

Laser frequency stabilization for optical trapping of Magnesium ions

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(Dated: October 27, 2016)

Abstract

Quantum simulation is a solution to problems that are too complex to be solved numerically or analytically by classical means. This method uses well-controlled quantum systems to mimic the behaviors of more complex systems. Our project aims to optically trap Magnesium ions in regular lattices, which promises simulation with strong interaction and precise controlling. In order to first trap the ground state of Magnesium atom, we need to stabilize the laser wavelength of 285nm. Iodine spectrum is often used as a reference for laser frequency due to its dense absorption lines. In this report, we will describe how to perform Iodine spectroscopy and frequency lock with very low input power, only 2.6mW.

As supplementary materials, we will also report the processes of coupling light into a Single Mode Fiber and amplifying radio-frequency signals for Acoustic-Optical Modulators.

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I. BACKGROUND

A. Introduction

Computational simulation is a method to guide experiments in complex problems where analytical calculations do not exist. However, there are numerous important problems where the computational complexity scales exponentially and goes beyond the capacity of any classical computers. These problems range from high-energy to condensed matter physics, medicinal chemistry, etc... As a solution, Richard Feynman suggested the use of quantum simulation, where well-controlled quantum systems can be used to mimic the behaviors of more complex ones. Quantum simulation opens up great opportunities to solve difficult problems like high-temperature superconductivity or medical drug design.¹

The most advanced systems so far for quantum simulation are neutral atoms trapped in optical lattices and ions trapped in electric and magnetic field. However, both approaches are still experiencing inherent difficulties when facing problems with strong interaction and long-range entanglement. Trapped neutral atoms interact with short range contact interaction and are less precisely controlled than ions; while trapped ions experience increasing heating rate when they are brought closer to each other and closer to the magnetic electrodes, thus strong interaction cannot be achieved. In our project, we are determined to solve this problem by combining both technologies: trapping Magnesium ions Mg^{25+} in pure optical potential, where a high-finesse cavity will be used to produce strong electric field.

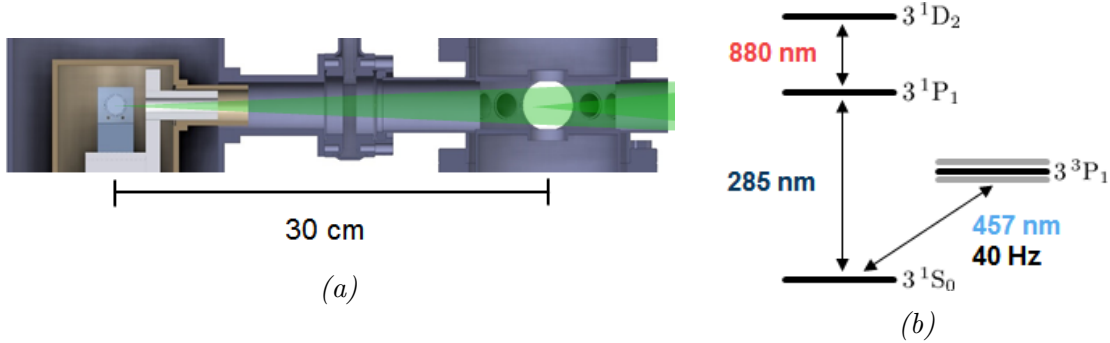


FIG. 1: (a) Trapping and cooling system: the chamber on the right is Magneto-Optical Trap (MOT) for neutral Magnesium atoms, the atoms will then be transported to the left for ionization and optical trap. (b) The energy level diagram of neutral Magnesium atoms, where the wavelength of 285nm is needed for trapping the ground state.

The first stage of the project is to trap neutral Magnesium ions in an Magneto-Optical Trap (MOT) (the neutral ions will then be transported to another chamber for further optical trapping and ionizing, see Fig. 1a). In the MOT, the wavelength of 285nm is required to trap the ground state of neutral Magnesium atoms, as can be seen from the energy level diagram in Fig. 1b. In our experiment, this wavelength will be generated by a laser diode emitting at

1140nm; the frequency is then doubled to 570nm, goes through frequency stabilization and then is doubled again to 285nm. In this report, we will demonstrate a frequency stabilization for the 570nm light using Iodine reference; the set-up is universal and can be applied for many other frequencies in the lab.

Iodine lock is a technique that uses Iodine spectrum as a reference to stabilize laser frequency. During physics experiments, lasers are usually expected to run over many days with frequency precision of tens of MHz. However, when there is no proper lock, laser frequency can drift hundreds of MHz off resonance after a few hours. Iodine vapor has a very dense spectrum with absorption lines every few GHzs, thus it is widely used as a reference to lock laser frequency.³ The Iodine lock setup was reconstructed by PhD student Lo⁴ in our group with a more compact setup, however he had to use 50mW of laser power for the lock. In this report, we will show that only an input power of 2.6mW is necessary. This power is 20 times lower than in Lo's report, while our saturation intensity is 1.4 times higher (see section 6). This significant improvement comes from using smaller beam diameter and more stringent alignment process. In the following sections we will explain in details the methods for Iodine spectroscopy and laser frequency stabilization.

B. Doppler broadening and Saturated Absorption Spectroscopy

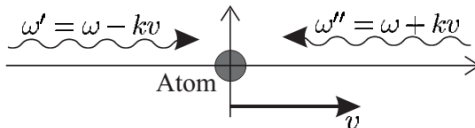


FIG. 2: Illustration of Doppler effect, taken from C. J. Foot's book,² where an atom is moving with velocity v and a source is emitting light at angular frequency ω . If the atom is moving toward the light source, in its inertial frame it will experience a higher frequency $\omega' = \omega + kv$. On the other hand, if the atom is moving away from the light source, it will experience a lower frequency $\omega'' = \omega - kv$.

Every atomic (or molecular) gas has a signature spectrum with absorption lines representing possible atomic transitions. However the Doppler effect can broaden the natural linewidth to the order of GHz, making many transition lines unresolved. In this section we will discuss the mechanism of Doppler broadening and the method of Saturation Spectroscopy used to counter this effect.

Due to Doppler effect, atoms moving at different velocities experience different frequency shifts in their inertial frames (Fig. 2). Let ω_0 be the resonant frequency of atoms at rest; atoms moving at velocity v will absorb light at frequency ω that satisfies

$$v = c \frac{\omega - \omega_0}{\omega_0}. \quad (1)$$

In a gas, the velocity follows Maxwell-Boltzman distribution where the fraction of atoms moving with velocity from v to $v + dv$ is given by²

$$f(v)dv = \sqrt{\frac{M}{\pi 2k_B T}} \exp\left(-\frac{Mv^2}{2k_B T}\right) dv \equiv \frac{1}{u\sqrt{\pi}} \exp\left(-\frac{v^2}{u^2}\right) dv, \quad (2)$$

where M is atomic mass, T is temperature, k_B is the Boltzman constant and $u = \sqrt{2k_B T/M}$ is the most probable speed. By changing the variable from v to ω , accordingly to equation (1), we can see that the absorption probability has a Gaussian line shape:

$$g_D(\omega) = \frac{c}{u\omega_0\sqrt{\pi}} \exp\left[-\frac{c^2}{u^2} \left(\frac{\omega - \omega_0}{\omega_0}\right)^2\right]. \quad (3)$$

This broadened lineshape has FWHM $\Delta\omega_D$ given by:

$$\frac{\Delta\omega_D}{\omega_0} = 2\sqrt{\ln 2} \frac{u}{c}, \quad (4)$$

The calculation of the most probable speed u can be simplified by

$$u = \sqrt{\frac{2k_B T}{M}} = 2230 \text{ms}^{-1} \times \sqrt{\frac{T}{300\text{K}} \times \frac{1 \text{ a.m.u.}}{M}}, \quad (5)$$

where M and T are given in amu and Kelvin respectively.

The Doppler-broaden FWHM of most atoms are around 0.5 to 10GHz, while the natural linewidth is only at tens of MHz². This results in imprecise spectroscopy, especially when addressing atomic hyperfine structures. For example, in our experimental set-up, the laser is 570nm and Iodine molecules have mass of $2 \times 127\text{amu}$. This leads to a Doppler FWHM of $\Delta f_D = 417\text{MHz}$, while the hyperfine natural linewidth is only from 5 to 10 MHz³.

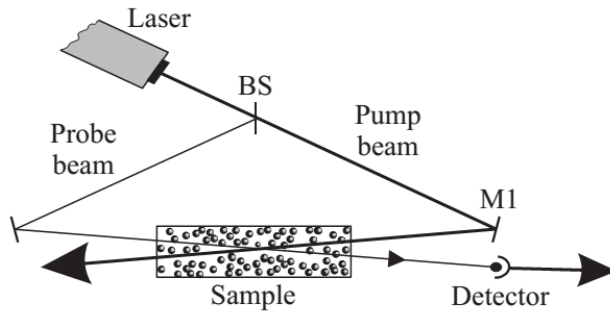


FIG. 3: A simple setup for saturated absorption spectroscopy,² where the strong pump and the weak probe beam are counter-propagated through the atomic gas cell.

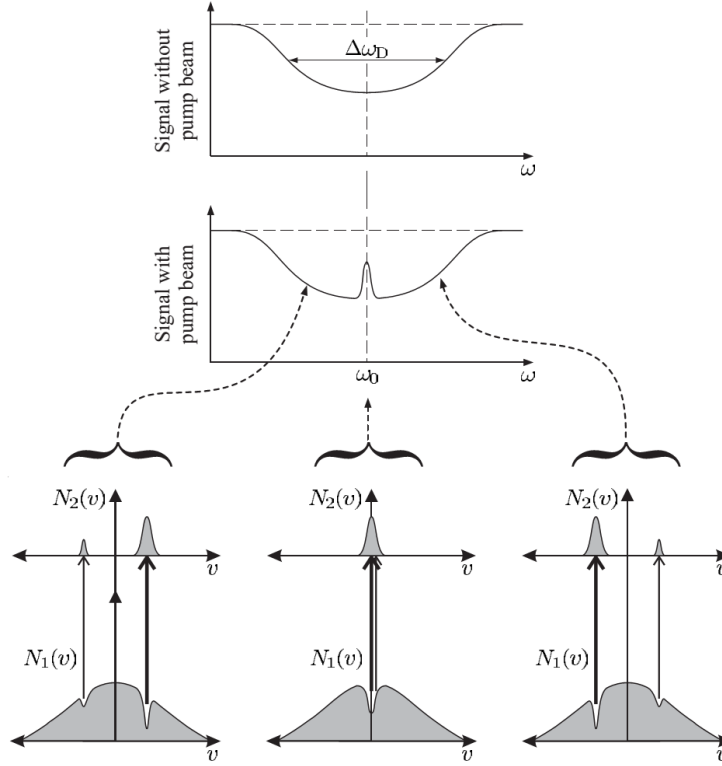


FIG. 4: Without the pump beam, the transmission linewidth of probe beam is broadened by Doppler effect; when the pump beam is turned on, the probe spectrum shows a narrow peak at resonant frequency. The three energy-level diagrams at the bottom explain this saturation peak.² Due to Doppler effect for opposite propagations, the pump and the probe beam always excite atoms at opposite velocities and thus, do not affect each other. However, when the laser is on-resonant, both beams get absorbed by the atoms at rest. Because the pump beam is very strong, it saturates all atomic absorption, leaving the probe beam better transmitted, thus create the narrow peak in the middle.

Saturated absorption spectroscopy is a technique designed to overcome Doppler broadening². In the simplest experimental set-up (Fig. 3), the laser beam can be separated by an unbalanced beam-splitter to produce a strong pump and a weak probe beam. They are then counter-propagated through the atomic gas cell. The probe beam is then detected and the pump beam discarded. When the probe transmission spectrum is scanned (Fig. 4), we see a Doppler-broadened absorption line. With the presence of pump beam, there will also be a narrow peak at the resonant frequency, this is called the saturated absorption line. The explanation for this is illustrated in Fig. 4, where you see the velocity distributions of an atom in ground state ($N_1(v)$) and excited state ($N_2(v)$). Due to Doppler effect, when the laser is scanned at frequency ω , only the atoms with velocity given by equation (1) are excited. Because the pump and probe beam are counter-propagated, they always address atoms at opposite velocities and thus, do not affect each other. However, when $\omega = \omega_0$, both beam will address the atoms at rest. Because the pump beam is very strong, it saturates

the atomic absorption and leaving the probe beam under-absorbed. This creates the narrow transmission line at the bottom of the Doppler-broadened feature.

The saturation intensity of the pump beam can be calculated by

$$I_{sat} = \frac{\pi \hbar c \Gamma}{3 \lambda_0^3}, \quad (6)$$

where Γ is the transmission linewidth, λ_0 is the laser resonant frequency, \hbar is the Planck's constant and c is the speed of light. For example, in our experimental project, we use 570nm light and the Iodine transition linewidth is 5 to 10MHz³, this leads to a saturation intensity of about 6W/m².

C. The lock-in amplifier

In our experiment, we will use lock-in amplifier to amplify spectroscopy signal. This section provides a theoretical explanation of how the lock-in amplifier work. Lock-in amplifiers are used to detect very weak electrical signal in the presence of high noise. In this technique, the signal $V_{s0}(t)$ has to be modulated by a frequency ω_s and phase θ_s :

$$V_s(t) = V_{s0} \sin(\omega_s t + \theta_s). \quad (7)$$

It worth noting that in order for lock-in amplifier to work, the original signal V_{s0} should vary in time very much slower than the modulating frequency ω_s . When this signal is input into the lock-in amplifier, it will be multiplied by an internal reference signal of frequency ω_r and phase θ_r ,⁷ giving a resultant signal of

$$\begin{aligned} V(t) &= V_{s0} V_{r0} \sin(\omega_s t + \theta_s) \sin(\omega_r t + \theta_r) \\ &= \frac{1}{2} V_{s0} V_{r0} \cos[(\omega_s - \omega_r)t + \theta_s - \theta_r] - \frac{1}{2} V_{s0} V_{r0} \cos[(\omega_s + \omega_r)t + \theta_s + \theta_r]. \end{aligned} \quad (8)$$

The signal then passes through a low pass filter. If $\omega_s \neq \omega_r$, both oscillating terms will be removed, giving nothing. However, if $\omega_s = \omega_r$ so that the second term becomes DC signal, and if the phase is chosen such that $\theta_s = \theta_r$, we will attain an output signal proportional to the signal amplitude

$$V_{out} = \frac{1}{2} V_{s0} V_{r0} \quad (10)$$

As a consequence, if we modulate the signal input by the same frequency and phase with the internal reference signal, all the noises oscillating at other frequencies will be suppressed, leaving a clean signal. An illustration of lock-in signal can be seen in Fig. 11 in section Results. The lock-in signal has a clear zero crossing, where it is positive on the left of the

center frequency and negative on the right. This can be used as an error signal which tells the laser whether the frequency has drifted to the left or the right of the spectrum. This error signal can be fed to the current control of the laser; the current will then be adjusted until the frequency is on-resonant again.

II. EXPERIMENTAL SETUP AND PROCEDURE

A. Coupling light into Single Mode Fiber (SMF)

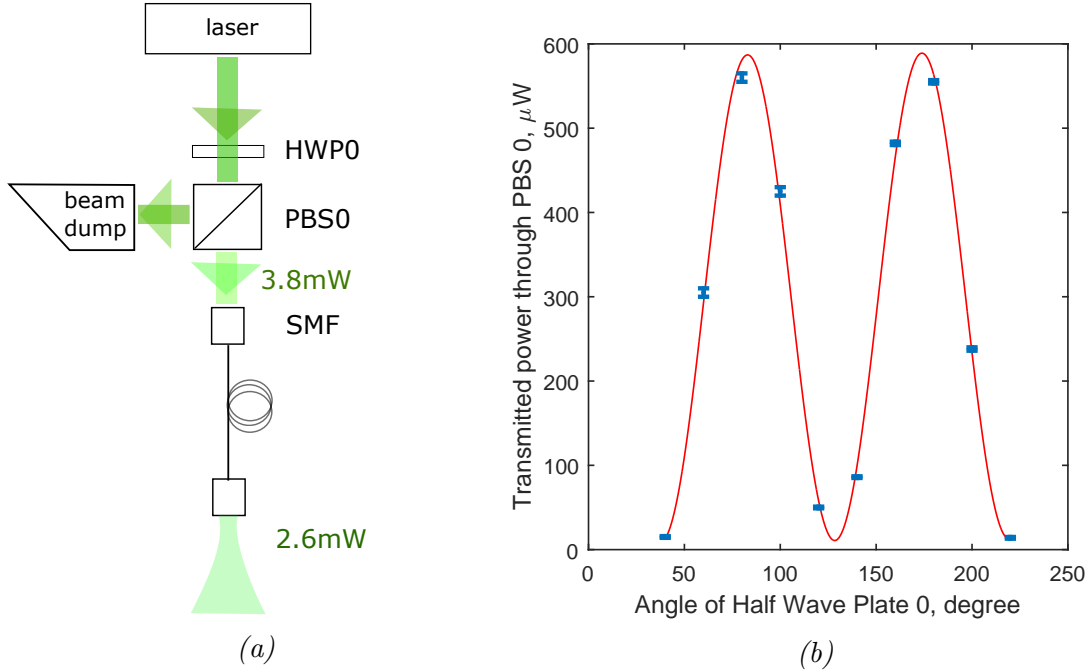


FIG. 5: (a) Optical layout of coupling light from TOPTICA laser into Single Mode Fiber (SMF). The output power can be flexibly adjusted by tuning the HWP0. As we only need a small fraction of the power, most of the power is reflected by PBS0 to the pump dump. (b) As the laser has a very high power of 75mW, at the beginning it was switched to scanning mode, where the laser cavity is driven quickly in and out of resonant, creating a small average power. The minimum scanning power of 15 μW is achieved at HWP0 angle of 40°. Laser cavity is then locked back to resonant, giving 3.8mW power. By choosing a suitable lens, SMF coupling is achieved with 68% efficiency, giving an output power of 2.6mW. The error bars show power fluctuations on the power meter; the red line shows a sinusoidal fit to the data points.

In this experiment, we use a TOPTICA Laser Diode that can output light at around 570nm.⁸ The laser has two outputs at different powers: one at 1.5mW the other at around 75mW accordingly to datasheet (I didn't measure this high power directly due to safety caution). The weak output is not strong enough to lock the laser; it only gives 0.8mW

pump power after all the mirrors and AOM, which produces very faint saturated absorption signal (see section II B 2 for more details). In order to have a bit more of pump power, we have to turn on the strong output, however use only a small fraction of its power and dump away the rest. The experimental setup is illustrated in Fig. 5a, where the light is directed through a Half Wave Plate (HWP0) and a Polarized Beam Splitter (pBS0). Most of the power is reflected to a beam dump, leaving only a small fraction transmitted. The HWP0 is turned to different angles to vary the transmitted power (Fig. 5b). Due to safety issue, the laser was kept in scanning mode (where the piezo is scanned to drive the cavity in and out of resonant very quickly, thus giving small average power). At 40° , the minimal scanning power of $15 \pm 1\mu\text{W}$ is attained. HWP0 is then safely locked. The piezo also locked back to resonant mode and we get 3.8mW of power.

Next, we had to select a suitable collimator to couple light into single mode fiber. The light from the laser is not entirely single mode. When we measured the beam profile, it seem to be collimated with a dominant Gaussian profile and beam width $100\mu\text{m}$, however it could not be efficiently aligned through two 1mm-diameter irises. The beam also does not have a perfect linear polarization and needs a Quarter Wave Plate in front of Half Wave Plate and Polarized Beam Splitter to achieve maximum transmission. Thus, for coupling light into SMF, we had to experimentally check a few different collimators (see Table I). It turned out that the 8mm-collimator gives the highest coupling efficiency of 68% (2.6mW out of 3.8mW input power). This lens however has the wrong anti-reflection coating (650-1050nm). A possible substitution in the future would be the 7.5mm-collimator listed in the table.

TABLE I: Collimator selection for coupling light to SMF

Part number	Focal length	Anti-reflection coating range	Coupling efficiency
F260APC-A	15.01mm	400-600nm (A)	30%
F240APC-780	8mm	650-1050nm (B)	68%
F240APC-A	7.86mm	350-700nm (A)	future work
F230APC-633	4.46mm	350-700 (A)	10%

After SMF, the output light then goes through a collimator of 4.46mm. This produces a collimated Gaussian beam with computed beam width of $537\mu\text{m}$, which remains collimated within the Rayleigh range of 1.6m. This range is sufficient for our experimental setup.

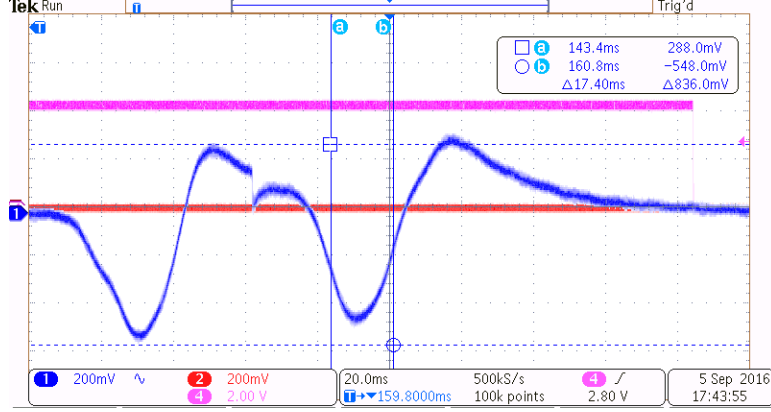


FIG. 6: An oscilloscope screen showing part of Iodine transmission spectrum with Doppler-broadened lines. The pink line shows piezo trigger signal, whose period specify a round cycle of piezo scan. The red line is redundant. The blue line shows the photodiode signal; the noncontinuous break in the middle happens when changing direction. According to the wavemeter, the frequency scan range is 6GHz, from there we can infer the FWHM of the line to be 680MHz.

B. Frequency lock to an Iodine line

1. Doppler-broadened spectrum of Iodine

Iodine broadened spectrum can be observed when we simply pass a laser beam through the vapor cell and detect the transmission power directly with a normal photodiode. In our experiment, the laser frequency was varied by scanning the piezo-controlled mirror of the laser cavity. The signal can be observed on an oscilloscope with trigger signal from the piezo scan (see Fig. 6). From wavemeter reading, the frequency was scanned from 525.3800 to 525.3860 MHz, which gives a span of 6GHz. From the oscilloscope display, a roundtrip of piezo scan is 302ms, and the FWHM of the broadened line is 17ms. We can then deduce that a Dopple line has FWHM of about 680MHz. This experimental result agrees in order of magnitude with the theoretical result 417MHz calculated in section I B. The discrepancy of 1.6 times might be caused by other broadening mechanisms like collision broadening and power broadening.²

2. Direct frequency lock

As an introduction, we will assume that the desired laser frequency directly matches an Iodine line (listed in⁵) up to ± 200 MHz (which is about the distribution range of all hyperfine features of that line). However, since the Iodine lines can be separated by ranges of GHz, it is very likely that the expected laser frequency does not match any lines. In this case, an AOM can be used to create a fixed offset between the desired and referent frequency, this

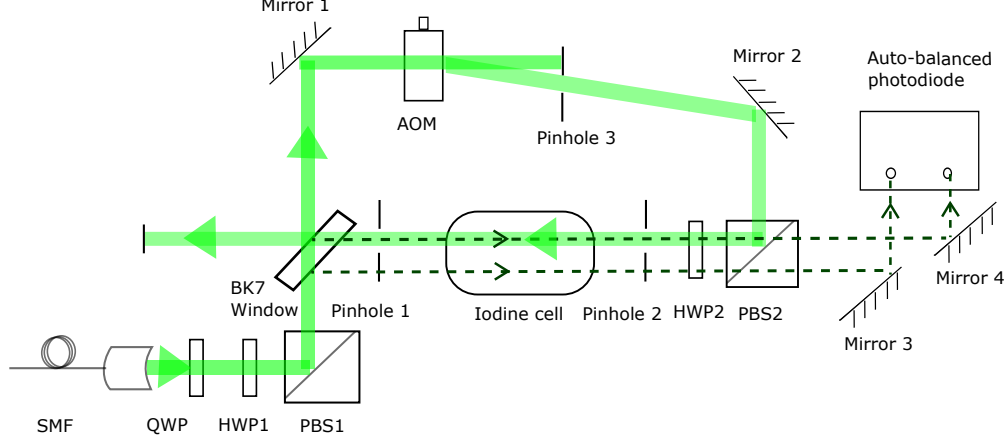


FIG. 7: *Experimental setup for direct Iodine lock, which was proposed by H.Y. Lo in his PhD thesis⁴. For detailed description please see in the text.*

technique will be described in section II B 3.

The experimental setup is described in Fig. 7. The 527nm light out of fiber first passes through a Quarter Wave Plate (QWP) and Half Wave Plate 1 (HWP1) to achieve a clean horizontal polarization, then get reflected at Polarized Beam Splitter 1 (PBS1). The beam then passes through a 5-mm thick BK7 window, where approximately 5% of power get reflected at each surface to produce reference and probe beams; the rest of the power continues to the Acoustic-Optical Modulator (AOM). The AOM is driven at 110MHz; this frequency is further modulated at 48.5kHz with a frequency deviation of 100kHz to produce lock-in modulated signal. (Theory about lock-in amplifier is detailed in section IC; the radio frequency signal for the AOM is prepared as in appendix A.) The first-order output of AOM then counter-propagates with the probe beam in a 10-cm glass cell of Iodine vapor. The probe and reference beam then get transmitted through HWP2 and PBS2 to reach the two inputs of A Nirvana Auto-balanced Photodiode. This Photodiode subtracts the reference from the probe intensity and amplifies the signal. The output of this photodiode is then fed to the lock-in amplifier. The lock-in amplifier has a reference signal which is synced with the AOM modulation driver. The output of the lock-in amplifier is then displayed on the oscilloscope.

The lock-in signal has a clear zero crossing (see Fig. 11), where it is positive on the left of the center frequency and negative on the right. This error signal tells the laser whether the frequency has drifted to the left or the right of the spectrum. This error signal can be fed to the current control of the laser; the current will then be adjusted until the frequency is on-resonant again.

Two points worth noting: Firstly, the polarizations of the beams do not affect spectroscopy signal. Polarization is only used as a trick to ensure pump and probe beams get reflected and transmitted separately at PBS2. Secondly, the AOM driving frequency of

110MHz will offset the pump frequency by 110MHz as compared to the probe. As a result, the saturated absorption peak will be offset from resonant frequency by 55MHz. Ideally we will want to minimize the driving frequency by selecting a suitable AOM.

Alignment procedure : As calculated in section II A, the laser beam has a very small width of only $537\mu\text{m}$. In order to improve saturated absorption signal, it's important to align pump and probe beam as much as possible. A stringent approach is to use two pinholes at diameter around 1mm (Fig. 7). Two PBSs, BK7 crystal and AOM have to be mounted with knobs to fine tune their angles (see Fig. 8). The pinholes are Thorlab adjustable irises with minimum diameter 0.8mm. The detailed steps are listed bellow for ease of reproduction:

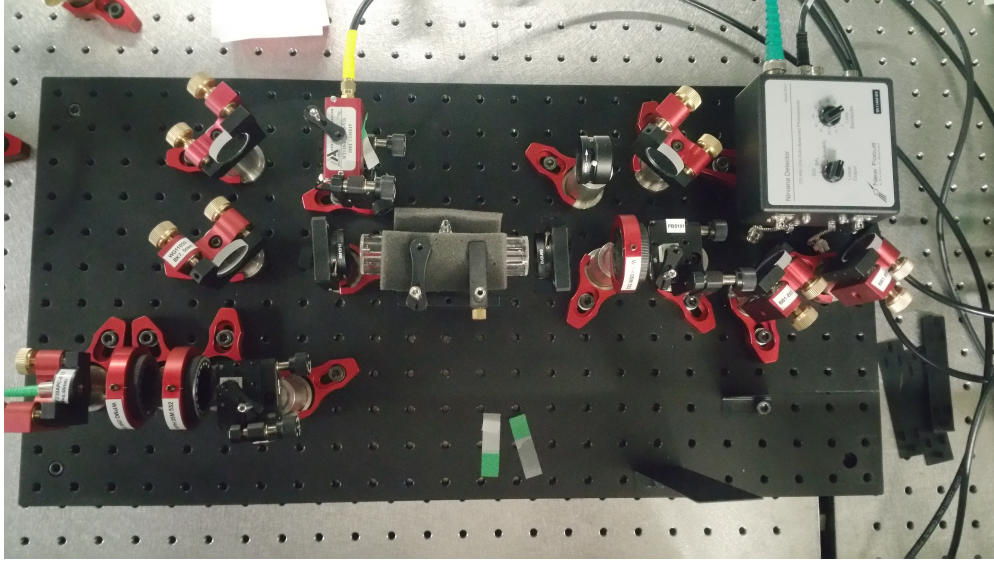


FIG. 8: Real optical breadboard for direct Iodine lock. In order to achieve good alignment, adjustable mounts are used for the two PBSs, the BK7 window and the AOM.

- Close two irises to minimum diameter of 0.8mm. Roughly align both pump and probe beams through two pinholes. Make sure that the beams are horizontal and parallel to the table surface.
- Measure the probe power before pinhole 1, then put the power meter behind pinhole 2, try to beam walk the probe beam through two irises until we see at least 80% output power.
- Adjusting mirror 1 and AOM until you see at least 85% power in the first-order deflected beam.
- Align pump beam through two pinholes to achieve at least 80% power efficiency.
- Open pinholes 1 and 2 to let the reference beam through. Adjust mirrors 3 and 4 to align the reference and probe beams perpendicular to the inputs of auto-balanced photodiode. Alignment of reference signal can greatly affect signal quality. For ease

of alignment, it might be helpful to temporarily increase laser power by tuning HWP0 (see Fig. 5).

- Couple diode signal to oscilloscope with $1M\Omega$ termination and AC coupling.
- Scan the frequency with Evil sweeping mode, this will produce less noise than the piezo scan. However, the frequency range is only about 200MHz so we will only see the bottom of the Doppler broadened profile, which appears as a concave arc on oscilloscope. Tune the piezo control to make this arc symmetric and then decrease the scale on oscilloscope. Keep repeating until we reach the minimum scale of 1mV. If you still cannot see any peaks, temporarily choose Average Acquisition mode on the oscilloscope. The peaks usually come together in a group of three or four hyperfine lines.
- Try to realign the reference and signal beam to optimize the peaks. An illustration of the photodiode signal can be seen in Fig. 11 in section Results.

Tuning the lock-in amplifier : To achieve nice signal, the lock-in reference signal should have very high frequency while the Evil scanning frequency should have very slow frequency. This ensures sufficient number of lock-in modulation cycles in every scanning cycle (as explained earlier in section IC) . In our setting we used Evil scanning period of 185ms and lockin reference frequency of 48.5kHz, which allows 10^4 locked-in modulations in every scanning cycle. The auto-balanced photodiode should have maximum loop. On the lock-in amplifier front panel, the time constant, sensitivity, filter and reference phase should be well-tuned as well. More details can be seen in Table II.

TABLE II: Recommended settings for Lock-in amplifier

Parameter	Recommended value
Reference frequency	48.5 kHz
Reference phase	-55.8°
Reference amplitude	2V
Time constant	300 μ s
Filter Slope/Oct	24dB
Sync Filter	ON
Sensitivity	20mV/nA
Reserve	Low noise

3. Indirect frequency lock

When the targeted laser frequency doesn't directly match any Iodine lines, it is possible to create an offset between laser and reference frequencies using a double-passed AOM.³ This

configuration helps to create a flexible offset without changing much of the original setup (see Fig. 9). QWP 1 and HWP 1 should be tuned to maximize transmission through the PBS1. Double-pass through QWP 2 changes light polarization from vertical to horizontal polarization, so that it will then be reflected by PBS1 and goes toward BK7 window.

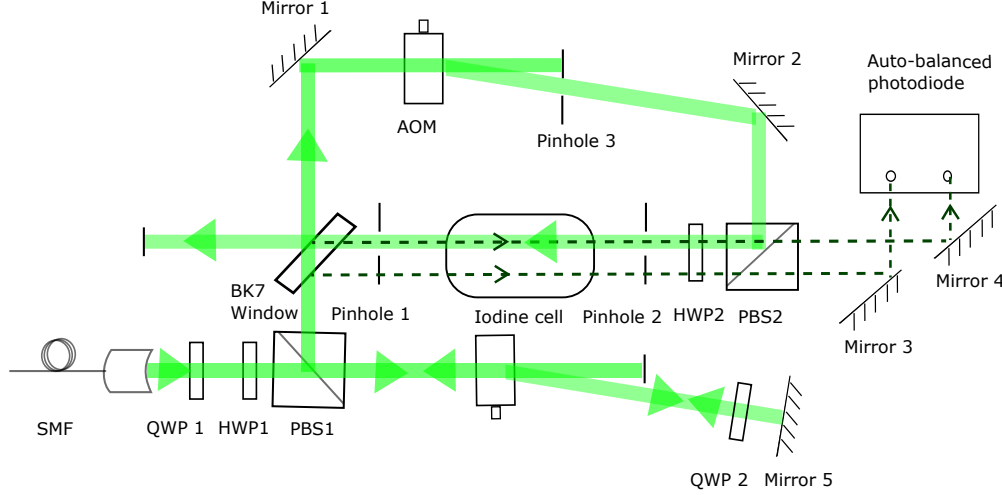


FIG. 9: Experimental setup for indirect Iodine lock⁴. Light is first transmitted through PBS1 , then double passed through an AOM and Quarter Wave Plate 2. This produces an offset of 2 times AOM driving frequency, at the same time flips light polarization from vertical to horizontal. Light then gets reflected by PBS1 and continues to the BK7 window.

III. RESULTS AND DISCUSSIONS

The first result in Fig. 10 shows that the Power Transmission of pump beam through Iodine cell is always $34 \pm 5\%$ for any pump power above $P_{min} = 0.1\text{mW}$. This shows that the pump absorption is always saturated. This can be explained as following: In our experiment, the beam is collimated with width $w = 0.5\text{mm}$, thus the average power near the center of beam can be approximated by $2P/(2\pi w) = 3000\text{W/m}^2$. This is many orders of magnitude above the saturation intensity $I_{sat} = 6\text{W/m}^2$ calculated in section I B.

Fig. 11 shows 6 different hyperfine structures resolved within a Doppler-broadened profile. Due to our short scanning range of around 150MHz, only one hyperfine cluster can be displayed separately on the oscilloscope at a time. We can lock our laser to any small lines, which has FWHM of around 5MHz. Fig. 11c shows an example of sudden noise elevation, which can wipe out the locked-in signal. This happened in the middle of experiment, when laser was turned on for more than 30 minutes. This might appear many times following physically shaking the table. (In fact, if we just knock the table the laser will flicker abit.) Subsequently tuning the piezo control gains can suppress the noise. This shows an example of how automated experiment could go out of order and frequent human intervention would

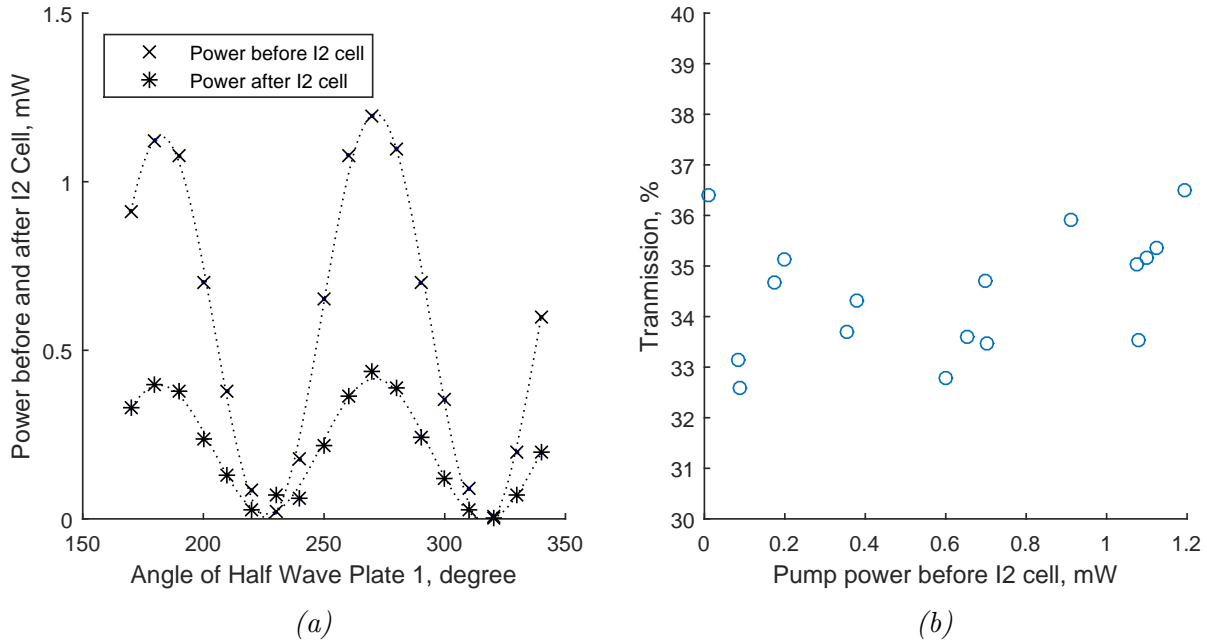


FIG. 10: (a) Pump transmission through the Iodine cell with varying power. The power is varied by tuning HWP1 angle (see Fig. 7). The black data points show pump power before and after the cell. The dotted line shows the sinusoidal fits. (b) The graph combines two power cycles from (a) to show clearly that the percentage transmission remains around $34 \pm 2\%$ regardless of pump power.

be required. A possible solution to batter noise is to increase the laser power many times higher than the minimum input of 2.6mW.

The lock-in signal has a clear zero crossing, where it is positive on the left and negative on the right. This can be used as an error signal which tells the laser whether the frequency has drifted to the left or the right of the spectrum. The laser frequency can be locked by changing the Evil to control mode, which calculates the aggregated PID error with a set Proportional gain and Integration gain. Fig. 12 shows the PID control gain settings and error signal, which is sent to the current modulation on the laser. The error signal shows many spikes, which can be seen on both computer and oscilloscope display. These spikes are electrical noises and never go to infinity. They will not destroy the laser however it is important to have external attenuation to the error signal before feeding it to the current control of laser diode.

IV. CONCLUSION

Many scientific problems in high-energy physics, condensed matter and medicinal chemistry involves many-body interactions with complexities that hinder any analytical calcula-

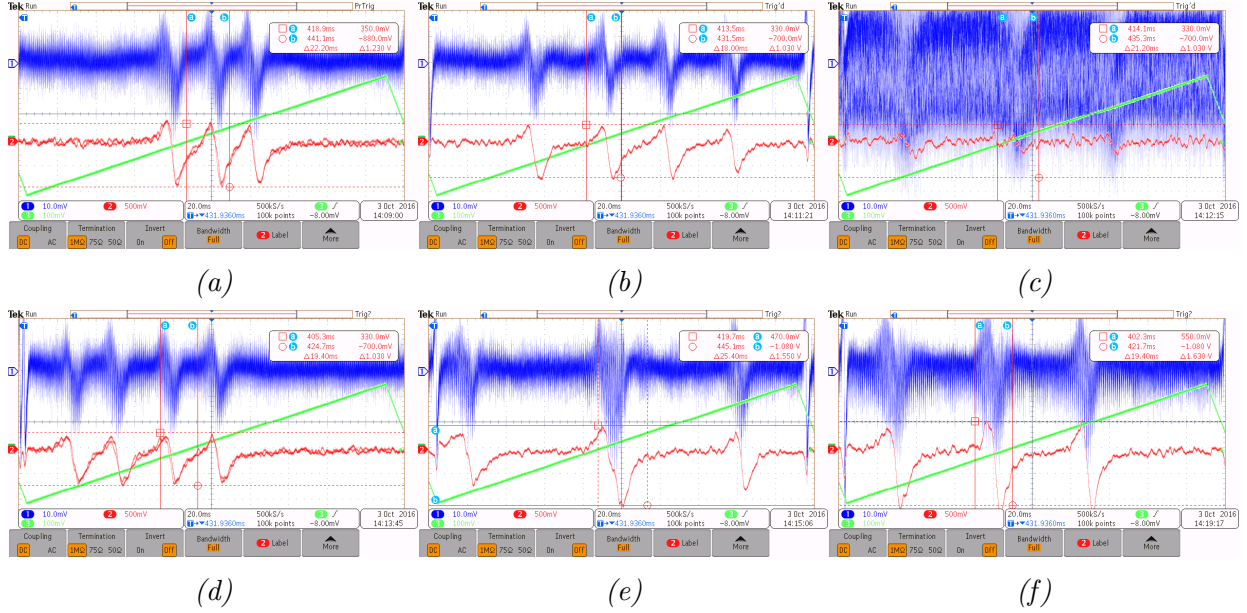


FIG. 11: Six hyperfine structures are resolved within the same Iodine broadened line 111 reported in⁵. This line has wave number 17524.6826cm^{-1} and a high relative strength of 70%. The structures are arranged accordingly to their positions from low to high frequency. Figure (c) shows an example of sudden noise elevation during the course of the experiment. The green line shows Evil trigger signal, blue line shows the auto-balanced photodiode signal. The red line is the locked-in amplified signal with clear zero-crossing, this signal will be fed to the Evil controller to compute PID error signal.

tions. Simulation on classical computers is also impossible because the problems scale exponentially and will take a time longer than the age of our universe. As a result, researches in these fields are often guided by experimental processes with trial-and-error method. In contrast, in Quantum simulation, the size of the problem can grow significantly more quickly with the size of the simulating device than it does for a classical computer.¹ This offers a venue of better simulation of complex systems. In order to realize quantum simulation with strong interaction and precise control, our group propose an optical lattice of trapped Magnesium ions. The Magnesium neutral atoms will first be trapped and cooled by 285nm light in a Magneto-Optical trap before being ionized and further trapped in regular optical lattice.

The frequency of the laser has to be stabilized within tens of MHz and thus has to be locked to an Iodine spectrum reference. In this report, we described the details setup and alignment process for Iodine lock with very low input power, only 2.6mW. The low power is achieved mainly by using a small beam diameter (1mm) and precise alignment of the beams. Saturated absorption spectroscopy is used to resolve the Iodine lines and lock-in amplifier is used to amplified signals. As a result, all fine structures and hyperfine structures of the Iodine line 111 (17524.6826cm^{-1}) are resolved. The laser frequency is then locked by an

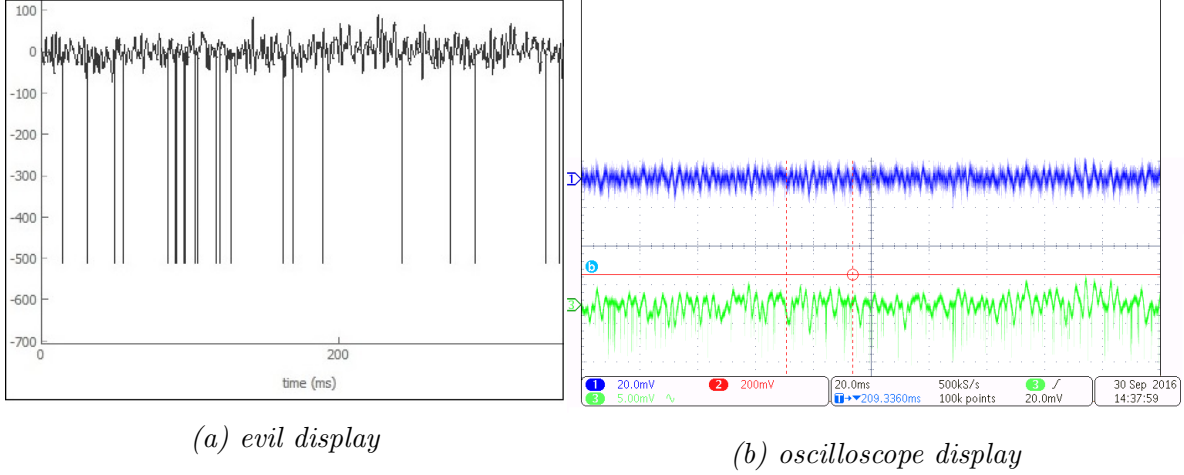


FIG. 12: (a) The Evil PID controller was set to Proportional Gain of 319 unit and Integration Gain of 3 unit. The error signal shows sharp spikes due to electrical noise. These have amplitude limited to -500mV and will go through 3dB external attenuation thus will not damage the laser. (b) The Evil output is AC coupled and shown on oscilloscope as the green line. The error signal is then fed to the current modulation input of laser diode. The resulting probe power, which is shown as blue line on the oscilloscope, experience some oscillation but stabilized within a small range.

Evil PID controller. Our set-up is very universal so many other laser frequencies in the lab (570nm, 532nm, 552nm...) can be locked by adding a frequency offset.

ACKNOWLEDGMENTS

I gratefully thank my supervisors Christoph Fischer and Matt Grau for their enthusiastic and close guidance, thank Prof. Jonathan Home for admitting me in for the internship with a longterm outlook for future Master thesis and maybe beyond. I would also like to acknowledge my Master Program Europhotonics-POESII for their open policies and their supports.

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¹ Tomi H. Johnson *et al.*, *What is quantum simulator*(EPJ Quantum Technology, 2014).

² Christopher J. Foot, *Atomic Physics*(Oxford University Press, 2005).

³ Brian E. King, *Quantum State Engineering and Information Processing with Trapped Ions*(PhD thesis, University of Colorado, 1999).

⁴ Hsiang-Yu Lo, *Creation of Squeezed Schrödinger's cat states in a mixed-species ion trap*(PhD thesis, ETH Zürich, 2007).

- ⁵ Simon Gerstenkorn and Paul Luc, *Atlas du spectre d'absorption de la molecule d'iode, lines 17500-18500*(Paris: Editions du Centre National de la Recherche Scientifique, 1978).
- ⁶ Bradley Armen, *Phase sensitive detection: the lock-in amplifier*(Department of Physics and Astronomy, The University of Tennessee, 2008).
- ⁷ Stanford Research System, *Model SR830 DSP Lock-in Amplifier* (2011).
- ⁸ The laser diode emits light at 1140nm, which is then amplified by tapered amplifier and converted to 570nm by resonant douplng cavity.

Appendix A: RF Amplifier for Acoustic Optical Modulators

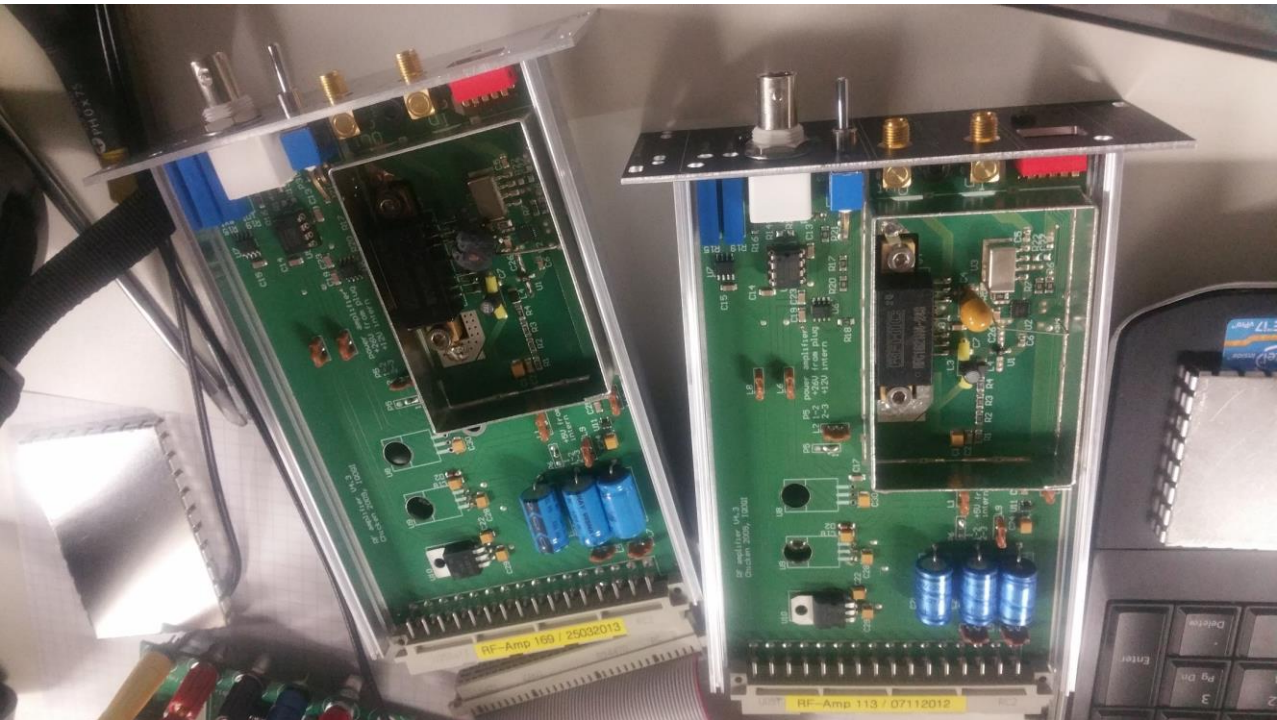
In Acoustic Optical Modulators (AOMs), radio-frequency voltage is applied to a crystal to change its index of diffraction. When light is input into the crystal, it interacts non-linearly with the acoustic wave and get diffracted with a small frequency shift. The frequency shift is controlled by the driving radio-frequency (RF) whose power has to be at the order of 30dBm. In our experiment, we use a RF amplifier from Innsbruck to drive the AOM. The device produces very clean and stable signals at high power. This appendix describes the characterization and manual instruction of the device.

Supply voltages

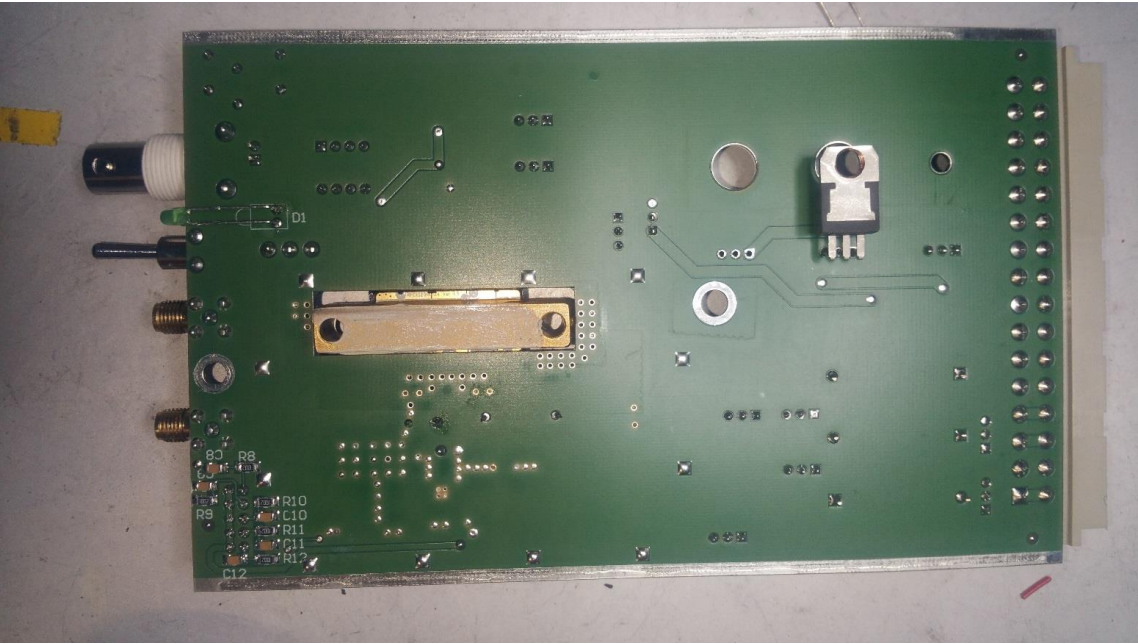
Supply voltage, V	Current (as displayed), A
24	0.49
-18	0.008
18	0.083
5	Redundant, took out

Electronic boards

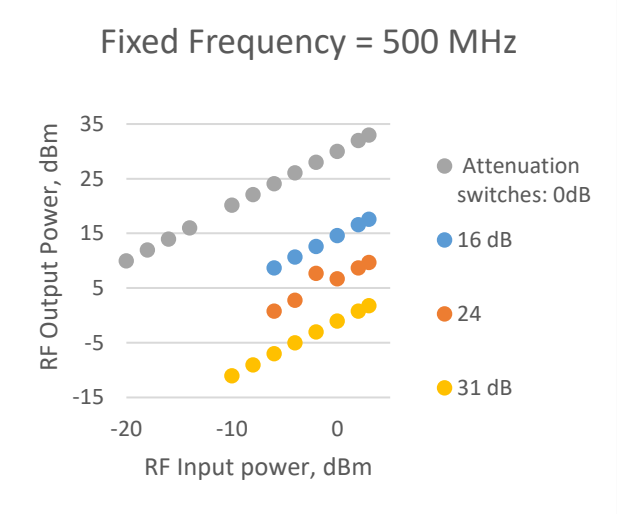
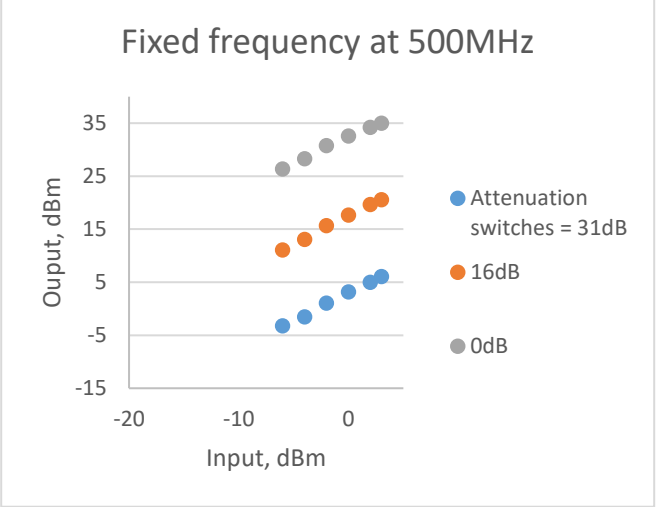
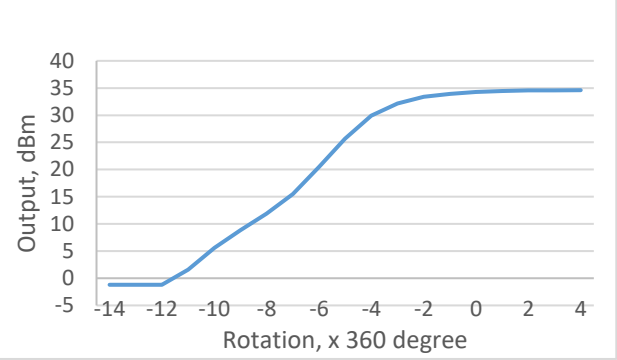
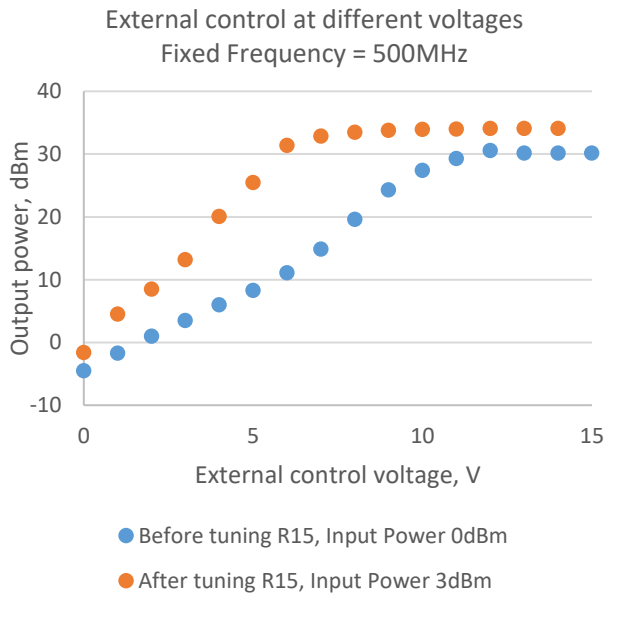
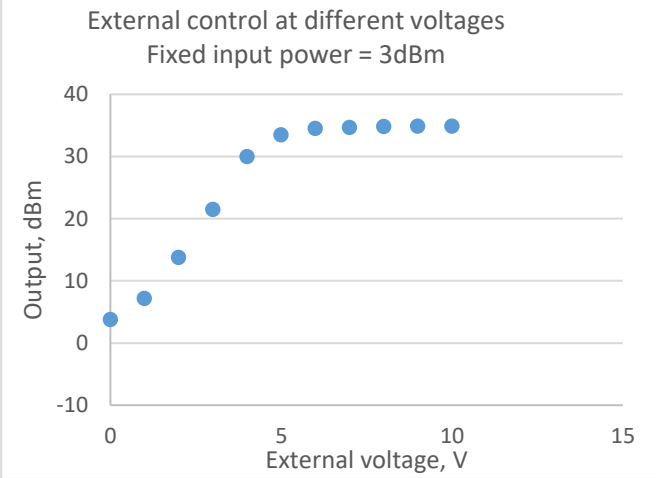
White board and black board:

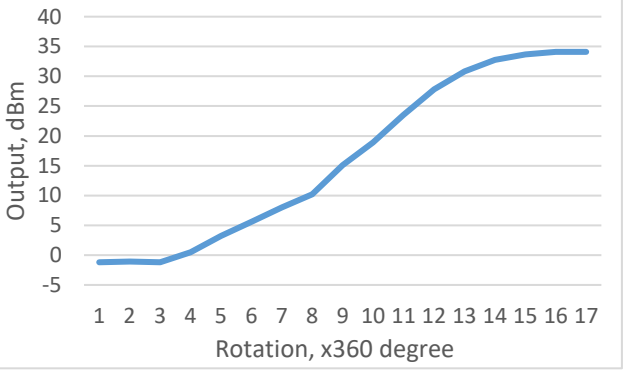
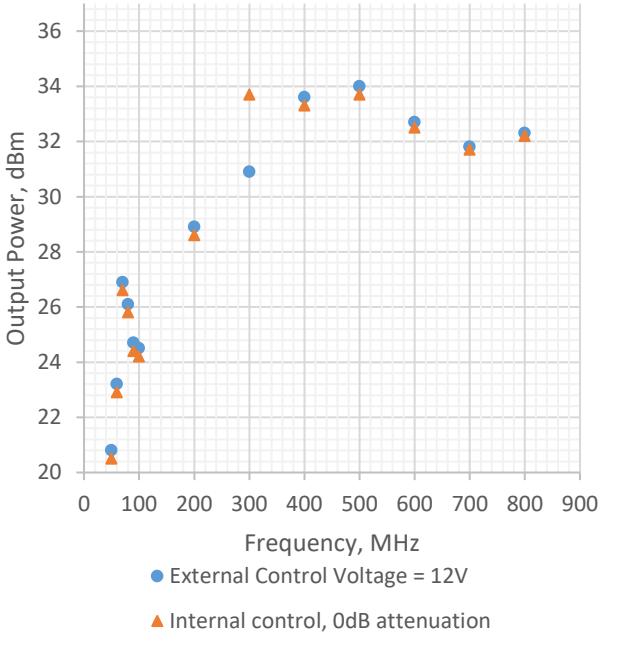
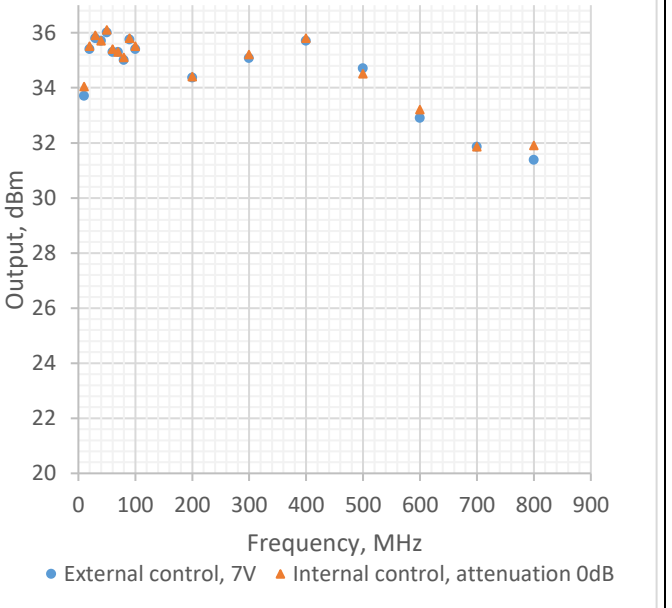


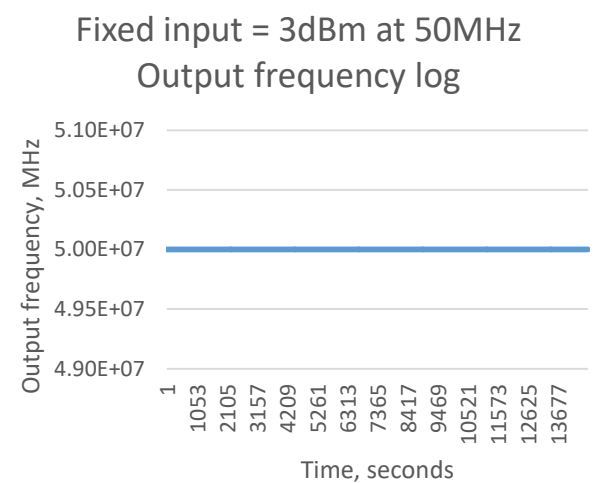
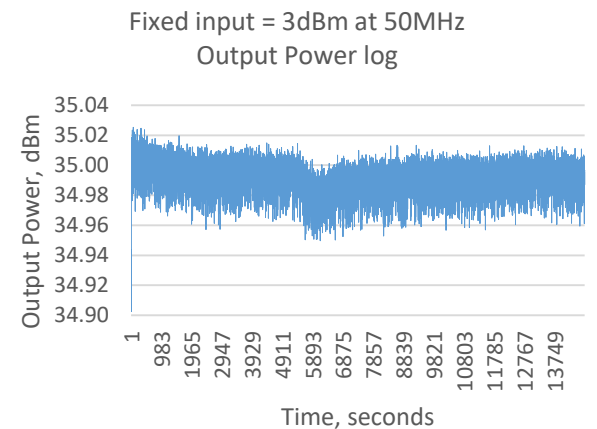
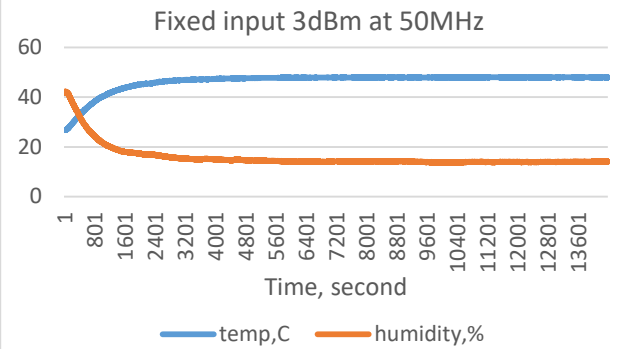
The back side of white board:



Performances

	White box	Black box
Internal control at different attenuations	<div><p>Fixed Frequency = 500 MHz</p></div>	<div><p>Fixed frequency at 500MHz</p></div>
Tuning R19	<div><p>White box, internal control 0dB attenuation Input at Fixed Freq 500 MHz, power 3dBm Tuning R19</p></div>	<div><p>Fixed frequency = 500MHz, input power = 3dBm, attenuation = 0dB. Power variation when tuning the resistor R19 : min -5dBm, max 35dBm</p></div>
External control	<div><p>External control at different voltages Fixed Frequency = 500MHz</p></div>	<div><p>External control at different voltages Fixed input power = 3dBm</p></div>

<p>Tuning R15</p>	<p>White box, external control 7V Input at fixed freq 500 Hz, power 3dBm Tuning R15</p>  <p>Output, dBm</p> <p>Rotation, x360 degree</p>	<p>Fixed freq = 500 MHz, input power = 3dBm, attenuation = 0dB. Use 7V. Power variation when tuning R15: min -5dBm, max 34.7 dBm</p>
<p>Frequency scan. Fixed input power = 3dBm</p>	 <p>Output Power, dBm</p> <p>Frequency, MHz</p> <p>● External Control Voltage = 12V ▲ Internal control, 0dB attenuation</p>	 <p>Output, dBm</p> <p>Frequency, MHz</p> <p>● External control, 7V ▲ Internal control, attenuation 0dB</p>
<p>Log data over the weekend</p>		<p>Note: Everything was stable over the weekend</p> <ul style="list-style-type: none"> - RF Generator TGR1040, stable - Used Oscilloscope MDO3014 for Spectrum Analyzation of Input Signal - Used Keysight FieldFox N9912A for SA of Output Signal. No small peaks observed even with frequency span of 1GHz. I only saw the higher-order Fourier peaks. <p>The data bellow just shows a portion of few hours:</p>



Possible improvements

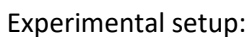
- As specified on the front panels: maximum input is 3dBm at 0dB attenuation
- The maximum input is mainly limited by the last amplifier MHW9267. I guess you can increase the input by a few more dBm, but not too much.
- For improvement, you can try changing MHW9267.

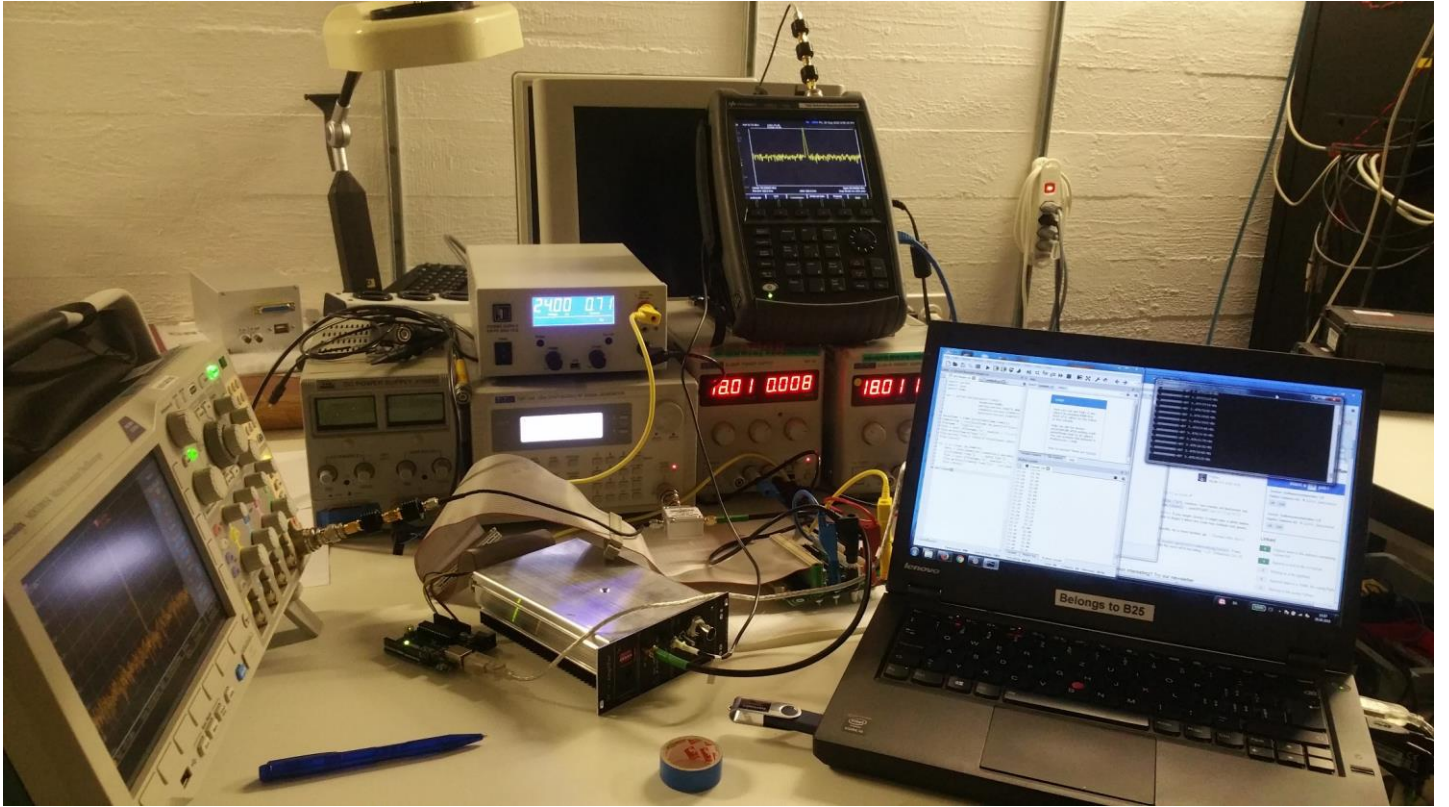
Short operational guide

The RF Amplifier is comprised of the series: attenuator1, attenuator2, amplifier1, amplifier1.

The amplifiers are fixed; we can only tune the attenuators. There are two separate circuits which you can choose by the switch in front

- Please see the circuit diagram with my annotation. Note: some redundancies in the circuit diagram. For example, U8 is in fact not soldered into the boards.





Control code to log Keysight FieldFox Spectral Analyser

The codes are written in C#. The file *HungFieldfoxProg.exe* establishes the communication with the Fieldfox spectrum analyser. It searches for the peak, and ask for the peak frequency and amplitudes. The returned values are displayed directly on the screen and cannot be grasped and saved into variables or be written to a file. The solution is to run *HungFieldfoxLog.exe*. This program will call *HungFieldfoxProg.exe* inside a process and grasp any screen display of this process into a variable. The variable can then be written into a file. For more information please refer to the group wiki page. The codes are documented bellow:

HungFieldfoxLog.cs

```
using System;
using System.Diagnostics;
using System.IO;
using System.Threading;
public class Example
{
    public static void Main()
    {
        string filename = "FieldFoxLogData"+DateTime.Now.ToString("yyyyMMddHHmmss")+ ".txt";
        string mydocpath = Environment.GetFolderPath(Environment.SpecialFolder.MyDocuments);
        File.WriteAllText(@filename, DateTime.Now+Environment.NewLine);
        File.AppendAllText( @filename, "Set marker at peak"+Environment.NewLine);
        File.AppendAllText( @filename, "#PeakFrequency,MHz
OutputPower,dBm"+Environment.NewLine);

        Process process = new Process();
        process.StartInfo.FileName = "HungFieldFoxProg.exe";
        process.StartInfo.Arguments = "10.0.0.6";
        process.StartInfo.UseShellExecute = false;
        process.StartInfo.RedirectStandardOutput = true;
        //process.StartInfo.RedirectStandardError = true;

        while(true)
        {
            process.Start();

            while (!process.StandardOutput.EndOfStream)
            {
                string line = process.StandardOutput.ReadLine();
                line = process.StandardOutput.ReadLine();
                line = process.StandardOutput.ReadLine();
                string DataLine = line;
                line = process.StandardOutput.ReadLine();
                line = process.StandardOutput.ReadLine();
                DataLine = DataLine + " "+line+Environment.NewLine;
                File.AppendAllText(@filename,DataLine);
                Console.WriteLine(DataLine);
                double number;
```

```

        if (Double.TryParse(line, out number))
            Console.WriteLine(number);
        else
            Console.WriteLine("{0} is outside the range of a Double",line); */
    }
    Thread.Sleep(1000);
    process.WaitForExit();
}
}
}

```

HungFieldFoxProg.cs

```

using System;
using System.Collections.Generic;
using System.Text;
using System.Net.Sockets;using System.IO;
namespace Network.Connect
{
    class Program
    {
        static TelnetConnection tc;
        static int Main(string[] args)
        {
            // defaultHostName is host name to use if one is not specified on the command line.
            string defaultHostName = "192.168.1.1";
            string hostName = defaultHostName;
            if( args.Length == 1 )
            {
                // If command line contains a '?' character, interpret this as help.
                if( args[0].Contains("?"))
                {
                    Console.WriteLine("Usage: N9912A_CS_Example.exe <hostName>\n\n"+
                        "Where optional hostName is an ip address or host name.\n" +
                        "If no hostName is supplied, the default (" +defaultHostName+") is used.\n\n"+
                        "e.g. N9912A_CS_Example.exe 10.10.1.1\n\nor\n\n" +
                        "N9912A_CS_Example.exe A-N9912A-22762");
                    return 0; // exit.
                }
                // Record hostname passed in on command line.
                hostName = args[0];
            }
            try
            {
                tc = new TelnetConnection();
                tc.ReadTimeout = 10000; // 10 sec
                // open socket on hostName, which can be an IP address, or use host name (e.g. "A-N9912A-
22762") used in lieu of IP address
                tc.Open(hostName);
                if( tc.IsOpen )

```

```

    {
        //Start your program here
        Write("CALC:MARK1:FUNC:MAX;");
        Write("CALC:MARK1:X?;");
        Write("CALC:MARK1:Y?;");
        //End your program here
        tc.Dispose();
        //Console.WriteLine("Press any key to exit.");
        //Console.ReadKey(); // continue after reading a key from the keyboard.
    }
    else
    {
        Console.WriteLine("Error opening " + hostName);
        return -1;
    }
    //FieldFox Programming Guide 5
}
catch(Exception e)
{
    Console.WriteLine(e.ToString());
    return -1;
}
// exit normally.
return 0;
}
/// <summary>
/// Write a SCPI command to the telnet connection.
/// If the command has a '?', then read back the response and print
/// it to the Console.
/// </summary>
/// <remarks>
/// Note the '?' detection is naive, as a ? could occur in the middle
/// of a SCPI string argument, and not actually signify a SCPI query.
/// </remarks>
/// <param name="s"></param>
static void Write(string s)
{
    Console.WriteLine(s);
    tc.WriteLine(s);
    if (s.IndexOf('?') >= 0)
        Read();
}
/// <summary>
/// Read the telnet connection for a response, and print the response to the
/// Console.
/// </summary>
static void Read()
{
    Console.WriteLine(tc.Read());
}
}

```

```

#region TelnetConnection - no need to edit
/// <summary>
/// Telnet Connection on port 5025 to an instrument
/// </summary>
public class TelnetConnection : IDisposable
{
    TcpClient m_Client;
    NetworkStream m_Stream;
    bool m_IsOpen = false;
    string m_Hostname;
    int m_ReadTimeout = 1000; // ms
    public delegate void ConnectionDelegate();
    public event ConnectionDelegate Opened;
    public event ConnectionDelegate Closed;
    public bool IsOpen { get { return m_IsOpen; } }
    public TelnetConnection() { }
    public TelnetConnection(bool open) : this("localhost", true) { }
    public TelnetConnection(string host, bool open)
    {
        if (open)
            Open(host);
    }
    void CheckOpen()
    {
        if (!IsOpen)
            throw new Exception("Connection not open.");
    }
    public string Hostname
    {
        get { return m_Hostname; }
    }
    public int ReadTimeout
    {
        set { m_ReadTimeout = value; if (IsOpen) m_Stream.ReadTimeout = value; }
        get { return m_ReadTimeout; }
    }
    public void Write(string str)
    {
        //FieldFox Programming Guide 6
        CheckOpen();
        byte[] bytes = System.Text.ASCIIEncoding.ASCII.GetBytes(str);
        m_Stream.Write(bytes, 0, bytes.Length);
        m_Stream.Flush();
    }
    public void WriteLine(string str)
    {
        CheckOpen();
        byte[] bytes = System.Text.ASCIIEncoding.ASCII.GetBytes(str);
        m_Stream.Write(bytes, 0, bytes.Length);
        WriteTerminator();
    }
}

```

```

void WriteTerminator()
{
    byte[] bytes = System.Text.ASCIIEncoding.ASCII.GetBytes("\r\n\0");
    m_Stream.Write(bytes, 0, bytes.Length);
    m_Stream.Flush();
}
public string Read()
{
    CheckOpen();
    return System.Text.ASCIIEncoding.ASCII.GetString(ReadBytes());
}
/// <summary>
/// Reads bytes from the socket and returns them as a byte[].
/// </summary>
/// <returns></returns>
public byte[] ReadBytes()
{
    int i = m_Stream.ReadByte();
    byte b = (byte)i;
    int bytesToRead = 0;
    var bytes = new List<byte>();
    if ((char)b == '#')
    {
        bytesToRead = ReadLengthHeader();
        if (bytesToRead > 0)
        {
            i = m_Stream.ReadByte();
            if ((char)i != '\n') // discard carriage return after length header.
                bytes.Add((byte)i);
        }
    }
    if (bytesToRead == 0)
    {
        while (i != -1 && b != (byte)'\n')
        {
            bytes.Add(b);
            i = m_Stream.ReadByte();
            b = (byte)i;
        }
    }
    else
    {
        int bytesRead = 0;
        while (bytesRead < bytesToRead && i != -1)
        {
            i = m_Stream.ReadByte();
            if (i != -1)
            {
                bytesRead++;
                // record all bytes except \n if it is the last char.
                if (bytesRead < bytesToRead || (char)i != '\n')
            }
        }
    }
}

```

```

        bytes.Add((byte)i);
    }
}
return bytes.ToArray();
}
int ReadLengthHeader()
{
    int numDigits = Convert.ToInt32(new string(new char[] { (char)m_Stream.ReadByte() }));
    string bytes = "";
    for (int i = 0; i < numDigits; ++i)
        bytes = bytes + (char)m_Stream.ReadByte();
    return Convert.ToInt32(bytes);
}
public void Open(string hostname)
{
    if (IsOpen)
        Close();
    m_Hostname = hostname;
    m_Client = new TcpClient(hostname, 5025);
    m_Stream = m_Client.GetStream();
    m_Stream.ReadTimeout = ReadTimeout;
    m_IsOpen = true;
    if (Opened != null)
        Opened();
}
public void Close()
{
    if (!m_IsOpen)
        //FieldFox Programming Guide 7
        return;
    m_Stream.Close();
    m_Client.Close();
    m_IsOpen = false;
    if (Closed != null)
        Closed();
}
public void Dispose()
{
    Close();
}
}
}
#endregion
}

```