Optical Wave Guides & Fiber Optics

- Optical wave guides are the basis of optical communications
- Wave guides consist of a high index inner core/layer n_1
- Surrounded by a lower index cladding n_2
- This creates the Total Internal Reflection (TIR) possibility
- Recall At a critical angle θ_c the beam is refracted 90^o

$$\frac{\sin(\theta_c)}{\sin(90^o)} = \frac{n'}{n}$$

$$\sin(\theta_c) = \frac{n'}{n}$$

- All larger angles (shallower to surface) reflected with no loss!!

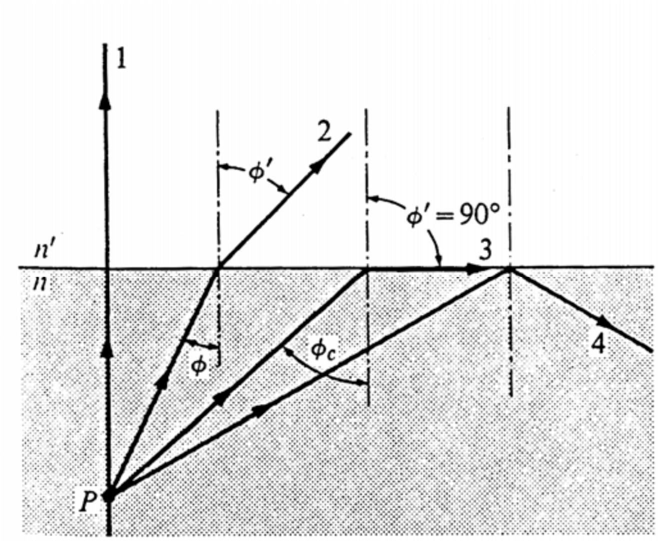
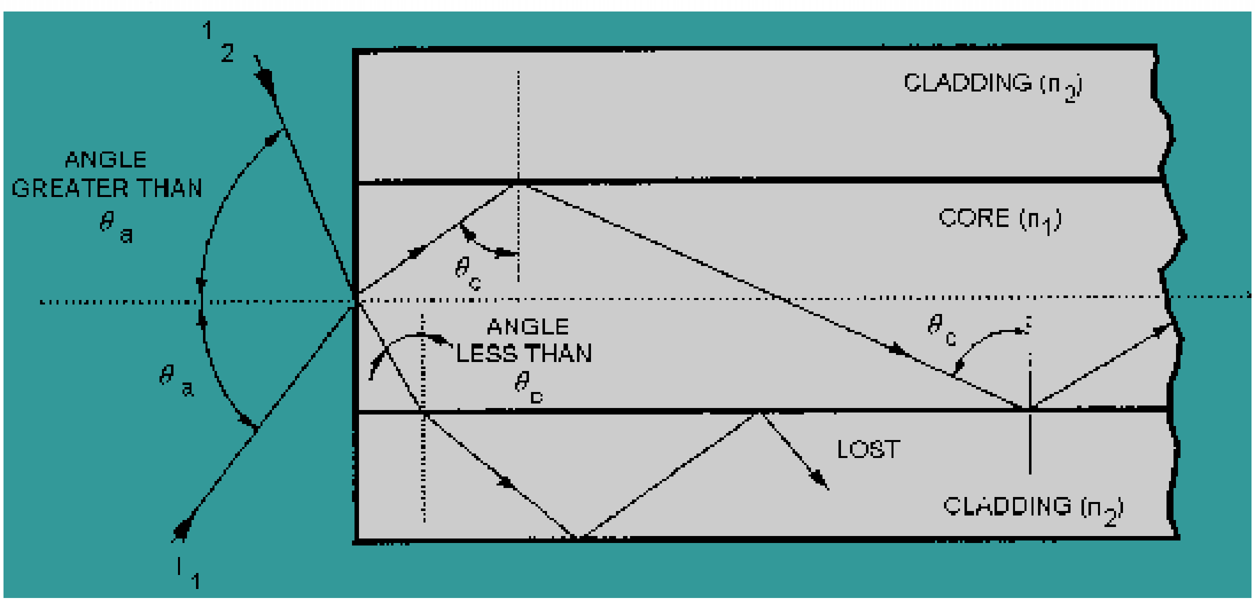
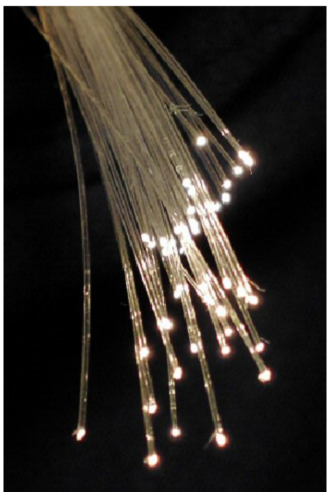


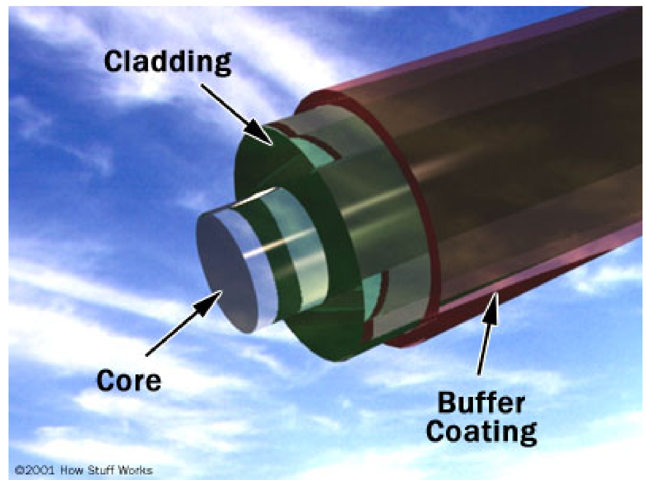
Fig. 38–7. Total internal reflection. The angle of incidence ϕ_c, for which the angle of refraction is 90°, is called the critical angle.

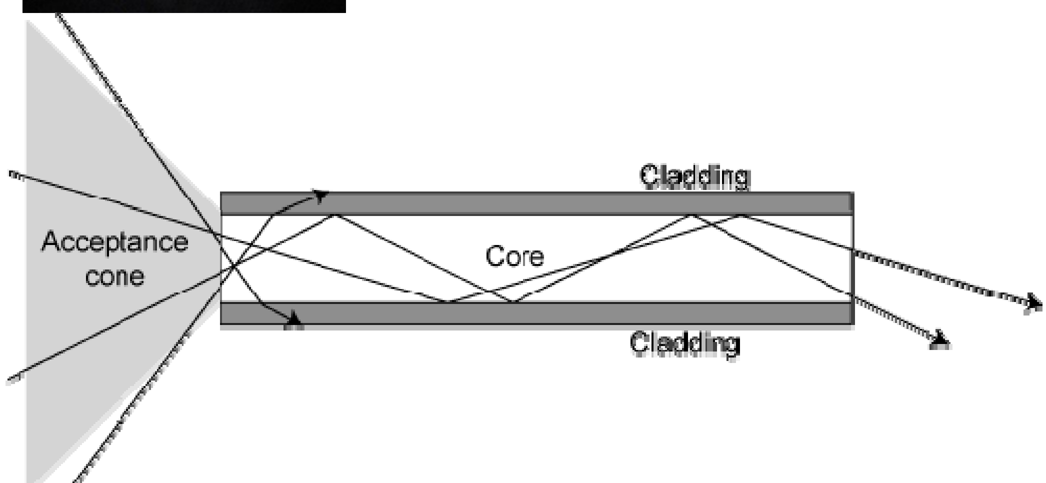


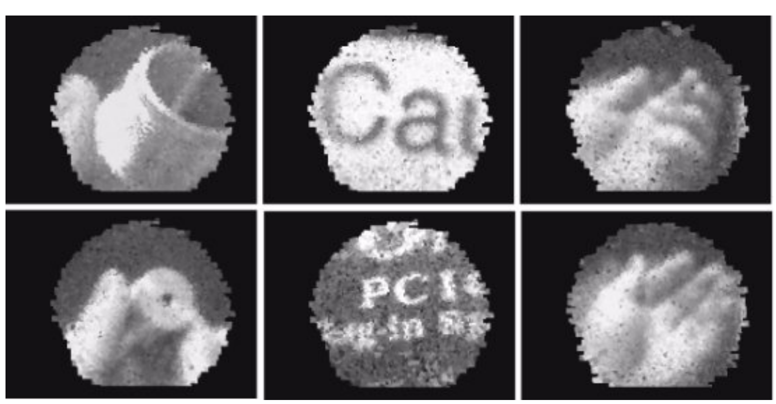
Confining Light to Wave Guide

- Concept of TIR by Jean-Daniel Colladon in 1841
- Optical fibers developed in 1956
- Surrounding glass core with low n cladding: Δn constant
- Thus light bounces through fiber by TIR
- Initial application: if have bundle of fibers can transmit image
- Flexible line for image transmission
- Only loss was in the absorption by the core glass



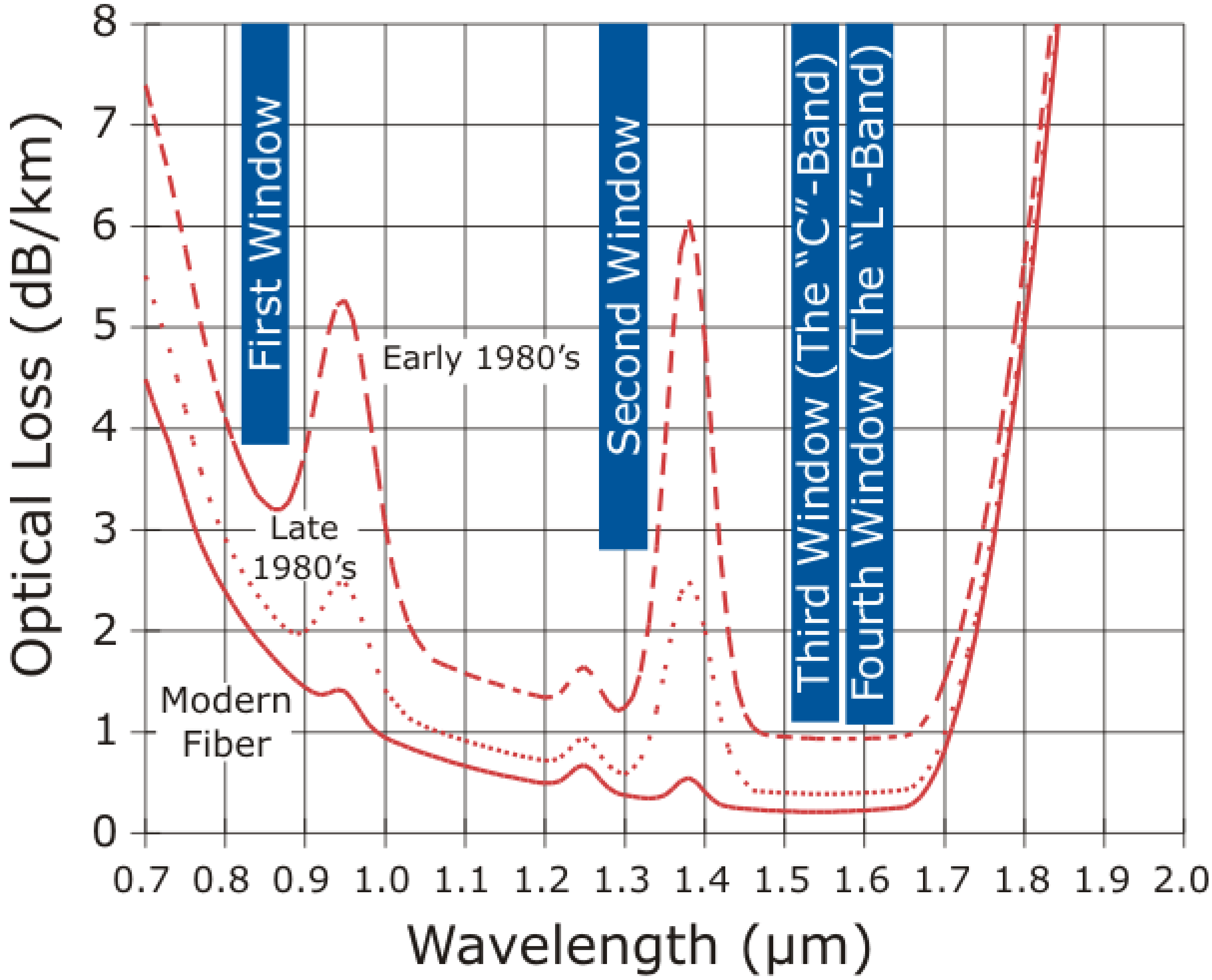






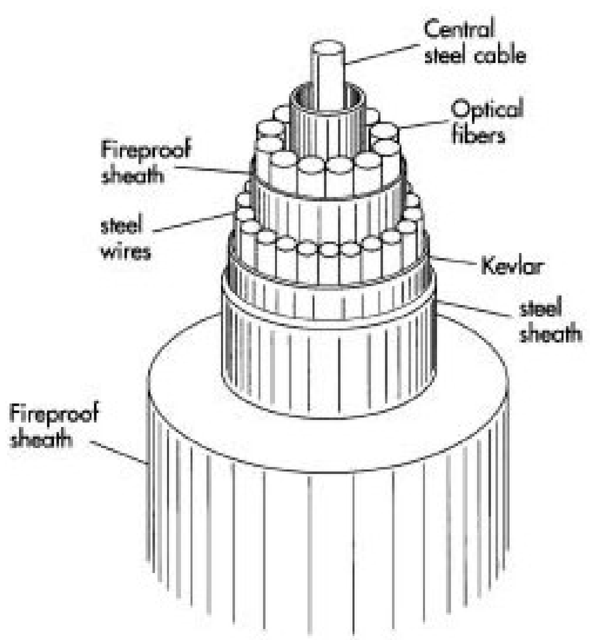
Optical Fiber Communications

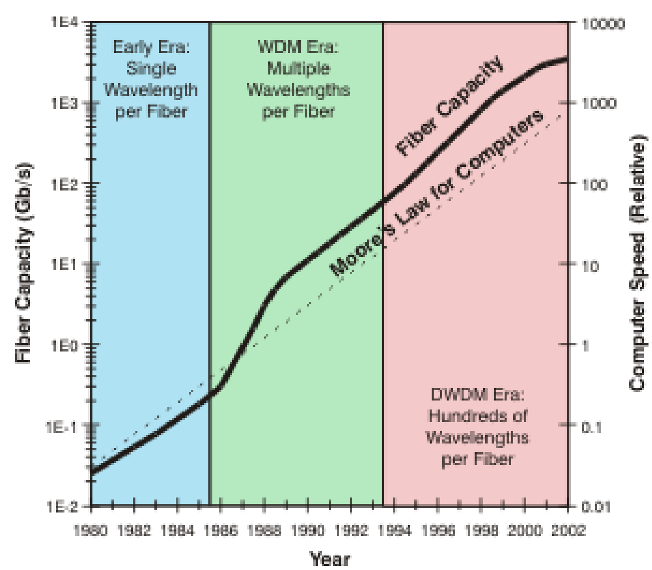
- Optical Fiber communications: Charles Kao & Charles Hockham
- Standard Telecommunication Laboratory in England in 1966
- At that time fiber had a loss of 1000 db/Km
- Stated if could get fiber to 20 db/Km would equal coaxial cable
- Need amplifier for 100 db loss – which was 5 km on coaxial
- Realized problem was impurity in glass
- 1970 Maurer, Keck, & Schultz of Corning Glass: 17 db/Km
- First long distance fibers used GaAs lasers at ~850 nm, 3-4 db/Km
- New lasers targeted 1310 nm min absorption band 0.5 db/Km
- 1977 Nippon Telephone & Telegraph went to 1550 nm 0.2 db/Km
- Modern fibers <<1 db/km
- Signal travels 500-800 km without amps.
- 1990 Bells labs achieved 7500 km at 2.5 Gb/s without amps

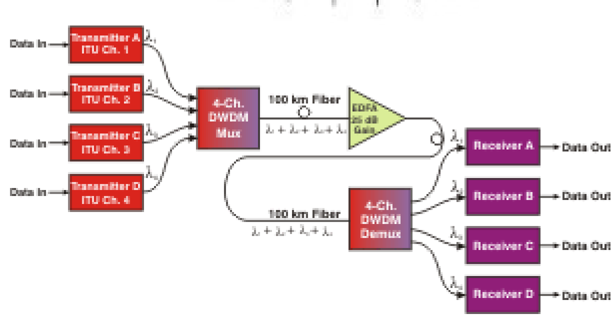


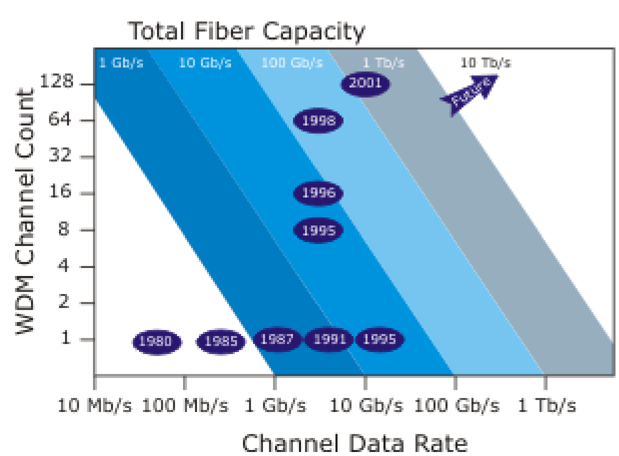
Fiber Communications

- After fiber next limits was getting lasers and detectors
- Needed long life (50,000 hrs) & speed at desired wavelength
- In 1980’s fiber cable: single coaxial size but many fibers
- Vast increase in bit rate to GigaBits/s
- Initial increase was single wavelength fibers
- Next change was Wavelength-Division Multiplexing (WDM)
- Different wavelengths do not interfere in cable
- Thus can keep cable the same and add many λ signals
- Replace with multiple laser diodes/detectors: each for one λ
- Currently Dense WDM (DWDM) 370 channels in single cable
- 2011 record 101Tbit/s (370 λ, 273 Gbit/s per channel)









Light Transmission in Fiber Cables

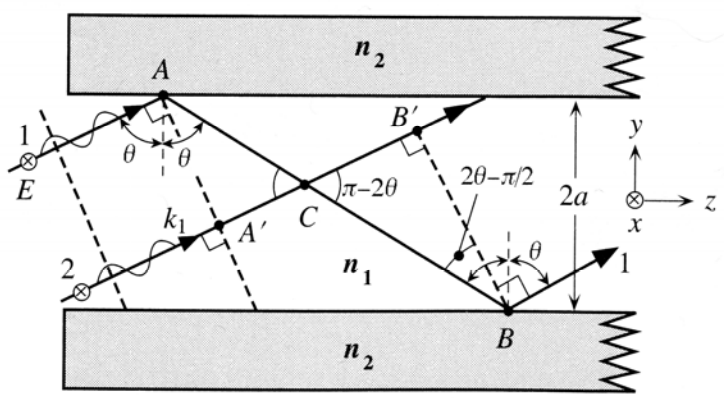
- Light traveling down the fiber has Emag wave distribution
- Consider a fiber with
  - core of radius a
  - core index n_1
- Solution of wave equations allows only certain angles θ_m
- Called the waveguide conditions

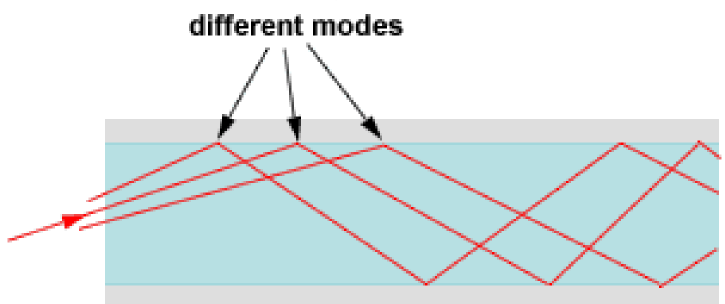
$$m\pi = \left(\frac{2\pi n_1(2a)}{\lambda}\right)cos(\theta_m) - \phi_m$$

Where m is an integer: the mode number

ϕ = phase change for given mode

FIGURE 2.3 Two arbitrary waves 1 and 2 that are initially in phase must remain in phase after reflections. Otherwise the two will interfere destructively and cancel each other.





Step-Index Multimode Fiber

Light Transmission in Fiber Cables

- Light traveling down the fiber has Emag wave distribution
- But wave is dependent on the angle of the reflections
- Diferrent angles give different modes
- The propagation constant for each possible mode angle is

$$\beta_m = \left(\frac{2\pi n_1}{\lambda}\right) sin(\theta_m)$$

- Emag wave in the fiber becomes

$$E(y,z,t) = 2E_m(y)\, cos(\omega t - \beta_m z)$$

Where y is axial radius, z length, t time

- Different modes different wave distribution

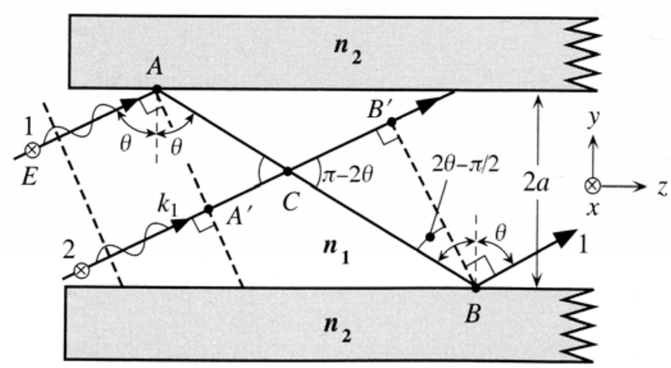


FIGURE 2.3 Two arbitrary waves 1 and 2 that are initially in phase must remain in phase after reflections. Otherwise the two will interfere destructively and cancel each other.

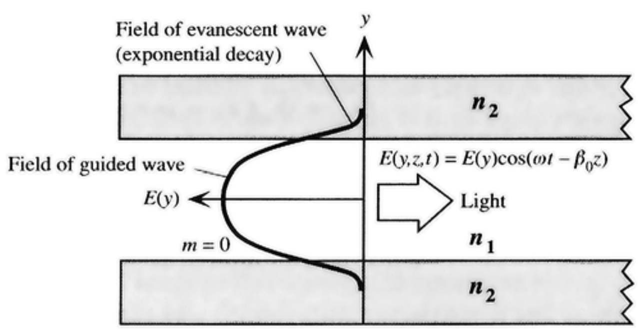


FIGURE 2.5 The electric field pattern of the lowest mode traveling wave along the guide. This mode has $m = 0$ and the lowest θ. It is often referred to as the glazing incidence ray. It has the highest phase velocity along the guide.

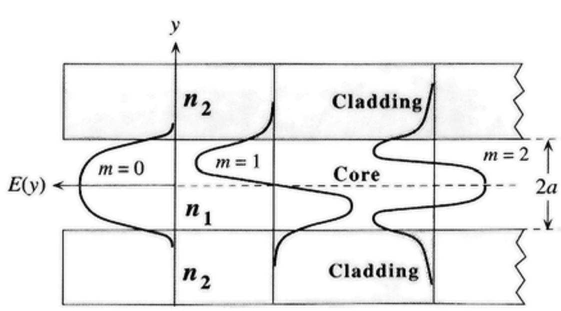
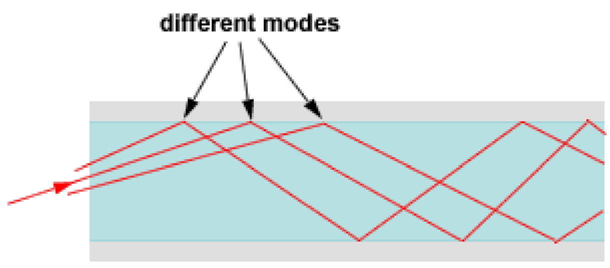


FIGURE 2.6 The electric field patterns of the first three modes ($m = 0, 1, 2$) traveling wave along the guide. Notice different extents of field penetration into the cladding.

Effect of Different Fiber Modes

- Modes of propagation have effect on the signal
- Different modes at different angles mean light path length changes
- Thus some modes arrive before others
- This creates a spreading of the light pulse



Step-Index Multimode Fiber

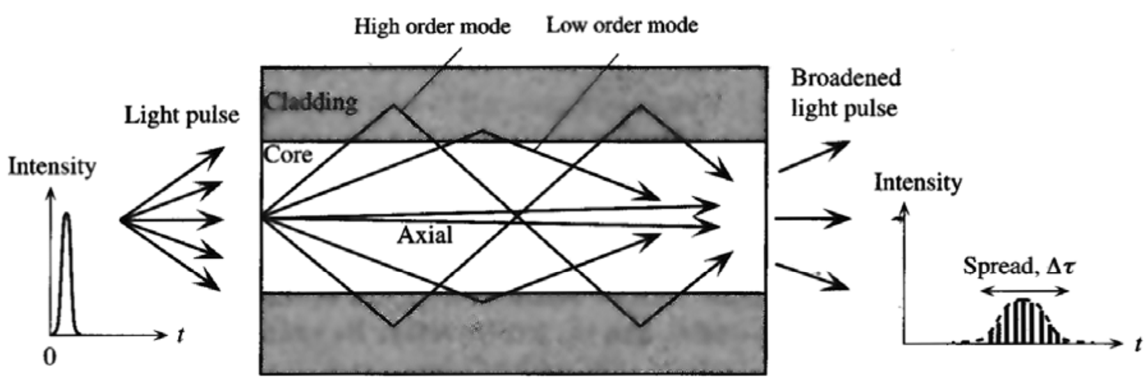


FIGURE 2.7 Schematic illustration of light propagation in a slab dielectric waveguide. Light pulse entering the waveguide breaks up into various modes that then propagate at different group velocities down the guide. At the end of the guide, the modes combine to constitute the output light pulse which is broader than the input light pulse.

Group Velocity and Phase Velocity

- Light speed is really the phase velocity v

$$\omega = vk$$

Where ω = 2πf = angular frequency
k = wave vector =2π/λ

- This is really the velocity of the waves
- However information travels in wave packets
- Wave packets have a frequency variation
- Frequency is modulated by slowly changing δω
- Have ω+δω and ω-δω frequency rang
- This packet moves with wave vector δk
- Thus the group velocity is given by

$$v_g = \frac{d\omega}{dk}$$

- In a vacuum

$$v_g = \frac{d\omega}{dk} = c = \textit{phase velocity}$$

- Each mode in a fiber travels with different group velocity
- Thus get spreading of information packet

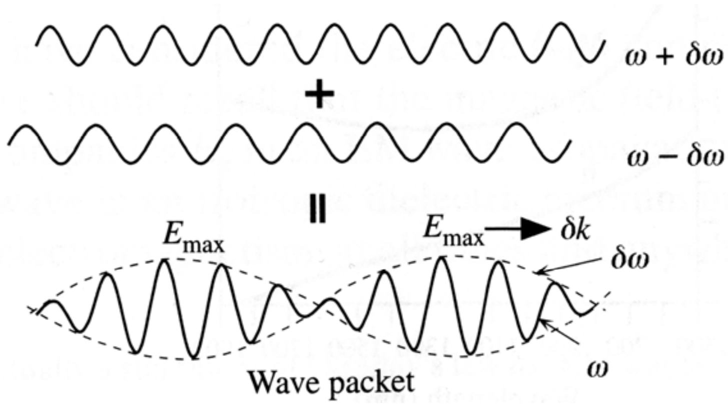


FIGURE 1.6 Two slightly different wavelength waves traveling in the same direction result in a wave packet that has an amplitude variation which travels at the group velocity.

Multi Mode and Single Mode Fiber

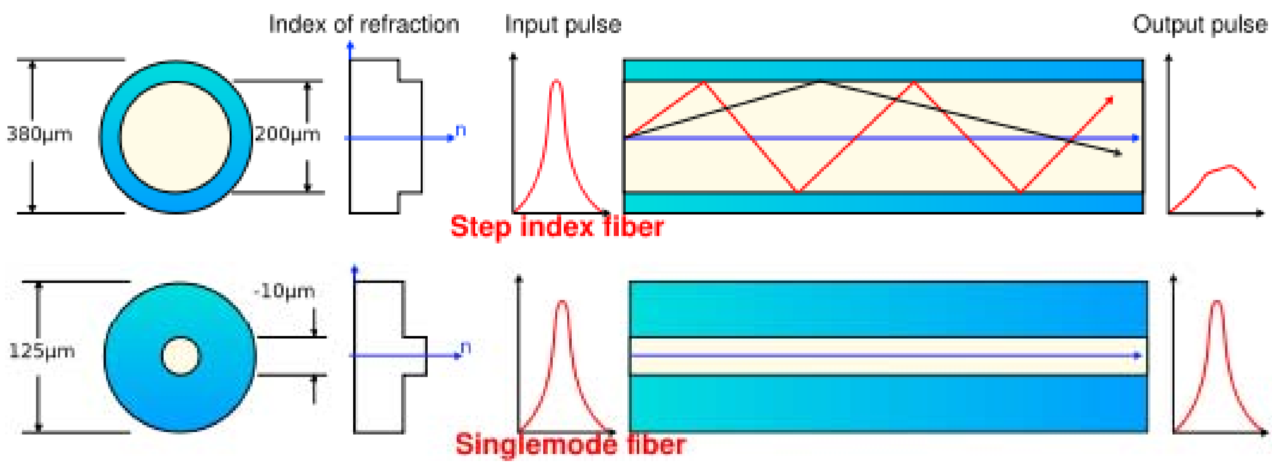
- Multi mode fiber results in spreading of signal
- But number of modes is set by core diameter and index
- Can change number of modes by changing these
- Want a single mode fiber m=0
- Number of modes are set by

$$m \le \frac{(2V - \phi)}{\pi}$$

- Where V is the V number given by

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}$$

- Thus get a single mode when V<2.405
- To create single mode make diameter of core very small
- Result much reduced pulse spreading
- Multi mode fiber 380 μm diameter with 200 μm core
- Single mode 125 μm diameter with 10 μm core
- Also in indexes much smaller



Acceptance Angle and Fibers

- Problem with single mode is harder to get signal into fiber
- Called coupling with the fiber
- Acceptance angle $\theta_a = \alpha_{max}$ max angle light can enter fiber

$$\frac{\sin(\theta_a)}{\sin(90^o - \theta_c)} = \frac{n_1}{n_0} \qquad \sin(\theta_c) = \frac{n_2}{n_1}$$

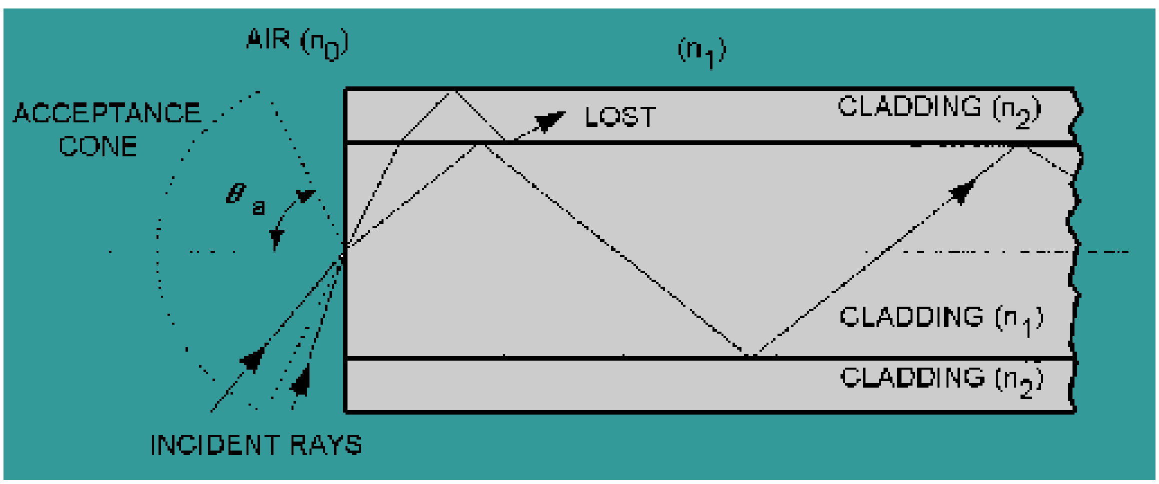
- Thus

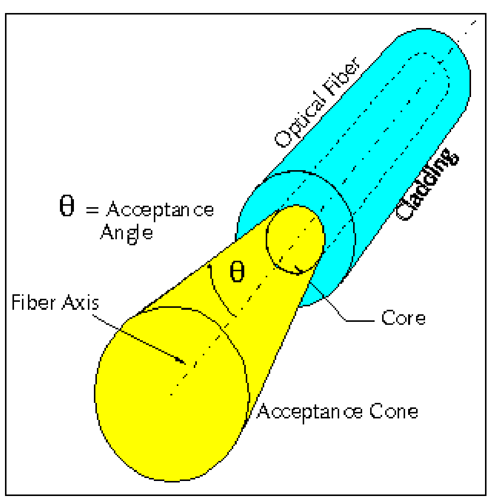
$$\sin(\theta_a) = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} = \frac{NA}{n_o}$$

- The fiber's Numerical Aperture is

$$NA = \sqrt{n_1^2 - n_2^2}$$

- Total Acceptance Angle is $2\theta_a$





acceptance cone

Single & Multi-Mode Fiber Acceptance

- Multimode fiber example
- n_1=1.480, n_2 = 1.460 with a core of 200 μm

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.480^2 - 1.460^2} = 0.2425$$

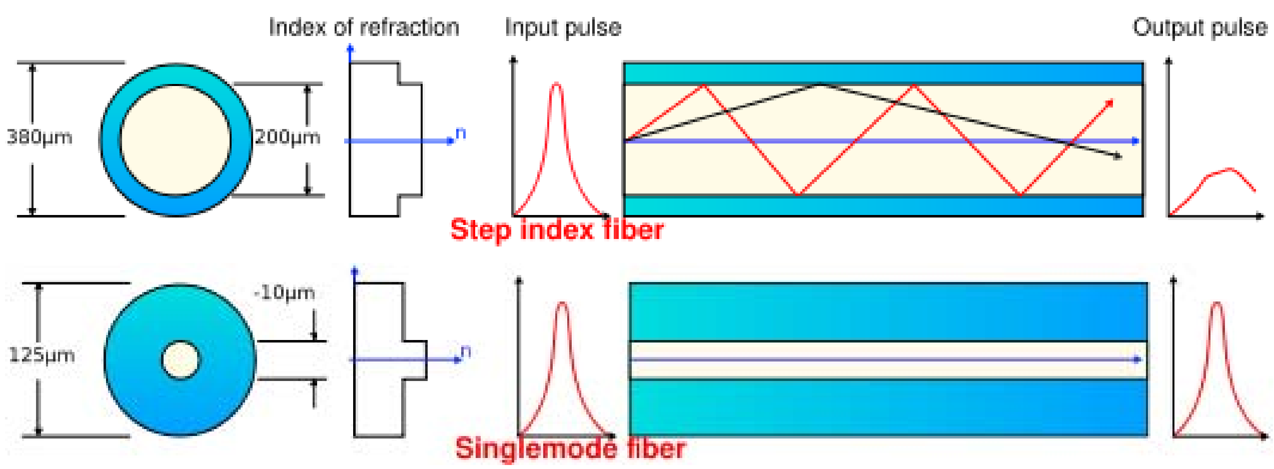
$$\theta_a = arcsin\left(\frac{NA}{n_o}\right) = arcsin\left(\frac{0.2425}{1}\right) = 14^o$$

- And total acceptance angle is 28°
- Now consider a single mode fiber
- n_1=1.480, n_2 = 1.4756 (only 0.3% larger) with a core of 5 μm

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.480^2 - 1.4756^2} = 0.1146$$

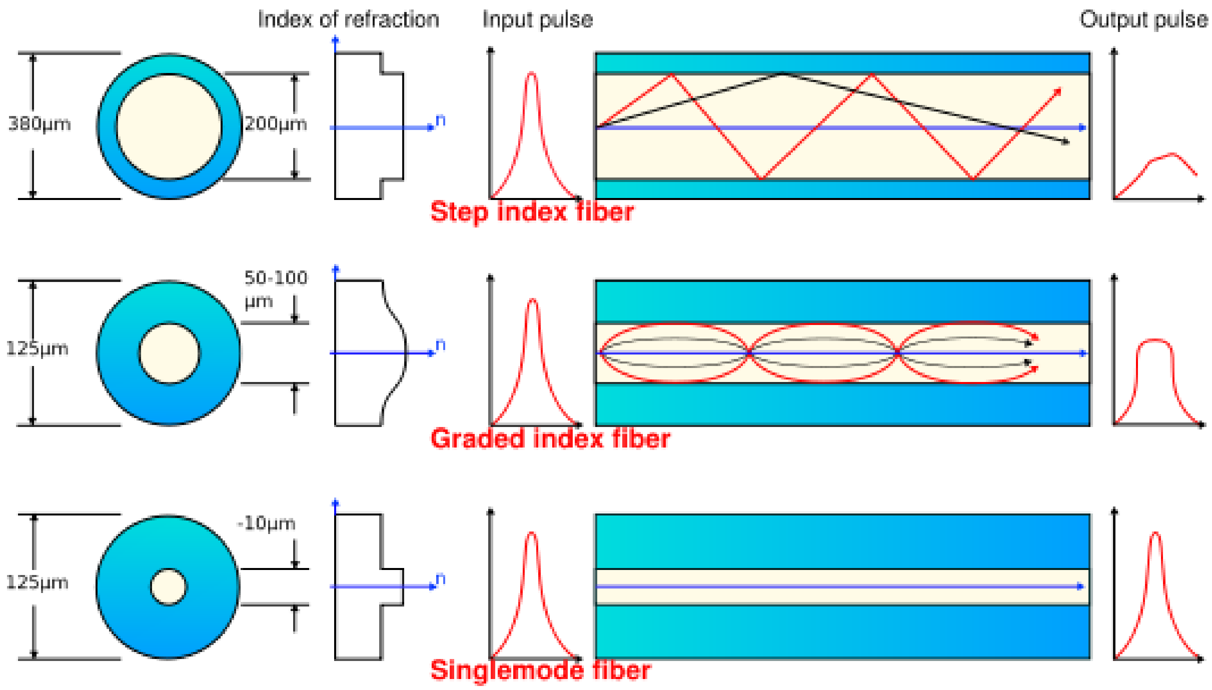
$$\theta_a = \arcsin\left(\frac{NA}{n_o}\right) = \arcsin\left(\frac{0.1146}{1}\right) = 6.58^o$$

- Thus much harder to couple light



Graded Index (GRIN) Fiber

- Due to small acceptance angle want alternative to single mode
- Uuse a GRaded INdex in the core (GRIN)
- Made by doping fiber with material that varies with postion
- Light now bends rather than reflects
- Get acceptance angle close to multimode
- But bit rate much higher than multimode



Fiber Dispersion and Bit Rate

- Dispersion of pulse in fiber sets the limit of bit rate
- Look at the Full Width Half Power (FWHP) of signal $\Delta\tau_{1/2}$
- Two pulse must be at least $2\Delta\tau_{1/2}$ apart to be separated
- Bit rate is thus

$$B \cong \frac{1}{2\Delta\tau_{1/2}}$$

- $\Delta\tau_{1/2}$ increase with distance so measure
- Dispersion = Bandwidth x distance

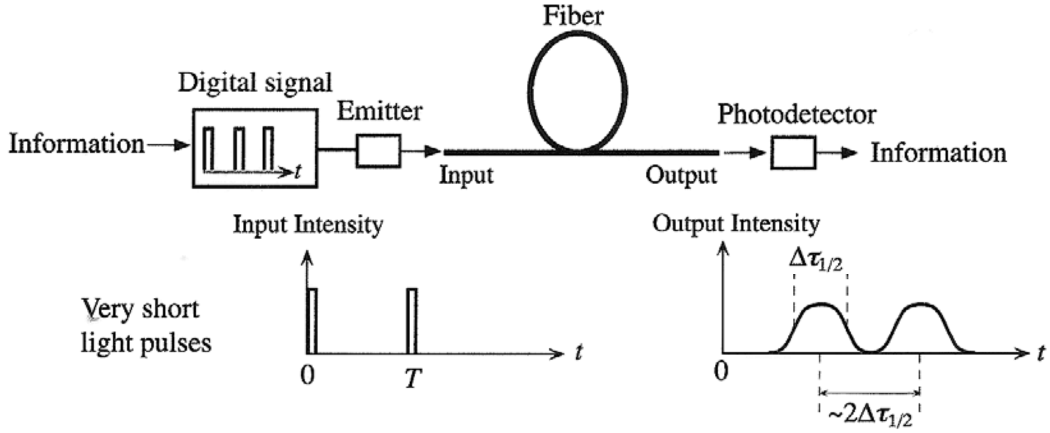
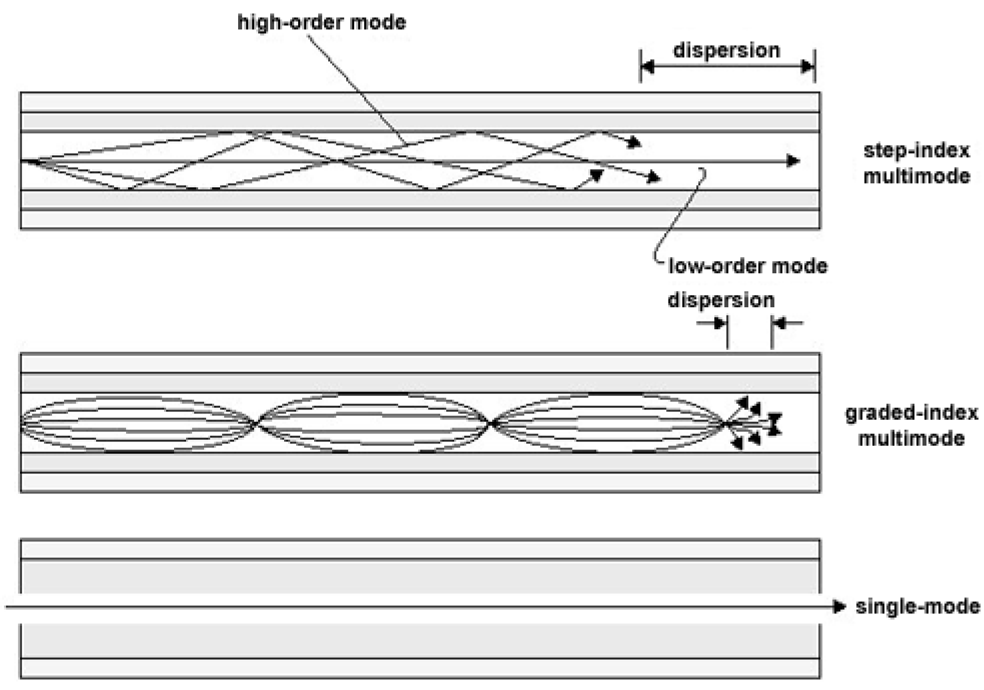


FIGURE 2.22 An optical fiber link for transmitting digital information and the effect of dispersion in the fiber on the output pulses.



Comparison of Multimode, GRIN and Single Mode

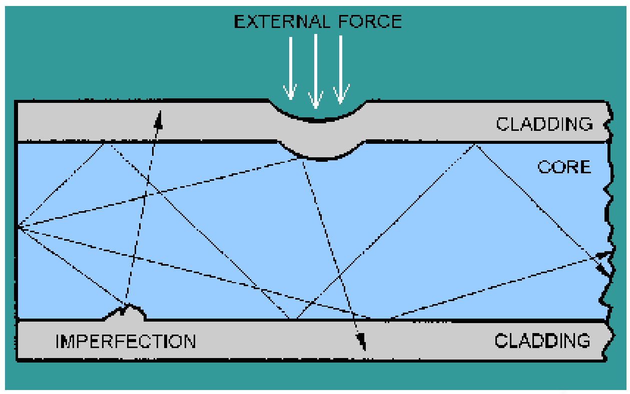
- **Multi mode:** high acceptance angle
- High dispersion ~20-100 Mhz km bandwidth product
- Can use LED's for emitters
- Easy to install – used for short distance networks
- **GRIN** acceptance angle near multimode: easy to connect
- Medium dispersion ~300 MHz km bandwidth product
- LED or lasers as emitters
- Medium distance networks
- **Single mode** small acceptance angle
- Thus harder to interconnect fibers
- Low dispersion 100 GB/s in field
- Laser diodes needed for narrow wavelength

TABLE 2.3 Comparison of typical characteristics of multimode step-index, single-mode step-index, and graded-index fibers. (Typical values combined from various sources.)

Property	Multimode step-index fiber	Single-mode step-index fiber	Graded index fiber
$\Delta = (n_1 - n_2)/n_1$	0.02	0.003	0.015
Core diameter (μm)	100	8.3 (MFD = 9.3 μm)	62.5
Cladding diameter (μm)	140	125	125
NA	0.3	0.1	0.26
Bandwidth × distance or Dispersion	20 − 100 MHz km.	<3.5 ps km^{-1} nm^{-1} at 1.3 μm >100 Gb s^{-1} km in common use	300 MHz km − 3 GHz km at 1.3 μm at 1.3 μm
Attenuation of light	4 − 6 dB km^{-1} at 850 nm 0.7 − 1 dB km^{-1} at 1.3 μm	1.8 dB km^{-1} at 850 nm 0.34 dB km^{-1} at 1.3 μm 0.2 dB km^{-1} at 1.55 μm	3 dB km^{-1} at 850 nm 0.6 − 1 dB km^{-1} at 1.3 μm 0.3 dB km^{-1} at 1.55 μm
Typical light source	Light emitting diode (LED)	Lasers, single mode injection lasers	LED, lasers
Typical applications	Short haul or subscriber local network communications	Long haul communications	Local and wide-area networks. Medium haul communications

Fiber Bending Loses

- When fiber is bent or has imperfection get increased loss
- Due to change in light angle to below critical angle
- Lose Total Internal Reflection
- The effective absorption coefficient α_B increases greatly
- Smaller radius of curvature, larger the light leaking out



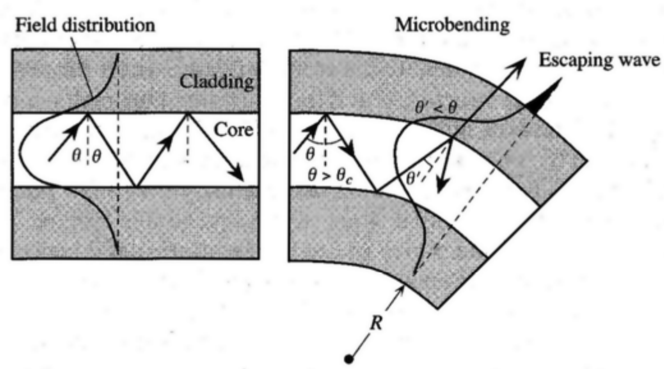


FIGURE 2.32 Sharp bends change the local waveguide geometry that can lead to waves escaping. The zigzagging ray suddenly finds itself with an incidence angle θ' that gives rise to either a transmitted wave, or to a greater cladding penetration; the field reaches the outside medium and some light energy is lost.

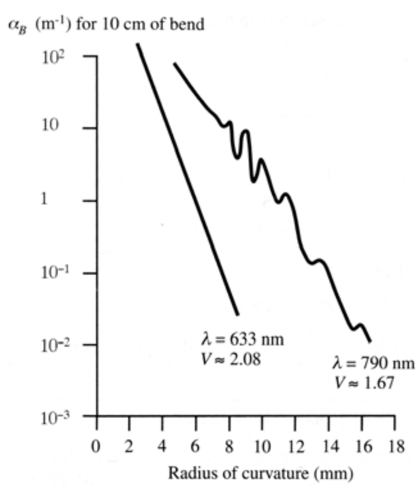
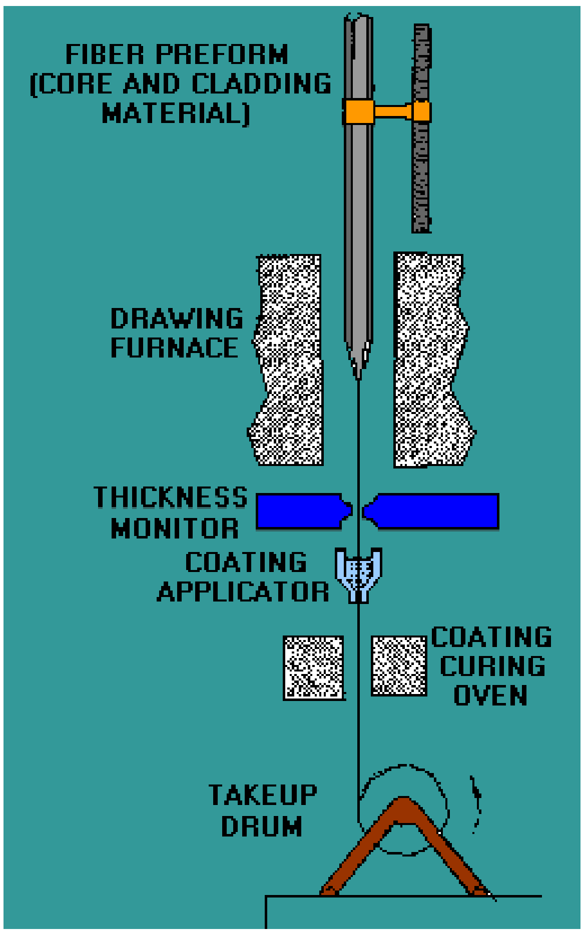


FIGURE 2.33 Measured microbending loss for a 10 cm fiber bent by different amounts of radius of curvature R. Single mode fiber with a core diameter of 3.9 μm, cladding radius 48 μm, $\Delta = 0.004$, $NA = 0.11$, $V \approx 1.67$ and 2.08 (Data extracted and replotted with Δ correction from, A.J. Harris and P.F. Castle, *IEEE J. Light Wave Technology*, Vol. LT14, pp. 34–40, 1986; see original article for discussion of peaks in α_B vs. R at 790 nm.)

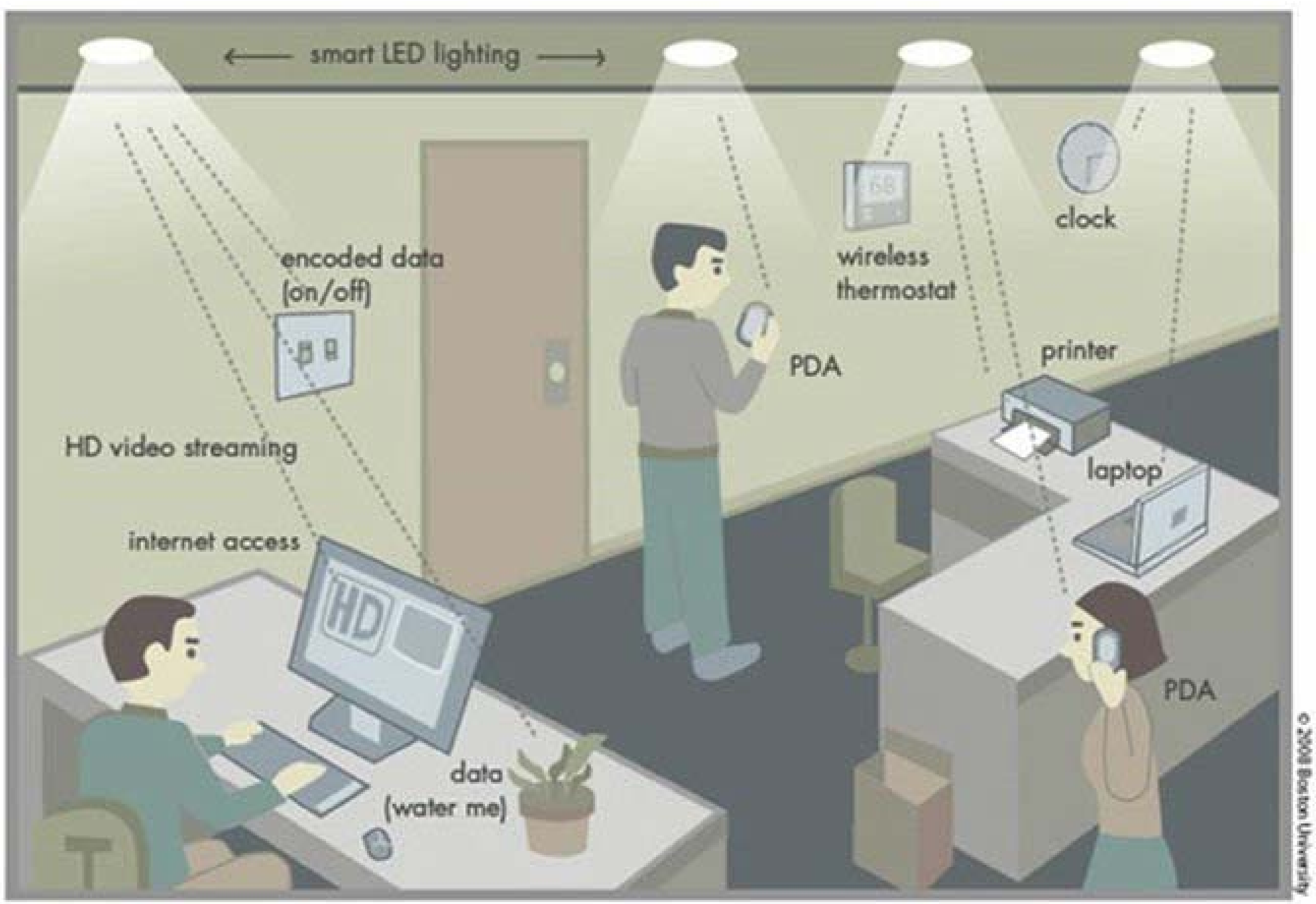
How Fiber is Made

- Fiber starts with rod of core and cladding
- Heated in drawing furnace- often rotated to make even
- Pulled into a narrow fiber
- Monitor fiber diameter – adjusted with pull rate
- Add plastic coating on outside
- Rolled into spool



Li-Fi Free space communication

- Wi-Fi microwave spectrum is getting crowded & speed limited
- With Internet of Things spectrum is becoming crowed
- LED Room lighting makes Light Fidelity (Li-Fi) a solution
- Many spectral ranges visible or Near IR wavelength
- 10,000x spectrum compared to Wi-Fi
- 1.6 Gbits/s test in field, 10 Gbits/s in lab
- Limited area both: Advantage less interference & higher security
- Even works underwater where wi-fi does not
- Problems – need more transmitters,
- Signal bounces limits speed due to variable path lengths
- Potential shadowing – ie areas with no reception.



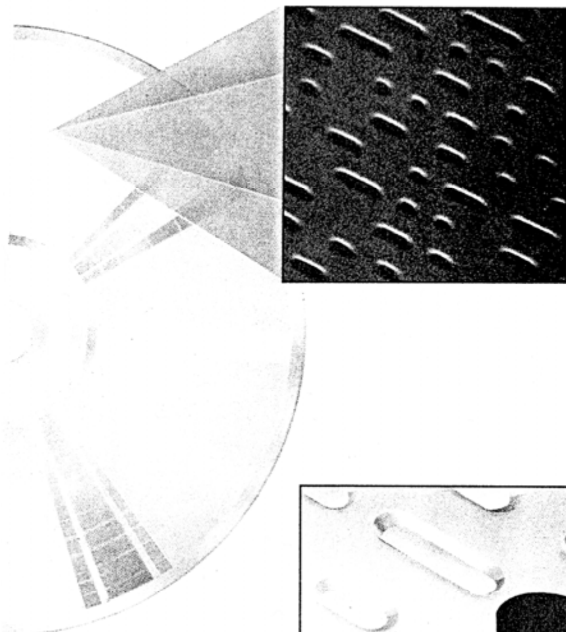
CD/DVD’s: Compact Disk

- Largest user of laser systems
- Began with Video disk by Philips & MCA
- Original video sold 1980
  1 - 1.5 hour disk
- Original version failed to compete with tape video
  >1990 strong high quality video market
- 1983 Sony & Philips developed Audio CD
- Now 50,000,000 CD's sold/year in Canada but 40,000 records
- CD declining due to mp3 files

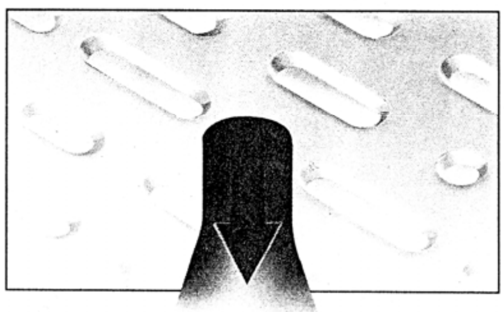
Fig. 2-1. The compact disc is only 120 mm in diameter with a large 15 mm center hole.

CD Operation

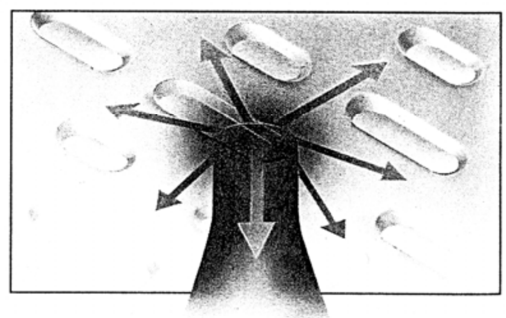
- 12 cm disk with plastics substrate, aluminum coating and plastic cover
- 0.6 micron wide pits, 1.6 micron spacing
- 4.8 Km of paying surface, 16,000 track/inch
- Designed Beethoven’s 9th symphony, now 74 minutes,



Topography of a disk. The pits on a prerecorded optical disk, here enlarged by a scanning electron microscope and seen from the laser’s point of view, resemble parallel lines of regularly spaced ridges. Each of these protrusions—the underside of a recorded pit—is the size of a typical bacterium, about .6 micron (.6 millionth of a meter) wide. If 3,000 pits were lined up side by side, they would be about as wide as this letter *o*.



The land’s bright spot. When the focused laser beam hits a flat space between pits—a so-called land—much of its light *(red arrow)* is reflected straight back toward the detector. At the point where the laser strikes the disk, it has been focused to a spot about a micron in diameter, almost twice as wide as a pit. This diameter is only a little larger than the wavelength of the laser light—the theoretical minimum. As a result, the beam, originally cone-shaped, assumes a cylindrical shape near its point of focus.



The pit’s dark spot. When the focused laser beam hits the protrusion of a pit, much of the light is scattered sideways, so that very little is reflected back to the detector. Thus, each time the beam moves from a land to a pit, the reflected light changes in intensity, generating a detector signal that can be decoded to reproduce the recorded data.

CD Operation

- Laser focused on surface
- Reflects back from the flats (land)
- Light scattered by the pit
- Actually looks for the change in reflectivity
- Easier to see a change than compare levels

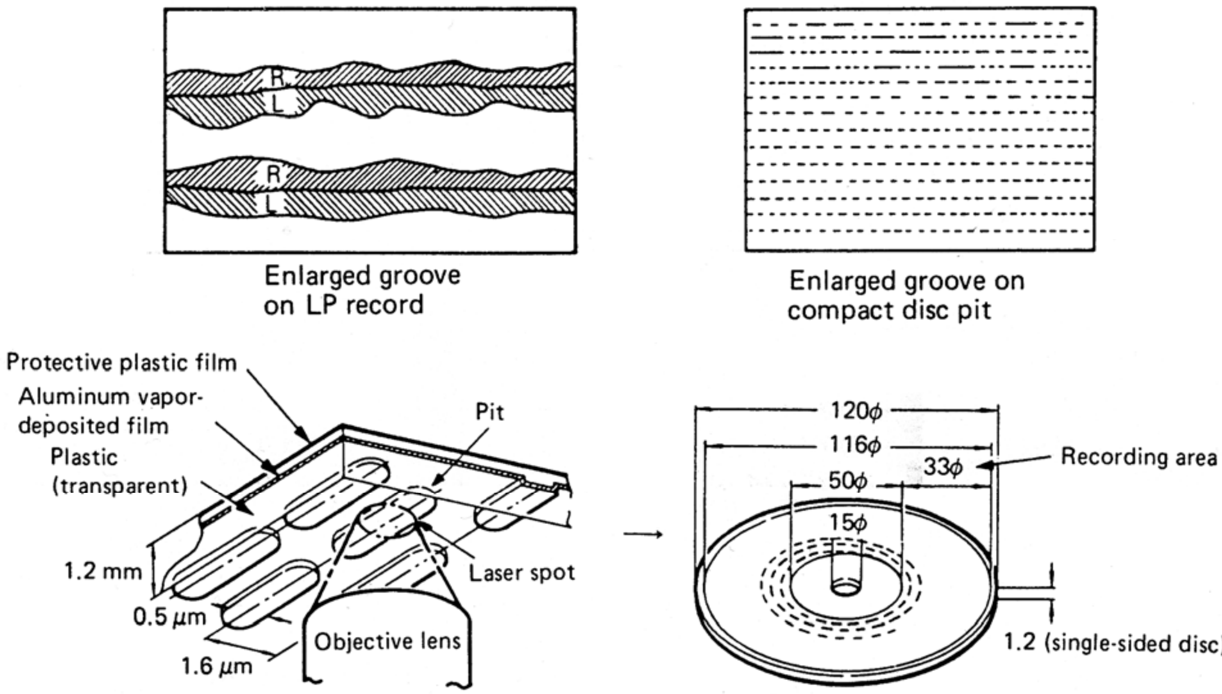
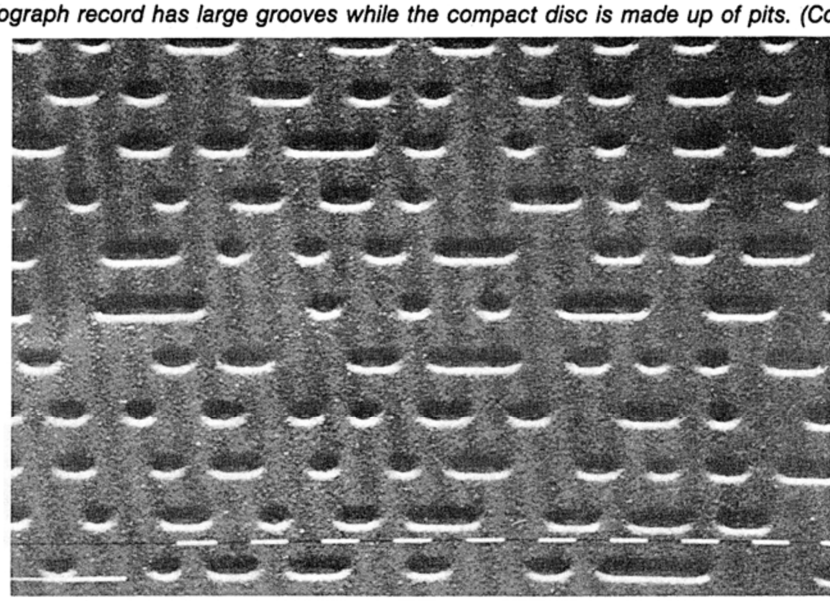


Fig. 2-2. The phonograph record has large grooves while the compact disc is made up of pits. (Courtesy of RCA Corp.)

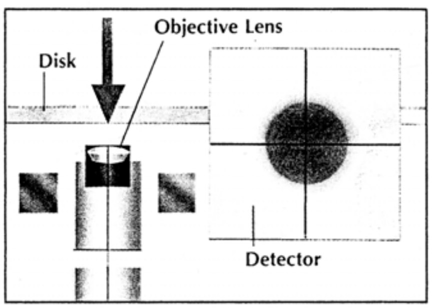


(b)

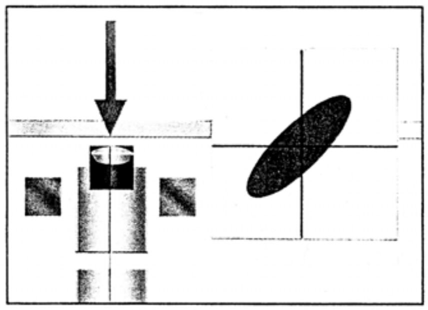
Fig. 7.34 (a) Schematic of a typical optical disk. The precise 'geometry' of a pit depends on a number of factors including the storage mode and readout technique employed. (b) Scanning electron micrograph of an optical disk (From G. Bouwhuis, A. Huijser, J. Pasman, G. Von Rosmalen, K. Schouharner Immink, *Principles of Optical Disc Systems* (1985). Courtesy Adam Hilger Ltd).

CD Operation

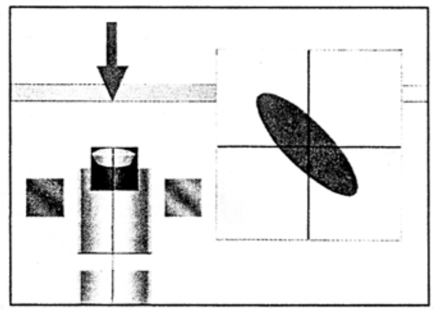
- Laser turned to parallel beam by collimating lens
  focused by objective lens
- Split beam means part goes to CD, part to detector
- Creates a focusing system using four sectors of detector
- Voice coil moves optical head, & tracking motor focuses
- Actually uses polarization of the light



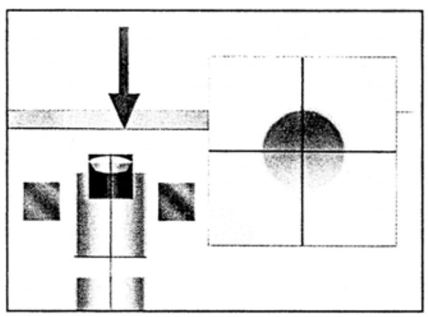
Lens in focus, on track. When the laser beam is properly focused on the center of the track *(red arrow)*, the reflected beam makes a fuzzy circle on the detector. Here, all quadrants of the detector receive the same amount of light, so no signal is sent to the voice-coil motors that guide the objective lens.



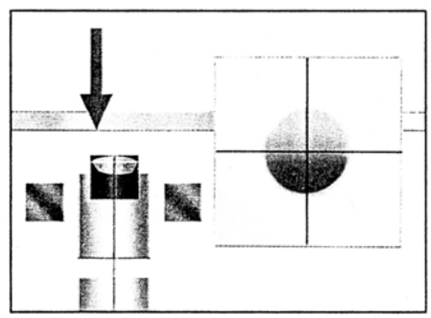
Lens too close. If the disk moves toward the lens, the light becomes a sharp, tilted oval. The northeast and southwest quadrants get more light, a signal for the focusing motor to move the lens back.



Lens too distant. If the disk moves away from the lens, the beam becomes a left-leaning oval, reversing the signal to the focusing motor and bringing the lens closer.

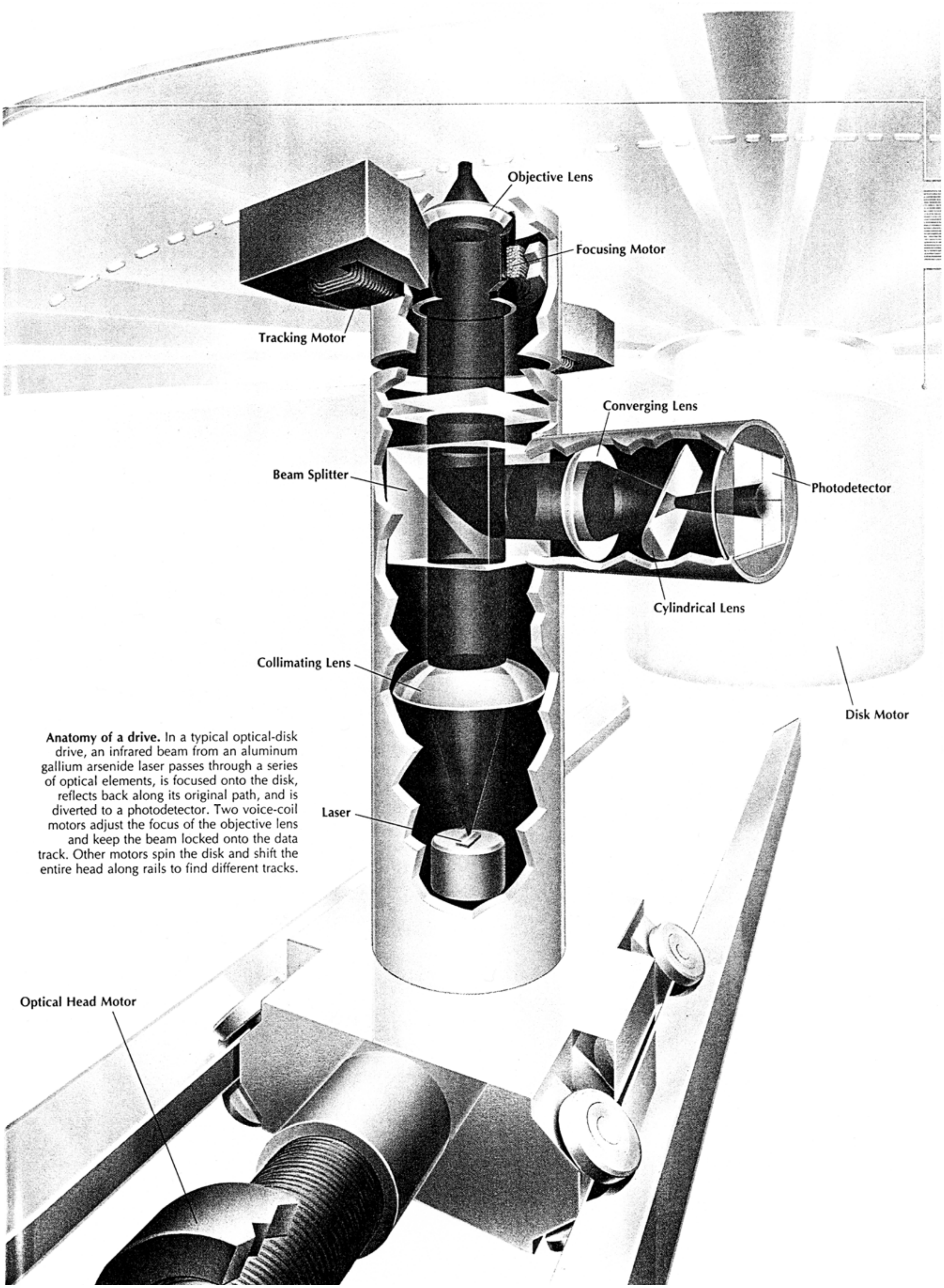


Beam inside track. If the track veers right, sending the beam inside the track, north quadrants of the detector receive more light because part of the beam falls only on lands. A correcting signal moves the lens right.



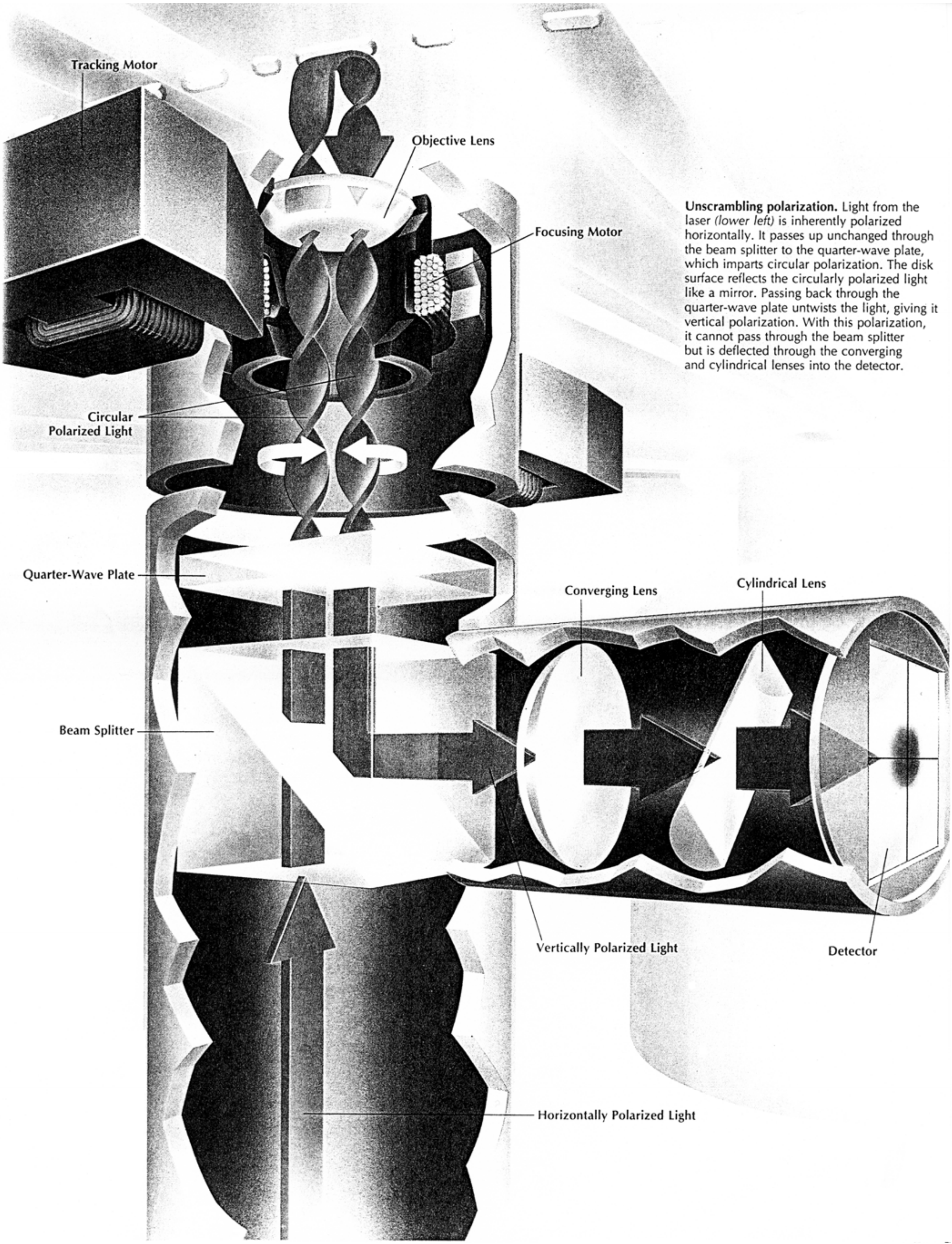
Beam outside track. Similarly, if the track veers to the left, the pattern of light on the detector is stronger to the south. A signal to the tracking motor returns the beam to the center before any data is misread.

CD Optics



Anatomy of a drive. In a typical optical-disk drive, an infrared beam from an aluminum gallium arsenide laser passes through a series of optical elements, is focused onto the disk, reflects back along its original path, and is diverted to a photodetector. Two voice-coil motors adjust the focus of the objective lens and keep the beam locked onto the data track. Other motors spin the disk and shift the entire head along rails to find different tracks.

CD Optics Polarization



Unscrambling polarization. Light from the laser *(lower left)* is inherently polarized horizontally. It passes up unchanged through the beam splitter to the quarter-wave plate, which imparts circular polarization. The disk surface reflects the circularly polarized light like a mirror. Passing back through the quarter-wave plate untwists the light, giving it vertical polarization. With this polarization, it cannot pass through the beam splitter but is deflected through the converging and cylindrical lenses into the detector.

CD Data

- Sample audo signal at 44.1 Khz
- 16 bit conversion = 90 Db range
- Master disk made by Argon laser on master plate
- Disks pressed in plastic, then aluminized
- Both sides pressed, best side used
- Error correcting codes added at ends

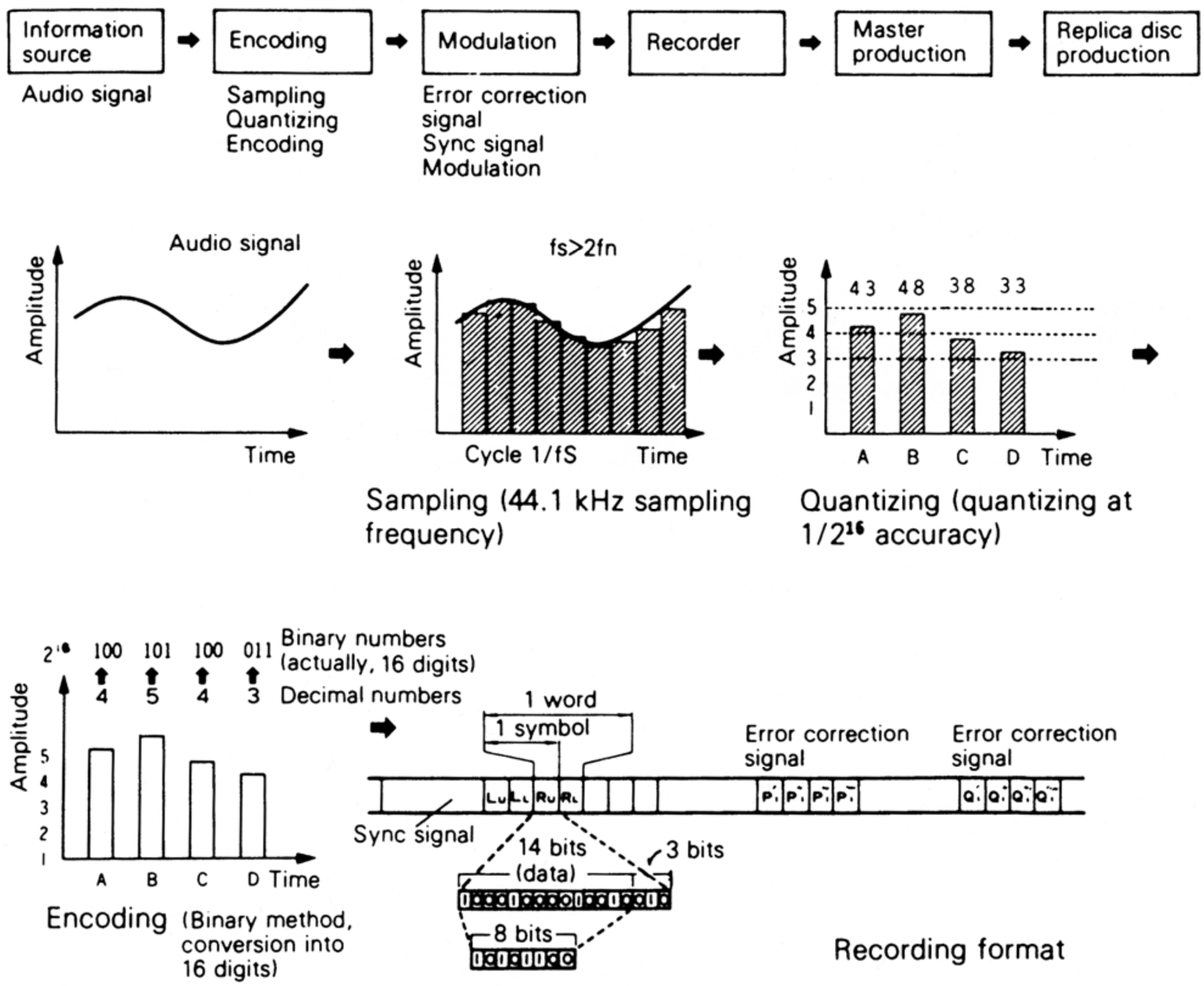
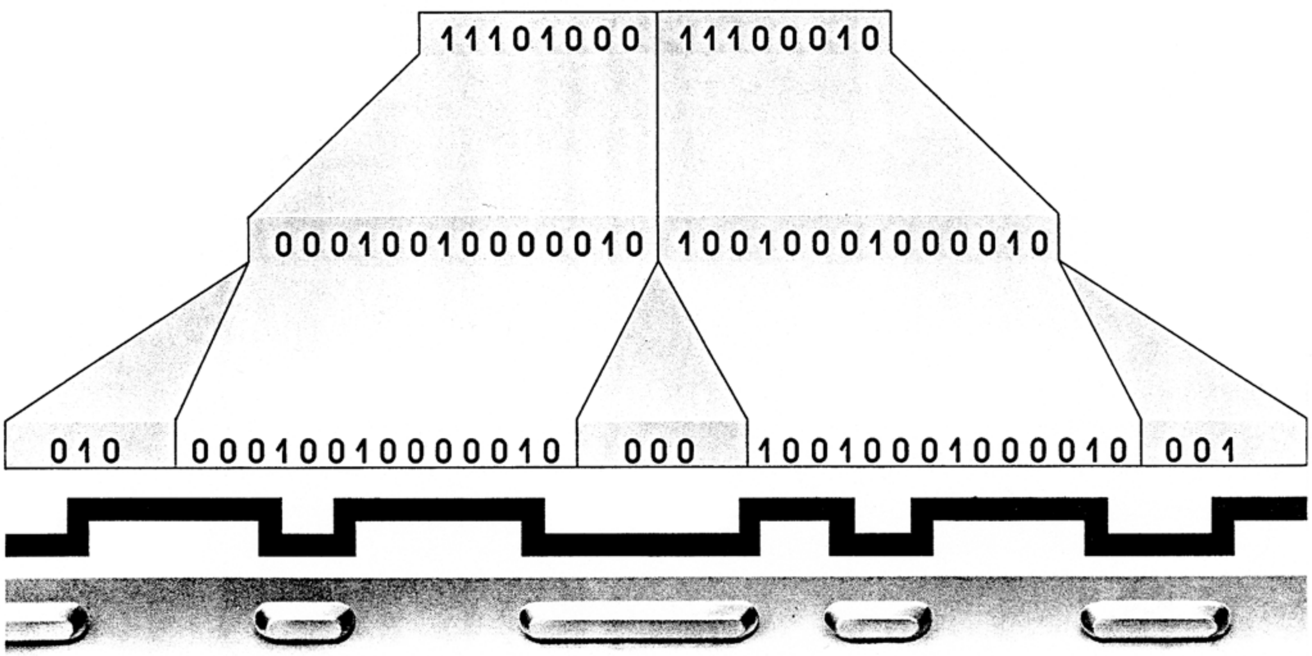


Fig. 2-3. The encoding and recording format of the compact disc. (Courtesy RCA Corp.)

CD Data

- Two 8 bits turned into 14 bit signal
- Must have more than 2
  but no more than 10 zeros in a row
- Add 3 merge bits to get that
- Transitions from pits to land or back what measured
- CD Roms use same setup, but different data combination
  better error correcting code (Reed-Solomon error correction)
- Generate 500 Mbytes data
- Fabrication costs started at $2-4 in 1983 now under $0.10



A code from CD-ROMs. In the eight-to-fourteen modulation on CD-ROM disks, two bytes of data *(top row)* are replaced by fourteen-bit symbols *(middle row)* in which ones have at least two but no more than ten zeros between them. Groups of three merge bits then link successive fourteen-bit symbols into a steady stream *(lower row)* that follows the rules about maximum and minimum zeros. Each one in this bit stream thus corresponds to a transition from land to pit, as indicated by the square-wave binary signal used to create pits and lands on the disk *(bottom)*. Playback reverses the process.

Immunity to Defects

- Error correcting codes removes some
- Focused below surface - surface defects eliminated
- Multisampling - measure several times

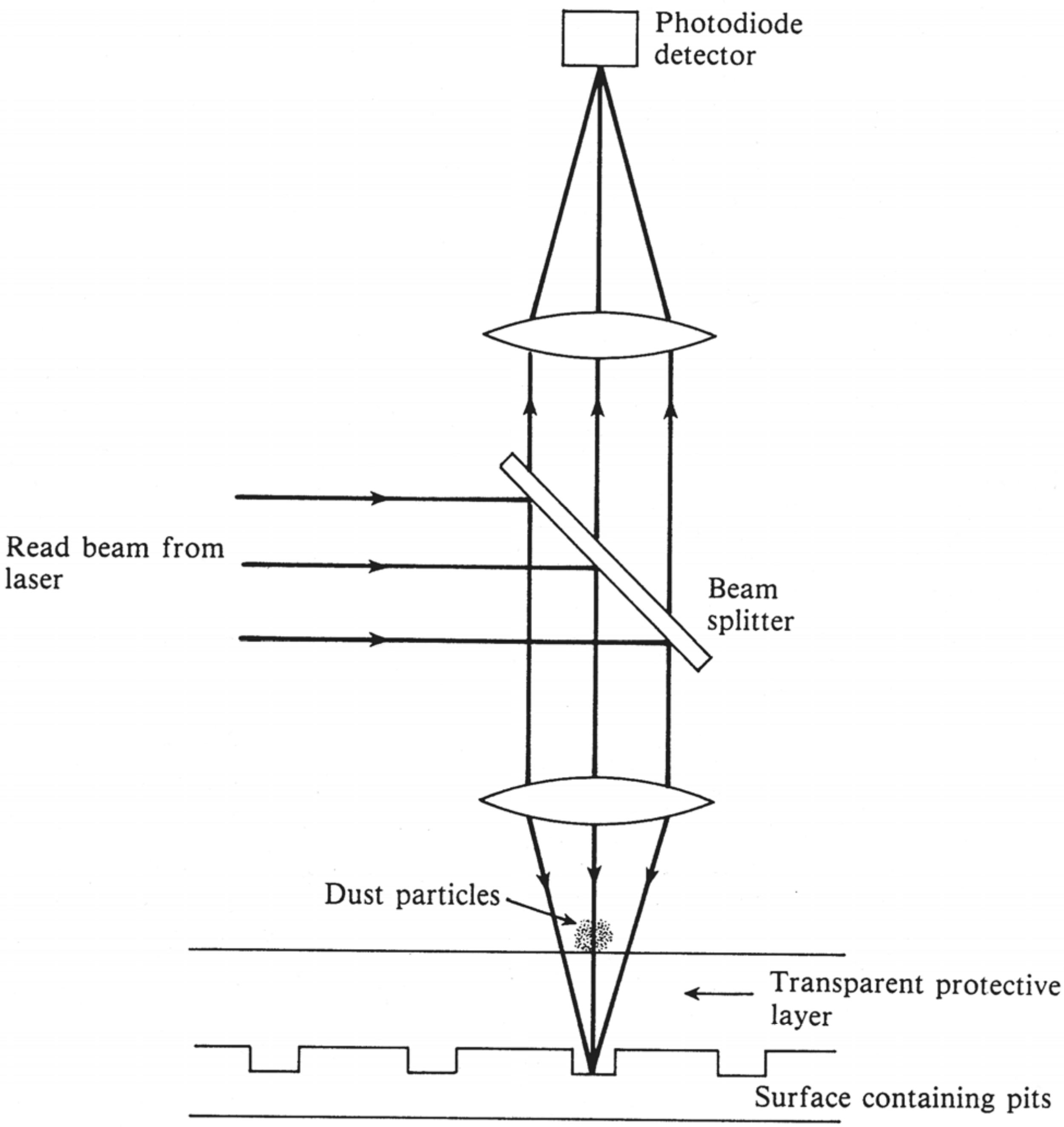


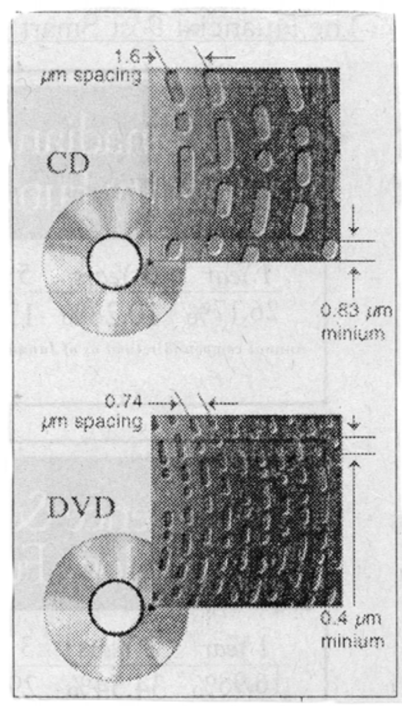
Fig. 7.35 The basis of readout from an optical disk. The read beam from a laser is focused onto the surface containing the pits. Particles of dust on the protective layer are not in focus and do not affect the readout process.

Digital Video Disk

- Designed for full video playback/recording
- Uses Red laser (650 nm) not IR (830 nm)
- Pit size 48%, date density 2.12x
- Total memory 4.8x to 3.28 GBytes: Transfer rate 9x CD
- DVD-R recordable, DVD-RAM printed
- Two sided, 2 levels/side top level partially reflecting
- Increase to 8.5 GB (2 sided), 17 GB (2 levels, 2 sided)
- Aimed at fully video playback of 2 hour movies
- Uses MPEG2 compression for video: movie aspect ratio
- Audio uses Dolby AC-3 for 6 track sound!
- Standard allows 50 GB with blue lasers!

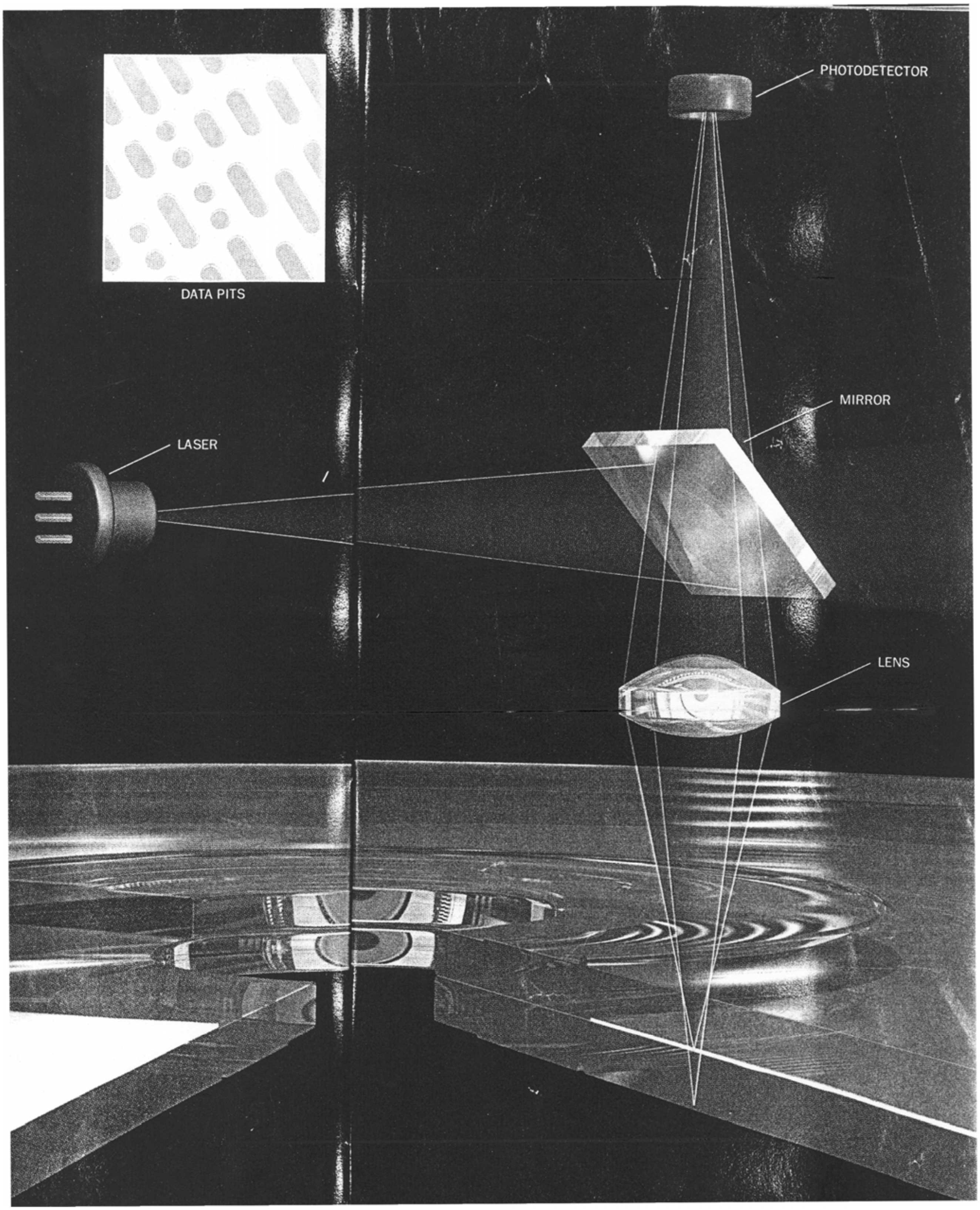
How the DVD and CD Compare

Feature	New Format	Old Format
Disc diameter	120 millimeters	120 millimeters
Disc structure	Two substrates, each 0.6 millimeter thick	One substrate, 1.2 millimeters thick
Minimum pit length	0.4 micron	0.83 micron
Laser wavelength	635 to 650 nanometers	780 nanometers
Capacity	Two layers, one on each side, 9.4 gigabytes total Two layers, both on one side, 8.5 gigabytes total Four layers, two on each side, 17 gigabytes total	One layer on one side, 0.68 gigabyte total
Numerical aperture	0.60	0.45
Track density	34,000 tracks per inch	16,000 tracks per inch
Bit density	96,000 bits per inch	43,000 bits per inch
Data rate	11 megabits per second	1.2 to 4.8 megabits per second
Data density	3.28 gigabits per square inch	0.68 gigabits per square inch



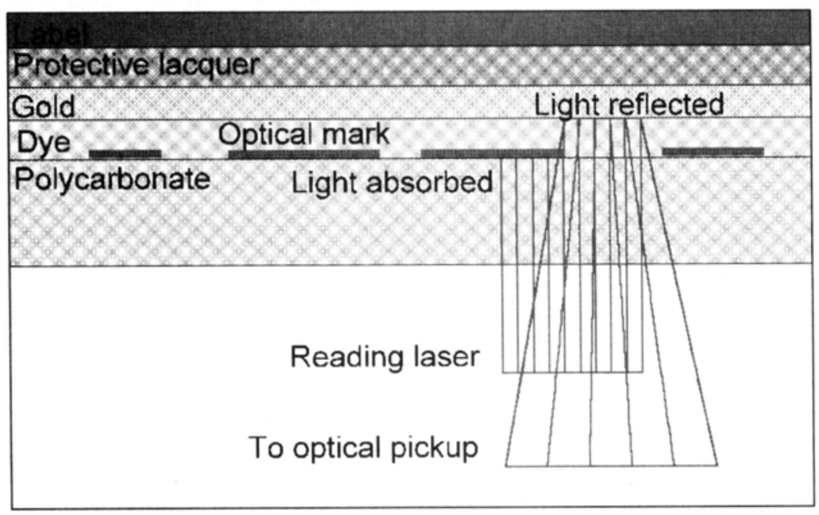
Digital Video Disk

- 2 level have two different focus points



CD-R Organic Dye Disks

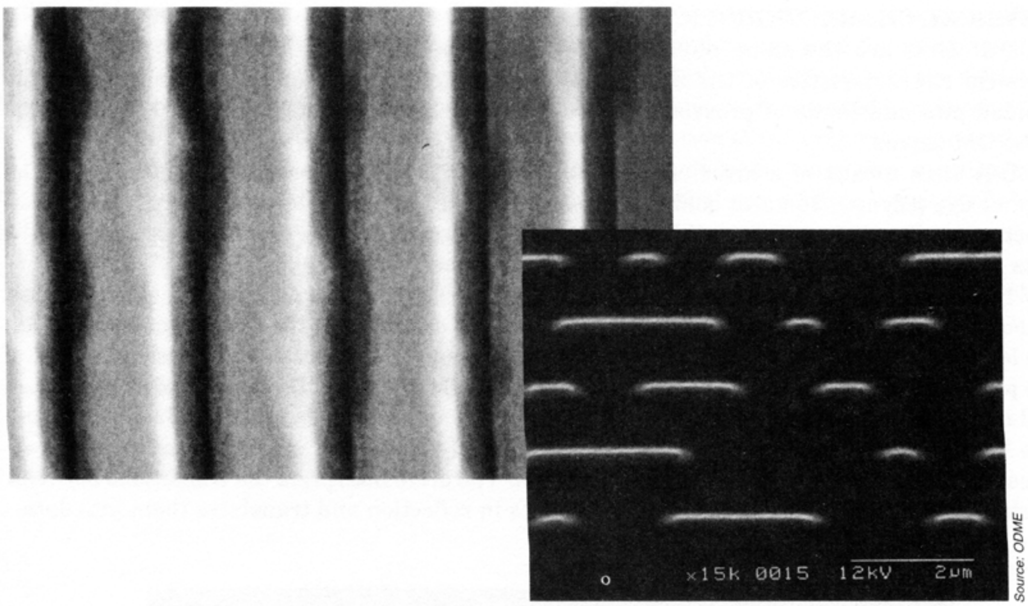
- CD-R (12 cm) uses organic die molecules
- Gold, silver or aluminum coating provides reflection
- Dye layer blue, green (better), gold (best) in unwritten state
- Laser writer 4-11 mW 790 nm (CD-R), 630-650 nm (DVD)
- Laser heats dye to 250 C (when 11 mW)
- Depending on dye either destroys dye or may disintegrate material
- Problem: ratio of dark/light spots 50%-30% regular
- Hence may not play in some CD/DVD players
- Higher tendency to have problems when player is moving



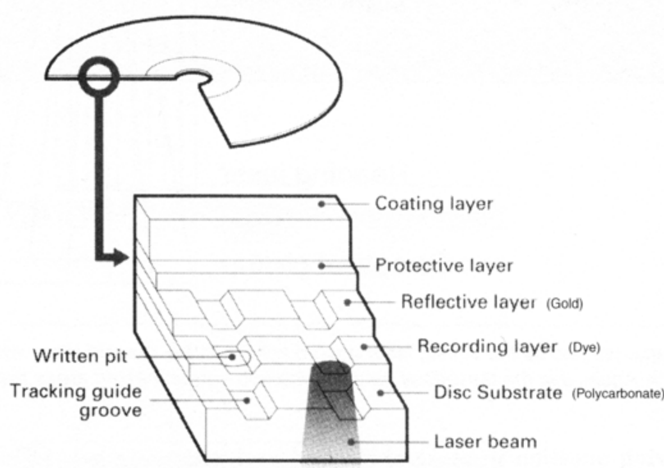
The optical marks created by the writing laser absorb light from the reading laser, while unmarked areas reflect the light back. Again, it is the transitions between marked and unmarked areas that represent binary ones.

CD-R/DVD-R/DVD+R Operation

- Different dyes use different processes: give different reflectivities
- Cheaper dyes burn to dark, have less reflection ratios
- Others melt or chemically degrade & heats recording layer
- Has less volume – cover layer melts in & creates pit
- Much harder to see the pits in CD-R under microscope
- Hence much less reflection
- Higher speed (52x) uses higher power lasers & rotation rate



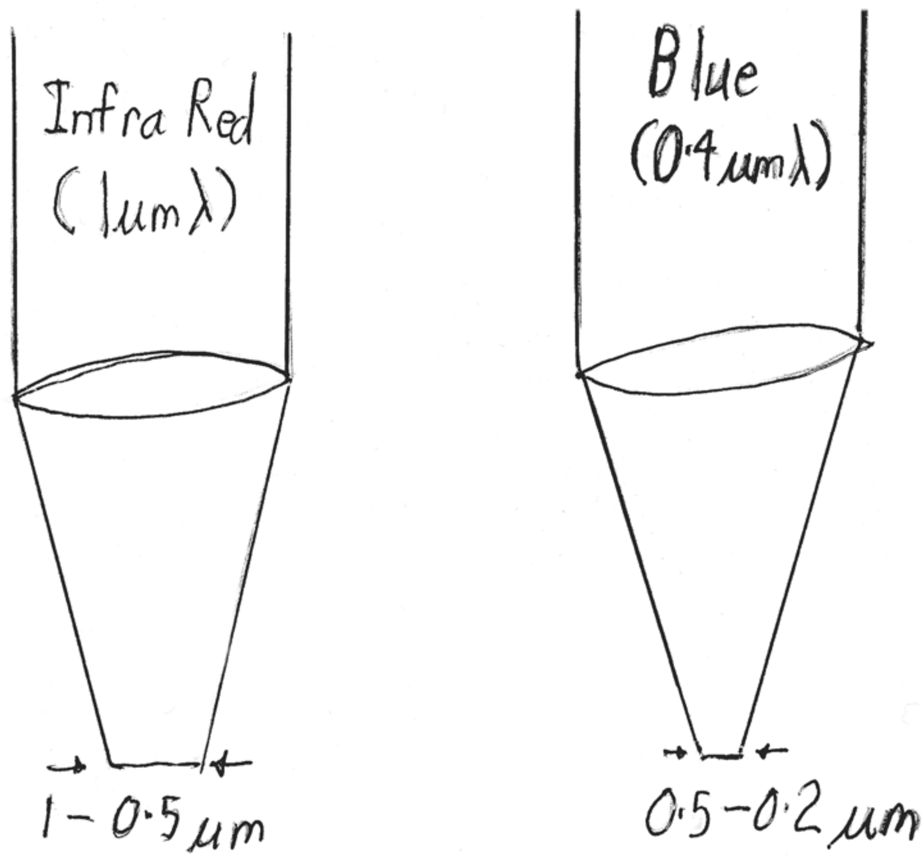
These enlarged photos of marks in CD-R dye polymer and molded pits in a pressed CD demonstrate that even if optical marks are not physically apparent, a laser can "see" the differences in reflectivity.



A CD-R disc uses a thin layer of pure gold, instead of aluminum, as a reflector, and adds a layer of organic dye polymer as a recording layer.

What Limits the Data on a CD/DVD?

- Each pit is one “bit” (0 or 1) of data
- How fast the CD turns (1.4 m/sec for single speed)
- Rotation speed limit: about 52x (72.8 m/sec)
- Beyond that disk destroyed by rotation stress
- Infrared GaAs light 830 nm & 790 nm currently
- Final DVD target Blue lasers ~405 nm to get 0.2 μm pits
- Problem is lifetime of Blue laser approaching 1000 hrs

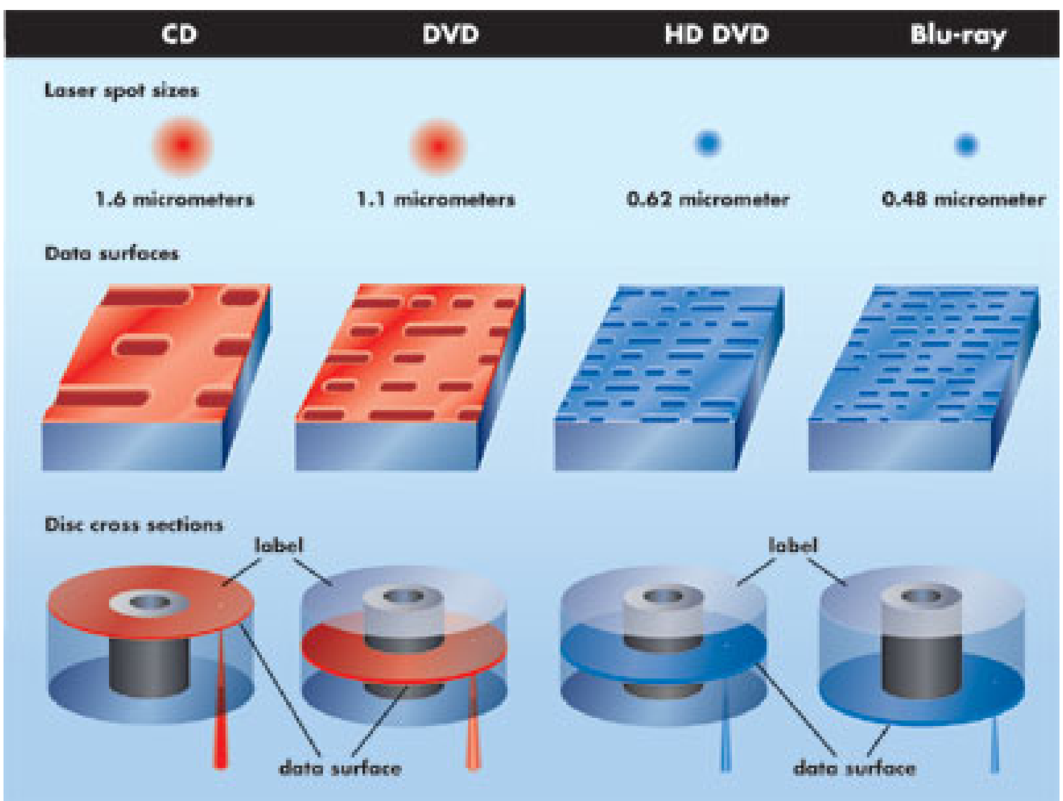


HD-DVD vs Blue Ray DVD Wars

- Next generation DVD format had two competitors
- HD-DVD: Toshiba, NEC, Microsoft, entertainment industry
- Blue Ray (BD): Sony, Hatachi, Panisonic, Apple etc (PC makers)
- All use 405 nm blue (really violet) laser diodes
- Blue Ray higher capacity (25 GB) vs HD (15 GB)
- Reason: Blue ray spot smaller (0.48 µm) vs HD (0.62 µm)
- Hence shorter pits/track: Blue ray 0.16 µm, HD 0.205 µm
- Track spacing: Blue ray 0.32 µm, HD 0.40 µm
- Problem is that Blue ray is much nearer the surface (0.1 mm)

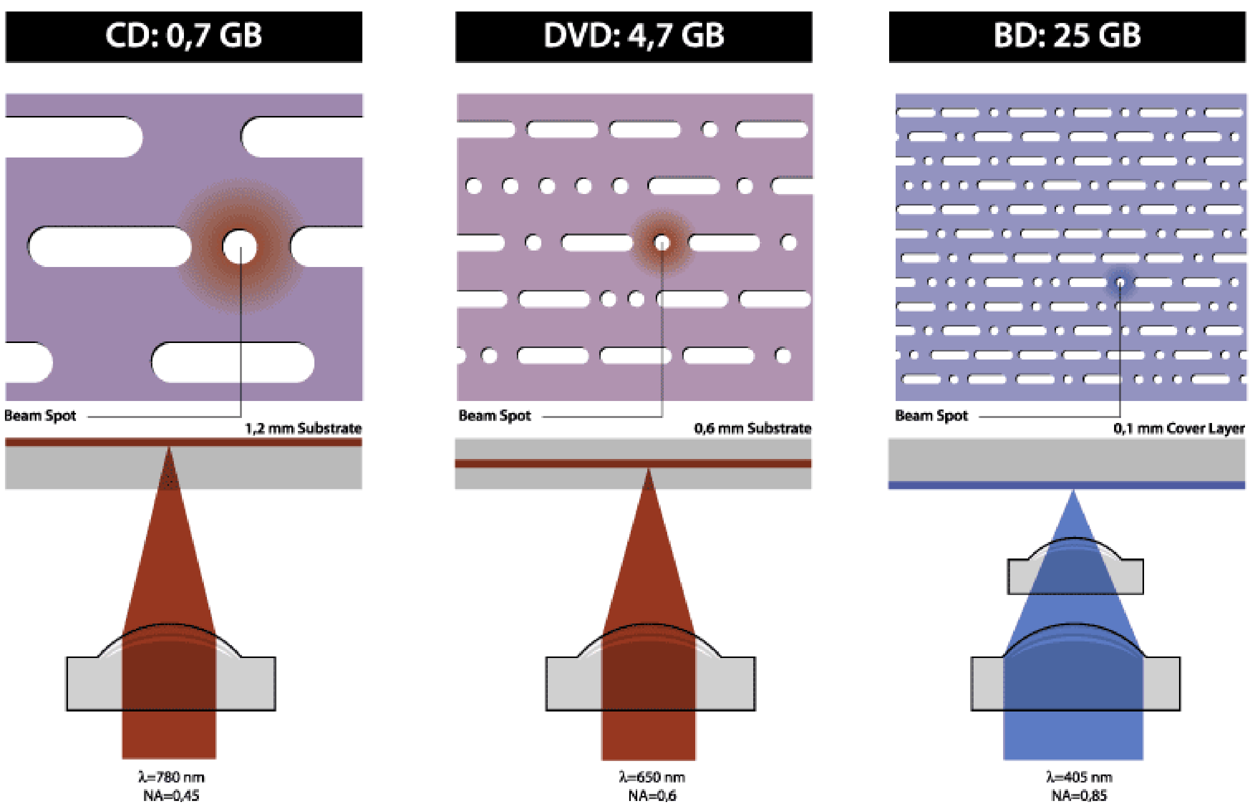
OPTICAL-DISC FORMAT SPECIFICATIONS

Prerecorded formats	CD	DVD	HD-DVD	BLU-RAY DISC
Maximum data rate, in megabits per second (Mbps)	1.4 Mbps	11 Mbps	36 Mbps	36 Mbps
Data capacity (single-side, single-layer), in gigabytes (GB)	0.74 GB	4.7 GB	15 GB	25 GB
Laser wavelength, in nanometers (nm)	780 nm	650 nm	405 nm	405 nm
Diameter of laser spot on data layer, in micrometers (µm)	1.6 µm	1.1 µm	0.62 µm	0.48 µm
Track pitch	1.6 µm	0.74 µm	0.4 µm	0.32 µm
Minimum pit length	0.83 µm	0.40 µm	0.204 µm	0.15 µm
Overall disc thickness	1.2 mm	1.2 mm	1.2 mm	1.2 mm
Distance from disc surface to data surface	1.1 mm	0.6 mm	0.6 mm	0.1 mm

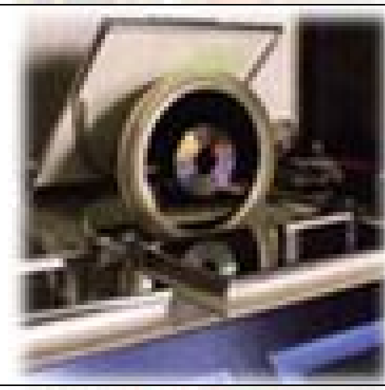


HD-DVD vs Blue Ray DVD: Why the Difference

- Problem is Blue ray uses Higher NA lens 0.85 vs HD 0.65
- Much shorter focus: Blue ray 0.1 mm vs HD 0.6 mm
- Allows for smaller spot, higher density
- But production equipment different:
- Blue ray 1.1 mm substrate (new technology)
- HD uses standard DVD 0.6 mm substrates
- HD simple modification to existing DVD lines & faster production
- Thought they would be to market first
- Blue ray can have 8 layers, up to 200 GB, HD 4 layers, 60 GB
- Initial format 2 hours of High Definition TV, 4 hours later
- Limit is really the codecs (digital decoding)
- Harder to make Blue Ray read current DVD's



CD/DVD Manufacturing: Creating Masters

Premastering • Converting the video/sound into data • Conversion to mpeg/compressed files	
Mastering • Glass master coated with photoresist • UV laser beam Recording writes data pattern • Develop resist to create pits • Sputter silver coating	
Electroplating • Electroplate nickel layer on glass master • 0.3 mm nickel forms mould for disk • Separate pressing mould from glass master • Called a stamper	

CD/DVD Disk Manufacturing

Pressing

- Liquefied polycarbonate injected into mould
- Cools to create base layer with pit pattern

Metallization

- Sputter deposit aluminum layer
- Creates reflective layer with pits

Varnishing

- Varnish lacquer layer spun on
- Forms hard layer for scratch protection
- Acts as vapour barrier to water
- Prevents Aluminum distruction

Labelling

- Silk screen printing the label

- Multilayer/Double sided disks
- Repeat stamp/metallize/varnish for each level

HD-DVD Blue Ray DVD Wars

- HD was backed by Toshiba/Microsoft/Hitachi
- Studios Paramount Pictures/Universal
- Blue Ray: Sony/Philips
- Studios Sony, MGM, Walt Disney,Universal, Warner Bros.
- Sony learned from Beta/VHS tape: get many on board
- HD advantage – could modify DVD production equipment
- But this did not help as Blue ray production exceeded HD
- Blue ray costs came down to same level <$1/disk
- Hence Disk cost to consumer was the same
- Make money when switch formats
- End case when major retails saw 2:1 Blue ray to HD sales
- Walmart/Best Buy switched in Feb. 2008
- But Blue ray has not replaced DVD: expected 50% by end 2008
- But Sept 2008 Blue ray only 8% of market, DVD 92%
- In 2015 Blue ray still only 30% of the market (not increasing)
- Only 44% of households have Blueray players
- Reason still too expensive in a down market
- 2016 Streaming results in Blue ray seeing 12% decline in sales
- Blue ray now focusing on Ultra HD 4K video released 2016
- 3840x2160 resolution up to 100 GB with 128 Mbit/s
- However little sales of this next gen video format
- Advantage harder to send in real time on internet