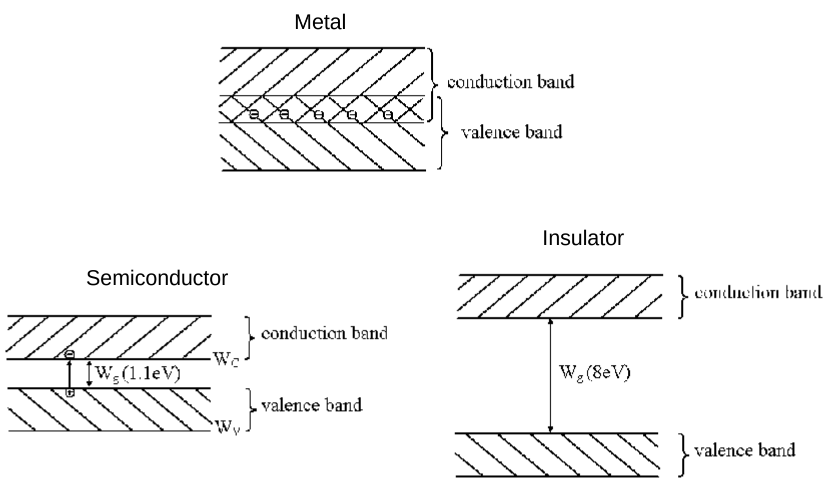
OPTI 380A
Intermediate Optics Lab 1 and 2: Semiconductor Light Sources

Tom Milster
Professor, College of Optical Sciences,
University of Arizona
milster@arizona.edu

Electronic Properties

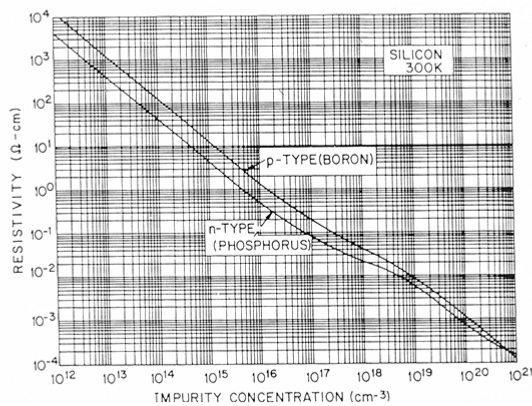


Valence band is completely full

Semiconductors

- Intrinsic (pure) semiconductor, majority carrier concentration n(Si) ~ 10^{10} cm^{-3}
- Extrinsic (doped) semiconductor
- Control of resistivity of silicon by over 9 orders of magnitude by adding small amount of impurities or dopants
- p-type, majority carrier is hole
- n-type, majority carrier is electron

Density of Si atoms 5×10^{22}cm^{-3}

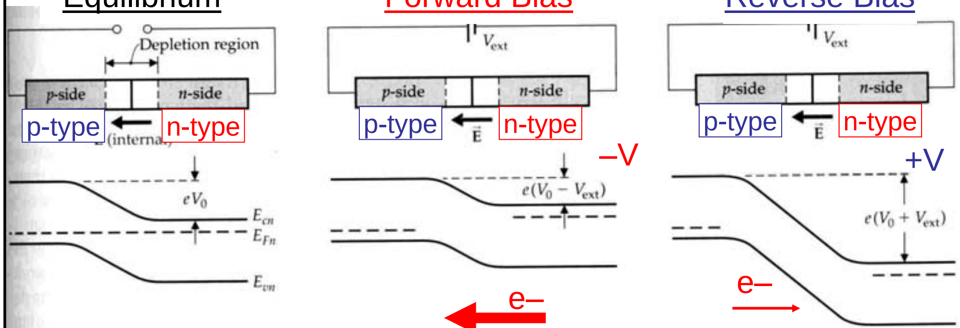


This is what makes everything possible!
Transistors, semiconductor lasers, diode detectors, CCDs …
which lead to computer, internet, mp3 players, digital camera …

PN Junction: Band Diagram under Bias

- Forward Bias: negative voltage on n-side decreases built-in junction potential → higher current of (majority) electrons from n to p-side.
- Reverse Bias: positive voltage on n-side increases junction potential → only very low current of (minority) electrons from p to n-side.

Equilibrium Forward Bias Reverse Bias



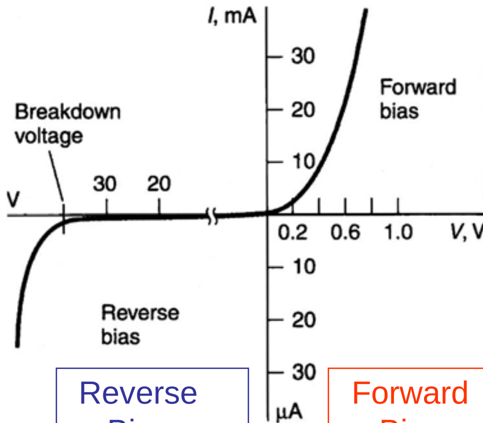
Majority Carriers Minority Carriers

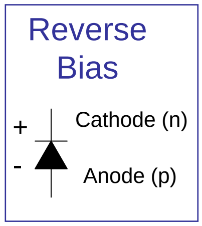
PN Junction: I-V Characteristics

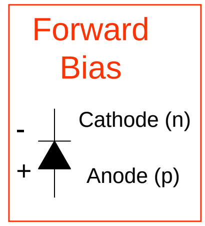
- Current-Voltage Relationship

$$I = I_o[e^{eV/kT} - 1]$$

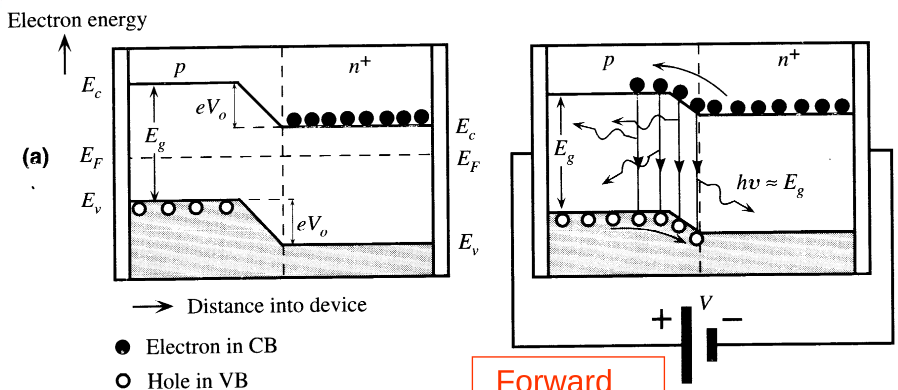
- Forward Bias: current exponentially increases.
- Reverse Bias: low leakage current equal to ~I_o.
- "Rectifying" pn junction passes current in only one direction!

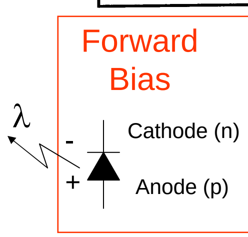




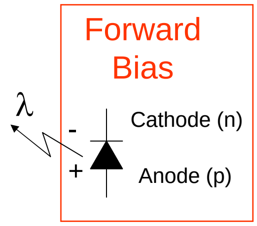


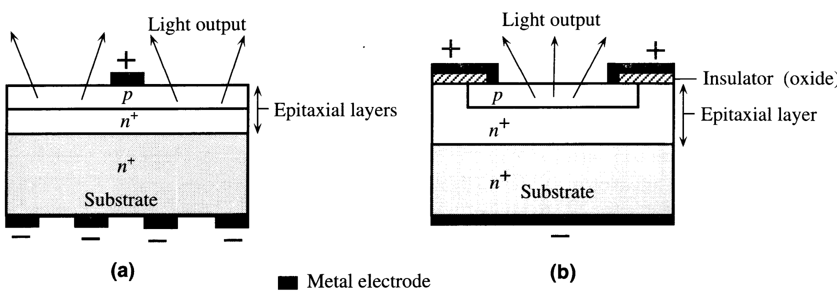
Light Emitting Diode (LED)





Light Emitting Diode (LED)





LED Far-Field Pattern

- ❑ LED far-field patterns vary greatly, depending on the electrode layout and the type of lens in which the LED is encased.
- ❑ The LED you will be using in the lab has this characteristic:

Cotco LED
LD-701CHR1-A5

50% Power Angle : 105°

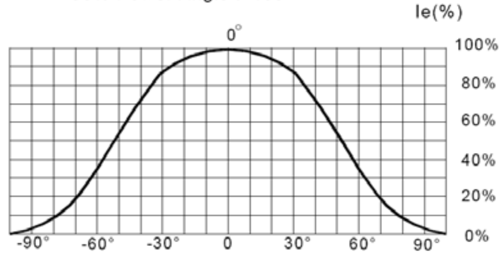


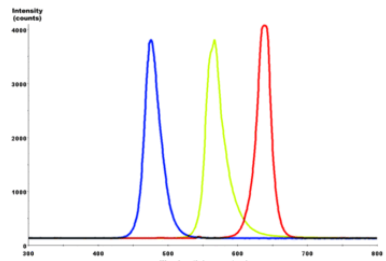
FIG.5 FAR FIELD PATTERN

Light Emitting Diode (LED)

- ❑ Semiconductor that emits incoherent narrow-spectrum of light upon application of a current.
- ❑ An LED is a semiconductor diode with a structure called the p-n junction.

Blue, green and red LEDs

Spectra of blue, yellow-green and red LEDs
FWHM is ~24-27 nm



Other LED Characteristics for This Lab

Cotco LED
LD-701CHR1-A5

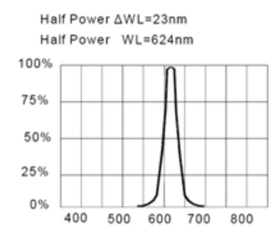
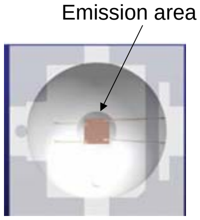


FIG.3 RELATIVE LUMINOUS FLUX VS. WAVELENGTH.

Emission area ~ 1mm^2



Features

- High luminous flux output for illumination
- Exposed pad design for excellent heat transfer
- Designed for high current operation
- Reflow soldering applicable

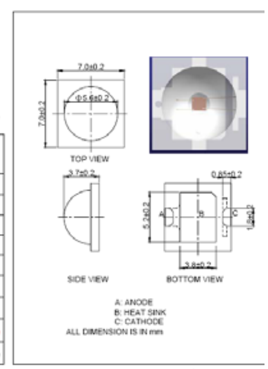
Absolute Maximum Ratings at Ta = 25°C (on metal core PCB)*

Items	Symbol	Absolute maximum Rating	Unit
Forward Current	I_F	450	mA
Peak Forward Current**	I_{FP}	700	mA
Reverse Voltage	V_R	5	V
Power Dissipation	P_D	1.2	W
Operation Temperature	T_{opr}	-40 ~ +85	°C
Storage Temperature	T_{stg}	-40 ~ +85	°C
Junction temperature	T_j	+115	°C
Junction-to-Ambient***	θ_{ja}	45	°C/W
Junction-to-case***	θ_{jc}	20	°C/W

*Metal core PCB defines as good heat transmission substrate (thickness of 2.0mm Al-based PCB in 20x20mm, θ_{jc} <20°C/W could do)

** Where pulse width <= 0.1msec, duty cycle <= 1/10 *** Rth test condition: mounted on 2.0mm Al-based PCB in size of 20x20mm

Package Outline

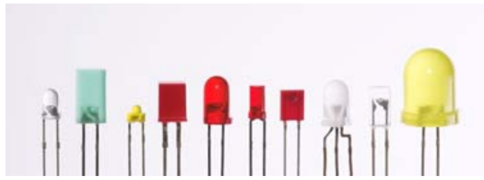


Typical Electrical & Optical Characteristics at Ta = 25°C (on metal core PCB)*

Items	Symbol	Condition	Min.	Typ.	Max.	Unit
Forward Voltage	V_F	I_F = 450mA		2.4	2.8	V
Reverse Current	I_R	V_R = 5V	---	---	10	µA
Luminous Flux	lumen	I_F = 450mA	21	32	---	lm
Dominant Wavelength	λ_D	I_F = 450mA	618	624	630	nm
50% Power Angle	$2\theta_{1/2}$	I_F = 450mA	---	105	---	deg

Inorganic semiconductor materials

College of Optical Sciences



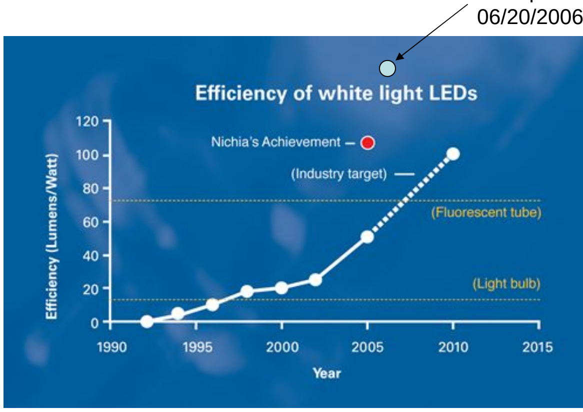
- aluminum gallium arsenide (AlGaAs) - red and infrared
- aluminum gallium phosphide (AlGaP) - green
- aluminum gallium indium phosphide (AlGaInP) - high-brightness orange-red, orange, yellow, and green
- gallium arsenide phosphide (GaAsP) - red, orange-red, orange, and yellow
- gallium phosphide (GaP) - red, yellow and green
- gallium nitride (GaN) - green, pure green (or emerald green), and blue
- indium gallium nitride (InGaN) - near ultraviolet, bluish-green and blue
- silicon carbide (SiC) as substrate - blue
- silicon (Si) as substrate - blue (under development)
- sapphire (Al2O3) as substrate - blue
- zinc selenide (ZnSe) - blue
- diamond (C) - ultraviolet
- aluminum nitride (AlN), aluminum gallium nitride (AlGaN) - near to far ultraviolet

White LED efficiency

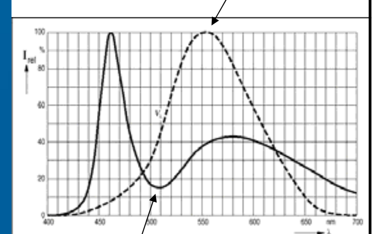
College of Optical Sciences

- Goal is to replace everything with LEDs

Cree produced 131 lumen/W 06/20/2006



true white



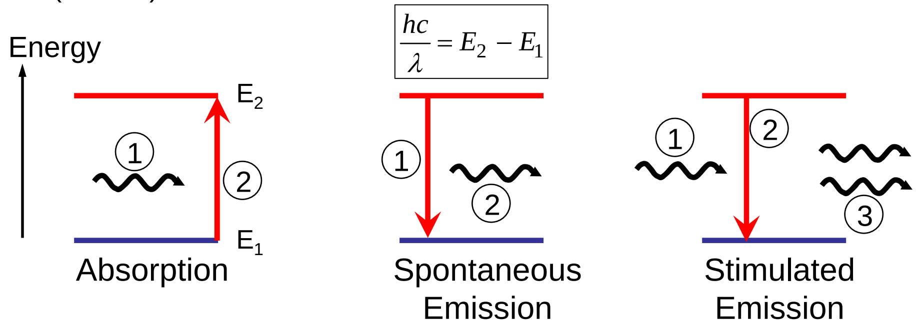
emitted wavelength (blue and converter material to yellow)

lumen = power weighted by luminosity function of human eye per unit of steradian

Devices: Light-related

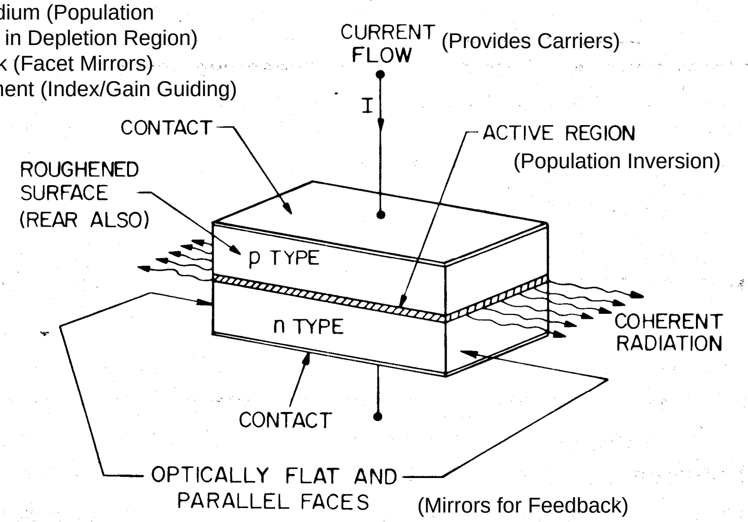
- Three major methods for light to interact with a material:
  - Absorption: incoming photon creates electron-hole pair (solar cell).
  - Spontaneous Emission: electron-hole pair spontaneously decays to eject photon (LED).
  - Stimulated Emission: incoming photon stimulates electron-hole pair to decay and eject another photon, i.e. one photon in → two photons out (LASER).

$$\frac{hc}{\lambda} = E_2 - E_1$$



Fabry-Perot Laser Geometry

A Laser Requires:
1.) Gain Medium (Population Inversion in Depletion Region)
2.) Feedback (Facet Mirrors)
3.) Confinement (Index/Gain Guiding)



Semiconductor Lasers: Spectral Output

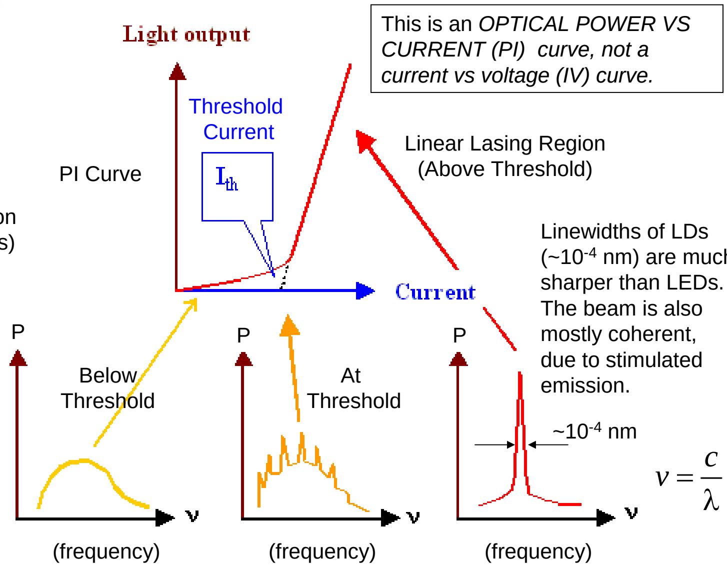
College of Optical Sciences

Lasing starts to occur when *gain* (due to population inversion) is greater than *losses* (due to absorption and mirror losses) of the cavity.

This is an *OPTICAL POWER VS CURRENT (PI) curve, not a current vs voltage (IV) curve.*

Power Spectra at Different Output Powers

Linewidths of LDs (~10^{-4} nm) are much sharper than LEDs. The beam is also mostly coherent, due to stimulated emission.



$$\nu = \frac{c}{\lambda}$$

Semiconductor Lasers: Multi-Mode Operation

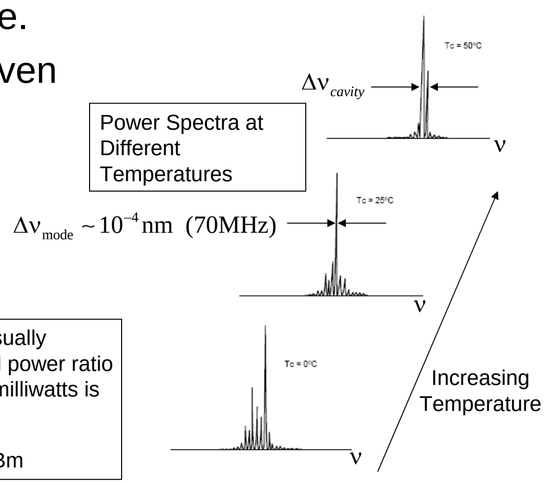
College of Optical Sciences

- ❑ Most commercial laser diodes have more than one dominant mode.
- ❑ Mode spacing is given by: $\Delta\nu_{cavity} = \dfrac{c}{2nL}$

c = speed of light (3x10^8 m/sec)
n = refractive index of cavity material (~ 3.5)
L = cavity length

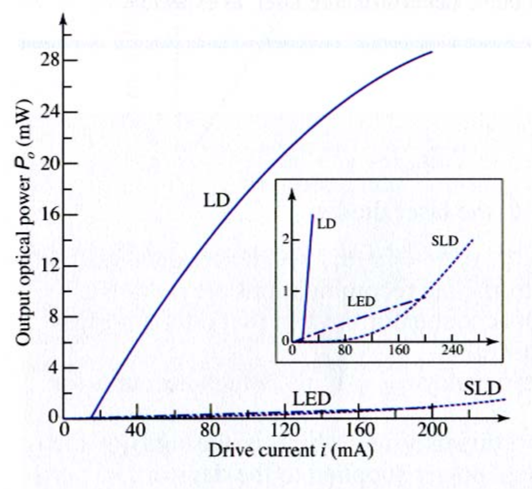
Optical Spectrum Analyzers (OSAs) usually specify power in terms of dBm (decibel power ratio referenced to one milliwatt). Power in milliwatts is given by

$$P = 10^{\frac{x}{10}}$$ where *x* is dBm



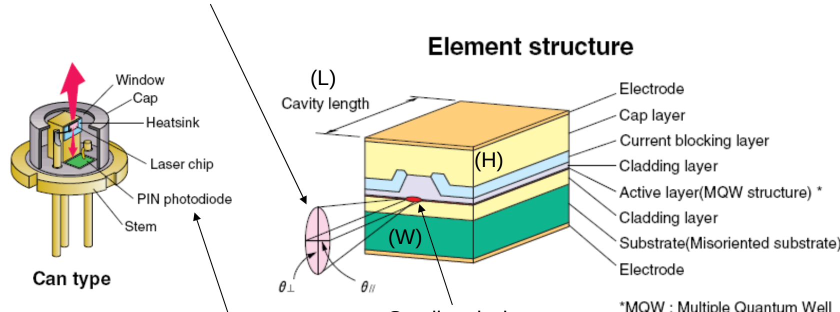
PI Curves for Different Semiconductor Light Sources

LED: Light Emitting Diode
(Lowest power output)
LD: Laser Diode
(Highest power output)
SLD: Super Luminescent Diode
(Higher power than LED)



LD Package and Structure

LD beams are elliptically shaped, due to diffraction from the small emission area at the front facet.

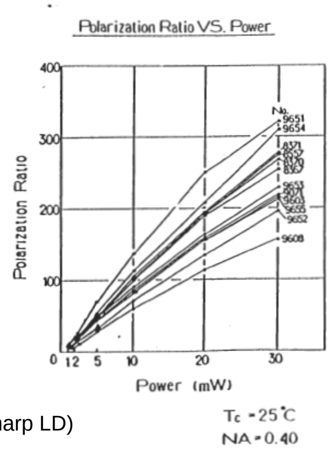


Small emission area
(~ 1μm by 3μm)

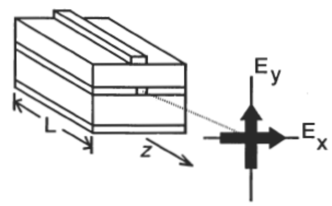
The PIN photodiode provides a way to monitor output power (back facet).

College of Optical Sciences
The University of Arizona

LD Polarization Ratio



(Sharp LD)



- polarization ratio = I_x / I_y
- mainly I_x due to waveguide
- ratio increases with power output

College of Optical Sciences
The University of Arizona

Red LD Used in This Lab

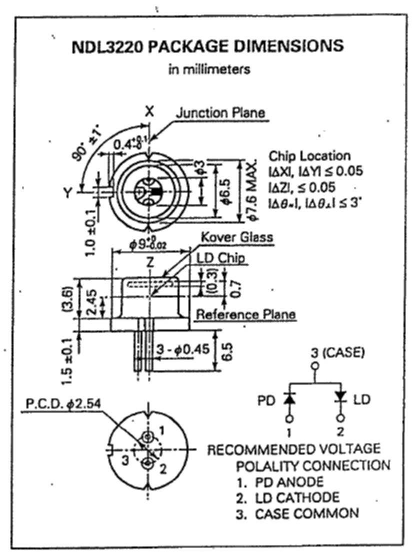
FEATURES

- Low Operating Current (Iop = 30 mA TYP.)
- Low Operating Voltage (Vop = 2.1 V TYP.)
- Wide Operating Case Temperature (Tc = −10 to +60 °C)
- Peak Emission Wavelength (λ = 670 nm TYP.)
- Fundamental Transverse Mode

ABSOLUTE MAXIMUM RATINGS (T_c = 25 °C)

Optical Output Power	P_o	6.0	mW
Reverse Voltage	V_R	2.0	V
Operating Case Temperature	T_c	−10 to +60	°C
Storage Temperature	T_{stg}	−40 to +85	°C
Monitor PD			
Reverse Voltage	V_R	30	V
Forward Current	I_F	20	mA

(Full Spec Sheet on Website)



College of Optical Sciences
THE UNIVERSITY OF ARIZONA

Measuring LD Beam Divergence

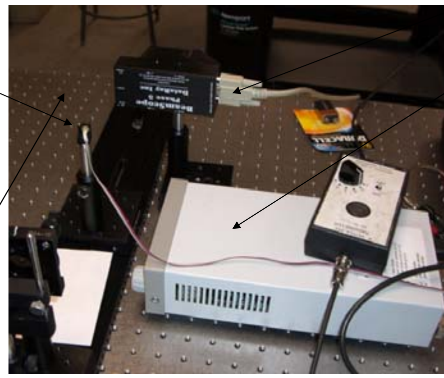
- Measure widths in x (||) at two z distances, calculate angle. Use FWHM Irradiance.
- Repeat for y (⊥) profile.

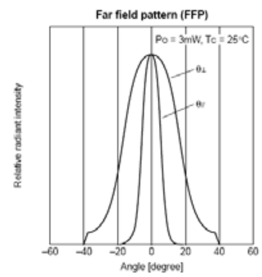
Beam Scope Profile Measurement Device (Manual on Website)

LD Power Supply

LD

Z Direction





Typical Catalog Graph

College of Optical Sciences
THE UNIVERSITY OF ARIZONA

The Concept of Radiance

(Mostly from Wikipedia)

- Radiance is useful because it indicates how much of the power emitted by an emitting surface will be received by an optical system looking at the surface from some angle of view. In this case, the solid angle of interest is the solid angle subtended by the optical system's entrance pupil. Since the eye is an optical system, radiance is a good indicators of how *bright* an object will appear.

Radiance is defined by

$$L = \frac{\mathrm{d}^2\Phi}{\mathrm{d}A\,\mathrm{d}\Omega\cos\theta} \approx \frac{\Phi}{\Omega A\cos\theta}$$

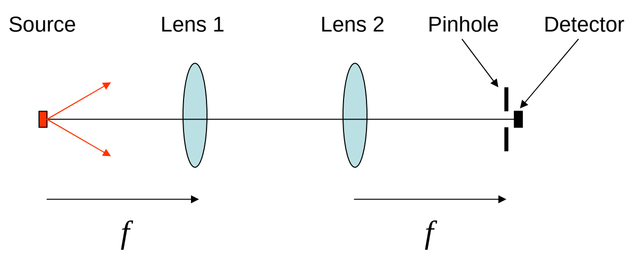
where

L is the observed or measured radiance ($W\cdot m^{-2}\cdot sr^{-1}$), in the direction θ,
Φ is the total radiant flux or power (W) emitted
θ is the angle between the surface normal and the specified direction,
A is the area of the source (m^2), and
Ω is the solid angle (sr) subtended by the observation or measurement.
The approximation only holds for small A and Ω where cos(θ) is approximately constant.

The spectral radiance (radiance per unit wavelength) is written L_λ and the radiance per unit frequency is written L_ν.

Measuring Relative Radiance

- ❑ Place Source 1 at the front focus of lens 1.
- ❑ Measure the power through the pinhole.
- ❑ Repeat for Source 2.
- ❑ Relative radiance is the ratio of the power measurements.

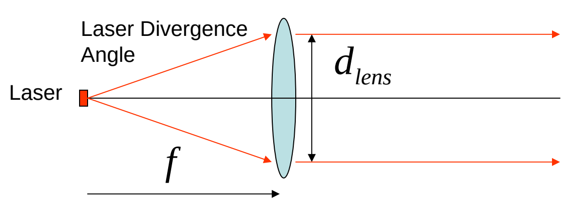


LD Collimation

- ❑ Numerical Aperture (NA) of the lens:

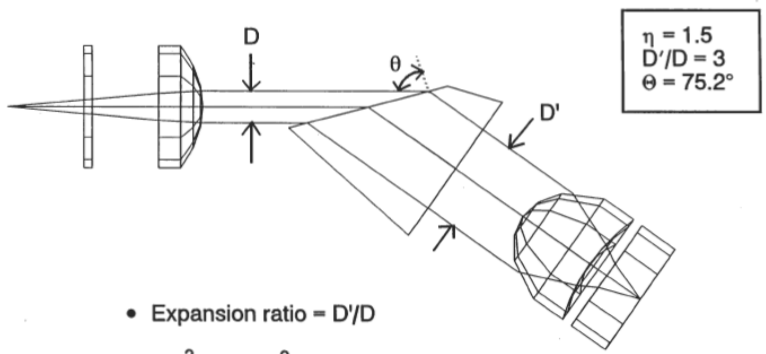
$$NA = \sin\theta_{\text{marginal}} \sim \frac{d_{lens}}{2f}$$

- ❑ NA of the laser is approximately the sine of the divergence angle (can be different in x and y)
- ❑ Match NA of laser beam to NA of lens



LD Circularization

Single Prism



- Expansion ratio = D'/D
- $\cos^2\theta = \dfrac{n^2 - 1}{(nD'/D)^2 - 1}$