Fundamentals of Photonics: Diode Lasers

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Overview

- Basics of diode lasers
- Diode structures
  - Edge emitters
  - Surface emitters
  - Arrays
- Diode materials and wavelengths
- High-power diodes and arrays
  - High-brightness and beam combination
- Emerging developments

Key points about diode lasers

- Compound semiconductors
  - Wavelength range depends on bandgap
- Recombination at junction
  - Converts current into light
  - Concentrating current and light improve efficiency
- Compact, mass producible, low cost
- High gain => low beam quality, high divergence
- Many applications – pumping or direct
- 48% of 2014 laser market (dollar volume)

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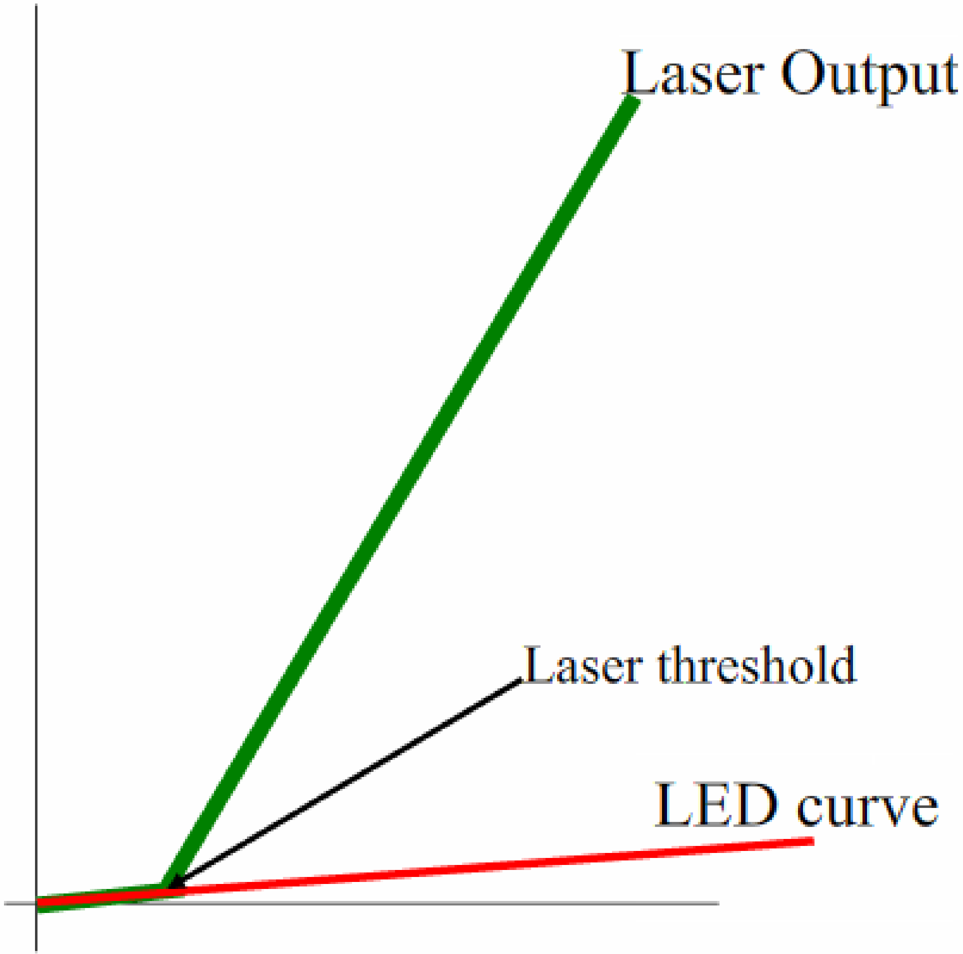
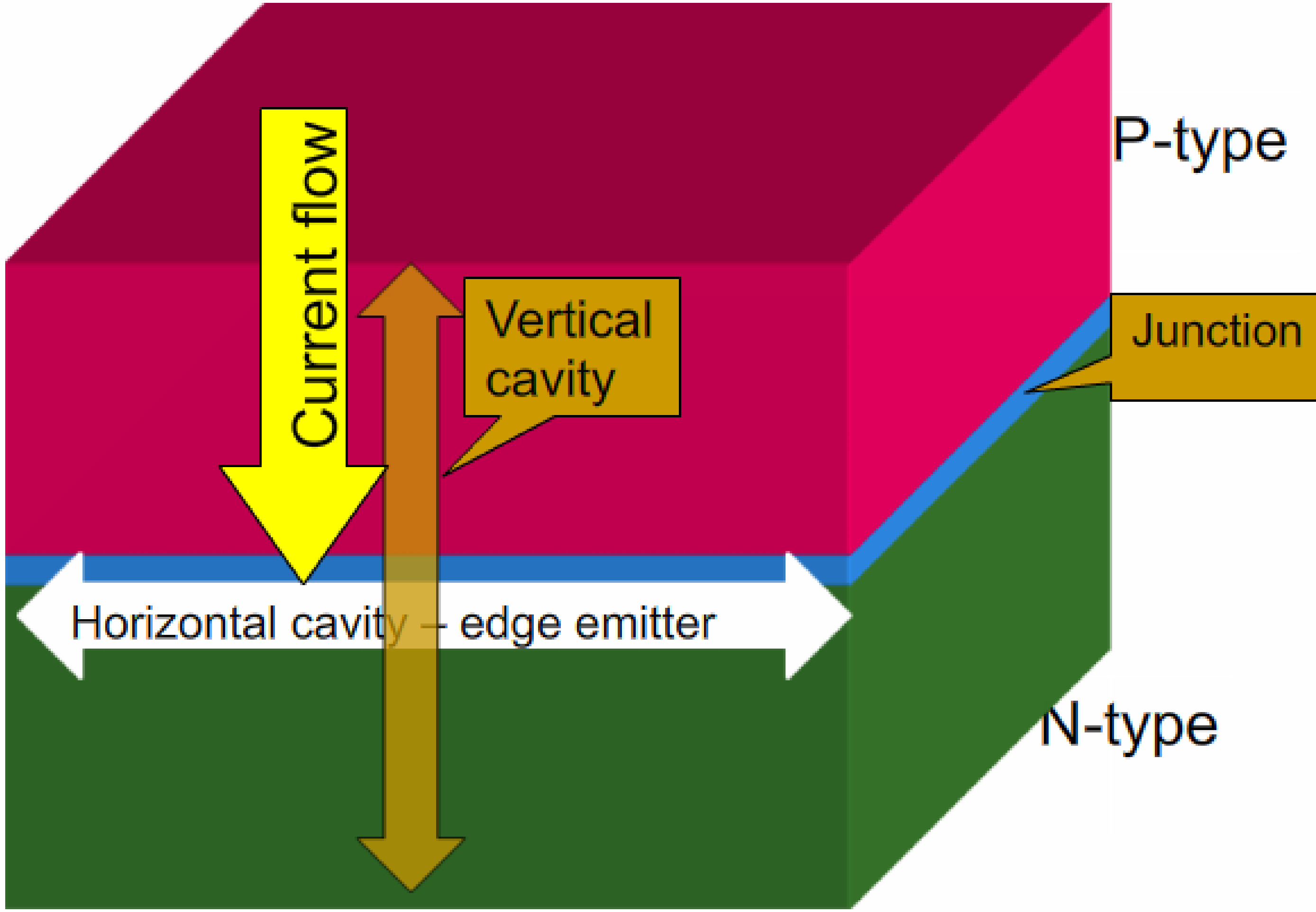
Diode laser output

- Output power rises rapidly above threshold
- Threshold relatively low
- High slope efficiency
- Overall efficiency increases with power
  - Record >70%
- Diode arrays can increase power
- Beam quality degrades at high power



Diode laser resonators

- Small chip
  - Shape depends on resonator
- Current vertical
- Resonator
  - Vertical surface emitter
  - Horizontal edge emitter

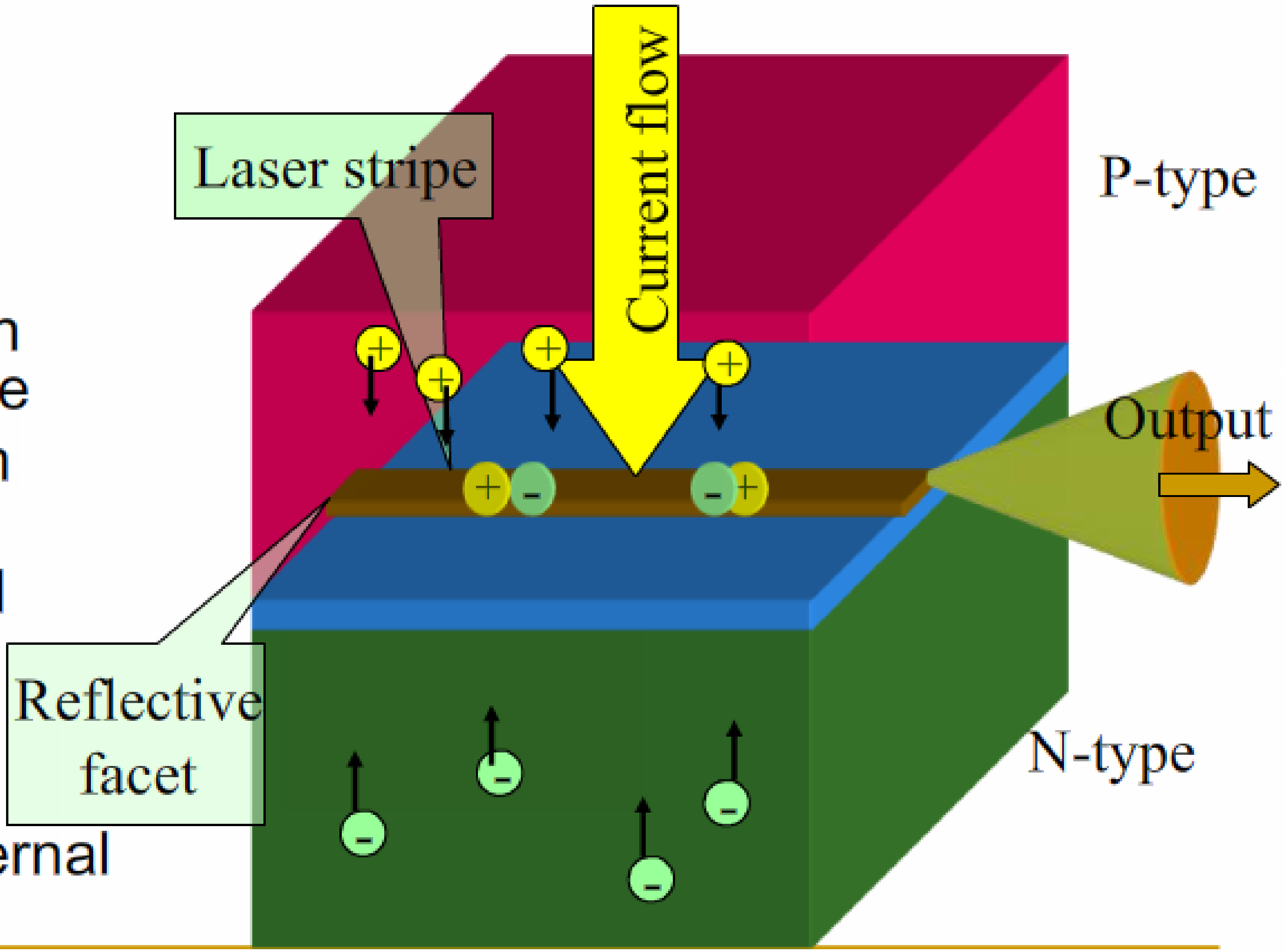


Diode laser structures

- Edge emitters (cavity in junction plane)
  - Narrow-stripe lasers
  - Single wide stripe lasers Tapered wide stripes
  - 1-D bars and arrays
  - 2-D stacks
- Surface emitters
  - VCSELs (vertical cavity)
  - Novel designs
    - Horizontal cavities with vertical output (junction plane)
  - Arrays

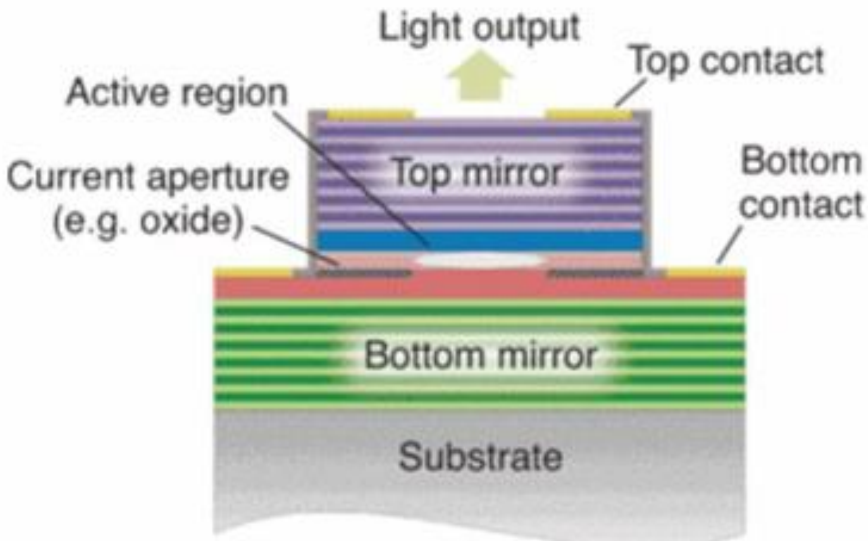
Basic stripe geometry edge-emitter

- Stimulated emission at junction
- Fabry-Perot resonator
- Waveguide in junction plane
- ~5 x ~0.5 μm stripe
- Single lateral mode
- Large beam divergence
- Complex internal structure



VCSEL (top emitter)

- Many variations
- Bragg reflectors
  - One output coupler
    - High reflectivity ~ 99.5%
  - One near-total reflector
  - Cavity length ~8 μm
    - DBR mirrors have depth
- Contacts out of beam path
- Current guiding structures
- Substrate
- Wide area output
  - Symmetrical beam
  - Less divergent than edge emitter



Edge emitter vs. VCSEL output

Edge Emitter

- Moderate threshold
- Larger active volume
  - Higher power
  - Efficiency to 60% commercial
    - to 71% R&D
- Small thin emitting area
  - Large divergence
  - Limits beam quality
  - Multiple emitters combine
- Long cavity (100s μm)
  - Multi longitudinal modes
  - DFB or DBR for singlemode
    - Single emitter

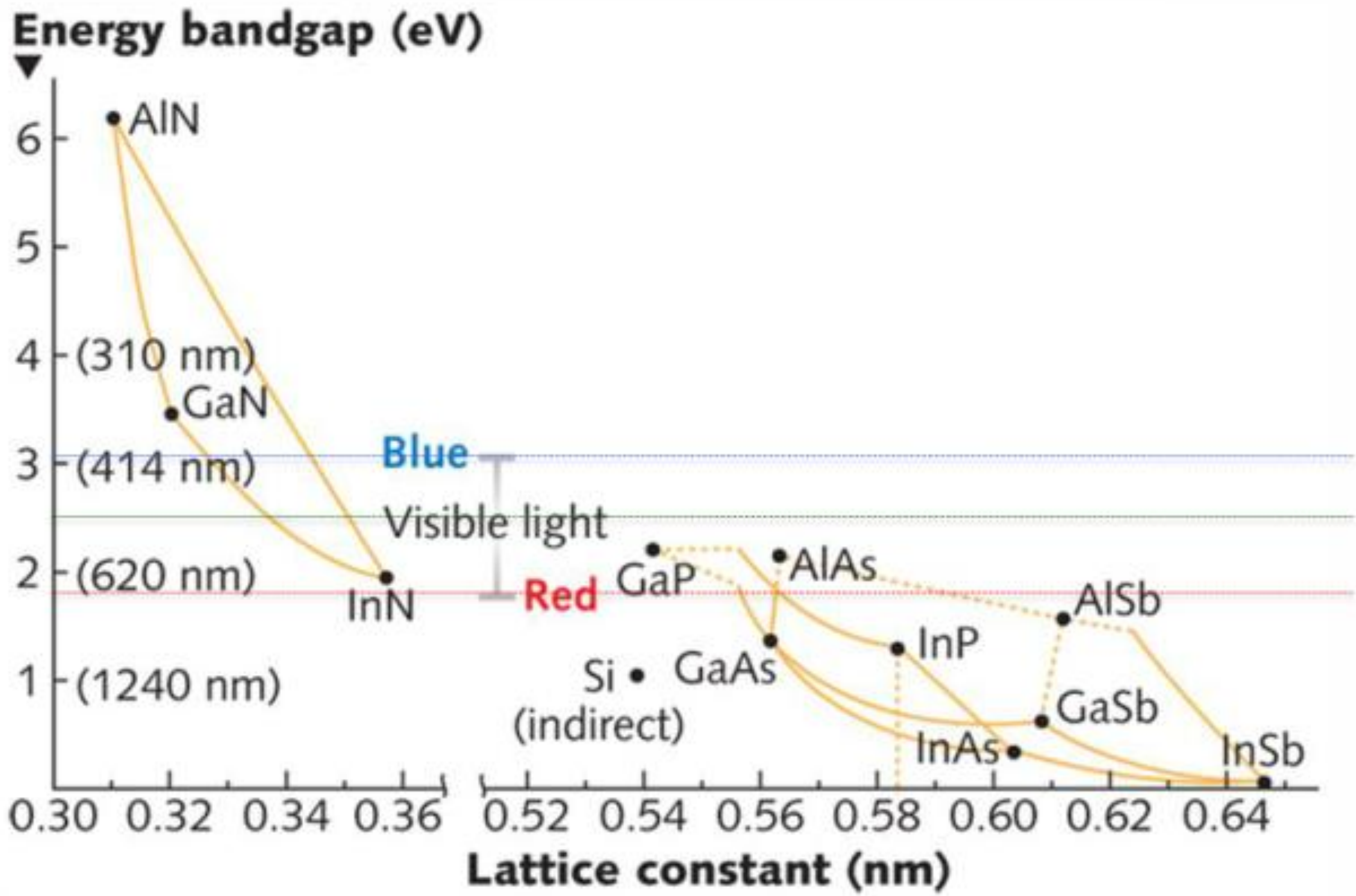
VCSEL

- Very low threshold
- Small active volume
  - Efficiency ~ 15% commercial
    - R&D to 56%
- Circular emitting area
  - 2-100 μm per VCSEL
  - Better beam quality
- Short cavity (~ 10 μm)
  - Single longitudinal mode in gain band
  - Stable wavelength
  - Narrow linewidth
  - Long coherence length possible
    - Single emitter

Diode laser wavelength

- Gain depends on active-layer bandgap
  - III-V semiconductors (ternary or quaternary)
  - Direct bandgap required for lasing
  - Limited range available
- Lattice matching requirement
  - Added layers match binary substrate
  - Strained layers ease requirements
- Cavity selects wavelength
  - Singlemode, DFB, multimode, tunable
  - Edge-emitting can be multi longitudinal mode
  - VCSEL cavity short, narrow-line

Bandgap/lattice constant III-V



Emission ranges of diodes

Material/substrate	Wavelength or range	Status
AlGaN/GaN	230-350 nm	Developmental
InGaN/(GaN or other)	360-525 nm (UV-green)	Commercial
AlGaInP/GaAs	625-700 nm (red)	Commercial
GaAlAs/GaAs	750-900 nm (near-IR)	Commercial
InGaAs/GaAs	915-1050 nm (near-IR)	Commercial
InGaAsP/InP	1100-1650 nm	Commercial
InGaAsSb/GaSb	1870-3300 nm	Comm/Developmental
Lead salts	2.7-30 µm	Cryogenic
Many others		R&D

Diode laser wavelengths and power levels

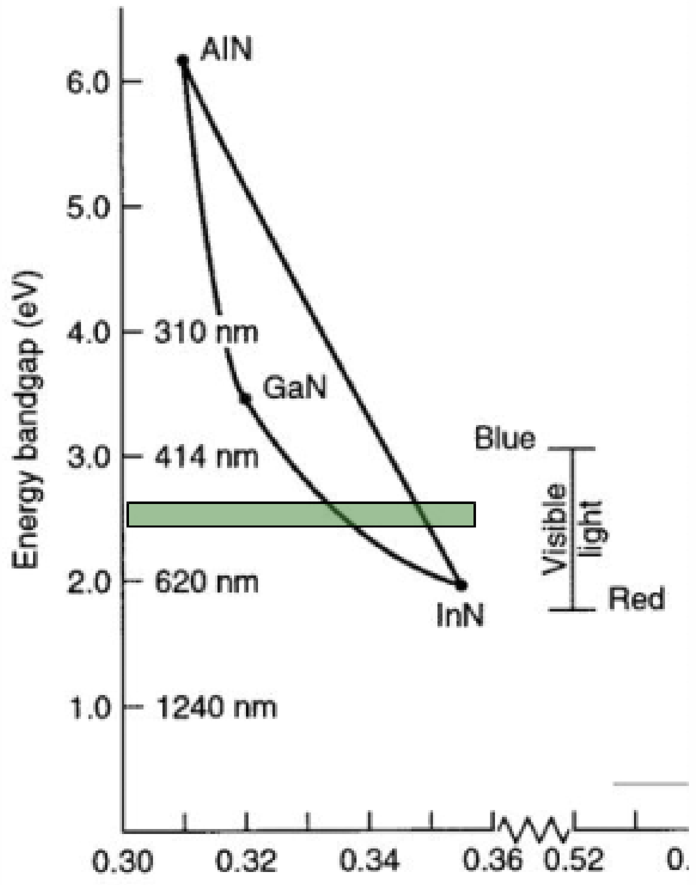
- Highest power
  - GaAlAs/GaAs 750-900 nm
    - 808 nm for Nd pumping
  - InGaAs/GaAs 915-1050 nm
    - 915-980 nm for Yb, Er fiber-laser pumping
- Respectable but not as high-power
  - GaInN - 350-488 nm (blue-UV)
  - GaInN green – lower power, 489-525 nm
  - AlGaInP/GaAs - 625-680 nm
  - InGaAsP/InP - 1100-1650 nm
  - (AlGaIn)(AsSb)/GaSb - 1850-2400 nm 1 W range

UV and blue diode lasers

- Shuji Nakamura breakthrough 1990s
- GaInN diodes
  - Increasing indium increases wavelength
- Sweet spot in violet-blue
  - 405 nm for Blu-ray disks (violet)
    - Maximum CW power ~ 10 W multimode
  - 445 nm blue lasers – up to 15-20 W
  - 460 nm for blue LEDs and LED lighting
- Increasing indium concentration causes problems in green

Green diode lasers

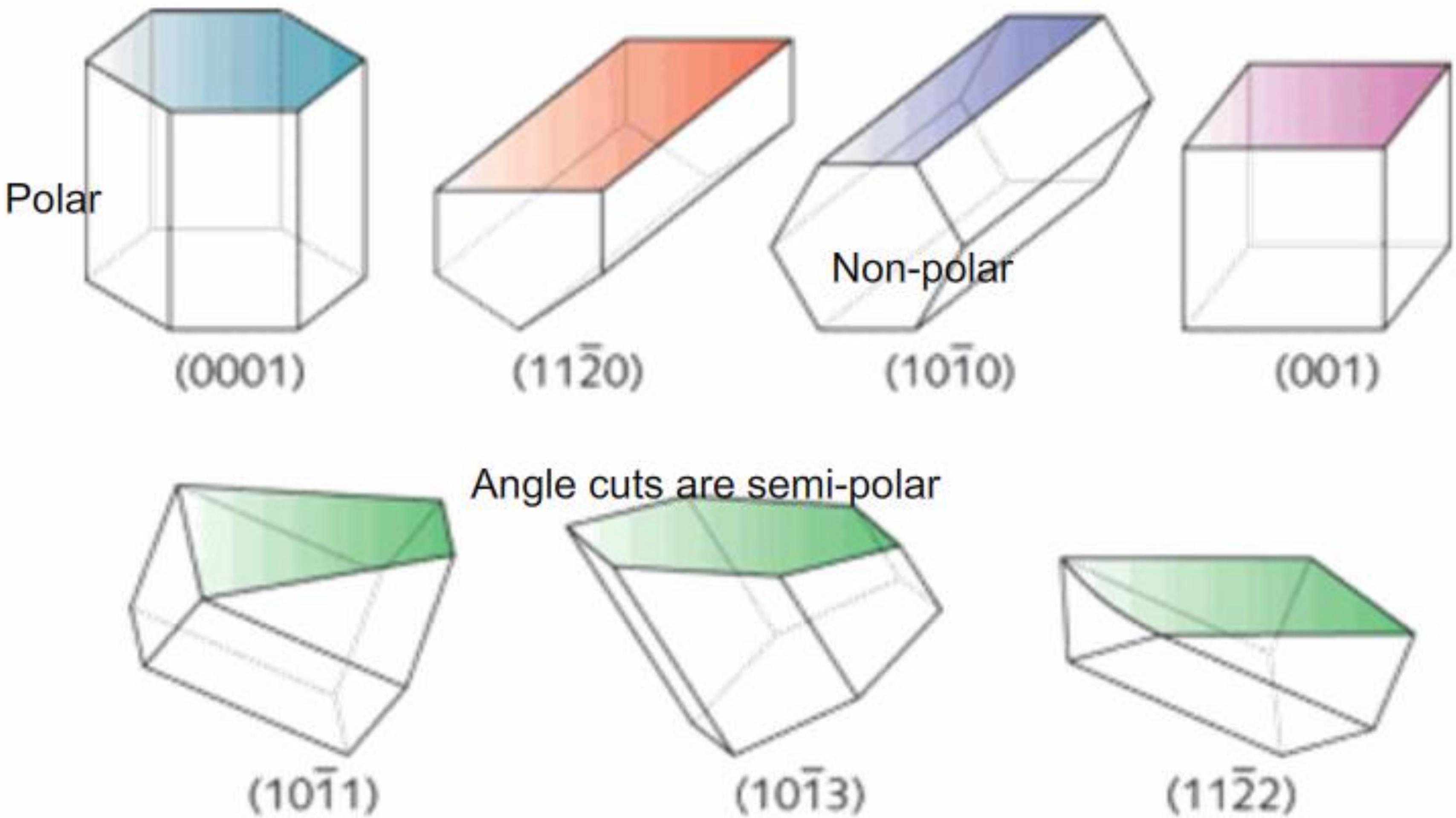
- III-V materials
  - InGaN on GaN
  - Modified blue diodes
  - Increasing indium increases wavelength
  - Room-T operation
- II-VI diodes
  - ZnSe et al



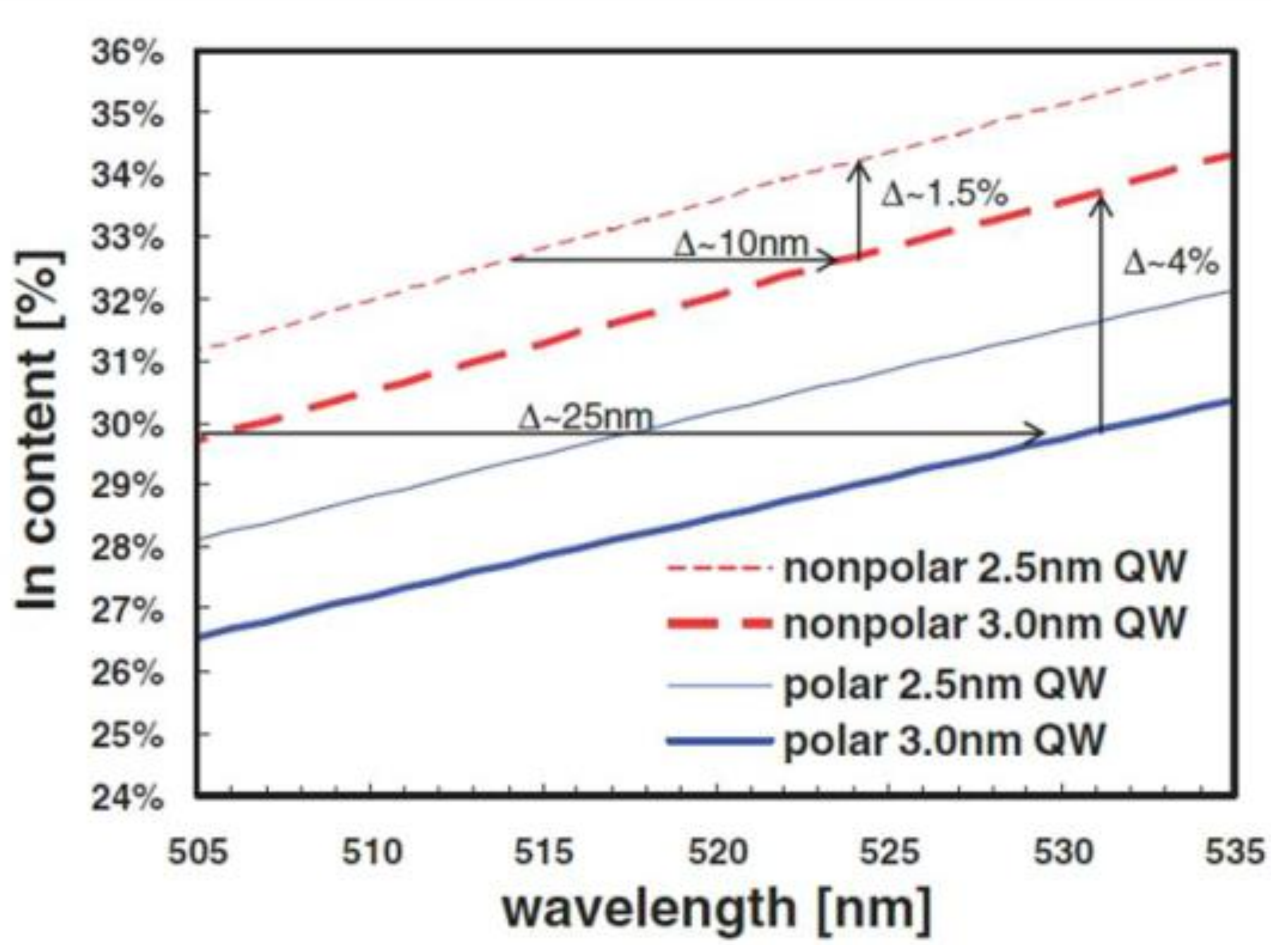
III-V nitride semiconductors

- Blue diode lasers a brilliant success
  - GaInN compounds on GaN
  - Jumped to short end of visible spectrum
    - 405 nm for Blu-Ray
  - Adding indium gives shorter wavelengths
  - Earlier designs limited to 15% indium
    - Longest wavelength around 488 nm
    - More indium increased defect problems
- $Ga_{0.7}In_{0.3}N$ band gap at 520-530 nm
  - New growth techniques in development
  - Key issue is crystal substrate orientation

GaN crystallography



Wavelength variation with composition



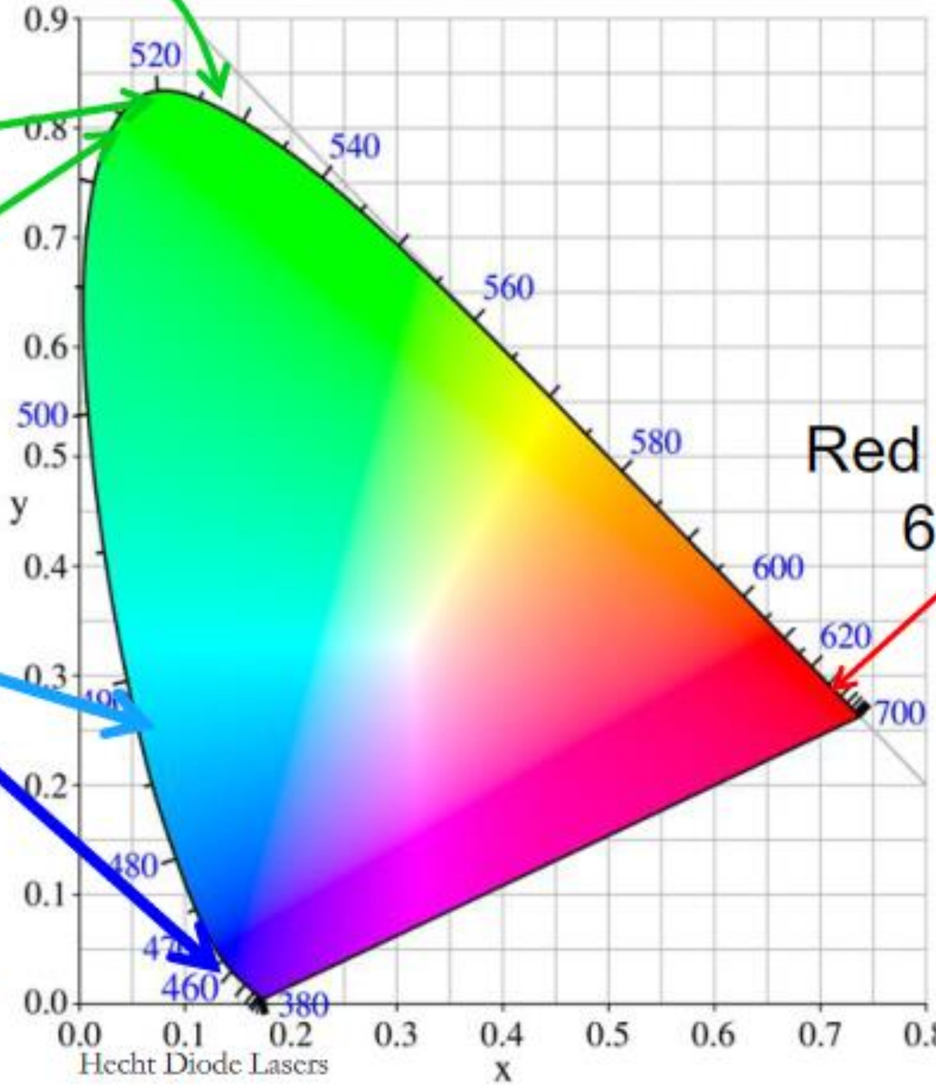
Osram art

State of the art in green diodes

- 515-520 nm laser diodes commercial
  - Commercial to circa 100 mW
- Nichia claims 1 W at 525 nm
- Longer wavelengths in development
- Pulsed operation to 535 nm
- Large diode laser gap in yellow and orange
- Developmental issues
  - Longer wavelengths
  - Lifetimes, power, material quality, efficiency
  - Manufacturing

Laser wavelength and color

- Green 525 nm
- 520 nm
- Commercial
  - 515 nm
- Blue diodes
  - 445, 488 nm



Red diodes
635 nm

Wikipedia art

Laser wavelength and color

- Green 525 nm
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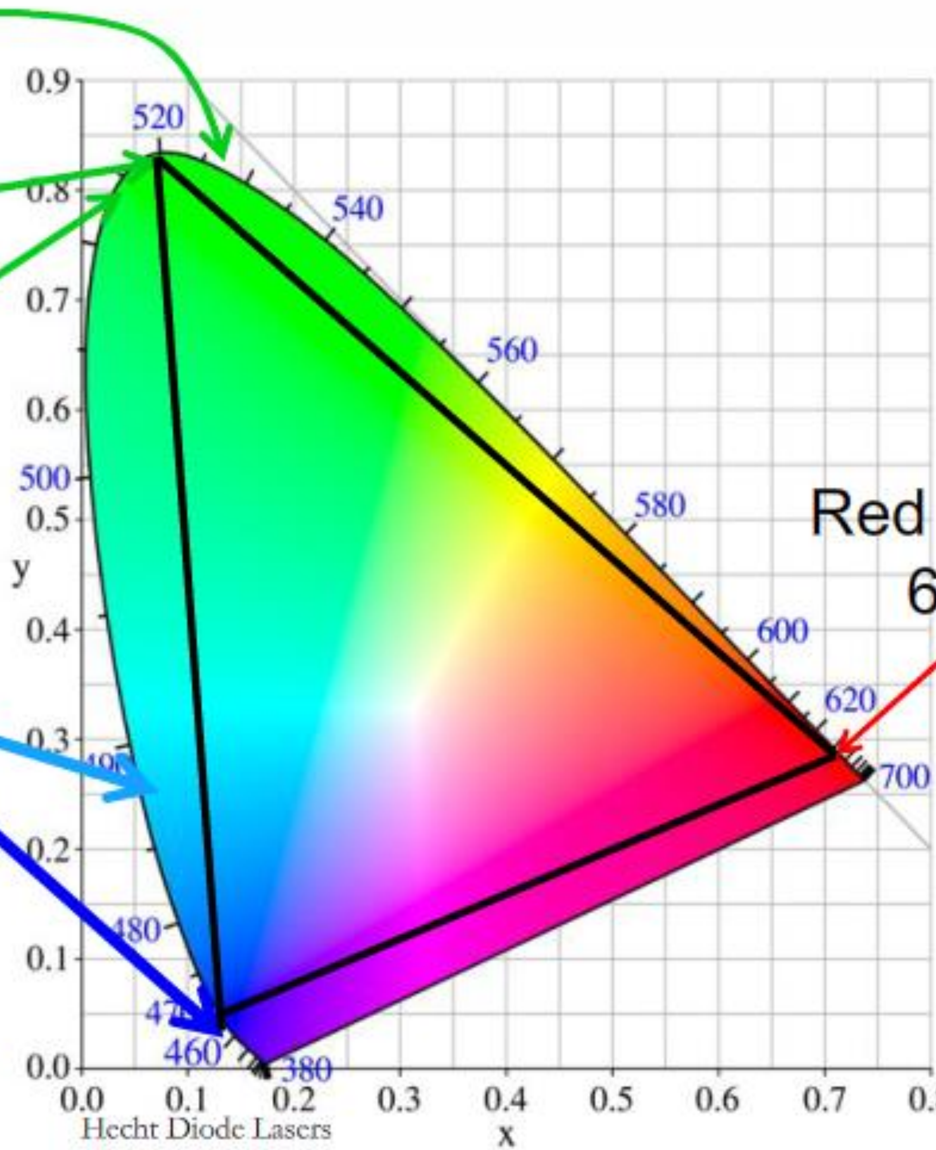


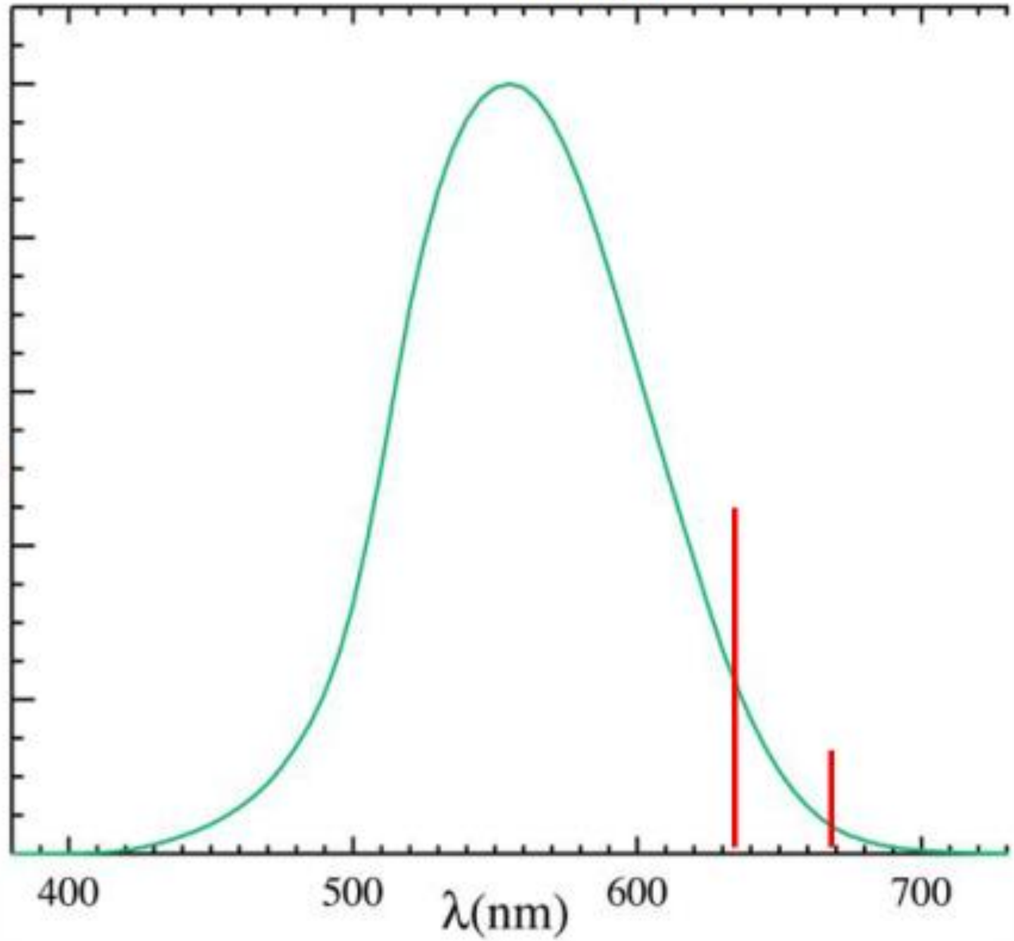
Red diodes
635 nm

Wikipedia art

Red diode lasers

- First at 670 nm
  - $Ga_{0.5}In_{0.5}P/GaAs$
- $Al_yGa_xIn_{1-x-y}P/GaAs$
  - Usually 635 nm
    - More visible
  - 625-700 nm
  - Singlemode to 150 mW
- Uses
  - DVD (650 nm)
  - Pointers (635 nm)
  - Scanners (635 nm)
    - He-Ne replacement
  - Instruments

Photopic vision
Wikipedia



GaAlAs diode lasers

- First diode lasers
- First room-T diodes
- 750-904 nm
- Al concentration
  - Decreases wavelength
  - Limits lifetime
- Easily lattice matched to GaAs
- Scalable to high power
- CD players 780 nm
- 808 nm Nd pumps
- 850 nm data links
- High-power uses
- VCSELs

InGaAs/GaAs

- 915-1050 nm
- High power
- High efficiency
- In increases wavelength
- Strained layers as In increases

- Pump lasers
  - 915 nm Yb-fiber
  - 940 nm Er, Yb
  - 980 nm Er-fiber
- Direct diode applications

InGaAsP/InP diodes

- First quaternary diodes
- 1100-1650 nm range
- Developed for fiber-optic applications
  - 1300 nm window
  - 1480-1650 nm window
- Moderate power
- Mainly fiber communications
- Narrow-line WDM
- Tunable lasers

Antimonide diode lasers

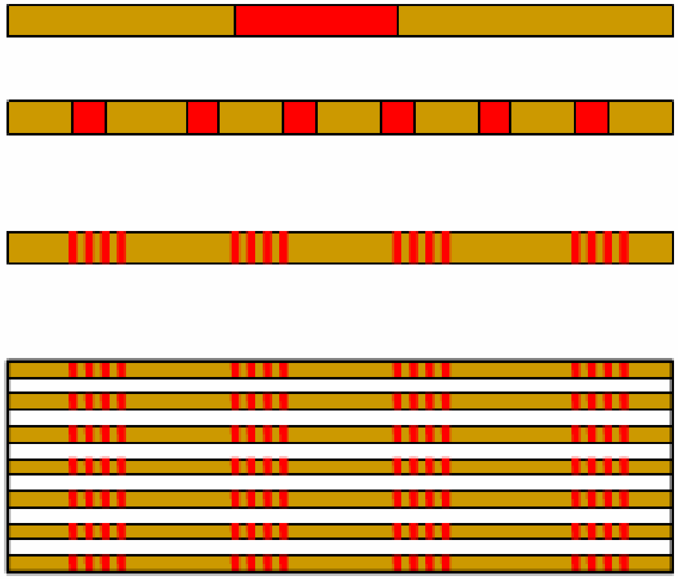
- AlGaAsSb/GaSb
  - 1.55-1.8 µm
  - First for long-wave fiber systems
- GaInAsSb/GaSb
  - 1.7-3.7 µm CW room T
    - 1.8-2.5 µm commercial
  - Longer wave cooled
- Applications being investigated
  - Plastic materials working
  - Mid-IR sensing
  - Laser pumping
- Important spectral gap

High power diode lasers

- Edge Emitters
- Make individual diodes bigger
  - Wide-area lasers
    - Wide stripe lasers
    - Tapered stripes
- Oscillator amplifiers
- Grouping many lasers together raises power
  - Multistripe monolithic laser array
  - Multiple arrays in linear bar
  - Stacks of multiple arrays
  - Terminology may vary

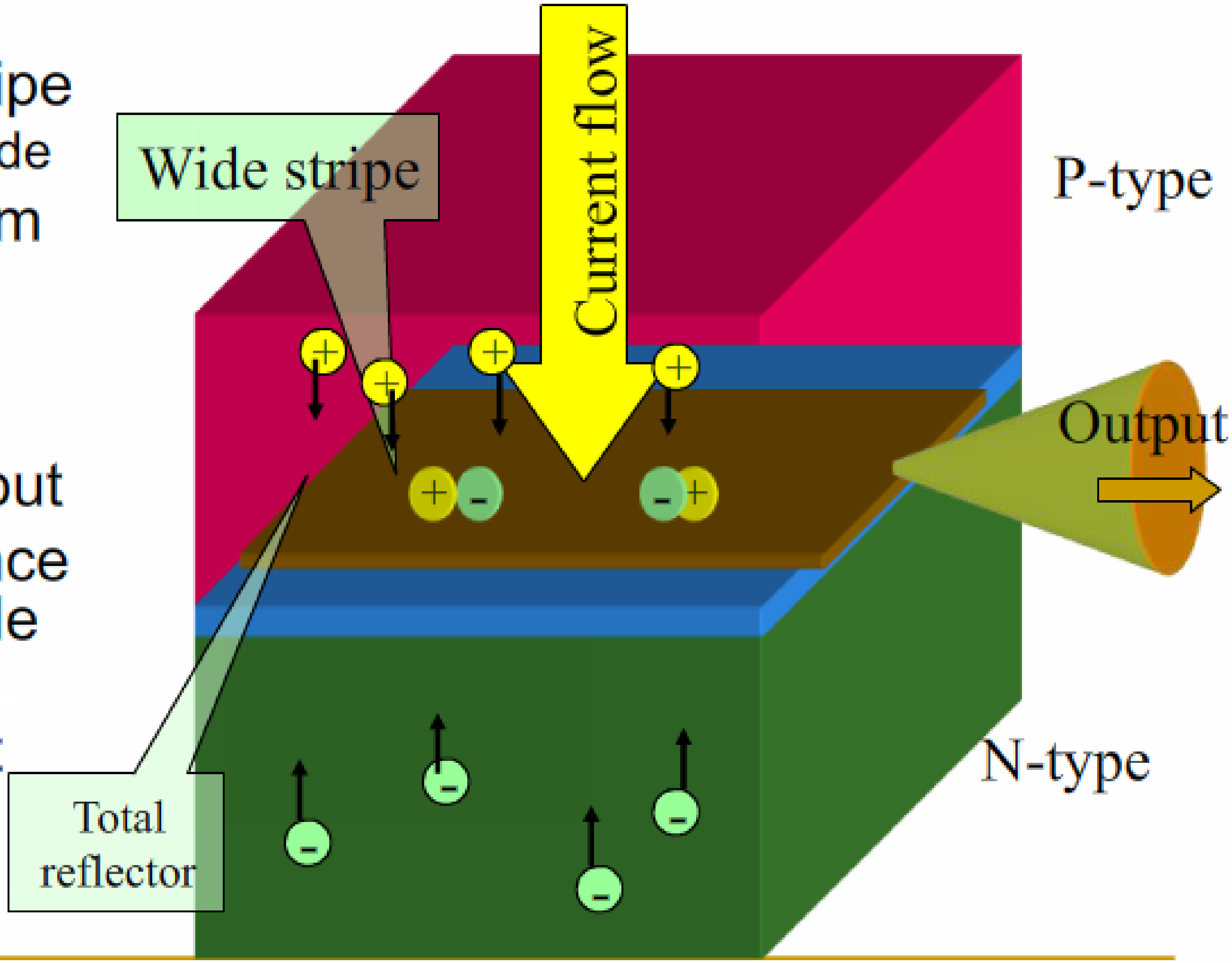
Types of High-Power Edge Emitters

- Wide stripe
  - Also tapered
- Array of stripes
  - Wide or narrow
- Bar - monolithic series of arrays
- Stack of bars
- Pulsed, QCW or CW
- May require cooling
- Spacing may vary

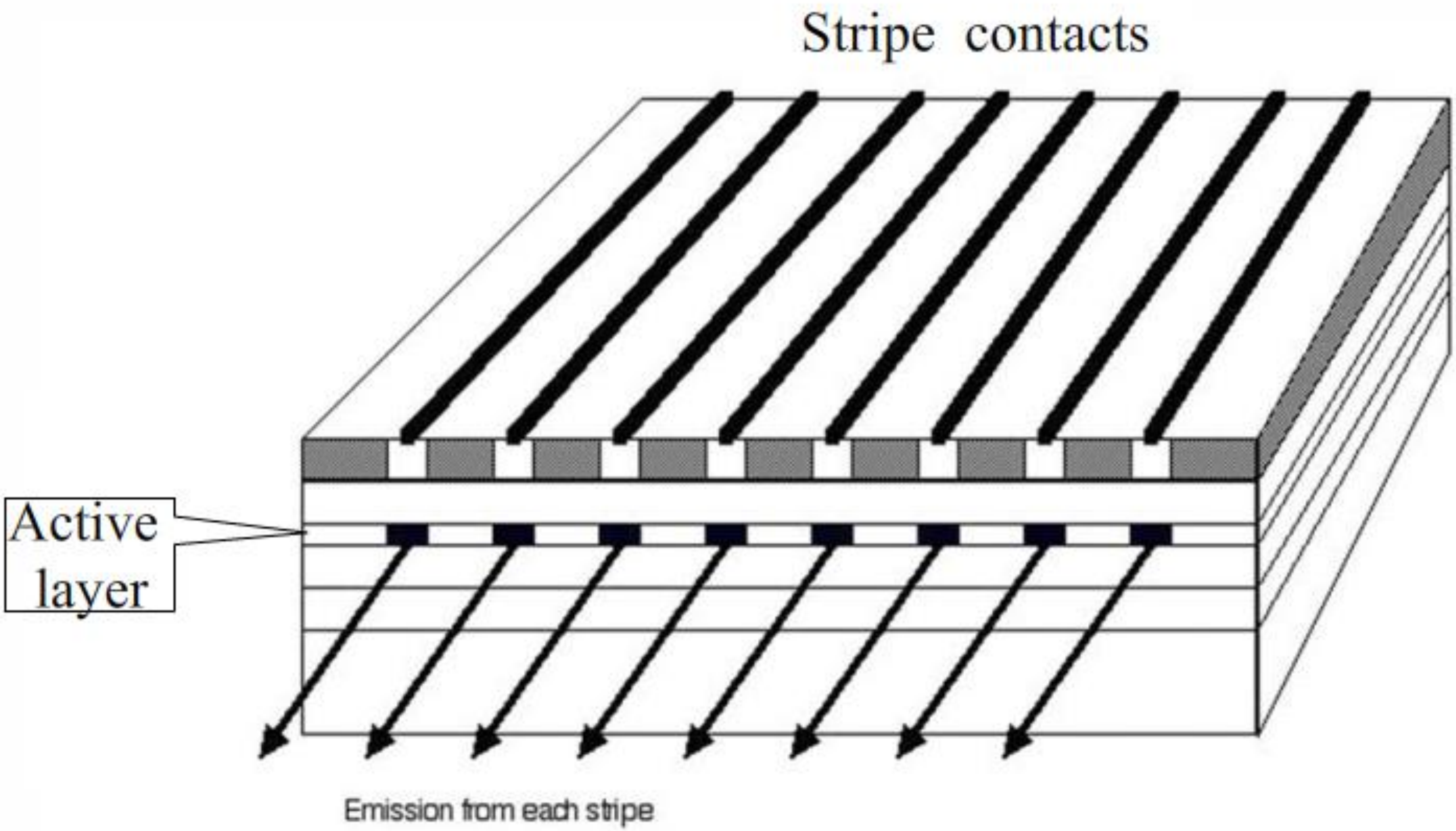


Wide-stripe edge-emitter

- Broad laser stripe
  - 100-200 μm wide
- High power from single aperture
- Emission from wide area
- Multimode output
- Beam divergence reduced by wide stripe
- Watts of output
- Good for fiber laser pumping

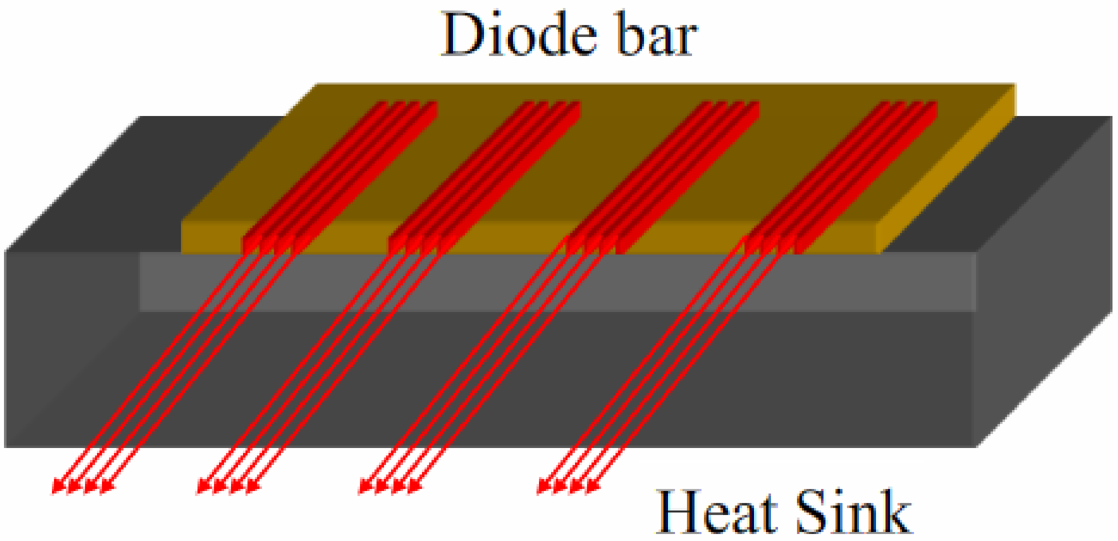


Monolithic edge-emitting diode array



Diode Laser Bar

- Multistripe arrays
- Spaced uniformly
- Mounted on heat sink
- Outputs spread and merge
- Beam quality issues



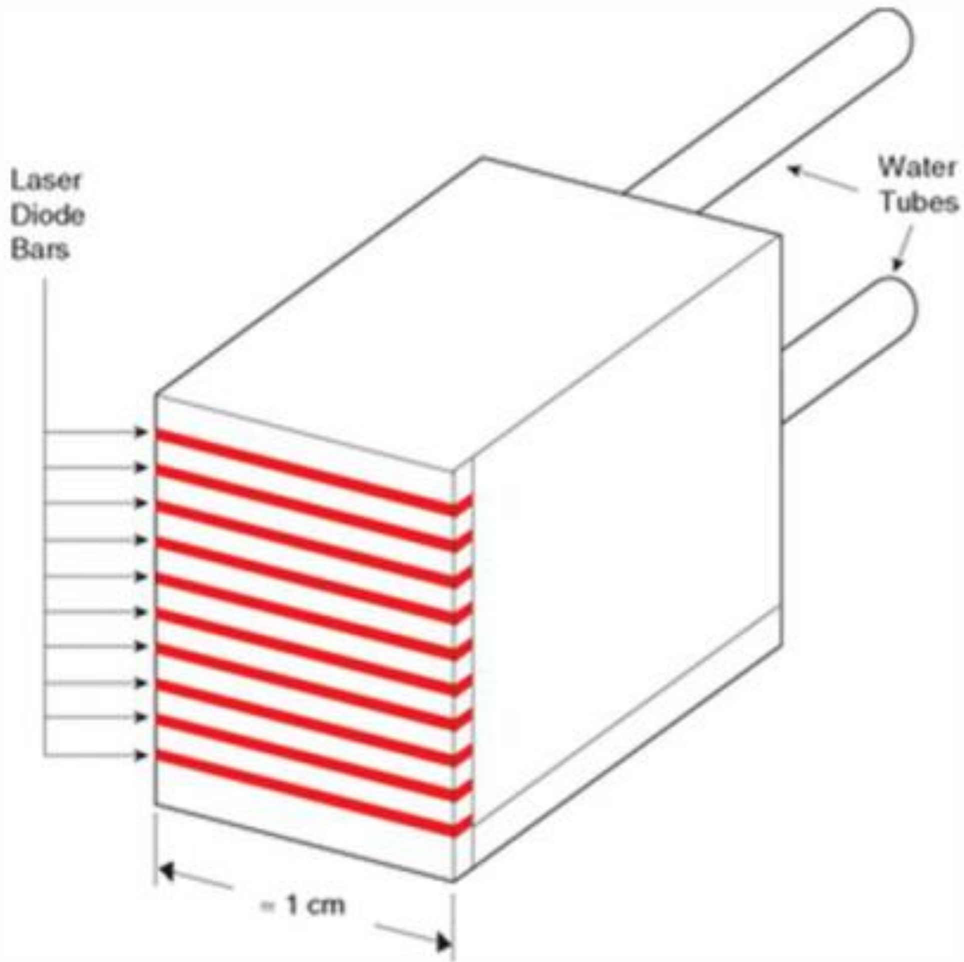
Stacked bar schematic

Bars ~ 1 cm wide

Space between bars

Liquid cooled

Kilowatt-class power possible



Newport illustration

Bar and stack performance

- **Good News**
- High power – to kWs
- High efficiency - 50%+
  - Laboratory results best
- Pulsed, QCW or CW
- Room temperature
- Long lived
  - 20,000 hours, with care
- Reasonable cost
  - For laser sources

- **Potential Issues**
- Cooling required
  - Heat in small volume
- Very low coherence
- Poor beam quality
  - Low brightness
  - Beam combination?
- Large emitting area
  - Long, thin from bars
  - Wide area from stacks
  - Fiber coupling

Power levels

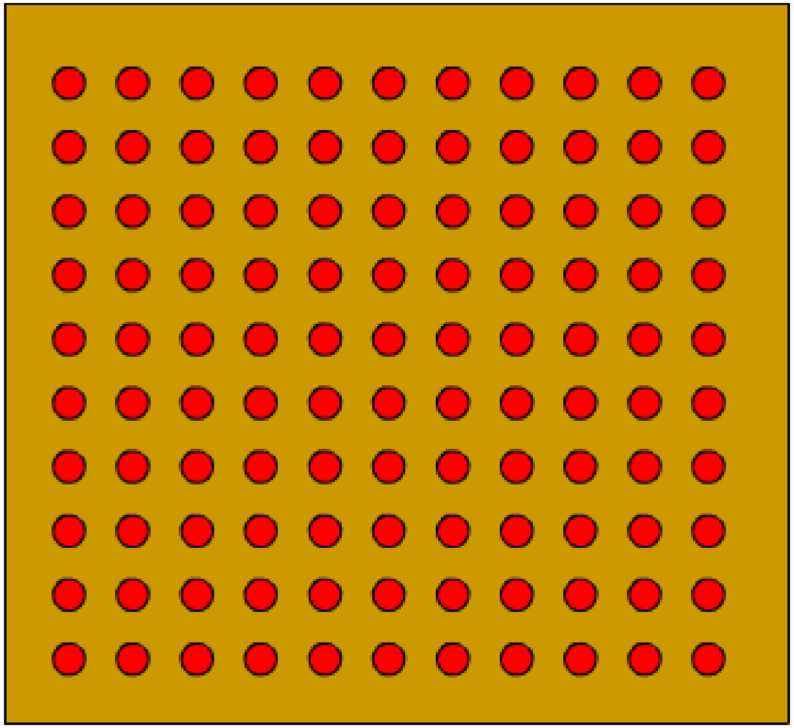
- Top powers for InGaAs and GaAlAs
- Individual lasers - watts to >10 W
  - Wide stripe or tapered
  - Fiber coupling possible
- Bars - 10s of watts up
- Stacks 100s of watts to kilowatts
- Quasi-CW gives higher powers
  - Specifications for peak power, not average
  - Duty cycle ~ 10% - 50%

High-power diode applications

- Diode pumping
  - Solid-state lasers
  - Fiber lasers and amplifiers
  - Optically pumped semiconductor lasers
- Direct diode industrial applications
  - Broad area applications – heat treating
  - Moderate intensity - Soldering
- Need for brighter beams
  - High brightness applications – cutting

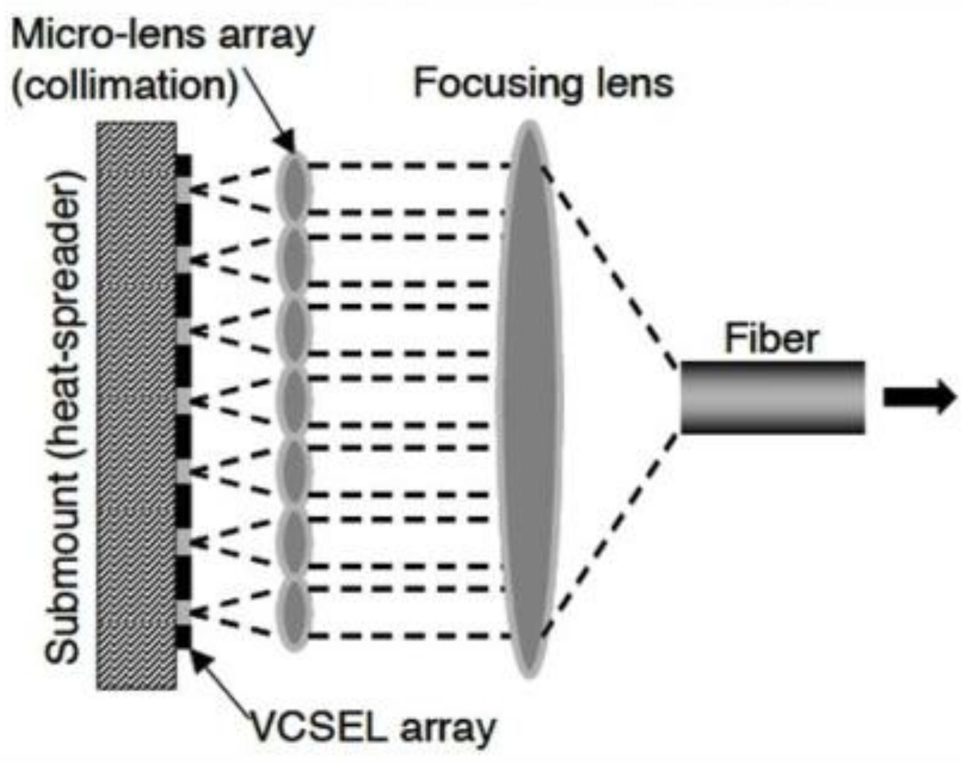
VCSEL Arrays offer higher power

- Single VCSEL power mW range
  - Limited by active volume
- Arrays of several hundred elements
  - Tens of watts
- Larger arrays, higher power



High brightness VCSEL array

- For coupling into optical fiber
- Thousands of singlemode emitters in array
- 976 nm
- Output from 400-µm, 0.46 NA fiber was 40 W

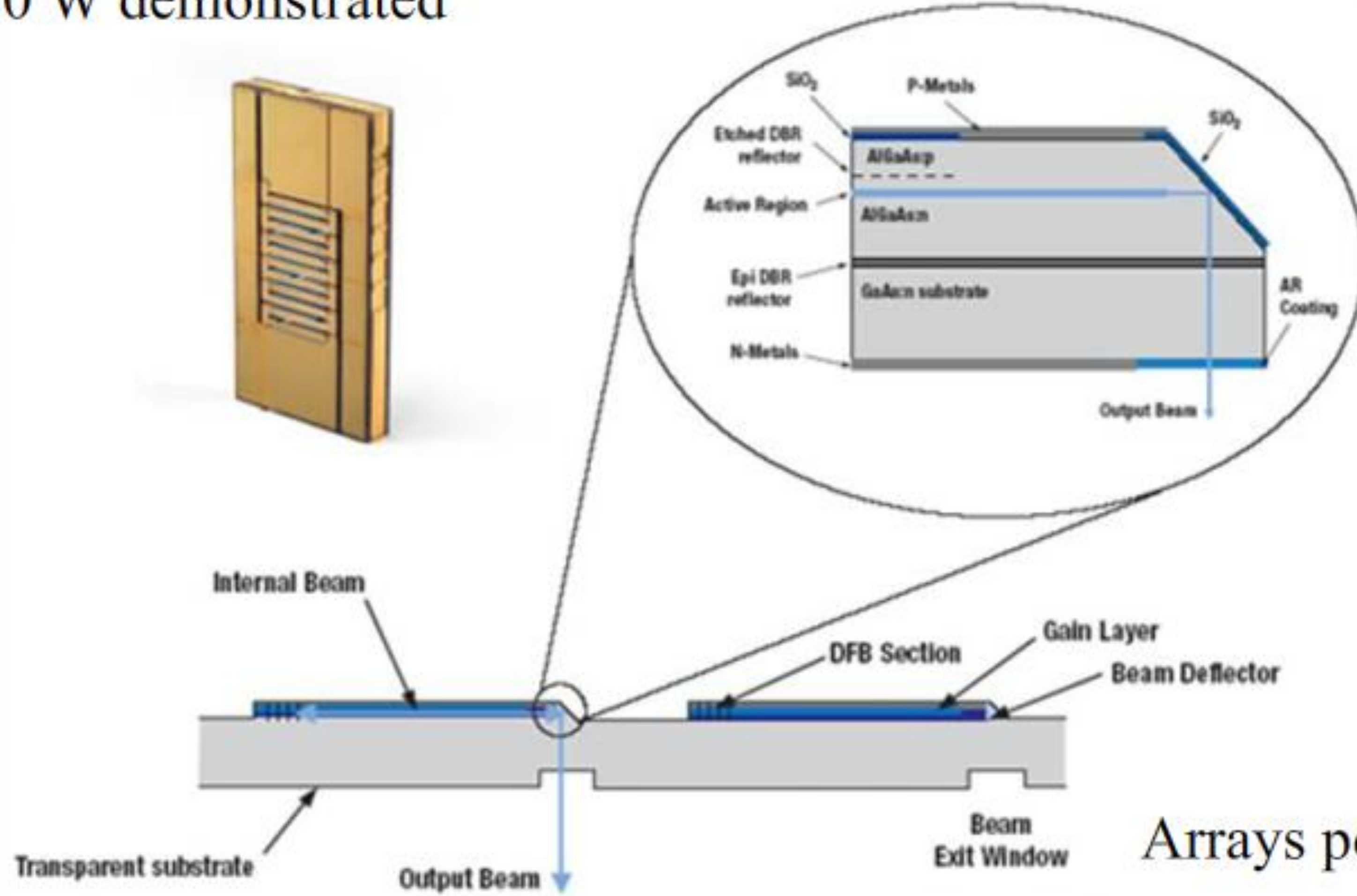


Princeton Optronics art

High-power surface emitting lasers

>250 W demonstrated

Horizontal cavity with 45° mirror

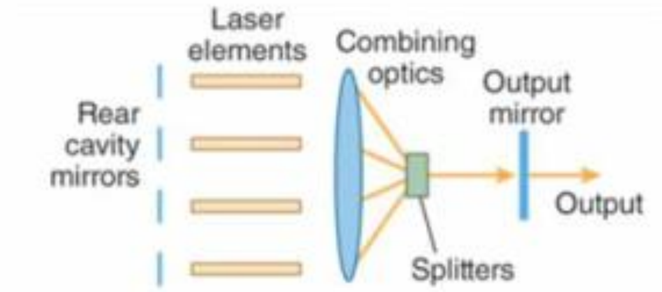


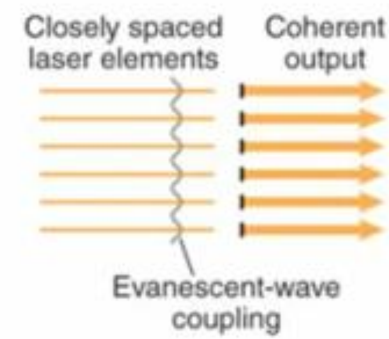
Arrays possible

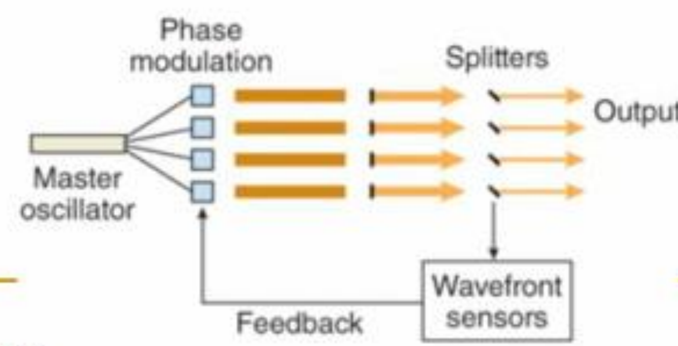
QPC Lasers

Coherent Beam Combination

- Phase matching multiple outputs
  - Oscillation in parallel cavities
  - Evanescent-wave coupling
  - MOPA configuration with phase adjustment among multiple cavities
- Tiled or shared aperture
- Pure optics difficult
- Electro-optical feedback loop may be easier



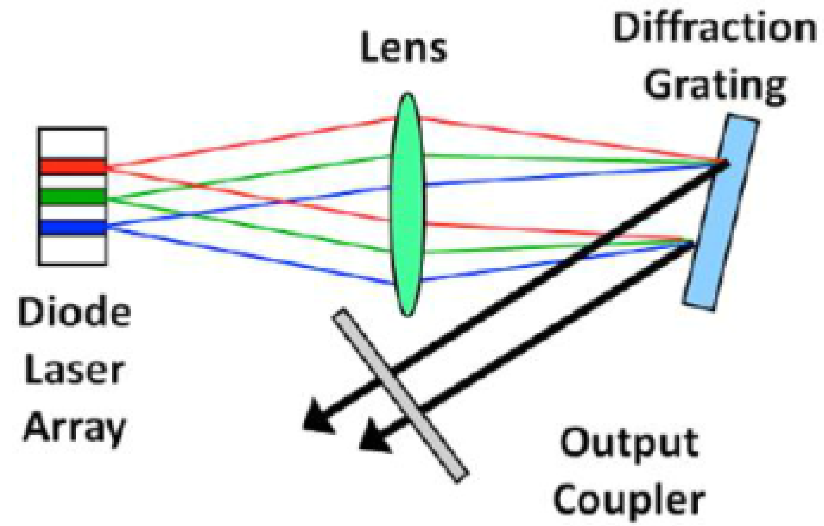




July 2008 LFW article

Spectral Beam Combination

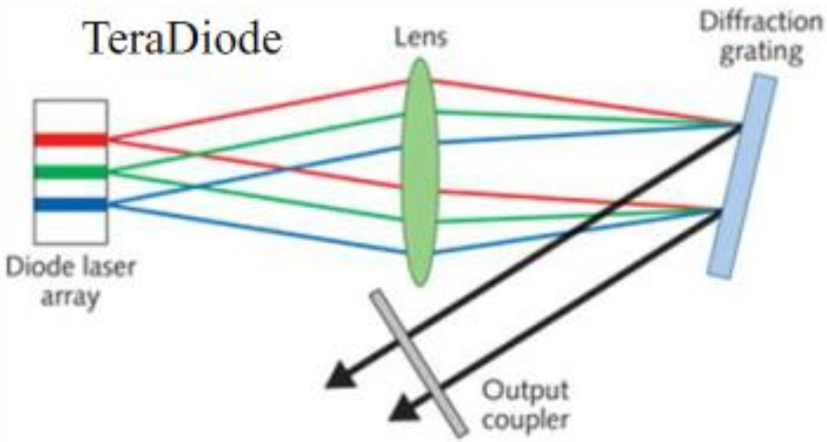
- Input beams at different wavelengths
- Multiplexed into system
- Can be dropped in through filters
- Through space or fiber
- Don't interfere because wavelengths differ

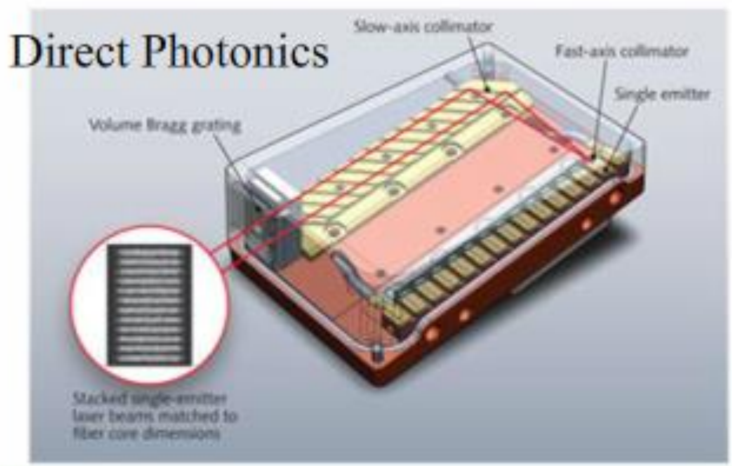


TeraDiode art

Spectral beam combination

- TeraDiode
  - Center 970 nm
  - 30 nm range
  - 2 kW from 100-µm fiber
- Direct Photonics
  - Optically stacks 12 emitters spatially
  - Stacks 4 wavelengths @ 2.5 nm intervals
  - 2 kW total output
- 30-40% efficiency

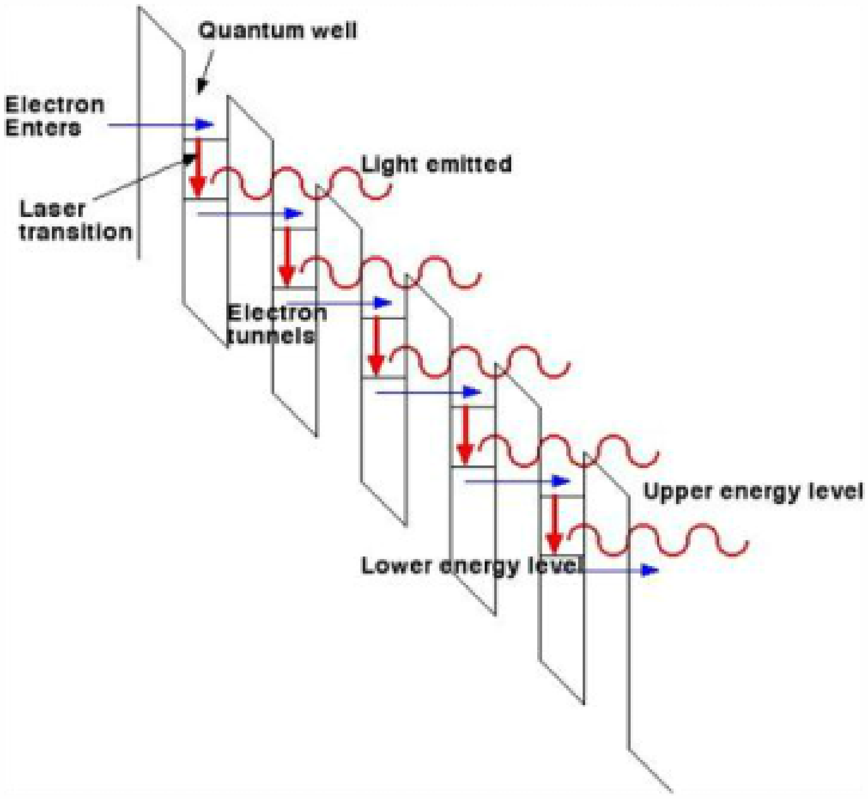




Semiconductors but not diodes

Quantum Cascade Laser

- Non-polar semiconductor
- No recombination
- Electrons flow through series of quantum wells
  - Emitting photon each time
  - Quantum well determines wavelength
- Wavelengths ~3 µm to THz

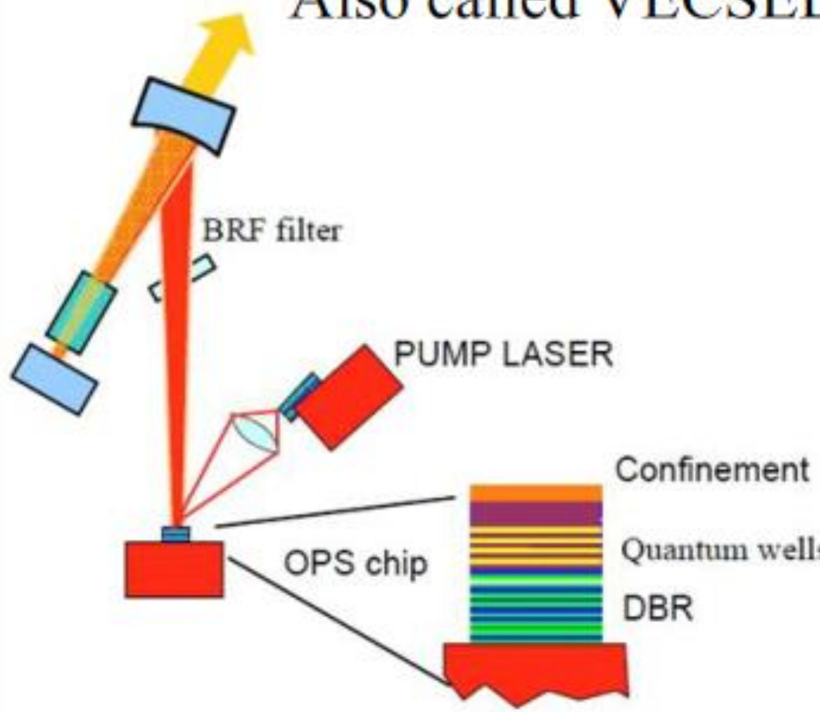


Semiconductors but not diodes

- Uses GaAs, other III-Vs
- Bragg reflector on bottom of device
- External cavity
  - Output coupler separate
- Individual devices tunable 15-180 nm
- Fundamental output wavelengths
  - 670 nm to 2.2 μm
- Harmonic generation 244-620 nm
- Big power advantage over VCSELs

Optically Pumped Semiconductor Laser

Also called VECSEL



Coherent art

Outlook: diode lasers

Attractions

- Very wide range of technology
  - Well established industry for III-V materials
  - Low power to high power
  - Synergy with LEDs
- High electrical efficiency
- Compact
- Low cost for lower power
- Cheap laser photons at high power

Development needs

- Fill wavelength gaps
  - Yellow, orange, deep UV
  - Better green lasers
  - Longer IR wavelengths
  - New materials
- Brighter beams
  - Better beam quality
  - Beam combination
- Cost reductions for high-power laser pumps
- Non-GaAs VCSELs
- More power from other III-Vs