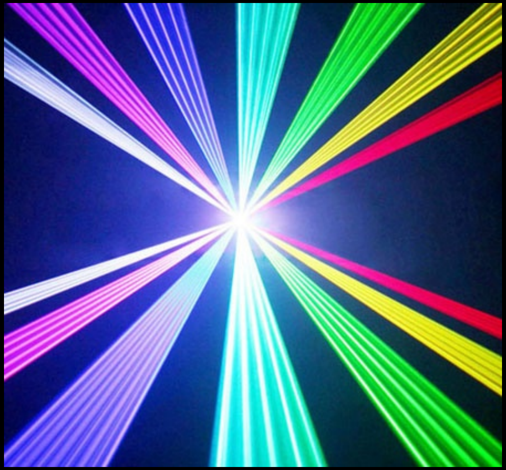
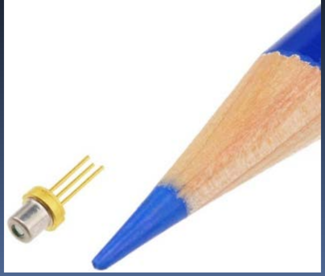
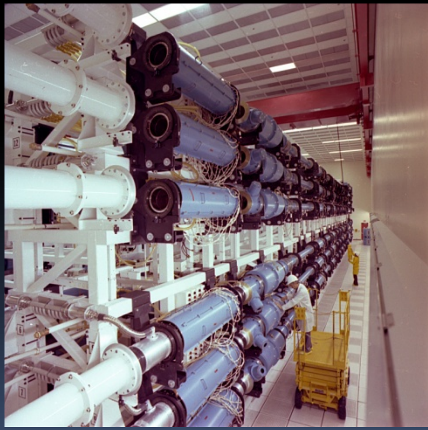


ECE 5368

LIGHT SOURCE: THE LASER P.2





Laser Primer

- Introduction
- Fundamentals of laser
- Types of lasers
- Semiconductor lasers

Laser Primer

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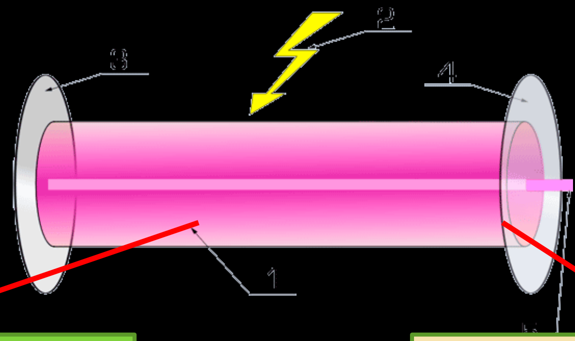
How many types of lasers?

Many many… depending on classification



Gain medium

- Materials
- Excitation and emission
- Pump control

Cavity structure

- Mode control (power)
- Wavelength control
- Integrated operation control

Example: Semiconductor single-mode tunable electroabsorption modulated laser

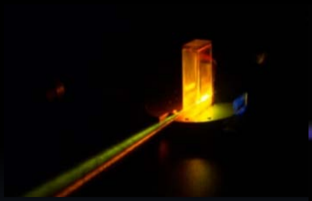
Media for optical amplification (and lasers)

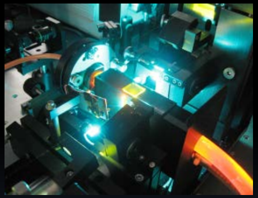
- Gas: atomic, molecular



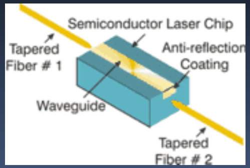


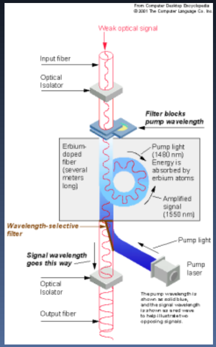
- Liquid: molecules, micro particles in a solution





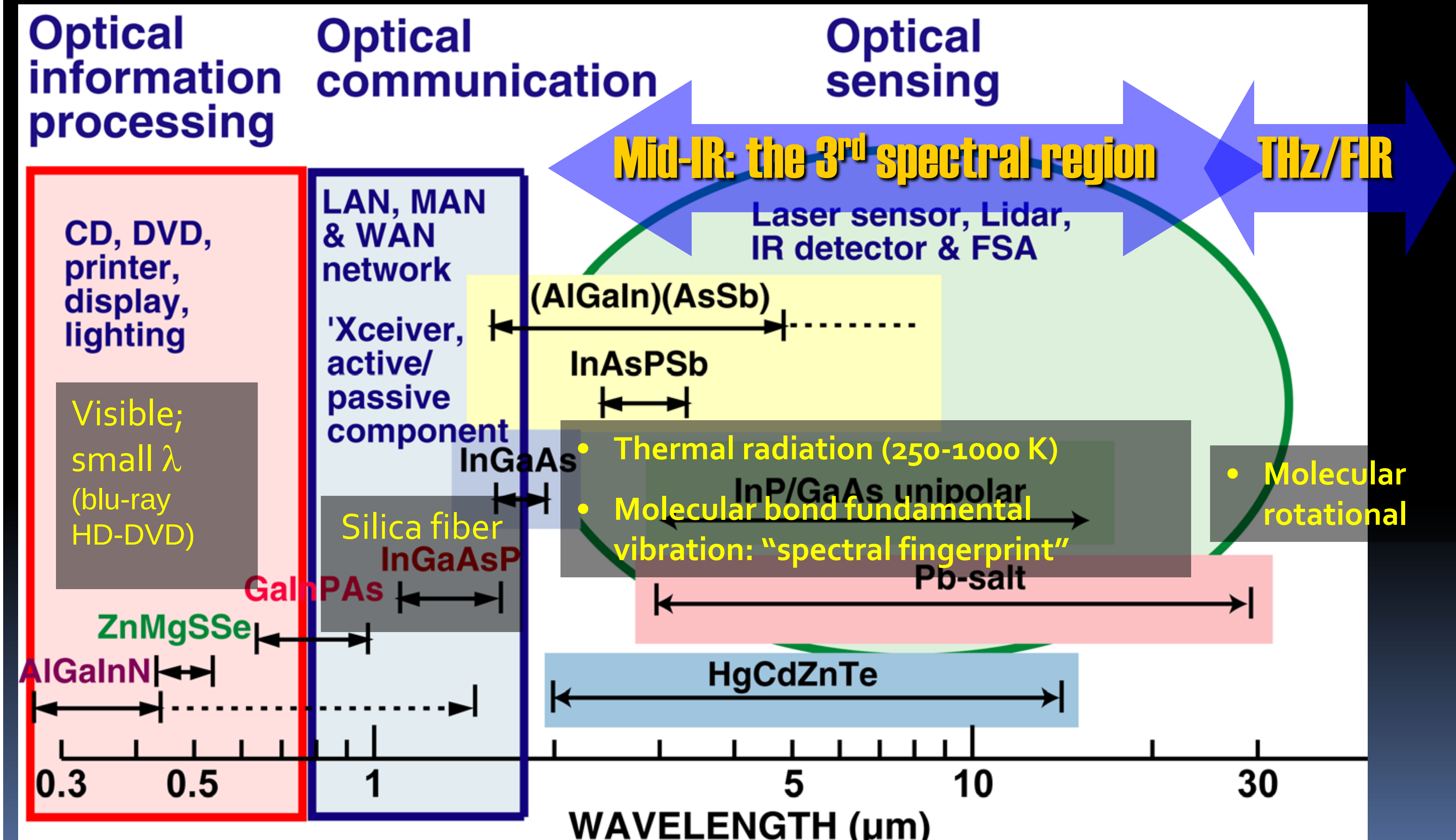
- Solid: semiconductor, doped materials (EDFA)



Semiconductor: A Primer

Semiconductor Photonics



Laser Primer

- Introduction
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- Types of lasers
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Semiconductor lasers

- Basic optical processes and electronic structure

Gain (loss) engineering :
- Materials: choice for wavelength range, e. g. 1.5 um – InGaAsP
- Structure: e. g. quantum wells

- Optical structure

Mode engineering :
- Waveguide design: planar, ridge
- Longitudinal mode control: e. g. DFB, tunable, multi-elements

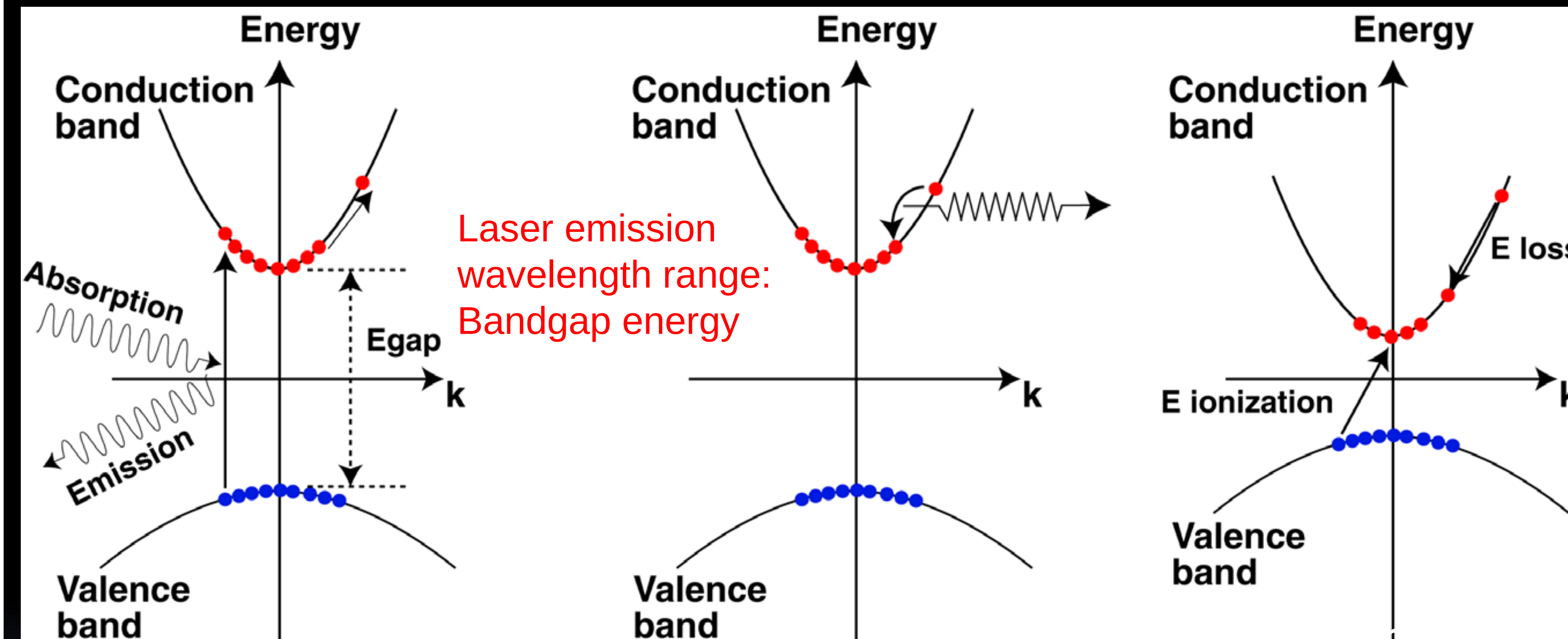
- Lasing mechanism

Operation:
- Threshold, power, efficiency
- Mode control: e. g. tunable, single-mode, side-mode suppression ratio

- Some common semiconductor lasers

Applications:
- Telecommunication
- Others: e. g. optical storage, sensing, spectroscopy imaging, …

Excitation and relaxation processes



Laser emission wavelength range: Bandgap energy

Momentum and energy conservation:

$$\mathbf{k}_e + \mathbf{k}_h = \mathbf{k}_{\text{photon}} \approx 0$$

$$E_e + E_h = E_{\text{photon}} = \hbar\omega$$

Momentum and energy conservation:

$$\mathbf{k}_{e\,\text{final}} + \mathbf{q}_{phonon} = \mathbf{k}_{e\,\text{init}}$$

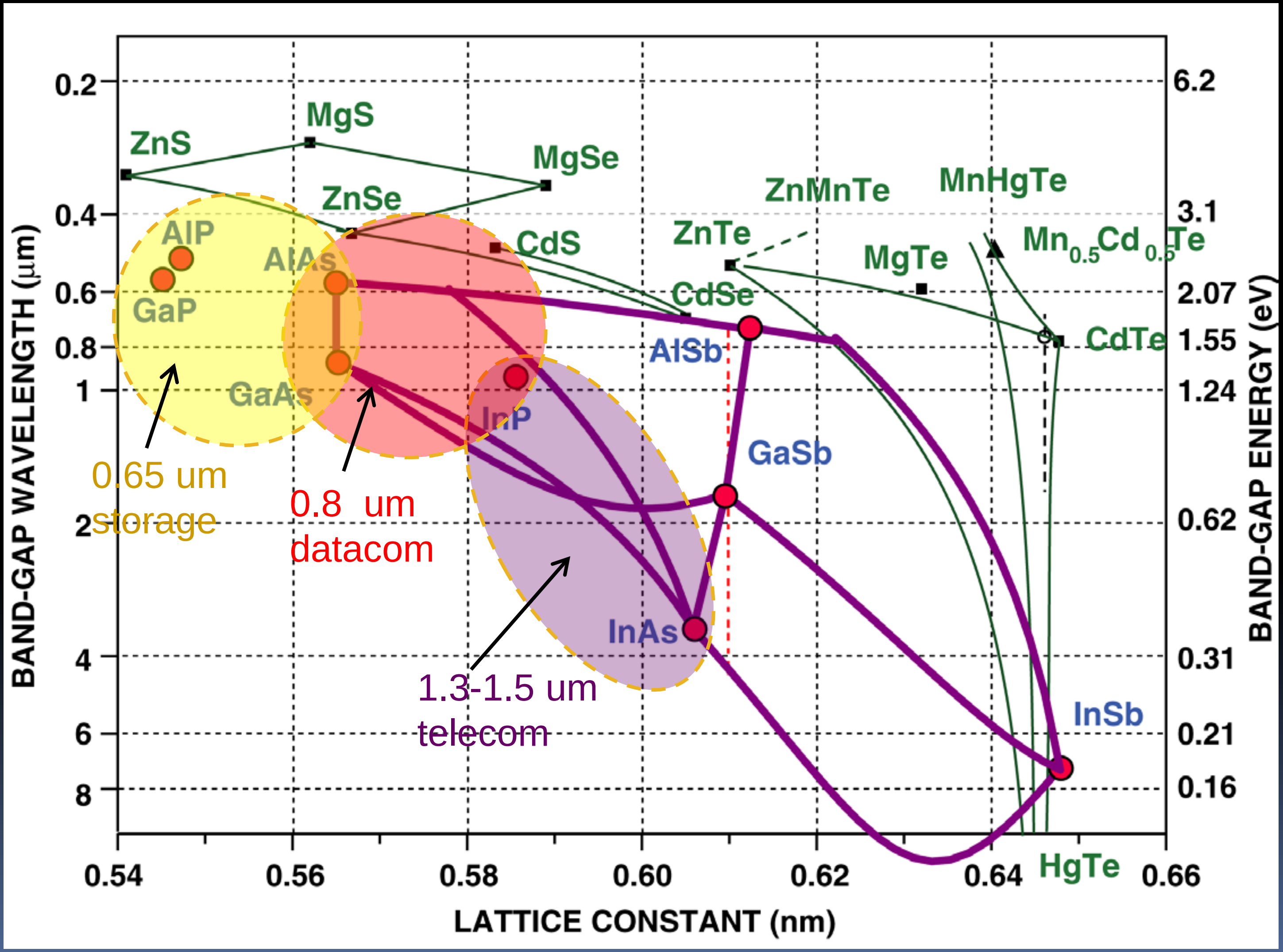
$$E_{e\,\text{final}} + E_{phonon} = E_{e\,\text{init}}$$

Momentum and energy conservation:

$$\mathbf{k}_{e2} + \mathbf{k}_h = \mathbf{k}_{e1\text{init}} - \mathbf{k}_{e1\text{final}}$$

$$E_{e2} + E_h = E_{e1\text{init}} - E_{e1\text{final}}$$

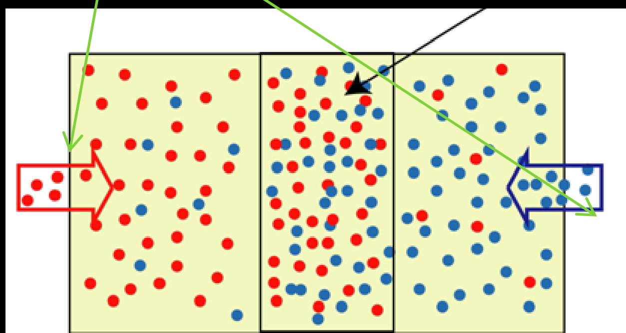
Common semiconductor bandgap energy vs. lattice constant

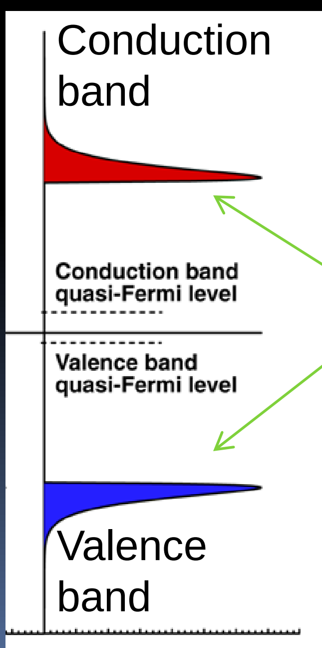


Design for the gain (active) region

Carrier injection

Active region

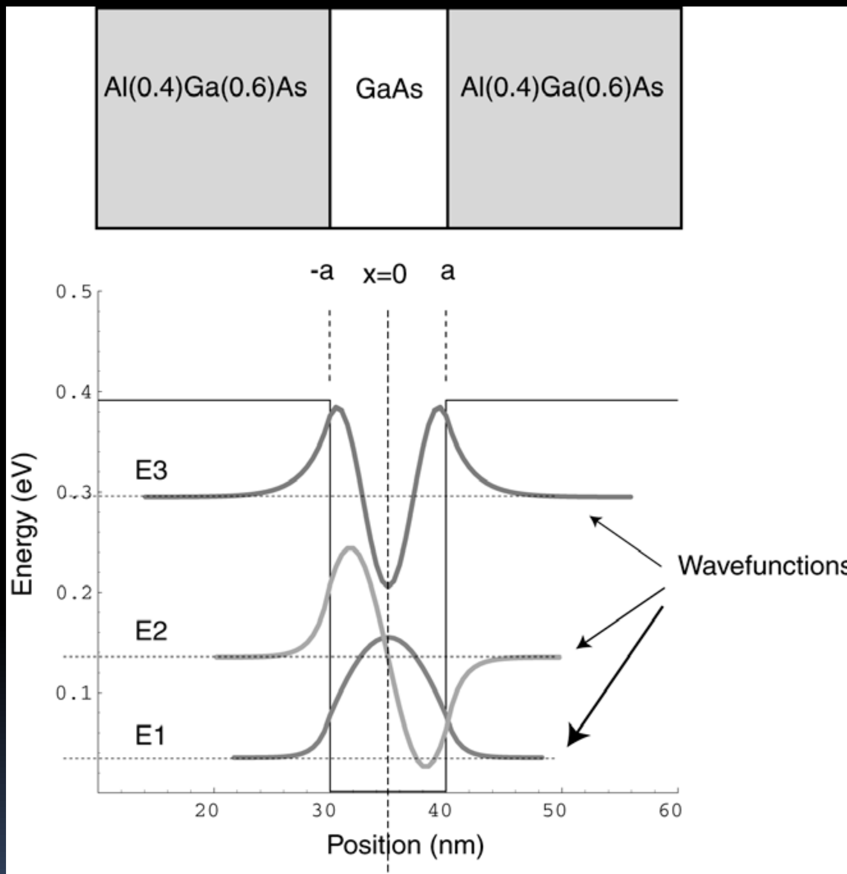




In active region, high carrier density of both electrons and holes are desired

- Active region is usually very thin (few nm – 100’s nm) because high carrier density is desirable for population inversion
- Heterostructure can be used to engineer favorable electron-hole properties to achieve:
  - High gain per unit of injection current for low threshold
  - Wide gain bandwidth for broad wavelength selectivity

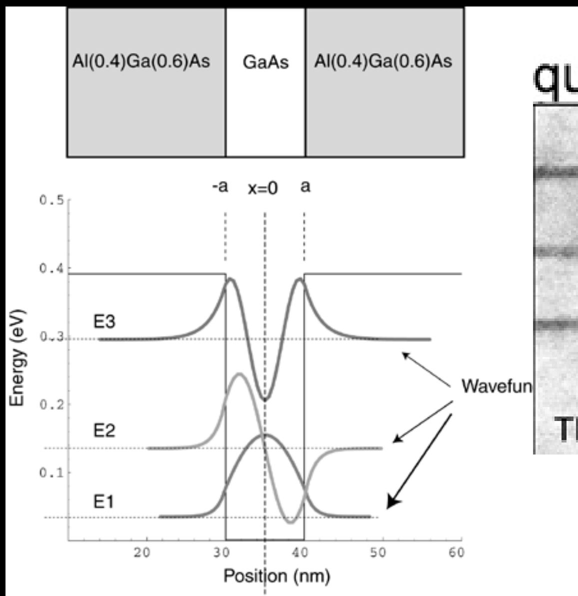
Quantum well structures

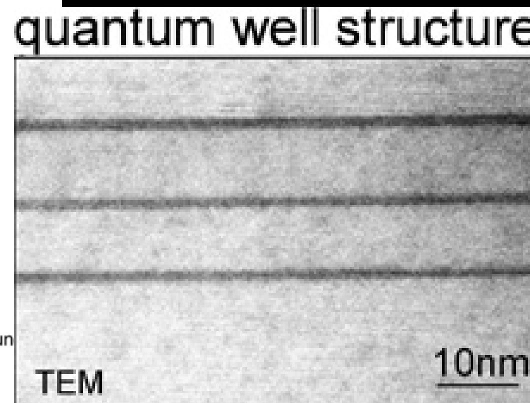


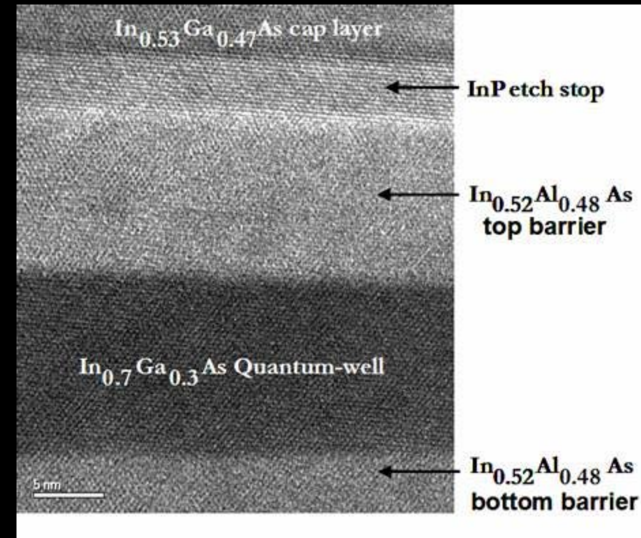
- Electrons and holes are confined in a plane ("well")
- Enhanced oscillator strength for higher spontaneous emission and stimulated emission
- Lower threshold
- Density state profile allows wider band spectrum: broader range of wavelength
- Lower carrier free absorption loss: higher laser efficiency

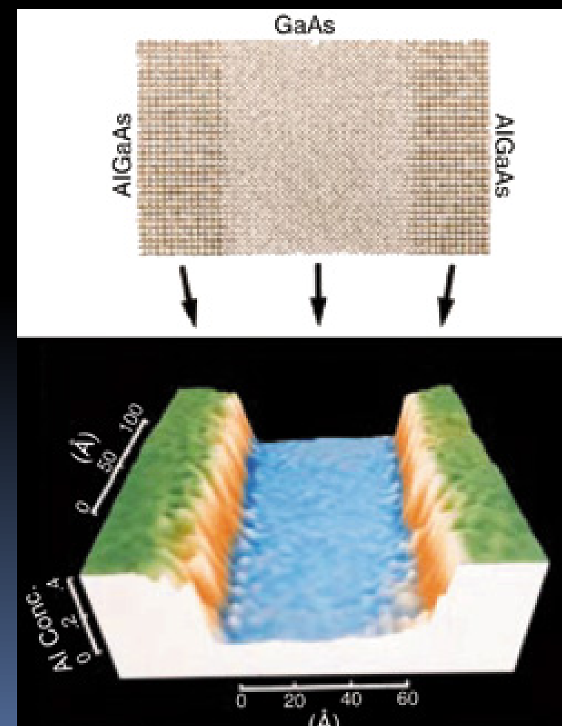
- Similar concept: quantum wires, quantum dots

Quantum well structures



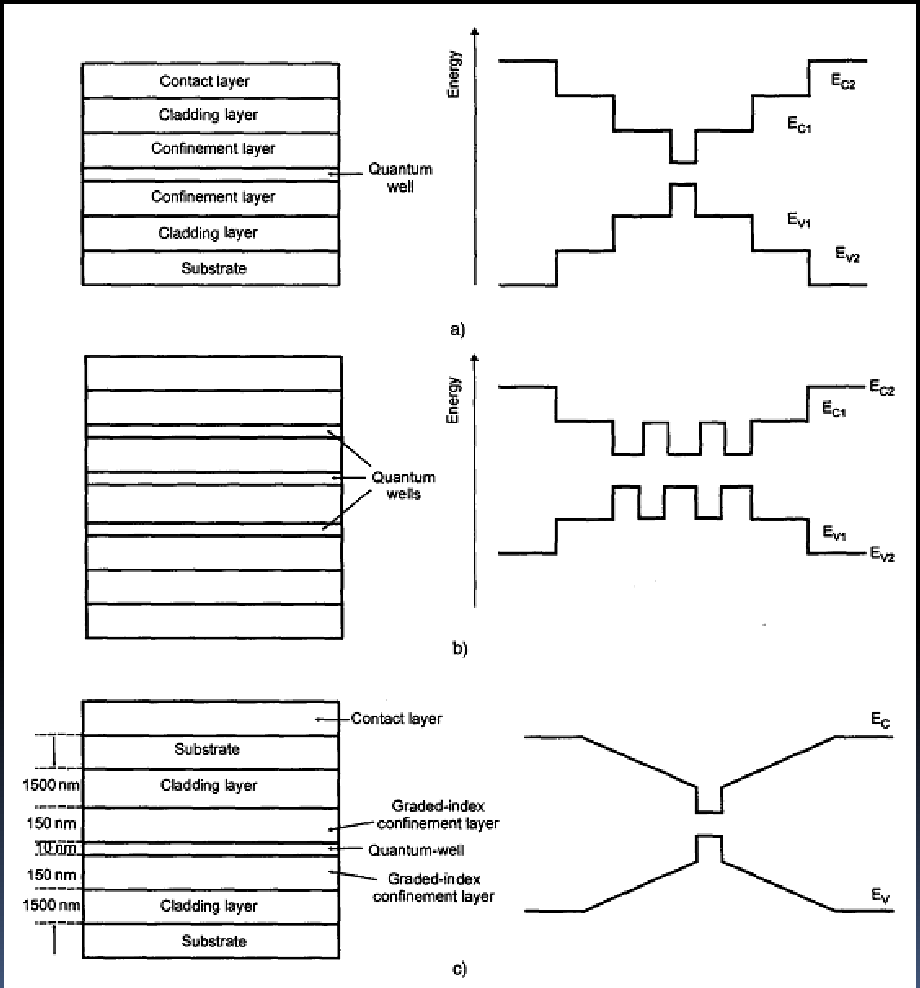






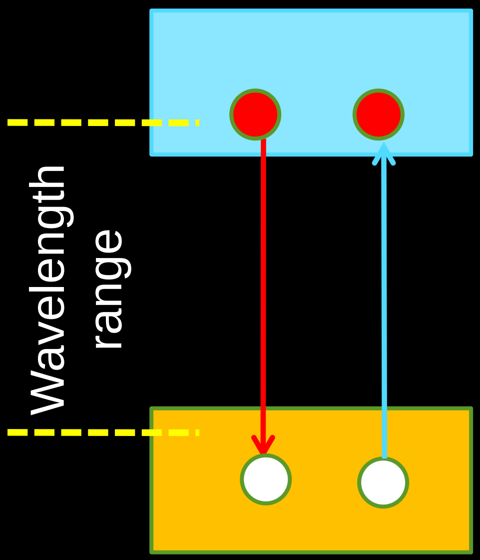
- Key enabling technology: crystal growth
- Epitaxy crystal growth: thin layers like skin. Layer by layer.
- Different crystals can be grown (called heterostructure)
- Molecular beam epitaxy (MBE), Metallo-organic chemical vapor deposition (MOCVD), liquid phase epitaxy (LPE)

Band structure (band diagram)



- Band gap engineering: the arrangement of different semiconductors to achieve certain band gap design for intended applications
- For lasers: this involves designing active layers and optical structure layers, together with overall transport consideration
- EEL involves waveguide
- VCSEL involves Bragg reflector: a structure that acts like a mirror.

Optical processes in semiconductors



Absorption:

$$\alpha(E) = \alpha_{FS} \frac{\lambda^2}{n_g} E \sum_v \frac{\left|\langle u_v^* | \mathbf{p} | u_c \rangle\right|^2}{m_o^2 c^2} \rho_{\text{joint}}\left(E = E_{v,\mathbf{k}} + E_{c,\mathbf{k}}\right)\left(F\left(E_{c,\mathbf{k}}\right) - F\left(E_{v,\mathbf{k}}\right)\right)$$

Spontaneous emission rate:

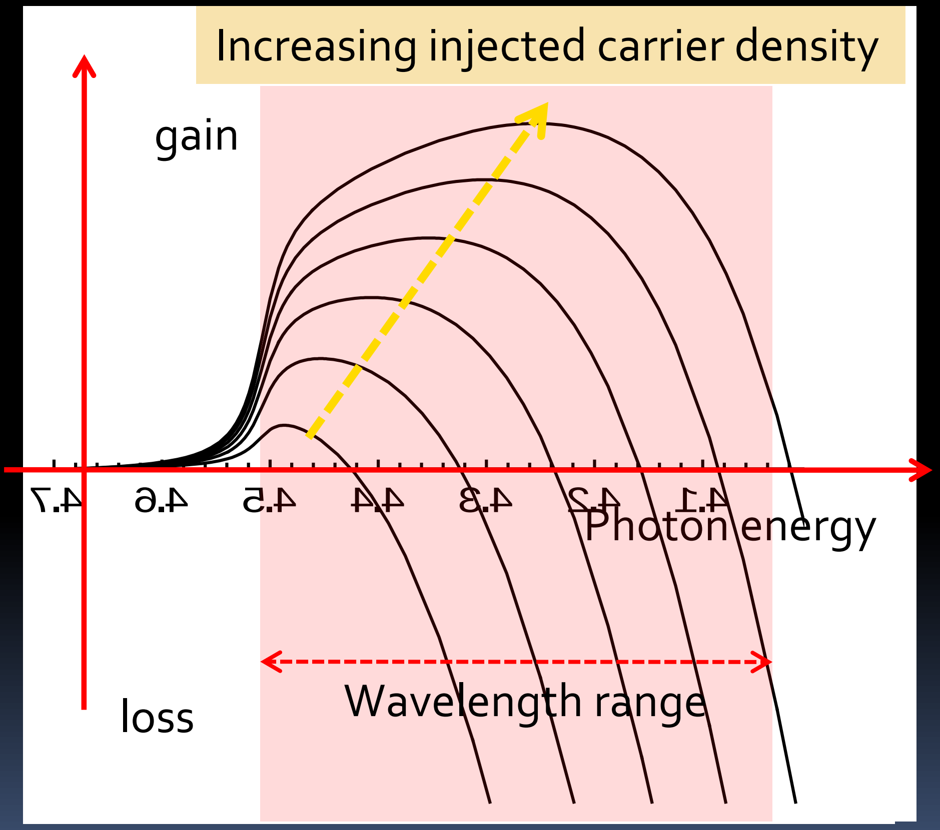
$$r_{\text{spont.}} = 8\pi n_g \alpha_{FS} \nu \frac{\left|\langle u_v^* | \mathbf{p} | u_c \rangle\right|^2}{m_o^2 c^2} \rho\left(E = E_f + E_i\right) F(E_v) F(E_c)$$

Optical gain

$$g(E) = r_{\text{spont.}}(E) \frac{\hbar}{4} \left(\frac{\lambda}{n_g}\right)^2 \left[1 - e^{(E-\mu)/k_B T}\right]$$

Optical gain spectrum

Material and electronic engineering



- The higher injected carrier density, the higher and wider gain spectrum
- Detailed electronic structure can be engineered for gain spectrum
- Wide gain spectrum: wide range of wavelength that can be chosen, or tunable from a structure: (a structure can be made into many lasers of different wavelengths)
- Cavity loss can de designed to tradeoff desired threshold, wavelength range

Semiconductor lasers

- Basic optical processes and electronic structure
- Optical structure
- Lasing mechanism
- Some common semiconductor lasers

Gain (loss) engineering :
- Materials: choice for wavelength range, e. g. 1.5 um – InGaAsP
- Structure: e. g. quantum wells

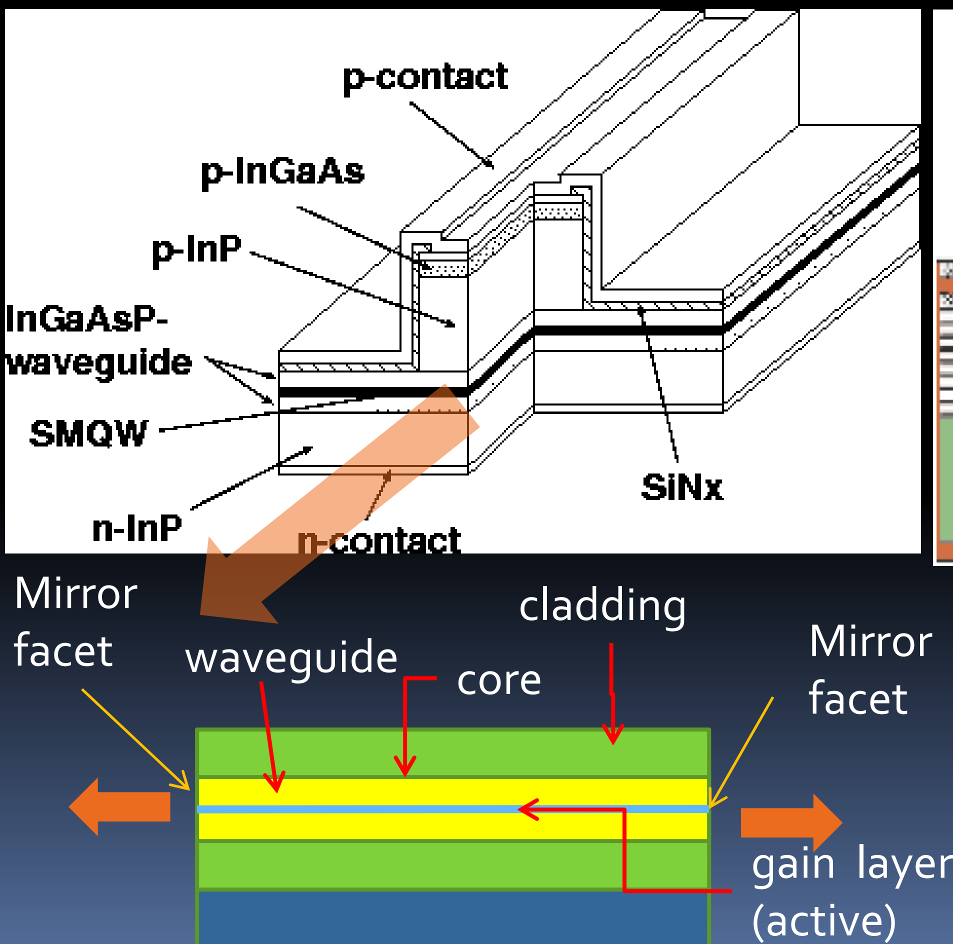
Mode engineering :
- Waveguide design: planar, ridge
- Longitudinal mode control: e. g. DFB, tunable, multi-elements

Operation:
- Threshold, power, efficiency
- Mode control: e. g. tunable, single-mode, side-mode suppression ratio

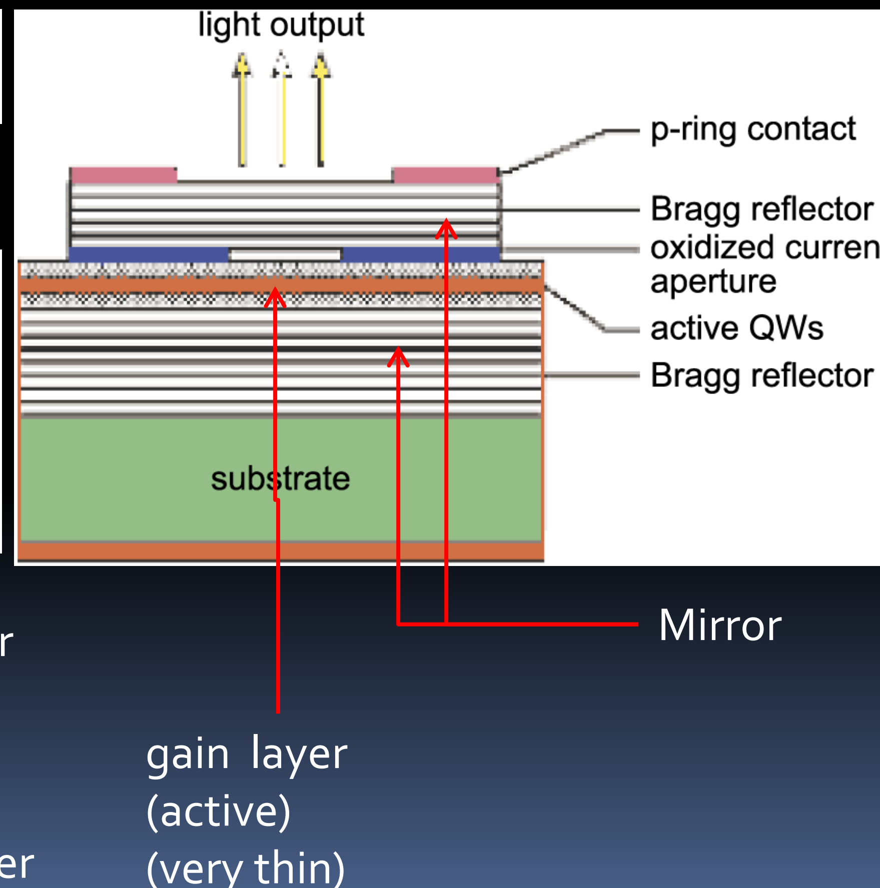
Applications:
- Telecommunication
- Others: e. g. optical storage, sensing, spectroscopy imaging, …

Semiconductor laser optical configuration

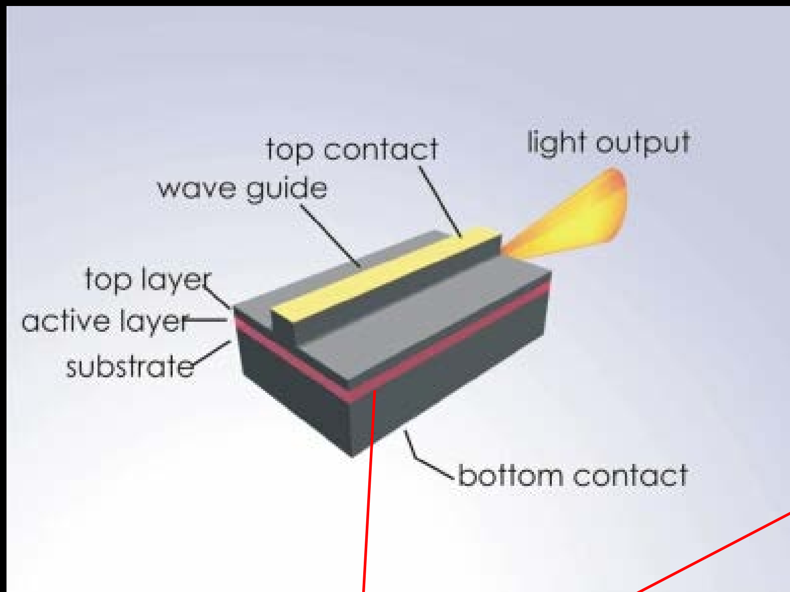
Edge Emitting Laser

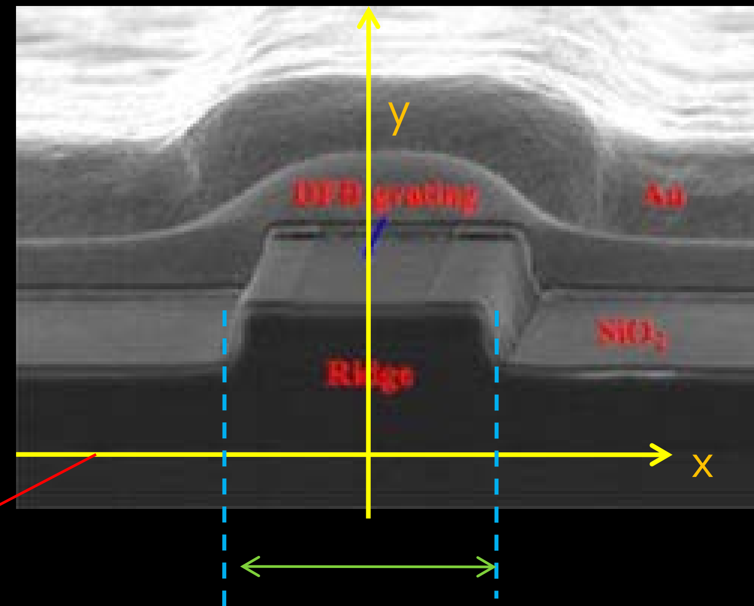


Vertical Cavity Surface Emitting Laser (VCSEL)



Waveguide for edge-emitting laser





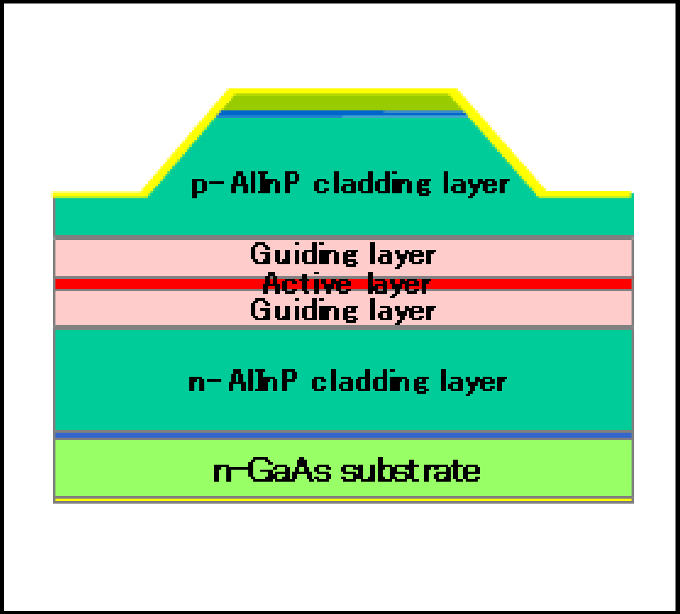
Planar waveguide in x dimension (as grown in epitaxy wafer).
Core dimension: ~0.2 – 2 um
Larger can be grown, but multimode. Cladding: ~1-5 um

Lateral confinement waveguide in y dimension: lithographically etched, can involve regrown, deposition
Core from ~3 um (single mode to 500 um: high power multi-mode)

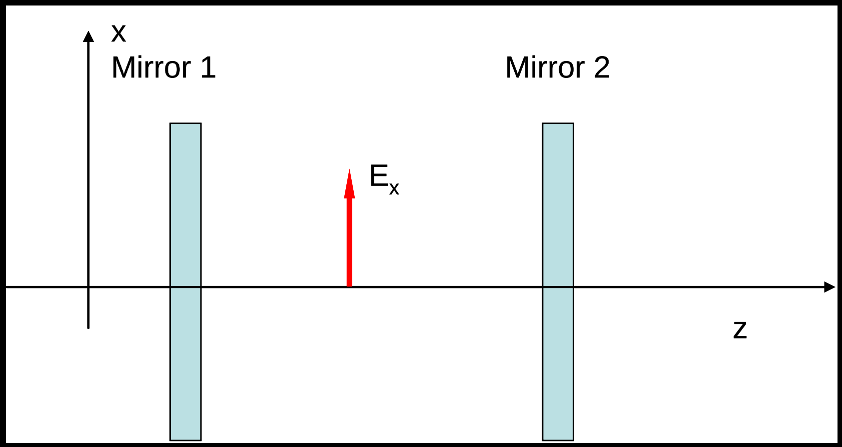
Cavity length: as low as ~50 um to ~3 mm

EEL waveguide design

- Start with slab waveguide, usually single mode (multi-mode can be done, but usually not desired)
- Design of slab optical waveguide modes done with considerations and trade-offs for transport property and optical gain property. Thin structure (single-mode) is also desired for transport in p-i-n structure
- Etched or implant and regrown … to make lateral confinement for rectangular waveguide.
- Narrow ridge: single mode. Wide: multi-mode, depending applications



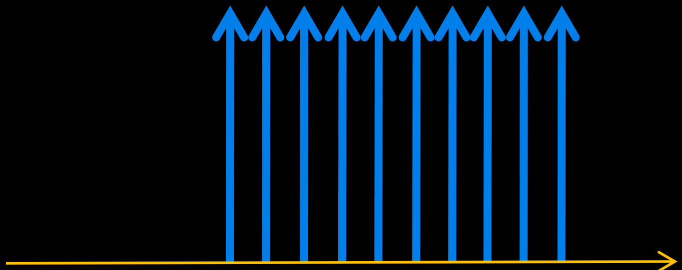
Longitudinal mode



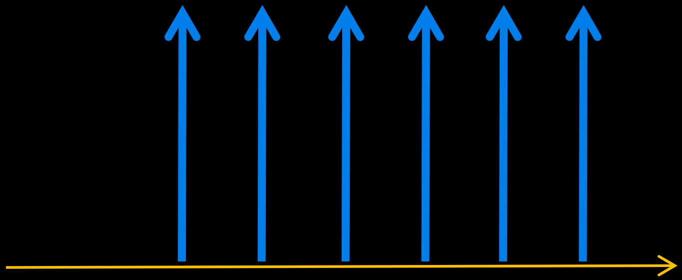
Frequency

$$\nu_m = m\frac{c}{2n_g L}$$

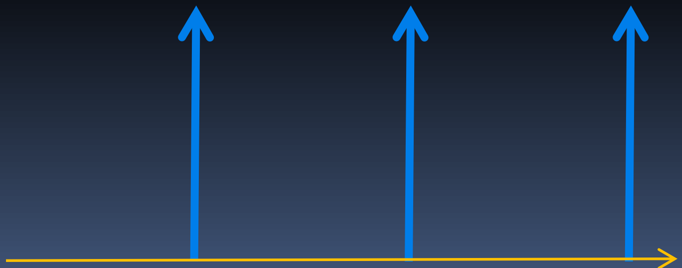
Long cavity



Short cavity



Super short cavity (e. g. VCSEL)



Laser mode design

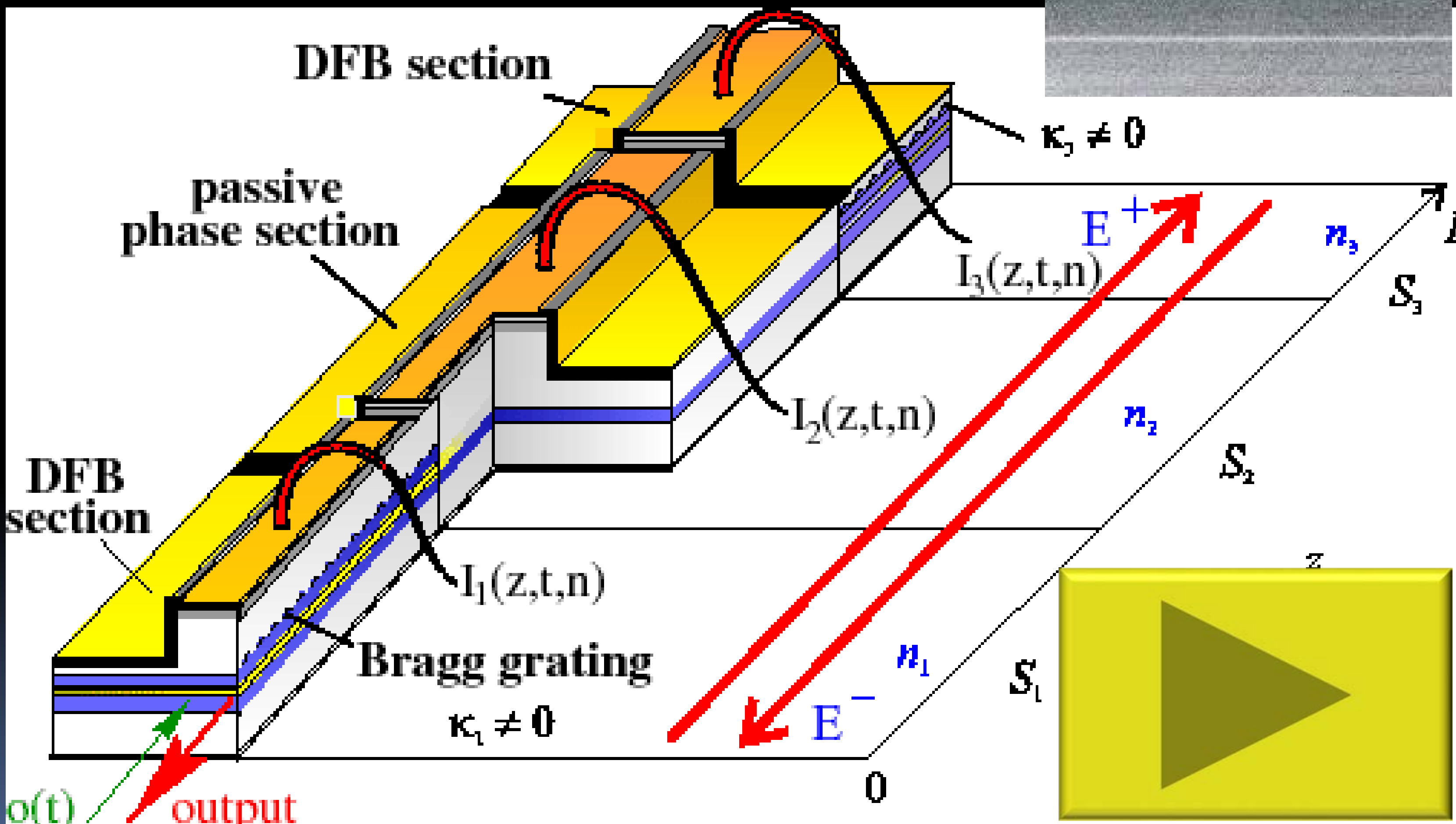
- It is desirable to control the laser longitudinal mode structure (either for single-mode or wavelength-tunable single-mode)
- Multiple optical segments within the cavity for mode control:
  - Phase control
  - Built-in grating: distributed feedback laser
  - Multiple-coupled cavity (complex mode structure)

Elements of longitudinal mode design

Multiple segments

Bragg grating

Advanced 3-segment DFB laser



Semiconductor lasers

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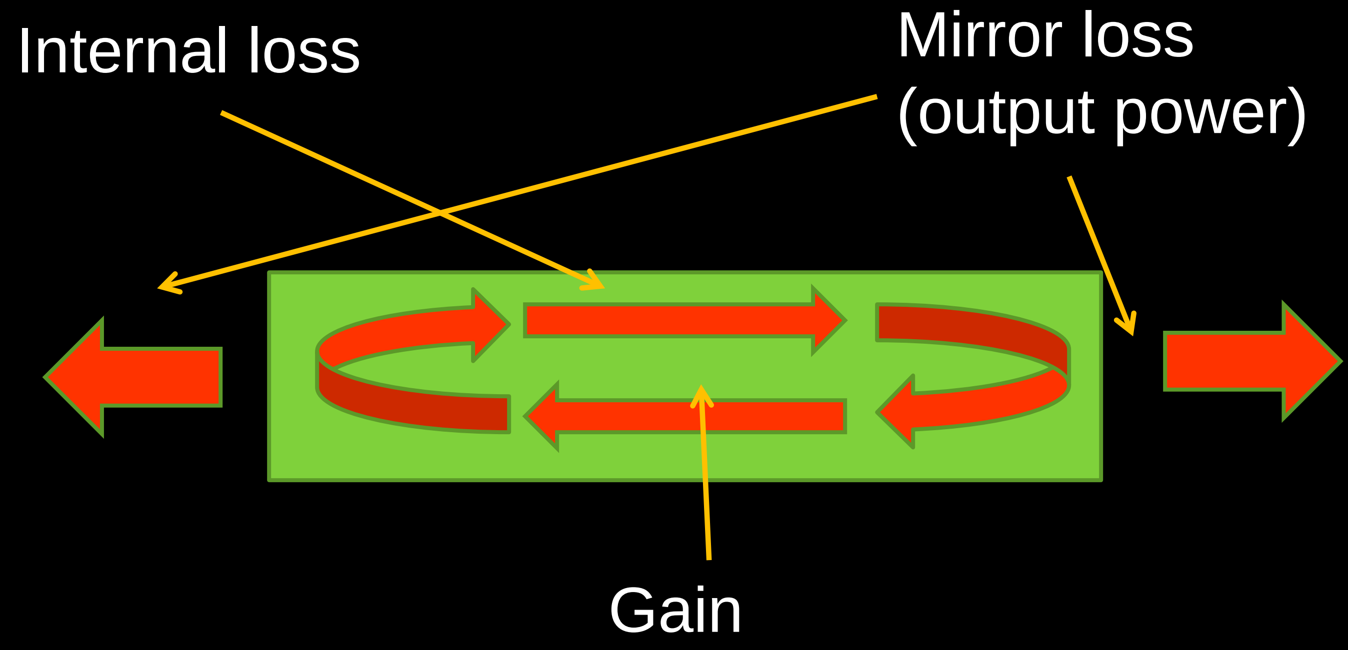
- Mode control: e. g. tunable, single-mode, side-mode suppression ratio

- Some common semiconductor lasers

Applications:
- Telecommunication
- Others: e. g. optical storage, sensing, spectroscopy imaging, …

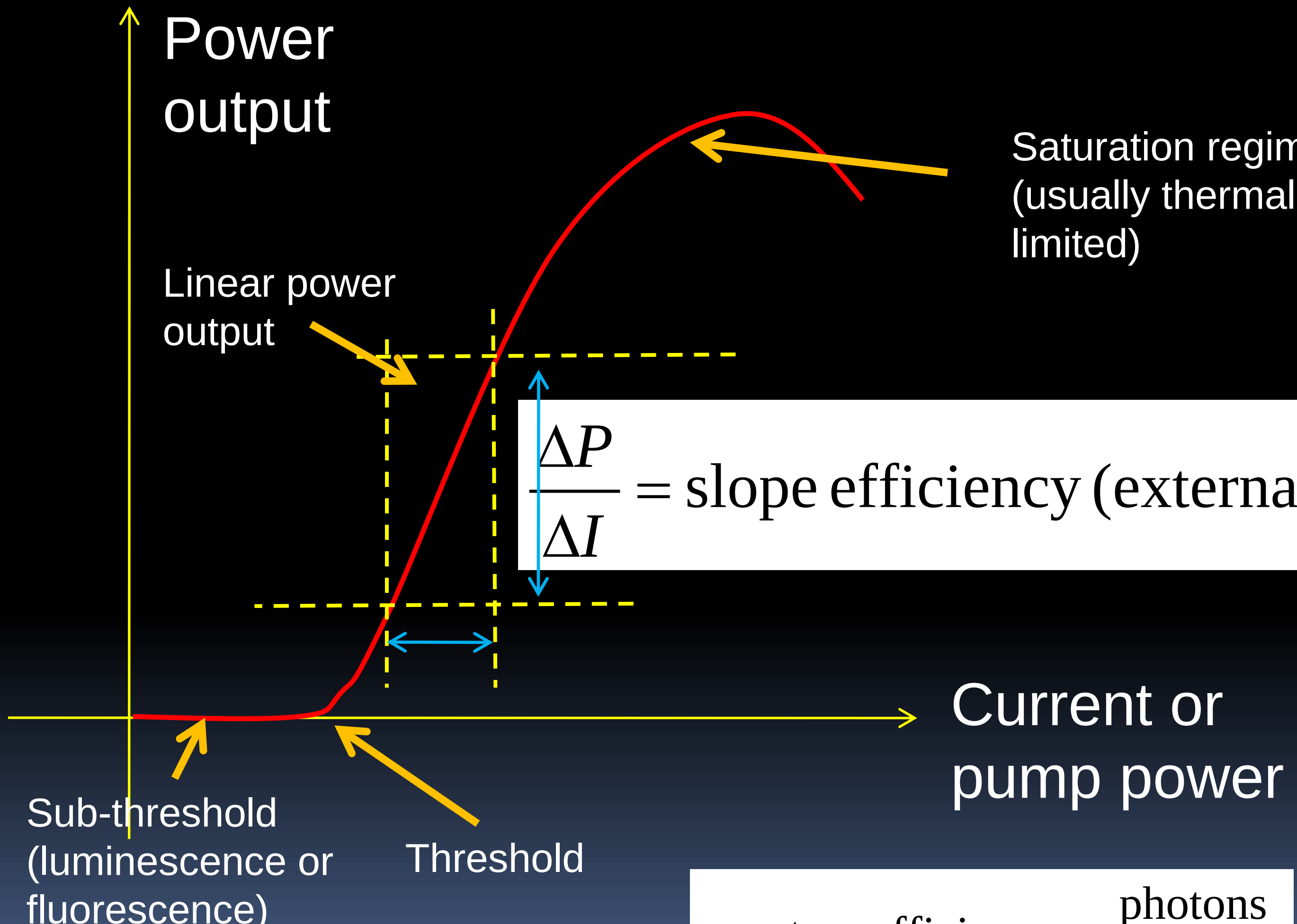
Condition for lasing



- Round trip loss: total loss as light travels one round trip inside the cavity: internal loss+ mirror loss
- Round trip gain: net gain in one round trip

Lasing starts: RT gain= RT loss

Laser power output



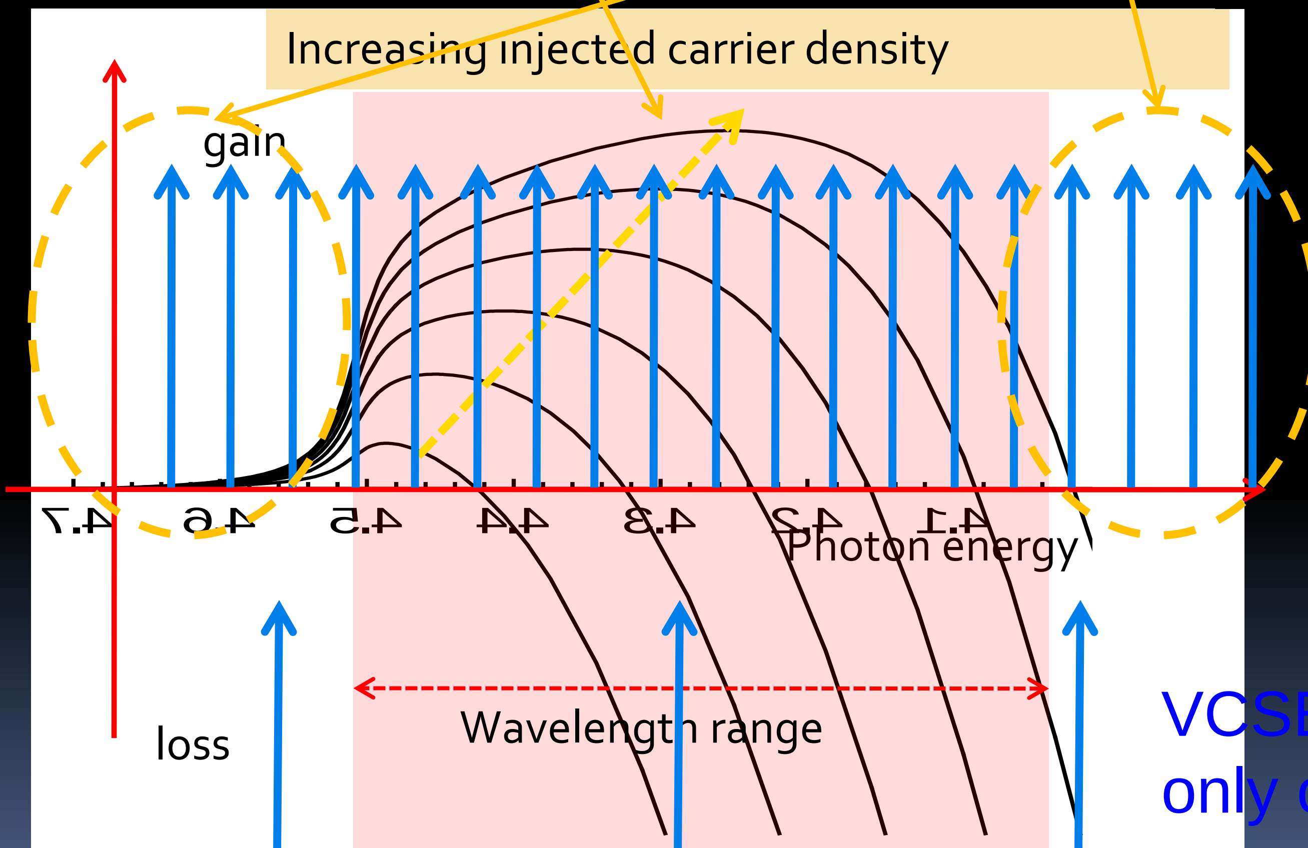
$$\frac{\Delta P}{\Delta I} = \text{slope efficiency (external)}$$

$$\text{quantum efficiency} = \frac{\text{photons}}{\text{electrons}}$$

Longitudinal mode vs. gain spectrum

Lasing modes (in gain spectrum)

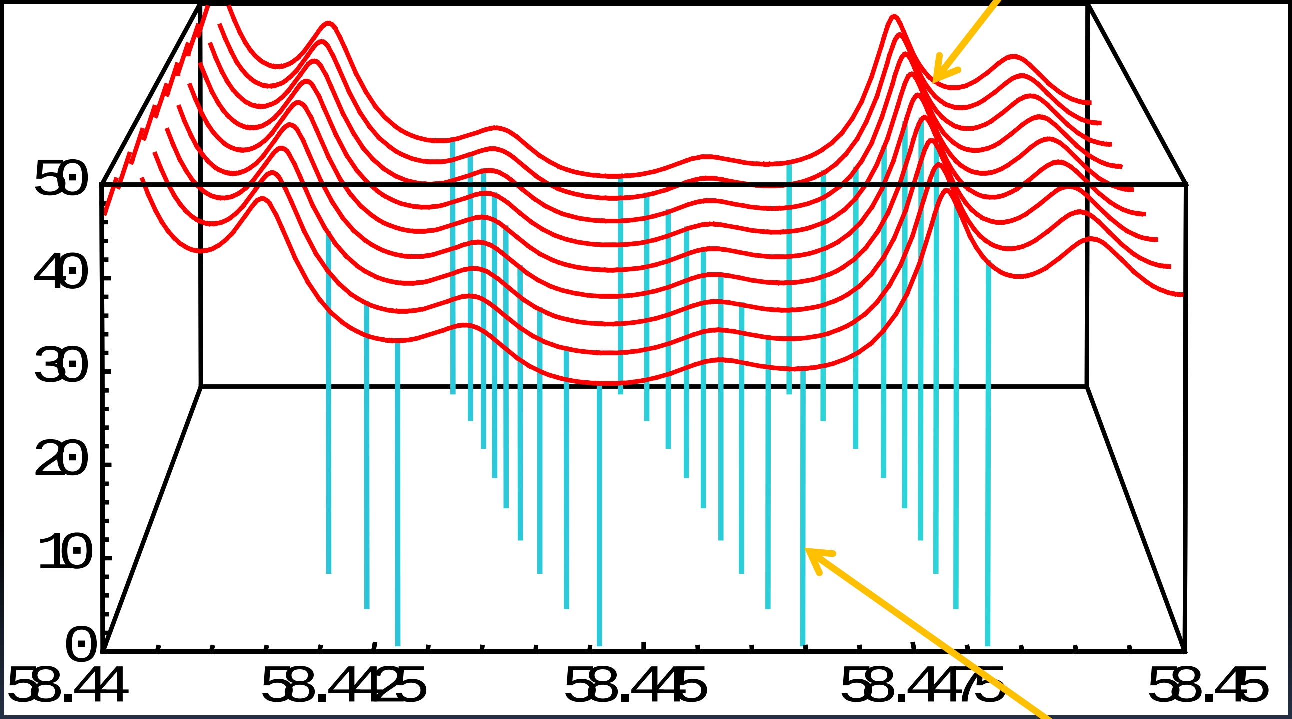
Non-lasing modes



VCSEL can have only one mode

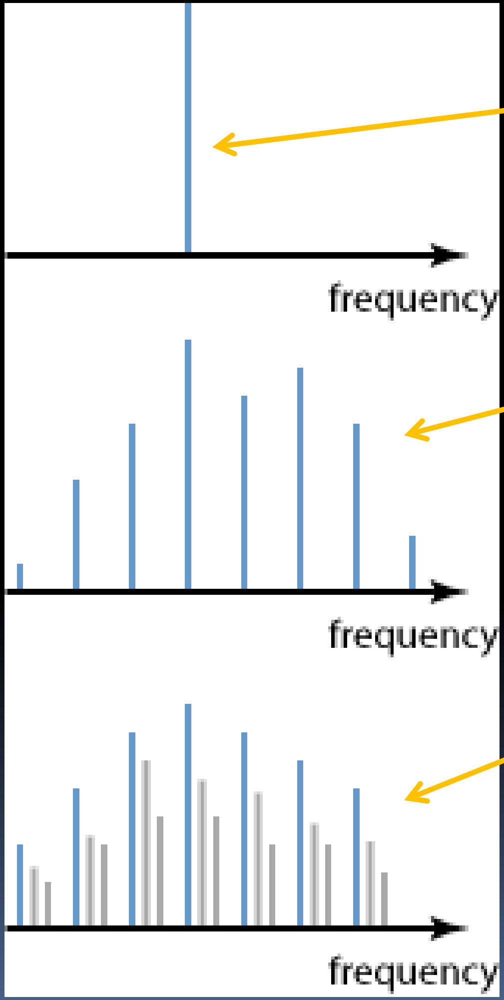
Cavity loss spectrum

Cavity round trip loss



Cavity longitudinal mode

Modes in laser spectra



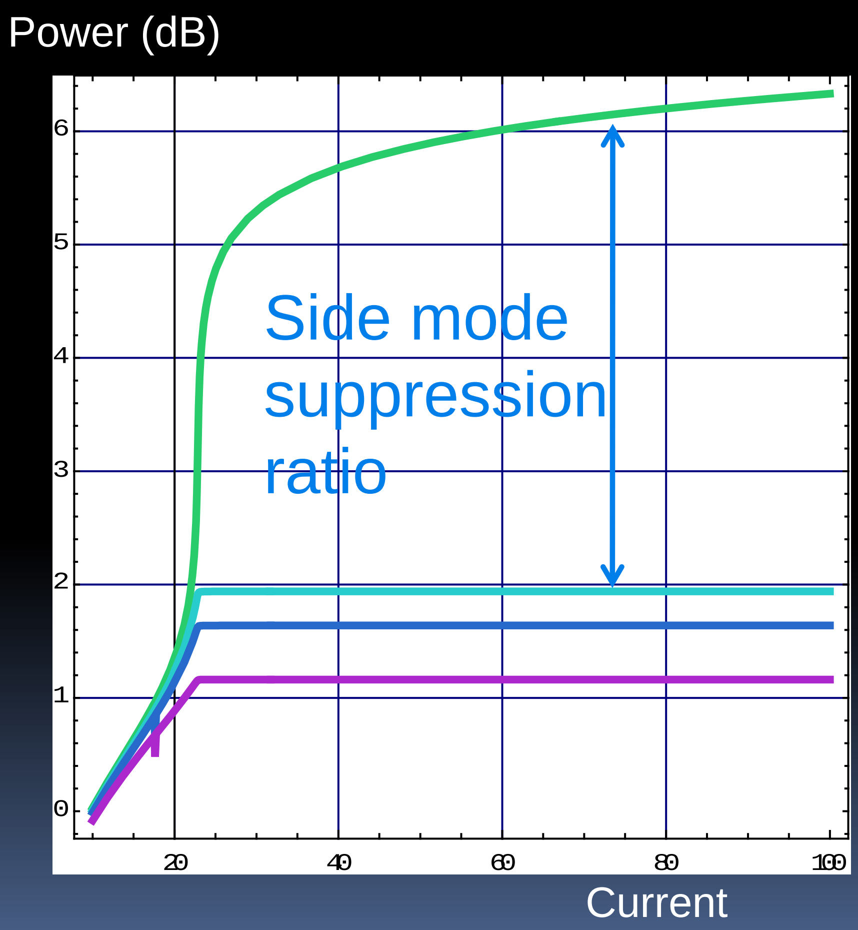
Single modes

Multiple longitudinal modes

Multiple longitudinal modes with multiple transverse mode

Lasing is strongest for modes with lowest loss-gain

Output power for different modes (rate equations)



- It is good enough to have SMSR~ 20 dB – 50 dB (depending on applications)
- For telecom, > 40 dB is preferred

Semiconductor lasers

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Common Semiconductor Lasers

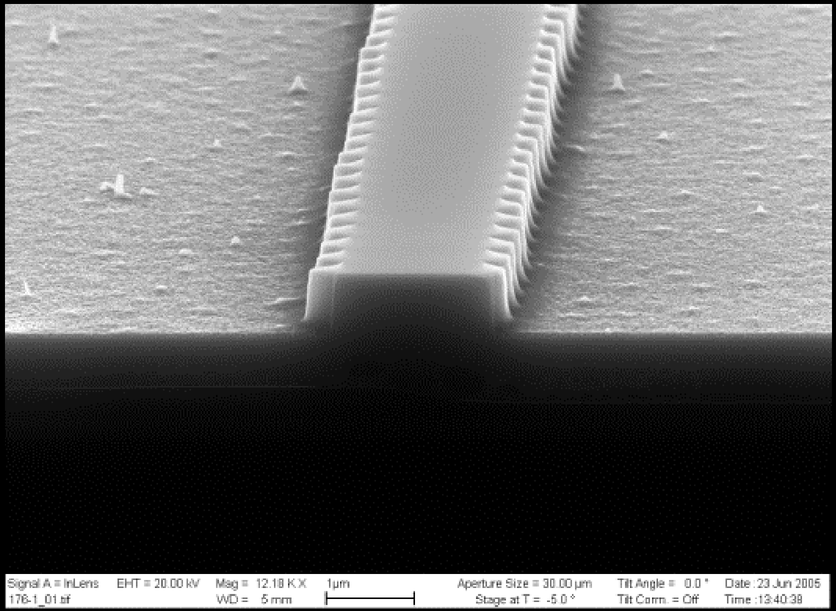
- Fabry-Perot
- DFB or DBR lasers
- VCSEL lasers
- Tunable Lasers

Types of semiconductor lasers for telecom

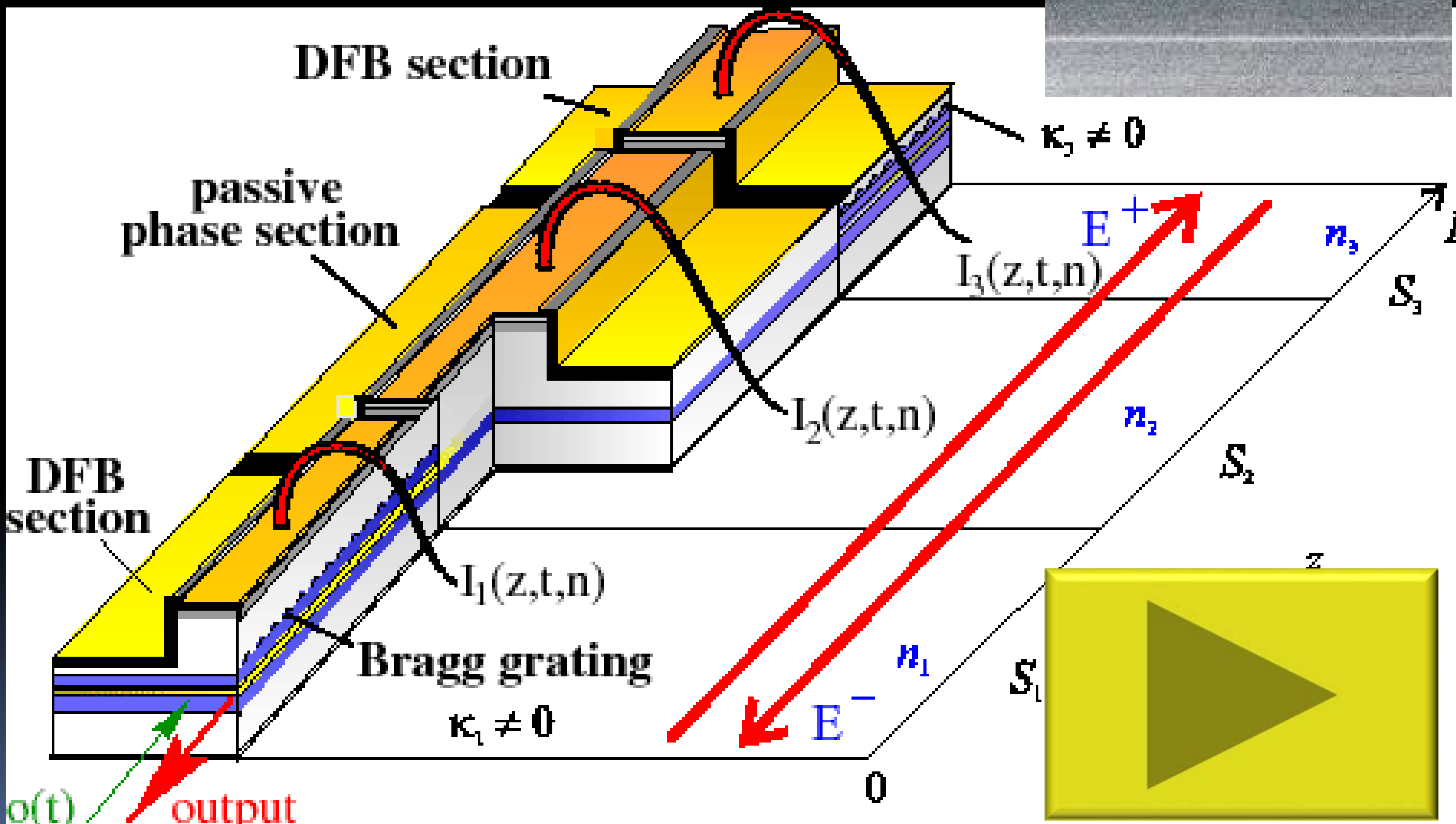
- Designed driven by applications
- Technical features:
  - Spectral accuracy, purity: single-frequency laser at desired wavelength; narrow linewidth
  - Power; threshold, efficiency
  - Noise: low amplitude fluctuation (low relative intensity noise)
  - Others: modulation behavior, (mode-locking) wavelength tunability
- Operational features: very important for telecom: reliability, lifetime, cost-performance, package and integratability, size, power consumption…

DFB Lasers

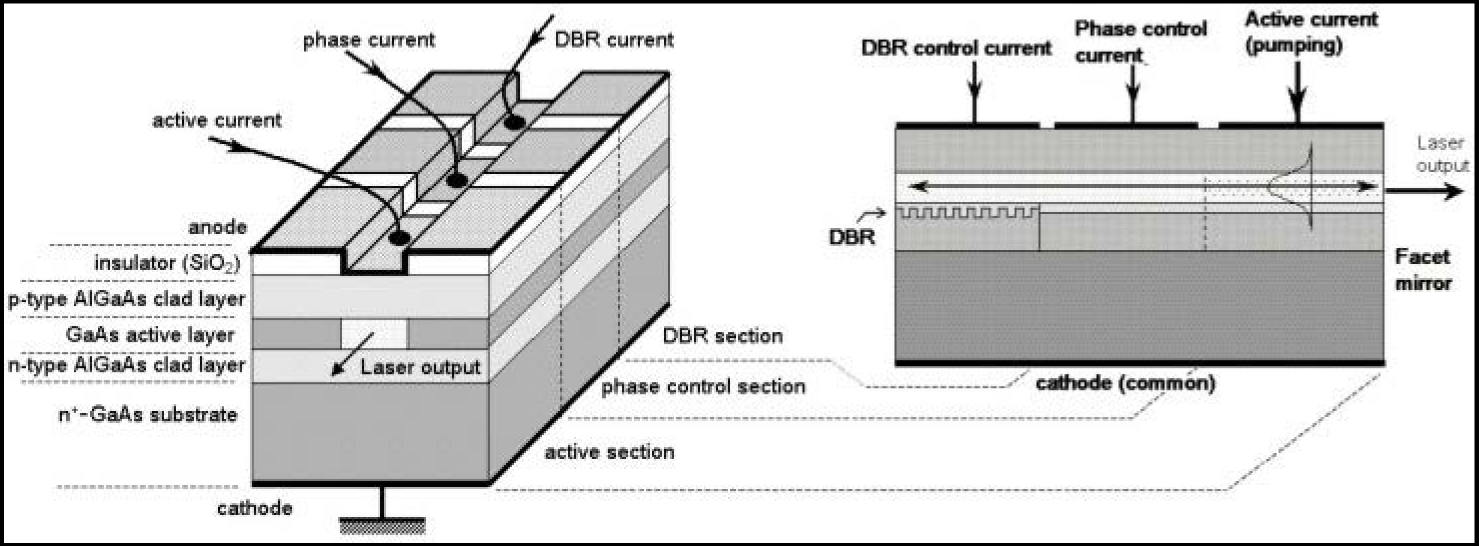
- Designed for single-frequency with integrated Bragg grating (BG)
- Fabrication sensitive: must have BG correct period for coarse wavelength accuracy
- Fine tuning frequency with temperature or internal phase segment when operated
- Sufficient power: ~few->10 dBm for many applications
- Most ubiquitous: used in most telecom systems



Advanced 3-segment DFB laser

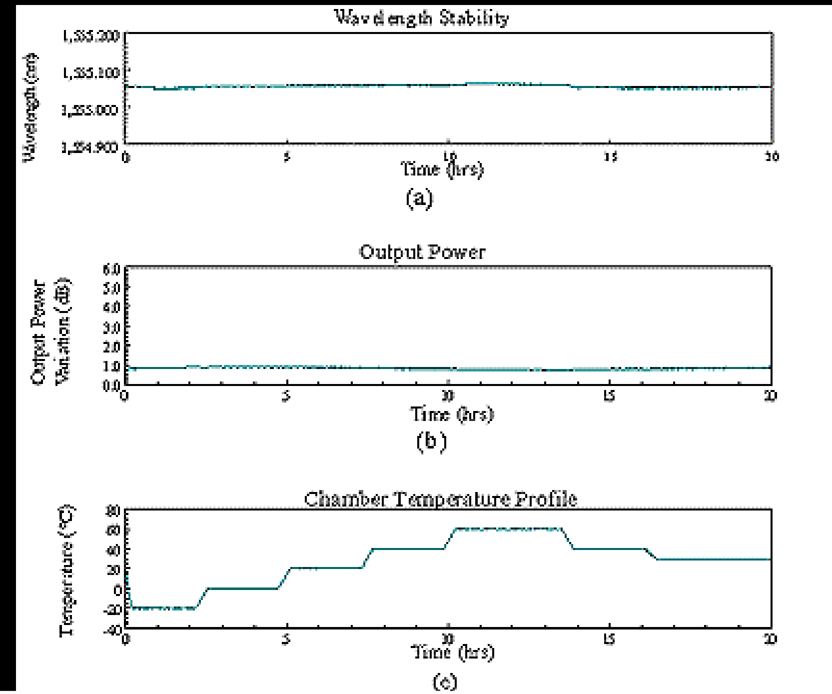


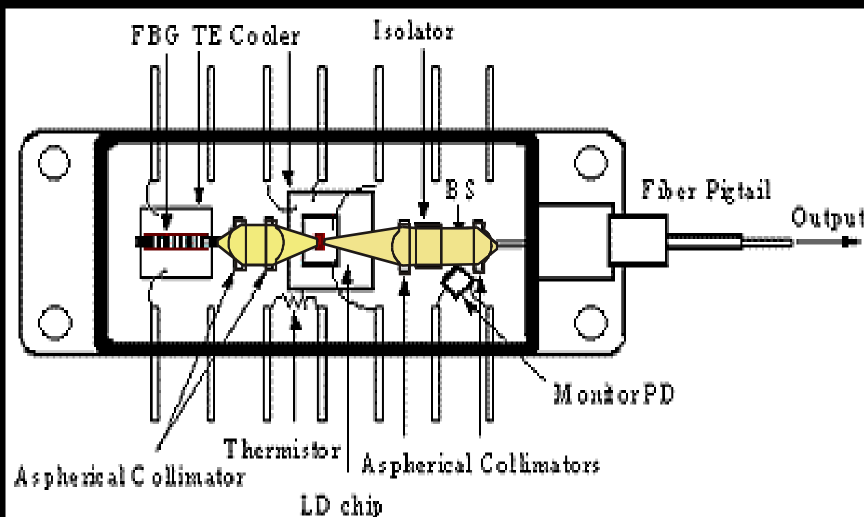
3-segment DBR

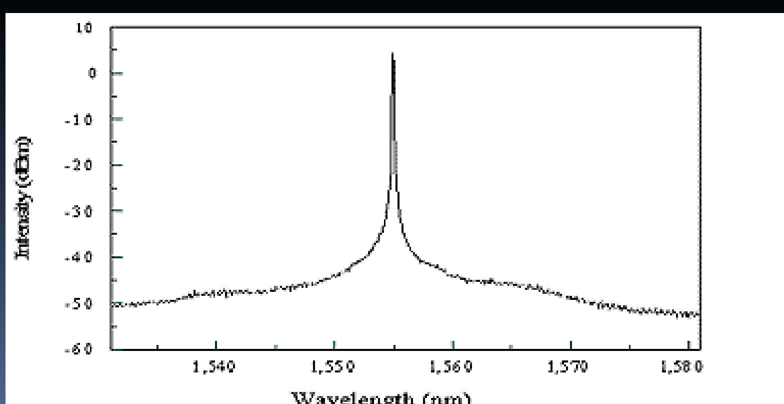


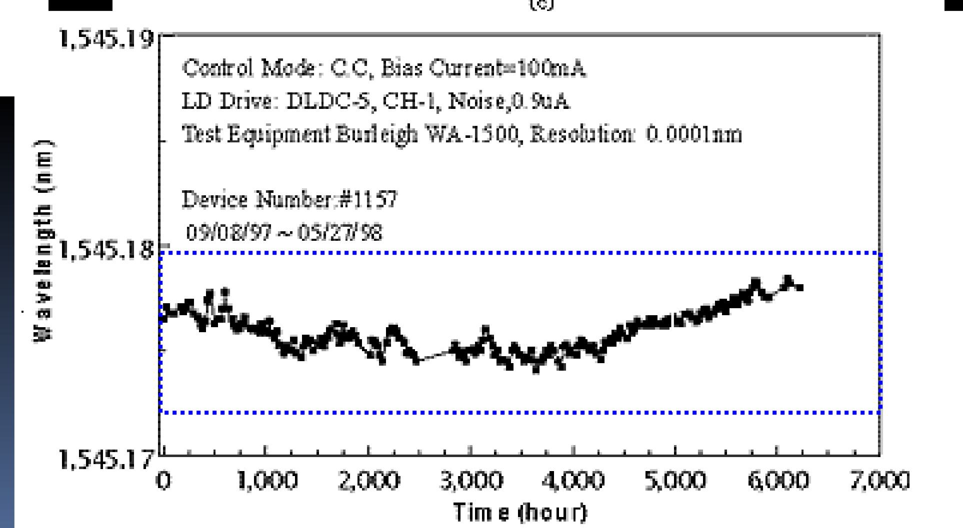
- Also with integrated Bragg grating (BG) BUT different from DFB: DBR is used as a narrow band mirror
- Similar with DFB about fabrication sensitive: but slightly more tolerance
- Also fine tuning frequency with temperature or internal phase segment when operated
- Less popular than DFB, but a variation is with Bragg fiber grating is also useful

An example of DBR concept, but with fiber BR instead of integrated BR



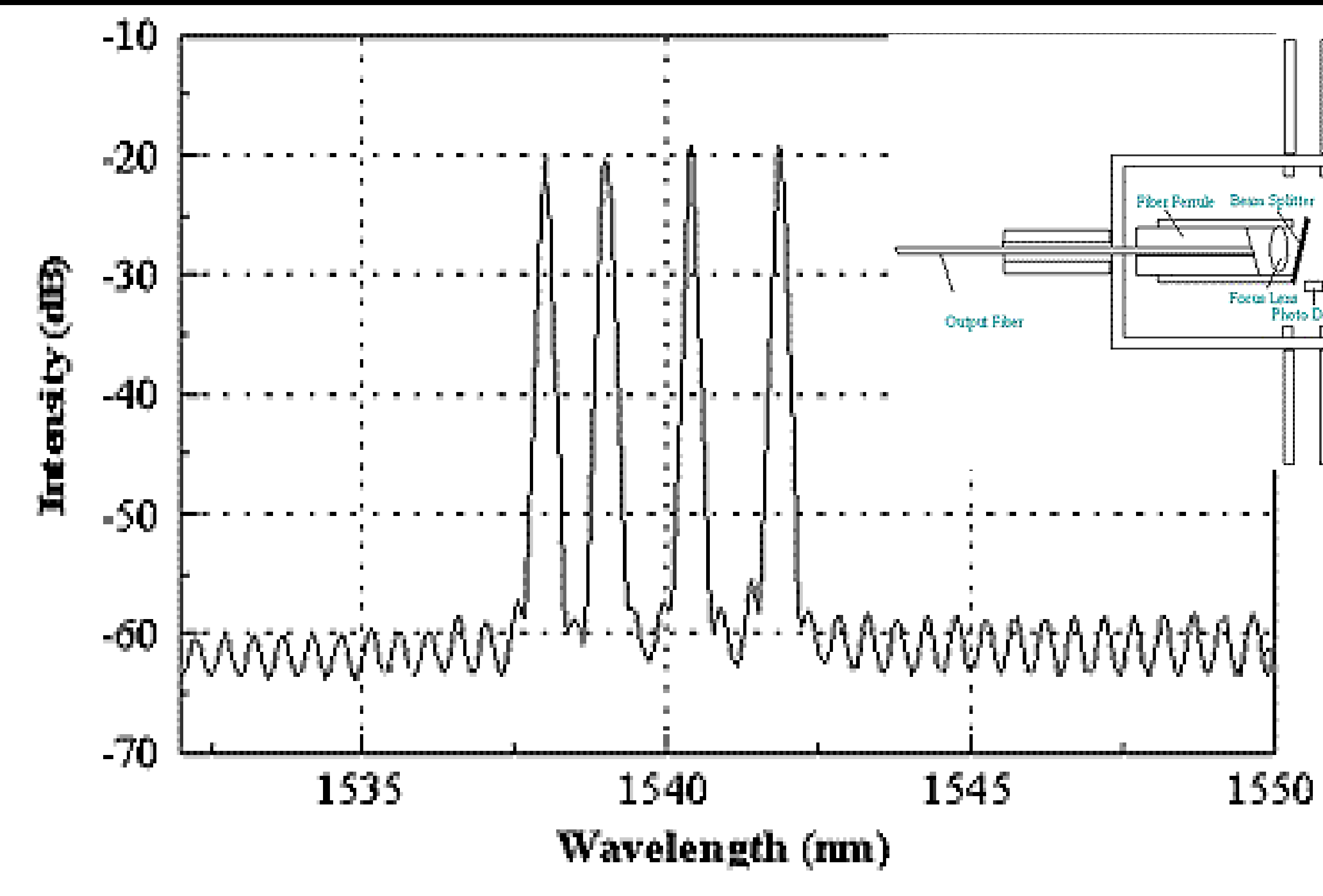


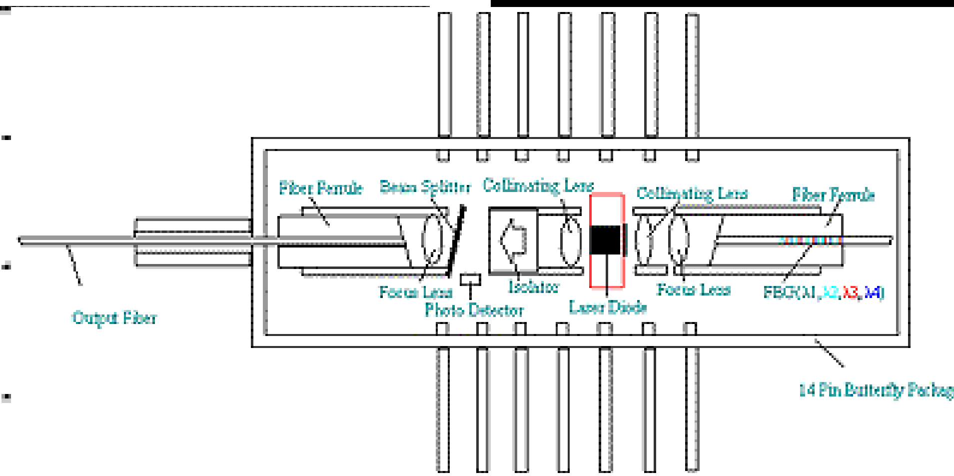




Multi-wavelength FBG transmitter

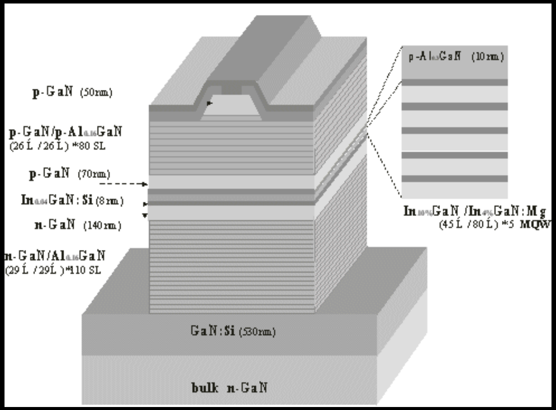
- Single gain elements, multi-λ FBG, single package (cost effectiveness)

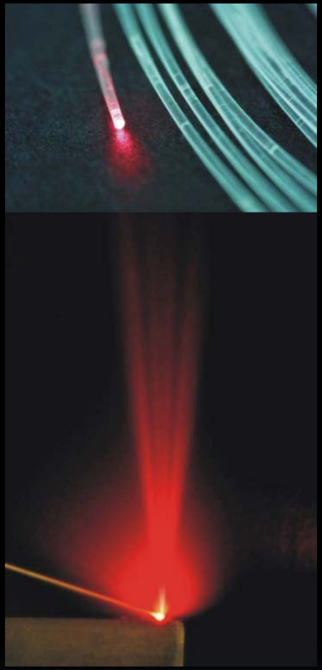


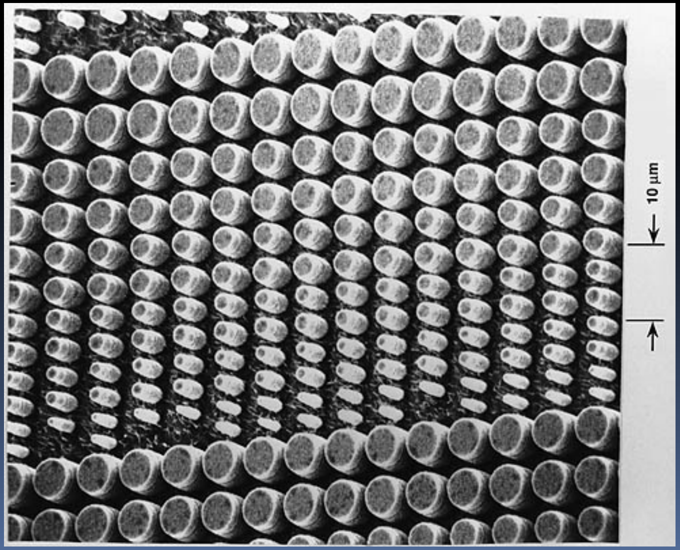


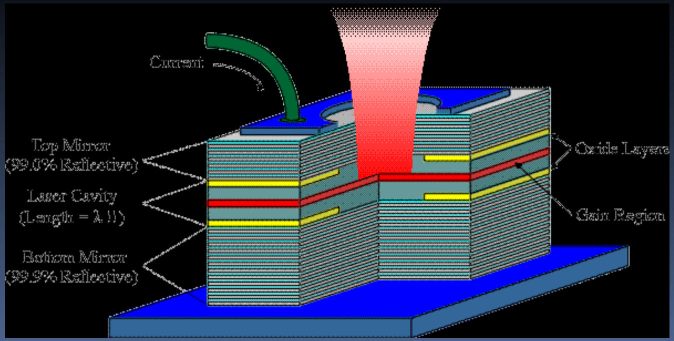
J. Pan (E-Tek Dyn.)

Vertical Cavity Surface Emitting Laser (VCSEL)



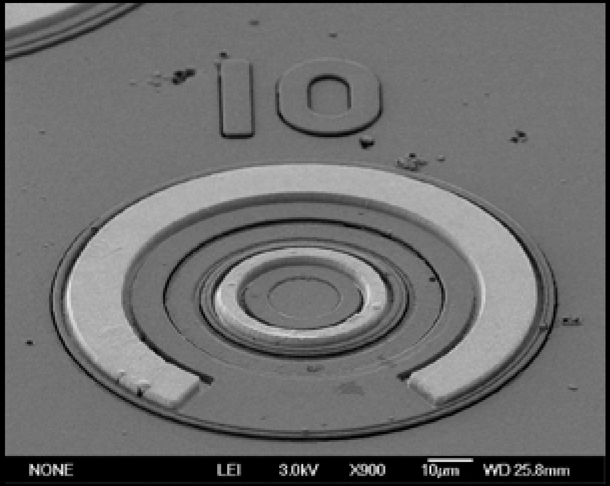


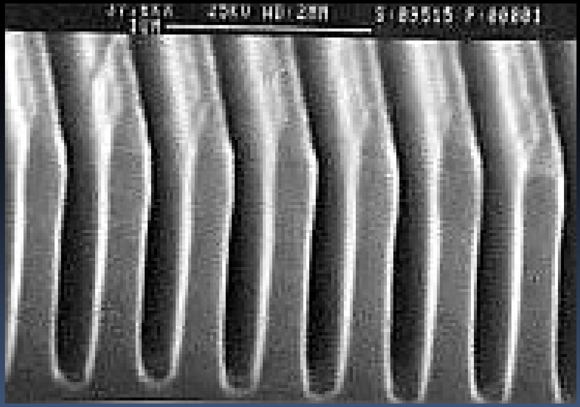




VCSEL

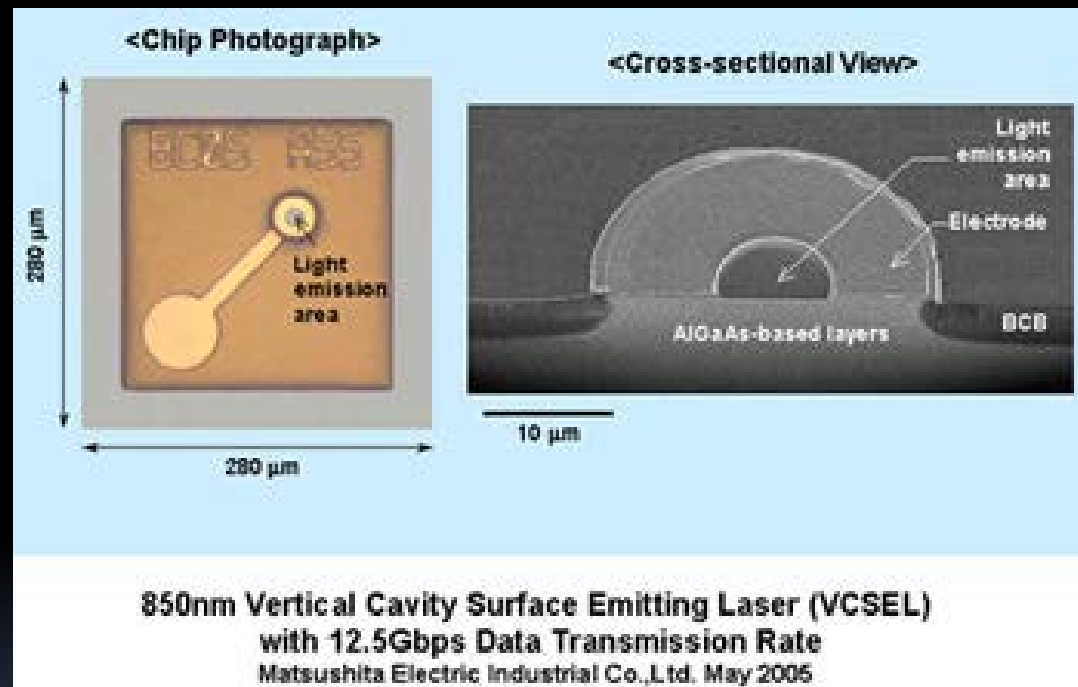
- Greatest advantages:
  - Very easy to get single frequency owing to short cavity
  - Ease of fabrication: no cleaving necessary like EEL
  - Small size: very large array possible
  - Symmetric divergence beam: ease of fiber coupling
  - Very inexpensive
- However…
  - Not as much power as EEL
  - Appropriate in less mission-critical application such as for LAN, SAN…





VCSEL

000 15KV X9,500 1µm WD17



<Chip Photograph>
<Cross-sectional View>
280 µm
280 µm
Light emission area
Light emission area
Electrode
AlGaAs-based layers
BCB
10 µm
850nm Vertical Cavity Surface Emitting Laser (VCSEL)
with 12.5Gbps Data Transmission Rate
Matsushita Electric Industrial Co.,Ltd. May 2006

Tunable lasers

External-cavity diode tunable laser