Fiber Link Components: Sources

- Sources
  - LEDs
  - Semiconductor lasers
- LEDs
  - Low cost
  - Modest power
  - Short-distance, low bit-rate links
- Lasers
  - Higher cost
  - Reasonable power
  - Long-distance, high bit-rate links

Sources-1

Semiconductor Sources: LEDs and Diode Lasers

- **Desirable properties:**
  - **Small size**
  - **850, 1300, or 1550 nm**
  - **Power**
  - **Linearity**
  - **Modulation simplicity**
  - **Modulation frequency response**
  - **Low cost**
  - **Reliability**

- **Source wavelengths**
  - ***Short wavelength sources*:**
    - **500→1,000 nm**
    - **Binary alloy (e.g., GaP: 600-700 nm)**
    - **Ternary alloy (e.g., GaAlAs: 800-900 nm)**
  - ***Long wavelength sources*:**
    - **1200→1600 nm**
    - **Quaternary alloy (e.g., InGaAsP: 1300-1600 nm)**

Sources-2

Sources: Light Generation by Semiconductors

- **Forward-biased *pn* junctions**
  - **Doped much heavier than electronic diode**
  - **Additional features to confine charge carriers and light field**

- **Light generation**
  - ***Radiative recombination* of electron and hole**
  - **Radiative and nonradiative recombinations possible**
    - » **Raise efficiency by flooding light-generating region with...**
      - **High density of charge carriers and...**
      - **High-power light**

Sources-3

Sources: Light Generation

- **Forward-biased *pn* junction**
  - **Holes injected into *n* material**
  - **Electrons into *p* material**
- **Carriers recombine with majority carriers near junction**
- **Energy released ≈ material band-gap energy E_g**
  - **If radiative, $\nu \approx E_g/h$**

- **Radiative transitions**
  - ***Spontaneous emission*:**
    - » **Incoherent**
    - » **Random polarized**
    - » **Random direction**
    - » **Adds noise to signal**
  - ***Stimulated emission*:**
    - » **Coherent light (same phase, polarization, and direction)**
- **Silicon and germanium are inefficient radiators**
  - **Semiconductor alloys used**

Sources-4

Sources: Wavelength and Materials

- **Wavelength and *bandgap energy* E_g of material**

$$\lambda = hc/E_g$$
$$\lambda[\mu\text{m}] = 1.24/E_g[\text{eV}]$$

- **Wavelength (and bandgap energy) also function of temperature**
  - **Increases by ~0.6 nm/C**

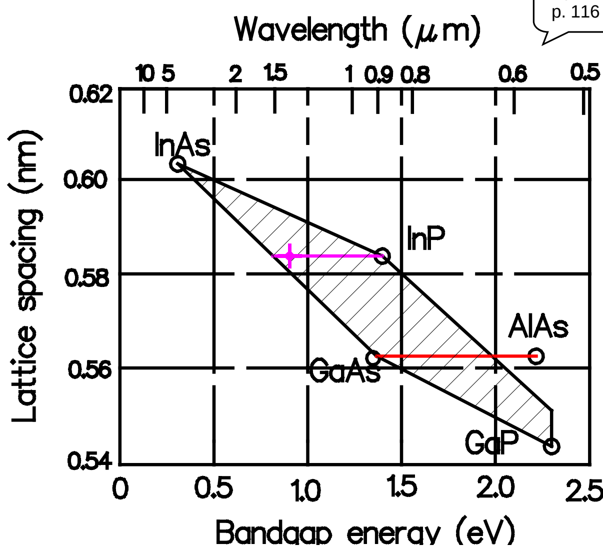
- **Typical wavelengths**
  - **GaP LEDs**
    - » **665 nm**
    - » **Short-distance, inexpensive systems**
  - **$Ga_{1-x}Al_xAs$ LEDs and lasers**
    - » **800 → 930 nm**
    - » **Early fiber systems**
  - **$Ga_{1-x}In_xAs_yP_{1-y}$ LEDs and lasers**
    - » **1300 nm (late '80s, early '90s, FDDI data links)**
    - » **1550 nm (mid '90s - present)**

- Bandgap energy E_g
  - ☞ Energy required to create hole-electron pair
  - ☞ Energy recovered when hole and electron recombine
  - ☞ Specified in eV (1 eV = 1.6×10^{-19} joules)

Material Design Constraints

- Constrained by wavelength and lattice spacing
  - Lattice spacing:
    - » Atomic spacing of layers
    - » Must be equal as layers are built (tolerance of 0.1%)
      - Horizontal lines only on diagram
  - Most long-wavelength devices built on InP substrate
    - » Horizontal line leftward from InP point
  - Short-wavelength
    - » $Ga_xAl_{1-x}As$ is horizontal line

Fig. 5.1 p. 116



Sources-6

Sources: Wavelength and Alloy Composition

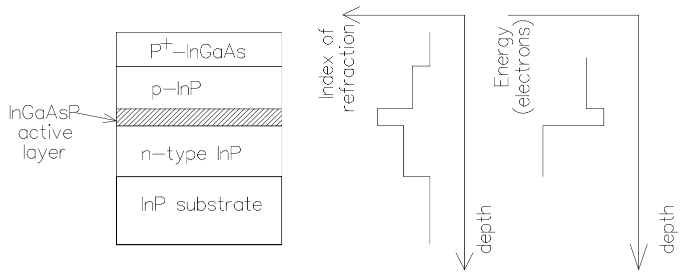
- $In_xGa_{1-x}As_yP_{1-y}$
  - 1000→1700 nm
  - Choose *x* and *y*
    - » $E_g(\mathrm{eV}) = 1.35 - 0.72y+0.12y^2$; find *y*
    - » $x = 0.4526/(1-0.031y)$; find *x*
      - For 1300 nm, $In_{0.72}Ga_{0.28}As_{0.61}P_{0.39}$
- $Ga_xAl_{1-x}As$
  - 800→900 nm
  - $E_g(\mathrm{eV}) = 1.424 +1.266x +0.266x^2$; find *x*
    - » Find *x* for desired wavelength
    - » *x* constrained to $0 < x < 0.37$ by transition efficiency

Sources-7

Sources: Typical Device Structure

- **Five-layer "sandwich"**
  - **Four primary layers grown on substrate**
    - » **Usually InP for long-wavelength sources**

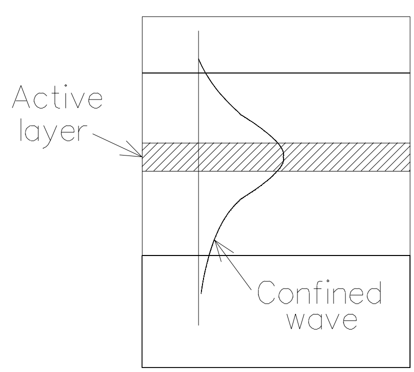
Fig. 5.2
p. 117



- **Layers help to confine current carriers and light in vertical direction**
  - ***Double heterostructure*** **⇒ efficient laser**
  - **High current-carrier density: layers form energy well**
  - **High light power: layers forms vertical optical waveguide**

Sources-8

- Layers
  - ☞ n-type InP buffer layer
  - ☞ Thin active region of p-type InGaAsP
  - ☞ p-type cladding layer of InP
  - ☞ Heavily-doped p+-type layer of InGaAs
- Optical waveguide
  - ☞ Appreciable field extends beyond active region
    - ✳ Field considerably wider in absence of confinement
  - ☞ Fraction of field within active region is function of
    - ✳ Active-layer thickness d and
    - ✳ Height of the index mismatches at interfaces



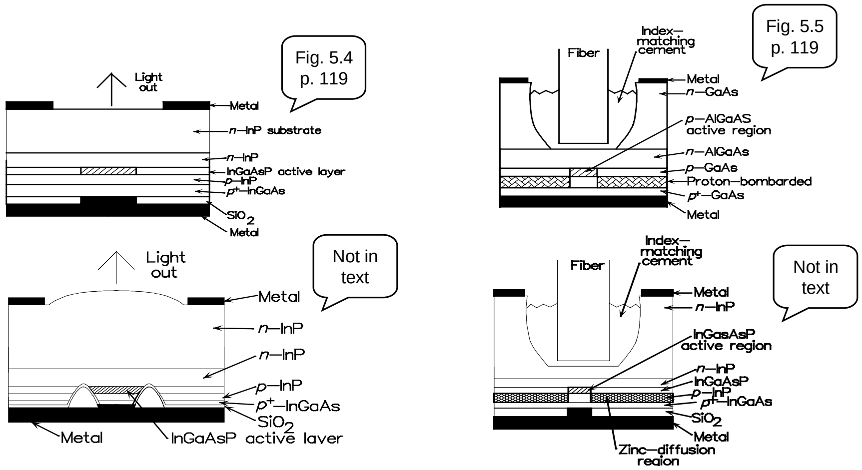
LED Preview

- Light Emitting Diodes (LEDs)
  - Incoherent light
  - Modest power levels
  - Wide beam divergence (poorly coupled into fibers)
  - Low modulation rate capabilities
  - Easily driven
  - Reliable
  - Inexpensive
  - Used for low bit-rate, short-distance links
- LED configurations
  - Surface emitters (SLEDs)
    - » Widely used in MM fiber systems
      - Wide-angle beams more efficiently coupled into MM fibers
  - Edge emitters (ELEDs)
    - » Used in both single-mode and multimode systems
    - » Provide tighter emission pattern
      - Efficiently coupled into fibers with low NAs

Sources-9

LEDs: Surface-Emitting LEDs

- **Also known as *SLED* or *Burrus emitter***
- **Light removed from top (or bottom) of device**
  - **Representative InGaAsP SLED (top left)**
  - **Representative GaAlAs SLED (top right)**
- **Diameter of emitter: ≤ fiber core diameter**



Sources-10

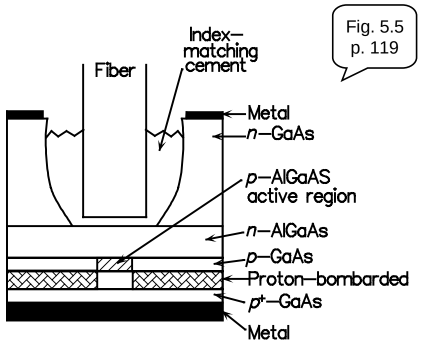
- InGaAsP device
  - ☞ Light emitted from circular planar region of active layer
    - ✳ 20→50 μm diameter
  - ☞ Double heterojunction structure around active region
  - ☞ Four layers grown on InP substrate are
    - ✳ *n*-type InP buffer layer; 2→5 μm high
    - ✳ *p*-type InGaAsP active layer; 0.4→1.5 μm high
    - ✳ *p*-type InP layer; 1 → 2 μm high
    - ✳ p^+-type InGaAs “cap” layer, about 0.2 μm high (reduces metal-to-semiconductor contact resistance)

- Horizontal confinement of current carriers
  - ☞ *Dielectric insulation* (e.g., SiO_2) layer with hole etched for current flow in limited area (top left)
  - ☞ *Proton bombardment* creates high-resistivity region outside of active region (top right)
  - ☞ *Mesa structure*: etch away surrounding material to form Isolated active region (bottom left)
  - ☞ *Zinc diffusion* into material forms low-resistivity channel for current flow (bottom right)

LEDs: SLED Coupling

- **Emitted light collected from either side of device**
- **GaAlAs device**
  - **GaAs substrate absorbs appreciable light**
  - **Etch well to allow fiber to approach active region**

Fig. 5.5 p. 119



- **InGaAsP**
  - **InP substrate does not absorb much light**
  - **Omit well**
- **Reflection losses**
  - **High reflection loss ($T \approx 70\%$) if coupled to air**
  - **Low critical angle causes much of light to be internally reflected**
  - **Quoted power is in air (includes source air reflection loss)**
  - **Solution: index-matching epoxy for joining fiber pigtail to source**

- Reflection losses

$$T = 1 - \left(\frac{n_{LED} - n_{air}}{n_{LED} + n_{air}} \right)^2$$

☞ High n

✳ InP: 3.4 , T = 70.2%

✳ GaAs: 3.6 , T = 68.1%

LEDs: SLED Output Beam Pattern

- **SLED output pattern**
  - **Circularly symmetric**
- ***Beam divergence:***
  - **Angular spread beam measured in far-field at half-power points**
  - **Either “full-angle” and “half-angle”**
    - » **Note specified conditions**
- **Typical 60° half-angle beam divergence for SLED**

Sources-12

LEDs: Edge-Emitting LEDs (ELEDs)

- **Remove light along device edge**
- **Representative InGaAsP ELED structures**
  - **Heterojunctions on both sides of active region**
  - **Four layers on substrate (like SLEDs)**
    - » **Active layer thinner (0.05 → 0.25 μm thick) than SLED (0.4 → 1.5 μm)**
    - » **Typical width ELED active region: 50→70 μm (match fiber core diameter)**
    - » **Typical length 100→150 μm**

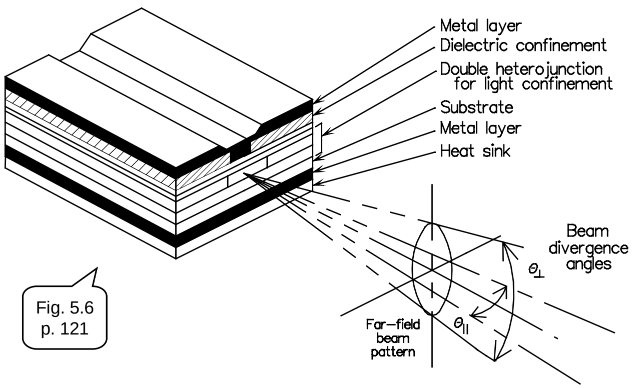
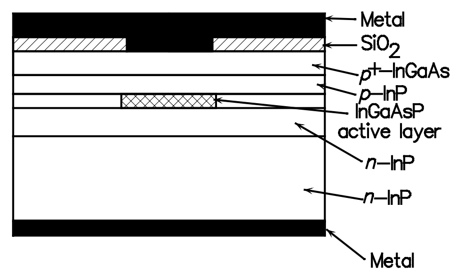


Fig. 5.6
p. 121

Fig. 5.7
p. 122

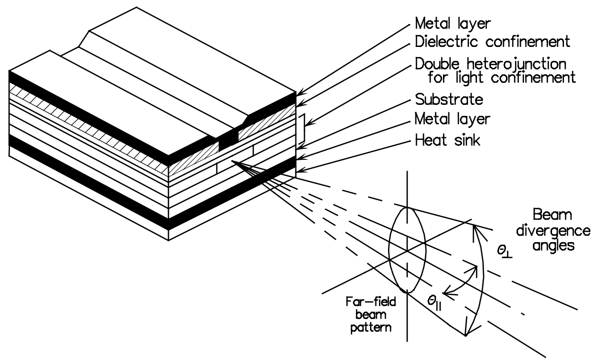


- Current confinement
  - ☞ Insulating SiO2 layer
    - ✳ Has stripe hole to laterally confine current

ELEDs: Beam Pattern

- Rectangular-shaped active region
  - Elliptical (far-field) beam
- Two beam-divergence angles
  - » *Perpendicular to junction*
    - Larger divergence
    - Typical 60° half-angle
  - » *Parallel to junction*
    - Smaller value
    - Typically 30° half-angle
- ELEDs produce ~1/2 to 1/6 power of SLEDs, but better coupling into fiber
  - Result: comparable coupled power for ELEDs and SLEDs

Fig. 5.6
p. 122

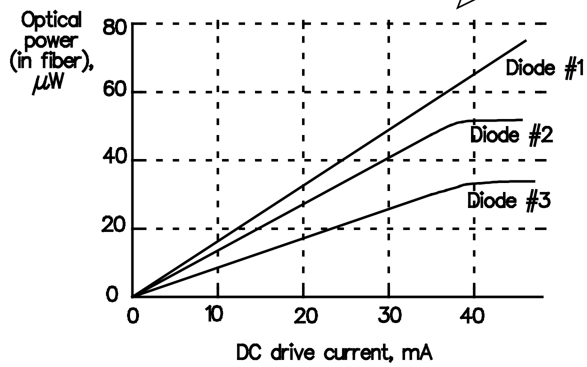


Sources-14

LEDs: Output Power Characteristics

- **LEDs for fiber communications**
  - **Power levels of several microwatts or tens of microwatts in fiber**
- **Output power is linear function of drive current**
- **Intensity modulate by modulating current**
  - **Ac signal will need dc bias**
  - ***Linearity of diode* output *P* vs. *I* curve**
    - **» Important for analog modulation**
      - **Low harmonic generation**
      - **Low intermodulation products**

Fig. 5.8
p. 123



LEDs: Spectral Width

- **Spectral width $\Delta\lambda$**
  - **Determines material and waveguide dispersion**
- **Spectral width $\Delta\lambda$ of LEDs approximated by**

$$\Delta\lambda'(\mu\text{m}) \approx 1.45\lambda'^2(\mu\text{m})kT$$

  - **Increases as ~λ^2**
  - **Typical spectral widths:**
    - » **GaAlAs: few → several 10s nm**
    - » **InGaAsP SLED: about 100 nm**
    - » **InGaAsP ELED: 60→80 nm**
- **Function of operating temperature**
  - **Heating device or operating at increased drive currents can increase spectral width**

- Lower $\Delta\lambda$ allows increased data rate if material and waveguide dispersion effects are limiting factor
- Long-wavelength LEDs have more $\Delta\lambda$ than short-wavelength
- Lasers have much narrower $\Delta\lambda$

LEDs: Modulation Bandwidth

- **LED response speed limited by**
  - **Carrier lifetime $\tau_{lifetime}$ (time duration of charge carriers in active region)**
- **LED power output follows modulation frequency response of**

$$P_{\text{out}} = P_0 \Big/ \left(1 + \omega^2 \tau^2_{\text{lifetime}}\right)$$

- **At given drive current, LEDs have power-bandwidth trade-off**
  - **Fast LED is low-power LED**
  - **Power-bandwidth product for LED is**

$$P\,\Delta f = \frac{hc}{2\pi q \lambda} \frac{J}{\tau_{\text{lifetime}}}$$

(*J* is current density)

- **Max bit rate: ~few 100s Mb/s**

Sources-17

- To measure LED modulation response:
  - ☞ Modulate source with variable-frequency signal
  - ☞ Detector converts incident optical power into current
    - ✳ Detector's electrical power: $P_{elec} \sim i^2 \sim P^2_{optical}$
      - ❖ Measure frequency response of detector electrical power out
  - ☞ Measure 3-dB frequency $f_{3\text{-}dB\ \text{electrical}}$ of detected *electrical* power
    - ✳ Measures frequency where $P^2_{\text{optical out}}(\omega)/P^2_{0\ \text{optical}} = 1/2$;
      - ❖ Then, $f_{3\text{-dB electrical}} = 0.634/2\pi\tau_{\text{lifetime}}$
- Reducing τ_{lifetime}
  - ☞ Low-drive-current LEDs
    - ✳ Increase doping level
  - ☞ High-drive-current LEDs
    - ✳ Reduce value of d (active region height) and/or...
    - ✳ Increase J

LEDs: Rise-time

- Time domain: alternative approach to LED response
- ***Rise-time:*** transition time from 10% to 90% of final value
- If negligible LED fall-time

$$f_{\max} = 1/t_r$$

- Expression for rise-time

$$t_r = 2.20\left(\frac{2kTC_s}{qI_p} + \tau_{\text{lifetime}}\right)$$

  - Capacitance C_s associated with active region (350→1,000 pF)
  - I_p: step size of current (make large for best speed)
- Fall-time minimized by
  - Overdriving turn-off (momentary negative bias when first turned off)

Sources-18

LEDs: Summary

- Pros:
  - Low cost
  - Reliable
  - Simple to modulate
- Cons:
  - Wide beam divergence
  - Relatively low power coupled into fiber
  - Relatively large spectral width
  - Suitable for systems using multimode fibers

    < several 100 Mb/s data rate

Sources-19

LED Spec Sheets

- **See course web site for sample spec sheets**

Sources-20

Laser Diodes: Preview

- **Most are edge-emitters (vertical surface-emitters under intense research)**
- **Edge-emitting laser structure much like an ELED**
  - **Double heterojunctions (confine charge carriers and optical fields in vertical direction)**
  - **Additional structures confine current and light laterally**
- **Differences between diode laser and ELED**
  - **More power than ELED**
  - **Couples more power into fiber**
  - **Active region thinner vertically and narrower horizontally**
  - **Multilayer reflectors added to ends to provide optical feedback (raises field strength to ensure stimulated emissions dominate)**
  - **Narrower $\Delta\lambda$**
  - **Smaller beam divergence**
  - **Faster modulation rates**

Sources-21

- Surface-emitting lasers arrays are “hot" research topic
  - ☞ Fabricate 10s x 10s arrays
  - ☞ Combine beams for increased power
  - ☞ Each beam can have separate wavelength
    - ✳ Separate beams for many parallel channels in single fiber (wavelength-division multiplexing)

Lasers: Gain-guided Lasers

- ***Gain-guiding:***
  - **Horizontal waveguide formed by change in *n* due to current carriers**
  - **Ex., *Stripe-geometry* laser diode**

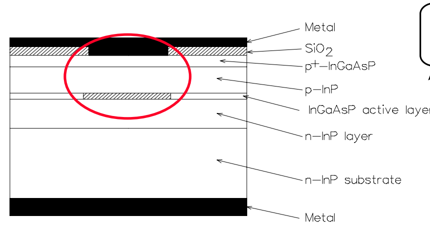
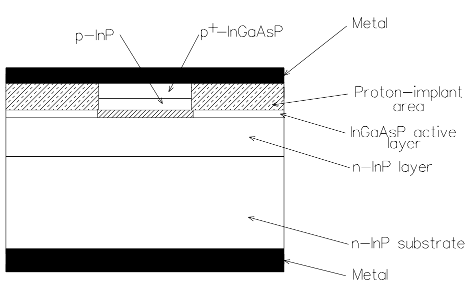


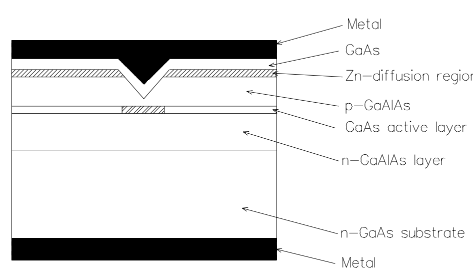
Fig. 5.9
p. 127

  - **Due to presence of current carriers**
    - » ***n* slightly higher in emitting region under stripe than adjacent regions**
    - » **Rise in *n* forms horizontal waveguide**
      - **Generated light guided both vertically and laterally**
      - **Minimizes absorption in non-active regions**
  - **Other techniques used (see text)**

Sources-22

- Insulation confines current
  - ☞ Layer of SiO2 added and narrow stripe (5→20 µm wide and 150→300 µm long) etched through
- Other methods of current confinement
  - ☞ Proton bombardment to create high-resistivity region (left)
  - ☞ V-groove etching - thinner cap has less resistance (right)





Lasers: Index-Guided Lasers

- **Alternative laser-diode structures**
  - **Incorporate deliberate material change in lateral direction to form waveguide**
- **Several structures (vertical waveguide done by heterojunctions)**
  - ***Buried heterostructure laser: n*-type InGaAsP active emitting region surrounded by *p*-type InP**

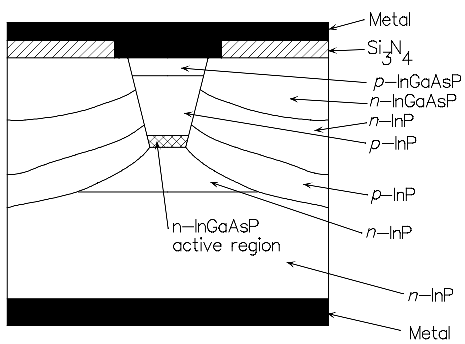
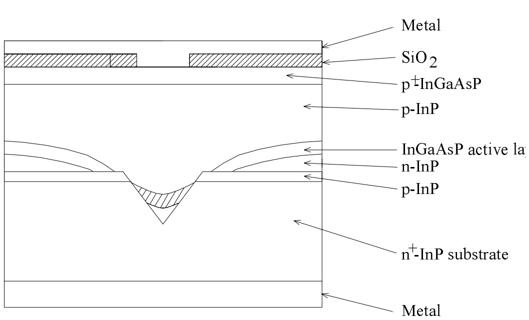


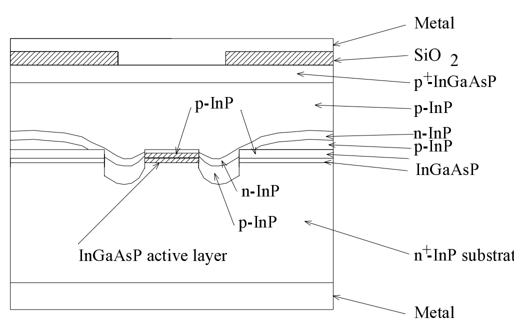
Fig. 5.10 p. 128

  - **Other structures possible (see text)**

Sources-23

- Buried-channel substrate laser: (left)
  - ☞ Active region “slumped" into etched groove, isolating active region
- Double-channel planar buried-heterostructure laser: (right)
  - ☞ Active region has channel on either side that isolates it and provides light-guiding

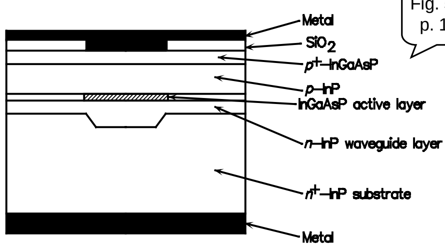




Lasers: Index-guided Lasers (cont.)

- Nearby structures can affect *n*
  - ***Inverted rib laser*** (left)
  - ***Ridge guide laser*** (right)

Fig. 5.11
p. 128



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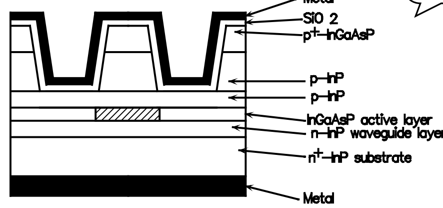


- Generally, index-guided lasers superior to gain-guided lasers
  - Lower threshold current
  - Better λ stability under pulsed operation
  - Narrower frequency spectrum

Sources-24

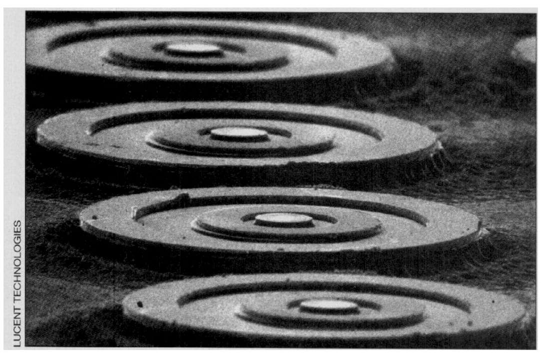
Lasers: Beam Patterns

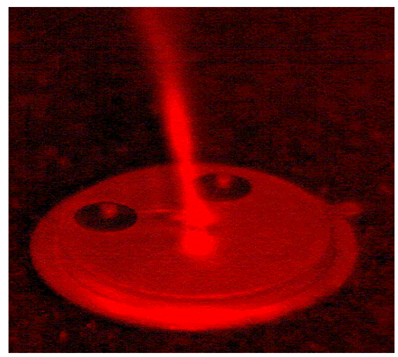
- Typical edge-emitting diode-laser active region
  - 250→500 μm long
  - 5→15 μm across
  - 0.1→0.2 μm high

- Elliptical (far-field) beam pattern
  - Perpendicular beam divergence: 30→50°
  - Parallel beam divergence: 5 → 10°
    - » Latter value ~1/5 of ELED's
    - » Laser beam more directional than LED
      - Beneficial coupling light into fibers

Surface-Emitting Lasers

- **VCSEL (Vertical cavity surface emitting lasers)**
- **“Hot” research topic**
- **Smaller, cheaper than ELEDs**
- **Arrange in an array**
- **Circular beam pattern**
- **Only at ~850 and 1300 nm, not yet widely available at 1550 nm**

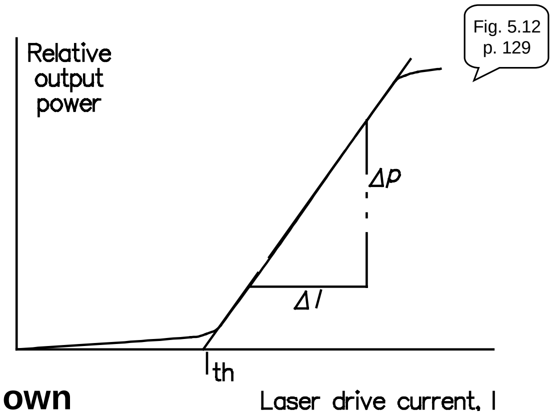




Sources-26

Lasers: Power Characteristics

- **Drive mechanism: current through forward-biased device**
- **Output characteristics**
- **Linear regions of operation:**
  - **Below "threshold": not lasing**
  - **Above "threshold": lasing**
- ***Threshold current*** **(I_{th}):**
  - **Key diode-laser parameter**
  - **Linearly extrapolate power line down to zero power**
  - **Make low as possible**
    - » **10→30 mA (index-guided lasers)**
    - » **60→150 mA (gain-guided lasers)**
- **Lasers less linear than LEDs**
  - **Additional effort to make linear lasers for analog modulation**



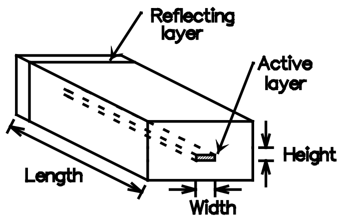
Sources-27

- Linearity
  - ☞ Nonlinearities
    - ✳ Saturation of power at high drive currents
    - ✳ Changes in power level associated with jumps in lasing wavelength
  - ☞ Minimize by
    - ✳ Avoid overdriving laser
    - ✳ Prevent wavelength jumps (i.e., stabilize operating wavelength)

Lasers: Laser Resonator

- ***Optical resonator***
  - Allows light to make equivalent of several passes through active region
- **Fabry-Perot resonator**
  - Parallel front and rear surfaces

Fig. 5.13 p. 131



Height: 0.1 – 0.2 μm
Length: 250 – 500 μm
Width: 5 – 15 μm
Sides: rough–cut
Front: cleaved
Back: 100% reflector

  - **Cleave crystal along crystalline planes**
    - » **Reflectivity of surface: ~36%**
  - **High gain eliminates need for coatings**
    - » **Add coatings for more power**

Sources-28

- Uncoated surfaces
  - ☞ GaAs (n = 3.63): 32%
  - ☞ InGaAsP(n = 3.71): 33%
- Mirror coatings
  - ☞ Back surface frequently coated with 100%-reflecting multilayer to improve power output
  - ☞ Higher power lasers
    - ✳ Front surface also coated with partially reflecting coating for protection

Lasers: Laser Frequency Modes

- **Optical resonator has modes (similar to fiber)**
- **Each mode oscillates at different frequency (*c/2nL* apart)**

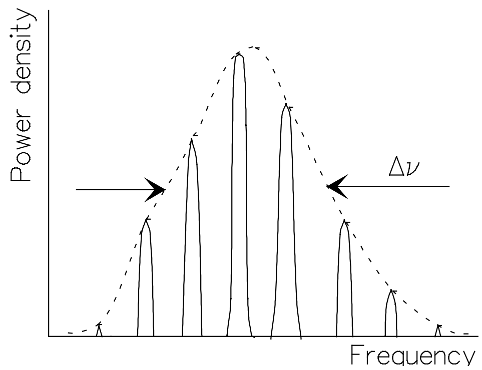


Fig. 5.14
p. 132

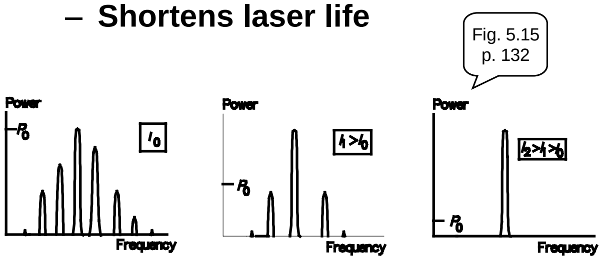
- **Minimize Δλ and dispersion by eliminating all modes but one**
  - **Then, Δλ determined by remaining mode width**
- **Power changes when operating mode jumps ("mode hopping")**
- **Want to operate with single mode for high data-rate applications**
  - **Minimum dispersion**

Sources-29

- Modes: EM waves that fit boundary conditions of resonator
- Mode frequency determined by
  - ☞ Spacing of resonator mirrors (longitudinal modes)
    - ✳ $\Delta\nu = c/2L$ (*L* is mirror separation)
  - ☞ Width and height of resonator (lateral modes)
    - ✳ Lateral mode frequency spacing more difficult to express

Lasers: Single-Mode Operation

1. **Operate at high current**
   - **Increases *side mode suppression ratio* (SMSR)**
   - **Shortens laser life**



2. **Change active region dimensions**
   - **Reduce height of region and waveguide layers**
   - **Reduce active region width (≤2 μm)**
     - » **Incorporate high-loss regions into edges of active region**
   - **Shorten resonator length**
     - **Decreases laser power**

- **Other techniques** (next slides) **preferred**

Sources-30

Lasers: Single-Frequency Diode Lasers

- **Problem: maintain single-frequency operation under pulsed operation**
  - ***Frequency chirp***
    - » **Pulsed current makes charges in active region undergo oscillatory behavior (*relaxation oscillations*)**
    - » **Cause *n* to change**
    - » **Cause ν to vary in time ("chirp")**
  - **Techniques to reduce chirp**
    - » **Bias "OFF" state just above threshold (incurs extinction ratio power penalty)**
    - » **Reduce active region volume (reduces power)**
    - » **Use external modulator with continuous laser (extra cost, increasingly popular)**
- **Better low-chirp single-frequency operation**
  - **Distributed-feedback (DFB) laser**
  - **Distributed Bragg reflector (DBR) laser**
- **Single-frequency operation easily upset by light reflected from any interface**
  - **Minimize reflections with *optical isolators***

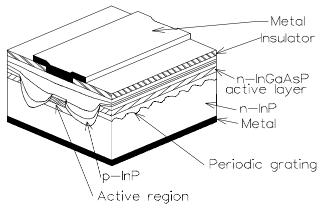
Sources-31

- Optical isolator
  - ☞ Linear polarizer combined with quarter-wave plate (fast axis at 45⌗ angle to linear polarizer)
    - ✳ Linear polarized in
    - ✳ Converted to circular polarized by quarter-wave plate
    - ✳ Reflection reverses direction ("handedness") of circular polarization
    - ✳ Reversed circular converted to orthogonal linear polarization by quarter-wave plate
    - ✳ Orthogonal polarization blocked by linear polarizer

Lasers: Distributed-Feedback (DFB) Laser

- **Reflector continuously distributed throughout lasing medium**

Fig. 5.17 p. 134



- **Phase-shifted grating**
  - **Improve stability under pulsed operation**
  - ***λ/4-shifted grating:* π/2 phase shift in middle (optimum phase shift)**

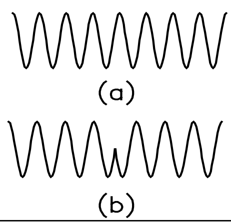


Fig. 5.18 p. 135

- **Pro:**
  - **Superior frequency stability**
  - **Narrower linewidth**
  - **Less temperature sensitivity**
- **Con: Harder to fabricate ($$)**

Sources-32

- Corrugation affects waveguide characteristics
  - ☞ Corrugation period, Λ, determines wavelength of maximum interaction

$$\lambda_B = 2n\Lambda/k$$

  - ✳ *n*: refractive index of mode in laser; k: integer (usually k = 1, sometimes 2)
  - ☞ Output at
  - ✳ *m*: integer (usually 0); L_g: grating length

$$\lambda = \lambda_B \pm \left(\lambda_B^2 (m+1)/2nL_g\right)$$

Lasers: Distributed Bragg Reflector (DBR) Laser

- **Uses corrugated interface to provide reflection**
- **Corrugated reflection sections located *outside* of active region**

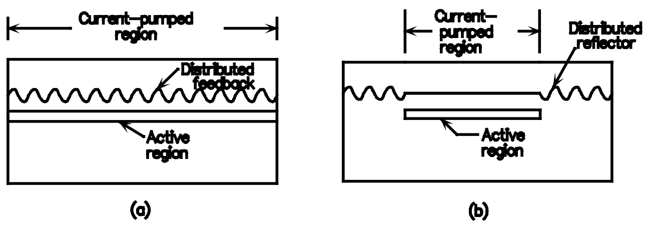


Fig. 5.19 p. 136

- **Compared to DFB laser**
  - **Pros: Easier to fabricate**
  - **Cons:**
    - » **Higher threshold current**
    - » **More susceptible to temperature**
    - » **More frequency chirp when pulsed**

- Operates at

$$\lambda_B = 2n_e\Lambda/l$$

✳ n_e: mode's propagation constant
✳ Λ:grating period
✳ l: integer (usually, l = 1)

Lasers: Temperature Dependence

- **Major problem** with laser diodes
  - Temperature dependence of I_{th}

$$I_{th} = I_0 e^{T/T_0}$$

T_0 : empirical constant fit to measured data (InGaAsP: T_0 = 50→70K; GaAlAs: T_0 =110→140K)

- Temperature control required
  - Incorporate thermoelectric cooler
  - Heat-sinks
  - Drive circuits can include temperature compensation circuit
    - » Use feedback and voltage control to cancel temperature changes

Sources-34

Lasers: Quantum-Well Lasers

- **Fabrication technology advances**
  - **Thickness of active layer ~5→10 nm**
  - **Electrons no longer modeled by behavior in bulk material** **(quantum mechanical description)**
- ***Quantum-well lasers*** **made with stacks of thin layers**
  - » **Nice combinations of**
  - » **Low threshold current**
  - » **Higher output power (and gain)**
  - » **Narrow linewidth**
  - » **Frequency stability under pulsed operation**
  - » **Low noise**
- **Demonstrated in GaAlAs (850 nm) for some time**
- **InGaAsP device research proceeding (1300-nm available; 1550 research)**

Sources-35

- Long-wavelength devices are multiple quantum well (MQW) lasers
  - ☞ Thin layers of active GaInAs alternated with thin barrier layers of GaInAsP
  - ☞ Form walls of an energy “well"
  - ☞ Can be built with mismatch of lattice constant (strained lattice)
    - ✳ Offer promise of improved performance over unstrained devices

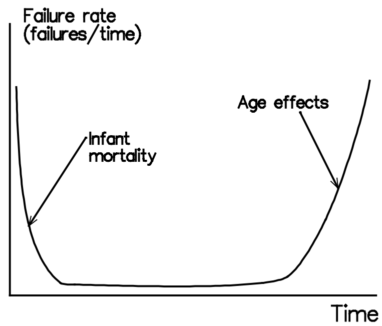
Sources: Power and Reliability

- **Power output decreases in time**

$$P_{\text{out}}/P_i = \exp(-t/\tau_m)$$

- **Weakest link in overall system reliability**
- **Early diode laser lifetimes: few hundreds of hours**
  - **Harsh electrical & optical environment**
- **Bathtub curve for failure rate**

Fig. 5.20
p. 1138



- **Most strenuous environment: continuous operation (CW)**
  - **Used for most testing**

Sources-36

- Laser power vs. time
  - ☞ τ_m measurement...
    - ✳ Find average time for power to reach certain fraction of initial value
      - ❖ Ex., Decreases to 90% power in 3 years
      - ❖ Takes 65.6 years to decrease to 10% of original power

Lasers: Degradation Mechanisms

- Facet damage
  - Damage to reflecting surfaces
  - Improved cleaving and protective coatings
- Ohmic contact degradation
  - Improved solders and heat-sinking
- Internal damage formation
  - Internal lattice defects along crystal dislocations
  - Was major problem in GaAlAs sources
    - Fewer problems in InGaAsP
  - Improved fabrication techniques
  - Degrades power in device infancy
    - Laser burn-in testing (about 100 hrs)
    - Reject devices with falling power

Lasers: Reliability Testing

- **Not a standardized process**
  - **Different testing conditions**
  - **Different sampling techniques**
  - **Different definitions of end of useful life**
    - » **End of life #1: Hold driving current fixed; power falls below usable amount (e.g., 1.25 mW)**
    - » **End of life #2: Monitor output power; when power falls, adjust drive current to maintain original power; drive current reaches maximum rated current**
    - » **Other definitions used**
- **Results quoted in statistical form; hard to interpret**

Sources-38

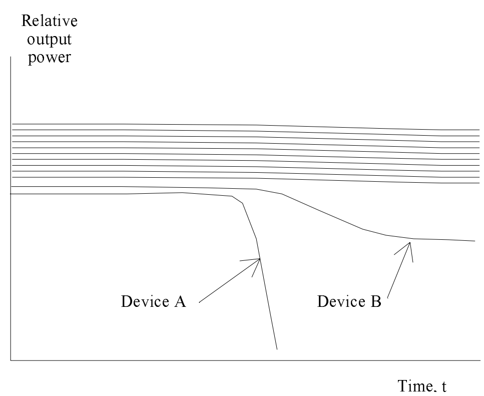
- Sometimes device performance measured below threshold
  - ☞ Particularly true when high-temperature test at high current can introduce new causes of degradation

Lasers: Testing

- Accelerate degradations by increasing...
  - Drive current or...
  - Temperature
- High current testing
  - Not used too frequently
  - To maximize source life...
    - » Operate at minimum required current
    - » Modest drive reductions produce large lifetime increases
- High temperature testing
  - Life dependence on temperature: $\tau \propto \exp(E/kT)$
    - » ***E***: empirically-determined ***activation energy*** (~0.7 eV)
  - Operate at lowest temperature in application
  - Preferred for testing
- Typical median lifetimes (cw)
  - AlGaAs lasers: 10^5 hrs; InGaAsP laser: much longer

Sources-39

- Increased drive current
  - ☞ Increasing current level decreases operating life $\tau \propto J^{-n}$
    - ✳ n: empirically-fit parameter (1.5→2.0)
  - ☞ Drive-current example
    - ✳ E.g., laser with 20-year life at 100 mA has expected life of 67.3 years at 50 mA
  - ☞ Accelerates facet degradation more than high-temperature testing
- Temperature example
  - ☞ E.g., laser with life of 10 years at 300K has predicted life of 25.4 years at 290K (and a 4.18 year life at 310K)
- Typical test result (see figure on right)



LEDs: Reliability

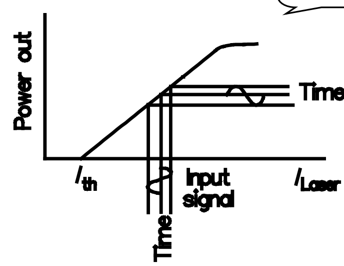
- Failure mechanisms similar to lasers
  - No facet damage in LEDs
    - » Benign current density and optical power (but often run at high drive currents to produce more power)
- Power degradation more gradual than lasers
  - LED lifetime aging degradation not an issue
- Burn-in testing can be used to remove devices that will exhibit infant failure
- Typical predicted lifetimes
  - $10^5 \rightarrow 10^8$ hours, depending on design and fabrication

Sources-40

Lasers: Modulation

- Modulation formats
  - Intensity modulate (IM): modulate drive current
  - Frequency modulated (FSK): pulse drive current (using chirp)
  - Phase modulated (PM): external modulator
- Mostly IM currently
  - Other formats require coherent detection
- Digital signals
  - Pulse drive current from I_{th} to larger value (later discussion)
- Bipolar ac signals
  - Bias point on power curve with dc current
  - Drive current deviates around bias

Fig. 5.24
p. 147



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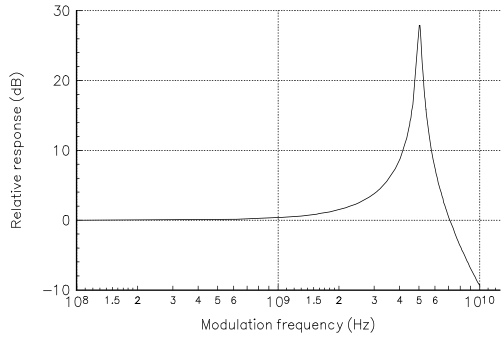
Lasers: Modulation Bandwidth

- **Modulation frequency response**
  - **Variable frequency sine-wave**

Fig. 5.22
p. 144



- **Frequency width described by 3-dB frequency**
  - **Most applications use only flat portion**
  - **Can use compensation to use full frequency response including peak**
- **Bandwidth of wide-bandwidth lasers: 10 - 50 GHz**

Sources-42

- Upper limit determined by
  - ☞ RC time constant
    - ✳ R: source/circuit resistance
    - ✳ C: device parasitic capacitance
  - ☞ Interaction of light and charge carriers in active region (complicated model)
- High bit-rate modulators
  - ☞ Microwave monolithic IC (MMIC) fabrication
  - ☞ Impedance matching to laser diode chip
  - ☞ Minimize parasitic capacitances

Source Noise: LEDs and Lasers

- LED noise: Noise-free
- Laser noise
  1. ***Relative intensity noise*** **(RIN):**
     - » Spontaneous emission light added to coherent light
     - » Negligible in powerful lasers
     - » Appreciable in weaker sources
  2. ***Partition noise:***
     - » Pulsed multimode lasers operate at several frequencies simultaneously
       - Power “partitioned" among modes
         - – Power distribution among modes changes
         - – Each change, power output fluctuates
       - Minimize with single-frequency laser (DFB laser)

Sources-43

Source Noise: Laser Noise (cont.)

3. Modal noise:

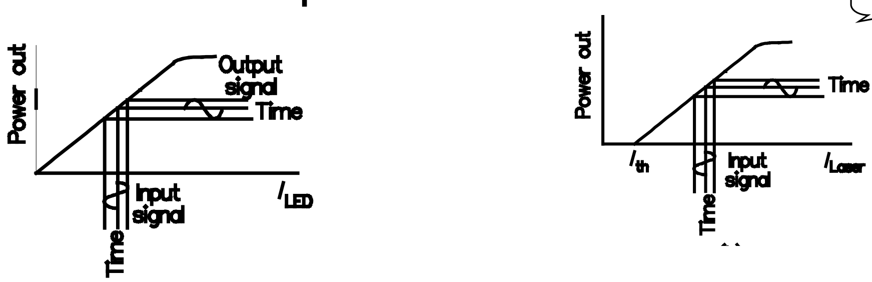
- » **Multimode source used with MM fiber**
- » **Splice/connector or imperfect MM fiber modifies mode power distribution** **(e.g., removes higher modes)**
- » **At fiber end...**
  - **Ideal fiber with all modes excited: no fluctuation in total power with time**
  - **Multimode source changes spectral distribution**
    - **Excites fiber modes with more or less power**
    - **Total source power minus that removed is time-varying** **(noise)**
- » **Solution...**
  - **Single-mode system**
  - **Use low-coherence source** **(e.g., super-radiant LED)**
    - **No interference pattern**

Sources-44

Sources: Electronic Driving Circuits

- **Forward-biased voltages of 1-2 volts with variable current drive**
- **Analog modulation**
  - **DC bias on linear portion of output power curve**
    - » **LED (left)**
    - » **Laser (right)**
  - **Time-varying signal**
    - » **Applied about bias point**
    - » **Signal amplitude kept small**
      - **Avoid nonlinear portion of characteristics**

Fig. 5.24
p. 147



Sources-45

- Bipolar electrical signals dc-shifted to unipolar representation before driving source

Sources: Electronic Driving Circuits (cont.)

- **Digital modulation**
  - **Device biased at low value of output for “0”**
    - » **Usually (but not always) zero power**
  - **Pulsed to higher output power for logical “1”**
  - ***Extinction ratio: r = P(“0”)/P(“1”)***
    - » **Most systems: *r = 0***
    - » **Nonzero *r* adds performance penalty**
      - **Usually reduces maximum data rate for given BER**

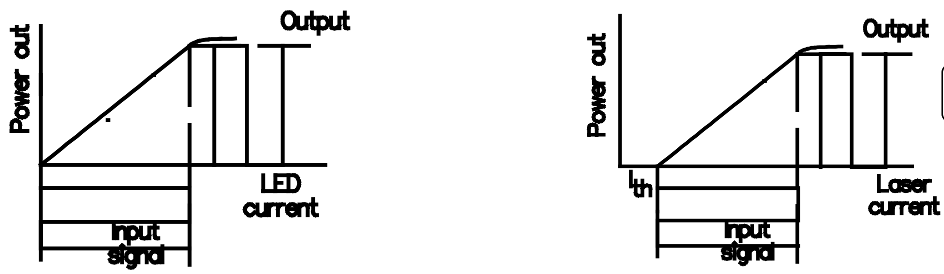
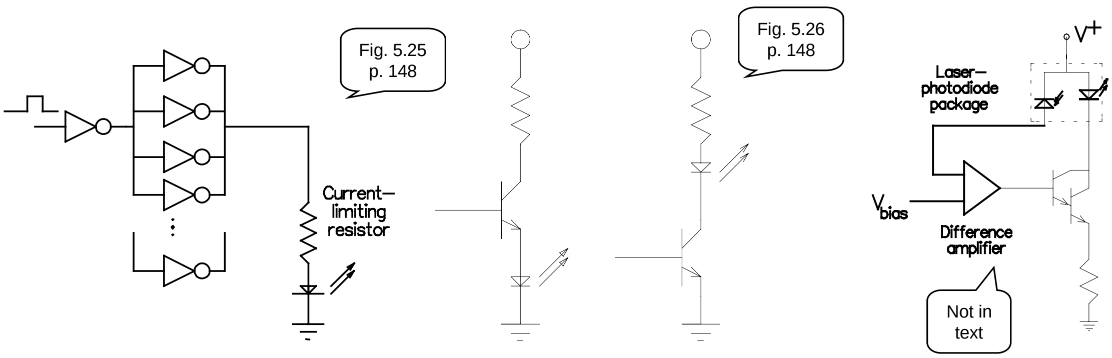


Fig. 5.23
p. 146

Sources: Driving Circuits

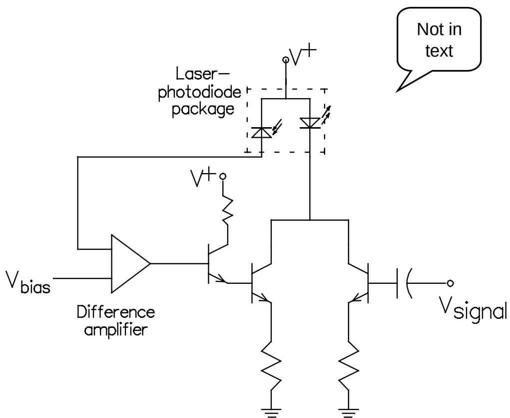
- **Pulsed operation**
  - **Direct drive (left)**
    - **» LEDs and lasers with low threshold currents**
  - **Transistor drives (center two)**
- **Maintain operating point stability with temperature changes**
  - **Sample output power from detector (mounted in laser package) and**
  - **Use feedback circuit to stabilize operating point (right)**

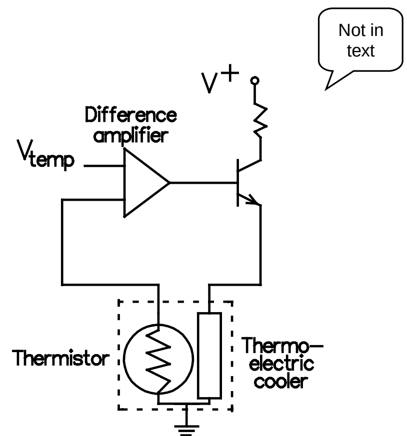


- For LEDs, momentary reverse bias and momentary overdrive can speed up LED response

Lasers: AM Driving Circuits (cont.)

- **Modified circuit to allow analog modulation (left)**
- **Closed-loop temperature stabilization with thermo-electric cooler (right) is popular**





- Closed-loop temperature circuit (right)
  - ☞ Thermistor (temperature-sensitive resistor) senses temperature
  - ☞ Feedback control used to control temperature to set-point
- Open-loop temperature control
  - ☞ Runs cooler continuously
  - ☞ Assumes enough cooling capacity to balance heating effects

Sources-48

Laser Spec Sheets

- See course web site for examples

Sources: Coupling Preview

- ***Coupling***: getting light into fiber
- Depends on...
  - Source size
  - Beam pattern shape and divergence angles
  - Fiber (a, NA^2, g)
- Mismatching source and fiber core sizes wastes power
  - Source diameter = core diameter is optimum
    - » If source diameter < fiber core (typical of laser), lens can...
      - Optically match sizes
      - Increase source directivity by magnification, M
      - Increase coupling by factor of M
    - » No remedy exists if source size > fiber core

Source Spatial Distributions

- Radiance of source: ***B(θ,φ)*** **[W•steradian^{-1}•m^{-2}]**
- **Three source power models**
  - ***Lambertian source***

$$B(\theta,\phi) = B_0 \cos\theta$$

  - ***Modified Lambertian***

$$B(\theta,\phi) = B_0 \cos^m \theta$$

  - ***Elliptical beam***

$$B(\theta,\phi) = \frac{B_0}{\left(\frac{\sin^2\phi}{\cos^T\theta} + \frac{\cos^2\phi}{\cos^L\theta}\right)}$$

Sources-51

Power Coupled Into Fiber

- **Equation for power into fiber for "butt-coupled" fiber...**

$$P_f = \int_{r=0}^{r_u} \int_{\phi_s=0}^{2\pi} \left(\int_{\phi=0}^{2\pi} \int_{\theta=0}^{\theta_{\max}} B(\theta,\phi) \sin\theta \, d\theta \, d\phi \right) \partial\phi_s \, r \partial r$$

- **θ_{max} = sin^{-1} NA and….**

$$r_u = \begin{cases} r_s & r_s < a \\ a & r_s \geq a \end{cases}$$

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Coupling: Lambertian Source and SI Fiber

- **Use appropriate *B*(θ,ϕ)**
- **Assume SI fiber (NA = sin θ_{max})**
- **See text for details of math**

$$P_f = \pi^2 B_0 \,\mathrm{NA}^2 r_s^2 \quad (r_s < a); \qquad P_s = \pi^2 B_0 r_s^2 \qquad \Rightarrow \eta = \frac{P_f}{P_s} = \mathrm{NA}^2 \quad (r_s < a,\ \mathrm{SI})$$

$$P_f = \pi^2 B_0 \,\mathrm{NA}^2 a^2 \quad (r_s \geq a); \qquad P_s = \pi^2 B_0 r_s^2 \qquad \Rightarrow \eta = \frac{P_f}{P_s} = \mathrm{NA}^2 \left(\frac{\mathrm{a}}{\mathrm{r_s}}\right)^2 \quad (r_s \geq a,\ \mathrm{SI})$$

Sources-53

Coupling Relations: Lambertian Source

Fiber	$r_s<a$	$r_s \geq a$
Step-index	NA^2	$NA^2(a/r_s)^2$
Graded-index	$NA^2\left[1-\left(\frac{2}{g+2}\right)\left(\frac{r_s}{a}\right)^g\right]$	$NA^2\left(\frac{a}{r_s}\right)^2\left(\frac{g}{g+2}\right)$

- **For step-index vs. graded index (r_s = a) …**

  $\eta_{SI} = 2\eta_{GI}$ **(3 dB more power coupled into SI fiber)**

Sources-54

Coupling Relations: Modified Lambertian Source

- **Problem 6.12 shows that…**

$$P_f = \frac{2\pi A_s B_0\left[1-\cos^{m+1}\theta_{\max}\right]}{\mathrm{m}+1} \quad (r_s < a); \qquad P_s = \frac{2\pi B_0 A_s}{m+1}$$

$$\Rightarrow \boxed{\eta = \frac{P_f}{P_s} = \frac{(m+1)\mathrm{NA}^2}{2} \qquad (r_s < a,\ \ \mathrm{SI})}$$

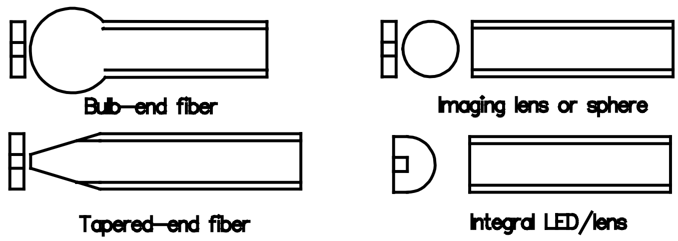
- **and that…**

$$\boxed{\eta = \left(\frac{(m+1)\mathrm{NA}^2}{2}\right)\left(\frac{\mathrm{g}}{\mathrm{g}+2}\right) \qquad (r_s = a,\ \ \mathrm{GI})}$$

- **Elliptical-beam sources require computer modelling**

Sources: Lens Coupling

- Source smaller than fiber core...
- Use *microlenses* to perform coupling
- Some lens geometries...



- Potential disadvantage
  - Additional fabrication steps
  - Requires fine alignment
- Advantages
  - If properly aligned...
    - » Coupling efficiency improvement = magnification of source

Sources-56

Sources: LED Coupling

- **SLEDs**
  - **Matches theory when coupled into large-core, large-NA fiber**
    - » **Less match when fiber has small core and small NA**
  - **Coupling improved by**
    - » **Reducing source size (improve heat sinking)**
    - » **Using lens to couple light**
      - **Improvements of 3→5 with bulb-end fiber**
      - **18→20 times with tapered-end fibers**

- **ELEDs**
  - **More difficult to model (elliptical pattern)**
  - **Narrower emission pattern (in one dimension) allows greater coupling efficiency for butt-coupled fibers**
  - **Cylindrical lens can improve coupling marginally**
  - **Bulb-end and tapered fibers improve coupling efficiency**

Sources-57

Sources: Laser Coupling

- **Elliptical beam patterns**
  - **Patterns much narrower than LED**
- **Additional difficulty incurred trying to couple into small core of SM fibers...**
  - **SM core diameters : 5→9 μm**
  - **Small core size increases sensitivity to misalignment**
- **Lens elements frequently used...**
  - **Micro-lenses**
  - ***Graded-index (GRIN) lenses***
  - **Reflections from lens elements and fiber can upset single-frequency lasers**
    - » **Isolators can be built into source package**

Sources: Summary

- Lasers vs. LEDs
  - Pros:
    - » Smaller $\Delta\lambda$ (less dispersion in SM fiber)
    - » More power into fiber
      - Higher output power
      - Higher coupling efficiency
      - ~10x more speed
  - Cons:
    - » Cost > 2x LED cost
    - » More temperature sensitive

- Short-λ region (~850 nm)
  - Modest data rates (<50 Mb·s^{-1})
    - » LEDs with MM fibers (SI and GI)
  - Higher data rates or SM fibers
    - » Laser diode

- Long-λ region (1300, 1550 nm)
  - Long-λ LEDs available
    - » Short-distance moderate-data rate links (FDDI)
  - Slower degradation than GaAlAs devices
  - Greater temperature sensitivity
  - $\Delta\lambda$ ~2.5 times $\Delta\lambda$ @ 850 nm (but less fiber dispersion)

Sources-59

- Single-frequency operation
  - ☞ Minimize material and waveguide dispersion
  - ☞ DFB and DBR lasers available

Sources: Summary (cont.)

- **Current laser opportunities**
  - **Narrower spectral width**
  - **Frequency stability**
    - » **Low chirp when pulsed**
  - **Lower threshold current (few mA)**
  - **Rapidly tuned wavelength**
  - **Settable λs (100 GHz [0.8 nm] separation)**
- **Quantum-well lasers**
- **VCSELs**

Next up: Receivers

Sources-60