Two-Photon Fluorescent Microscope

Undergrad Team Updates

1/10/22- 2/1/22

Tiyana and Cass

Main Goals and Progress

- Examine general structure for a non-confocal fluorescent microscope, its common elements, and how they work.
- Learning the basic mathematics behind lens functionality, focus, and magnification.
- Building a V1 working design for the microscope and ordering parts
- Considering past data structure and optimization of future data
- Working to automate laser setting adjustments with code
- Familiarity with optical equipment/safety procedures/assembly
- Laser alignment practice with quantitative analysis
- Started analysis of signal/power loss through subsystems of a basic setup

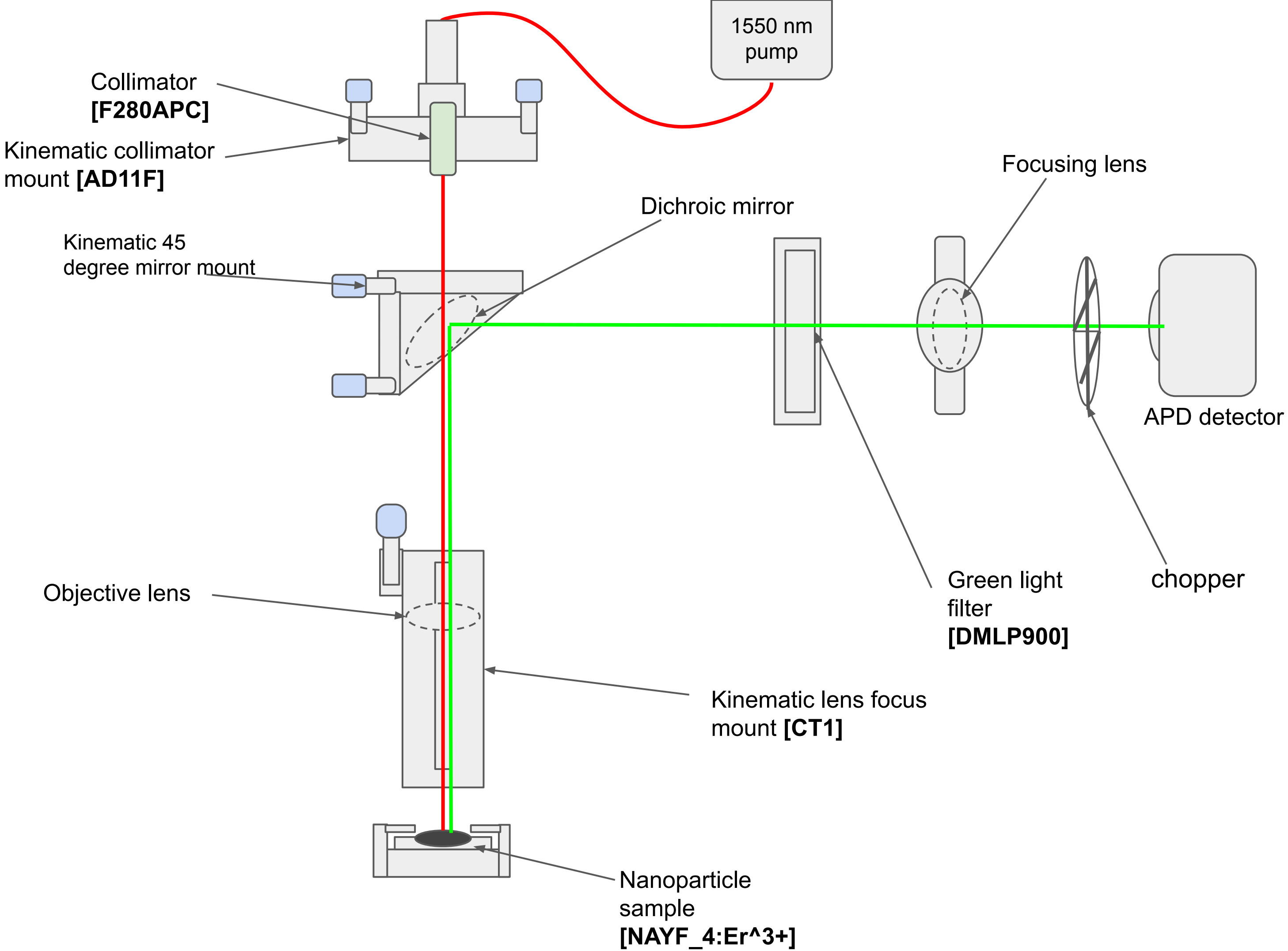
General Structure of Microscope & Elements

- **Source (pump)**: 1550 nm
- **Optical Fiber**
- **Collimators**
- **Dichroic mirrors:** laser line mirrors
- **Lenses**: objective lenses: aspherical lenses
- **Filters**: transmission vs reflection properties
- **Mounts**: kinematic and static
- **Translation stage**
- **Chopper**
- **APD:** Avalanche Photon detector
- **Specimen:** Upconversion Nanoparticles: 980 & 550 nm emission
- **Optical cage system, breadboards & optical bench**:

30 mm
cage
system

980 nm

1550 nm



1550 nm
pump

Collimator
[F280APC]

Kinematic collimator
mount **[AD11F]**

Focusing lens

Dichroic mirror

Kinematic 45
degree mirror mount

APD detector

Objective lens

Green light
filter
[DMLP900]

chopper

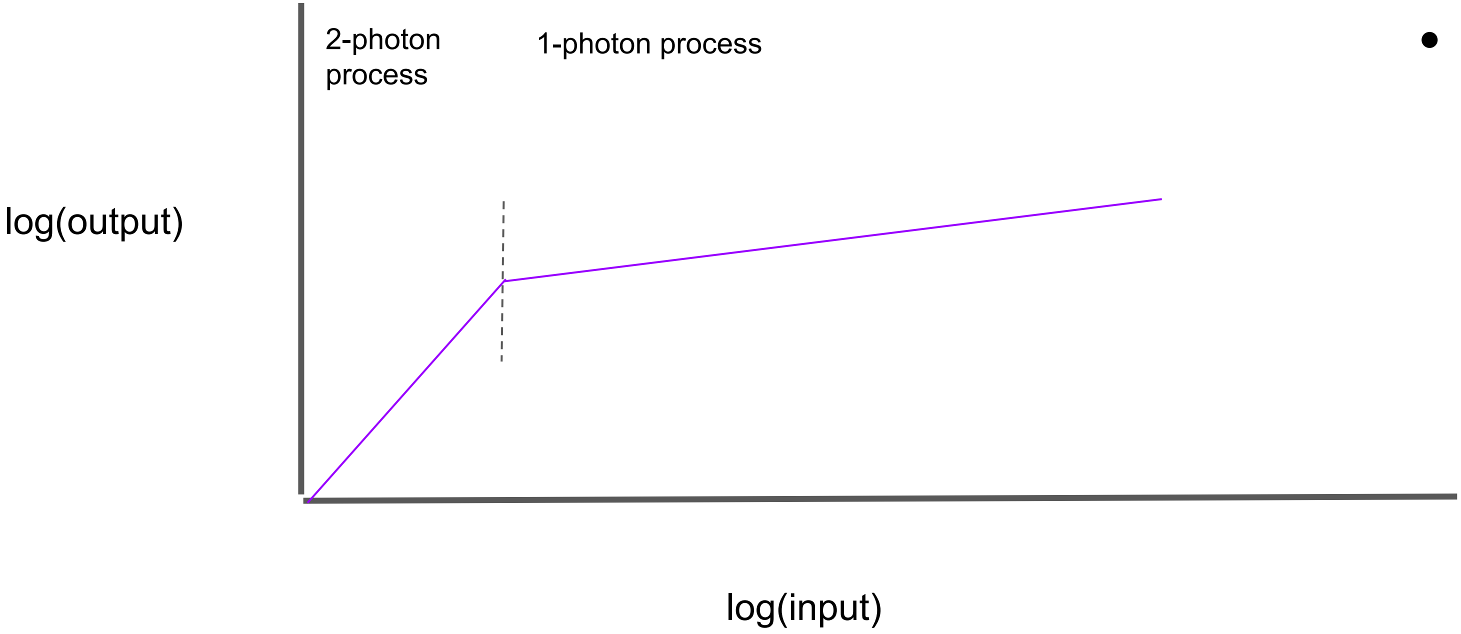
Kinematic lens focus
mount **[CT1]**

Nanoparticle
sample
[NAYF_4:Er^3+]

V1 DESIGN

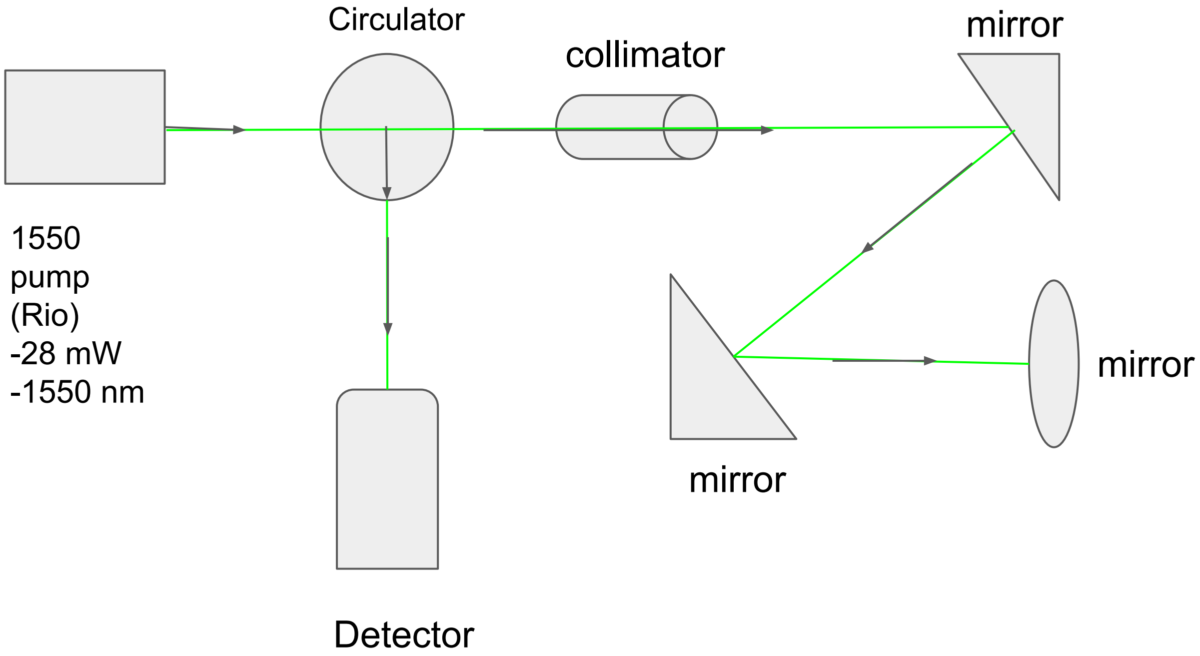
- Mostly Thorlab components

Data



- Looking for turning point to be same in both light sources

Laser Alignment



- Course alignment with red laser
- Inspection and cleaning of fiber cable tips
- 4 degrees of freedom
- Fine alignment with kinematic mounts
- Still getting the hang of walking the beam
- Best alignment so far produced **2.32 mW** back
- Measured 5.15 mW loss through circulator

Automating Laser Setting Adjustments

Our goal:
Using Python code to control the keyboard and mouse, so that the computer can enter the input power value we set automatically.

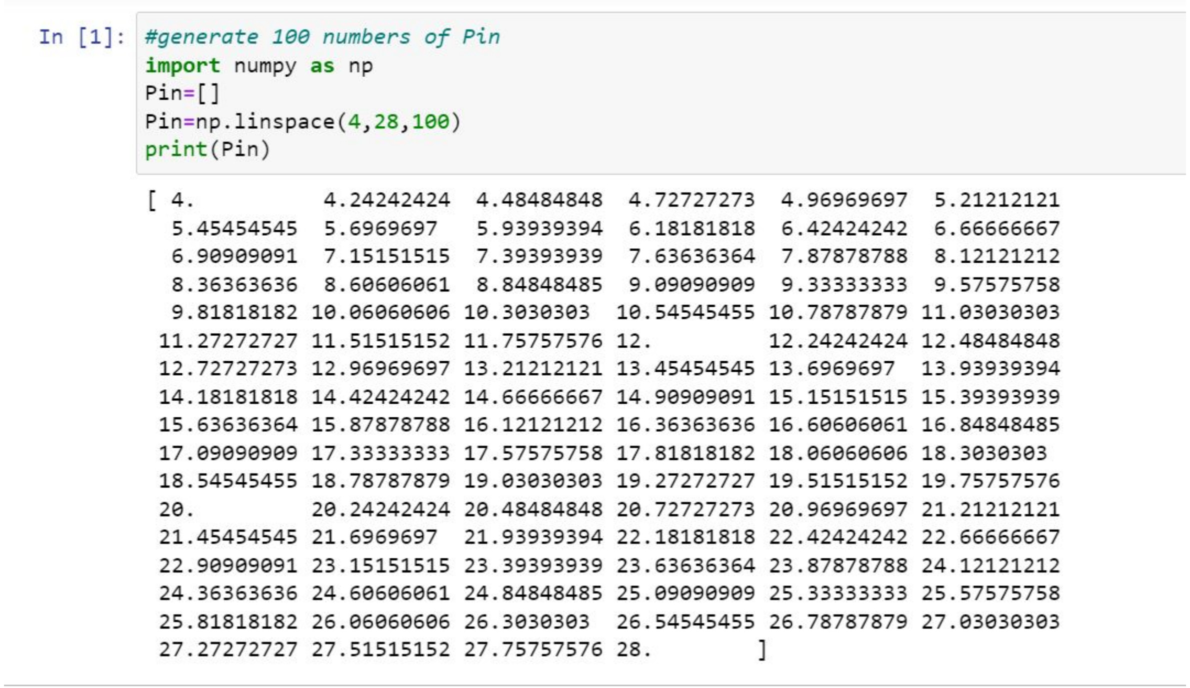
Original steps:

a. set cursor position
b. Click
c. delete previous values
d. type the new number
e. hit "enter"
f. repeat steps above per 30 seconds or 1 min

What we already have:
Win32.api package

Before we get started

With numpy.linspace, we generated 100 data between 4 and 28 (mW), those are the P in values we chose:

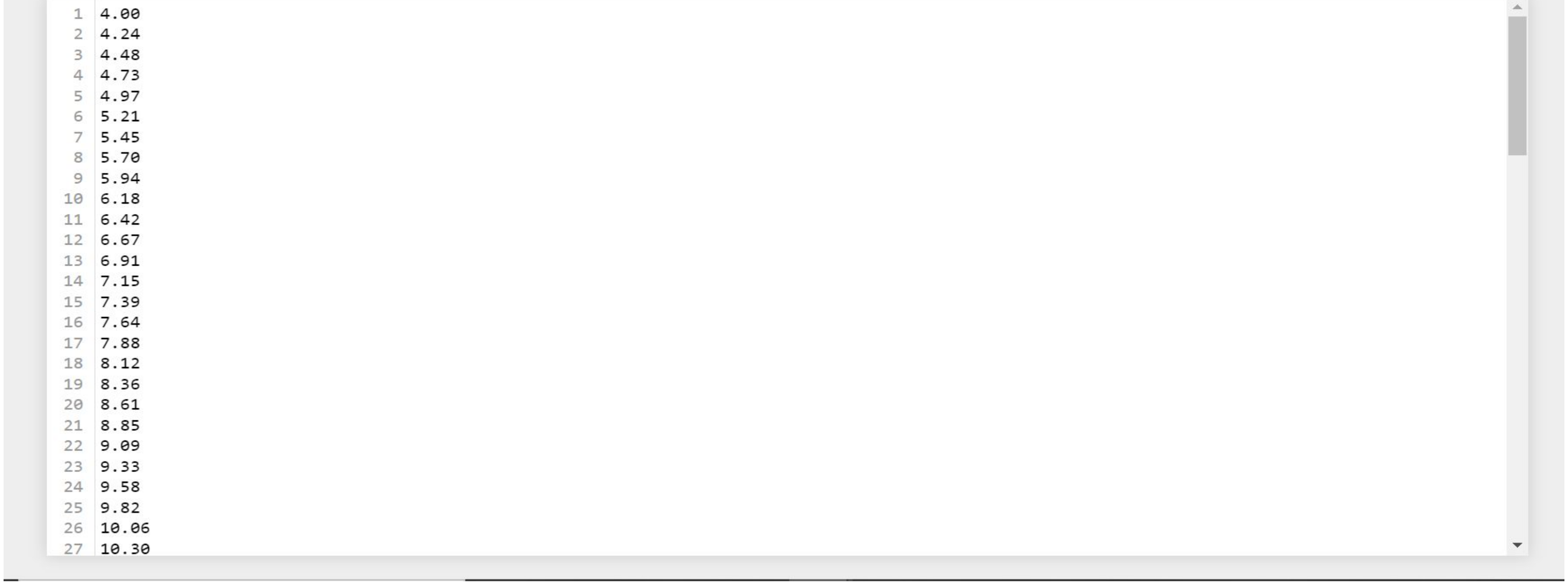


```
In [1]: #generate 100 numbers of Pin
        import numpy as np
        Pin=[]
        Pin=np.linspace(4,28,100)
        print(Pin)
```

```
[ 4.          4.24242424  4.48484848  4.72727273  4.96969697  5.21212121
  5.45454545  5.6969697   5.93939394  6.18181818  6.42424242  6.66666667
  6.90909091  7.15151515  7.39393939  7.63636364  7.87878788  8.12121212
  8.36363636  8.60606061  8.84848485  9.09090909  9.33333333  9.57575758
  9.81818182 10.06060606 10.3030303  10.54545455 10.78787879 11.03030303
 11.27272727 11.51515152 11.75757576 12.         12.24242424 12.48484848
 12.72727273 12.96969697 13.21212121 13.45454545 13.6969697  13.93939394
 14.18181818 14.42424242 14.66666667 14.90909091 15.15151515 15.39393939
 15.63636364 15.87878788 16.12121212 16.36363636 16.60606061 16.84848485
 17.09090909 17.33333333 17.57575758 17.81818182 18.06060606 18.3030303
 18.54545455 18.78787879 19.03030303 19.27272727 19.51515152 19.75757576
 20.         20.24242424 20.48484848 20.72727273 20.96969697 21.21212121
 21.45454545 21.6969697  21.93939394 22.18181818 22.42424242 22.66666667
 22.90909091 23.15151515 23.39393939 23.63636364 23.87878788 24.12121212
 24.36363636 24.60606061 24.84848485 25.09090909 25.33333333 25.57575758
 25.81818182 26.06060606 26.3030303  26.54545455 26.78787879 27.03030303
 27.27272727 27.51515152 27.75757576 28.        ]
```

Continued…

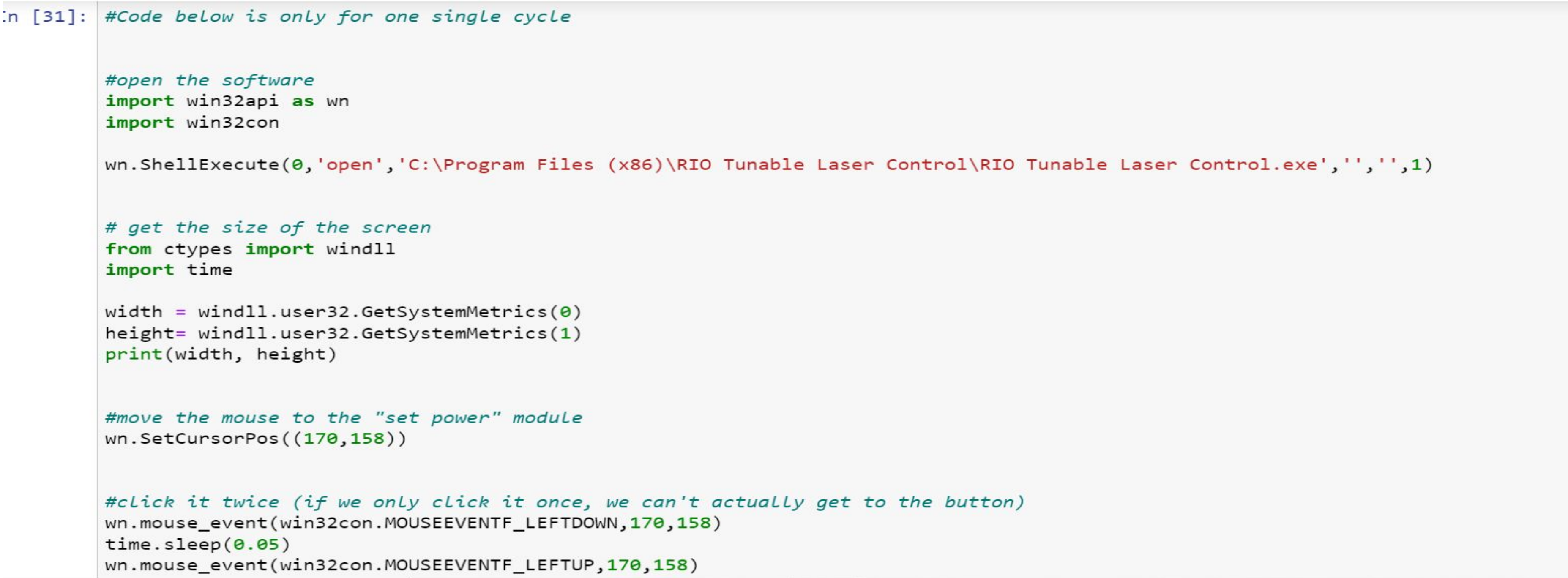
As we saw, because of the reason that the numpy module comes with, the data generated are infinite decimals. So we turned this into txt form so that they look more elegant:



```
4.00
4.24
4.48
4.73
4.97
5.21
5.45
5.70
5.94
6.18
6.42
6.67
6.91
7.15
7.39
7.64
7.88
8.12
8.36
8.61
8.85
9.09
9.33
9.58
9.82
10.06
10.30
```

This file can be opened successfully already but can not be read so far. The reason will be talked about later.

a. Set cursor position & b. click



```
n [31]: #Code below is only for one single cycle


        #open the software
        import win32api as wn
        import win32con

        wn.ShellExecute(0,'open','C:\Program Files (x86)\RIO Tunable Laser Control\RIO Tunable Laser Control.exe','','',1)


        # get the size of the screen
        from ctypes import windll
        import time

        width = windll.user32.GetSystemMetrics(0)
        height= windll.user32.GetSystemMetrics(1)
        print(width, height)


        #move the mouse to the "set power" module
        wn.SetCursorPos((170,158))


        #click it twice (if we only click it once, we can't actually get to the button)
        wn.mouse_event(win32con.MOUSEEVENTF_LEFTDOWN,170,158)
        time.sleep(0.05)
        wn.mouse_event(win32con.MOUSEEVENTF_LEFTUP,170,158)
```

- Use win32api to call the software
- Get the size of the screen so that we can estimate the coordinate of the “set power” bar
- After getting the approximate coordinates, MOVE the mouse there
- “Click” it twice

c. delete previous values & e. Hit “enter”

With win32api.keybd_event, this totally work.

So far we can delete the previous digitals.

```
#Delete the 4 digitals (and 5 if it looks like 12.48)
import win32api
win32api.keybd_event(0x08,0,0,0)
win32api.keybd_event(win32con.KEYEVENTF_KEYUP,0)
win32api.keybd_event(0x08,0,0,0)
win32api.keybd_event(win32con.KEYEVENTF_KEYUP,0)
win32api.keybd_event(0x08,0,0,0)
win32api.keybd_event(win32con.KEYEVENTF_KEYUP,0)
win32api.keybd_event(0x08,0,0,0)
win32api.keybd_event(win32con.KEYEVENTF_KEYUP,0)
win32api.keybd_event(0x08,0,0,0)
win32api.keybd_event(win32con.KEYEVENTF_KEYUP,0)



#enter the number from Pin or a

#!!! incompleted yet


#hit enter
#win32api.keybd_event(0x13,0,0,0)
#win32api.keybd_event(win32con.KEYEVENTF_KEYUP,0)
```

```
1920 1080
```

Difficulty so far: d. type the new number

We can't use the computer **keyboard** to copy any element in the original list or txt file now.

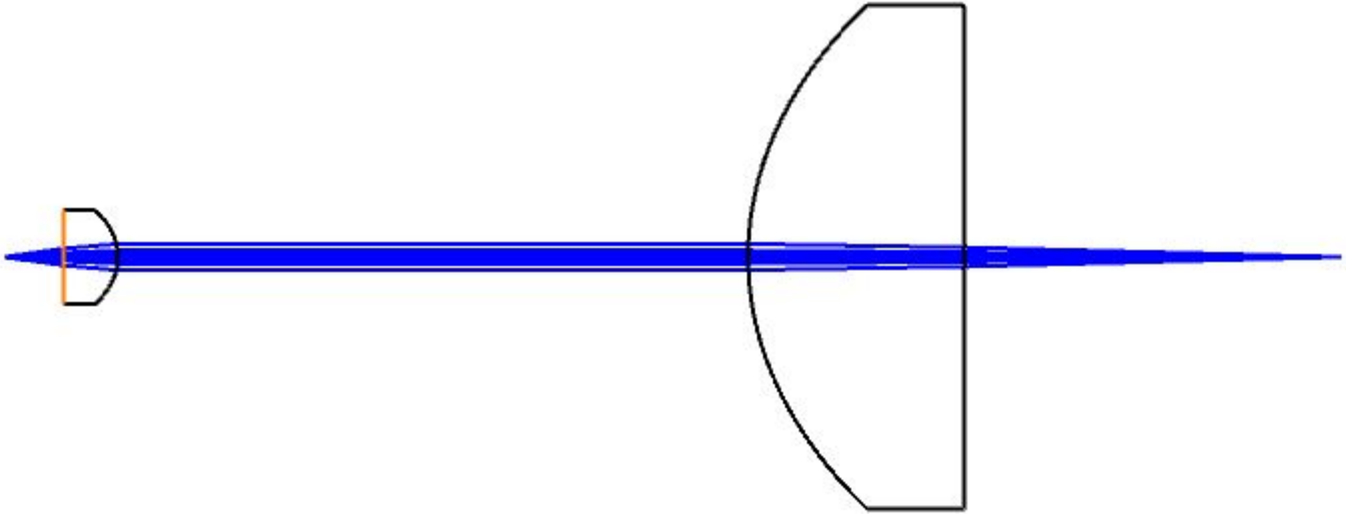
Strategies that might work:

- Install pywinauto package
- Install pyautogui package
- (The one I prefer the most) Check if the “RIO tunable laser control” software has a LabVIEW version of the laser driver or source program
- Change the RIO laser to M squared laser. (will definitely work)

Other topics of discussion/research

- Immersion objective lenses pros and cons
- Consideration of mirror slide for specimen to enhance collection efficiency
- Aspherical lens vs spherical lens for spherical aberration correction
- Use of Lock-in amplifiers for noise reduction

Zemax Simulations



2/1/22 - 2/21/22

UPDATES

Cass & Tiyani

Mirror-Enhanced Fluorescent Microscopy

Mirror-enhanced super-resolution microscopy-Yang 2016

- Replacing microscope slide with mirror
- First-surface mirror with protective SiO_2 coating and adjustable thickness
- Constructive interference with a high NA objective can occur within the specimen
- Question: will the 2 photon process be ambiguous with this interference/reflection? Will it make the data unusable because photons that reflect may not reflect in pairs causing an energy transfer upconversion specifically as the emission process?
- This was done with confocal microscope with oil immersion objective (NA 1.4)
- Doubled signal intensity
- Emission wavelength ranged from 470-670 nm
- Resolution: ~19 nm
- Mirror-enhanced super-resolution microscopy | Light: Science & Applications (nature.com)

Understanding Upconversion Nanoparticles (UCNP)

- About 1- 100 nm in size
- Ideal for high surface area to volume ratio
- Can bond proteins on outside of particle which bond to different structures
- 2-25 % doping
- Effects similar to operations in bulk semiconductors
- Cross relaxation
- Energy transfer upconversion
- Role of crystal lattice

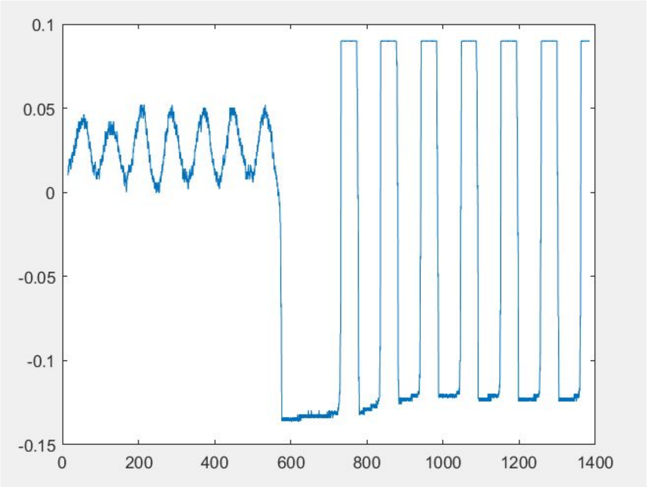
***Related:
Experimentally obtained (by chemist team) lifetime of nanoparticles was far longer than expected or thought possible. Thoughts to redo this under more controlled conditions

Lock-in Amplifier

- Goal is to calibrate
- Overloads and need to find base overload point and then attenuate it appropriately to make sure it does not overload for our scope
  - Max input voltage
- Did not get very far with this (yet)
- Need to read manual to gain deeper understanding of basic controls

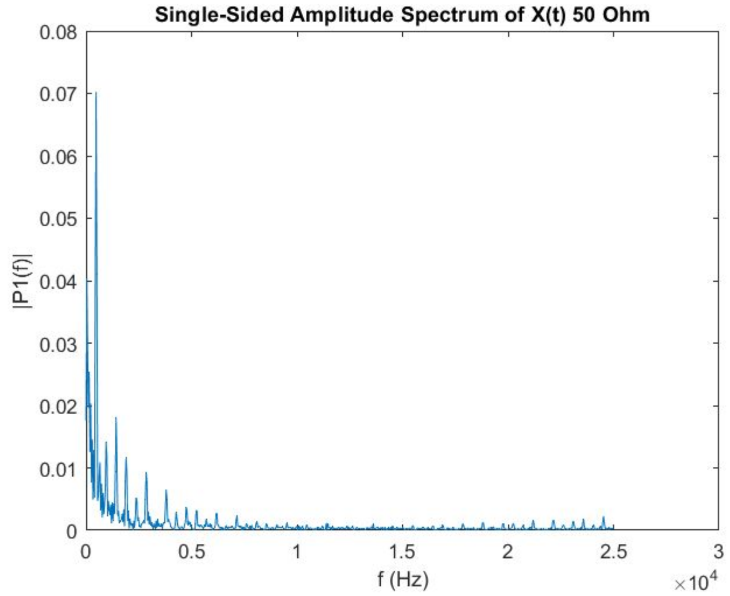
Testing FemtoWatt Detector

- Oscillatory behavior found when detected power drops below threshold
- Tested with variable attenuator but could not quantify : turns not repeatable
- Best results for attenuation was slightly uncoupled in tandem with power control from laser source
- Completed initial noise analysis with single trace before and after oscillatory behavior (POST ITS)
- Found 1 Mega Ohm seemed to stop the oscillatory behavior altogether
  - Jan found part that may solve this problem as we only have 50 MOhm for the actual experiment currently
- Research into Fourier Transform theory



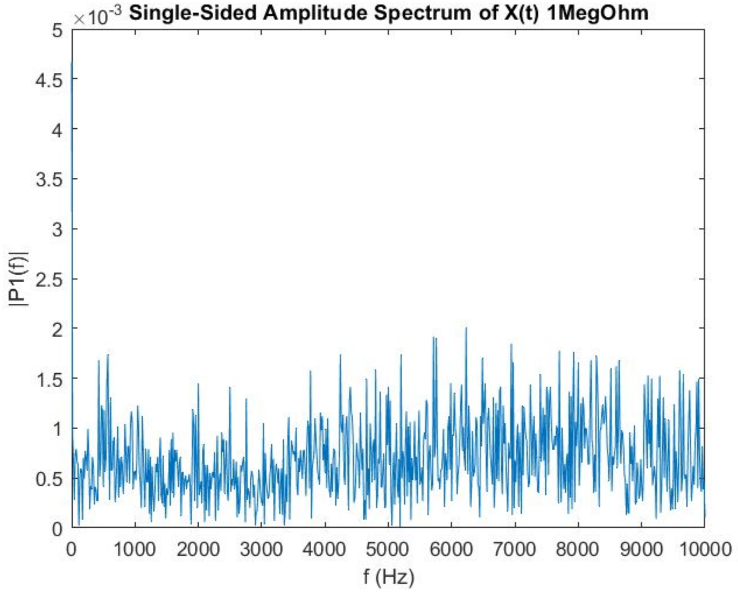
Brief Summary of Noise Analysis on FW Detector

Noise floor (fft) with 50 ohm (oscillatory behavior cut out) :



Avg Power :
2.6680e-12 W

Noise floor (fft) with 1 MOhm :

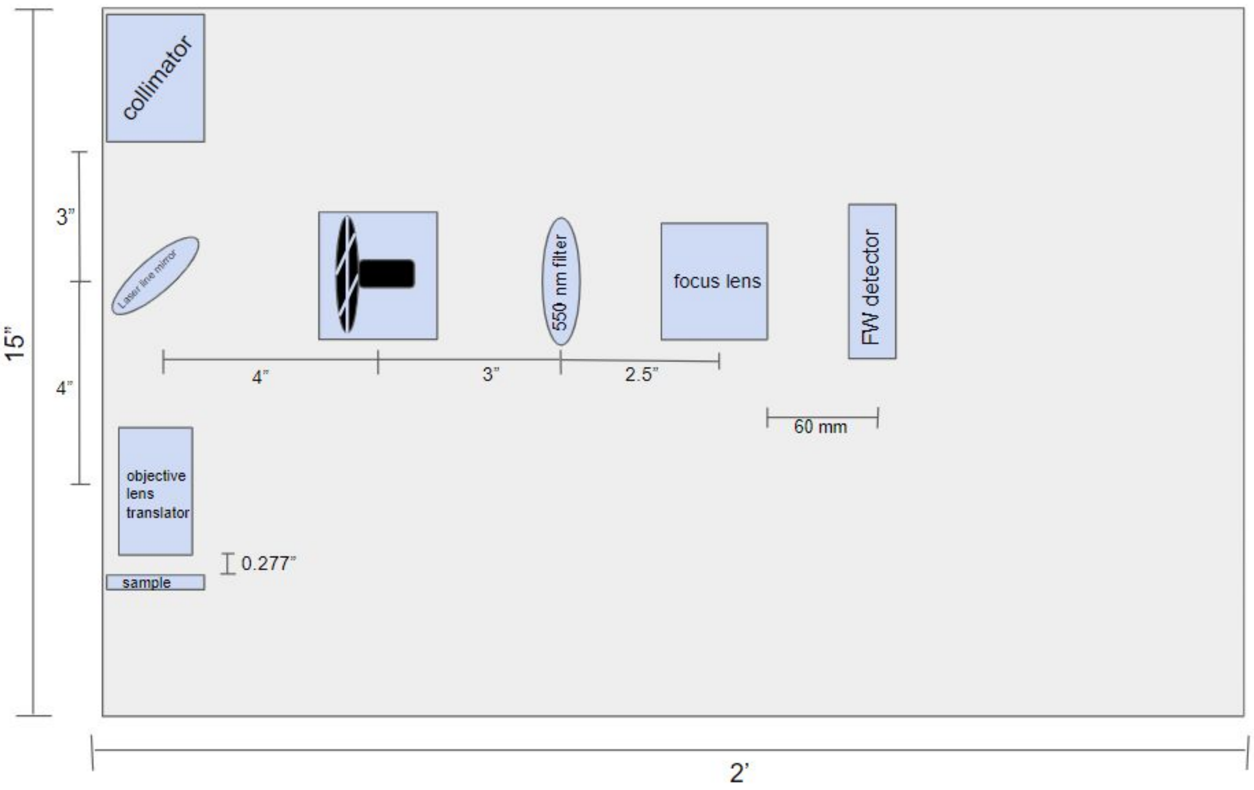


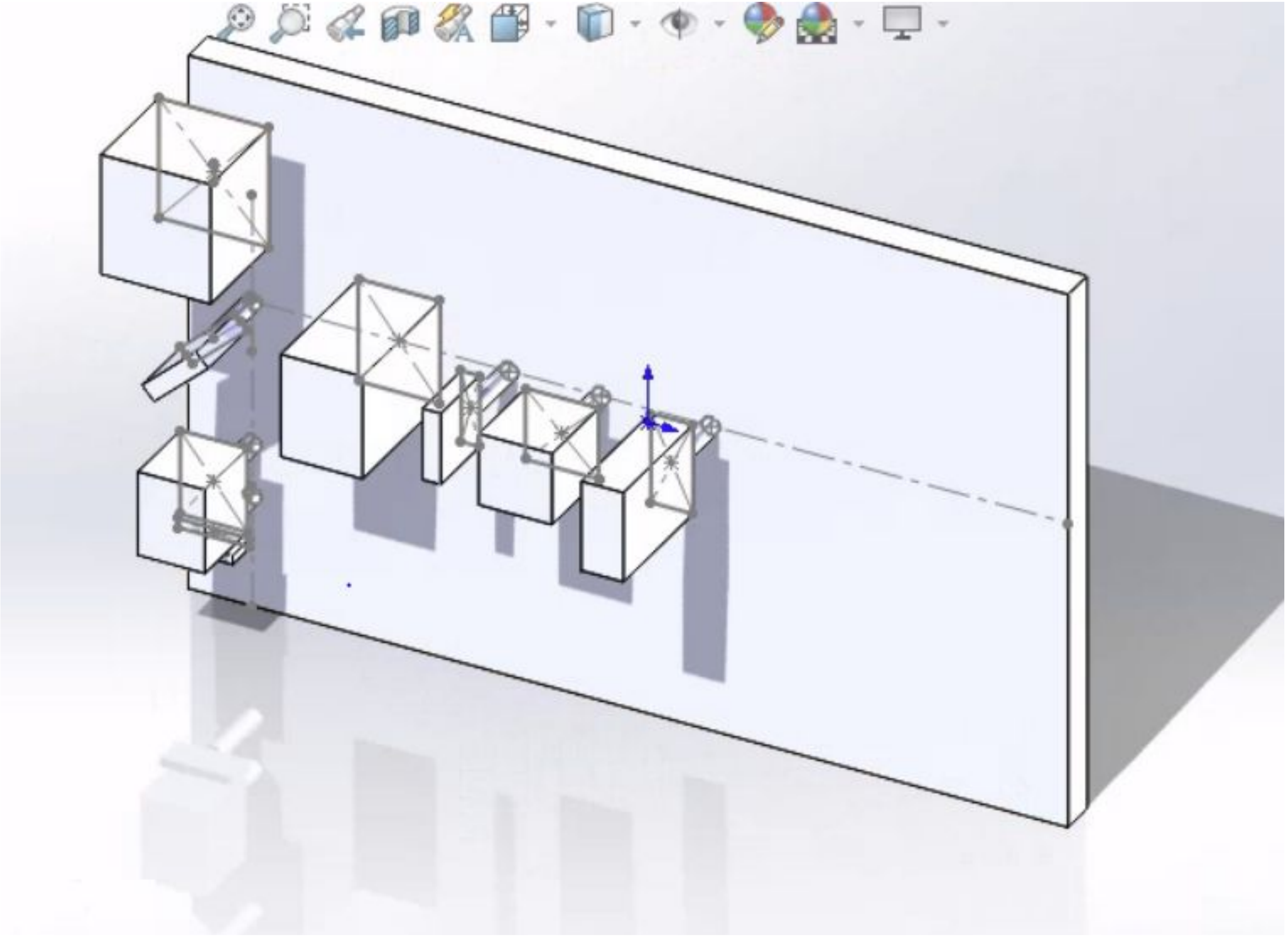
Avg Power:
-5.2680e-13 W

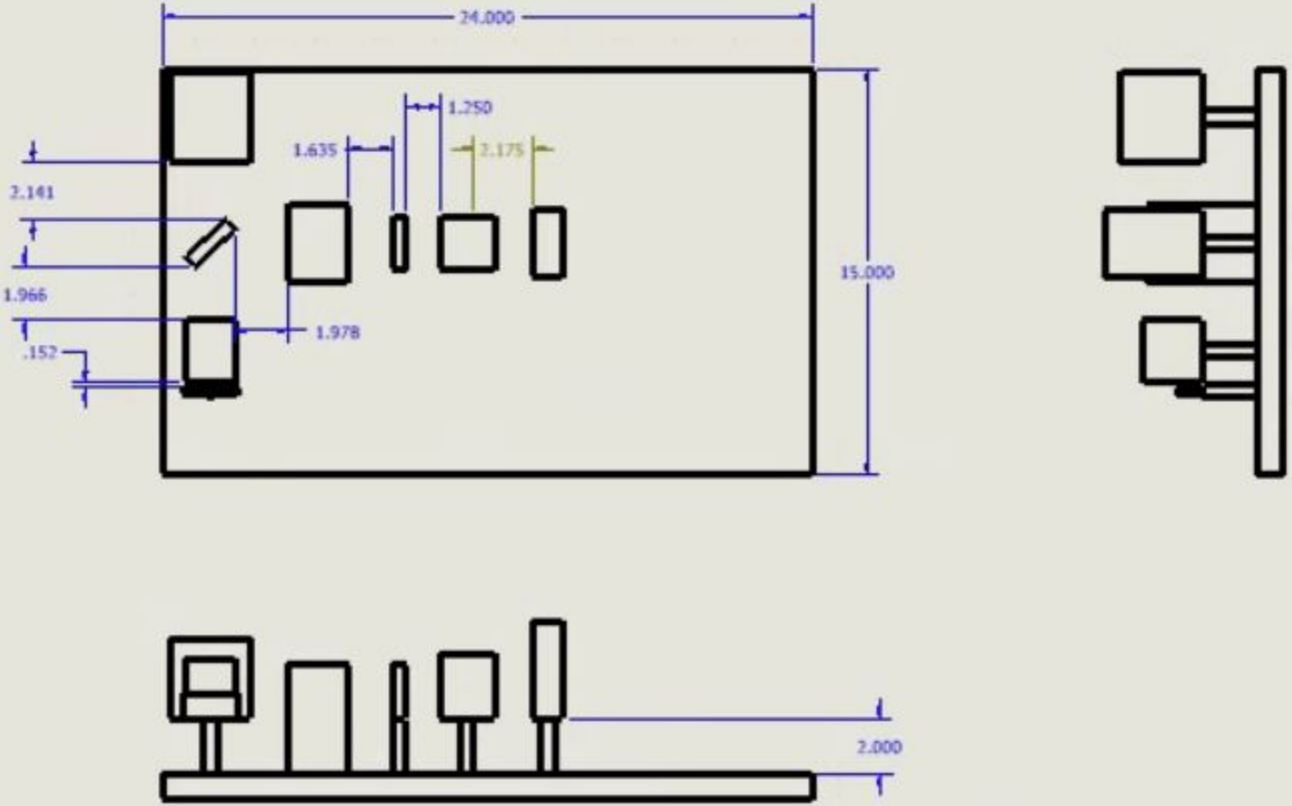
Hardware update

- After some nosing around found a shop to cut the breadboard into the correct size
- Board is now vertical and ready for assembly of other optical parts
- Laser line mirror & CT1 came in
- Still missing collar for small beam collimator (backorder) but moving toward using other collimator created with lens (1mm focal length)
- Waiting on attachment part

Schematic Updated and Dimensioned






24.000
1.250
1.635
2.175
2.141
1.966
1.978
.152
15.000
2.000

Action points moving forward

- Figure out how to mount CT1 to board
- Integrate Tiyani's code with Lock-in Detector control code
- Zmax optical simulations
- Beam waist calculations for collimator
- Lock in Detection calibration and overload limit handling
- 1 MOhm configuration plug in
- Lifetime measurement verification

2/20 - 2/26 UPDATES

Hardware updates

- All parts have come in except collimator collar and possibly 1 MOhm coupling device?

Follow up questions from last week

- Lifetime measurements? Leads on verification?
- Zmax Sim? Any interesting results so far? Will we get to play with Zmax?

Still to be done:

- Finish measuring losses by subsystem
- Integrate code with Lock-in detector
- Calibrate lock in detector for overload limits

Starting the Building/ Alignment/Calibration Process

- Started with pigtail with in-house made collimator, the 45 degree mirror (both in kinematic mounts) and the CT1 without lens at first down to a mirror and back for rough alignment
- Goal was to align and measure loss within system through each part
  - Found that there was too much fluctuation of the power back
  - Found some loose set screws and corrected
  - When using C610-TME-B, found about 12.5% loss (expecting around 5%). Best coupling back was about 7 mW (without lens)
  - Were concerned about back reflection but found fluctuation still present regardless of lens on/off
  - Ultimately decided the fluctuations were coming from the circulator (which won't be a problem in the future)
  - Found that we were not getting the coupling we hoped for and switched collimators a few times.
  - Ended up finding satisfactory coupling with the F260APC-1550 collimator

Starting the Building/ Alignment/ Calibration Process

NOTEWORTHY STRUGGLES & HOT TIPS

- Initially had trouble aligning because of running out of freedom on one point
  - Found fix by adjusting height of collimator itself and resetting kinematics.
- Getting better at finding returning beam and counter-correcting with initial kinematic mount to provide more freedom at points where it is needed
- CT1 without lens proved to be very helpful while aligning straight down
- Loss in the system seemed to vary depending on collimator?
  - Ask about this?
- Considering back reflection and phase “noise” with interference

Starting the Building/ Alignment/ Calibration Process

Where things ended

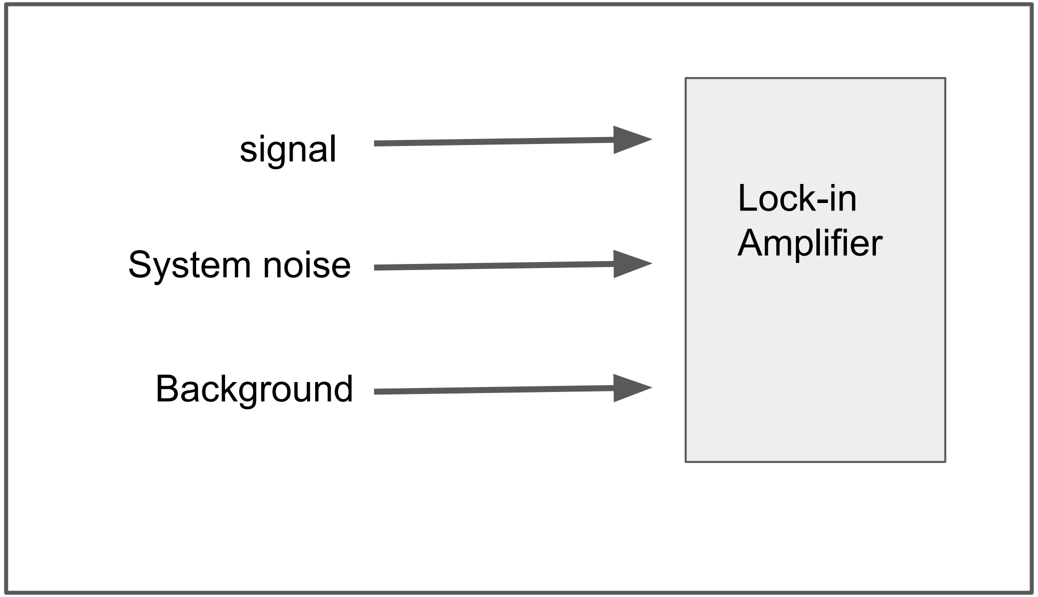
- Saw minimal loss with F260APC-1550 collimator paired with lens when properly aligned.
- Should be able to measure loss more accurately moving forward
- Best coupling so far with lens: 47.4% (13.28 mW back out of 28 mW in)
    - Not sure if beam is going straight down because of position of CT1/ cage mount
    - Still have not mastered walking the beam
    - Only slight increase with lens from ~12 mW without it
- Ready to integrate dichroic mirror?

Measured losses so far:

Collimator + circulator	~13.2 %
mirror	~3.3%
550 filter	~3.4%

2/27/22 - 3/7/22 UPDATES

- Research on Lock in Amplifier



signal

System noise

Background

Lock-in Amplifier

Lock-in Amplifier research

Input/raw signal = $Vs(t) = (Vx)\sin((Ws)t+a)$

Reference signal = $Vr(t) = (Vr)\sin((Wr)t)$

a = phase

- Lock-in amplifier mixes/multiplies input signal and reference signal:

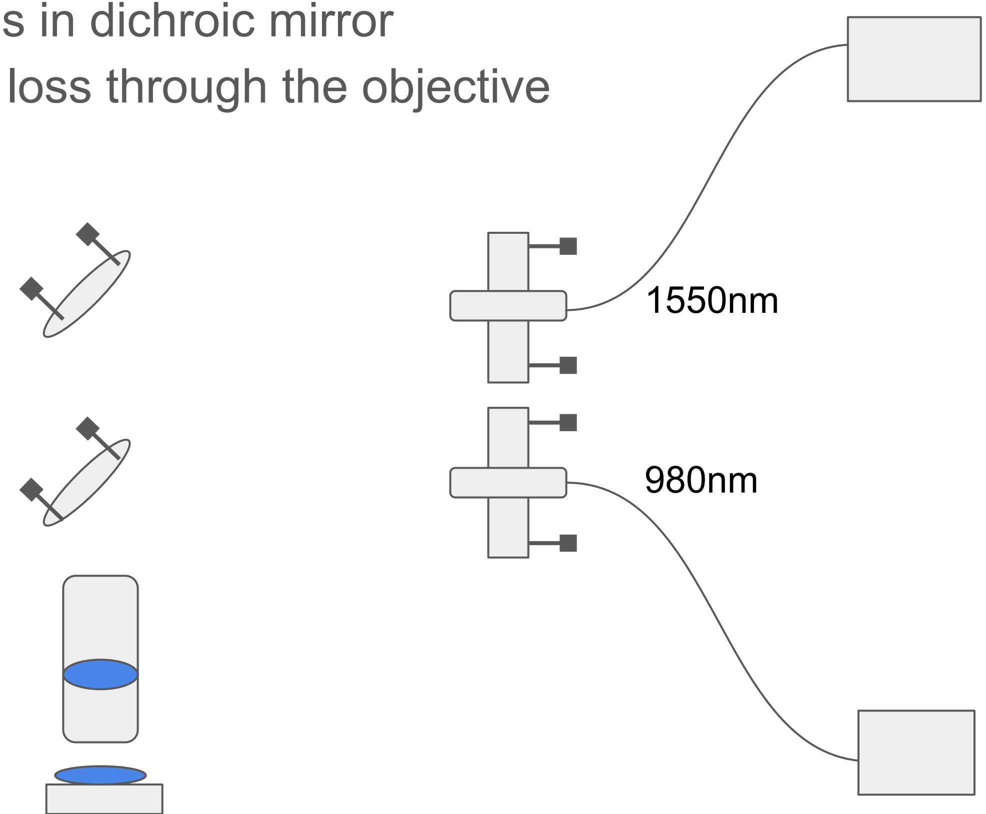
$$VsVr = (\tfrac{1}{2})(Vx)(Vr)[\cos[(Ws)t + (Wr)t + a] - \cos[(Ws)t-(Wr)t + a]]$$

- Integrating over many cycles will end up summing to zero
- However if $Ws = Wr$, then the integration is preserved with the cosine of a constant
- The lock in amplifier in tandem with the chopper accomplishes this, and we are left with only the frequency where the input and the reference are the same
- The end result is the filtering of every frequency except Ws. The effective bandwidth can be incredibly narrow
- 2 channels/mixers in order to handle cases $a=90$ degrees for $\cos(90)=0$. Second channel operating on $\cos(a+90)$. This prevents signal collapse

Aligning for the 90 degree outbeam

- Measured 0% loss in dichroic mirror
- Measured 15.6% loss through the objective

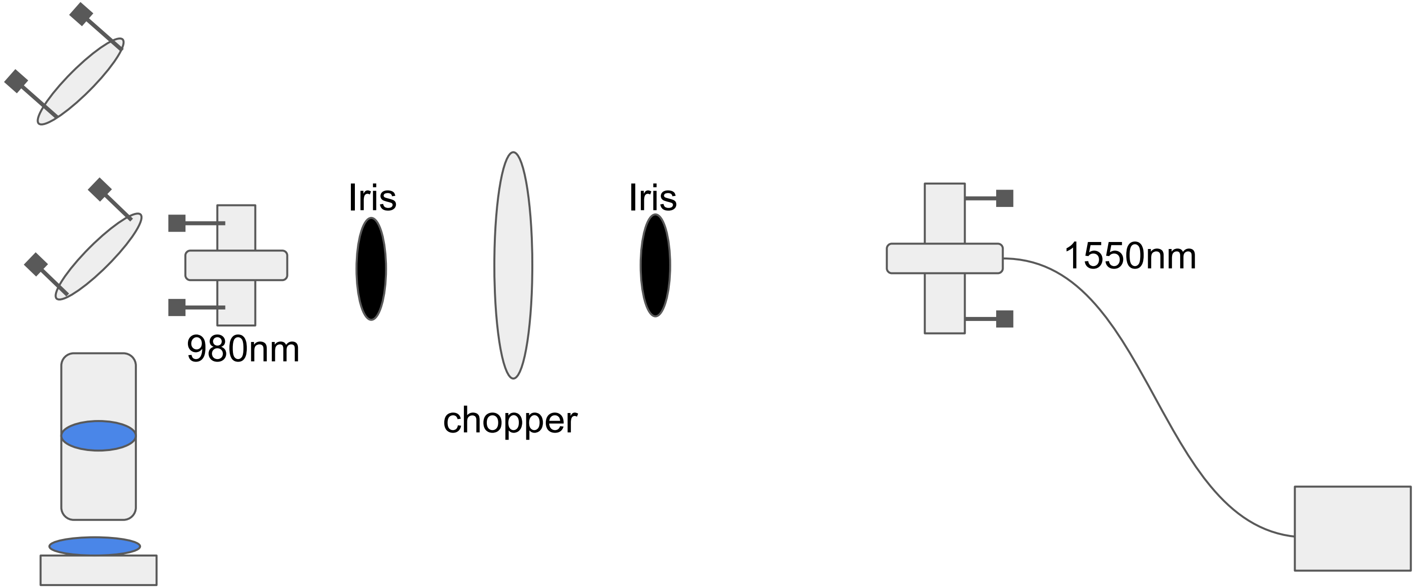
First iteration:



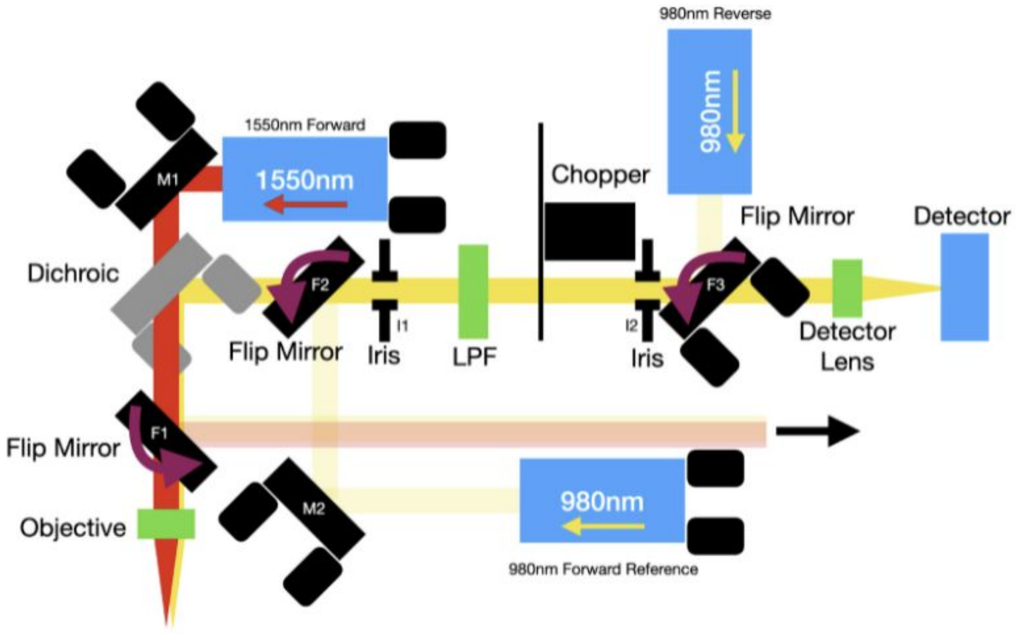
Second iteration for 90 degree out-beam alignment

- Aligned beams to overlap

First iteration:



Alignment detailed procedure & third iteration build



Steps moving forward

- Finish alignment setup via procedure
- Follow procedure for alignment steps
- Use camera and detector to characterize alignment and performance
- Attenuate for the FW detector and install
- Integrate lock-in amplifier
  - Look at completing introduction task to lock-in via manual
  - Calibrate lock-in for coupling required and overload limits
- Move forward on data acquisition

Updates

Cassidy Bliss

3/8/22 - 3/27/22

Alignment with updated schematic and procedure

- After rough alignment, found that focus caused translation (1550 beam)
    - Used phosphor camera & software to correct.
        - Attenuated power to not saturate/damage camera
    - Found coma aberration and corrected by bringing beam toward the direction where focus resides
- Went on to back propagate 9080 nm beam
    - Found that dichroic was initially backwards
- Align 980 nm beam to aligned 1550nm by using the flip mirror and 4 degrees of freedom out of the system
- Then align irises to that collinear pair after
    - This proved to be difficult in the free-standing system

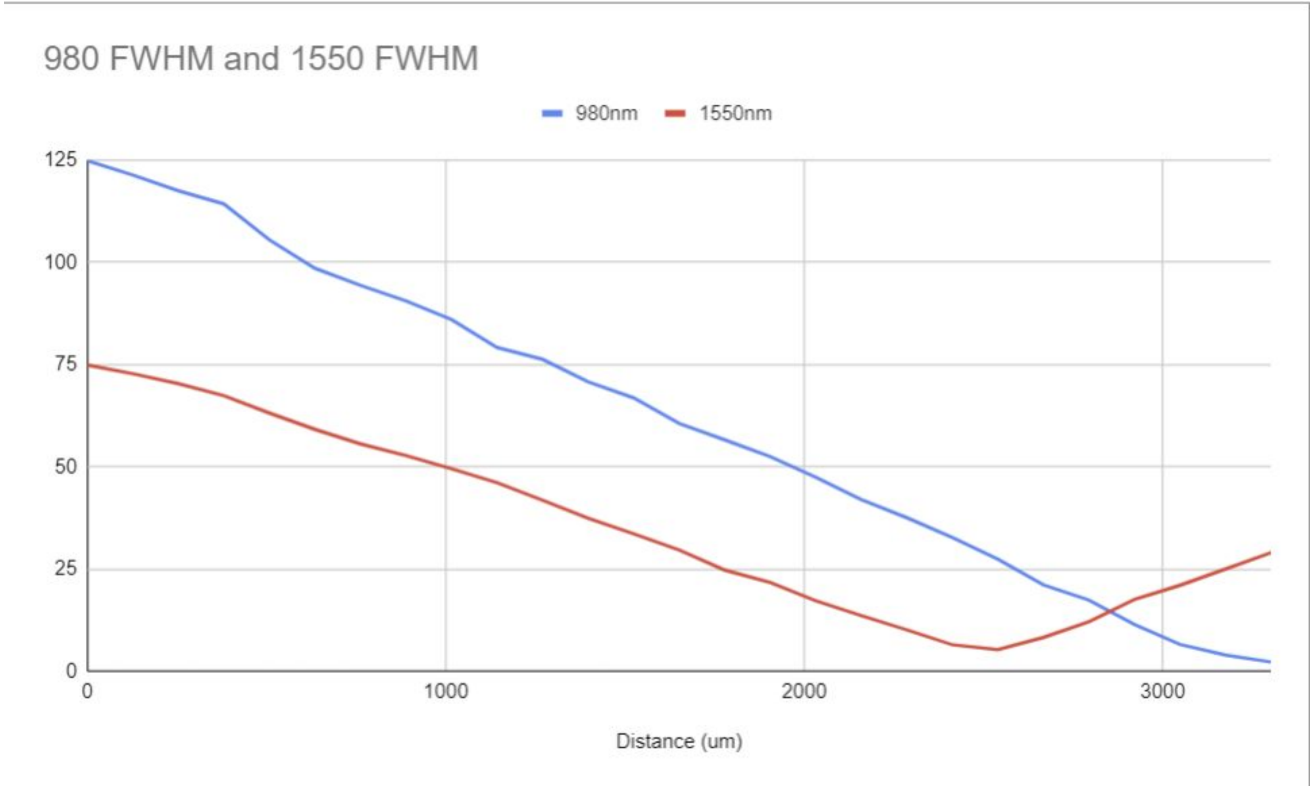
Using the Phosphor Camera to Quantify Alignment through the irises

- Observed where each iris was focusing by closing one while the other was open
  - Found that they were not focusing in the same place
  - Made adjustments to the positions of the irises (NOT THE BEAM)
  - Got video of airy discs and focusing of each iris

Cage Mounting and Re-alignment

- New parts came in to replace current mounts etc. for cage system replacement.
- Alignment was a little simpler with this setup
- Found that 1550 and 980 beams had different focal lengths
  - Spoke about divergence of the 1550 collimator and possibly replacing
- Took separate data with more data points to examine full width half maximum vs position of lens
  - Originally completed with both beams instead of individually
  - Re-took data and video of alignment with irises.
  - Used Image J software to calculate from image snapshots at varying positions

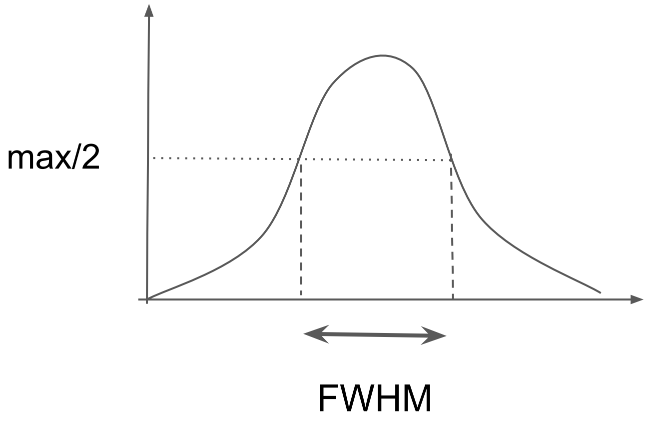
Results from Data



- Virtually the same results as Jan
- Focusing at different points but may not be an issue?
- Data points every 5 thousandths of an inch

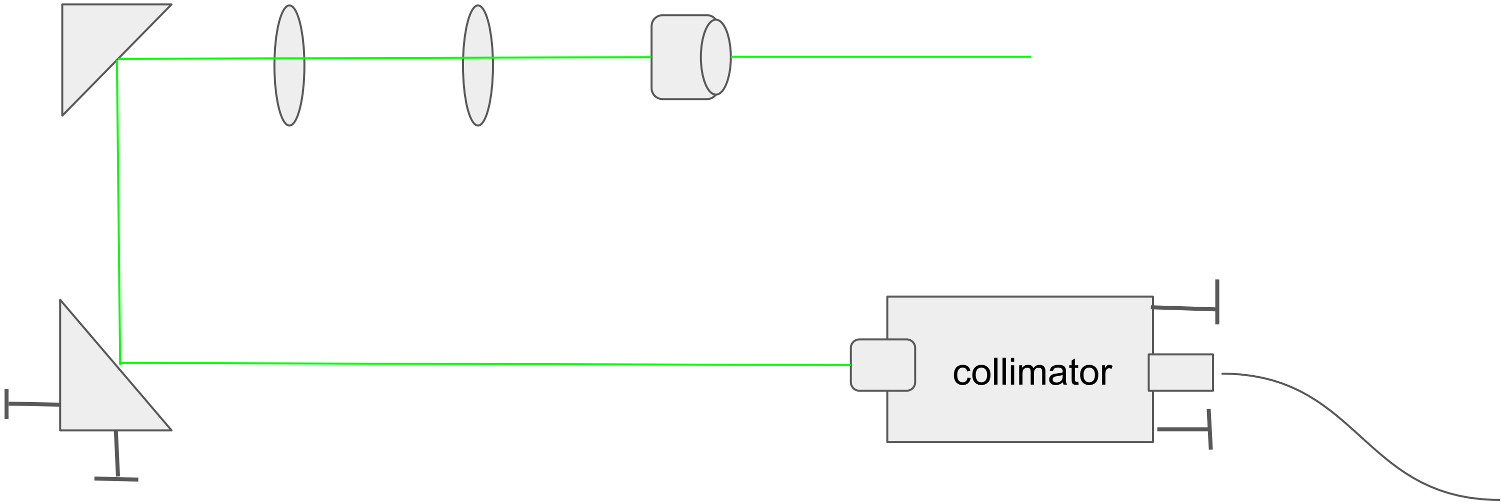
Normal Distribution and FWHM

- Understanding the math and reasoning behind using FWHM to represent the beam
- Derivation of sigma value from Image J analysis from normal distribution of gaussian fit
- Relationship between FWHM and sigma



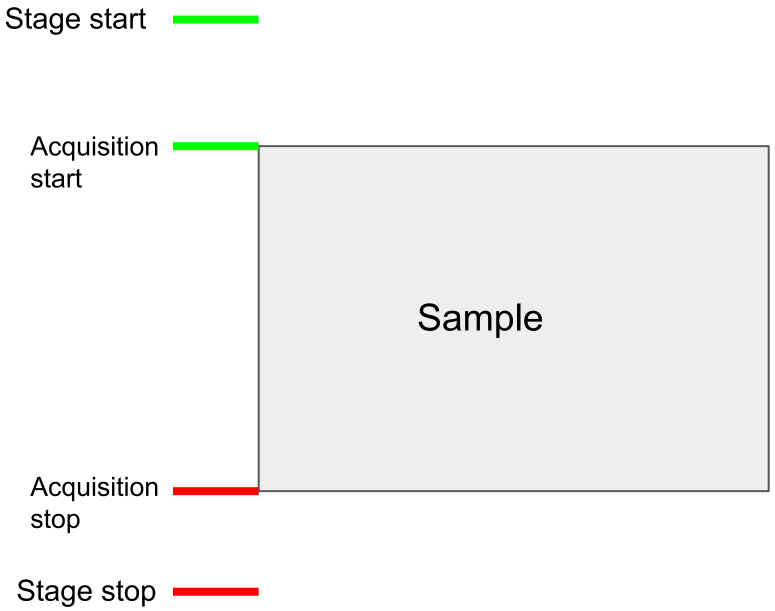
Aligning the Forward Propagating 980 nm beam

- Added third collimator and aligned forward propagating beam to iris position (representing current alignment). Had trouble with clipping on iris



Updates 3/28-4/28

Understanding Theory Behind Imaging Code



- Delay between stage acceleration and acquisition markers
- Ensures stage moving at stable velocity through actual data acquisition

Understanding Theory Behind Imaging

1 Sweep

Understanding Theory Behind Power Sweeps

- Rio produces 4-28 mW range
- Want a range of 10-28 mW

Data Output columns:

P_in	V_ Out	Std Dev ^2 of V_out	log(std dev) of V_out

- Plot log(P_in) vs. log (P_out)
    - log/log plots good for high dynamic range (data range of dependent variable)
- Can’t get all powers at once, must attenuate signal while keeping the 1st sweep non-attenuated, acting as the foundation of the data acquisition
- Can get the 2nd-last sweeps to overlap starting with the “absolute truth” using some proportionality cofactor array.

Understanding Powersweep Analysis Goals

- Take average noise measurement (V) for the detector
- Read all data into one matrix
- Create array to store empirical correction
- Subtract noise from all data (arrays in matrix)
- Multiply correction factors through matrix
- Plot with for loop and include error bar iteratively with standard deviation
- Convert to Log/Log plot and error bars to log(std deviation).

Measured Loss Through Collimator

Before Fiber Tip	29.6 mW
After Fiber Tip	29.4 mW
Before Collimating Lens	29.4 mW
After Collimator Lens	29.0 mW

Summary in dBm:

Loss Through Fiber Tip	-6.99 dBm
Loss Through Collimator Lens	-3.98 dBm

Optimizing Detector Efficiency Through Position

- Signal optimization with oscilloscope and 1550 nm beam with sample in place.
- Had Trouble with hitting a ceiling and then being out of translation freedom.
- This problem occurred iteratively and when I would try to move the base to allow more freedom, would lose signal completely.
- Found that one problem was that I was starting with too weak of a signal (4 mW).
- Found attenuating with power from RIO was not best

What ended up working:

- Starting with a strong signal and attenuating with the irises
- Box off for finding best base position
- Optimize base position first with translations set to default
- Zoom in to V/division on oscilloscope as maxes hit in each direction.
- Attenuate with both irises as needed, not with power from RIO
- This process took half the time and worked the first time

Light Shielding Complete

- Build rail standoff from shelf for light shielding
- Sewed blackout curtain to fit rail
- Blackout foil around holes and edges.

(Insert picture here)

Calibrating Focal Length Shift

- With both 980 nm and 1550 nm beams on, used phosphor camera and highly attenuated power to: (A) do fine alignment on the beam paths, and (B) Correct focal length shift as much as possible.

- Then with varying attenuation, took pictures of both the 980 nm and 1550 nm beam through the same distance at every hundredth of an inch.

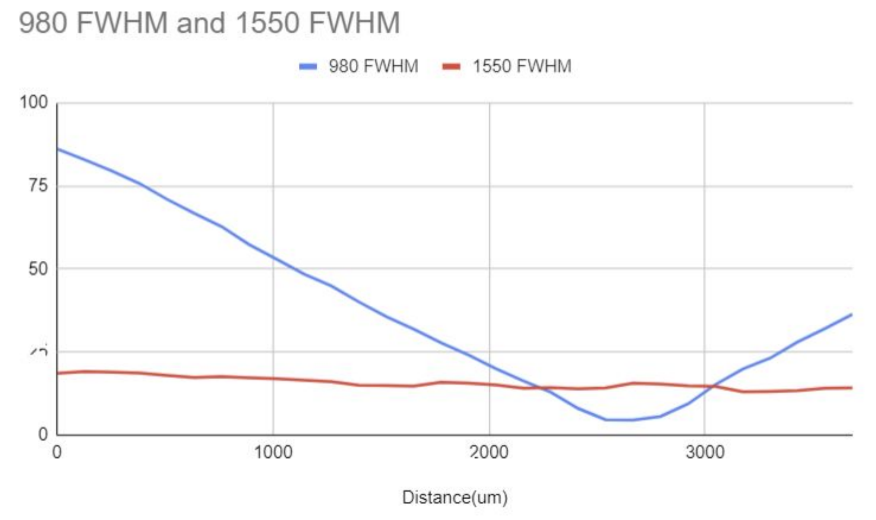
<u>Notes:</u>

- The back propagating 980 beam required the flip camera to be reinstalled into the system, creating the need for the alignment procedure to be redone.

Results from image processing on focal length shift

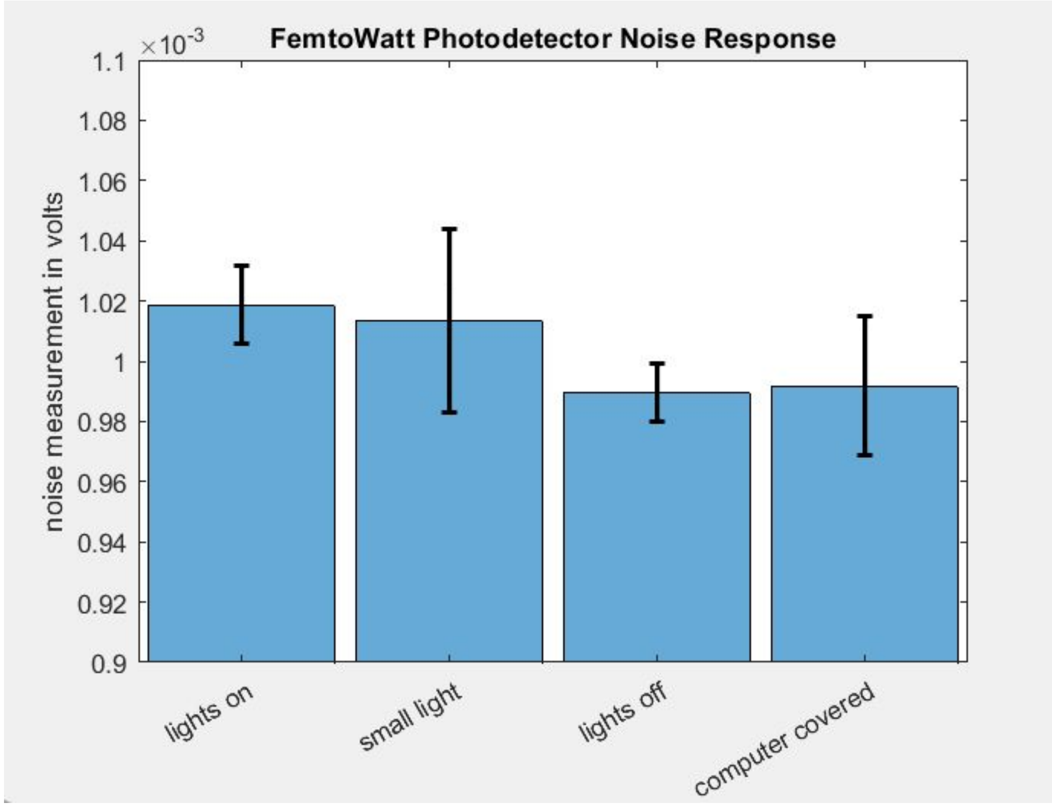
FOLLOW UP WITH JAN

log(980FWHM) and log(1550FWHM)



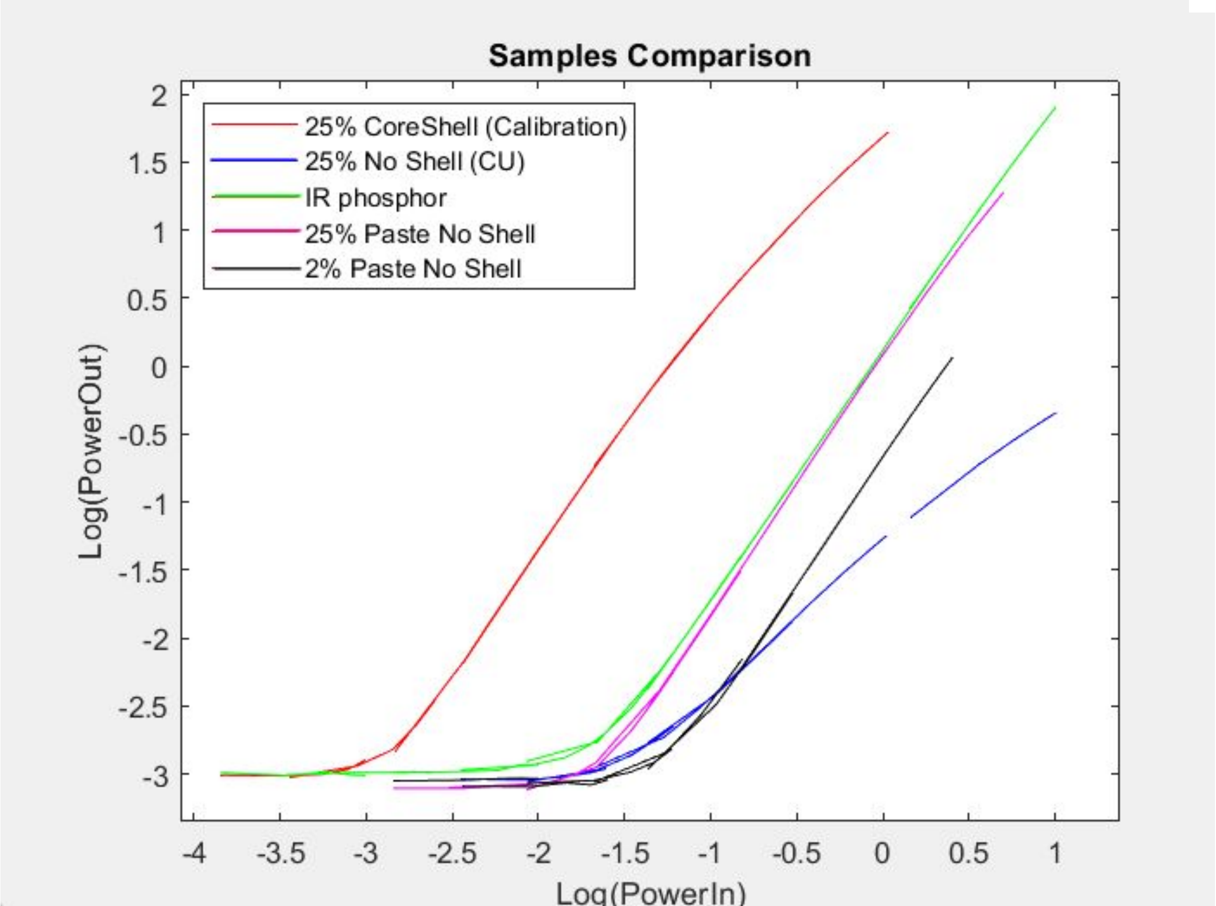
980 FWHM and 1550 FWHM

FW PD Noise Response with new light shielding

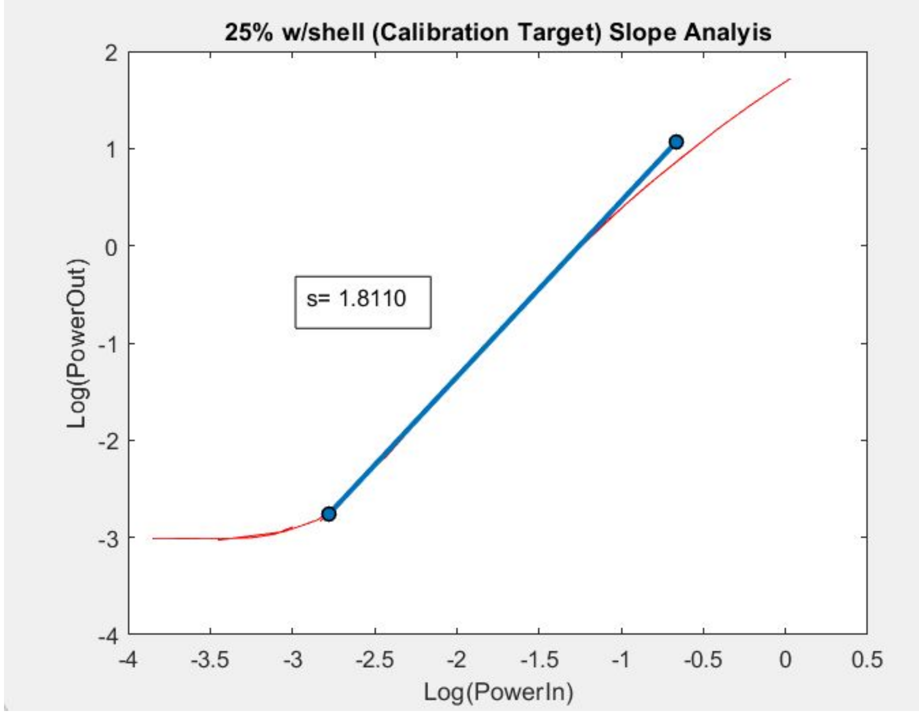


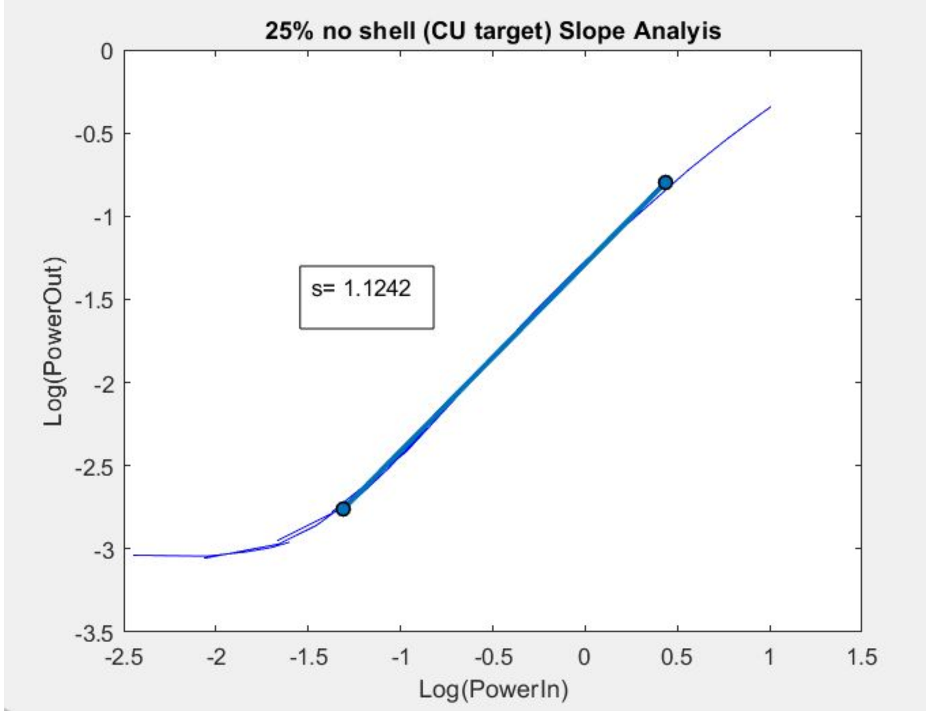
UCNP Meeting 5/25/22

Data Collection from 5 Samples with Current Alignment

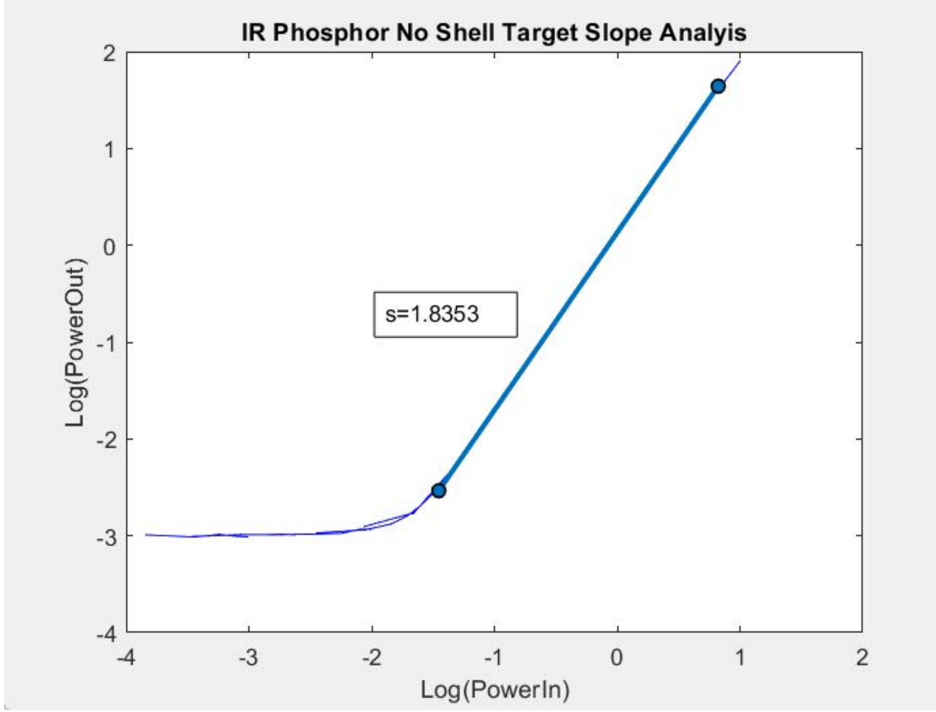


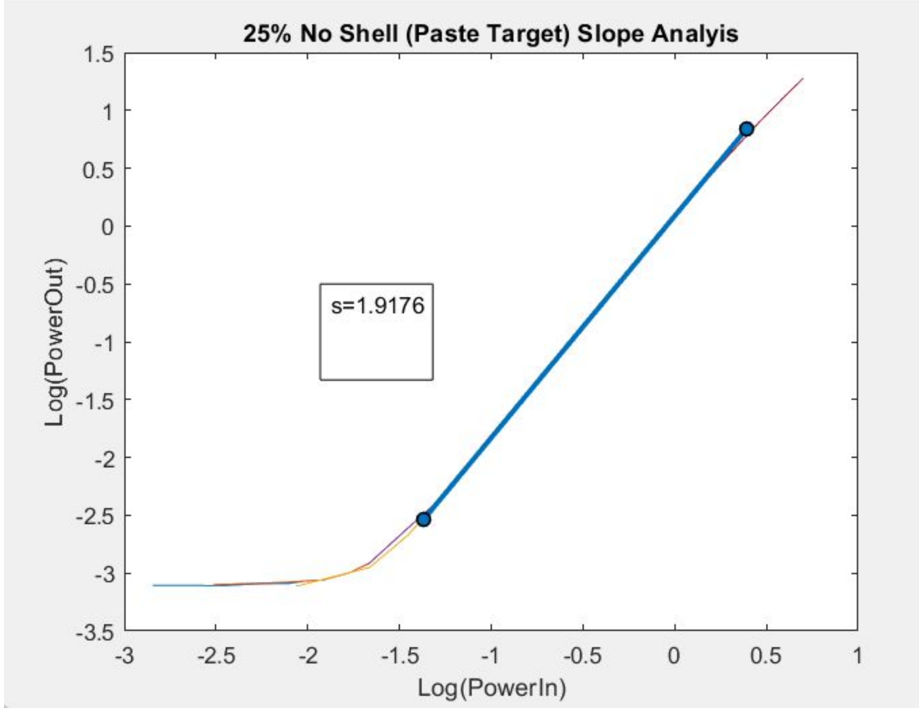
Individual Slope Analysis of Sample



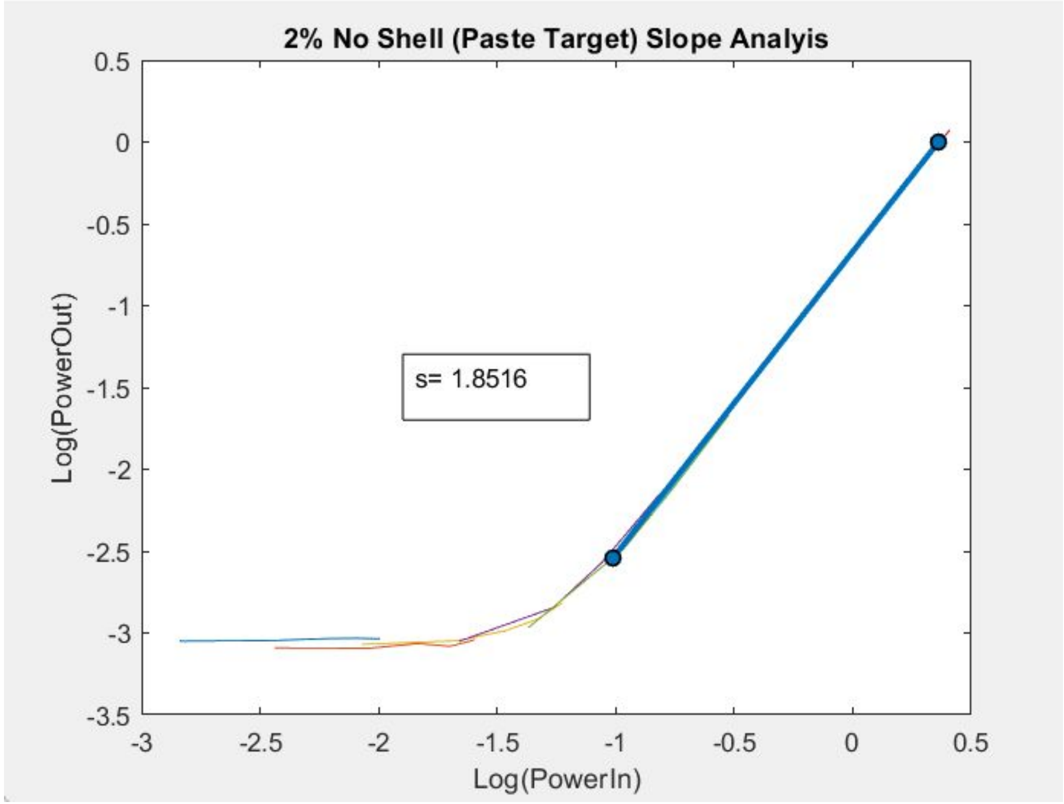


Individual Slope Analysis of Samples



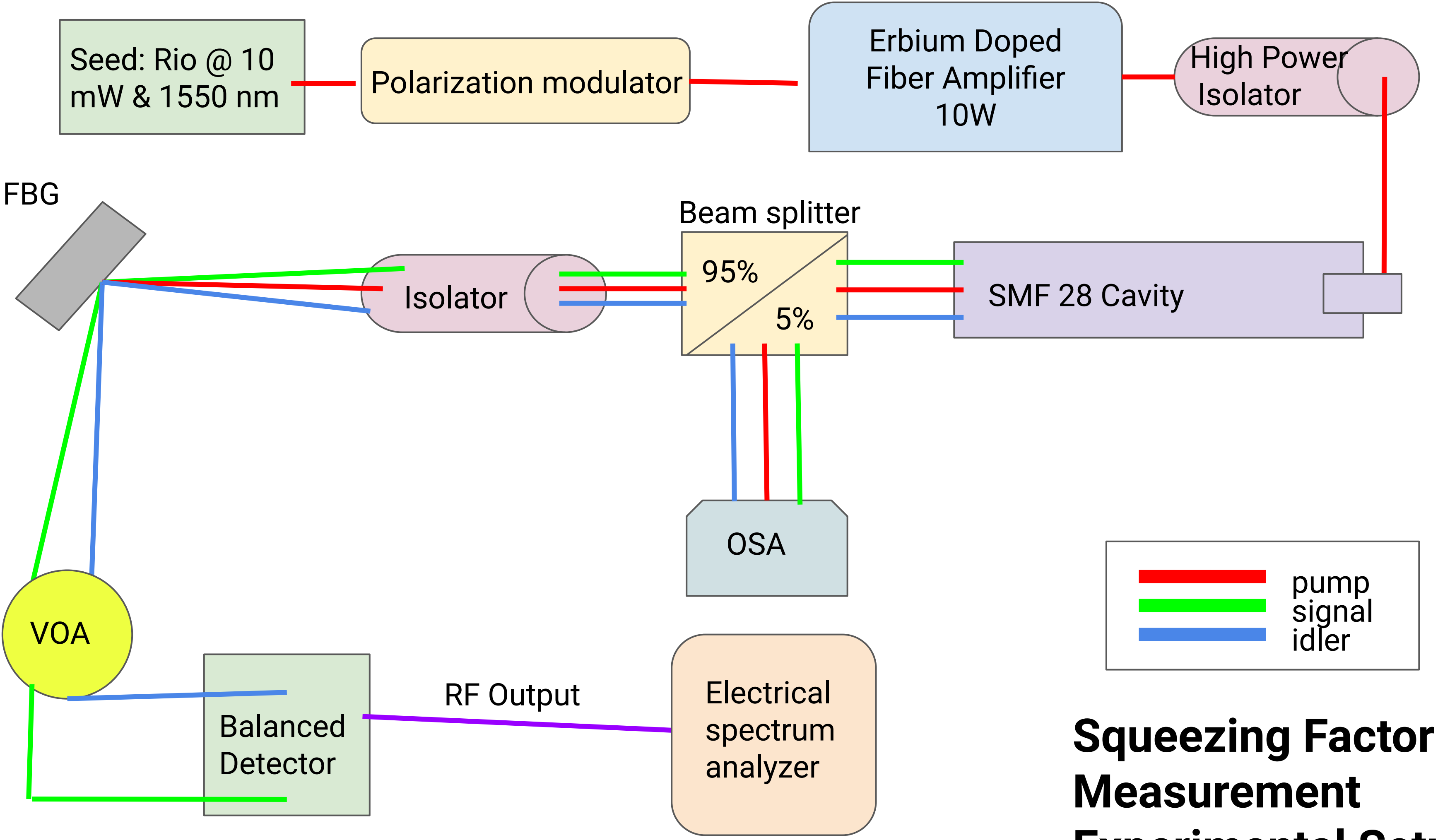


Individual Slope Analysis of Samples



Summary of Slope Findings:

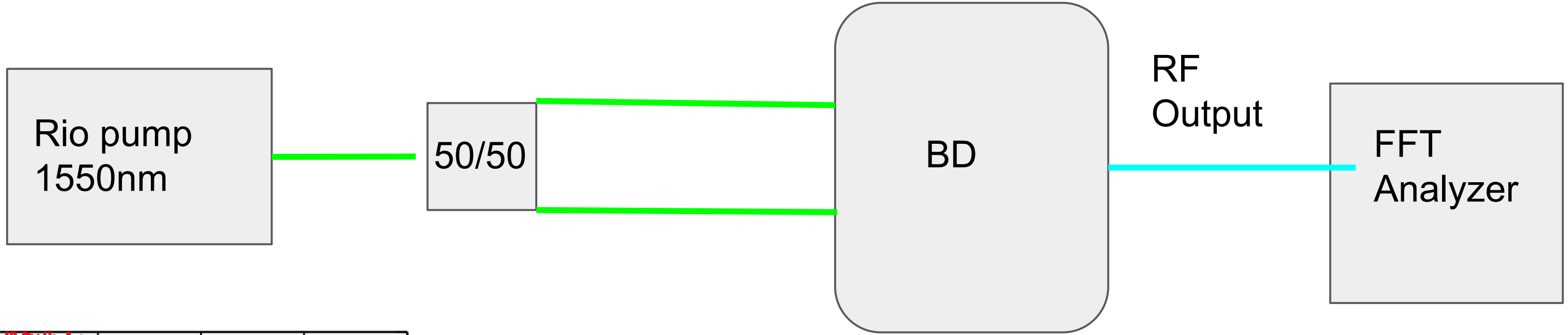
Sample	**Slope**
25% Core@shell (calibration target)	1.811
25% no shell (CU target)	1.1242
IR phosphor	1.8353
25% Paste (no shell)	1.9176
2% Paste (no shell)	1.8516



🟥 pump
🟩 signal
🟦 idler

Squeezing Factor Measurement Experimental Setup

Experimental Setup for Shot Noise Calibration



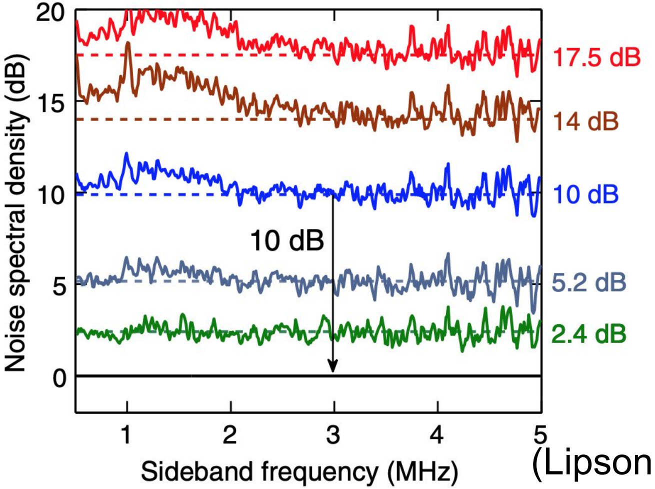
Rio pump
1550nm

50/50

BD

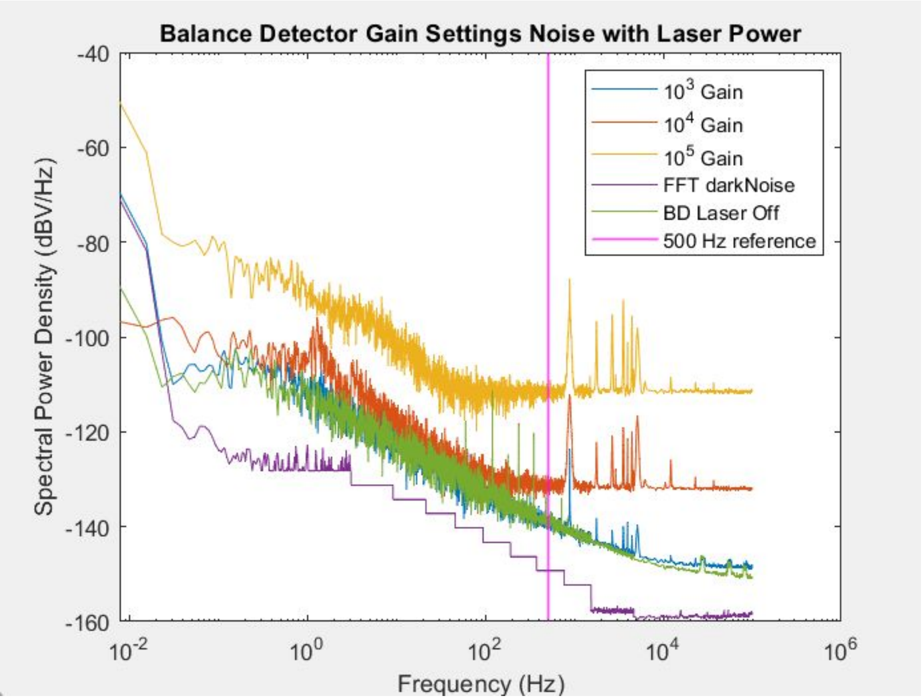
RF
Output

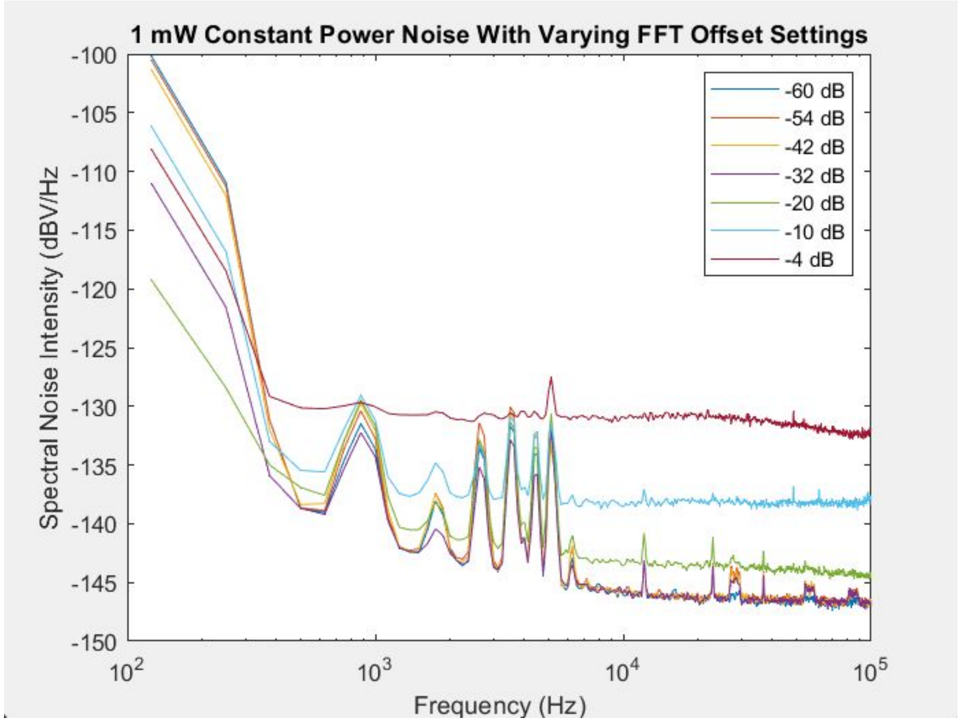
FFT
Analyzer



(Lipson 2015)

Gain Settings and Offset Setting Analysis

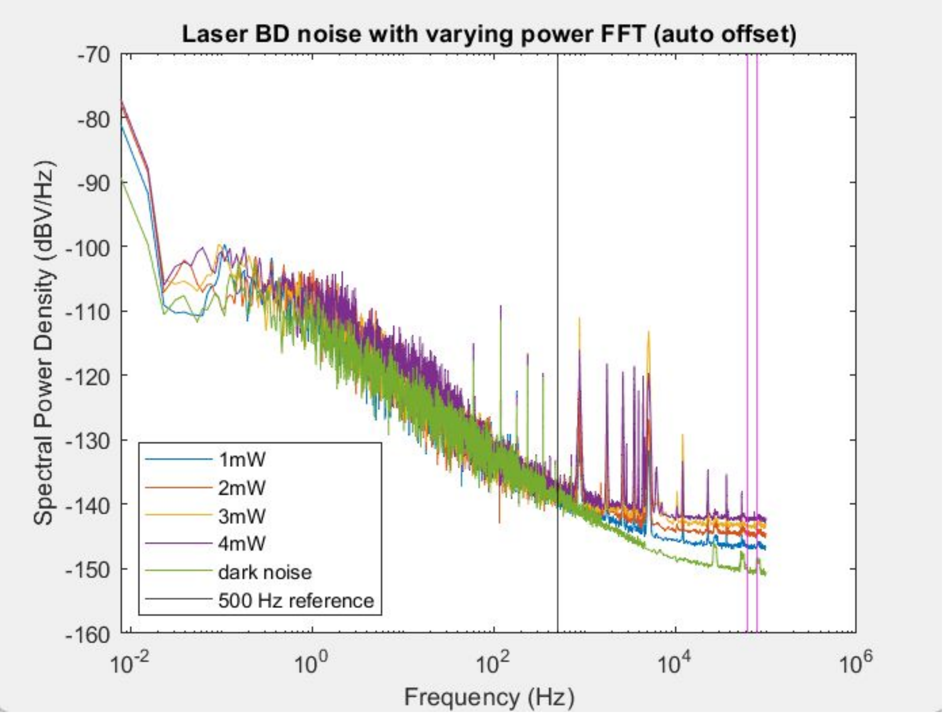




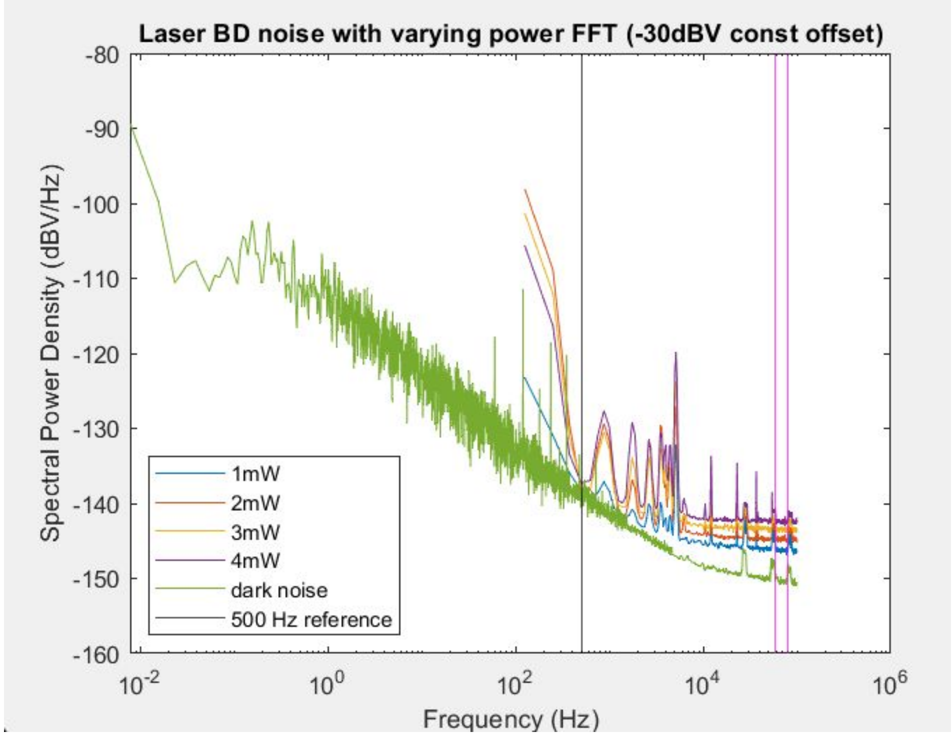
10^3 gain setting likely best option

Auto offset may not be a good option for data acquisition

Balanced Detector Laser Noise with Varying Powers

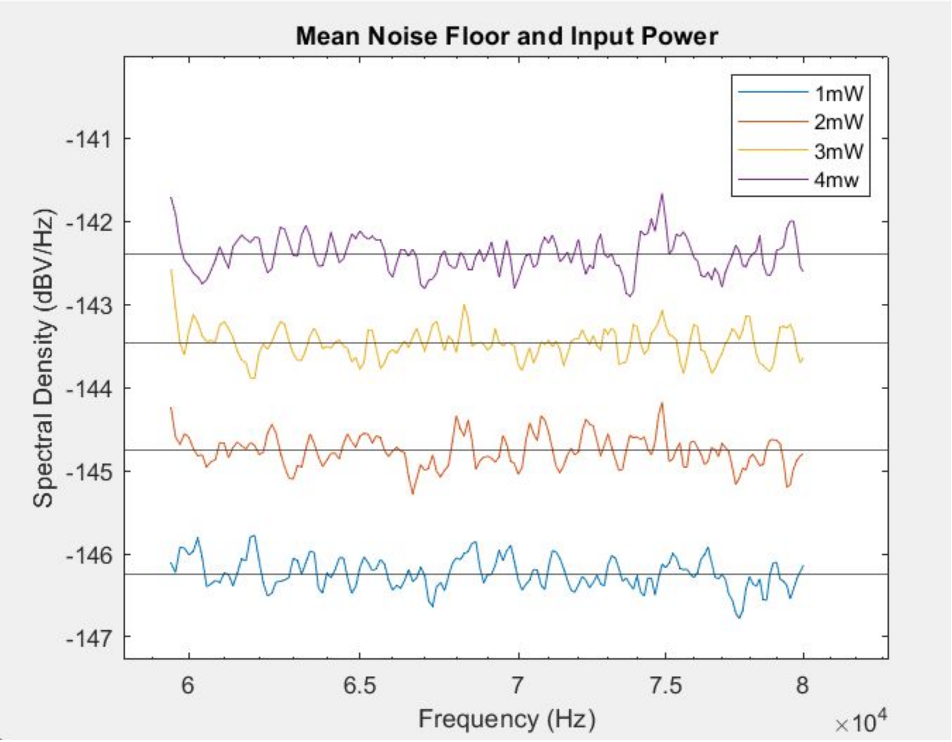


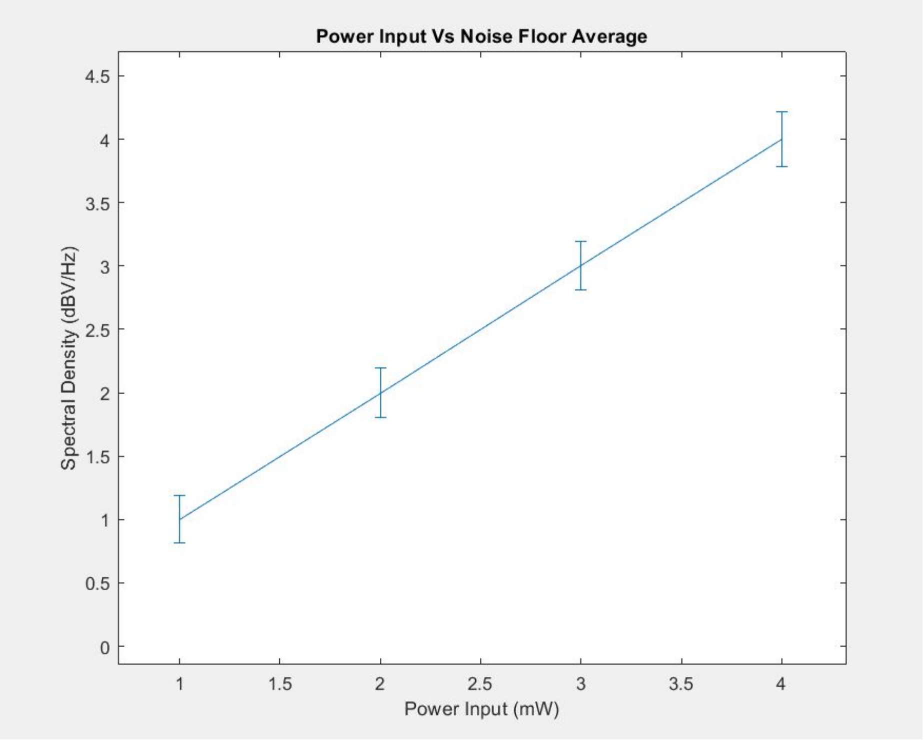
Auto Offset



Constant Offset

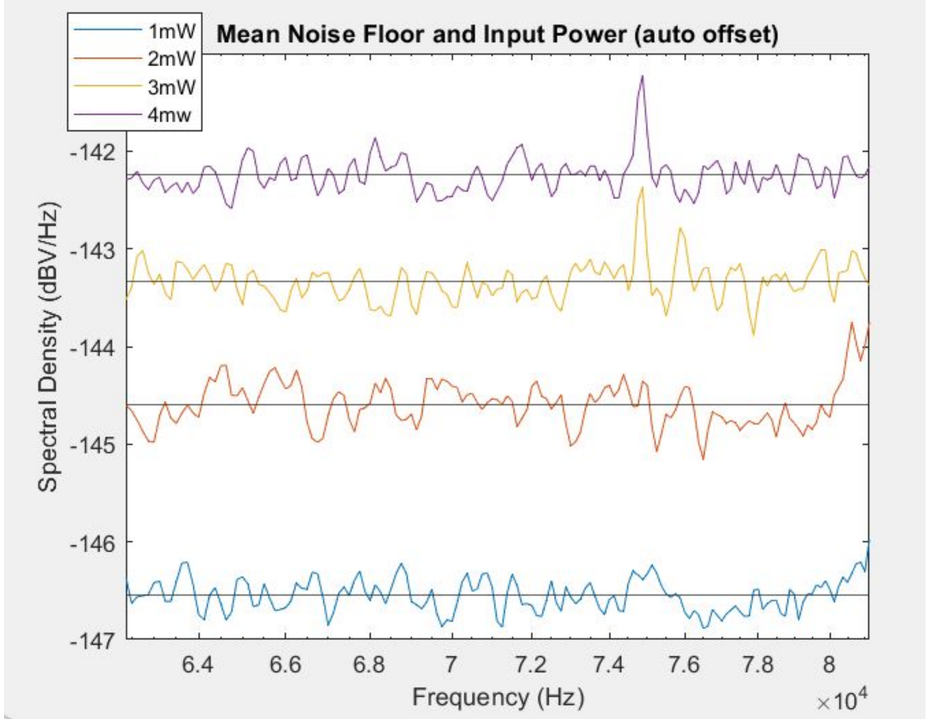
Constant Offset Noise Floor with Varying Powers

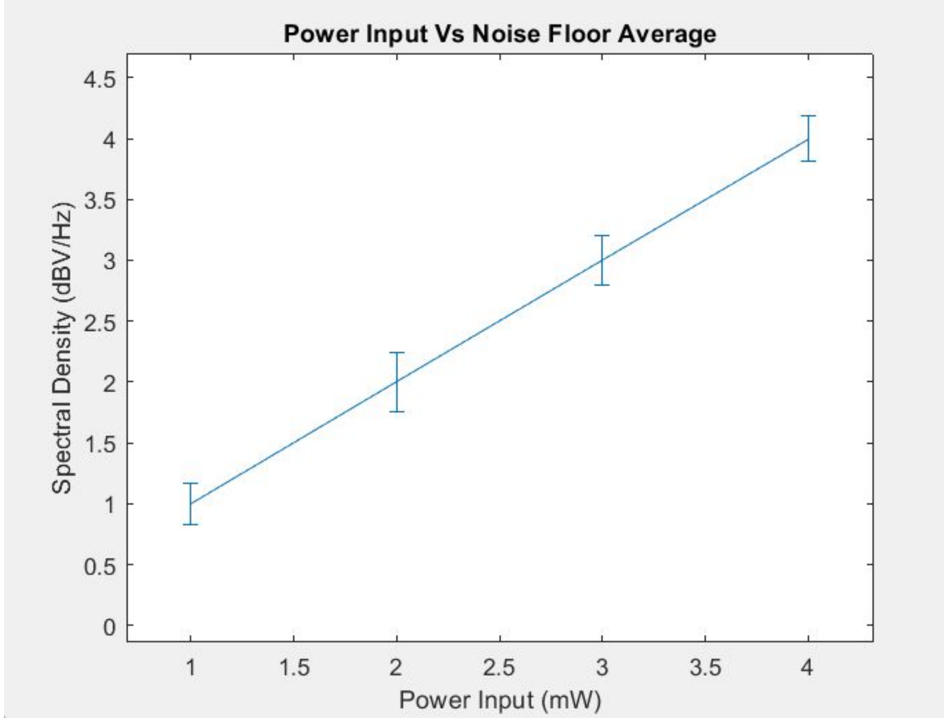




Linear Relationship

Auto Offset Noise Floor with Varying Powers





Also linear relationship

Goals

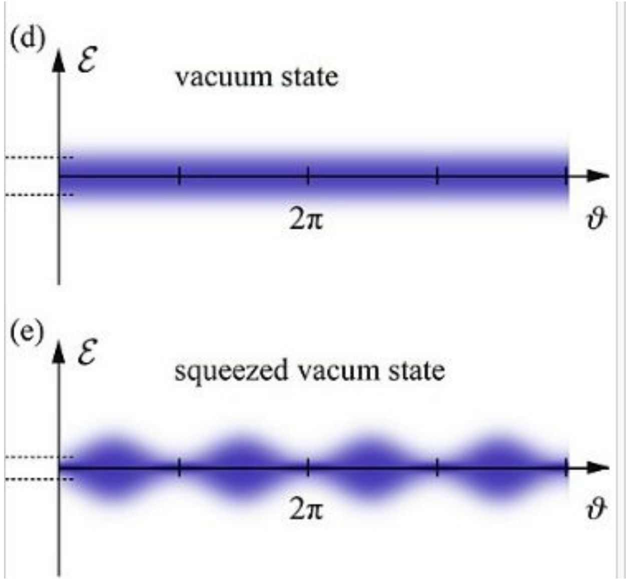
- Identify proper LO for shot noise calibration measurements
- Verify theory for squeezing factor
- Locate parts for squeezing factor
- Finish squeezed light stabilization
- Make sample measurements with squeezed light

in Fiber Squeeze Light: Generation and Characterization

Cassidy Bliss

Introduction to Squeeze

- Squeezed States of light have noise below the standard quantum limit in one quadrature component
- One property of uncertainty is lowered and consequently the others are increased as per Schrodinger's Uncertainty Principle
- In our case, we generate two-mode squeezed vacuum or twin-beam state (TWB), which means that the intensities of the light beams are correlated with each other at the quantum level.



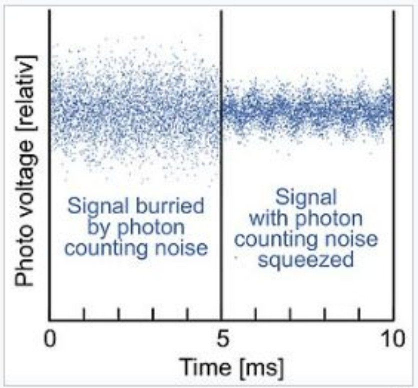
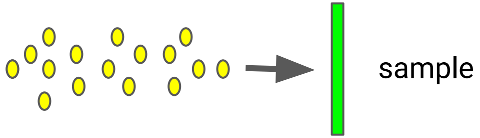


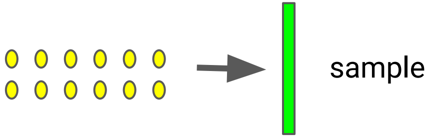
Fig. 4: Photo voltages of a photo diode detecting light.

Why are We Using Squeeze light over Classical Source?

- In our UCNP fluorescent microscope, our system is designed around a two-photon upconversion process within the nanoparticles with a 1550 nm light source.
- For biological applications, our concept relies on two photons arriving at the sample at the same time to avoid cellular damage
- We hope to see an enhancement of this upconversion process by using a squeeze light source, increasing our signal to noise ratio, and allowing lower input power with comparable results for imaging purposes without risk of cellular damage.



Photons from classical source

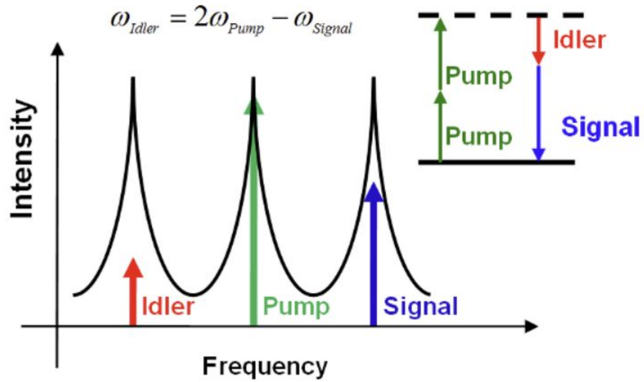


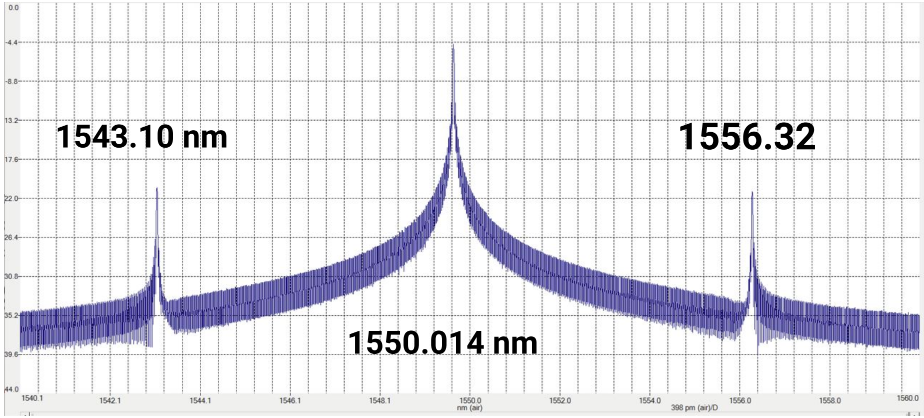
Photons from squeezed light source

Degenerate Four-Wave Mixing in Optical Fiber

- Degenerate four-wave mixing (DFWM) is a X^3 (third order nonlinear) process
- Caused by the dependence of refractive index on the intensity of the optical power resulting from the Kerr effect

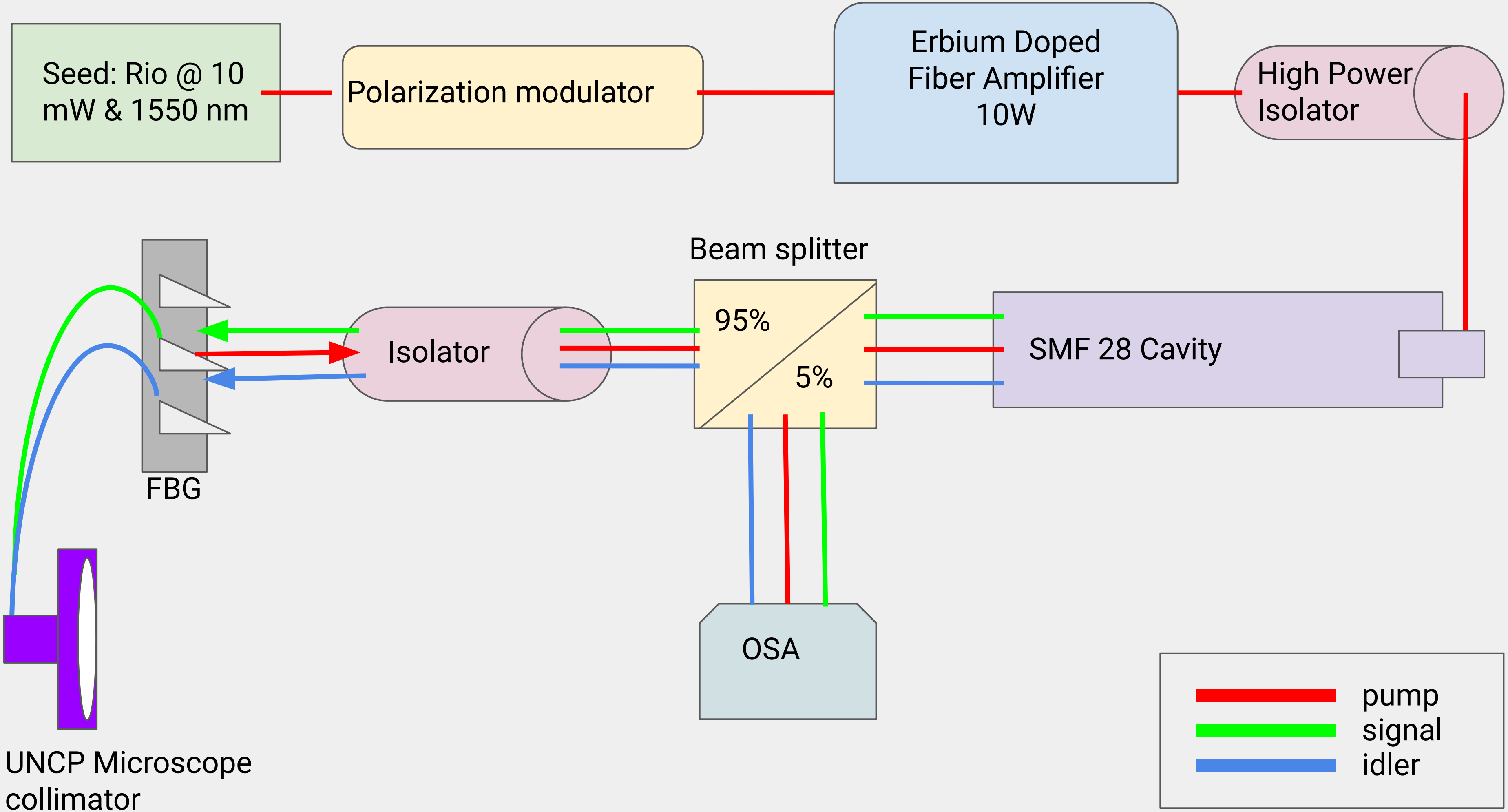
- Here, the signal and the idler are our squeezed light twin beams




Our Squeezing as seen on Spectrum Analyzer

Our Squeeze Light Source

- Seed from Rio at 10 mW
- Two-mode squeezing using fiber as resonance cavity
- SMF 28 as cavity : 1 cm in length
- Thermal control tuning
- Output signal and idler of equal polarizations
- Signal and idler have different frequencies


Seed: Rio @ 10 mW & 1550 nm
Polarization modulator
Erbium Doped Fiber Amplifier 10W
High Power Isolator
Beam splitter
95%
5%
SMF 28 Cavity
Isolator
FBG
OSA
UNCP Microscope collimator
pump
signal
idler

Characterizing Squeeze Light

① **Squeezing Factor (relative to shot noise)**

The Squeezing factor gives us the difference between SNL and squeeze light noise (in dBm)

$$S(\Omega) = 1 - \frac{n_c n_d}{1 + \Omega^2 \tau_c^{\ 2}}$$

$\Omega =$ *sideband frequency,*

$n_c = 1 - \frac{Q_L}{Q_i}$ = ratio of coupling losses to total losses

$\tau_c =$ cavity photon lifetime

n_d = the detection efficiency

In essence, the squeezing factor will tell us the expected noise loss of the given system, which will tell us how ‘well’ the squeeze light is being generated as it relates to pairs of entangled photons at the source.

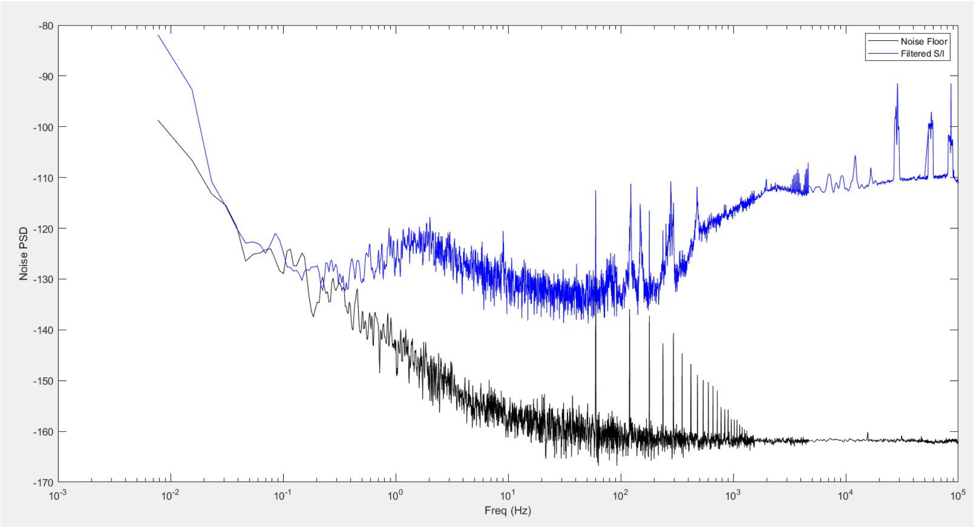
The quality of squeezing quantitatively depends on the ratio between the losses given by the intrinsic quality factor Qi and coupling coefficient determined by the loaded quality factor QL

Experimentally, we can measure the squeezing factor by finding the shot noise level of our system with a classical laser source and then measuring the noise of our squeeze light system

Characterizing Squeeze Light

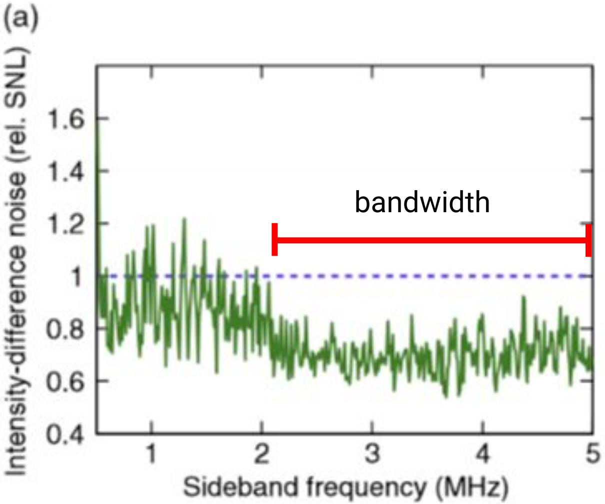
2 Stability of Squeeze Light

- A measurement of how much the squeeze light fluctuates in power over a bandwidth

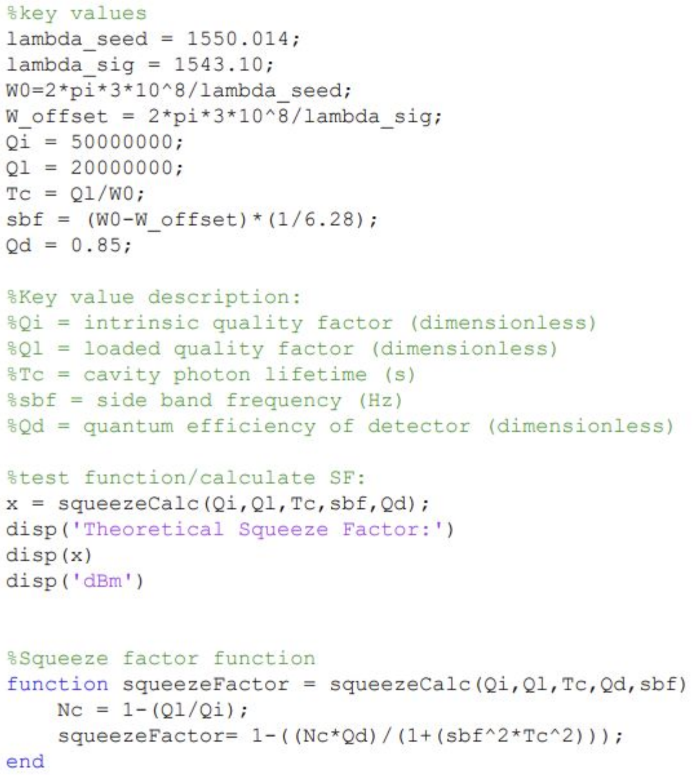


3 Squeezing Bandwidth

- A measurement of the bandwidth of the squeeze noise that is below the SNL



Preliminary Theoretical Results: Squeeze Factor

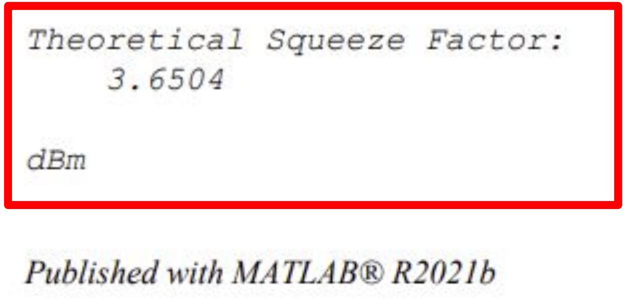


```
%key values
lambda_seed = 1550.014;
lambda_sig = 1543.10;
W0=2*pi*3*10^8/lambda_seed;
W_offset = 2*pi*3*10^8/lambda_sig;
Qi = 50000000;
Ql = 20000000;
Tc = Ql/W0;
sbf = (W0-W_offset)*(1/6.28);
Qd = 0.85;

%Key value description:
%Qi = intrinsic quality factor (dimensionless)
%Ql = loaded quality factor (dimensionless)
%Tc = cavity photon lifetime (s)
%sbf = side band frequency (Hz)
%Qd = quantum efficiency of detector (dimensionless)

%test function/calculate SF:
x = squeezeCalc(Qi,Ql,Tc,sbf,Qd);
disp('Theoretical Squeeze Factor:')
disp(x)
disp('dBm')


%Squeeze factor function
function squeezeFactor = squeezeCalc(Qi,Ql,Tc,Qd,sbf)
    Nc = 1-(Ql/Qi);
    squeezeFactor= 1-((Nc*Qd)/(1+(sbf^2*Tc^2)));
end
```



```
Theoretical Squeeze Factor:
    3.6504


dBm
```

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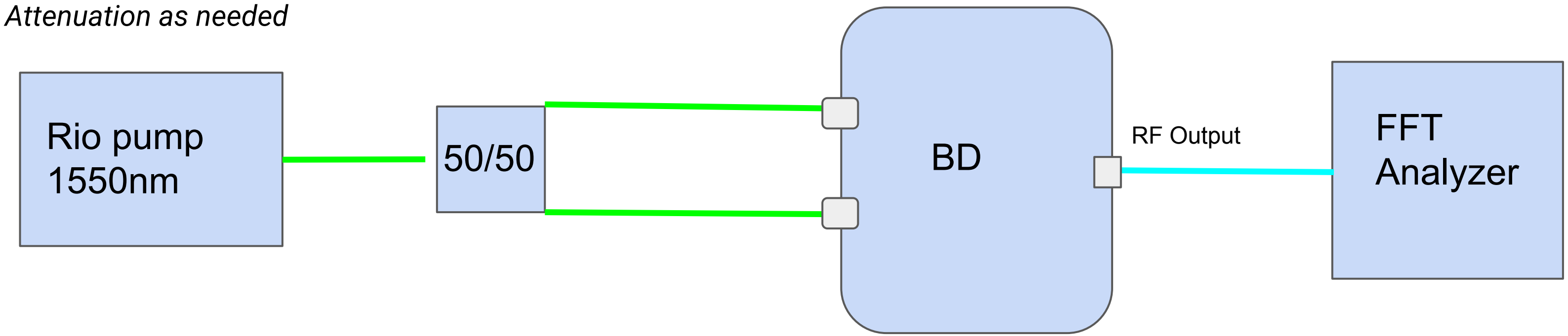
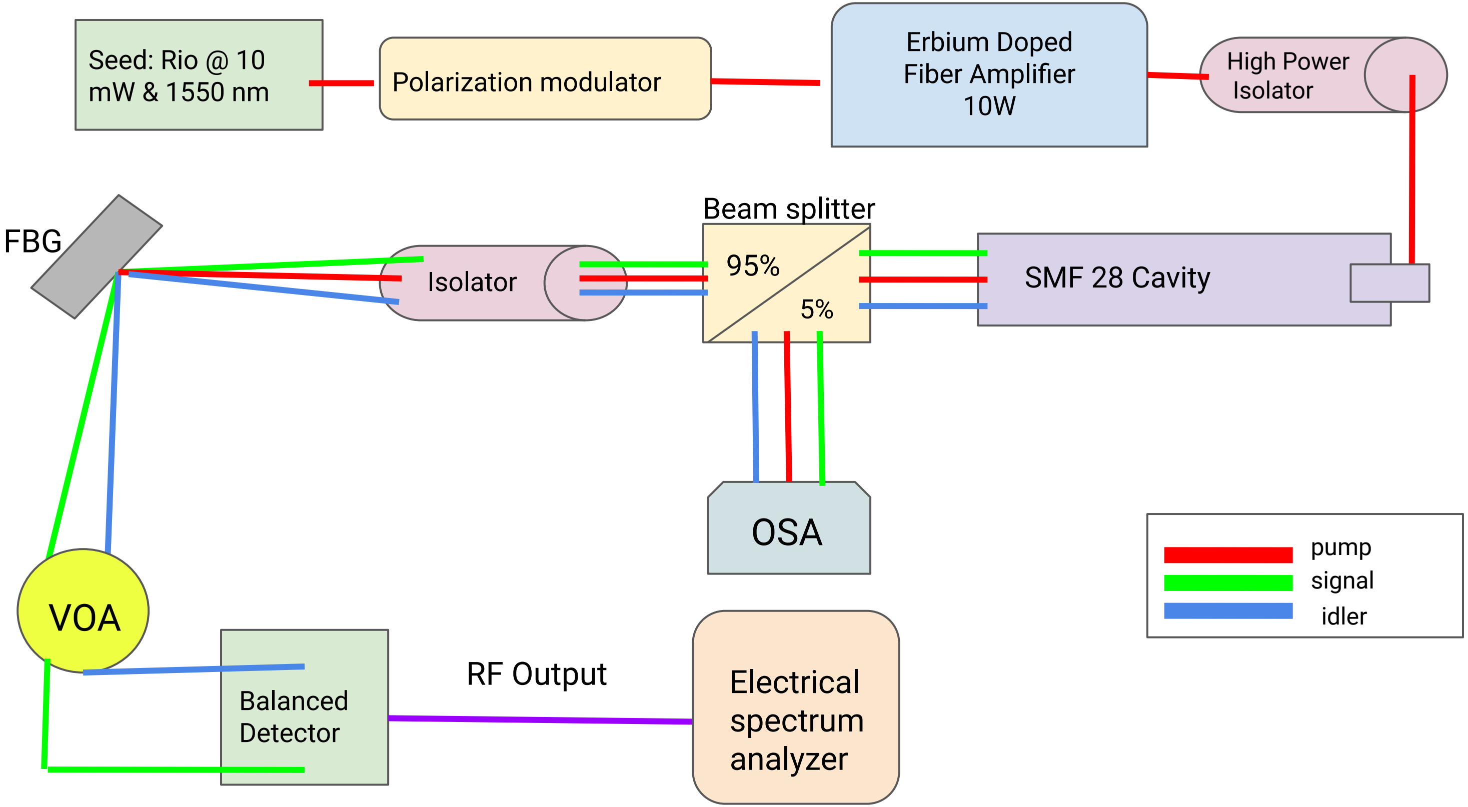
Experimental Setup for Shot Noise Calibration



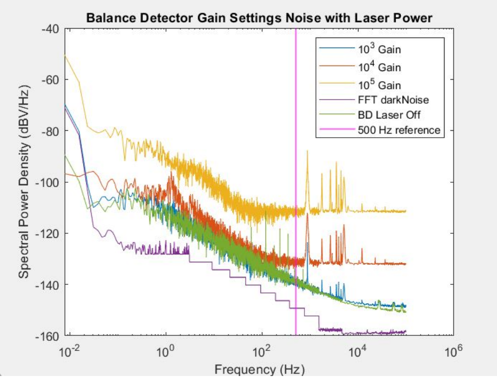
Experimental Setup for Squeeze Noise Measurement



Experimental Procedures

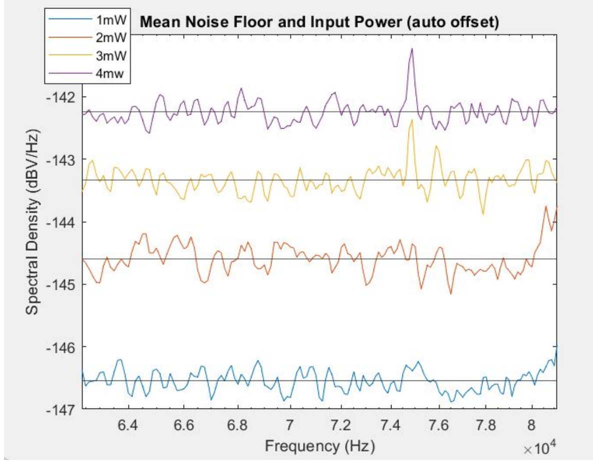
Account for Noise Sources and Optimization

- Laser Noise
- FFT Analyzer Noise
- BD Noise
- Optimize and quantify stability of source



Measure SNL

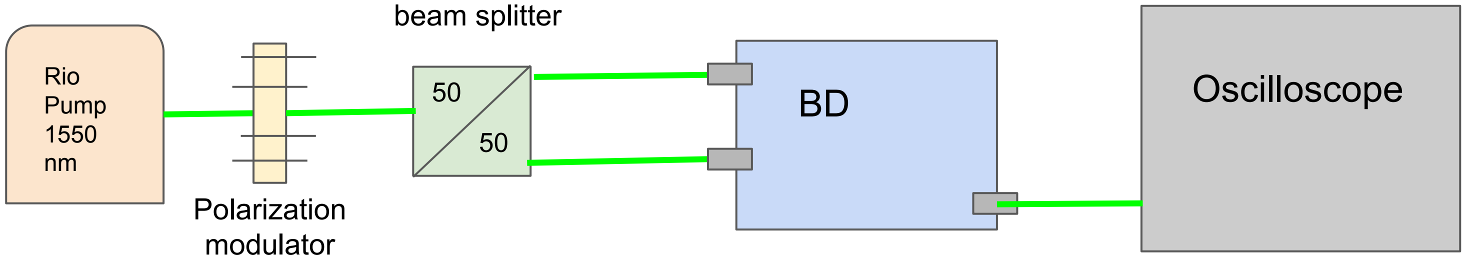
- Measure the noise floor of the squeeze light system using RIO laser source



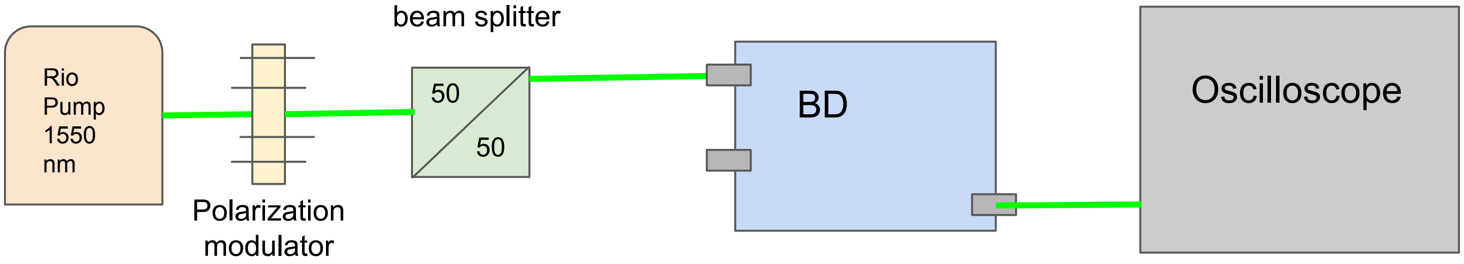
Measure Squeeze Light Noise

- Filter out the pump and separate the signal and idler with Fiber Bragg Grating
- Mix with Local oscillator at higher frequency reference signal
- Input signal and idler separately into Balanced detector
- Tap into the RF output ESA for noise measurement

CMRR Updated measurement setup



Balanced
Output

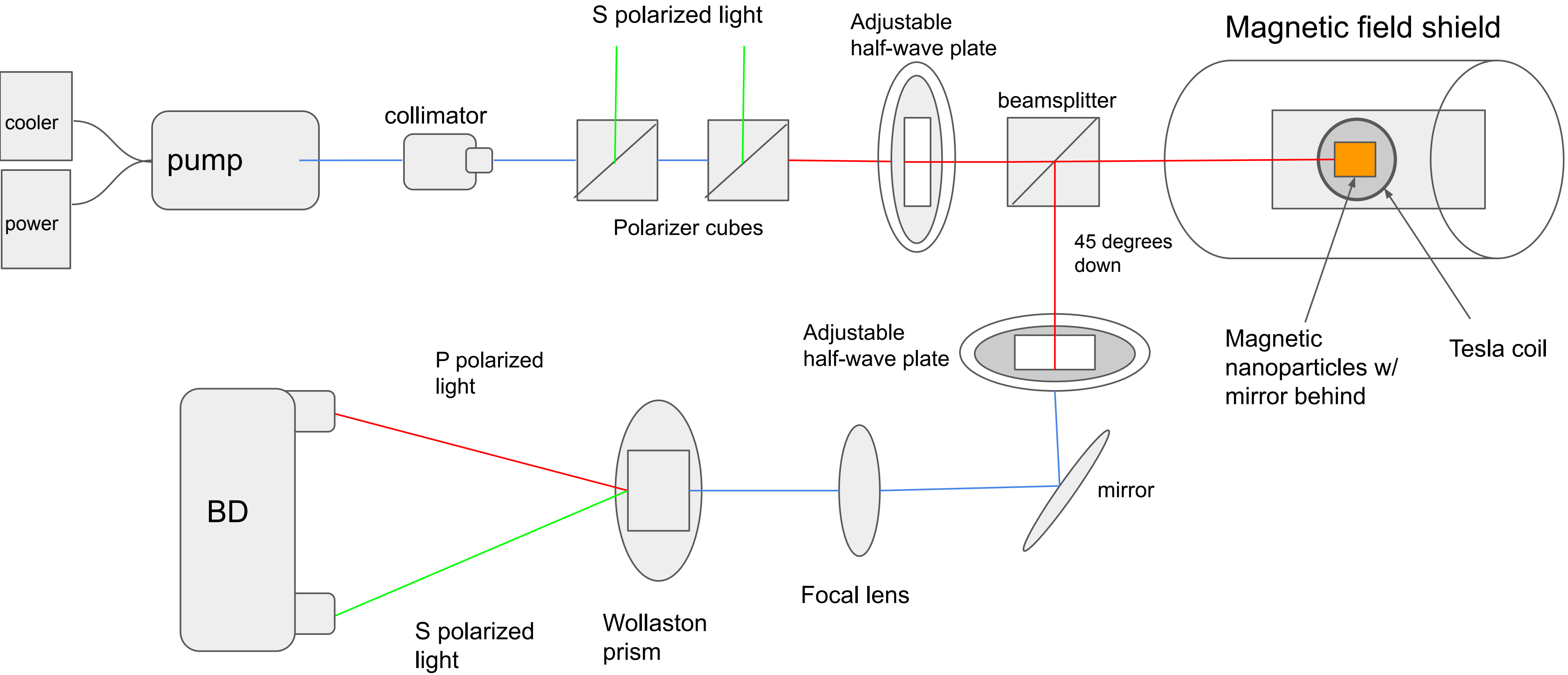


Unbalanced
Output

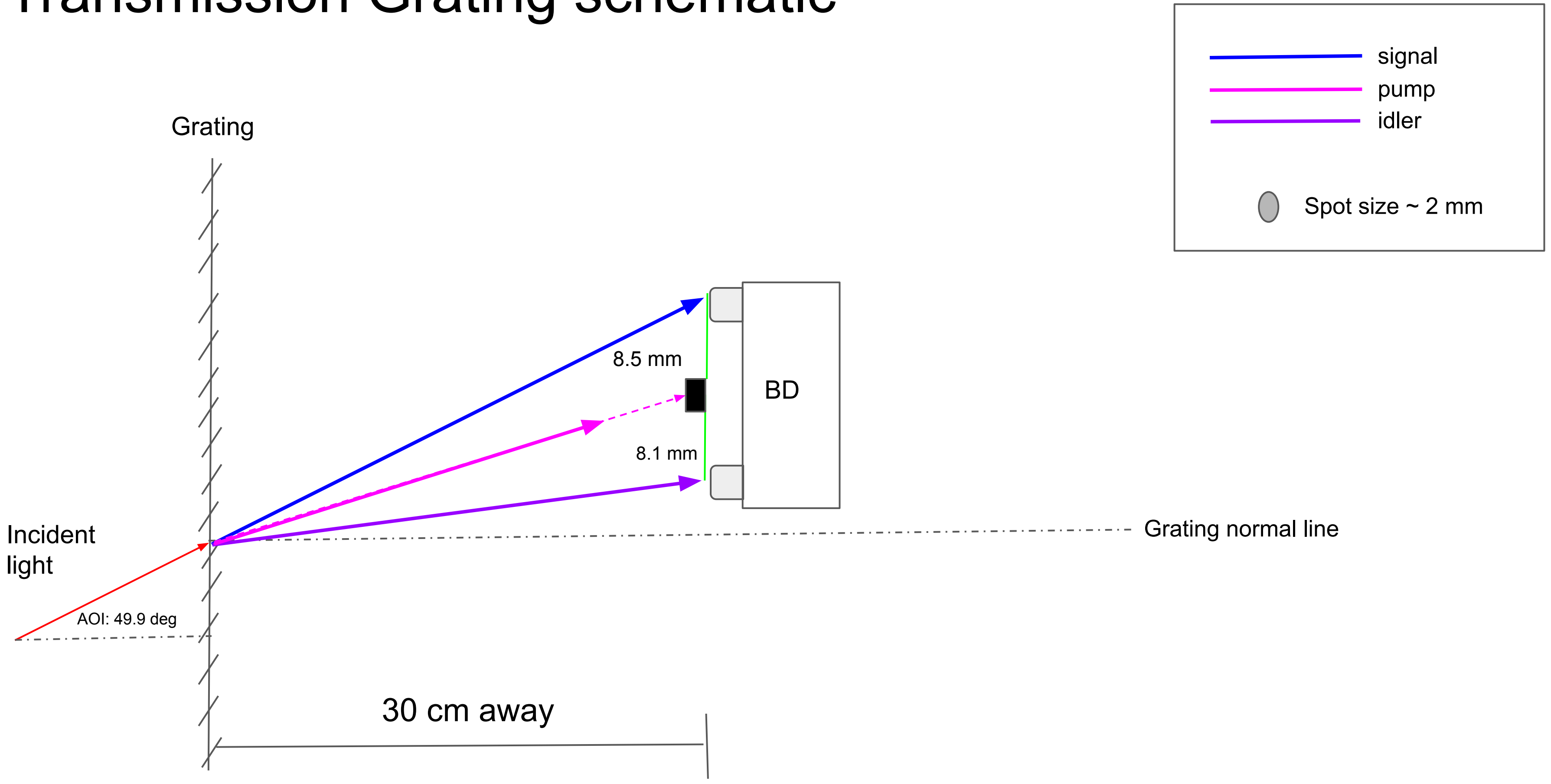
New Alignment Calibration Power Results With Optimization:

Input Power (uW)	Output Voltage Previous (mV)	Output Voltage New (mV)
50	800	saturated
10	46	2200
5	14	750
3	5.1	390
2	2.32	200
1	1.15	90

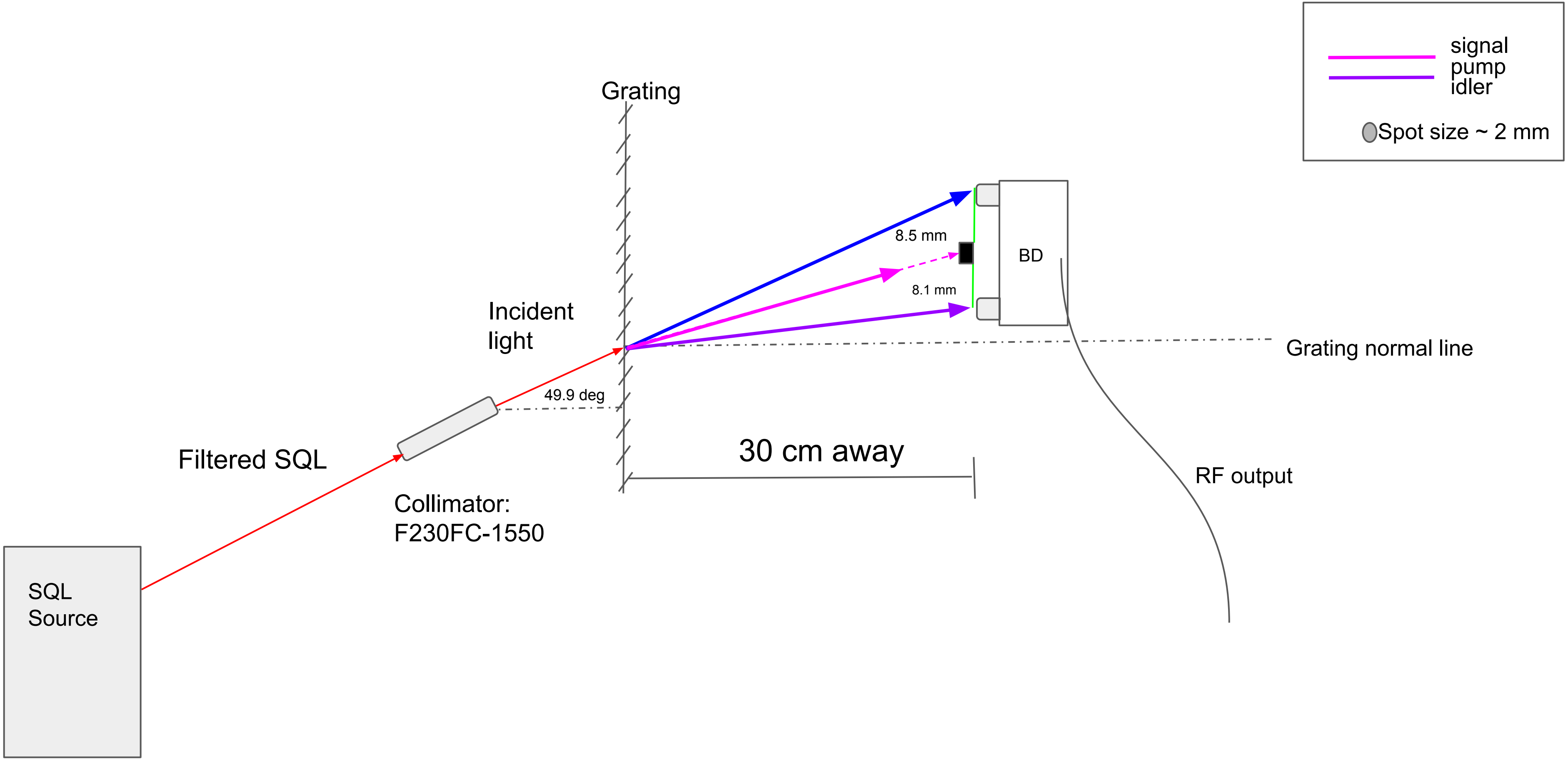
MNP Schematic



Transmission Grating schematic



Characterization Of SQL Setup



signal
pump
idler

Spot size ~ 2 mm

Grating

8.5 mm

BD

8.1 mm

Incident light

Grating normal line

49.9 deg

Filtered SQL

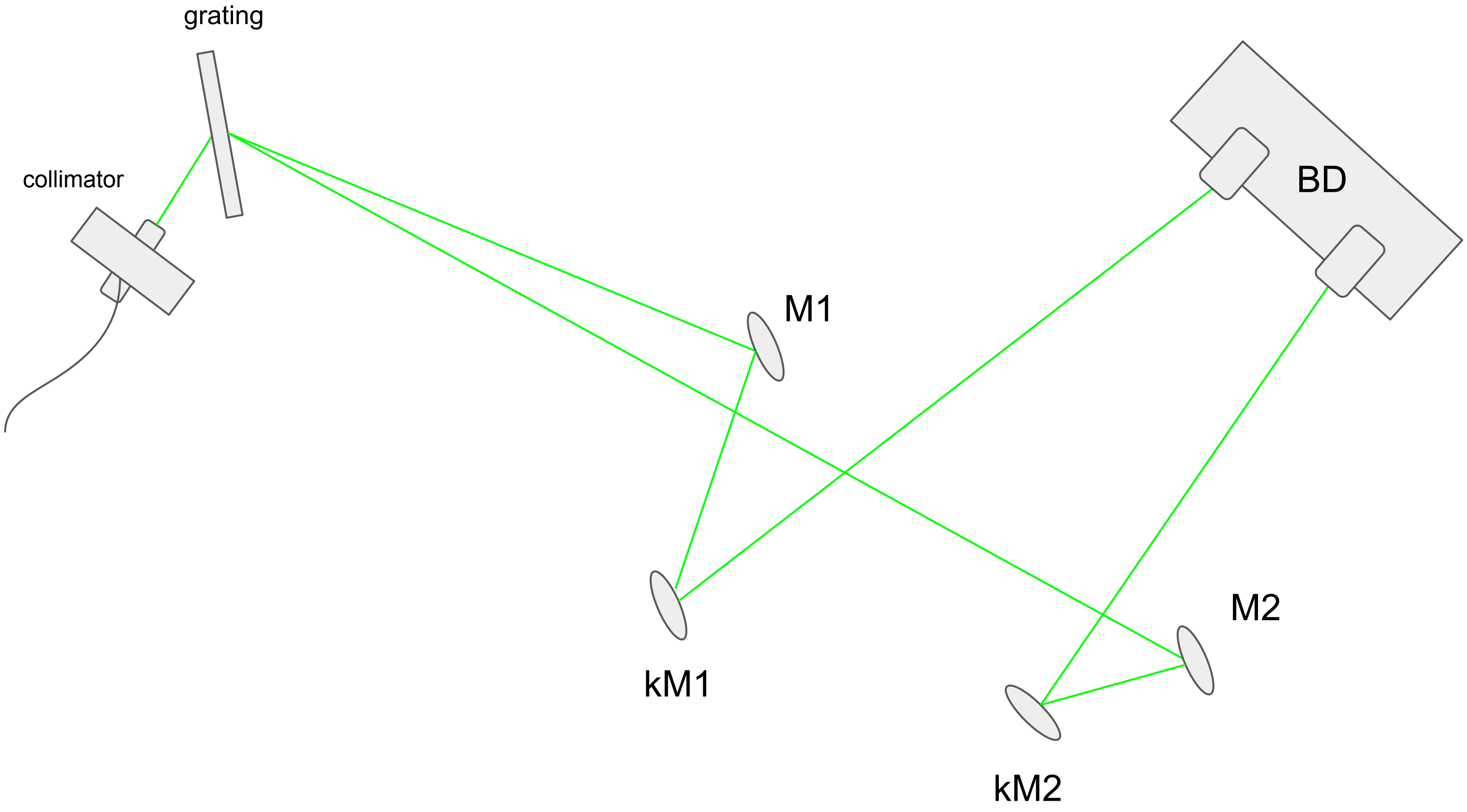
30 cm away

RF output

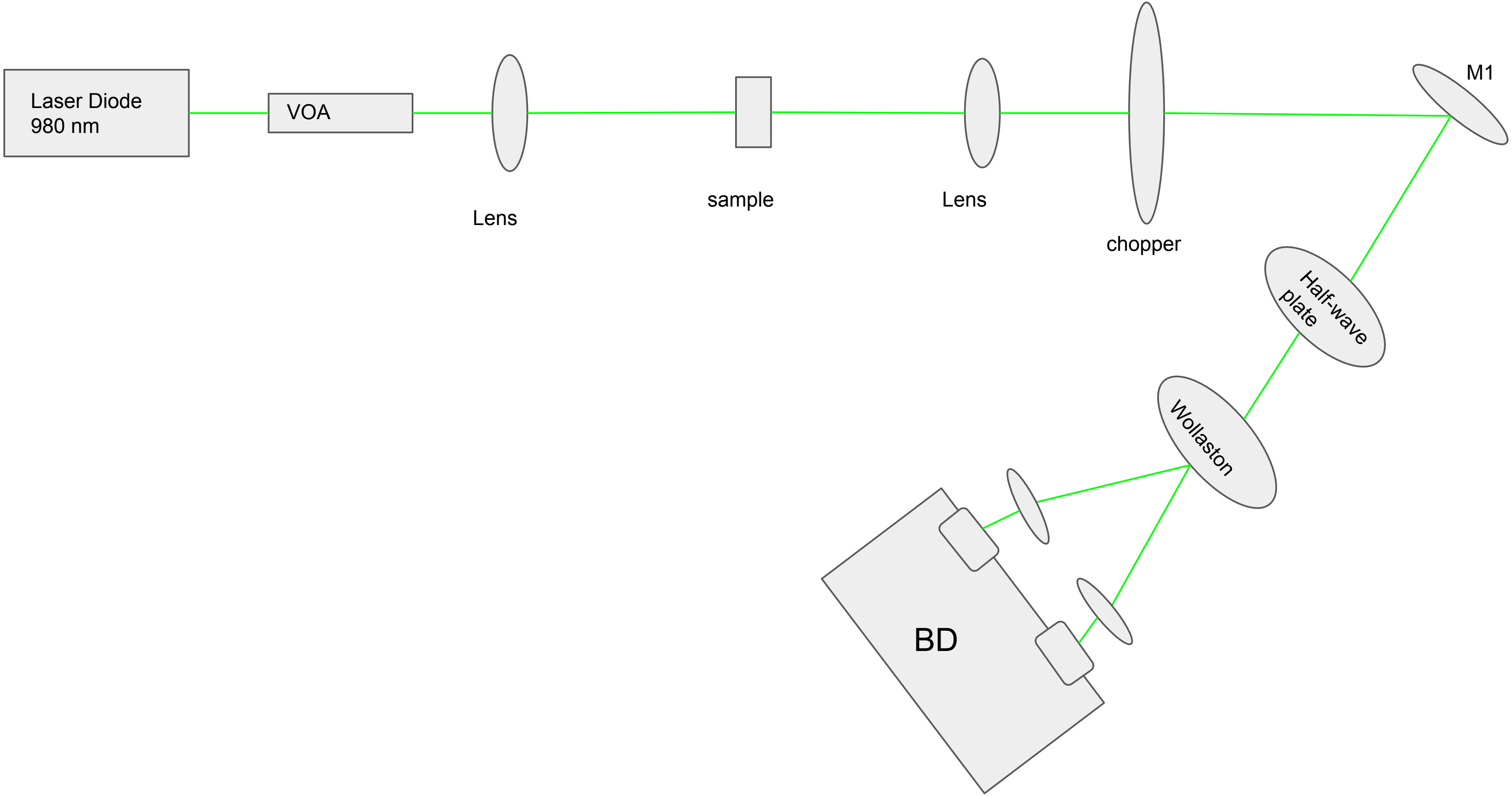
Collimator: F230FC-1550

SQL Source

Char. of SQL Grating Setup



Updated Magnetometer Setup



Ideal SQL signal as seen on oscilloscope for polarization tuning purposes