symphotic Tii corporation

Monochromator Training

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www.symphotic.com
Monochromators separate light into its component colors. The exit slit only allows a small amount of light through, usually one “color” or wavelength.
Spectrographs separate light into its component colors. There is no exit slit: a large spectrum is seen by an imaging sensor.
Gratings

Gratings create interference patterns

Different wavelengths interfere at different angles off the grating
Grating orders

- Interference can happen more than once.
- All wavelengths interfere at one angle off the grating. This is called 0 order.
- Each wavelength can interfere in more than one order.
The Grating Equation

\[ m \lambda / a = \sin a \pm \sin \beta_m \]

- **m** = order number
- **a** = groove spacing (nm)
- \( \lambda \) = wavelength (nm)
- **a** = angle of incident light
- \( \beta_m \) = angle of diffracted light of m order
Solving the grating equation

- $m\lambda/a = \sin a \pm \sin \beta_m$
- Note the order overlap highlighted in yellow:

<table>
<thead>
<tr>
<th>g/mm</th>
<th>a</th>
<th>$\lambda$</th>
<th>$\alpha$</th>
<th>m</th>
<th>$\beta_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2400</td>
<td>416.6667</td>
<td>200</td>
<td>0.00</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>2400</td>
<td>416.6667</td>
<td>200</td>
<td>0.00</td>
<td>1</td>
<td>28.69</td>
</tr>
<tr>
<td>2400</td>
<td>416.6667</td>
<td>200</td>
<td>0.00</td>
<td>2</td>
<td>73.74</td>
</tr>
<tr>
<td>2400</td>
<td>416.6667</td>
<td>400</td>
<td>0.00</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>2400</td>
<td>416.6667</td>
<td>400</td>
<td>0.00</td>
<td>1</td>
<td>73.74</td>
</tr>
<tr>
<td>1200</td>
<td>833.3333</td>
<td>600</td>
<td>0.00</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>1200</td>
<td>833.3333</td>
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<td>0.00</td>
<td>1</td>
<td>46.05</td>
</tr>
<tr>
<td>60</td>
<td>16666.67</td>
<td>600</td>
<td>0.00</td>
<td>23</td>
<td>55.89</td>
</tr>
<tr>
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<td>16666.67</td>
<td>600</td>
<td>0.00</td>
<td>24</td>
<td>59.77</td>
</tr>
<tr>
<td>60</td>
<td>16666.67</td>
<td>600</td>
<td>0.00</td>
<td>25</td>
<td>64.16</td>
</tr>
</tbody>
</table>
Dispersion

- **Angular dispersion**: \( D \)
  
  \[ D = \frac{d\beta}{d\lambda} = \frac{m}{a \cos \beta} \]  
  (the change in the angle of diffraction per incremental change in wavelength is equal to the order number divided by the groove spacing times the cosine of the angle of diffraction)

  - By substitution: 
    \[ D = \frac{\sin a + \sin \beta}{\lambda (\cos \beta)} \]

- **Linear Dispersion**
  
  \[ \frac{dL}{d\lambda} = f(d\beta/d\lambda) = f \times D \]  
  (the change in distance [mm] per change in wavelength [nm] is equal to the focal length of the monochromator times the angular dispersion)

  - **Reciprocal Linear Dispersion** = \( 1/\text{linear dispersion} \)

- Dispersion varies with wavelength and incident angles
Reciprocal linear dispersion in the MS257 monochromator

reciprocal linear dispersion for the MS257 using a 1200 g/mm ruled grating at the blaze wavelength (catalog value is 3.2)
Resolving Power, $R$

- $R = \frac{\lambda}{d\lambda}$
  - $W$ is the illuminated width of the grating

- Two wavelengths, $\lambda$ and $\lambda + d\lambda$ are resolved if they can be separated by the monochromator.
Resolving Power of a grating, \( R \)

- \( R = \frac{\lambda}{d\lambda} \)
  - \( = \frac{W (\sin \alpha + \sin \beta)}{\lambda} \)

  - *W is the illuminated width of the grating*

  For a 1200 g/mm grating with a 350 nm blaze, at 350 nm:
  
  \[
  R = \frac{50,000,000 \times (\sin 0 + \sin 24.835)}{350 \text{ nm}}
  \]

  \[
  = 60,000
  \]

  \[
  d\lambda = \frac{350 \text{ nm}}{60,000} = 0.006 \text{ nm}
  \]

  (however, this is a mathematical calculation only: *Resolution depends on other factors*)
Resolution

- Resolution is the ability to separate wavelengths. It is usually expressed in FWHM (full width at half max.) Resolution depends on the dispersion, slit width, and optical aberrations. Even though a grating may have resolving power, other factors limit resolution.
Factors affecting resolution:

- Monochromator focal length: greater focal length gives greater resolution.
- Slit width: Narrower slit width gives greater resolution.
- Groove density: more lines/mm gives greater resolution, i.e. increased resolving power of the grating.
- Grating order.
- Pixel size in spectrograph detector: smaller pixel width gives better resolution (the limit for resolution is twice the detector pixel size).
Double Monochromator: Subtractive

- Greatly reduces stray light, rejects unwanted orders or wavelengths
  Performs like a bandpass filter
Double Monochromator: Additive

- Reduces stray light, rejects unwanted orders or wavelengths. Increases resolution or increases throughput (but not both)
Triple spectrograph using subtractive pre-monochromator

**Triple Spectrograph:**

G1 and G2 in triple act as a tunable band rejection filter. Many reflections increase light losses.

G1 and G2 comprise a subtractive dispersion double monochromator. S2 blocks laser light and admits a desired passband.

focal plane and detector
Monochromator spectrograph types

- **Ebert-Fastie.** Uses one mirror to collimate incoming light and focus dispersed light.
  - 77250 1/8 meter monochromator.

- **Czerny-Turner.** Uses two separate mirrors for collimation and focusing.
  - MS257.
Getting light into a monochromator

- **Throughput**
  - Also called geometric extent or etendue, is defined by this equation:

  \[ G = A \Omega \]

  Where \( G \) is the throughput, \( A \) is the image area of the entrance slit, and \( \Omega \) is the solid angle of the grating area projected on the collimating mirror.

  \( A \) is the height x width of the entrance slit.

  \( \Omega \) varies with the angle of the grating so it changes with wavelength.

  \( \Omega \) depends on the inverse square of the focal length.
Getting light into a monochromator

- $\Omega$ is equal to $a/f^2$, the projected area of the grating divided by the square of the focal length of the mirror.

- $\Omega$ is unitless, but is referred to in units of steridians

- $f$ is the focal length

- $a = h \times w$ where $w$ is the projected width of the grating, equal to:
  
  \[ w = w' \times \cos \theta \]

  where $w'$ is the grating width and $\theta$ is the angle of rotation.
Getting light into a monochromator

- Grating efficiency:
  - Varies with wavelength, design, and manufacture.
  - 77742 is ruled
  - 77741 is holographic

Fig. 5 Efficiency curves of 77741 1200 l/mm 250 nm blaze, and 77742 1200 l/mm 350 nm blaze gratings.
Getting light into a monochromator

- More Throughput:
  - Larger slits—select the largest slits for your application
  - Smaller grating angles—Select a grating that will cover your wavelength requirements at smaller angles
  - Work close to peak of the grating efficiency curve
  - Illuminate the full slit height
Getting light into a monochromator

“Filling the acceptance cone”

- Light must be focused on the monochromator slit using a lens or mirror with the same F/#
  - Source image should be the same size as the slit to reduce vignetting
  - F/# should match
  - Magnification may change: \( m = \frac{(F/#)_2}{(F/#)_1} \)

Fig. 5 A condenser and secondary focusing lens system.
Getting light into a monochromator

Example

- 2 nm bandwidth in visible range using 6253 150 W Xenon lamp and a 77200 ¼ meter F/4.4 monochromator with a 1200 g/mm grating with a 350 nm blaze (77233)
Getting light into a monochromator

Example

- 2 nm bandwidth requires a slit size of 0.6 mm, slit height is 18 mm (77216)

\[
\text{Slit Width (mm)} = \frac{\text{bandwidth (nm)}}{\text{RLD (nm/mm)}} = \frac{2}{3} = 0.66
\]

- Arc dimensions are 0.5 mm wide by 2.2 mm high.

- Focusing lens should be F/4.4 to match monochromator optics.

### Table 2: Approximate Resolution of Fixed Slits

<table>
<thead>
<tr>
<th>Slit Width ((\mu\text{m}))</th>
<th>Slit Height (mm)</th>
<th>Monochromator Resolution* @ 500 nm (nm)</th>
<th>Slit Model No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2</td>
<td>0.1**</td>
<td>77222</td>
</tr>
<tr>
<td>25</td>
<td>3</td>
<td>0.15**</td>
<td>77220</td>
</tr>
<tr>
<td>50</td>
<td>6</td>
<td>0.25**</td>
<td>77219</td>
</tr>
<tr>
<td>120</td>
<td>16</td>
<td>0.4</td>
<td>77218</td>
</tr>
<tr>
<td>280</td>
<td>18</td>
<td>1</td>
<td>77217</td>
</tr>
<tr>
<td>600</td>
<td>18</td>
<td>2</td>
<td>77216</td>
</tr>
<tr>
<td>760</td>
<td>18</td>
<td>2.5</td>
<td>77215</td>
</tr>
<tr>
<td>1240</td>
<td>18</td>
<td>4</td>
<td>77214</td>
</tr>
<tr>
<td>1560</td>
<td>18</td>
<td>5</td>
<td>77213</td>
</tr>
<tr>
<td>3160</td>
<td>18</td>
<td>10</td>
<td>77212</td>
</tr>
<tr>
<td>6320</td>
<td>18</td>
<td>20</td>
<td>77211</td>
</tr>
</tbody>
</table>

* For 1,200 l/mm gratings; to obtain the resolution with other gratings multiply by the "Wavelength Counter Multiplier" in Table 1 on the previous page.

** Resolution with a diode array is limited by array element width.
Table 1 Comparison of Condensers

<table>
<thead>
<tr>
<th>Source Model No.</th>
<th>Condenser Type</th>
<th>Aperture inch (mm)</th>
<th>Lens Multiplication Factor*</th>
<th>Transmittance Range of Lens Material**</th>
<th>Size Series***</th>
</tr>
</thead>
<tbody>
<tr>
<td>66906</td>
<td>F/1.5, single element fused silica</td>
<td>1.3 (33)</td>
<td>0.06</td>
<td>200 - 2500 nm</td>
<td>1.5 inch</td>
</tr>
<tr>
<td>66907</td>
<td>F/1, two element fused silica</td>
<td>1.3 (33)</td>
<td>0.11</td>
<td>200 - 2500 nm</td>
<td>1.5 inch</td>
</tr>
<tr>
<td>66919</td>
<td>F/0.85, single element molded Pyrex® Aspheric</td>
<td>1.3 (33)</td>
<td>0.13</td>
<td>350 - 2500 nm</td>
<td>1.5 Inch</td>
</tr>
<tr>
<td>66908</td>
<td>F/0.7, four element borosilicate crown Aspherab®</td>
<td>2.7 (69)</td>
<td>0.18</td>
<td>350 - 2500 nm</td>
<td>3 Inch</td>
</tr>
<tr>
<td>66909</td>
<td>F/0.7, four element fused silica Aspherab®</td>
<td>2.7 (69)</td>
<td>0.19</td>
<td>200 - 2500 nm</td>
<td>3 Inch</td>
</tr>
</tbody>
</table>

Table 2 50 - 200 W Arc Lamps

<table>
<thead>
<tr>
<th>Lamp Type</th>
<th>Effective Arc Size W x H (mm)</th>
<th>Lamp Model No.</th>
<th>Appropriate Socket Adapter Model No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 W Xe</td>
<td>0.4 x 0.8</td>
<td>6251</td>
<td>66150</td>
</tr>
<tr>
<td>75 W Xe (Ozone Free)</td>
<td>0.4 x 0.8</td>
<td>6263</td>
<td>66150</td>
</tr>
<tr>
<td>100 W Xe (Ozone Free)</td>
<td>0.4 x 0.8</td>
<td>6257</td>
<td>66150</td>
</tr>
<tr>
<td>150 W Xe</td>
<td>0.5 x 2.2</td>
<td>6253</td>
<td>66151</td>
</tr>
<tr>
<td>150 W Xe (UV Enhanced)</td>
<td>0.5 x 2.2</td>
<td>6254</td>
<td>66151</td>
</tr>
<tr>
<td>150 W Xe (Ozone Free)</td>
<td>0.5 x 2.2</td>
<td>6255</td>
<td>66151</td>
</tr>
<tr>
<td>150 W Xe</td>
<td>0.5 x 1.5</td>
<td>6262</td>
<td>66152</td>
</tr>
<tr>
<td>50 W Hg</td>
<td>0.2 x 0.35</td>
<td>6282</td>
<td>66158</td>
</tr>
<tr>
<td>100 W Hg</td>
<td>0.25 x 0.25</td>
<td>6281</td>
<td>66150</td>
</tr>
<tr>
<td>200 W Hg</td>
<td>0.6 x 2.2</td>
<td>6283</td>
<td>66144</td>
</tr>
<tr>
<td>200 W Hg (Xe)</td>
<td>0.5 x 1.5</td>
<td>6291</td>
<td>66152</td>
</tr>
<tr>
<td>200 W Hg (Ozone Free)</td>
<td>0.5 x 1.5</td>
<td>6292</td>
<td>66152</td>
</tr>
</tbody>
</table>

Fig. 1. The rear reflector collects the lamp’s back radiation, adding up to 60% to the total source output.
Getting light into a monochromator
Example

- Beam diameter is 33 mm, so focus of secondary lens should be about 150 mm
  
  \[
  \text{F/}\# = \frac{\text{Focal Length}}{\text{Aperture}},
  \]

  \[
  \text{Focal Length} = (\text{F/}\#)(\text{Aperture}) = 4.4 \times 33 \text{ mm} = 145.2 \text{ mm} \approx 150 \text{ mm}
  \]

  Image size options:
  
  (entrance slit is 0.6 mm x 18 mm)

  Using F/1.5 lens:
  \[
  (0.5 \text{ mm} \times 2.2 \text{ mm}) \times (4.4/1.5) \approx 1.5 \text{ mm} \times 6.5 \text{ mm}
  \]

  Using F/1.0 lens:
  \[
  (0.5 \text{ mm} \times 2.2 \text{ mm}) \times (4.4/1.0) \approx 2.2 \text{ mm} \times 10 \text{ mm}
  \]

  Using F/0.85 lens:
  \[
  (0.5 \text{ mm} \times 2.2 \text{ mm}) \times (4.4/0.85) \approx 2.6 \text{ mm} \times 11 \text{ mm}
  \]
Getting light into a monochromator
Example

- Vignetting: The image is wider than the slit, so some power will be lost. The useful height of the slit is equal to the magnified height of the image.

\[ V = \frac{a \times b}{(mw \times mh)} \]

\[ b = ma, \text{ so } V = \frac{a}{mw} \]

- Relative power:

\[ P \propto V \times \left( \frac{m^2}{(F/\# \text{ of imaging lens})^2} \right) \]

With F/1.5 condenser, relative power=
\[ \left[ \frac{0.6}{1.5} \right] \times \left( \frac{4.4}{1.5} \right)^2 \left( \frac{4.4}{2.2} \right)^2 = 0.18 \]

With F/1.0 condenser, relative power=
\[ \left[ \frac{0.6}{2.2} \right] \times \left( \frac{4.4}{1.0} \right)^2 \left( \frac{4.4}{0.85} \right)^2 = 0.27 \]

With F/0.85 condenser, relative power=
\[ \left[ \frac{0.6}{2.6} \right] \times \left( \frac{4.4}{0.85} \right)^2 \left( \frac{4.4}{0.85} \right)^2 = 0.32 \]

- Highest relative power is with the F/0.85 condenser
Monochromator Power output

\[ P_o = P_i V F E_m R^4 \]

- \( P_o \) = Power output in mW
- \( P_i \) = Power reaching the entrance slit plane in mW
- \( V \) = Vignetting factor due to slit smaller than image
- \( F = \left( \frac{F/\#_{\text{illuminator}}}{F/\#_{\text{monochromator}}} \right)^2 \)
  (when \( F/\# \) does not match.)
- \( E_m \) = Grating efficiency
- \( R^4 \) = Reflection efficiency (with 4 reflections)
Conclusions:

- Resolution depends upon focal length, slit widths, groove density, optical design and aberrations.
- Use a grating with a blaze angle closest to the lowest wavelength of the spectral range.
- Use filters to remove unwanted wavelengths.
- Match the Monochromators F/#.
- Use low F/# imaging optics wherever practical.
- Use slits that are completely filled by the image.
- Use smaller slits for better resolution, but light will be lost through vignetting.
Acknowledgements

- Our thanks for the assistance of the staff of Thermo Oriel