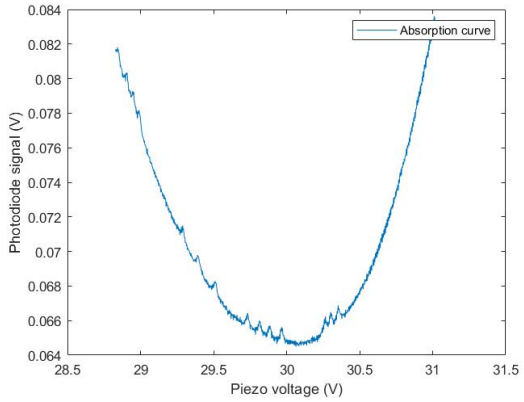

Figure 16: Zoomed absorption curve of the iodine around 5 393 872 000Hz

We can see the transmission peaks that we want to lock onto. We can now compute the error signal, with the lock in amplifier.

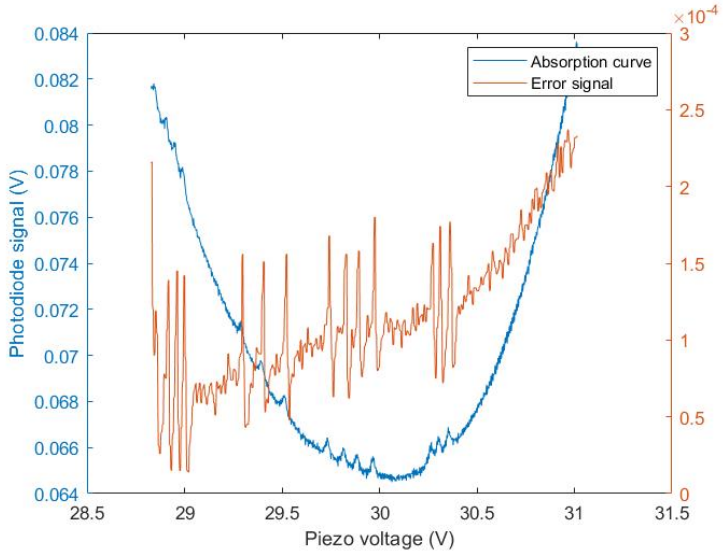

Figure 17: Absorption curve and the error signal

The error signal can be optimized by changing the lock in amplifier parameters and the intensity of the transmission peaks. We also need to eliminate the interference between the pump and the probe beam that can induce errors on the signal.