Components of Optical Instruments

Chapter 7 III
UV, Visible and IR Instruments
Grating Monochromators

- Principle of operation:
  - Diffraction
- Diffraction sources:
  - grooves on a reflecting surface
- Fabrication:
  - Master Grating is mechanically ruled on a flat polished surface with a diamond, to produce identical closely spaced parallel grooves
- Replica grating:
  - are cast using 'liquid plastic'. Then they are coated with a reflecting material

Echellette Grating

- The grating is blazed/grooved to produce broad faces used for reflection and narrow unused faces.
- How does it work?
  - Maximum constructive interference between two beams originating from two adjacent faces occurs when the difference in path travelled is equal to one wavelength or an integral multiple of the wavelength.
  - Different wavelengths are diffracted at different angles.

\[
\begin{align*}
n\lambda &= (CB + BD) \\
CB &= d \sin i \\
\angle CAB &= \angle i \\
BD &= d \sin r \\
\angle DAB &= \angle r
\end{align*}
\]

\[
n\lambda = d (\sin i + \sin r)
\]
• Holographic grating:
  – two laser beams are focused on a photosensitive surface to create grooves
• Concave Gratings
  – Lines ruled on a concave spherical mirror
  – Do not need internal collimating and focusing optics
• Typical sizes:
  – 1- 10 cm, 300 to 2000 grooves/mm

**Performance Characteristics**

• Dispersion
  – Determines the ability of a monochromator to separate different wavelengths
  – Angular dispersion
    \[
    \frac{dr}{d\lambda} = \frac{n}{d \cos r}
    \]
  – Linear dispersion if \( r \) is small < 20º
    \[
    D = \frac{dy}{d\lambda} = \frac{fdr}{d\lambda} = \frac{d\lambda}{fdr} = \frac{d \cos r}{nf}
    \]
    \[
    D^{-1} = \frac{d}{nf}
    \]
• Resolving Power
  – Determines the limit of the ability to separate adjacent images that have a slight difference in wavelength
  – Better for longer gratings, smaller d, higher n

  \[ R = \frac{\lambda}{\Delta \lambda} \]
  \[ R = nN \]
  \[ N : number \ of \ grooves \]

• Light Gathering Power
  – Determines the ability of the monochromator to collect radiation from the entrance slit
  – F-number F, speed

  \[ F = \frac{f}{d} \]
  \[ f: focal \- length \ of \- mirror \ or \- lens \]
  \[ d: diameter \ of \- mirror \ or \- lens \]

Echelle grating

• Two dispersing elements in series
  – Echelle grating + low resolution prism or grating

• \( i \geq 63^\circ 26 \)

  \[ n\lambda = 2d \sin \beta \]
  \[ D^{-1} = \frac{d \cos \beta}{nf} \]
C-3 Monochromators Slits

- Entrance and Exit slit
  - Rectangular images of the entrance slit are produced on the focal plane that contains the exit slit
- Effect of Slit Width on Resolution
  - Bandwidth: span of monochromator settings (in units of wavelength or cm$^{-1}$) needed to move the image of the entrance slit across the exit slit
  - Effective bandwidth ($\Delta \lambda_{\text{eff}}$) (spectral bandpass or spectral slit) is the range of wavelengths at the exit slit at a given monochromator setting. Is equal to half the bandwidth when the two slits are equal.

$$D^{-1} = \frac{\Delta \lambda}{\Delta \nu}$$

$$\Delta \lambda_{\text{eff}} = wD^{-1}$$

$w$: slit width

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Echelle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length</td>
<td>0.5 m</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Groove density</td>
<td>1200/mm</td>
<td>79/mm</td>
</tr>
<tr>
<td>Diffraction angle, $\beta$</td>
<td>10°22'</td>
<td>63°26'</td>
</tr>
<tr>
<td>Order $n$ (at 300 nm)</td>
<td>1</td>
<td>75</td>
</tr>
<tr>
<td>Resolution (at 300 nm), $\lambda/\Delta \lambda$</td>
<td>62,400</td>
<td>763,000</td>
</tr>
<tr>
<td>Reciprocal linear dispersion, $D^{-1}$</td>
<td>16 Å/mm</td>
<td>1.5 Å/mm</td>
</tr>
<tr>
<td>Light-gathering power, $F$</td>
<td>$f/9.8$</td>
<td>$f/8.8$</td>
</tr>
</tbody>
</table>
E. Radiation Transducers

E-1 Introduction

• Early detectors in Spectroscopy
  – Human eye
  – Photographic plates
  – Films

• Properties of an Ideal Transducer
  – High sensitivity
  – High signal to noise ratio
  – Constant response over a wide range of wavelengths
  – Fast response
  – Response directly proportional to radiant power
  – Low dark current

\[ S = kP \]
\[ S = kP + k_d \]
General Classification of Transducers

• Photon transducers: photoelectric / quantum detectors
  – Photoemissive: Photon $\rightarrow$ emission of electrons $\rightarrow$ photocurrent
  – Photoconductive: Photon $\rightarrow$ electron to CB $\rightarrow$ enhanced conductivity
  – Used in UV, Vis and near IR

• Heat transducers
  – Average radiant power $\rightarrow$ thermal conduction
  – Mainly used in the IR region

E-2 Photon Transducers

• **E-2-1 Vacuum Phototubes**
  – Photoelectric effect
  – Photoemissive surfaces
  – Operational Amplifier
Photoemissive surfaces

- **Bialkali**: most sensitive
  - K/Cs/Sb (117)
- **Red-sensitive**:  
  - Ag/O/Cs (S-11):
- **Flat-response**:  
  - Ga/As (128): flat response

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E-2-2 Photomultiplier Tubes

- **Components**
  - Photocathode surface
  - Dynodes: maintained at increasing potential relative to cathode
  - Anode
  - Operational Amplifier (OP AMP)
- **Nature of signal from a PMT**
  - a series of charge packets
  - may have $10^6$ electrons and be 5 ns wide
  - Output is a current
  - Very sensitive in UV and vis
  - Fast response

\[
\text{anode.pulse sec}^{-1} \times 10^6 \frac{\text{electrons}}{\text{anode.pulse}} \times 1.6 \times 10^{-19} \frac{\text{coulomb}}{\text{electron}} = 1.6 \times 10^{-7} \frac{\text{coulombs}}{\text{sec}}
\]
Dark Current in Photomultipliers

- Sensitivity limited by dark current
- Origin of dark current (output signal when no light is present)
  - Thermal emission*: spontaneous emission of electrons
  - Cold-Field Emission: spontaneous emission due to sharp surfaces/edges in the presence of high electrical field
  - Radioactivity
  - Ohmic leakage: resistance in the tube will cause an IR drop, thus flow of current

Silicon Photodiode Transducers

- Reverse-biased pn junction on a silicon chip
- ER generates holes and electrons in depletion layer
- Less sensitive than photomultiplier
- Spectral region (190 - 1100 nm)
E-3 Multichannel Photon Transducers

- Allows the simultaneous detection of all resolution elements of the spectrum
- Types
  - Photodiode arrays (PDA)
    - Common number of diodes: 1024
  - Charge-Transfer Devices (CTDs)

E-4 Photoconductivity Transducers

- Used in the near IR region (0.75 µm - 3 µm).
- Semiconductors whose resistance decreases when they absorb radiation of wavelength between 0.75 µm and 3 µm.
- Change in conductivity is measured.
- Sulfides, Selenides, Stibnides of lead, cadmium, gallium and indium.
E-5 Thermal Transducers

- Operational principle:
  - IR radiation raises temperature of a black body with low heat capacity.
  - Temperature increase is a measure of radiant power.
  - Typical radiant power in IR: $10^{-7}$ to $10^{-9}$ W.
  - Typical temperature changes: order of 0.001 K.
- Problem: thermal noise (thermal radiation emitted by other surfaces).
  - Housing of detector must be evacuated and shielded from thermal radiation from other surfaces.

Examples of Thermal Transducers

- THERMOCOUPLES
  - Couple: two identical pieces of metal connected by a dissimilar metal
  - e.g. Bi and Sb
  - Potential difference will develop at the junction due to differences in temperature.

- BOLOMETERS (Thermistors)
  - Resistance thermometer made of Pt, Ni or semiconductors.
  - Principle of operation: large change in resistance as a function of temperature

- PYROELECTRIC TRANSDUCERS
  - Used in FT IR, which requires fast response
  - Pyroelectric materials: dielectric material with a long lived polarized state.
  - Principle of operation: temperature dependence of polarization in absence of electrical field is a measure of radiant power.
  - IR $\Rightarrow$ temperature change $\Rightarrow$ charges distribution change $\Rightarrow$ measurable current in the external circuit.
  - Pyroelectric material: Triglycine sulfate $(\text{NH}_2\text{CH}_2\text{COOH})_3\cdot\text{H}_2\text{SO}_4$. 

G. Fiber Optics

- Fine strands of glass or plastic
  - Diameter: 0.05 \( \mu \text{m} \)-0.6 cm
- Transmits Radiation over long distances
  - Used for transmitting images (medicine) and for illumination
- Operational Principle
  - Total Internal Reflection

\[
\text{Numerical aperture} = n_3 \sin \theta = \sqrt{n_1^2 + n_2^2} \\
\text{if } n_1 > n_2 > n_3
\]