

i

lab 1 Session 1: SF

O. Prelab Q 1:

- a) Given a 5mm diameter field of view at the object, what diameter should the iris at field stop be set to? Under Köhler illumination.

→ Note Given that in Köhler illumination. Field stop (FS) is imaged onto object plane by field lens ($L_2, f_{\text{field}} = 50\text{mm}$) and Condenser lens ($L_3, f_{\text{condenser}} = 100\text{mm}$). This is the 4-focal system

$$\text{Magnification, } M_{\text{im}} = \frac{f_{\text{condenser}}}{f_{\text{field}}} = \frac{100\text{mm}}{50\text{mm}} = 2$$

field stop \rightarrow object

$$\rightarrow \text{Illuminated diameter: } D_{\text{obj}} = M_{\text{field}} D_{\text{Fieldstop}}$$

$$D_{\text{FS}} = D_{\text{obj}} = \frac{5\text{mm}}{2} = 2.5\text{mm}$$

is the value we must set the iris diameter

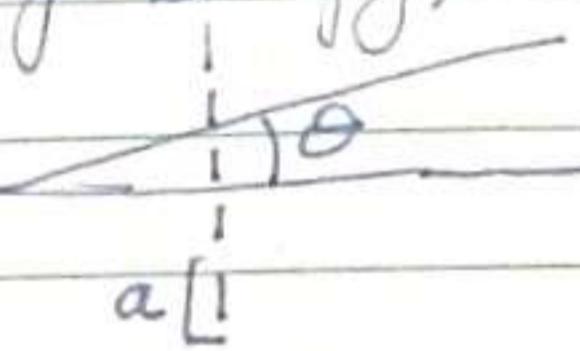
Then fine tune while watching object illumination

ii

- b) To resolve diffraction orders clearly from 10 lp/mm Ronchi ruling, what pinhole diameter at the aperture stop should be used so that diameter (FWHM) of each diffraction order peak is $\approx 1/10$ of the spacing between adjacent orders?

→ For a grating of period a , the diffraction angles satisfy,

$$\sin \theta_m \approx \theta_m \approx \frac{m\lambda}{a}$$



→ In the Back focal plane of objective / Fourier plane, transverse position is $x_m \approx f_g \theta_m \approx f_g \frac{m\lambda}{a}$

So spacing between adjacent orders is:

$$\Delta x = x_{m+1} - x_m = f_g \frac{\lambda}{a} (m+1) - f_g \frac{\lambda}{a} m$$

$$\Delta x = \frac{f_g \lambda}{a} (m+1-m) = \boxed{\frac{f_g \lambda}{a}}$$

Recall: $f_g = 150 \text{ mm} = 0.15 \text{ m}$, $\lambda = 525 \text{ nm} = 525 \times 10^{-9} \text{ m}$

$$a = 1 \times 10^{-4} \text{ m}$$

$$\therefore \Delta x = 0.15 \times 525 \times 10^{-9} \text{ m} = 7.875 \times 10^{-9} \text{ m} = 0.7875 \text{ mm}$$

$$\text{So target FWHM: } \omega_{\text{target}} = \frac{1}{10} \Delta x \approx 0.07875 \text{ mm}$$

→ Approximate the diffraction-limited spot size at Fourier plane as the airy disk FWHM for circular pin hole aperture: $\text{FWHM}_x \approx 1.03 \frac{\lambda f}{D_{\text{pin hole}}}$

$$D_p$$

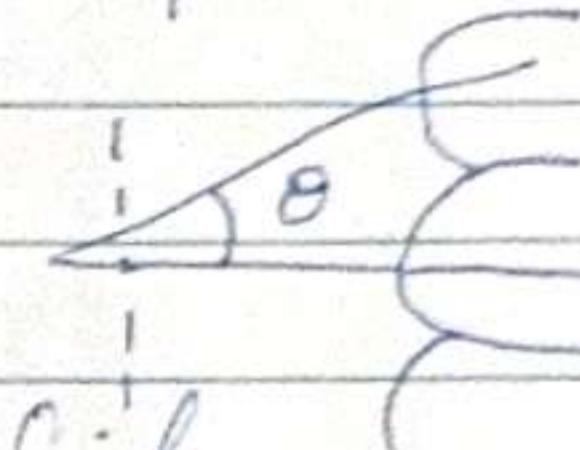
iii

c)

Spectral Broadening of grating order

For a Ronchi ruling (transmission grating) with pinhole

$$d \sin \theta_m (\lambda) = m \lambda$$



if illumination is not monochromatic but has a finite spectral width $\Delta \lambda$ around central λ_0 , then the same diffraction order is produced at slightly different angles for different wavelengths.

For small bandwidth, the angular spread is approximately

$$\Delta \theta_{\text{spec}} \approx \left| \frac{\partial \theta_m}{\partial \lambda} \right|_{\lambda_0} \Delta \lambda \quad (1)$$

→ Taking differential: $d \cos \theta_m \times \frac{\partial \theta_m}{\partial \lambda} = m$

$$\therefore \frac{\partial \theta_m}{\partial \lambda} = \frac{m}{d \cos \theta_m}$$

So spectral contribution to FWHM is:

$$\Delta \theta_{\text{spec}, m} \approx \frac{m}{d \cos \theta_m} \Delta \lambda$$

* The zero order ($m=0$) does not move with wavelength, so it has no spectral broadening. It's observed FWHM is set by the imaging/illumination angle, dominated by aperture-stop pin hole.

iv

①

For a circular pinhole of diameter a , the far-field pattern is an Airy disk. $\Delta\theta_0 \approx 1.03 \cdot \frac{\lambda_0}{a}$

from Airy disk formula for circular aperture FWHM.

If the total FWHM of the m -th order is dominated by both aperture diffraction: $\Delta\theta_0$ & spectral broadening $\Delta\theta_{\text{spec},m}$

The total width is $\approx \Delta\theta_m = \sqrt{\Delta\theta_0^2 + \Delta\theta_{\text{spec},m}^2}$

$$\Rightarrow \text{To find } m, \Delta\theta_m = 2\Delta\theta_0$$

$$\Rightarrow \sqrt{\Delta\theta_0^2 + \Delta\theta_{\text{spec},m}^2} = 2\Delta\theta_0 \Rightarrow \Delta\theta_{\text{spec},m}^2 = 3\Delta\theta_0^2 \Rightarrow \Delta\theta_{\text{spec},m} = \sqrt{3}\Delta\theta_0$$

$$\text{Plug } \Delta\theta_{\text{spec},m}: \frac{m}{d\cos_m} \Delta\lambda = \sqrt{3} 1.03 \cdot \frac{\lambda_0}{a}$$

Assuming small θ_m , $\cos\theta_m \approx 1$

$$m \approx \sqrt{3} \times 1.03 \cdot \frac{\lambda_0 d}{a \Delta\lambda} \approx 1.78 \cdot \frac{\lambda_0 d}{a \Delta\lambda}$$

$$\Rightarrow \text{From question: } \Delta\lambda = 30 \text{ nm} = 30 \times 10^{-9} \text{ m} \quad d = 200 \mu\text{m} = 200 \times 10^{-9} \text{ m} \\ a = 100 \mu\text{m} = 100 \times 10^{-9} \text{ m}$$

$$m = \frac{1.78 \times 525 \times 10^{-9} \times 200 \times 10^{-9}}{100 \times 10^{-9} \times 30 \times 10^{-9}} = 62.3$$

but should be more like 6.2 (extra m
so 7th order).

This provides a practical limit on how high a diffraction order can be reliably used: At low orders, spectral broadening is small, peaks are narrow & sharp. At high orders, angular dispersion scale with m , so finite LED Bandwidth causes each order to spread out more.

Lab Session 1: Spatial Filter (Exploring the Equipments)

Date: Thursday, 08-Jan-2026, Lab Partner: Nathan
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1. Goals

a) Short Term goals:

- i) Create a good sketch of the overall setup
- ii) Set up the camera & Software, understand the gain & exposure parameters enough for a sharp image
- iii) Find the right position to place magnification lens for sharpening
- iv) Keep a look out for sources of uncertainty because this is a very sensitive experiment.

②

b) Long Term Vision

- i) Complete Setup inside Lab Setup 1, familiarize with equipment
- ii) Familiar all information regarding the components in Pre lab Question 1.
- iii) Explore real space imaging using the line grating test object
- iv) Finish Lab 1 Testing
- v) Ensure beam & lens are centered also with camera
- vi) Think about what we need for Lab 2.
- vii) Review Fraunhofer diffraction & relationships in Fourier transform
- viii) Understand CMOS Camera factors like exposure time, gain, -

2. Apparatus

Rail:

- ↳ Optic Rail & Saddles
- ↳ Posts: 3", 4", 6"

Translational Stages (for microscope stage/ filter positioning)

Sources & Cameras:

- ↳ LED Source ($\lambda = 525\text{nm}$) (Bandwidth 25nm) LED S2SL
- ↳ Real-space camera (FLIR Blackfly) on 6" post Imaging / Illuminatio Optics
- ↳ Magnifier lens ($f \approx 300\text{mm}$, marked ∞) Schenck double lens
- ↳ Objective lens ($f = 150\text{mm}$) ↳ field lens ($f = 50\text{mm}$) plano-convex

achromatic doublet

- ↳ Condenser lens ($f \approx 50\text{mm}$) ↳ 0.5" iris (small field stop)
- ↳ 200 μm pinhole on XY translation mount (aperture stop) LM XY mount
- ↳ Large iris (Block stray light)
- ↳ Lens tube, CCD cover disk

Test Object:

- ↳ Variable line grating (Thorlabs) !! Do not touch with Bare Hands !!

Software:

- ↳ NI Vision Assistant ↳ Lab View Program: Dual_Camera_Lens_Profile v2.vi

(3)

3. Sketch

fig 1°

LED

(L1)

Collector lens

(FS)

Field Stop

lens

f1

20 cm from Rail

4.

f2

f3

f4

f5

f6

f7

f8

f9

f10

f11

f12

f13

f14

f15

f16

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f18

f19

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f153

f154

Pinhole
(AS)
Aperture Stop(L₁)
Collector
lens(L₂)
Condenser
lens(F₁)
Field
Stop(L₃)
Field
lens

Objid

Grating

Focu
PlaneOPTIC
Magnification

AX18

f₁f₂f₃f₄f₅f₆f₇f₈f₉f₁₀f₁₁f₁₂f₁₃f₁₄f₁₅f₁₆f₁₇f₁₈

(4)

7. i) Some Useful Background Theory

* Kohler Illumination Brief:

⇒ Field stop (controls illuminated area at object)

⇒ Pinhole (aperture stop) controls angular extent / coherence of illumination.

⇒ Field lens forms an image of LED onto aperture stop.

* Diffraction grating relation: $d \sin \theta_m = m \lambda$

d = grating spacing (m), θ_m = diffraction angle for order m

λ = LED emission wavelength

ii) Background on the Variables in the lab.

Independent variables (we change):

→ Pinhole diameter (aperture stop) → Condenser lens position

→ Field stop iris (set illumination field) → Grating/object position

Dependent Variables (we expect to measure):

→ Max lp/mm we resolve on the grating (resolution limit)

→ Diffraction order Spacing

Control Variables (we keep fixed):

→ LED Source, $\lambda = 525\text{nm}$ → Room light Blocked

→ lens choices

(5)

8.

Detailed Procedure.

8.1) Initial placement of LED + collimator lens.

Established the far end of the rail as the one near door to limit light from outside into the setup

Placed LED + collimator lens on far end of rail (≈ 20 cm from end of rail). Measured using scale on railing

Set height of the LED source as 21.5 ± 0.05 cm take into account for end of railing ref.

Ensured LED source sits right over the center of the rail.

& that the beam propagates approx. on centre of line. ✓

Quickcheck:

Check:

To adjust the collimator, we adjust so the image of the LED chip is in clear focus when we flip the source & project onto a $\sim 5\text{m}$ away wall it looks as sharp as we can. without a clear waist focus or along the rail.

No waist focus; so we diverge & never converge.
Showing it is collimated enough.

8.2) Ensure Software is able to show image.

Verified the program on LabView, Rud-Camera-Line-Profil v2.vi on the pc desktop.

It shows two panels.

Use Exposure 900ps, 1 Gamma & 18 gain

Mounted the camera on a 6 inch pole, 30 cm on the other side (opposite side to LED).

TIP: the size of the base saddle is 3 cm. So if you want the camera to be at 30 cm. you must set 28.5 & 31.5 on either side

⑥

Quick Check:

Make Sure CCD face is exposed by removing the lens tube.

- * Rotate the Source after Putting a post collar & adjust height of camera post 21.5 ± 0.05 cm
→ Used a Ruler to measure.

8.3) Aligning magnification lens

* Magnification lens 30 cm in front of camera (Between Camera & Source). The lens is of $300\text{mm} = f$. Use "4" post

Move curved part of magnification lens toward the source.

The ∞ symbol or lens is away from camera. After making the position of LED with empty saddle & Remove LED post.

We moved the magnification lens until the image is sharp on a white card at $\approx 71.5 \pm 0.05$ cm on rail.

Success: We found a sharp focus with lens centered & equipment square to optic axis. The Image Confirms this ✓

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9. Post lab 1 Reflections :

* We found it very difficult to focus the light through a minor lens to camera.

* We spent too much time on set up so we now try to only do rough set up & then go back fine tune for accuracy

Goals Review: (Refer to Pg 1-2)

a) Short Term goals : Everything from sketch(i) to position of magnification lens was found (iii). But iv) the uncertainty we lost time and could only explore uncertainty of the optics rail. Must find more uncertainty next lab.

b) Long Term goals : Seems like we were a bit ambitious.

It precision needed in the equipment set up meant we did we were slow to do the placement of and adjustments.

i) We did not finish Set up 1 ✗

ii) Partially familiarized with information needed for pre lab 1 -

iii) We explored real space imaging but only with half the set up ✗

iv) Could not Reach Testing ✗

v) Yes Beam, lens, camera were well aligned ✓

vi) Limited Thoughts on Lab 2, focus remains on Lab 1

vii) Learned Fraunhofer Diffraction but is only relevant for pre labs

viii) Understood CMOS Camera, features & exposure time ✓

(8)

To do next lab :

Complete goals incomplete in last page

Move to the next part of lab Setup 1, specifically add objective lens, image grating object, place pin hole and as specified by the lab script while all the elements are co-linear and square to the rail.

(a)

1. Goals : i) Complete Lab Setup 1 following the post lab Reflections on (page 7-8) of lab notebook.
- ii) Explore Uncertainty Sources.
- iii) Familiarize information for pre lab 1
- iv) Explore real Space imaging but with full set up.
- v) Reach & Do the Testing of the Setup to Qualitatively Verify the Set up.
- vi) Add Objective lens, pin hole
- v) Image the grating object & Resolve a grating $> 10 \text{ lp/mm}$

2. Apparatus, sketch & Reference : Same as Lab Session 1 : Refer to page 2-3 of notebook.

3. Procedure conducted :

3.1) Verify the old set up & distances.

Focus on a new object & verified the distance of the focal length as recorded by lab script pg 30.

Objective lens at $60.5 \pm 0.05 \text{ cm}$ from Start of rail.

Open the Dual-Camera-line-Profile-v2.vi or NI Vision Accretion Software. This is the default software file on the Desktop.

→ Set Gamma = 1

→ Disable Auto Gain, set gain as 18

→ Disable Exposure Auto,

→ To do this open Block Diagrams in NI Vision, click on Vision Accretion 1. Change the Value of Auto Gain & Auto Exposure as off.

Adjust and Set Sharpness & Contrast

Final: Exposure Time : 12000 μs

Gamma: 1 Grain is 18. (no need to change)

Lab Session 2: Spatial Filtering (Finishing Set up 1)
Date: Thursday, 8-Jan-2026. Lab Partner: Nathan

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4.1) Error Identification for Uniform illumination

4.2) Sosio theory & Explanation of Errors

4.3) Corrections made

5) Post lab 2 Reflection:

6) Goal Evaluation & what to do next lab

(10)

- 2:15 PM Return LED Source to previous position on the Rail, at 20 ± 0.05 cm away from end of Rail
 → Verify it is aligned to the centre of rail

3.2 Place Objective lens

- Place a new $f = 150$ mm lens, at 45 cm from magnification lens to Right. Centre-to-centre
 → ie place new lens at 45cm + 60.5 cm on the Rail
 $\text{mark} = 105.5 \pm 0.05$ cm
 → Left Height of lens to make rays go through center of lens. Centre Horizontally & Vertically.
 → Note: The 150mm lens must be having a fine zoom control Silver colour on the lens.
 → Tip, look at the shadow with LED on, PL The camera must be co-centric to the lens aperture

3.3 Place Test object & View object on Screen

Place Variable line grating object on the translating microscope stage objective, facing the objective to the metallic coating on the grating. Saddle of "3".

(Test object)

The grating had a Thor Lab test on it, we try to focus on that!

The position of grating at best focus is 123.5 ± 0.05 cm
 Exposure time 3000 ps, Gamma = 1 & Gain is 18

(11)

Now, adjust the vertical & horizontal fine course dial until you see > 10 LP/mm.

Success: → We were able to make 12.5 LP/mm.

3.4 Place Condenser lens

Placing Condenser lens $f \approx 100$ mm, at 100mm or 10 cm from the grating i.e. rail at 134 ± 0.05 cm Centre the lens by ensuring the illuminated part of the object seen is centred in the camera mag. lens. Focus the object.

Need to use small Hex Ball driver to loosen the set screw on the lens mount for the Condenser lens to Centre the lens, reighten the screws to secure the position.

3.5 Place pin hole & Align with mirror

The 200pm pin hole is already on the LM1 XY translating mount & it is centred.

Place it Right of Condenser lens at 10 ± 0.05 cm away from lens on the Source Side.

→ Ensure pin hole shadow is centred on Condenser lens using the X, Y knobs.

Tip place a white card after the Condenser lens to observe the image to Centre it

Place the Blue coated or one side mirror, 10 ± 0.05 cm from the condenser lens & auto collimate, i.e., observe the back reflection onto the pinhole. Make dots concentric.

Quick Check

Make Sure: Illumination Beam remains centred on the line of the object & stays centred on objective & CCD.

(12)

Insert $f = 50\text{mm}$, condensor lens to image LED source onto pinhole (focus it).

"LED image focused onto aperture stop. (pinhole)

→ Remove pinhole by uncoupling it from the mount
But keeping the saddle, i.e., 144 ± 0.05 cm
as rail.

→ Adjust field lens height to keep Beam centered at object & objective.

⇒ Real field lens is $50\text{mm} = f$, plano convex lens.

Replace pinhole & confirm LED image is focused onto pinhole

3.6 Place field Stop Iris

3:35 PM - Placed 0.5" iris (field stop) (ID 12, small diameter)
as adjustable field stop.

⇒ Centered it on Beam.

⇒ Temporarily removed pinhole to focus the sharp edges of the iris on the camera image by sliding iris along rail.

This was closest to the 50mm lens "field lens" we could get to.

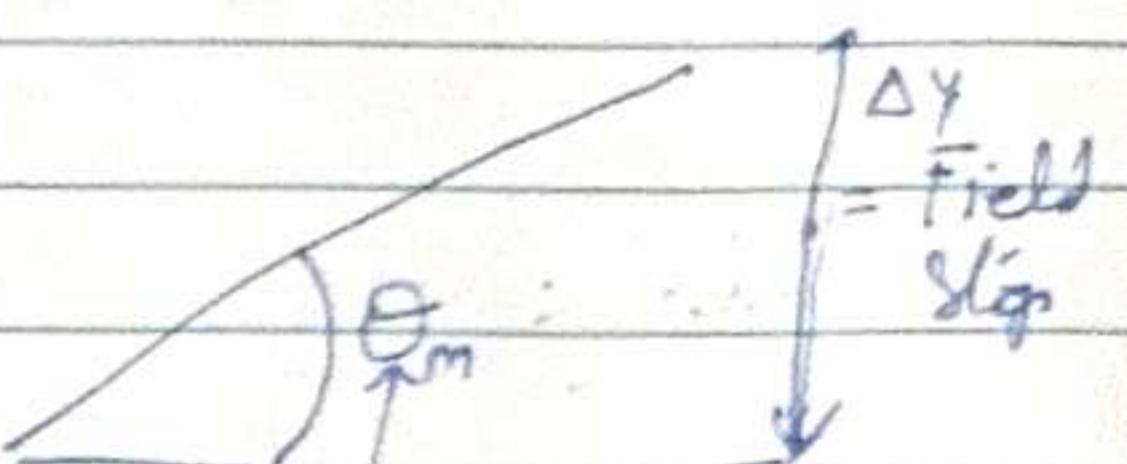
At smallest aperture, the centre of iris should be on the camera centered too.

Reduce the iris to get $\sim 5\text{mm}$ illuminated field at the grating.
Use a white black card to see this field of view.

(13)

Explaining Theory for our Observations (Note)

Note: Field stop controls illuminated area on the object, aperture stop controls the effective 'size' of the object's size.
So control diameter angular exalt.



Aperture Stop

3.7 Final elements to Block stray light

Finally add a large mounted iris in on the Source side after field iris to reduce stray LED light Beams.

Add a lens tube to the camera to Block ambient room light

4.1 Error Identification for Uniform illumination

When Iris is reduced to $\sim 5\text{mm}$ illumination on the grating.
We did not observe uniform illumination \geq .

→ On the top left corner There was a clear gradient.

We thought it was a screen glare from room but nope even with dark door it remained.

Professor Paul assisted us,

→ We observed that even if we placed a white card after each element. We could see exactly where the non uniform illumination started.

→ So, LS & L4 were pointing the wrong direction
→ Because one lens was rotated too much, each element after that tried to correct it But this caused more & more error.

"Curious why this Makes non-uniform illumination" !! Sketch Behind →

Errors :

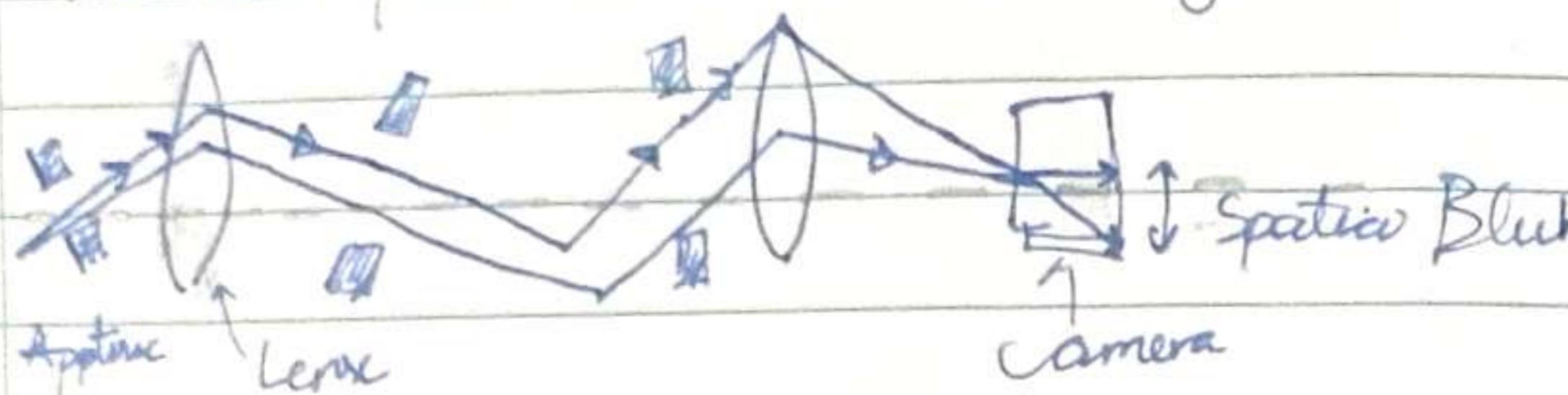
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4.2

Sone Theory & Explanations of our Errors.

Incorrect placement sketch (Rough & Inaccurate)

fig 2:



Observe How mis placed lenses & apertures cause some light to travel more: Optical path length changes so light focuses on different points!

This is what causes the non-uniform illumination

4.3

Correction: Make all of them aligned & co-centric

TIP:

Learnings

Do not need to remove all the elements & saddle!
If the focus is right, the issue is just the rotation of the elements.

So, You can unscrew the element (like lens) from its holder mount while the post & saddle are in place.

So unscrew element by element towards the same until the illumination on a card is uniform.

4.4

Probable sources of errors:

lens focus points

Railings, it is really straight?

In proper lens position

camera accuracy.

15

5.

Post lab 2 Reflection:

In Post lab 1 reflections (Pg) we noticed that we were too slow & Behind expected Schedule. To compensate we tried to do rough placements this lab but as professor Paul noted this has led to some issues causing non square alignment of saddle.

DO:

We also noted that next lab, we should have a better sketch for the experiment. One that has both the aspect rotation distances of components But also the direction they point in.

The main issue was that we had one aperture rotated off centre & that caused all following lenses & apertures to be rotated. But !! We learnt cool tricks to just remove the lens (unscrew it) from its holder & then go back to an earlier stage of the experiment. Super cool! I am impressed by how modular the optics lab is ! :)

To clarify

ASK →

Clarify the distances on the grating before next lab.

Ask →

How to speed up experiment?

Ask →

Documentation for the Rail Train

Ask →

I think I went the lens manufacturing documentation to find the errors in the lens. ??

Find →

Lab View & Camera Accuracy.

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6. Goal Evaluation & what to do next lab

- We completed the lab set up but we found errors.
Next lab we must redo this set up strategically to correct this.
- We found & thought of the sources of errors but not Quantitatively. Try to do this next lab
- We roughly explored the equipments needed for Pre lab 2 like Rabi Ruling
- Explored Real Spacing with full set up
- Was not able to do the Testing, Next lab after doing corrections we will do this
- Added objective lens & pinhole elements ✓
- We imaged 12 lp/mm ✓ (max 11 and 10 lp/mm). We almost went to the 15 lp/mm but it was a little too blur

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For logistical Reasons, the next lab would be the "Lab Period 2" even though technically would be the third week of lab.

D. Pre lab Question 2

*Rabi Ruling consists of a series of long parallel slits (slit width, b) & (period, a)

→ Monochromatic light incident on object diffracts & forms far-field (Fraunhofer) diffraction pattern

$$\Rightarrow \text{Eq. 32: } I(\theta) = I_0 \left(\frac{\sin B}{B} \right)^2 \left(\frac{\sin N\alpha}{N\sin \alpha} \right)^2$$

where $\alpha = \frac{ka}{2} \sin \theta$, $B = \frac{kb}{2} \sin \theta$, $K = 2\pi$ (Source lab Script pg 11)

→ Starting from the lab Script's eq 30; in 1D Fraunhofer field at angle θ , the field intensity is proportional to the Fourier transform of the aperture / mask function $a(x')$ or $f(x')$ or $\Pi(x')$
"This lab script uses $a(x')$, lesson uses $f(x')$ while $\Pi(x')$ "

$$\therefore \text{Eq. 30: } E(x) \propto \int_{-\infty}^{\infty} a(x') e^{i k x' x} dx'$$

$$\text{or using } u = K\theta x; E(\theta) \propto \int_{-\infty}^{\infty} a(x') e^{i K \theta x' x} dx'$$

In the paraxial approximation & small angle Regions (Remember we are quite far away from the mask) $\theta_x \approx \sin \theta$ & $u = K\theta_x \approx K \sin \theta$

$$\therefore E(\theta) \propto \int_{-\infty}^{\infty} a(x') e^{i K x' \sin \theta} dx'$$

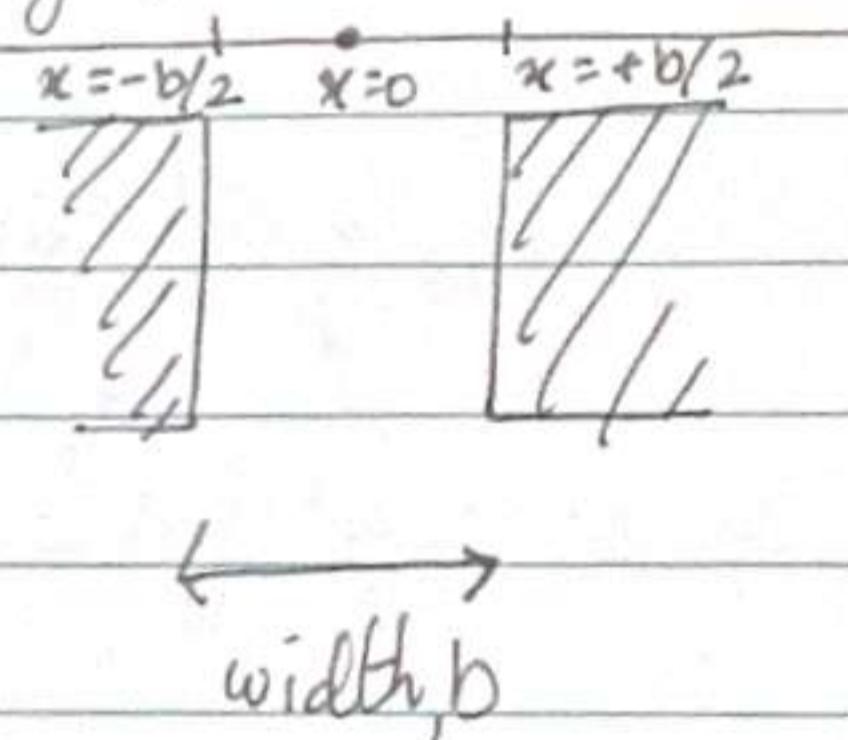
(18)

Now let a single slit of width b centered at $x'=0$.
Its single aperture function for transmission would be.

$$\Pi(x') = \begin{cases} 1, & |x'| \leq b/2 \\ 0, & \text{otherwise} \end{cases}$$

Do not panic! all this says is, if your light beam is positioned between the slit (ie it is not blocked by the slit, it passes through) other wise it is blocked & no light

See here →



if you are between slit
you pass.
Sketch

Moving on,

The Fourier transform for a single slit would be the following. (we do a single slit Fourier transform instead of the full pattern because using a dual comb we can just later on use properties of F.T (Fourier Transform) to multiply.)

Convolution in object space is multiplication in the Fourier space.

$$E_1(\theta) \propto \int_{-\infty}^{\infty} \Pi(x') e^{-i k x' \sin \theta} dx' = \int_{-b/2}^{b/2} e^{-i k x' \sin \theta} dx'$$

$$\begin{aligned} \text{Note: } \frac{e^{i\theta} - e^{-i\theta}}{-i} &= 2 \sin \theta \quad \text{use} \\ \frac{e^{i\theta} - e^{-i\theta}}{-i} &= 2 \sin \theta \end{aligned}$$

$$\Rightarrow = \frac{e^{-i k x' \sin \theta}}{-i k \sin \theta} \Big|_{-b/2}^{b/2} = \frac{e^{-i k (b/2) \sin \theta}}{-i k \sin \theta} - \frac{e^{+i k (b/2) \sin \theta}}{-i k \sin \theta}$$

$$= 2 \sin(Kb/2 \sin \theta), \text{ now let } \beta = \frac{Kb \sin \theta}{2}$$

$$E_1(\theta) \propto \frac{b \sin(\beta)}{\beta}, \quad \beta = \frac{Kb \sin \theta}{2}$$

This is the envelope function

(19)

Quoting Lipson (pg: 245 - 247)

A diffraction grating is given by

$$f(x) = a(x') \otimes \sum_{n=0}^{N-1} s(x-na) \quad (\text{eq 8.53 Lipson})$$

↑
Single Aperture Mask ↓
Diffraction of Light
slits

a , line spacing (period)
 N , Total nos of slits

The Intensity or the Diffraction Pattern is The F.T.

$$\Rightarrow I(u) = |E(u)|^2 = \mathcal{F}\{f(x)\}$$

$$\mathcal{F}\{f(x)\} = E_1(\theta) \times \sum_{n=0}^{N-1} e^{-i n u a} \quad (8.45) \quad u = \frac{2\pi}{\lambda} (\sin \theta - \sin \theta_i)$$

Note $\sum_{n=0}^{N-1} e^{-i n u a}$, as $N \rightarrow \infty$, the sum is, $\sum_{m=-\infty}^{\infty} s(u - 2\pi m/a)$

The index m is called order of diffraction. When $m=0$, N is first. The geometric series becomes, $= \frac{1 - e^{-i u Na}}{1 - e^{-i u a}} \quad (8.47 \text{ Lipson})$

$$\text{The intensity, } I(u, v) = \left| \frac{1 - e^{-i u Na}}{1 - e^{-i u a}} \right|^2 = \frac{\sin^2(u Na/2)}{\sin^2(u a/2)}$$

Now again $\alpha = ka \sin \theta = ua$ is how we define in this lab (look at Lab Script pg 22)

Singl Slit Repeating Slits

∴ The total Amplitude becomes: $E(\theta) \propto \frac{\sin \beta}{\beta} \frac{\sin(N\alpha)}{\sin(\alpha)}$

$$\text{Total Intensity } I(\theta) \propto |E(\theta)|^2 \propto \left(\frac{\sin \beta}{\beta} \right)^2 \left(\frac{\sin(N\alpha)}{\sin(\alpha)} \right)^2$$

$$I(\theta) = I_0 \left(\frac{\sin \beta}{\beta} \right)^2 \left(\frac{\sin(N\alpha)}{\sin \alpha} \right)^2 \quad \text{If you let } N=2$$

Singl Slit Envelope (P. diffraction)

You get Young double slit effect.

Pre-lab Question 2

Your Ronchi ruling consists of a series of long parallel slits (slit width b , period a). Monochromatic light incident on the object diffracts and forms a far-field (Fraunhofer) diffraction pattern.

(a) Derive Eq. (32) for the far-field diffraction intensity pattern of N slits.

(b) Make sample plots for different values of N and a , and describe qualitatively how each parameter affects:

- the spacing between diffraction orders,
- the width of diffraction peaks,
- and the overall envelope of the pattern.

(c) Explore the effect of varying the duty cycle b/a . How does it affect the relative intensity of diffraction orders (including which orders may be suppressed)?

(d) In the experiment, diffraction orders will not be perfectly sharp and may broaden with order. Briefly explain at least two physical reasons why a real diffraction pattern may deviate from the ideal prediction of Eq. (32). (Hint: consider finite source size, finite spectral bandwidth, and imperfect alignment/aberrations.)

Eq. (32):

$$I(\theta) = I_0 \left(\frac{\sin \beta}{\beta} \right)^2 \left(\frac{\sin(N\alpha)}{N \sin(\alpha)} \right)^2$$

Where:

$$\alpha = \frac{k a \sin \theta}{2}, \quad \beta = \frac{k b \sin \theta}{2}, \quad k = \frac{2\pi}{\lambda}$$

B)

Make sample plots for different values of N and a , and describe qualitatively how each parameter affects:
• the spacing between diffraction orders,
• the width of diffraction peaks,
• and the overall envelope of the pattern.

$$I(\theta) \propto \left(\frac{\sin(N\alpha)}{N \sin(\alpha)} \right)^2$$

```
In [9]: import matplotlib.pyplot as plt
plt.style.use('dark_background')
import numpy as np
```

Note:

Here a is the grating period of the Ronchi ruling and b is the slit width (close to $b = a/2$, but it may differ slightly). (LabScript: Pg 11)

```
In [10]: def I(theta, N, a, lam=None, I0=1.0):
    """
    theta : array of angles (rad)
    N    : number of slits
    a    : grating period (m)
    lam  : wavelength (m), default 525 nm
    I0   : overall I scale
    """

    lam = (lam or 525) # nm (Lab Script Pg 22)
    lam = lam * 10**(-9) # m
    b = a/2 # (Lab Script Pg 11 and inspired by code in Pg 12)

    k = 2*np.pi / lam
    alpha = 0.5 * k * a * np.sin(theta)
    beta = 0.5 * k * b * np.sin(theta)

    single_slit = (np.sin(beta) / beta)**2
    interference = ((np.sin(N*alpha) / (N*np.sin(alpha)))**2

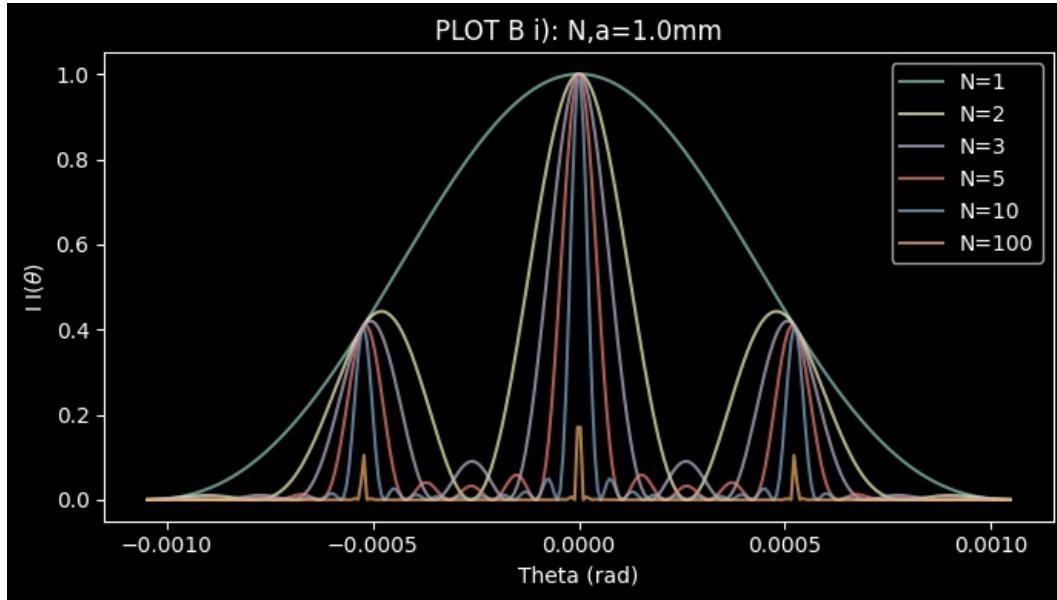
    return I0 * single_slit * interference
```

i) Keeping a constant, Changing N

```
In [11]: theta = np.linspace(-np.pi/3000,np.pi/3000,300)
N_lst = [1,2,3,5,10,100] # different numbers of slits
a_lst = [1,10,100,1000] # mm

# Keeping a constant, Changing N
#plt.subplot(1,2,1)
plt.figure(figsize=(7,4))
for i in range(len(N_lst)):
    a = a_lst[0]
    a = a * 10**(-3) # m
    #plt.subplot(len(N_lst),2,i+1)
    # sharex = True
    plt.plot(theta, I(theta,N=N_lst[i],a=a) , label=f"N={N_lst[i]}",alpha=0.7)

plt.title(f"PLOT B i): N,a={a*1000}mm")
plt.xlabel("Theta (rad)")
plt.ylabel(r"I I$(\theta)$")
plt.legend()
plt.tight_layout()
plt.show()
```



ii) Vary a at fixed N

```
In [12]: theta = np.linspace(-np.pi/300,np.pi/300,3000)
plt.figure(figsize=(16,8))

N = N_lst[0]

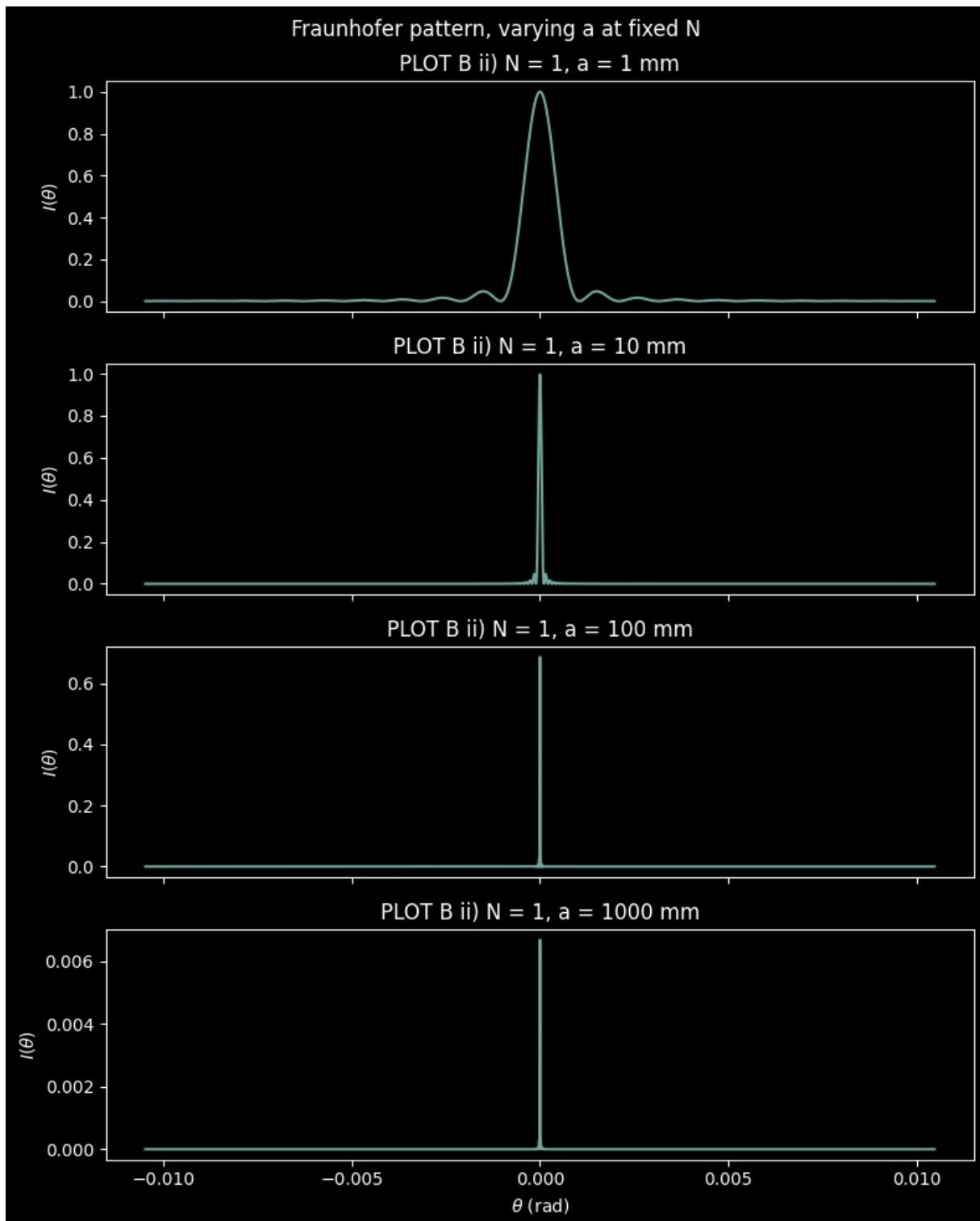
fig, axs = plt.subplots(len(a_lst), 1, figsize=(8, 10), sharex=True)

for i, a_mm in enumerate(a_lst):
    a = a_mm * 1e-3 # convert mm -> m
    I_vals = I(theta, N=N, a=a)

    axs[i].plot(theta, I_vals, alpha=0.8)
    axs[i].set_ylabel(r"$I(\theta)$")
    axs[i].set_title(f"PLOT B ii) N = {N}, a = {a_mm} mm")

axs[-1].set_xlabel(r"$\theta$ (rad)")
fig.suptitle("Fraunhofer pattern, varying a at fixed N", y=0.98)
fig.tight_layout()
plt.show()
```

<Figure size 1600x800 with 0 Axes>



iii) Grid

```
In [13]: # Angle range (rad) – chosen to show several diffraction orders
theta = np.linspace(-5e-3, 5e-3, 2000)    # ~±0.3 degrees

# Columns: different N
N_list = [2, 5, 10, 20]
```

```

# Rows: different grating periods a (in mm)
a_list_mm = [0.1, 0.2, 0.5, 1.0] # adjust to taste

# -----
# Create grid of plots: rows = a, cols = N
# -----


n_rows = len(a_list_mm)
n_cols = len(N_list)

# A4 in landscape: about 11.69 x 8.27 inches
fig, axes = plt.subplots(
    n_rows,
    n_cols,
    figsize=(11.69, 8.27),
    sharex=True,
    sharey=True
)

# If there's only one row/col, make axes always 2D-indexable
axes = np.atleast_2d(axes)

for i, a_mm in enumerate(a_list_mm):
    a_m = a_mm * 1e-3 # convert mm -> m
    for j, N in enumerate(N_list):

        ax = axes[i, j]
        I_vals = I(theta, N=N, a=a_m)

        ax.plot(theta, I_vals, lw=1.0)

        # Top row: label with N
        if i == 0:
            ax.set_title(f"N = {N}", fontsize=10)

        # First column: label with a
        if j == 0:
            ax.set_ylabel(f"a = {a_mm:.2f} mm\nI(θ)", fontsize=9)

        # Keep ticks small so everything fits nicely
        ax.tick_params(axis='both', which='both', labelsize=8)

# Common x-label
fig.text(0.5, 0.04, r"$\theta$ (rad)", ha='center', fontsize=11)

# Optional overall title
fig.suptitle("PLOT B iii) Fraunhofer Diffraction of a Ronchi Ruling\n(rows: a, columns: N)", fontsize=12)

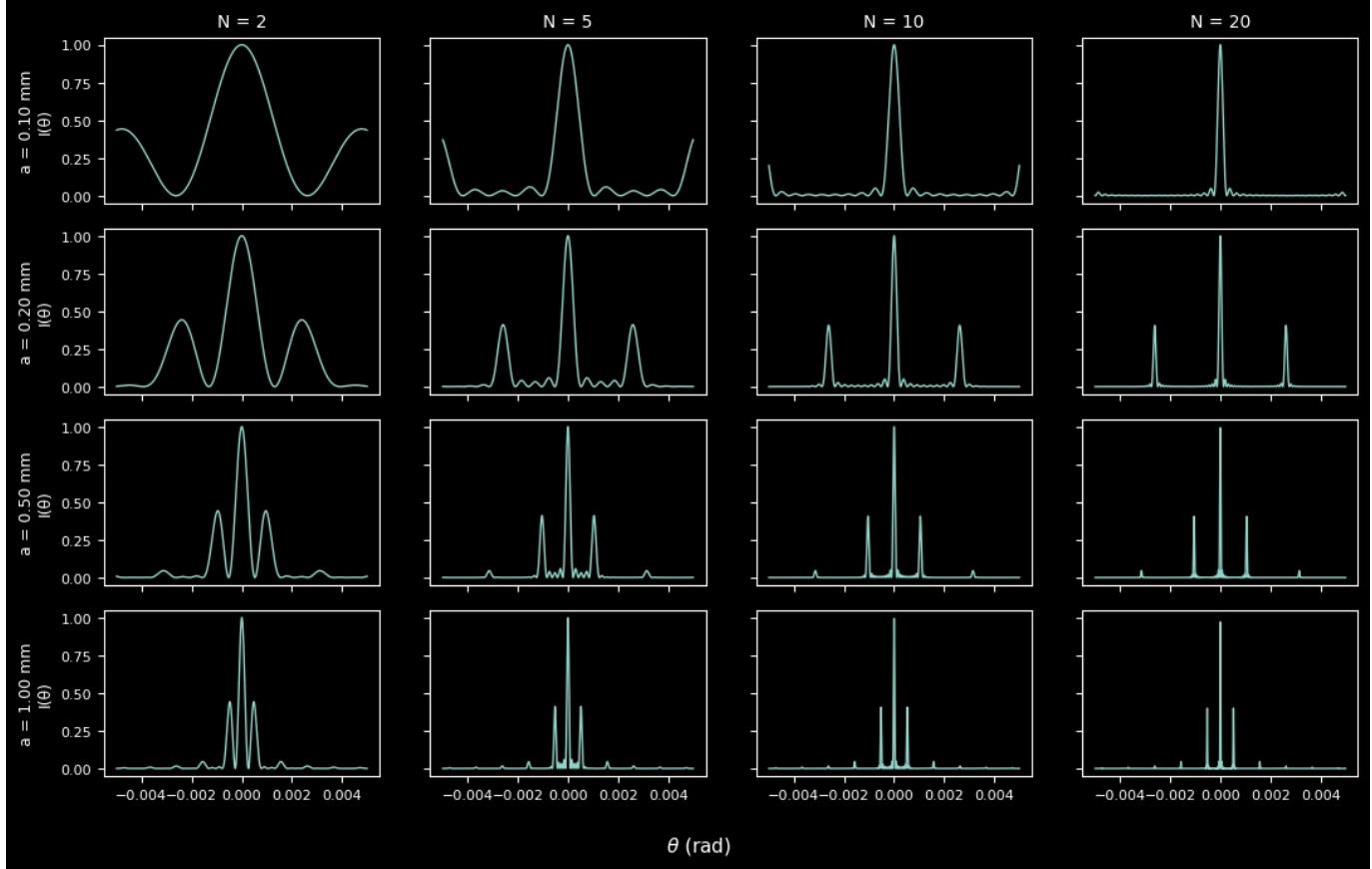
# Make layout tight for A4 printing
fig.tight_layout(rect=[0.03, 0.07, 0.97, 0.93])

# Optional: save for printing
# plt.savefig("ronchi_grid_A4.pdf", dpi=300, bbox_inches="tight")

plt.show()

```

PLOT B iii) Fraunhofer Diffraction of a Ronchi Ruling
(rows: a, columns: N)



Fraunhofer Diffraction of a Ronchi Ruling: Effect of Slit Number N and Period a

Each panel shows the normalized far-field intensity $I(\theta)$ for a 1D Ronchi ruling, modeled as a grating of N identical slits with period a and duty cycle $b/a = 0.5$ (i.e., slit width $b = a/2$).

Rows correspond to different grating periods a (in mm), and columns correspond to different numbers of illuminated slits N . The diffraction pattern is computed from the standard N -slit Fraunhofer formula:

$$I(\theta) \propto \underbrace{\left[\frac{\sin(\beta)}{\beta} \right]^2}_{\text{single-slit envelope}} \times \underbrace{\left[\frac{\sin(N\alpha)}{N\sin(\alpha)} \right]^2}_{\text{N-slit interference}}$$

Variables Defined:

- $\alpha = \frac{1}{2}k\sin\theta$
- $\beta = \frac{1}{2}kbs\sin\theta$
- $k = 2\pi/\lambda$
- $\lambda = 525 \text{ nm}$

Key Qualitative Features

- **Effect of increasing N (across columns):** The principal maxima become narrower and sharper, and the side lobes (subsidiary maxima) become more numerous but relatively weaker. This matches the behavior of the interference term: $[\sin(N\alpha)/(Ns\sin\alpha)]^2$.
- **Effect of increasing a (down rows):** The angular spacing between diffraction orders decreases approximately as $\Delta\theta \sim \lambda/a$. Larger periods produce more closely spaced peaks.
- **Single-slit envelope:** The overall envelope is set by $[\sin(\beta)/\beta]^2$. This broadens when b is smaller and narrows when b is larger. For a fixed duty cycle $b = a/2$, changing a simultaneously rescales both the order spacing and the envelope width.

Assumptions and Simplifications

Category	Description
Regime	Fraunhofer (far-field): The pattern is the Fourier transform of the aperture; no Fresnel-region effects.

(20)

b)

Plotting logic, Pseudo code

For i in range list N :

For i in range list N :

- plt. subplot(2, len(N), i)
 - plt. plot(theta, I(argument)) include i & a[0]
genet from np.linspace
 - plt.Titel(f' N {S13}

ily for a do with j.

Geometry	Scalar & 1D: Polarization, finite slit height, and 2D structures are ignored.
Light Source	Perfectly Coherent: Single wavelength $\lambda = 525 \text{ nm}$ with no spectral bandwidth.
Optics	Idealized: No lens aberrations, misalignment, detector noise, or finite pixel size.
Normalization	Per-subplot: Intensities are normalized to their own maximum for shape comparison.

Note: Under these idealized assumptions, the plots isolate the pure dependence of the Fraunhofer diffraction pattern on the grating period a and the number of illuminated slits N .

c)

Effect of varying the duty cycle b/a . How it affects the relative intensity of diffraction orders (including which orders may be suppressed).

I will be Fixing the N at 5 and $a=0.20\text{mm}$

and Vary the duty, b/a

```
In [14]: import numpy as np
import matplotlib.pyplot as plt
from fractions import Fraction as frac

def I_var_ba(theta, N, a, b_by_a, lam_nm=525, I0=1.0):
    """
    Calculates Fraunhofer intensity using the np.sinc identity.
    np.sinc(x) is defined as sin(pi*x)/(pi*x).
    """
    lam = lam_nm * 1e-9
    # s is the 'order' coordinate: (a*sin(theta))/lambda
    # When s is an integer, we are at an interference maximum.
    s = (a * np.sin(theta)) / lam

    # 1. Single Slit Envelope
    # Nulls occur when (b*sin(theta))/lambda is an integer.
    # This is equivalent to s * (b/a) being an integer.
    envelope = np.sinc(s * b_by_a)**2

    # 2. Interference Pattern
    # This identity avoids division by zero at sin(theta) = 0.
    # It normalizes the peak height to 1.0.
    interference = (np.sinc(N * s) / np.sinc(s))**2

    return I0 * envelope * interference

# --- Parameters ---
lam_nm = 525
N = 10
a_mm = 0.20
a = a_mm * 1e-3

# Define duty cycles (b/a). b must be <= a.
b_by_a_list = [1.0, 1/2, 1/3, 1/4, 1/5, 1/7]
theta = np.linspace(-np.pi/120, np.pi/120, 5000)

fig, axs = plt.subplots(len(b_by_a_list), 1, figsize=(8, 12), sharex=True)

for i, b_by_a in enumerate(b_by_a_list):
    I_vals = I_var_ba(theta, N, a, b_by_a, lam_nm)

    # Convert theta to 's' for the plot to see integer orders clearly
    s_vals = (a * np.sin(theta)) / (lam_nm * 1e-9)

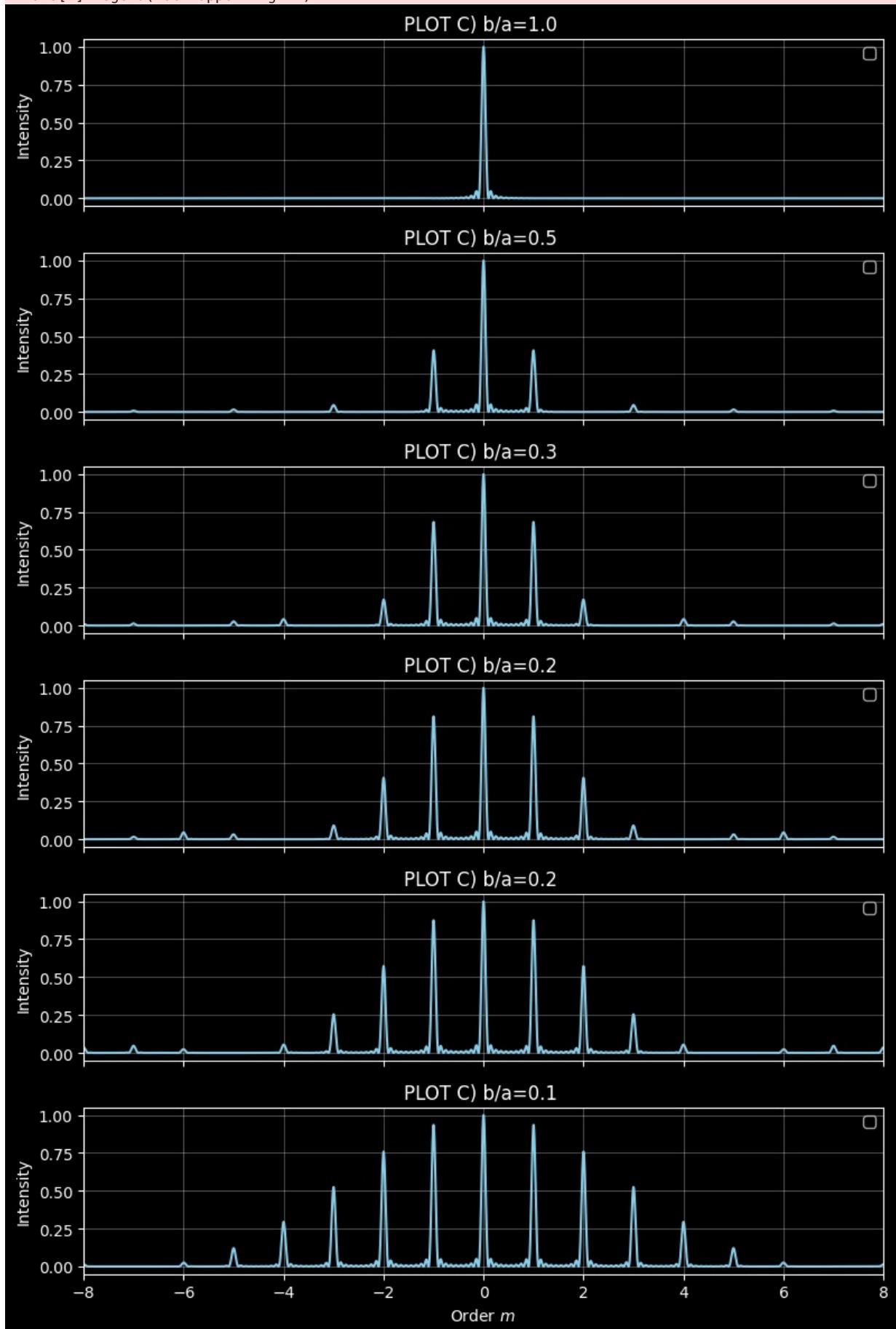
    axs[i].plot(s_vals, I_vals, color='skyblue')
    axs[i].set_ylabel("Intensity")
    axs[i].legend(loc='upper right')
    axs[i].grid(alpha=0.3)
    axs[i].set_title(f"PLOT C) b/a={b_by_a:.1f} ")

    # Highlight where orders SHOULD be (integer s)
    # If a peak is missing at an integer s, you've found a missing order!

axs[-1].set_xlabel("Order $m$")
plt.xlim(-8, 8)
plt.tight_layout()
plt.show()
```

```
C:\Users\ahila\AppData\Local\Temp\ipykernel_19348\677395210.py:48: UserWarning: No artists with labels found to put in legend. Note that artists whose label start with an underscore are ignored when legend() is called with no argument.
```

```
    axes[i].legend(loc='upper right')
```



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Qualitative Explanations.

Spacing Between Orders:

As a increases, the diffraction order $\lambda \sin \theta / \lambda$ length
 N has no effect

Width of Diffraction Peak

As N increases, diffraction peaks become narrower & sharper.

Overall Envelope

\Rightarrow As b gets smaller, produces wider envelope, more diffraction orders are visible.

(22)

d) Effect of Varying b/a , the duty cycle, and how that affects the relative intensity.

\Rightarrow Note the suppressed diffraction orders.

\Rightarrow Let me do this to graphically.

= look at attached plot

We observe that as we decrease the duty cycle from 2 to $1/100$. The relative intensities of the ± 1 diffraction orders increases.

When $b/a > 1$, it is actually not even existant.

for $b/a = 0.5$ to $1/100$ do in excel

In the code, I was not observing missing orders initially, so I later on found out, the 0/0 value was not handled effectively, so I switched to using "np.sinc"

= Explanations:

As b/a decreases and the slit becomes narrow, the single slit diffraction pattern has more peaks, so i.e., more higher order retain intensity. More power is concentrated in higher order m's.

= Suppressing orders.

When our the numerator goes to zero, the intensity of the order is suppressed.

(23)

$$\sin\left(\frac{\pi m b}{a}\right) = 0, \text{ when } \frac{mb}{a} \pi = n\pi, n \in \mathbb{Z}$$

$$\therefore \text{at } \frac{mb}{a} = n,$$

for the rochi valley, $b/a = 1/2$ even

$$\frac{Im}{I_0} \propto \left[\frac{\sin(\pi m/2)}{\pi m/2} \right]^2$$

when even m's, $\pm 2, \pm 4, \pm 6 \dots$

$$\Rightarrow \pm 2\pi = n\pi, \pm 4\pi = n\pi, \pm 6\pi = n\pi \dots$$

so these become zeros. and hence are suppressed. while odd Powers remain

likly for rochi valley, $b/a = 1/3$

when m's, $\pm 3, \pm 6, \pm 9$ are suppressed.

(24)

Q)

In experiments, diffraction orders will not be sharp & may blur.

The reasons boil down to what the physical reality is.

1) Finite source size

→ Realistically we will not have an infinite source, we would only have a finite extended source from our LED & aperture which we have a finite angular extent. So the grating is illuminated by a smaller range of incident angles θ_i .

For each incident angle, the grating equation $a(\sin\theta - \sin\theta_0) = m\lambda$ gives slightly different output angles θ for the same m .

→ Measured intensity has a superposition (convolution) of many slightly shifted patterns. This leads to broader diffraction patterns of each order. Rather than being delta functions we have sinc functions.

→ It won't be sharp as the contrast decreases.

2) Finite spectral Bandwidth.

→ Now Eq 32 assumes an mono chromatic illumination λ . But although we have a largely mono chromatic source that is indistinguishable by eye, it still has a bandwidth of 25 nm for a central wavelength of $\lambda_0 = 525\text{ nm}$ (Refer to Lab Script Appendix : pg 22).

→ For a given order m , different wavelengths satisfy $a \sin\theta_i \lambda = m\lambda$. Some see slightly displaced peaks, an angular broadening & more blurring for high orders.

Lab Session 3: SF

Date: Thursday 15-Jan-2026,

Lab Partner: Natha

Table of Content

1. Goal

2. Apparatus, References, i) Additional Apparatus ii) Additional References.

3. New sketch

9. Goal Evaluation

4. Procedure

10. Reflection plan for Next lab

5. Testing the Set up

6. Analysis

7. Major Issues

8. Uncertainty Notes

Note: Since my lab partner isn't going to be here for a while, I've decided to work on some preparation & sketches I wanted to improve from last lab.

1. Goal:

i) Correct & Make a better experiment sketch

ii) Use methods from lab lab to go back & correct the optical configuration (pg:)

iii) Do the testing for the Lab Setup 1 & ensure we are getting expected Results

iv) Fix & Complete Lab Setup 2. v) take Fourier plane using narrow card & verify that a stable diffraction pattern can be observed

vi) Place the camera at Fourier plane & record at least one set of diffraction - order positions for the 10lp/mm Ronchi ruling

vii) Measure the imaging magnification for a real-space image of the grating &

viii) Identify major limitation in illumination uniformity & document one check & verification

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2. Apparatus Refers

Refer one again to same

as (pg 2-3)

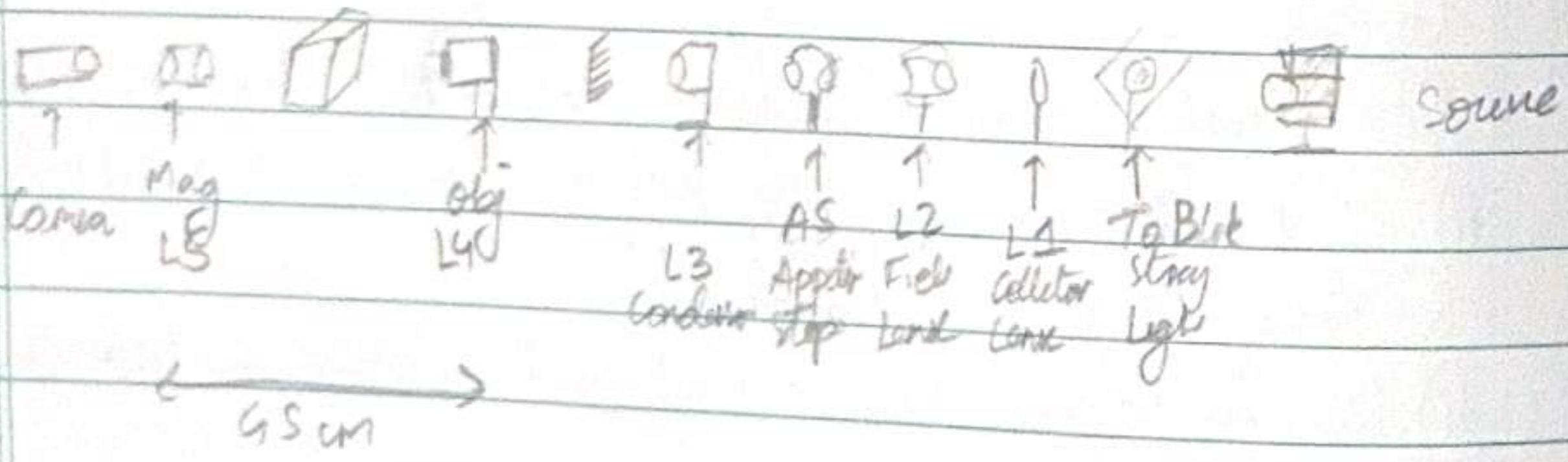
i) Additional Apparatus to meet lab 3 :

- * Ronchi Ruling & Camera BFS-03-1652M-CS
- * Adjustable iris (field stop) & pinhole at aperture stop (200 μm)
- * Paper to wedge the saddle & cover the pin hole stage

ii) Additional Refers

- * Hecht, Eugene, Textbook Optics (Library)
- * Lipson, Modern Optic, 4th edition (Library)

3. Updated sketch. (Appendix Sketch to show lens Orientation)



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4. Procedure

4.1 Corrective measures :

Based on the figure we adjusted the direction the lens face in the sketch. Align all of the lenses square to the rail
Nathan joined the lab

1:45 PM

4.2 Aligning Lense Alignment By working Backward Attempt 1
we trying to work Backward, removed the l4.

Then trying to decrease the pin hole size at
Using the small pin hole & the image on the camera, we are
trying to align the placements of the lenses.

4.3) Restarting Configuration after Magnifying lens (Attempt 2)

We tried the above & this was difficult to align, so moving to
different Method

Trying to Reset configuration after the magnification step

(150mm)
Placed objective lens 45 ± 0.05 mm from magnification lens

Skip portion of grating, it is correct. The grating is moved to
get 12. lp/mm in focus

There was ununiform illumination but it was from the outer
wings of the aperture. Removing it fixed it.

We moved the mount on the condenser lens by unscrewing it

Adjust the pin hole & the x-y dial. The image is centered.
we verified with the aperture dot

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Attempt to wedge printer paper for pinhole saddle to align it

This did not help much. We just put a new saddle.
This worked!

4.4 Setup Check

- * Verified optical train still assembled from Session 2
- * Turned room lights down; confirmed lens tube installed to reduce ambient light

Quick Check: 4.5 Beam centering through the system

* Place a white card after each element (sliding from source & towards camera side)

Success!
* Confirmed the beam stayed centered

* Observed largely uniform light! Yay!

5. Testing the set up

Switched back on the NI acquisition software & the preset for this lab, stored at the desktop. (Just like referring to page 5, lab Session 1, Section 8.2)

Using the virtual dial on the grating object mount, center the image on the software such that the 10 lpm/m grating is on the center well illuminated.

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Testing

Using the line tool on the Image Panel, we make a line over the diffraction pattern over a length of 1mm. (oving pixel 255 to B28 on x axis)

Camera has a pixel of 1440×1080 (Given on the Software itself)
(cross checked by viewing the Bottom Right corner)

BFS-03-16S2M-CS documentation or canvas for the camera says each pixel is $3.45 \mu\text{m}$

∴ image size is, $(1328 - 225) \text{ pixel} \times 3.45$

The grating we used was 10 lines per 1 mm.

∴ we observed 24 lines.

The object distance is:

$$\begin{aligned} 10 &: 1 \text{ mm} \\ 24 &: x \end{aligned}$$

$$\Rightarrow 10/x = \frac{24}{10} = 2.4 \text{ mm}$$

2.4 mm on object gis. $(1328 - 225) = 1103 \text{ pixel}$

$$\therefore 1103 \times 3.45 \mu\text{m} = 1103 \times 0.00345 \text{ mm}$$

$$M = \frac{i}{o} = \frac{1103 \times 0.00345}{2.4} = 1.585 \text{ magnification}$$

We are below it, we needed a magnification of 2 (Prelab 2) only ≈ 1.6 .

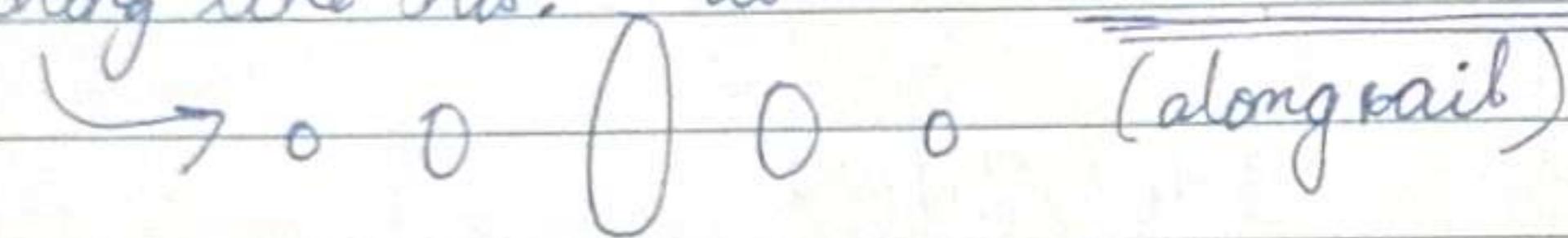
$$\text{This is from the 4-f relay: } M = \frac{\text{image distance}}{\text{object distance}} = \frac{300}{150} = 2$$

(30)

adjusted the field stop iris such that we see only about 15 lines in full good illumination.

Moved a white card along the camera side of the objective region to find plane where sharp order peaks appeared.

Something like this. at $\approx 94 \pm 0.05$ cm



Place a camera on this plane, & fine adjusted the base. This spot was on camera side after the L_4 lens.
at 93.5 ± 0.05 mm.

Taking measurements of the diffraction pattern on LabView
Exposure: 1500 μs; Gain: 1, Gamma: 15. Auto exposure off.

Data: 0 0

390 674 953 : Pixel
 $\leftarrow 284 \rightarrow 279$

$$\text{avg pixel } \frac{284 + 279}{2} = 281.5 \text{ pixels}$$

$$\text{dagain } 281.5 \text{ pixels} \times 0.00345 \text{ mm} \\ = 0.971175 \pm 0.05 \text{ mm}$$

This is distance between the central & the first maxima.

Even, Hot spots on the camera formed a strong central dot.

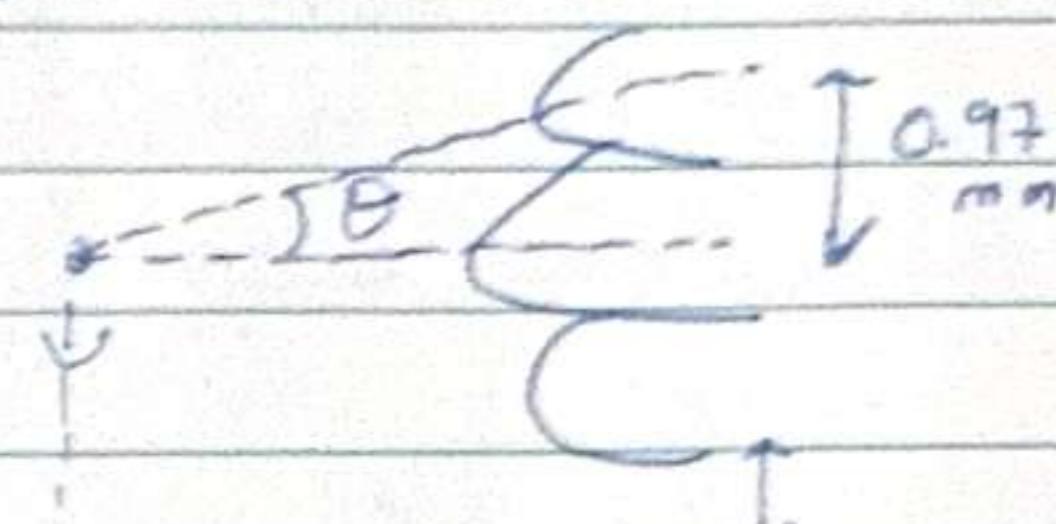
(31)

6. Analysis

To find the angle

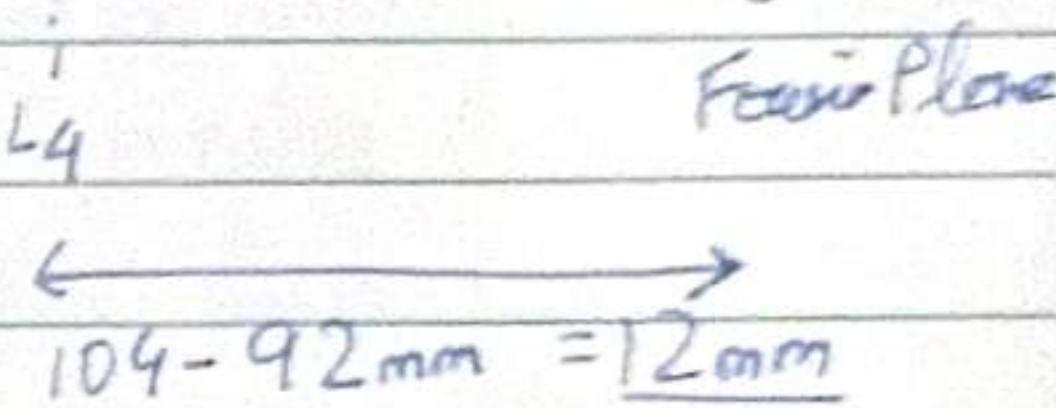
Under Small angle approximation $\sin \theta \approx \theta$

$$\therefore \theta = \frac{0.97}{12} = 0.080833 \text{ rad}$$



The Labscript also suggests:

$$\sin \theta = \frac{\lambda}{d} = \frac{528}{12 \text{ mm}}$$



We took an image of the Fourier image using the "Save figure" button on the panel.

→ Saved it to canvas on: "Ahilan & Nathan Group/Lab 1-Spatial filtering"
Session3/2026-01-15_SES3_Fourier Imaging_01.tiff"

Figure

Saved

(32)

7. Major Issues:

- ISSUE 1) Found Very Bright spots equally in the centre. Made it harder to see exactly where the centre is (Reflected Image in canvas, look in last page.)
- ISSUE 2) Fine alignment of Rail & Saddle but this was easily mitigated with different Saddle. Keep this in mind for future labs.

8. Uncertainty notes:

- ⇒ Pixel measurement: $\pm 1-2$ pixels, But each pixel is $3.45 \mu\text{m}$ size, we have an uncertainty of $\pm (3.45-6.9) \mu\text{m}$ to the spacing in diffraction pattern. Hence to the θ angle as well.
- * ⇒ In future lab, we should find this value!

9. Good Evaluation

- 1) locate Fourier plane ✓
- 2) Camera at Fourier plane + recorded spacing ✓
- 3) Magnification measurement + comparison ✓
- 4) Noted limitations ✓

(33)

10. Reflections & Plan for next lab:

- 1) After coming home & looking at the Fourier diffraction pattern image, I realized it might not be camera hot spot! When we reloaded the default preset, we did not spend too much time on the exposure & gain values! Our notes on (Pg) confirm this!
- ⇒ Next lab; control & decrease exposure values & see if that helps.
- ⇒ Zach, our TA suggested to about the over exposure at the lab actually, & told us we could use a "gaussian distribution" to further help identify the center. If time permits after the project for this lab. We will explore this.
- 2) We could improve the Fourier-plane placement & also make the magnification accuracy more close to 2. But Because of how much time we spent in this, maybe I want to move on & improve accuracy in lab 6-8.
- 3) We should have taken images of the Image Panel! Next lab we should do it too.