Diffraction Gratings

- Recall diffraction gratings are periodic multiple slit devices
- Consider a diffraction grating: periodic distance a between slits
- Plane wave light hitting a diffraction grating at angle θ_i
- Then light gets bent to output angle of diffraction θ_m
- Light of second slit path is increased by

$$\Delta = \Delta_1 + \Delta_2 = a\left[sin(\theta_i) + sin(\theta_m)\right]$$

- Want the plane waves to be in phase for constructive interference
- Thus require path difference to be multiple of wavelength

$$\Delta = m\lambda$$

$$a\left[sin(\theta_i) + sin(\theta_m)\right] = m\lambda$$

- Where m is an integer (+ or -)
- Thus light will be spread out in colours at different angles

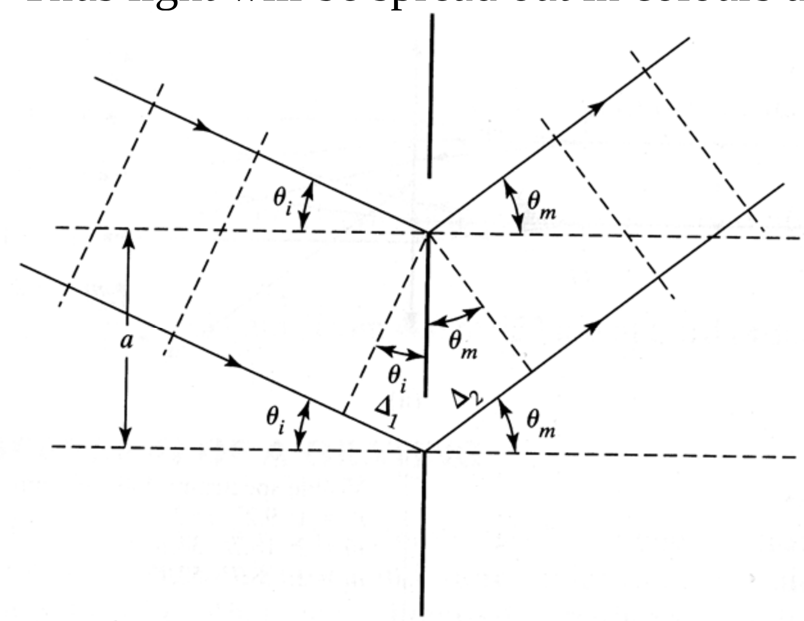
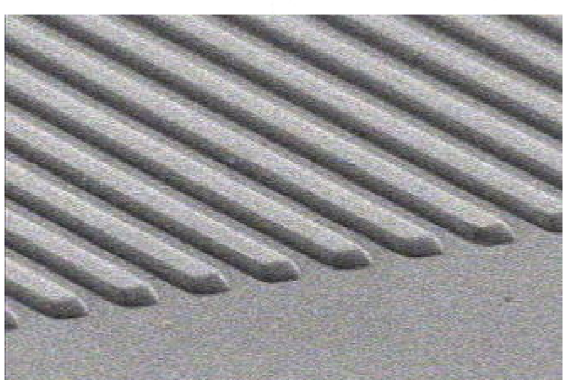


Figure 12-1 Neighboring grating slits illuminated by light incident at angle θ_i with the grating normal. For light diffracted in the direction θ_m, the net path difference from the two slits is $\Delta_1 + \Delta_2$.



Free Spectral Range

- One problem is that each wavelength has multiple orders of angles
- What is the spectral range before wavelengths overlap
- λ_1 is the shortest detectable wavelength
- λ_2 is the longest detectable wavelength
- Then for non-overlap require

$$m\lambda_2 = (m+1)\lambda_2$$

- Thus the free spectral range is

$$\lambda_{fsr} = \lambda_2 - \lambda_1 = \frac{\lambda_1}{m}$$

- Non overlap range smaller for higher order

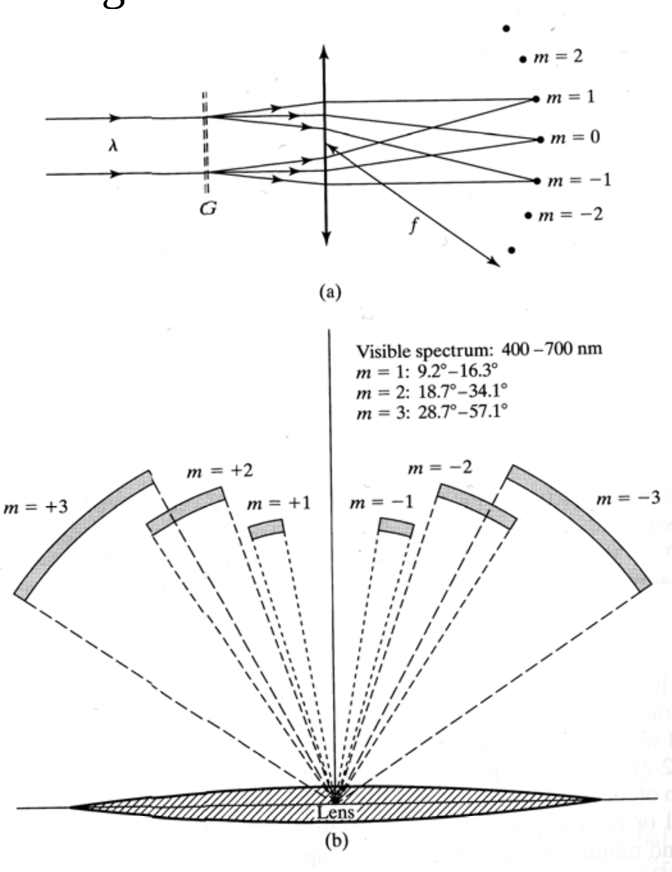
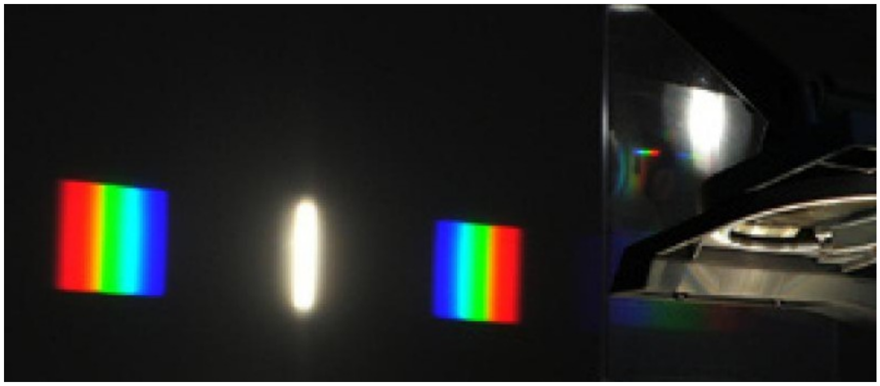
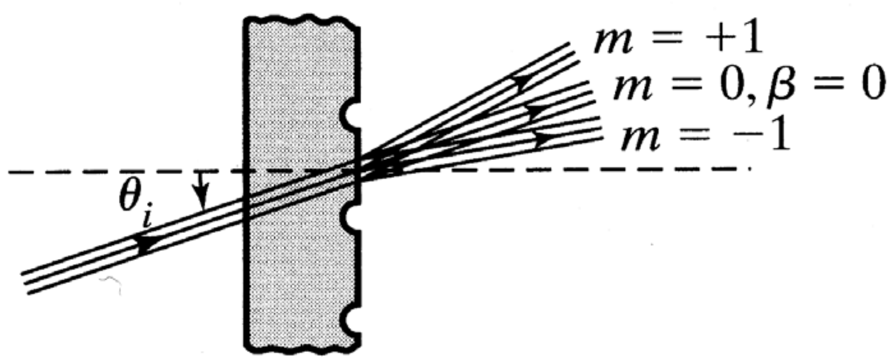


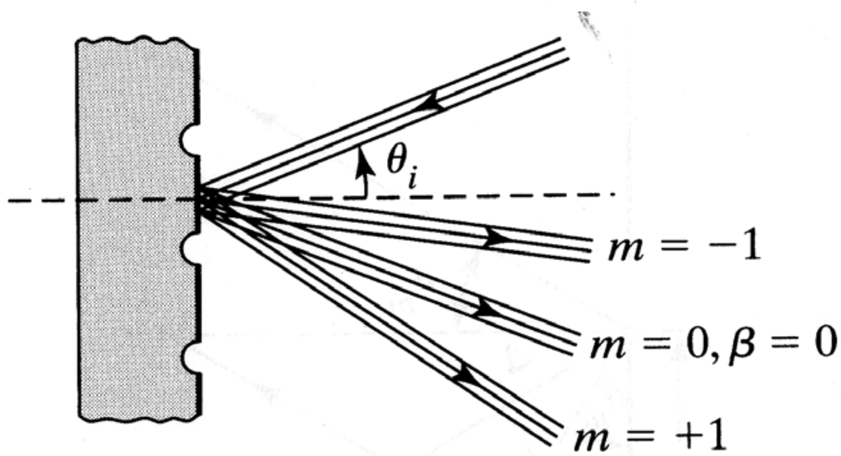
Figure 12-2 (a) Formation of the orders of principal maxima for monochromatic light incident normally on grating *G*. The grating can replace the prism in a spectroscope. Focused images have the shape of the collimator slit (not shown). (b) Angular spread of the first three orders of the visible spectrum for a diffraction grating with 400 grooves/mm. Orders are shown at different distances from the lens for clarity. In each order, the red end of the spectrum is deviated most. Normal incidence is assumed.

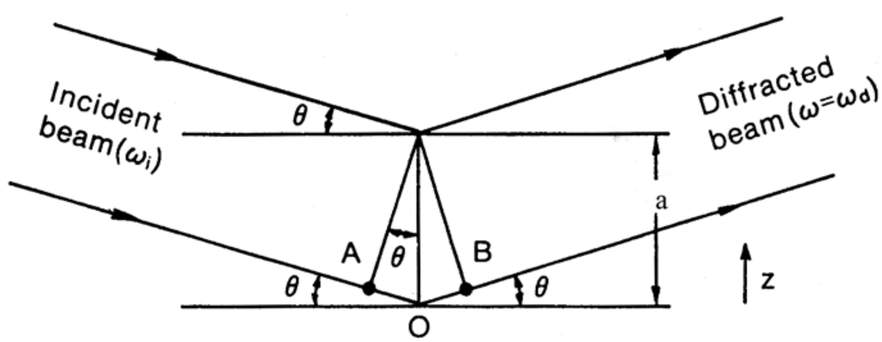


Types of Gratings

- Gratings can be of two types
- Transmission gratings: light comes from behind
- Reflection gratings: light reflects off surface
- Transmission common for small gratings





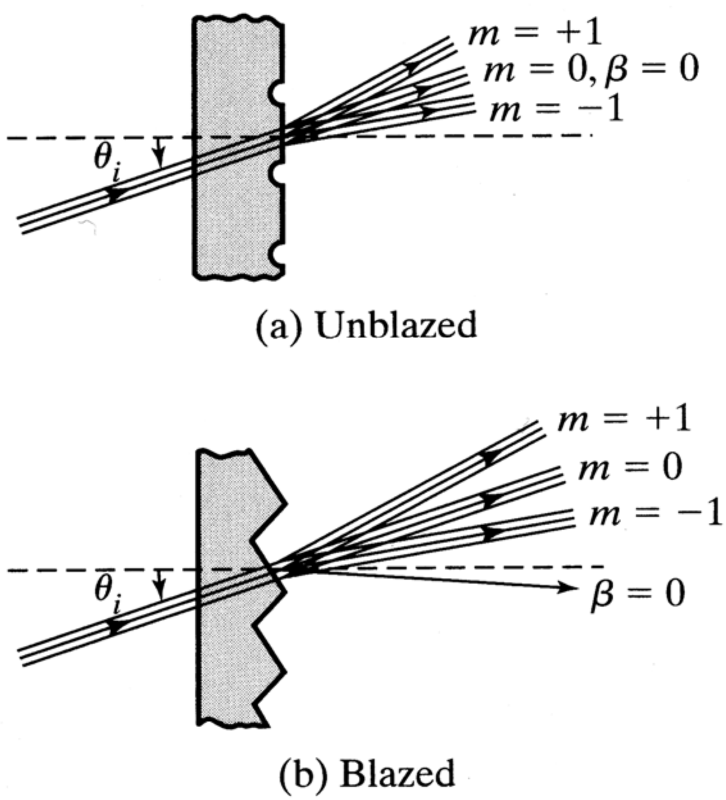


Blazing

- Can angle gratings to change the angle light comes off at
- Plane gratings called "unblazed"
- Gratings with angle called Blazed
- For transmission do this by creating series of prisms
- Specified by the blazing angle

Brightest peak is a the zeroth order in diffraction
Blazing moves the brightest peak to another order m
Peak occurs when β=0
Then for the blaze and θ_b the equations change to

$$a\left[\sin(\theta_i) + \sin(2\theta_b - \theta_i)\right] = m\lambda$$



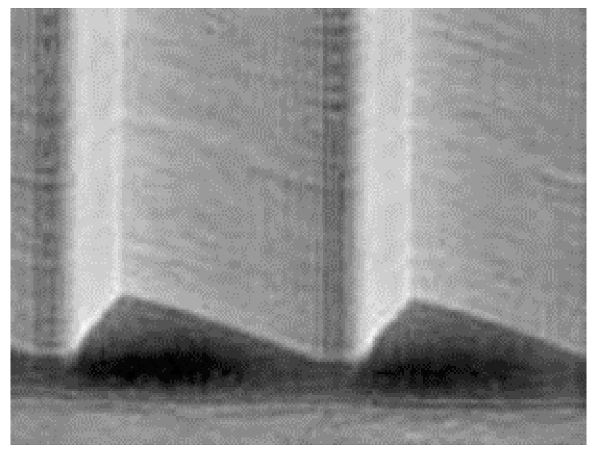
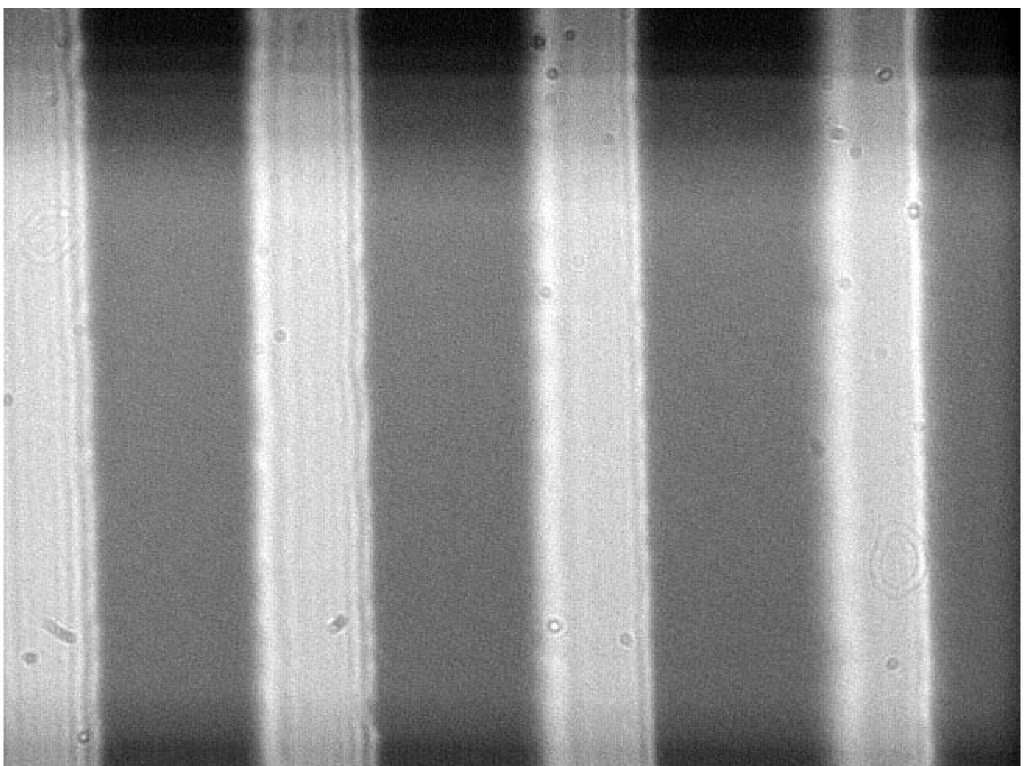
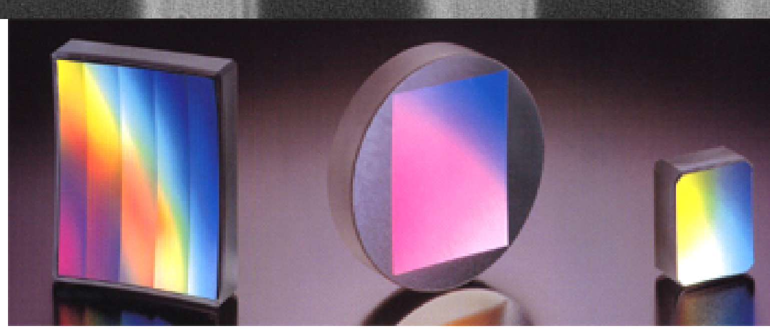


Figure 12-4 In an unblazed transmission grating (a), the diffraction envelope maximum at $\beta = 0$ coincides with the zeroth-order interference at $m = 0$. In the blazed grating (b), they are separated.

Creating Gratings

- Gratings created in 3 methods
- Machined – high accuracy machining with a milling grove
- Makes master gratings
- Commonly uses replicas – copy of grating masters
- Using microfabriction methods
- Deposit aluminium on plate & cover with photoresist
- Use grating patterings
- Alternatively use mask with grating pattern
- Expose resist, develop it and etch pattern
- Etch aluminium film leaving reflecting and non reflecting areas
- When viewed in white light get spectrum





Interference Gratings

- Creating grating with interference methods
- 2 possibilities – wedge type interference
- Take monochromatic beam (laser) split in 2
- Combine two beams at plate
- Lines on plate function of the very with angle of beams
- Can get line/spaces below 100 nm

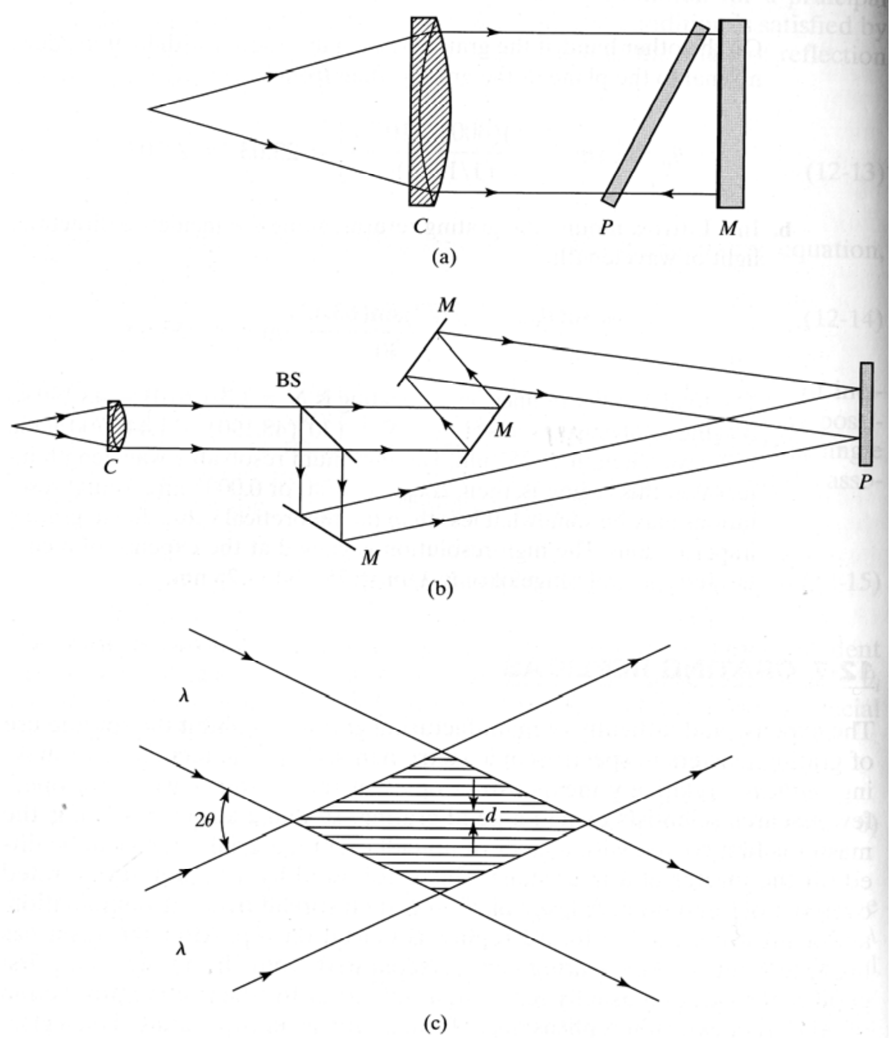


Figure 12-7 (a) Michelson system for producing interference gratings, including collimator C, mirror M, and photographic plate P. (b) Holographic system for producing interference fringes including collimator C, beam-splitter BS, mirrors M, and light-sensitive plate P. (c) Production of interference fringes in the region of superposition of two collimated and coherent beams intersecting at angle θ.

Spectrometers

- Usually start with a slit to give narrow source
- Add concave mirror to create parallel beam
- Reflect off grating to create spectrum
- Then another mirror to create focus light to detector
- Rotate grating to get different lines
- Often motorized to sweep spectrum – record the data with λ
- Use high sensitivity detector (photodetector)
- Common types Echelle two gratings
- Czerny-Turner – single grating
- These also call monochromoters
- Longer the length – higher the accuracy

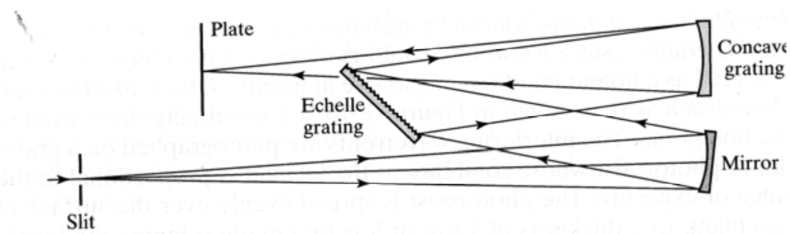


Figure 12-9 Side view of the echelle spectrograph. The echelle is positioned directly over the slit-to-mirror path, but the plate is offset in a horizontal direction.

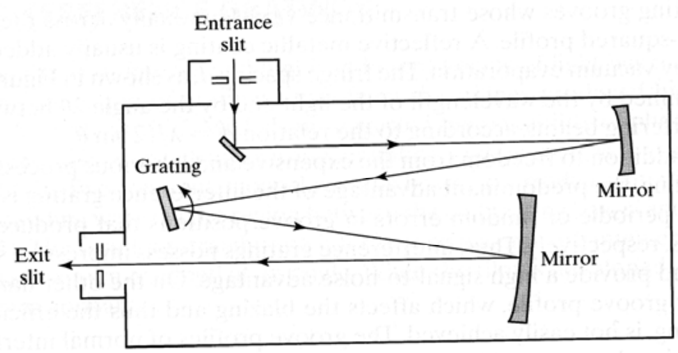
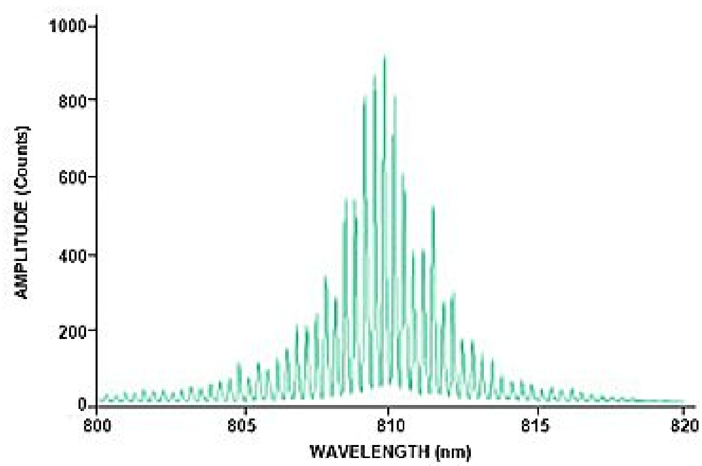
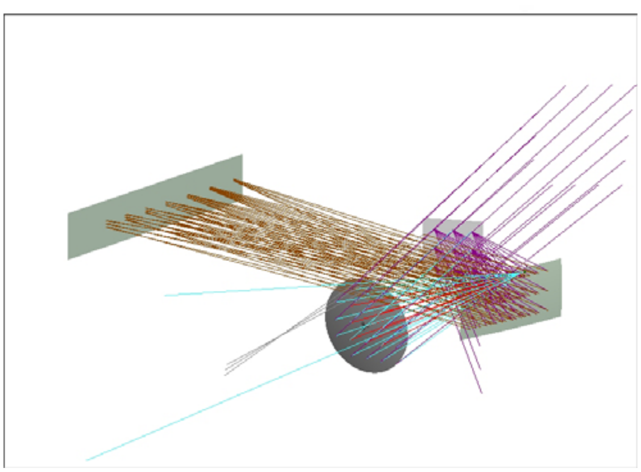


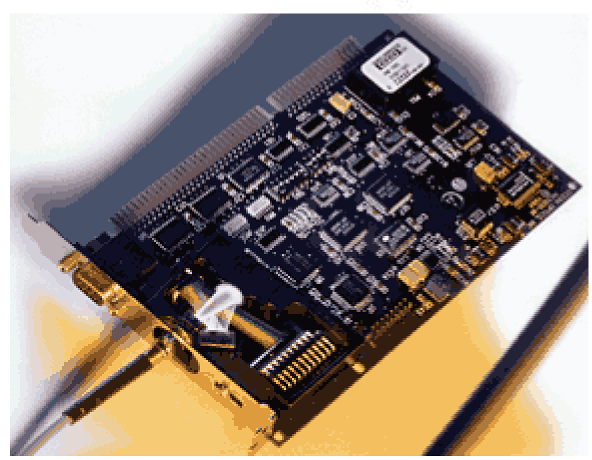
Figure 12-10 Czerny-Turner spectrometer.

CCD Spectrometers

- New spectrometers small, use CCD detector array
- Eg. from Ocean Optics
- Spectrometer input from fiber optics
- Connected to computer by USB cable
- Select the gratings to give line width, wavelength range
- Typical 200-1100 nm
- Output plots intensity vs wavelength to computer display
- Gives rapid analysis of spectrum
- Typically about 4 nm width per pixel at detector







Deflecting & Shuttering Laser Beams

- Often need to scan laser beam over an area
- Also need change CW or long pulse to short pulse
- Often use motor driven mirror system
- Scanning mirror systems: 1 or 2 axis scanners
- Alternative: Rotating Polygon mirrors
- Often combined with scanning mirrors

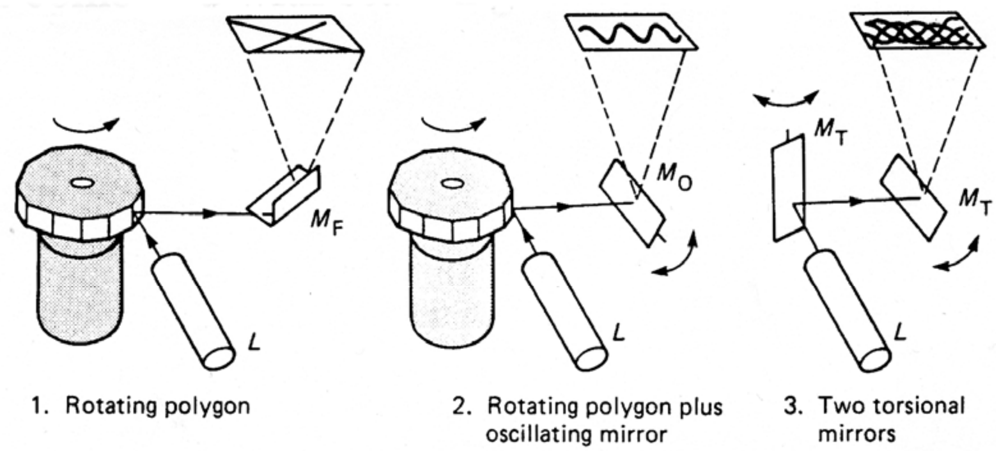
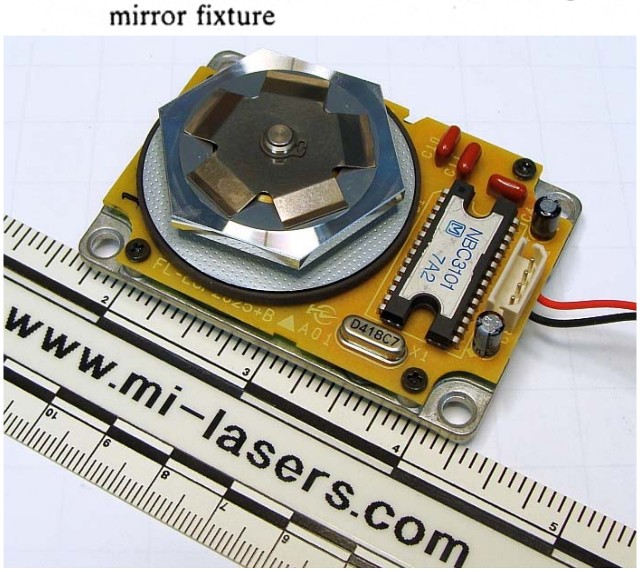
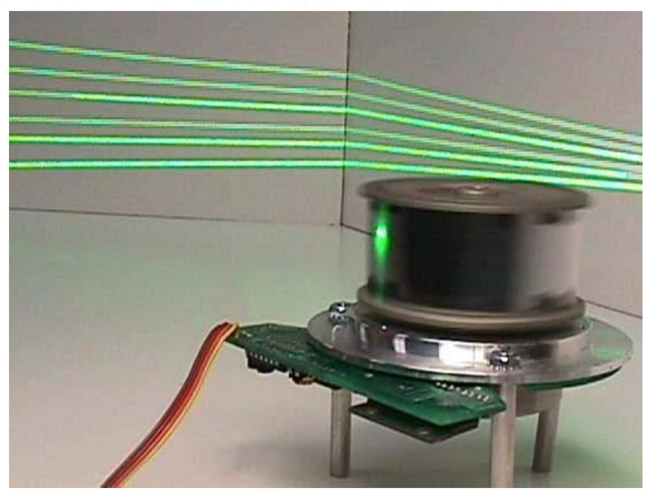


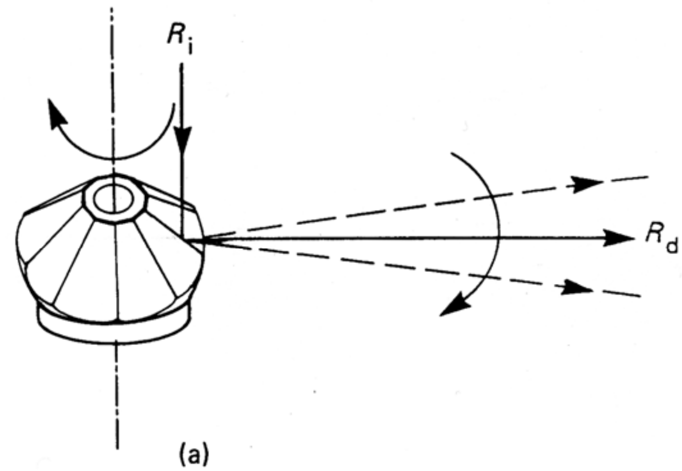
Figure 12.37 Out-of-contact reading. The laser beam is made to trace a complex pattern on the scanned item. L, laser; M_F, folding mirrors; M_O, oscillating mirror fixture; M_T, torsional mirror fixture





Shutters & Scanners: Mechanical Systems

- Motor driven rotating shaft with mirror
- Advantage: relatively low cost & reliable
- Disadvantage: moving parts, hard to change rates
- Rotating N faced pyramidal deflectors most commonly used
- For shutters beam passes through a aperture
  hence only specific angle beam seen in system
- Used in Q switches



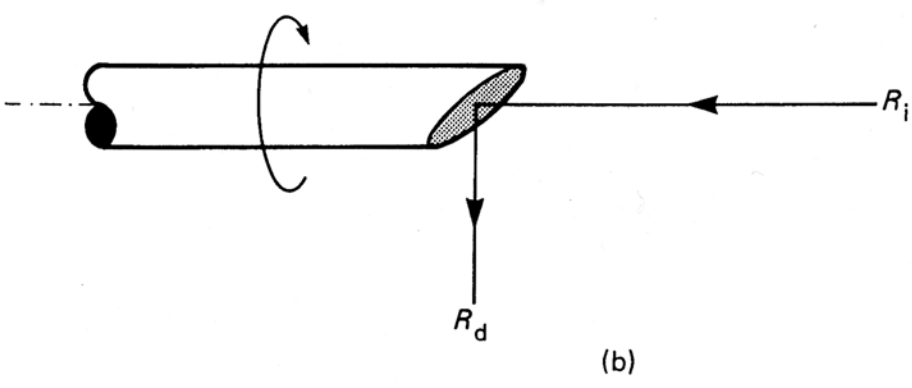


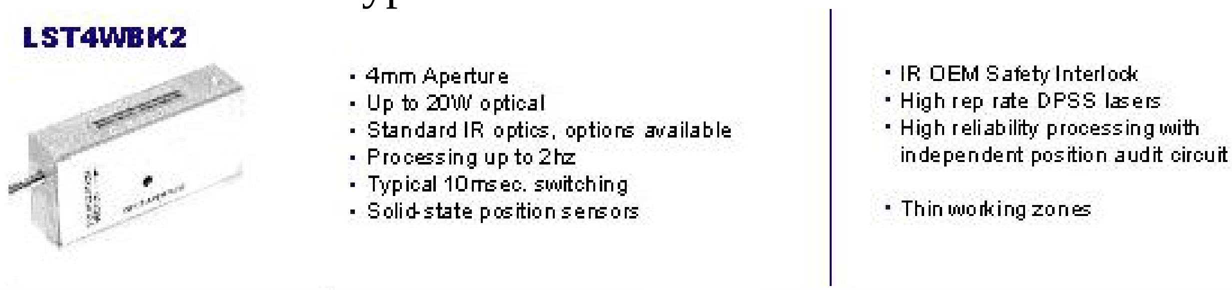
Figure 10.17 (a) Truncated shaft deflector and (b) pyramidal deflector

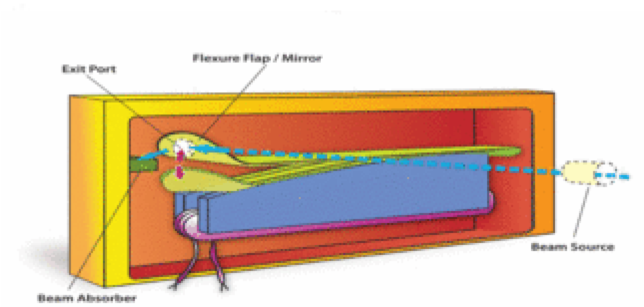
Mechanical Shutters

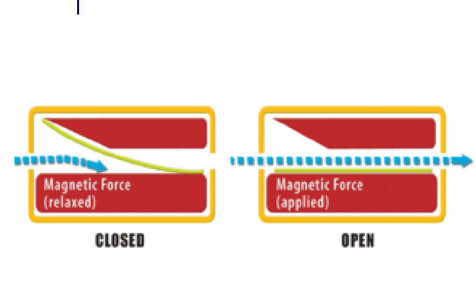
- Rotating Choppers (Rotating wheels with holes in them)
- Rotating speeds set by external controller
- Shutter speed up to 50 microsec
- But best for repeated shutter
- Guillotine type: block with aperture
  Electromechanical thin blades, wedge or iris block beam
- Usually magnetic coil drives metal blade into beam
- Time more than 1 msec -very unstable near 1 msec

Rotating Shutter/Chopper

Guillotine type Shutter







Deflecting & Shuttering Laser Beams

- Holographics reflectors:
  Holograms create effective mirror that reflects beam
- Beam position controlled by angle rotation of hologram
- widely used in supermarket bar code readers

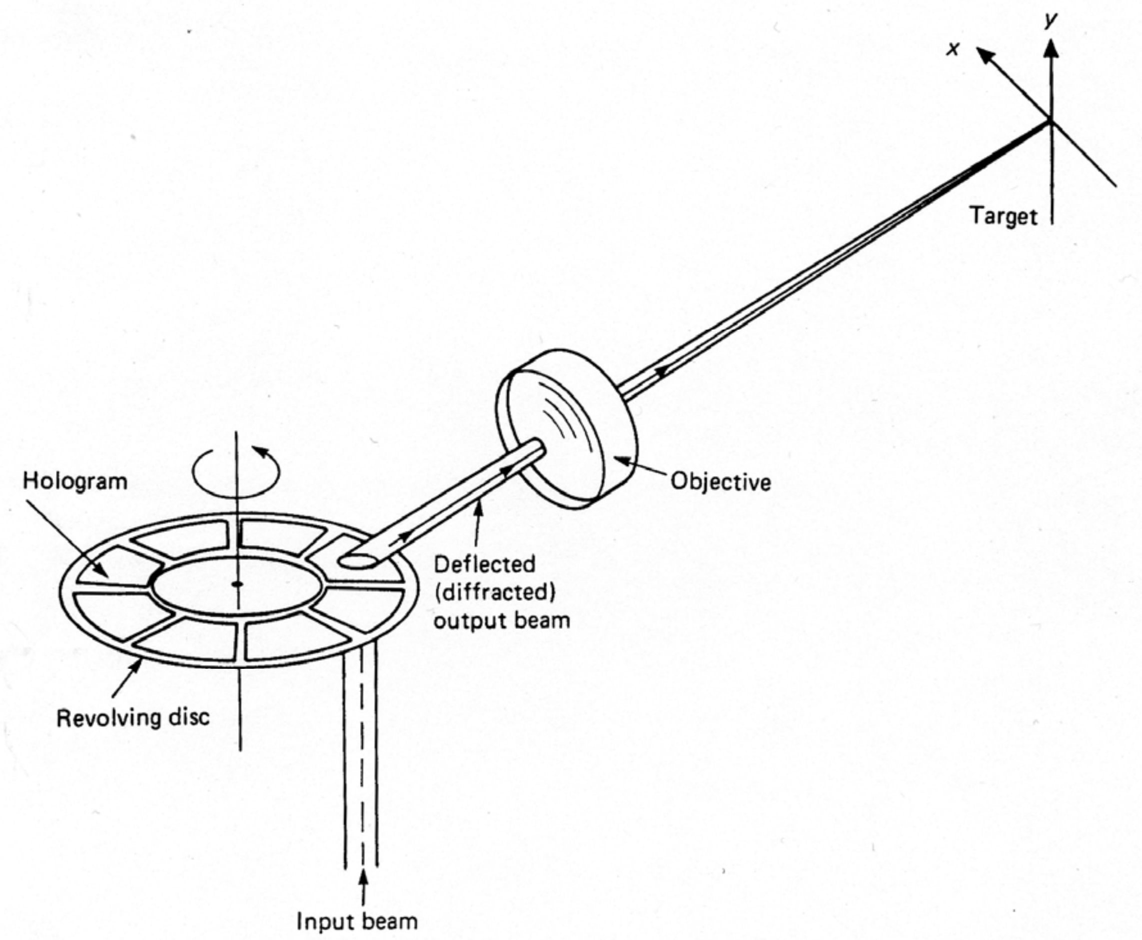
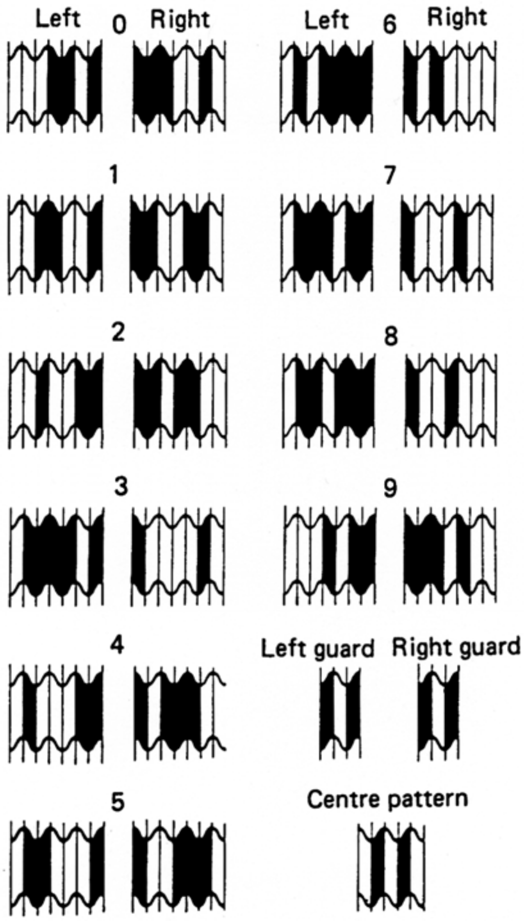


Figure 10.25 A holographic scanner uses a rotating disc containing a number of holograms

Bar Code Scanners

- Originally for Computer codes
- Beam scans over bar code
- Coverted to digital value
- Widest application of HeNe lasers now: stability & beam quality
  Now mostly converting to diode lasers

Figure 12.33 The UPC code Grocery A version Note the presence of user-readable numerals

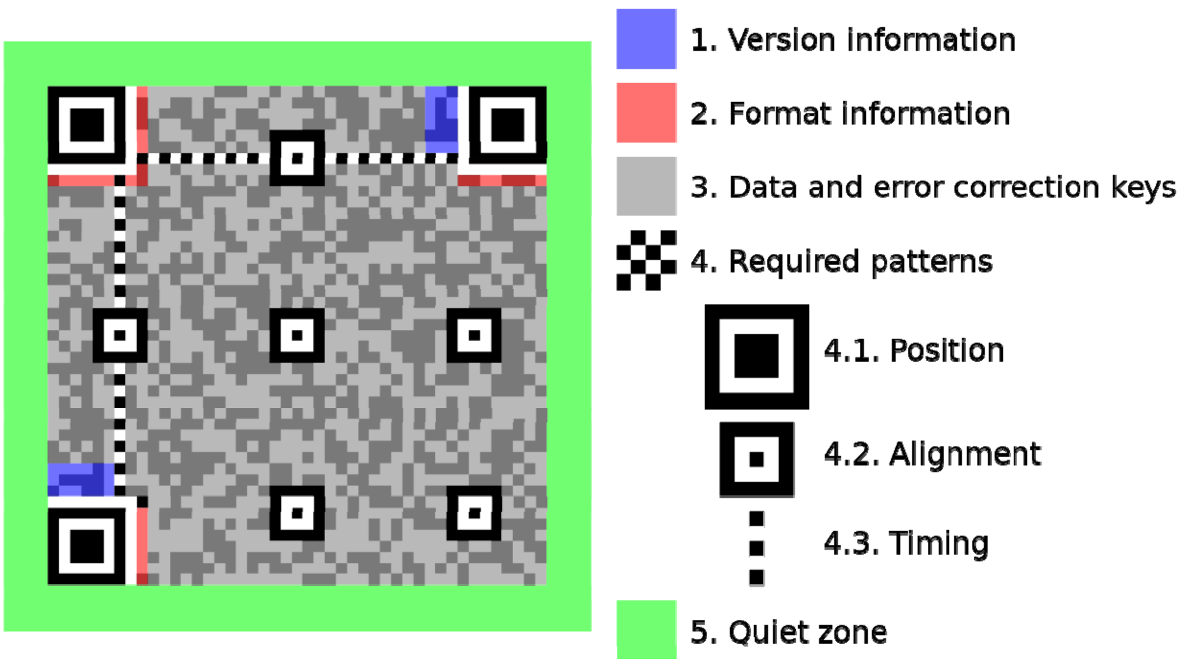


UPC	
Character	*No. of width*
0	3.2.1.1
1	2.2.2.1
2	2.1.2.2
3	1.4.1.1
4	1.1.3.2
5	1.2.3.1
6	1.1.1.4
7	1.3.1.2
8	1.2.1.3
9	3.1.1.2
start/stop	1.1.1

Figure 12.34 The way UPC decimal digits are formed

QR Codes

- QR (Quick Response) Codes are 2D evolution of barcodes
- Developed by Japanese Auto industry for part tracking
- Generally not laser scanned – use camera & decode
- Adds alignment marks (3 corners), version, info
- Can store up to 7089 numbers or 4296 characters
- Even a Japanese Kanji character set
- 3D QR codes now being developed – much higher density
- Read by laser scan (eg product, pill serial no tracking)



Diffraction Gratings as Beam Deflectors

- Recall diffraction gratings produce beams at several orders
- For large N gratings the Principal Maxima are narrow angles
- Hence beams deflected to specific angles
- Can create deflector by selecting beam angle

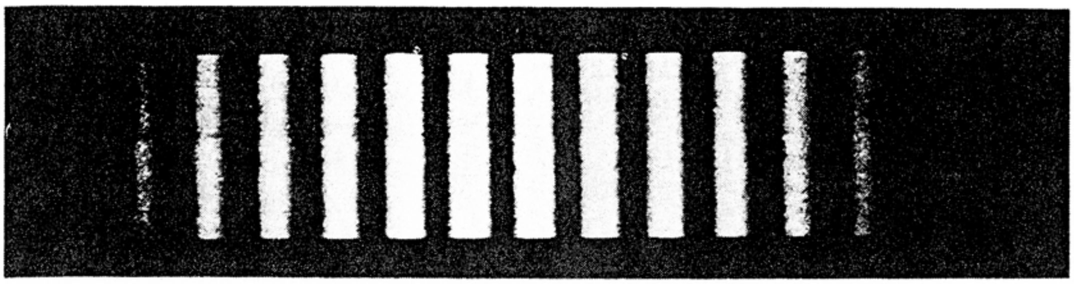


Figure 10.21 Interference fringes

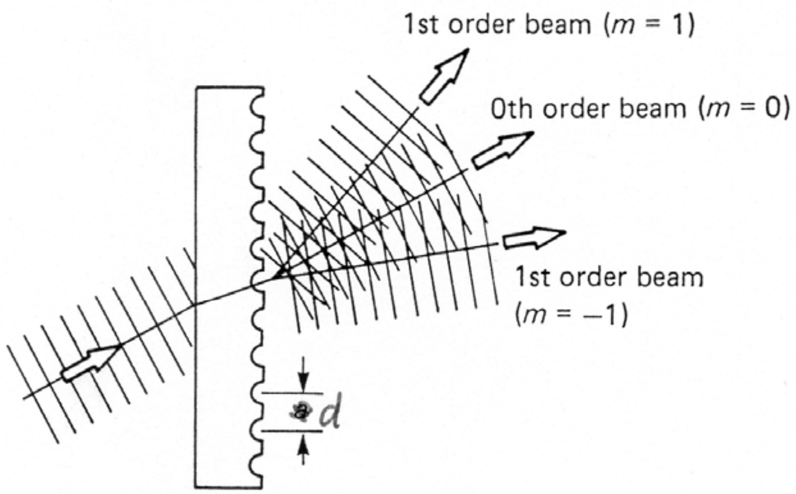
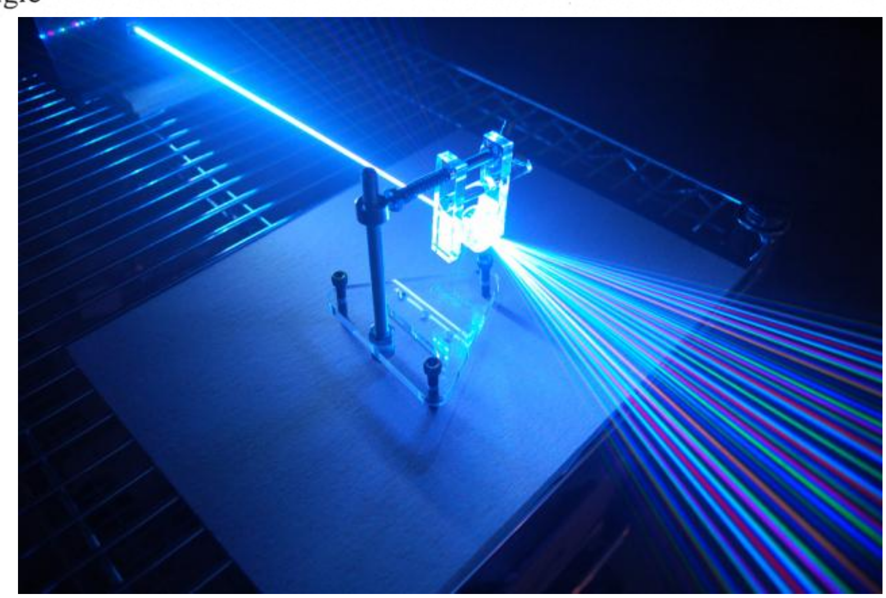


Figure 10.22 A diffraction grating produces several beams, each leaving the structure at a different angle



Acousto-Optic Deflectors

- Consider a material whose index of refraction is significantly changed by acoustic waves
- Eg. Lithium Niobate, quartz
- A piezoelectric transducer attached to one end
- Apply ultrasonic waves, eg 40 MHz
  Creates a diffraction grating from index changes
  Ultrasound wavelength λ_s in the material sets the grating d

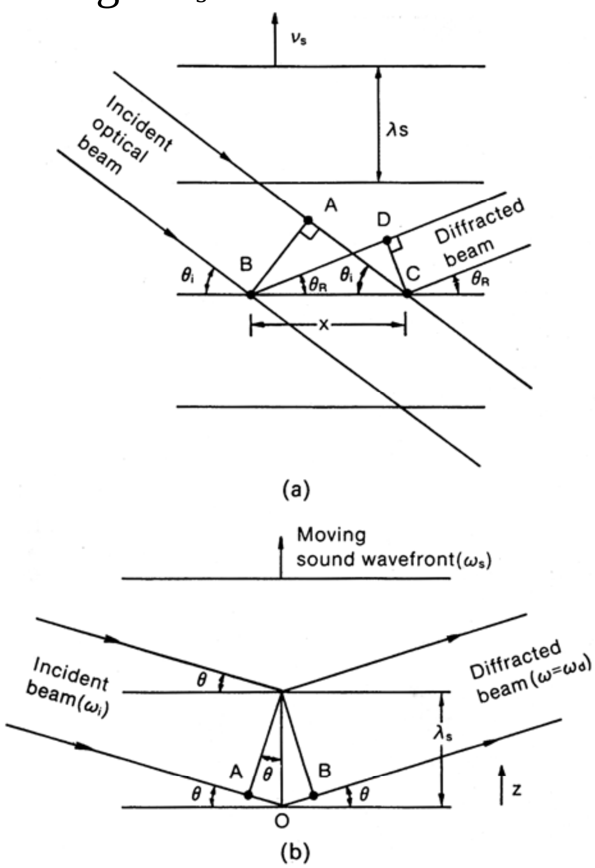
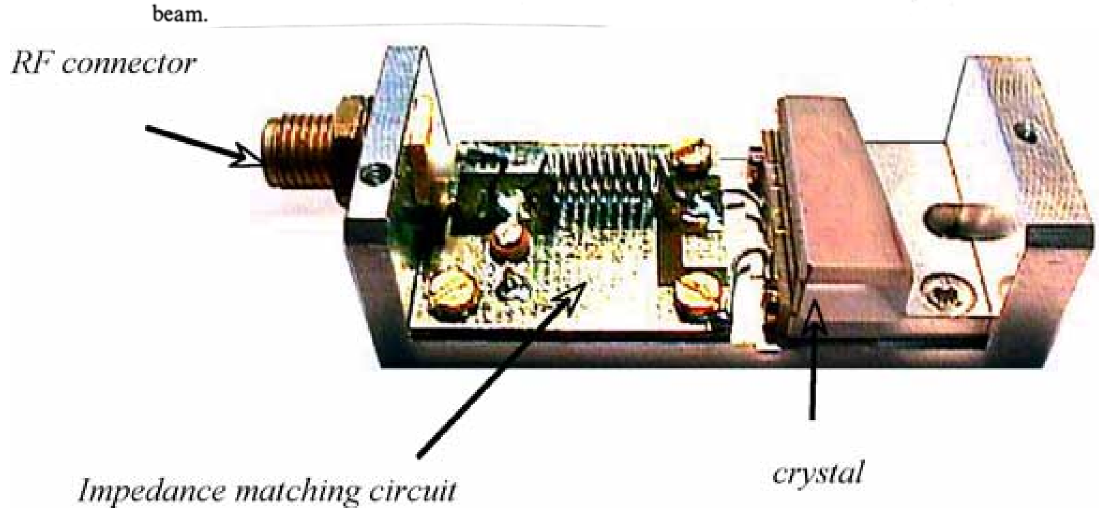


Fig. 2.12.22. Acousto-optic interaction with incident and diffracted light beams. The horizontal lines separated by the acoustic wavelength λ_s represent the moving sound beam.



Acousto-Optic Deflectors

- If beam enters crystal at angle θ
- The it will be deflected constructively when

$$2\lambda_s \sin(\theta) = m\lambda$$

where m is any integer

- Typical defection is about 0.5 degrees
- Use slits to select only the desired beam
- Called a Bragg Cell
  (Angle for only one output is Bragg angle)

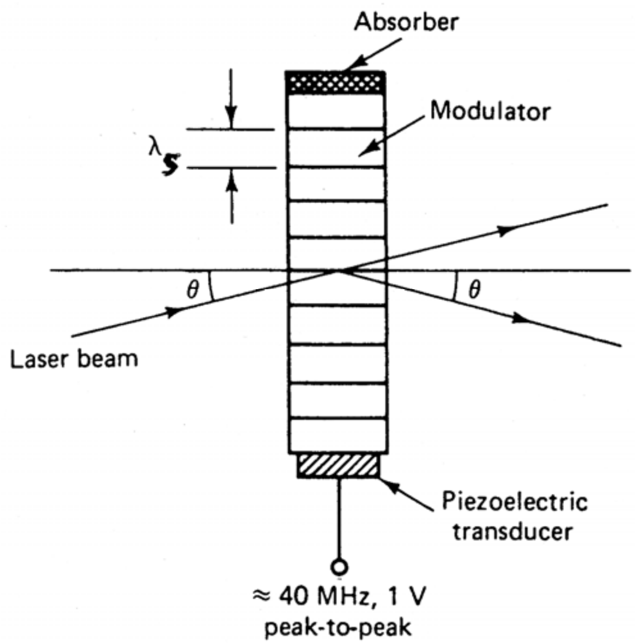


Figure 1-31 Acousto-optical modulator.

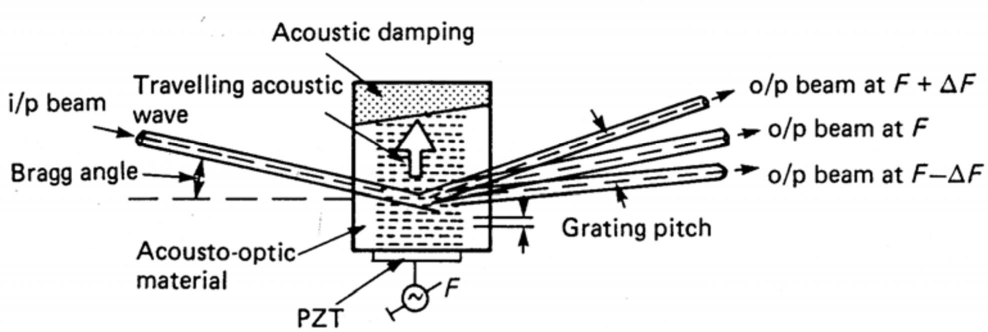


Figure 10.24 The Bragg cell. Incoming radiation must be directed at the diffraction plate at the Bragg angle. Zero-order beam not shown

Acousto-Optic Analogue Modulators

- Use the Bragg Cell for deflections
- Focus output through a slit
- By deflecting beam change intensity through slit
- Focus light from slit into parallel beam

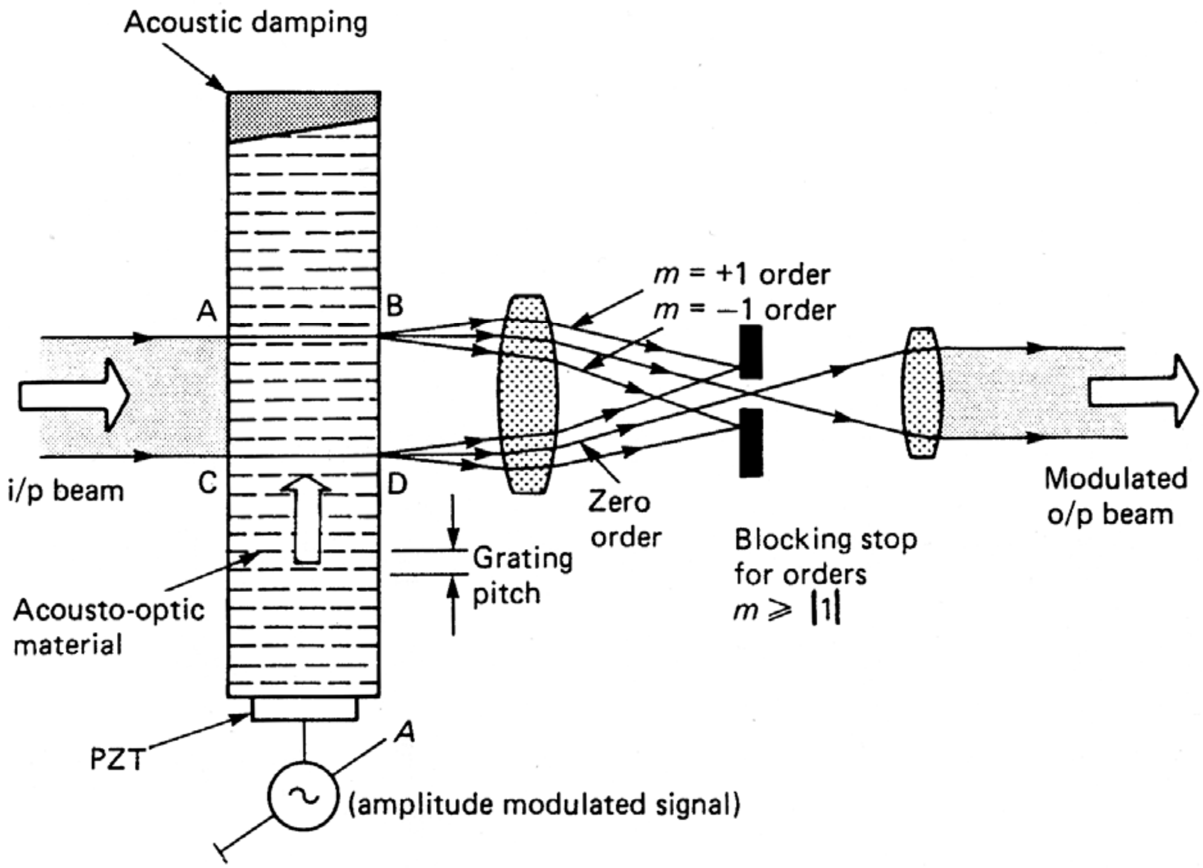


Figure 10.32 Analogue modulation with an AO crystal. Beam intensity depends on the amplitude of the modulating signal

Electro-Optic Shutters

- Generally work by changing of polarization angle
- Work by an interaction between applied electric fields and optical properties of materials

$$\Delta\left(\frac{1}{n^2}\right) = rE + PE^2$$

- r = coefficient for linear electro-optic effect
- Called Pockels effect (devices are Pockels Cells)
- P coefficient for quadratic electro-optic effect Kerr effect

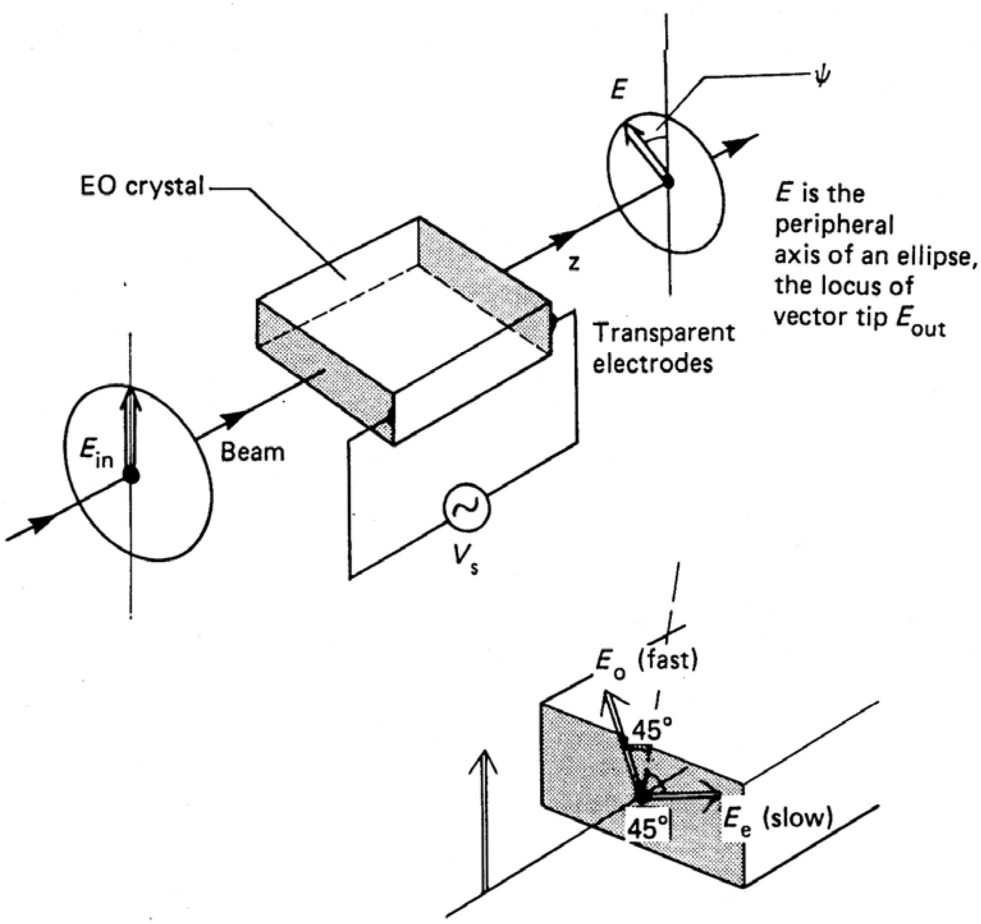


Figure 10.38 Phase modulation of a plane polarized beam in an EO crystal. Beam, crystal and field must be adequately orientated. Note that the phase shift ϕ (retardation angle) is proportional to the controlling voltage, *V*

Pockels Cell

- Get a Change in Polarization with E field

$$\Delta n = n - n_0 = \pm \frac{1}{2} r n_0^3 E$$

- Changes are different in different axis

$$\Delta n = n_x - n_0 = + \frac{1}{2} r n_0^3 E$$

$$\Delta n = n_y - n_0 = - \frac{1}{2} r n_0^3 E$$

- This creates an effect called birefringence
- Assuming a parallel plate capacitor length l with voltage V

$$E = \frac{V}{l}$$

$$n_x - n_y = r n_0^3 \frac{V}{l}$$

- Thus phase shift due to light speed change in different directions
- Total shift ϕ a function of cell length L light travels in

$$\varphi = \frac{2\pi}{\lambda}\left(n_x - n_y\right)L = \frac{2\pi}{\lambda} r n_0^3 \frac{V}{l} L$$

- Note V is often applied perpendicular to light so L & l different
  However in some cells (as in diagram) L & l are the same

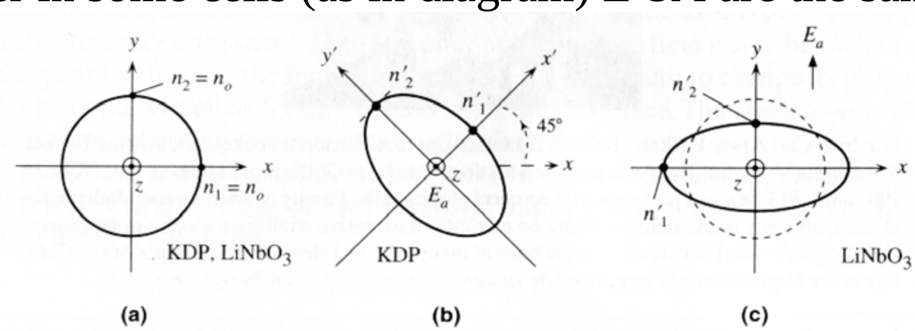


FIGURE 7.19 (a) Cross section of the optical indicatrix with no applied field, $n_1 = n_2 = n_o$ (b) The applied external field modifies the optical indicatrix. In a KDP crystal, it rotates the principal axes by 45° to x' and y' and n_1 and n_2 change to n'_1 and n'_2. (c) Applied field along y in LiNbO$_3$ modifies the indicatrix and changes n_1 and n_2 to n'_1 and n'_2.

Electro-Optic Shutter

- Typical materials:
  KDP   Potassium Dihydrogen Phosphate
  KD*P   Deuterated Potassium Dihydrogen Phosphate
  $LiNbO_3$ Lithium Niobate
  $LiTaO_3$ Lithium Tantulate
- Also GaAs
- Best currently KD*P get 90% rotation
  good for Argon Ion multiline
- Note must carefully adjust offset voltages
  and swing voltages
- Typical values 200 - 1000 V
- Makes a good fast switch
  speed limited by speed of amplifier
- Typical values 2 microsec rise time
  faster (picosec) for special shutters/amplifiers

Material	**n**	**r(10^{-12} m/V)**
Ammonium dihydrogen Phospate (ADP)	1.522	7.8
Potassium dihydrogen Phospate (KDP)	1.510	10.6
Deuterated Potassium dihydrogen Phospate (KD*P)	1.502	26.4
Lithium Niobate	2.232	30.8
Lithium Tantalate	2.179	30.3

Electro-Optic Shutter

- Take in polarized light
- Output polarization dependent on applied E field
- Polarizer on output
- For high power use Brewster reflecting Polarizer
- Reflect beam of polarization from “off” E field
- Absorb reflected beam in a “Beam Dump” – large absorbing metal
- Beam through if turned “on” E field
- No energy absorbed in shutter – thus can handle large powers

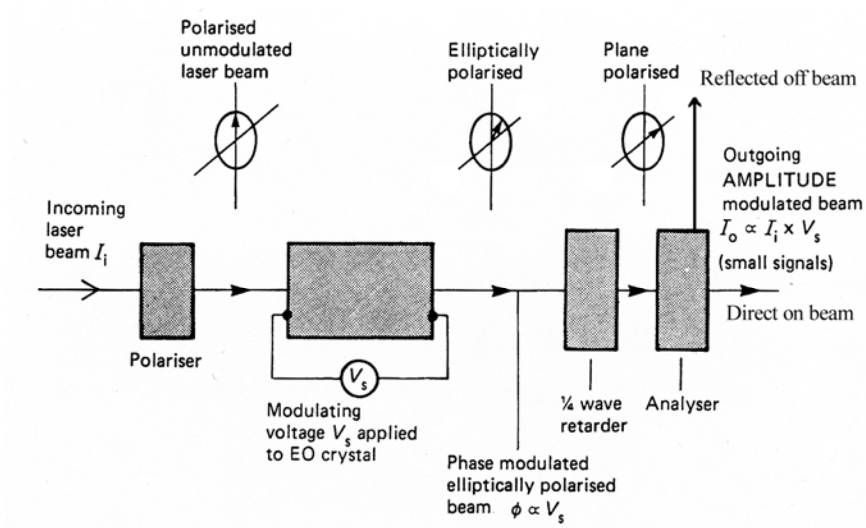
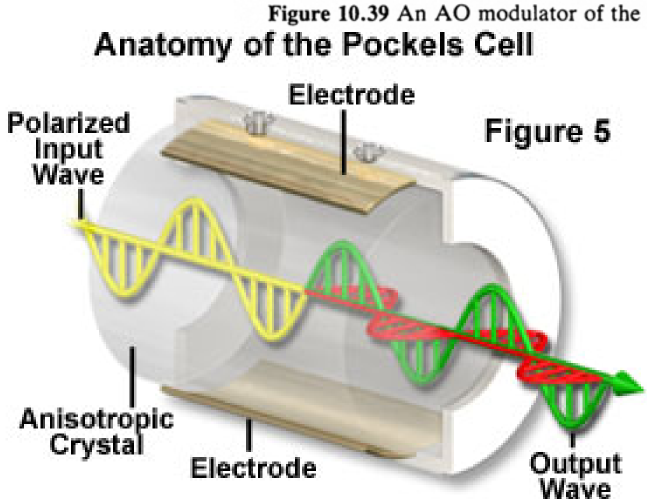


Figure 10.39 An AO modulator of the longitudinal type



Deflectors as Q Switches

- Recall pulsed pumped lasers
- Laser pulse starts when threshold exceeded
- Continues until below threshold
- However could get much high pulse intensity
  if delay lasing beyond threshold
- Do this by detuning cavity (Q switching)
- Result is very powerful short pulse
- However total power lower than without Q switch

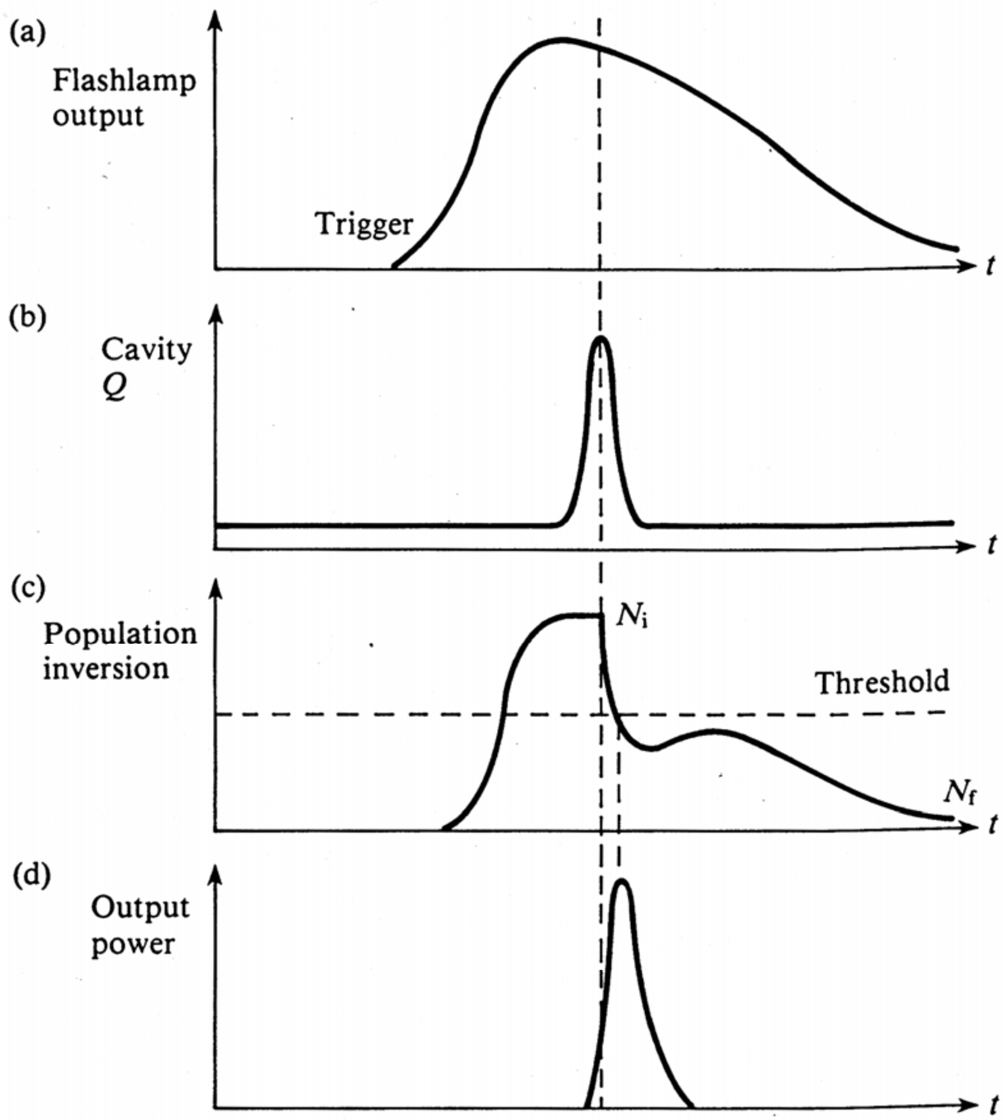


Fig. 3.11 Schematic representation of the variation of the parameters: (a) flashlamp output; (b) cavity *Q*; (c) population inversion; (d) output power as a function of time during the formation of a Q-switched laser pulse.

Q Switch in Cavity

- All methods involve putting something in cavity
- Mechanical shutters, Electro-optic and Acousto-optic modulators used
- Deflect or eliminate beam (i.e. low Q) pulse peak of pop inversion
- Pulse synchronized with pump pulse end/centre

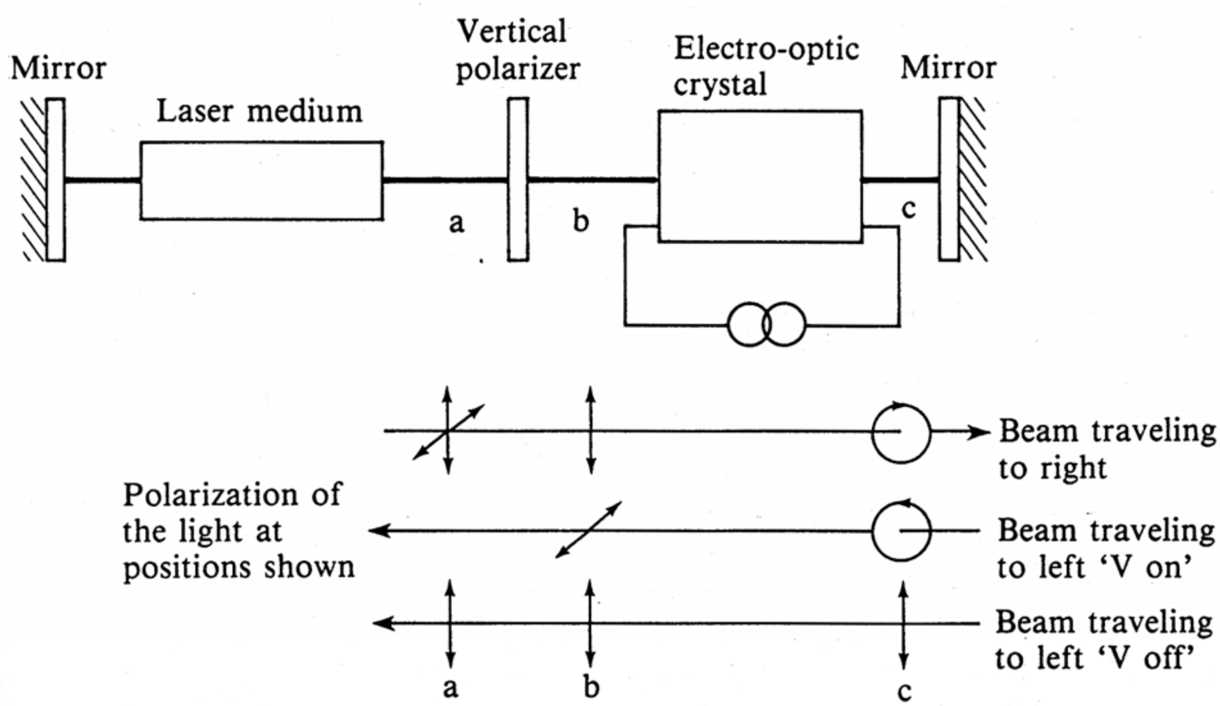


Fig. 3.12 Electro-optic crystal used as a Q switch. With the voltage V on, the electro-optic crystal acts as a $\lambda/4$ plate and converts the vertically polarized light at b into circularly polarized light at c. The reflected light is converted to horizontally polarized light and eliminated by the polarizer so that the cavity Q is low. With V off, the crystal is ineffective and the cavity Q is high.

Acousto-Optic Q Switch

- Deflector placed at an angle in cavity
- Deflects beam with ultrasound applied

Set so pulse

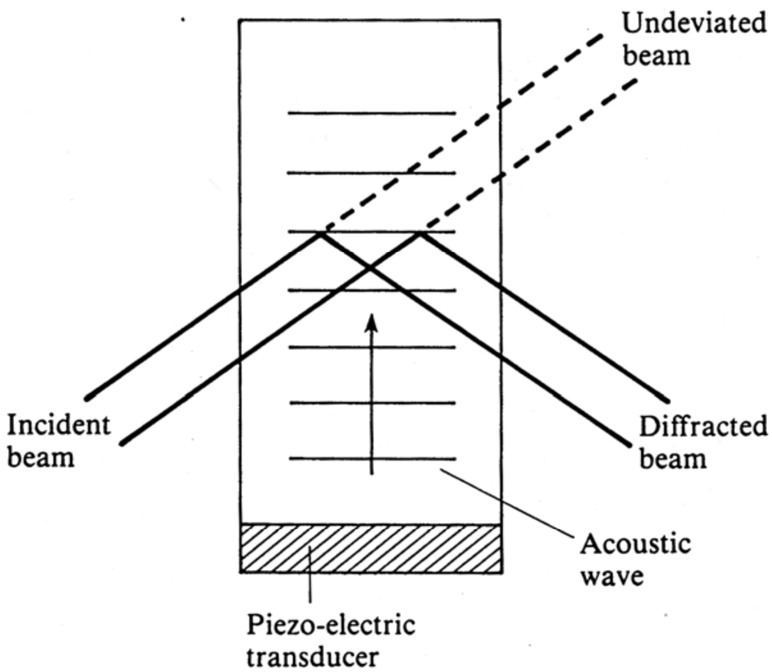
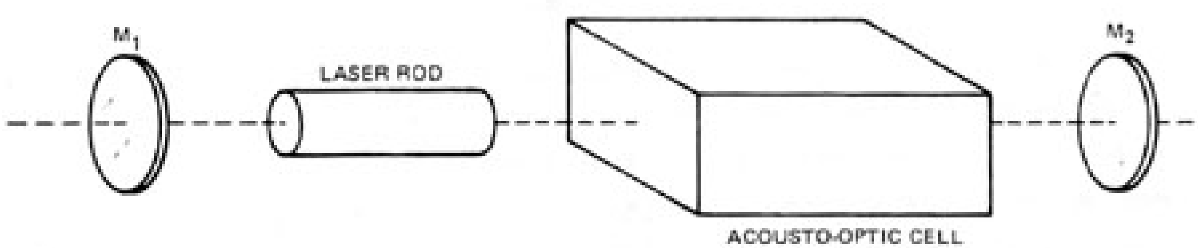


Fig. 3.13 Operation of an acousto-optic *Q* switch device. For simplicity the effects of refraction on the beams entering or leaving the transducer are ignored.



Saturable Absorber Q Switch

- Saturable absorbers are solid state Q switches
- Dyes which absorb until reach certain light intensity
- Above threshold absorption loss suddenly decreases
- Does not need any control system
- Dye selected for the need.
- Used to stabilize modes in femtosecond laser pulses

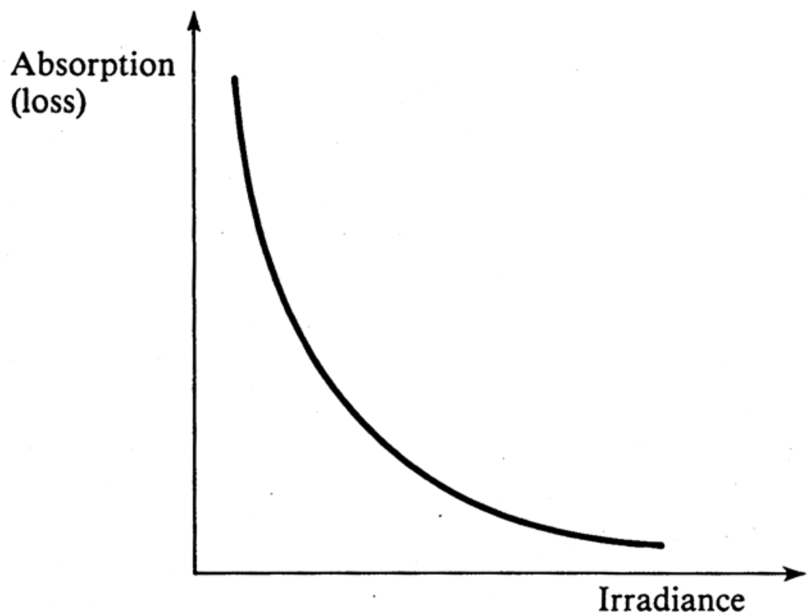
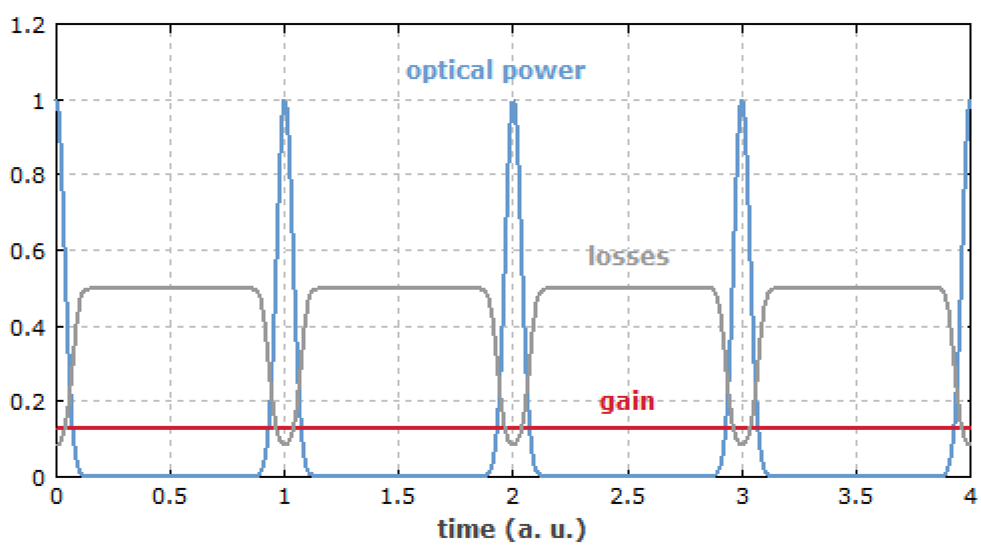


Fig. 3.14 Absorption as a function of incident light irradiance for a saturable absorber.



Temporal evolution of optical power and losses in a passively mode-locked laser with a fast saturable absorber. The shorter the pulse becomes, the faster will be the loss modulation. The gain stays approximately constant, as gain saturation is weak.

Mode Locking & Saturable Dyes

- Recall lasers can operate in many modes
- Normally each mode is independent of others
- Mode Locking causes many modes to be phase locked together
- Use a saturable dye within cavity to cause this
- When modes out of sync power is low: saturable dye absorbs
- When modes move into sync higher power – dye saturates
- Mode locking starts: feeds back into laser & dominates
- Some gain media is naturally saturable & mode locks
- Mode locking creates very short pulses – picosec to femtosec
- Pulse duration τ_p for single mode is related to freq spacing

$$\Delta\nu = \frac{c}{2L} \quad \tau_p = \frac{1}{\Delta\nu}$$

- Minimum pulse length is approximately coherence time
- For M modes locked together then frequency becomes

$$\Delta\nu_M = M\Delta\nu = \frac{Mc}{2L} \quad \tau_{pM} = \frac{1}{\Delta\nu_M} = \frac{2L}{Mc}$$

- Thus pulse duration decreases as M increases

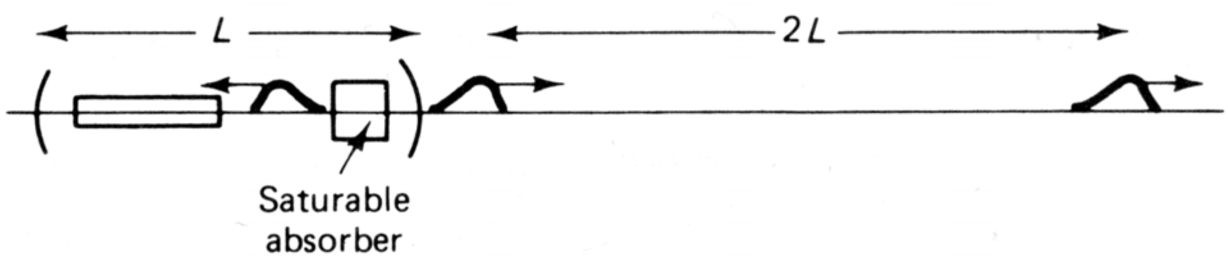


Figure 6-6 Mode-locked pulses.