光電子學導論

(7) Semiconductor Lasers

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Semiconductor Lasers

- **The material is "semiconductor"**
  - **At very low temperature, their conductivity is low**
  - **At high temperature, they act like conductors**
    (temperature ↑ ⇒ conductivity ↑)
    (For metals: temperature ↑ ⇒ conductivity ↓)
- **They are (the most widely used) "lasers"**
  - **Active medium ⇒ p-n junction (active layer)**
  - **Pumping scheme ⇒ Current injection (usually)**
  - **Laser mirrors ⇒ Cleaved end surfaces (usually)**

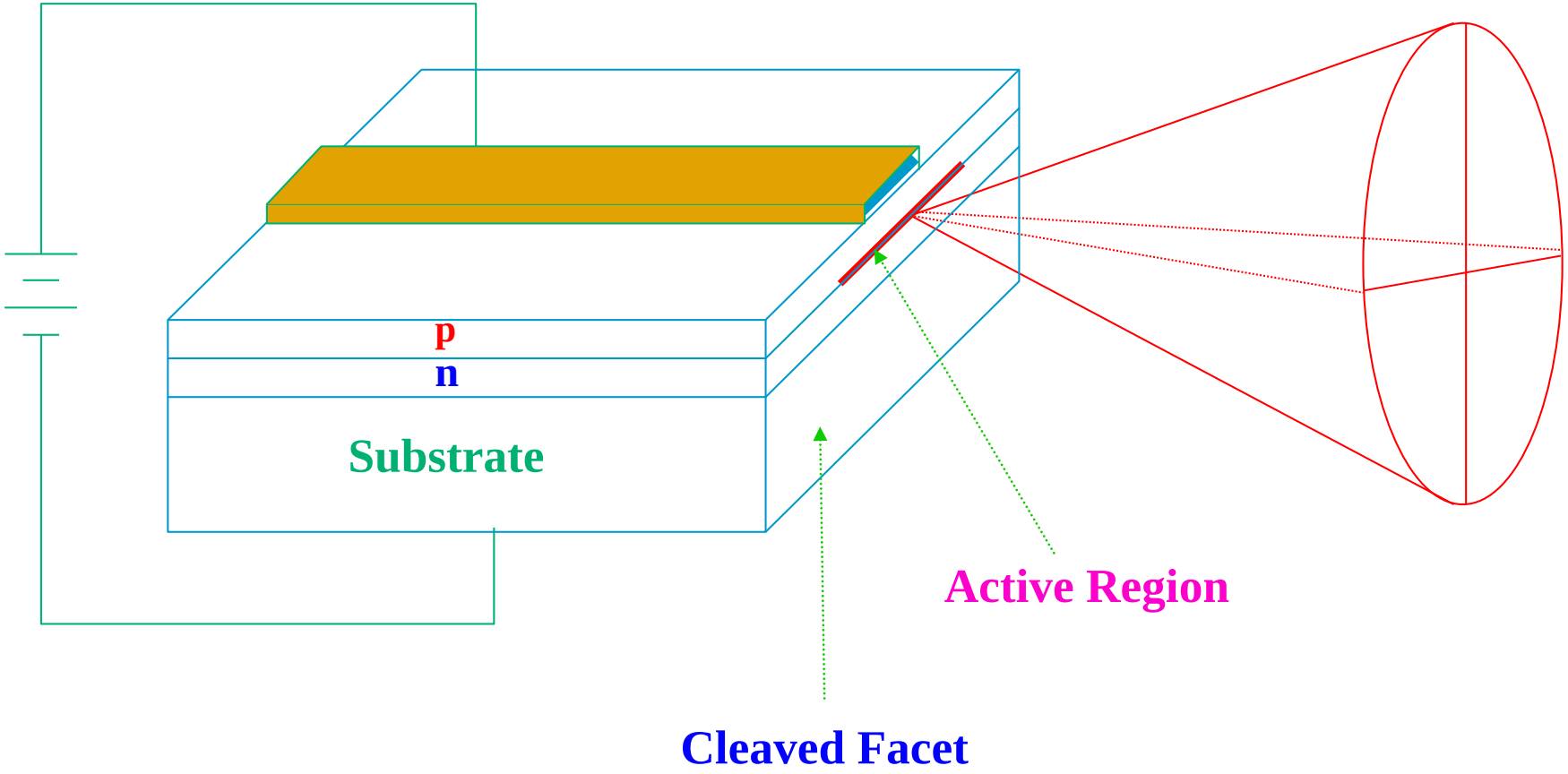
Historical Perspective

- In 1962 several groups reported the laser action in semiconductors. The device consisted of a forward-biased GaAs p-n junction.
- In 1963 it was suggested that semiconductor lasers might be improved if a layer of one semiconductor material were sandwiched between two cladding layers of another semiconductor that has a relatively wider band gap (i.e., the double-heterostructure laser).
- In 1969 room-temperature operation of a heterostructure laser was demonstrated using the liquid-phase epitaxial (LPE) for the growth of GaAs and $Al_xGa_{1-x}As$ layers.
- In addition to AlGaAs lasers, room-temperature operation of a 1.1-μm InGaAsP laser in the pulsed mode was reported in 1975.
- In 1977 the wavelength was extended to 1.3 μm. Several groups in 1979 reported on InGaAsP lasers operating in the vicinity of 1.55 μm. By 1984 the use of InGaAsP lasers in long-haul optical communication systems had reached the commercial stage.
- AlGaInP and InGaN semiconductor lasers are developed in the past few years that have important application in high-density DVD, as well as short-distance and medium-distance optical fiber communication.

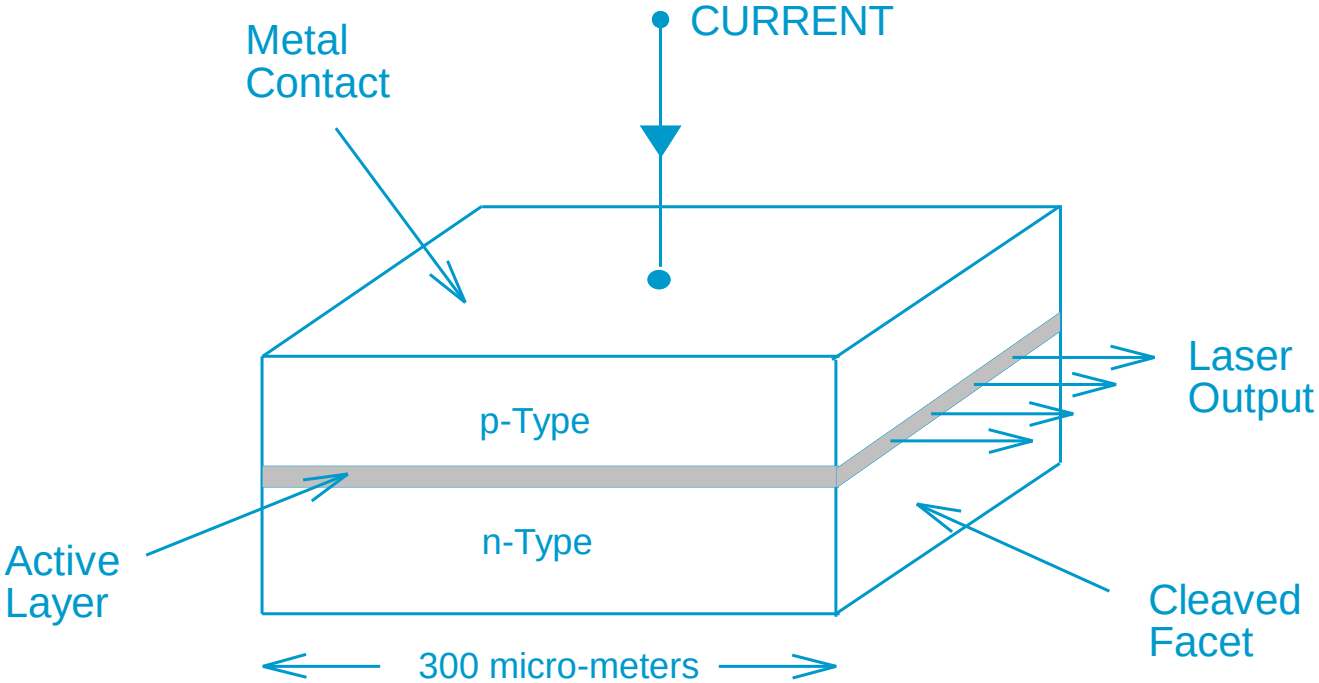
Laser Diode & Light-Emitting Diode

- Small Size, Light Weight
- Long Operation Lifetime (>> 1000 hours)
- High Efficiency, Low Power Consumption
- High Power Density, High Brightness
- Very Low Price (A laser pointer costs only a hundred NT!)
- Wide Bandwidth (Ranging from ultraviolet, visible, to infrared spectrum)
- Perfect for Optical Fiber Communication

Edge-Emitting Laser (EEL)



Pumping Level Required for Laser Action



Size of a Laser Diode ≈ 300 μm (L) × 200 μm (W) × 100 μm (H)

Laser Threshold: $R_1R_2e^{2gL} = 1$ $g = (1/2L)\ln(1/R_1R_2)$

If $R_1 = R_2 = [(n-1)/(n+1)]^2 = [(3.5-1)/(3.5+1)]^2 = 0.3$,

Then $g = [1/(2\times300\times10^{-6})]\ln[1/(0.3\times0.3)] \approx 4000\ m^{-1} = 40\ cm^{-1}$

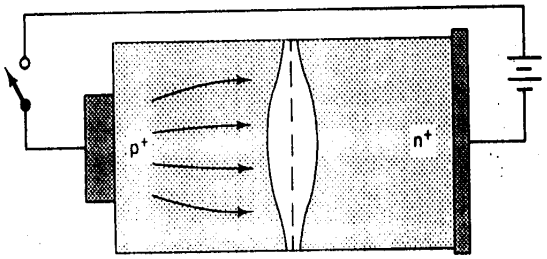
Problems of a Homojunction Semiconductor Laser

- In a traditional homojunction semiconductor laser, as in the case for every equilibrium *p-n* junction, the Fermi level is constant throughout the device with no current flow.
- When the junction is biased in the forward direction, the Fermi level splits because of the injection of minority carriers (electrons into the *p* region, holes into the *n* region) and there exists a region near the junction where there is simultaneously a high density of electrons and a high density of holes.
- Because of the much higher mobility of electrons compared to that of holes, most of the injection is by electrons into the *p* region. The electrons recombine with the majority holes after diffusing a distance, d ($\approx$ 0.93 μm for GaAs).
- The lateral laser mode might extend over a larger distance than the diffusing distance d. In this situation, the central part of the laser mode experiences gain, whereas the edges experience loss.
- The simple *p-n* junction lasers have two major drawbacks: (1) the injected minority carriers are "free" to diffuse that dilutes the spatial distribution of recombination and thus the gain; (2) there is very little guiding and confinement of the electromagnetic wave being amplified.

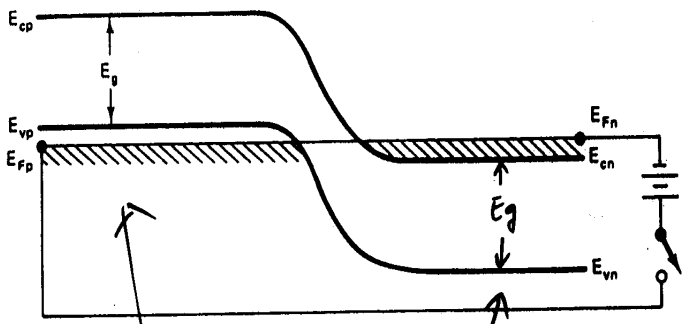
Homojunction Semiconductor Lasers

同質材料

→ p & n have same materials (e.g., GaAs)

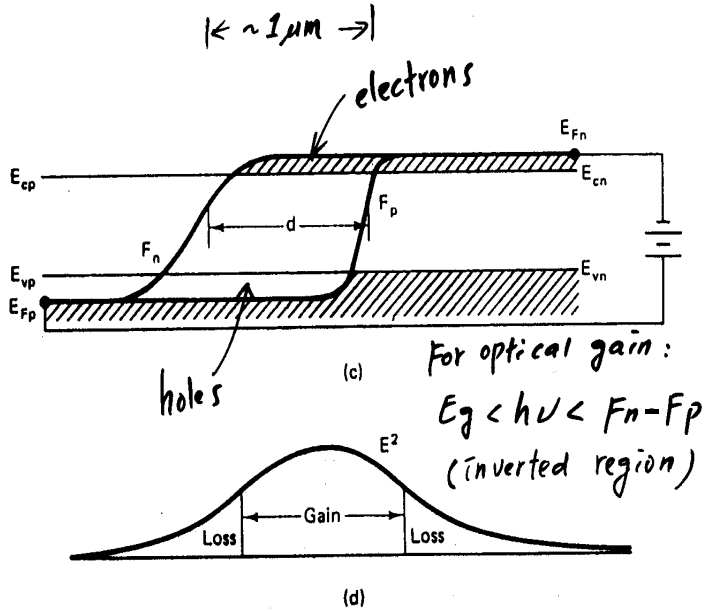


(a)



(b)

Same Eg.



For optical gain:

$E_g < h\nu < F_n - F_p$

(inverted region)

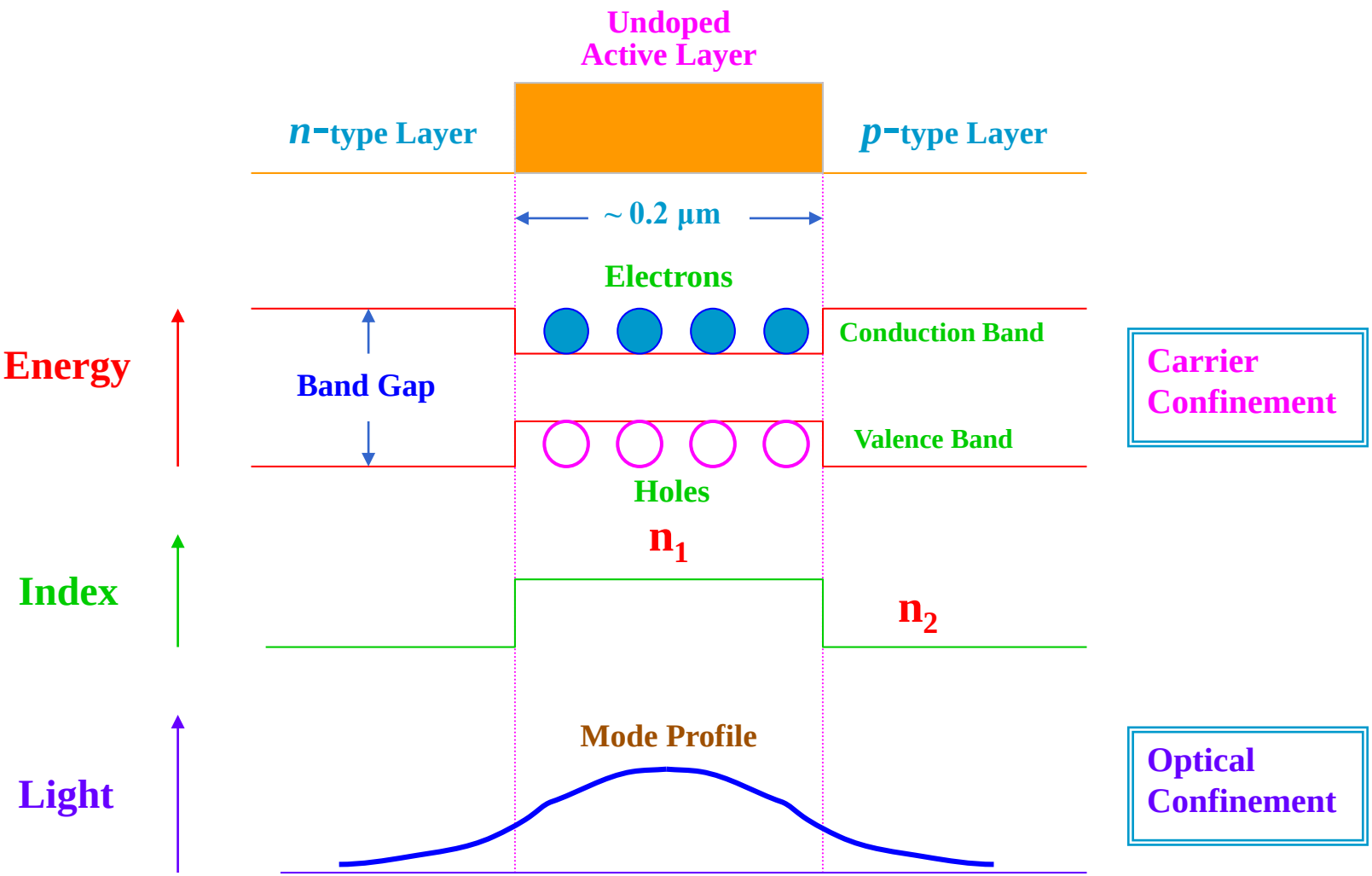
Figure 11.10 The homojunction laser: (a) shows a cross section of the junction with the bowed area being due to current spreading; (b) and (c) show the band diagram in equilibrium and with injected current; (d) illustrates the electromagnetic mode experiencing gain and loss.

Notes.

① Direction of laser light is out of (or, into) paper.

② Tail of optical (lateral) modes experiences losses.

Double-Heterojunction (DH) Structure



AlGaAs Double-Heterostructure Semiconductor Lasers

$E_g \cong 1.424 + 1.247x$ eV

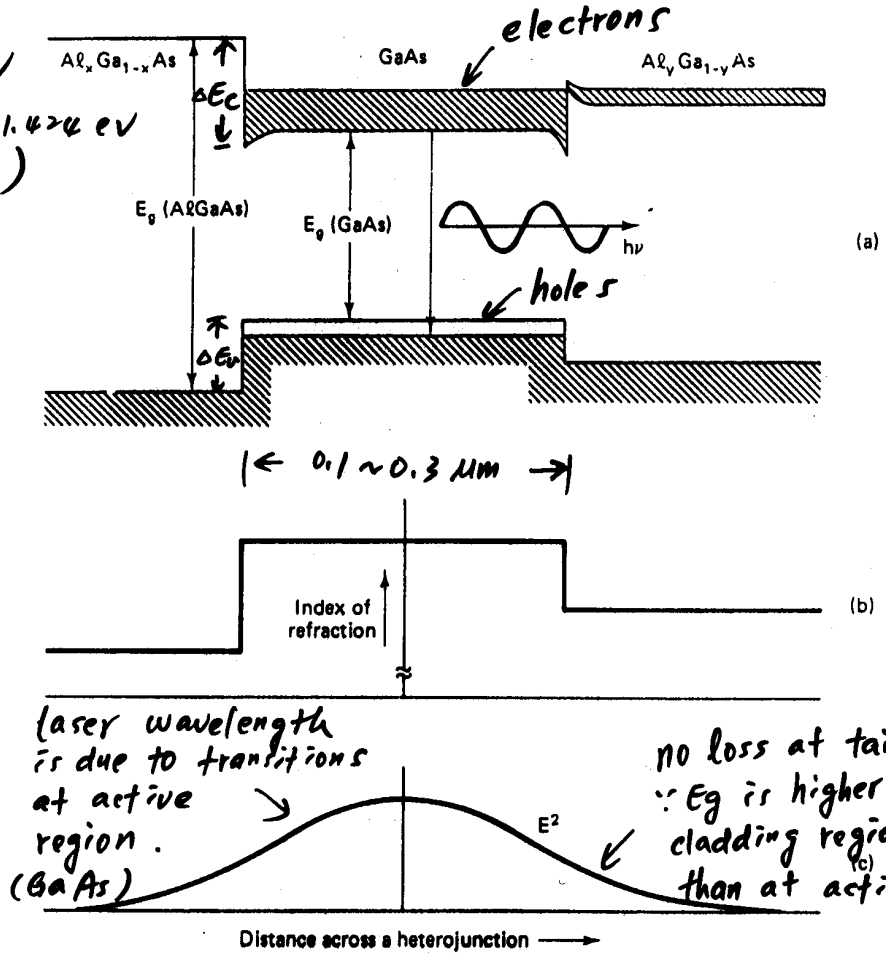
$\therefore E_g(AlGaAs) > E_g(GaAs)$ ← 1.424 eV

$\Delta E_g = E_g(AlGaAs) - E_g(GaAs)$

$\Delta E_c \cong 0.65\,\Delta E_g$

$\Delta E_v \cong 0.35\,\Delta E_g$

ΔE_c, ΔE_v → Band offset of conduction and valance bands.



E_g : ← good carrier confinement

n : ← good optical confinement

no loss at tail. ∵ E_g is higher at cladding region (AlGaAs) than at active region (GaAs)

Figure 11.13 The band diagram for a forward-biased heterostructure in (a), the refractive index in (b), and a sketch of the light intensity in the vicinity of the active region in (c).

Quantum-Well Semiconductor Lasers

- A double-heterostructure laser consists of an active layer sandwiched between two higher-gap cladding layers. The active layer thickness is typically in the range of 0.1 to 0.3 μm.
- If the double-heterostructure laser with an active-layer thickness of ~10 nm is fabricated, the carrier (electron or hole) motion normal to the active layer is restricted. As a result, the kinetic energy of the carriers moving in that direction is quantized into discrete energy levels similar to the quantum-mechanical problem of the one-dimensional potential well.
- Quantum-well lasers have many advantages: (1) laser wavelength can be varied by changing the width of quantum well, (2) lower threshold current, (3) higher quantum efficiency, and (4) narrower linewidth.
- If there is only one quantum well in the active layer, we call it a Single Quantum Well (SQW) structure; if there are a few quantum wells in the active layer, we call it a Multiple Quantum Well (MQW) structure.

Eigenfunction and Eigenenergy in a Quantum-Well Structure

For infinite well :

$$E_n = \frac{\hbar^2 k_n^2}{2m^*},$$

$$k_n \cdot L_z = n\pi, \quad n = 1, 2, 3, \cdots$$

$$\Rightarrow E_1 = \frac{\hbar^2 (\pi/L_z)^2}{2m^*}$$

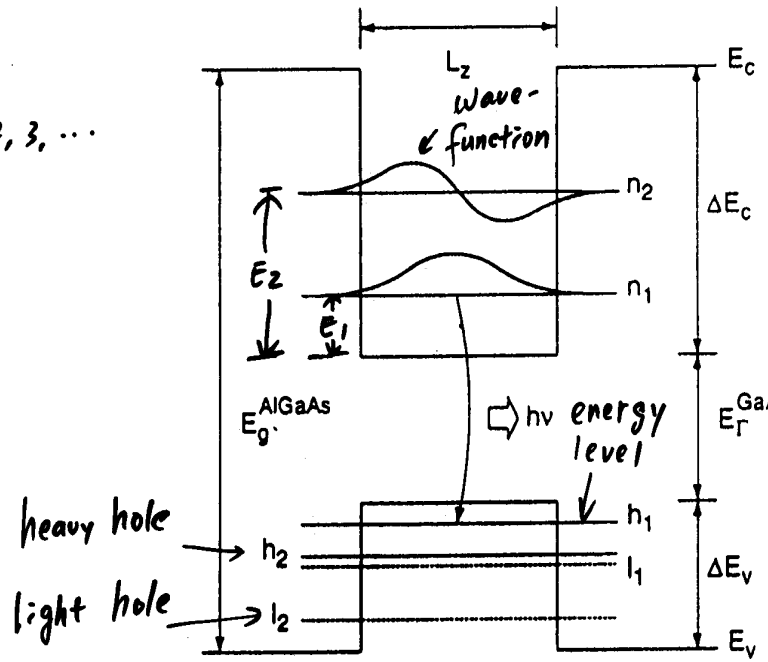
$$E_2 = \frac{\hbar^2 (2\pi/L_z)^2}{2m^*}$$

$$\vdots$$

$$E_n = \frac{\hbar^2 (n\pi/L_z)^2}{2m^*}$$

$$\uparrow$$

$$L_z \downarrow \Rightarrow E_n \uparrow$$



Wavefunctions :

① Inside the well
⇒ sinusoidal functions

② outside the well
⇒ exponential functions

$(= 0.65\ \Delta E_g)$

$(= 0.35\ \Delta E_g)$

(即, Active layer 愈窄, 能階愈往上升).

FIGURE 1.1. The eigenfunctions and eigenenergies for the first two conduction-band electron quantum states in an $Al_xGa_{1-x}As$-GaAs quantum-well heterostructure. By convention the lowest energy quantum state is the $n = 1$ or n_1 state. Also shown are the first two light-hole and heavy-hole valence-band eigenenergies.

E_n increases when the width of quantum well, L_z, decreases.

Confined State Energy as a Function of L_z for $GaAs/Al_{0.2}Ga_{0.8}As$

The region of band gap is not shown in this figure.

E is the energy separation between the quantum state and the bulk band edge.

E = 0 indicates the bottom of conduction band, or, the top of valence band.

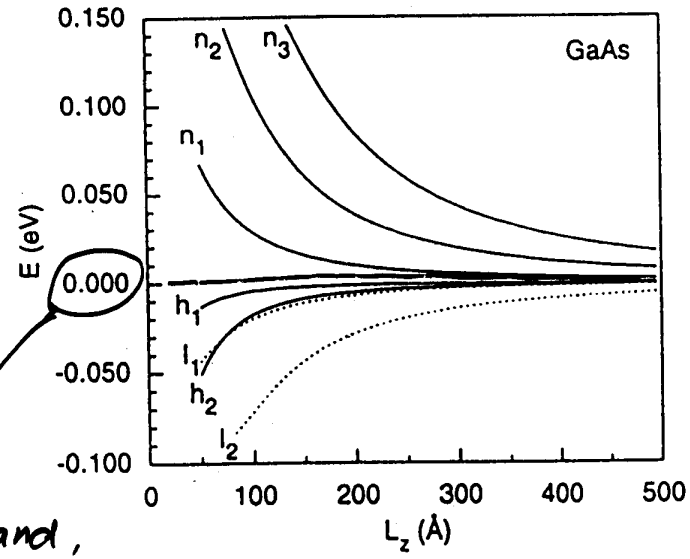


FIGURE 1.2. The confined state energy E as a function of quantum well width (L_z) for a realistic quantum-well heterostructure having a GaAs quantum well and $Al_{0.20}Ga_{0.80}As$ barrier layers. Positive energy corresponds to the electron energy above the bulk GaAs conduction-band edge and negative energy corresponds to hole energy below the bulk GaAs valence-band edge.

Note: if $T = 300\,^{\circ}K$, $kT = 0.026\ eV$.

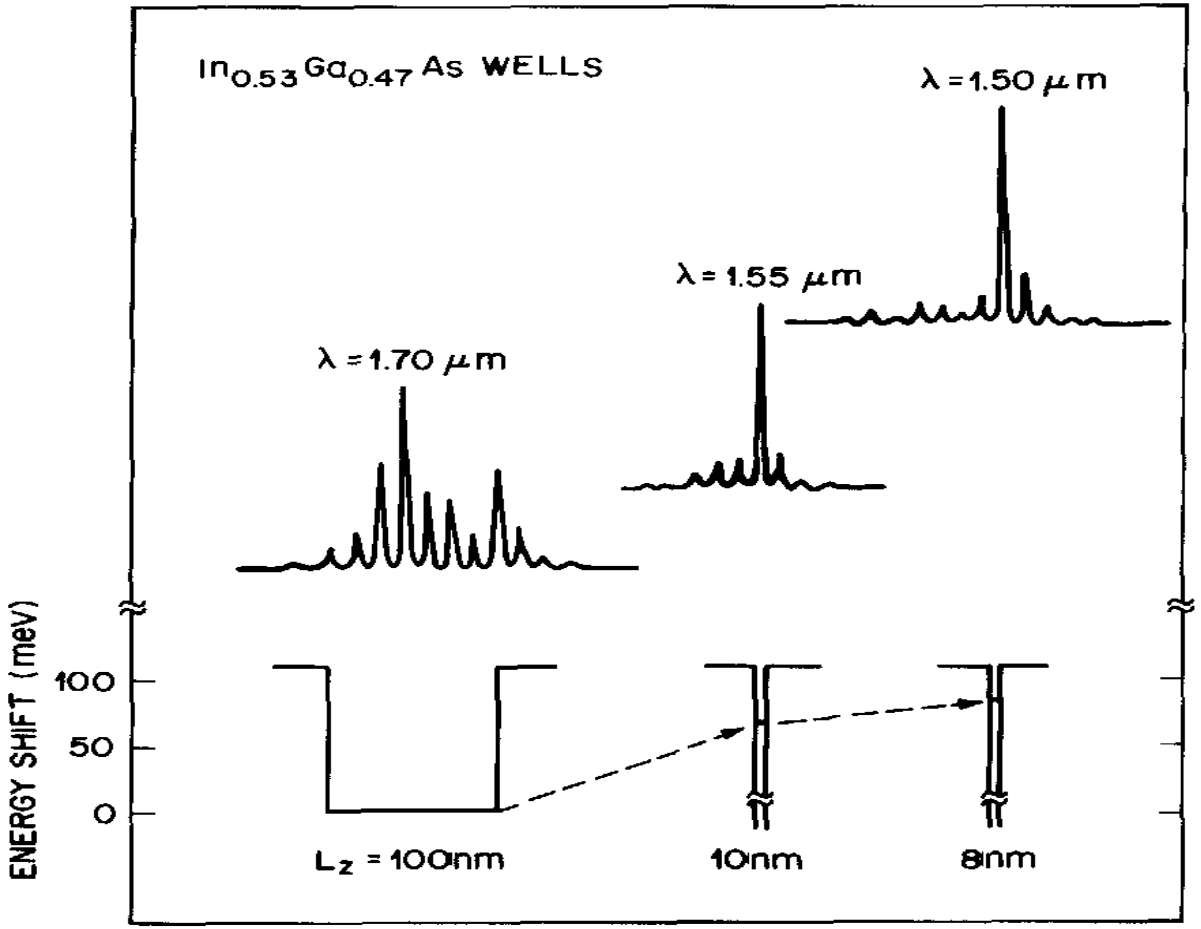
$\Rightarrow$ It's necessary that $L_z \leq 150\ \text{Å}$ in order to observe the quantum-size effect at room temperature in these structures.

Usually, $30\ \text{Å} < L_z < 100\ \text{Å}$

Note: $E_n \cong \dfrac{[\hbar(n\pi/L_z)]^2}{2m^*}$

$\Rightarrow L_z \downarrow \rightarrow E_n \uparrow$

Manipulating the Laser Wavelength by Varying the Thickness of the Quantum Well



$L_z \downarrow$

$\rightarrow \lambda \downarrow$

Fig. 9.7 Longitudinal-mode spectra for three well thicknesses of an InGaAs-InP multiquantum-well structure. The wavelength shift corresponds to the energy-level shift of the quantum well (dashed lines). (Courtesy of H. Temkin)

Some Important Semiconductor Lasers

- **Fiber Communication: InGaAsP (λ: 1.31 / 1.55 μm)**

  Dispersion is minimum at 1.31 μm (less signal distortion); Loss is minimum at 1.55 μm (longer distance between repeaters).

- **CD Player/CD ROM: AlGaAs (λ: 780 nm)**

  Storage capacity ≈ 0.67 GB.

- **DVD: AlGaInP (λ: 650 nm)**

  Storage capacity ≈ 4.7 GB.

- **High-Density DVD: InGaN (λ: 405 nm)**

  Storage capacity > 18 GB.

Optical Fiber Communication

- The transmission of optical signals from source to detector can be greatly enhanced if an *optical fiber* is placed between the light source and the detector.
- One type of optical fiber has an outer layer of very pure fused silica (SiO_2), with a core of germanium doped glass having a higher index of refraction. Such a *step-index fiber* maintains the light beam primarily in the central core with little loss at the surface. The light is transmitted along the length of the fiber by internal reflection at the step in the refractive index.
- In a step-index fiber, different modes propagate with different path lengths, which causes an extra dispersion in addition to the chromatic dispersion that caused by the fact that the refractive index is a function of wavelength. This type of dispersion can be reduced by *grading the refractive index of the core* such that various modes are continually refocused, reducing the differences in path lengths.

Distortion Caused by Dispersion

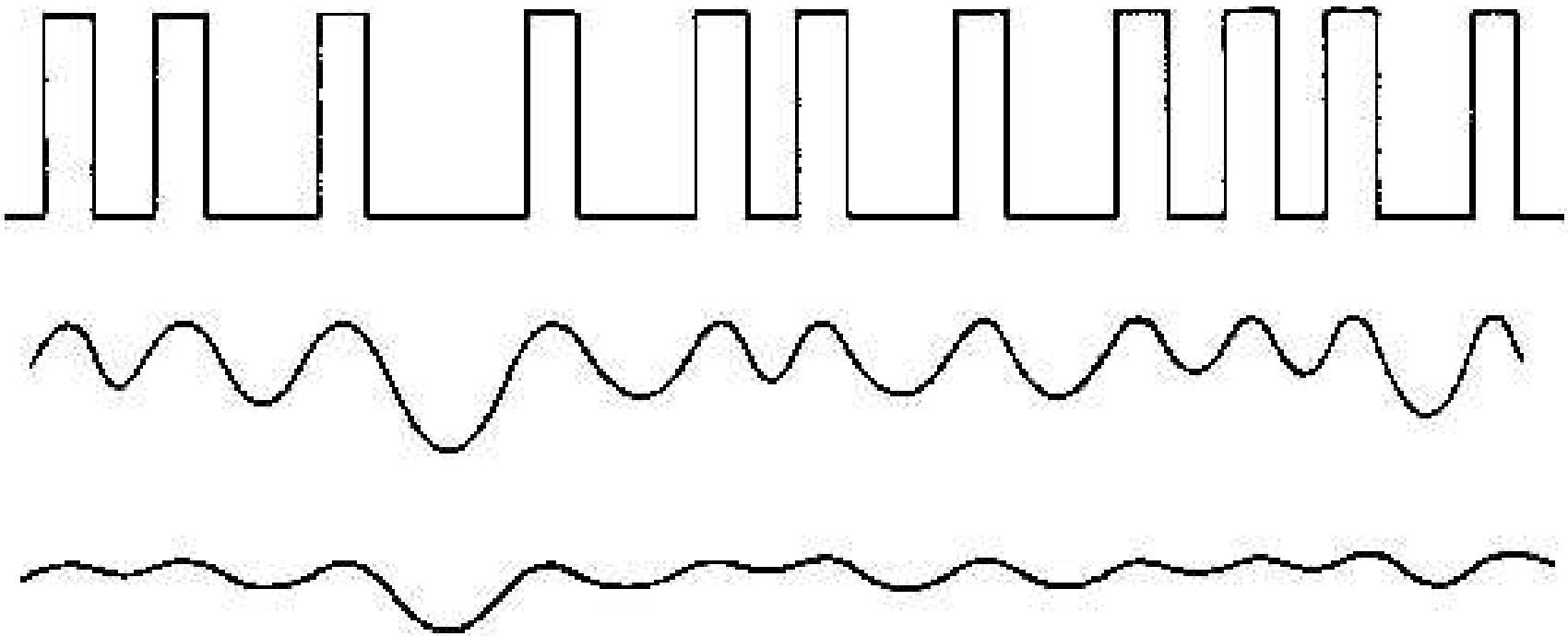


Figure 5.74 Rectangular pulses of light smeared out by increasing amounts of dispersion. Note how the closely spaced pulses degrade more quickly.

Step-Index and Graded-Index Fibers

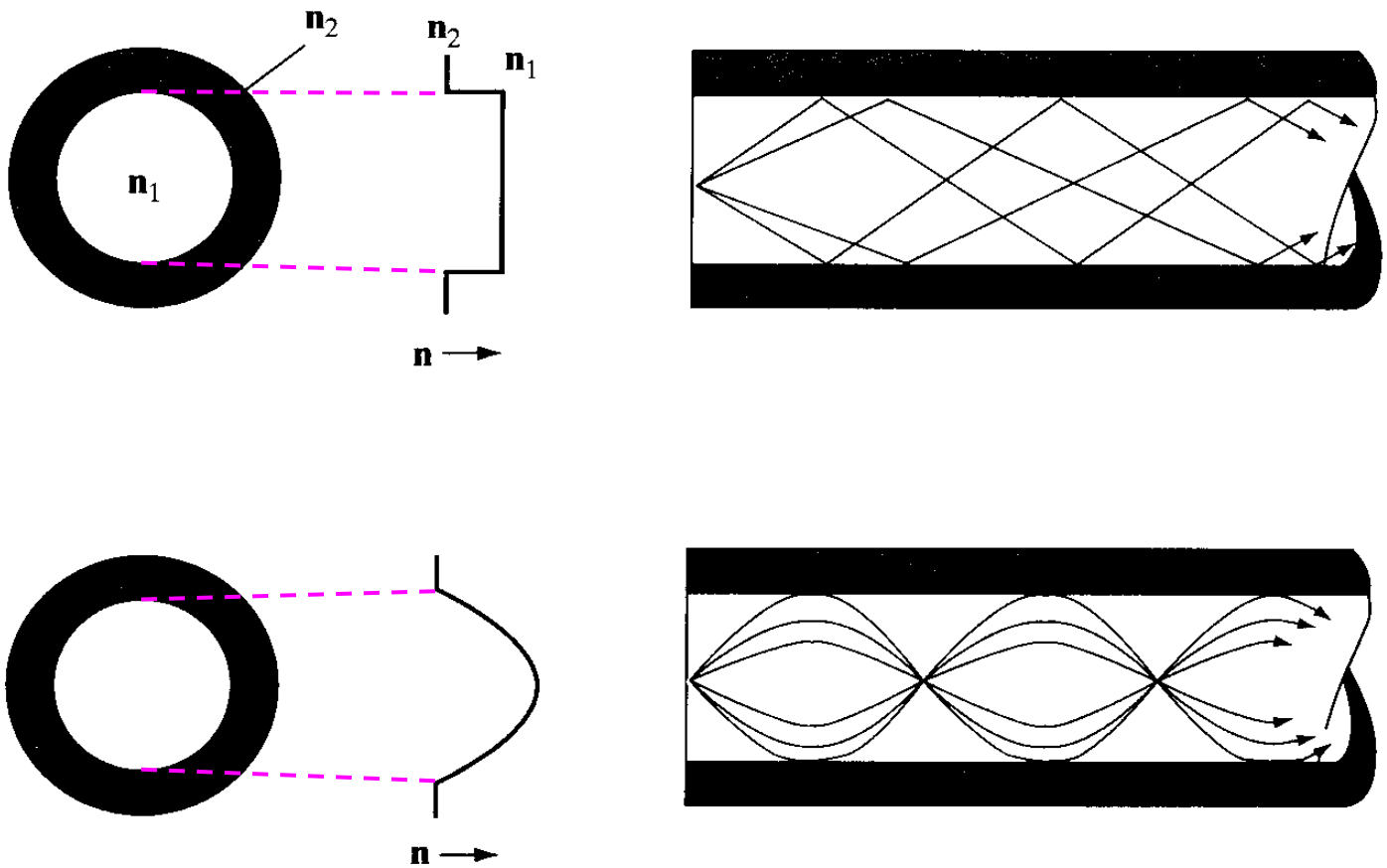


Figure 8–12
Two examples of multimode fibers: (a) *step-index*, having a core with slightly larger refractive index **n**; (b) *graded-index* having in this case a parabolic grading of **n** in the core. The figure illustrates the cross section (left) of the fiber, its index of refraction profile (center), and typical mode patterns (right).

Index Profiles of Three Fiberoptic Configurations

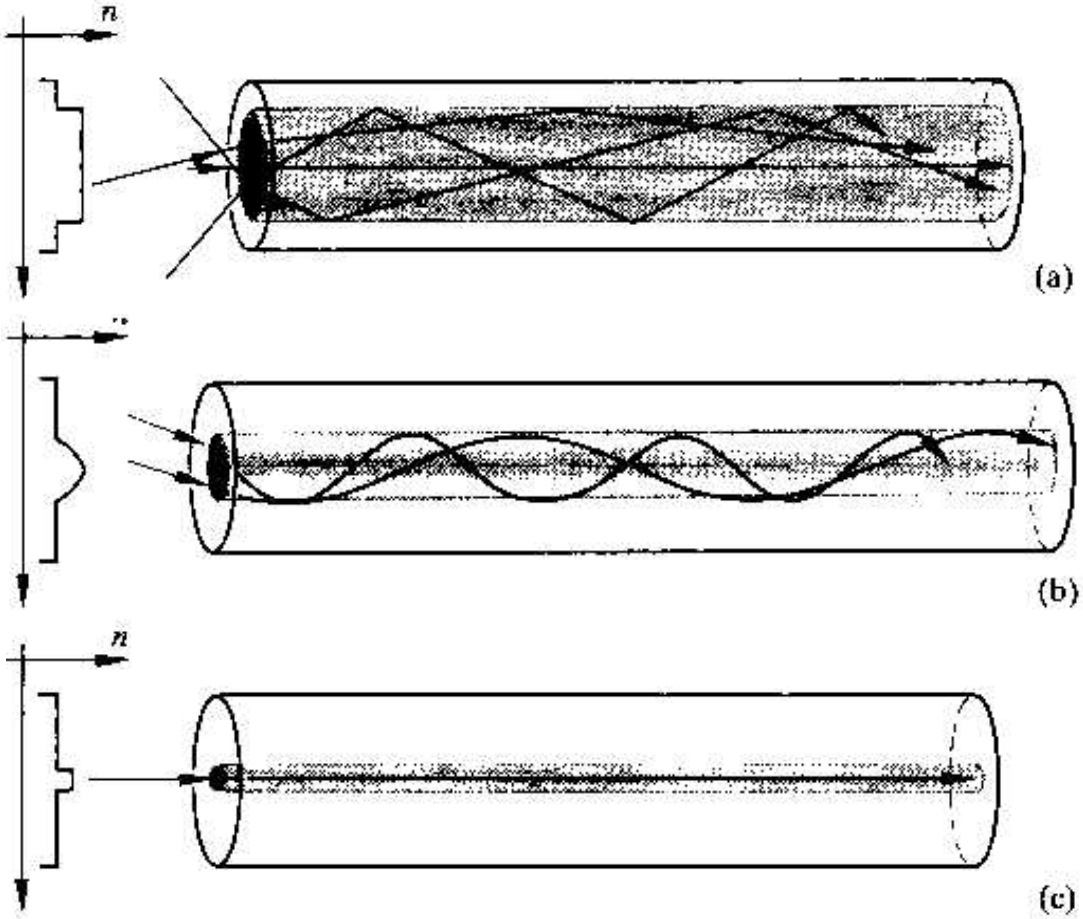
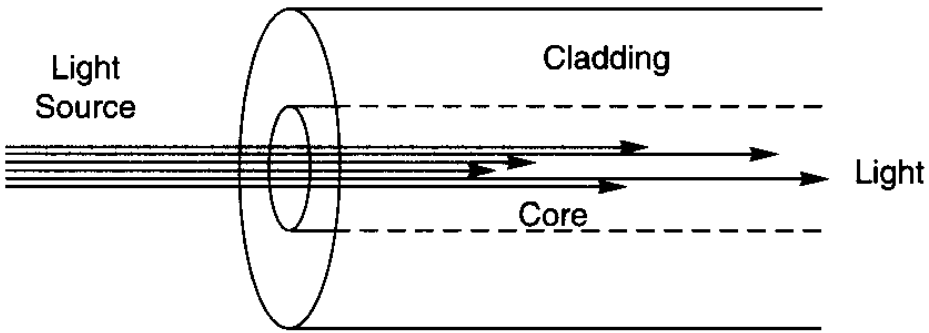
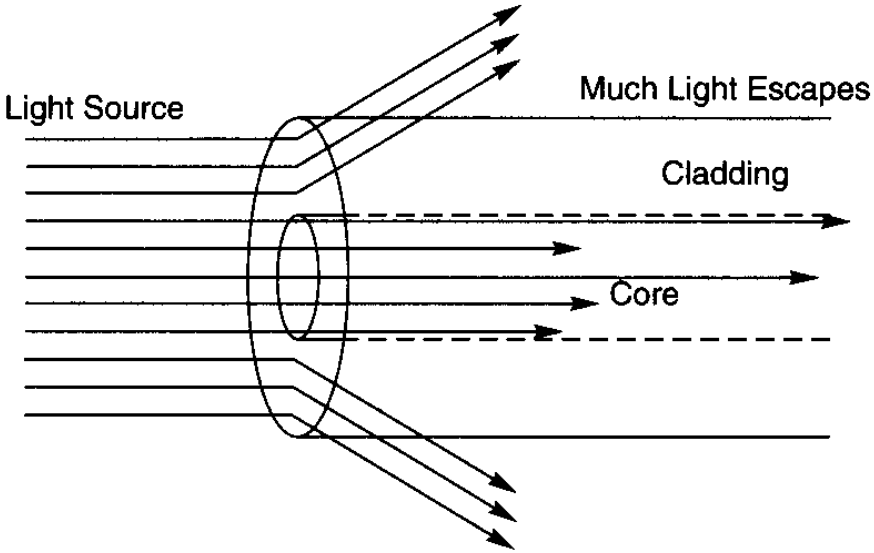


Figure 5.72 The three major fiberoptic configurations and their index profiles. (*a*) Multimode step-index fiber. (*b*) Multimode graded-index fiber. (*c*) Single-mode step-index fiber.

Match Between Light-Source and Core Diameter

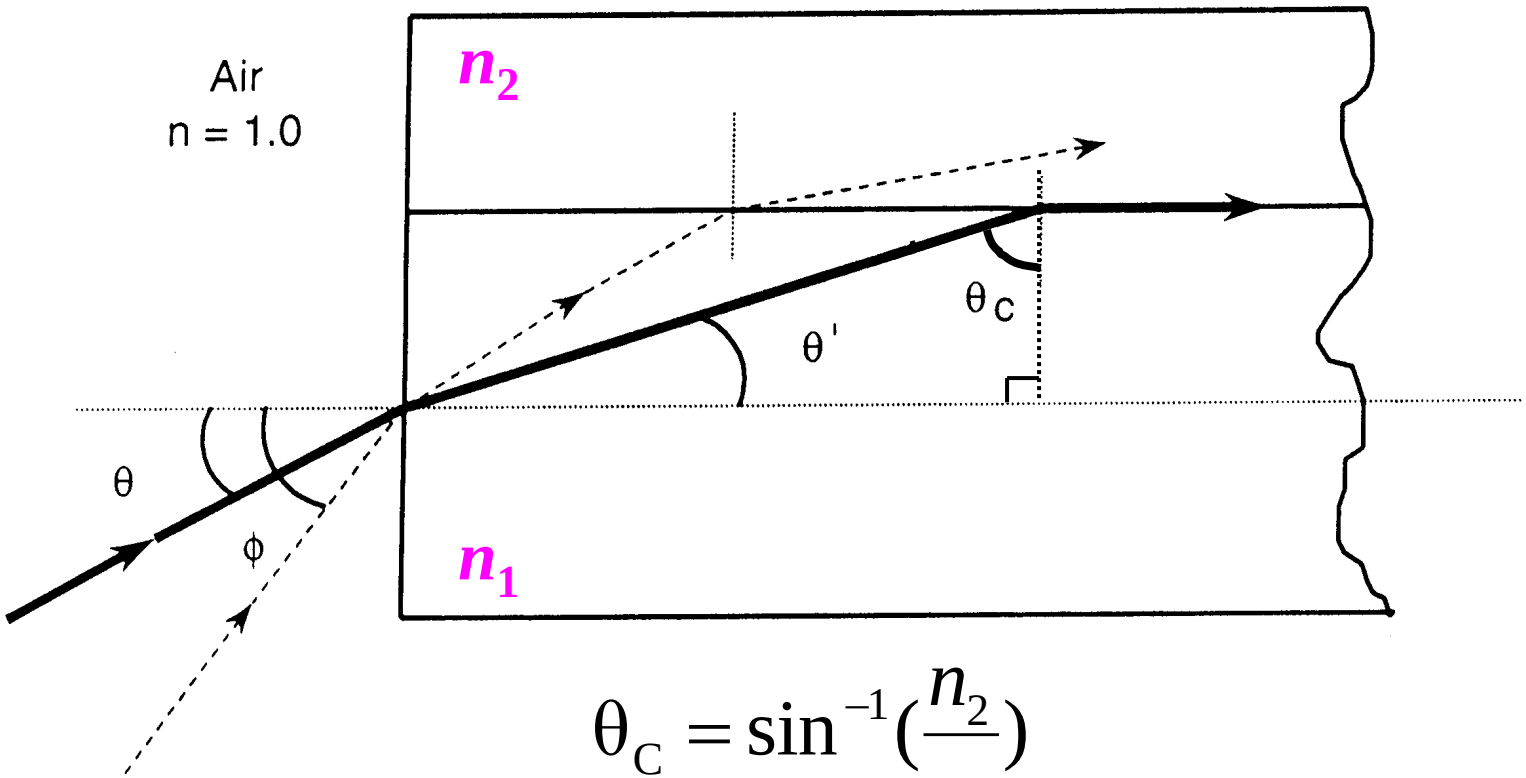


Light Source Well Matched to Fiber



Light Source Poorly Matched to Fiber

Application of Total Internal Reflection

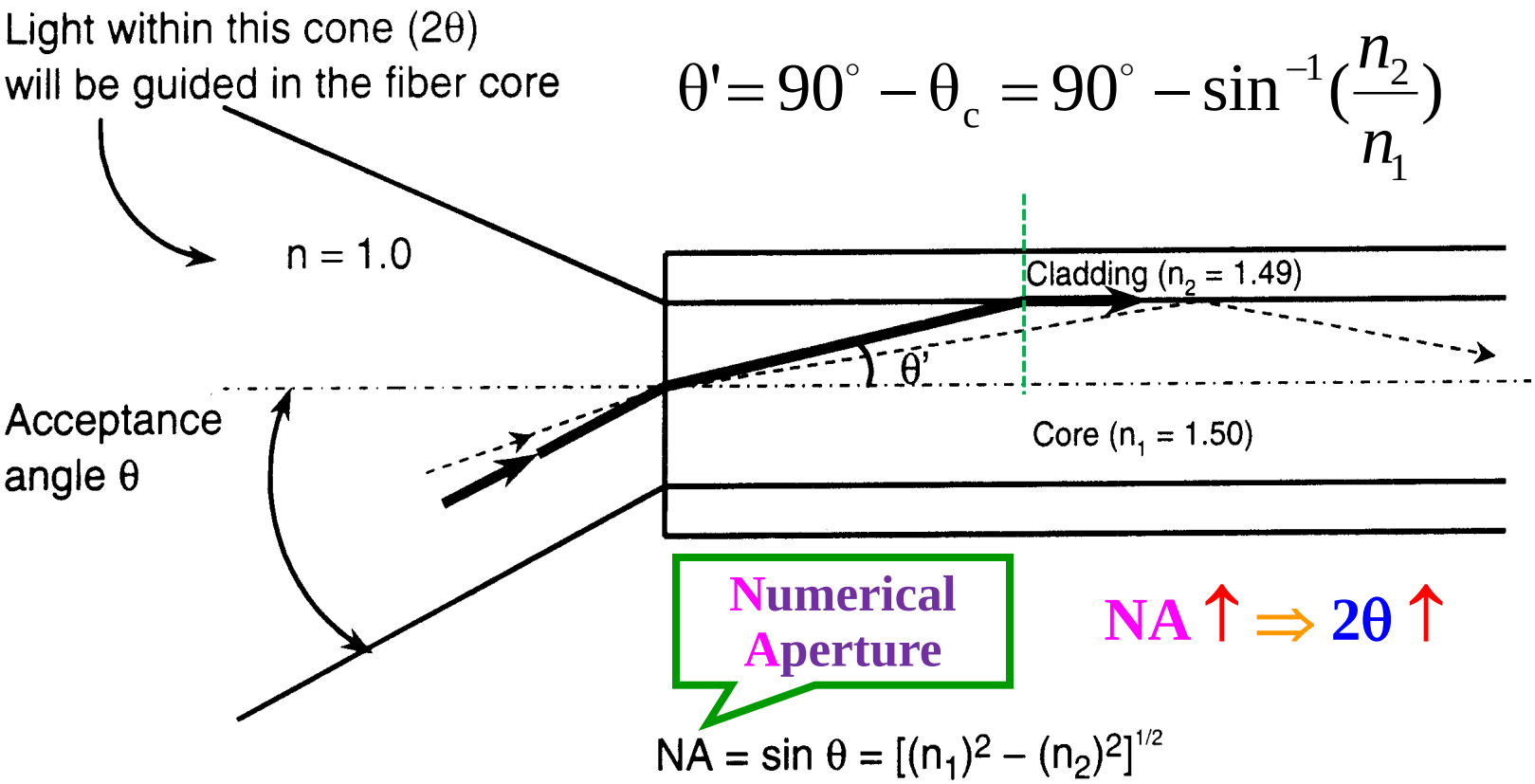


$$\theta_C = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

Figure 4.13 Internal reflection using two different glass media.

Acceptance Angle Measured by Numerical Aperture

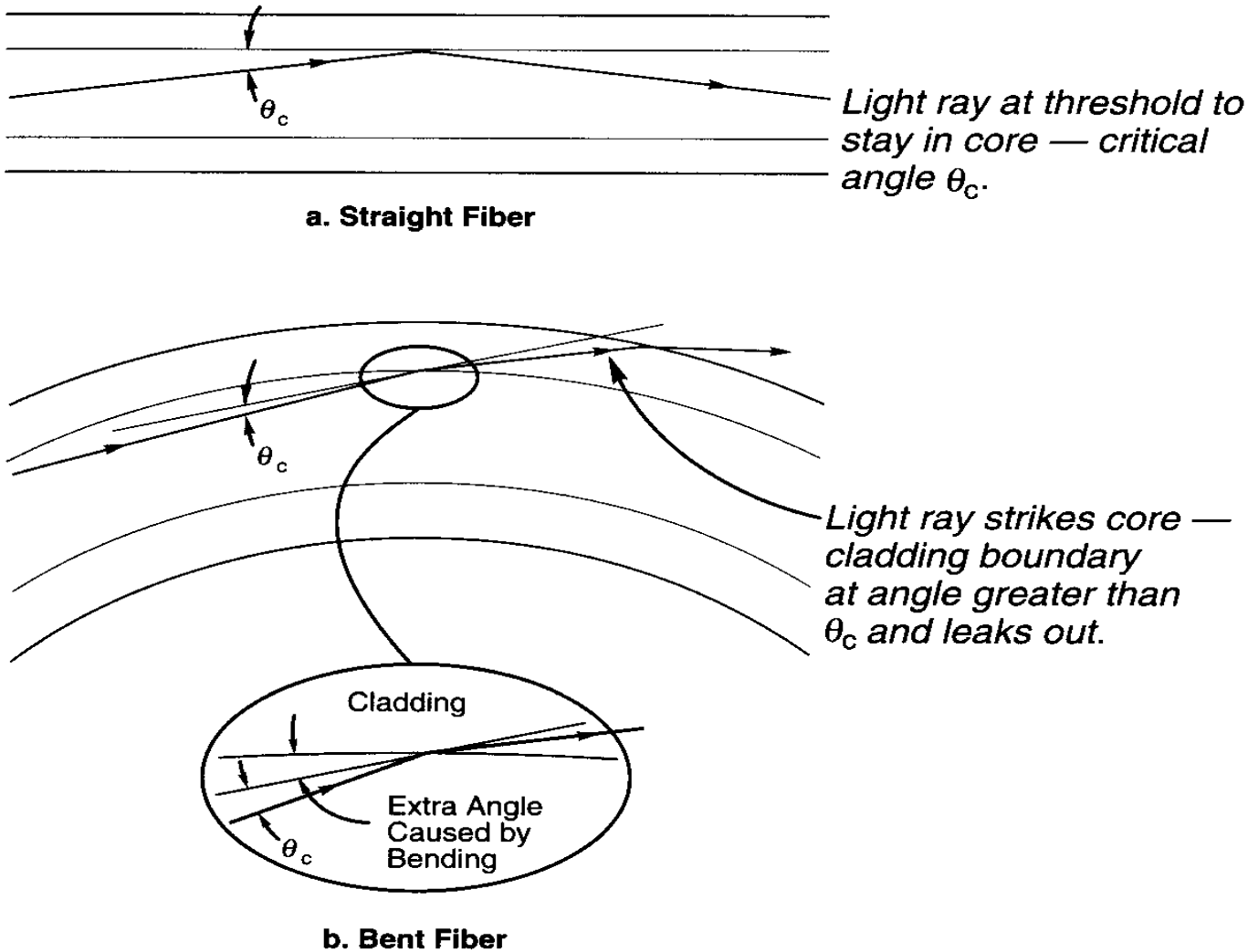
$$\theta' = 90^\circ - \theta_c = 90^\circ - \sin^{-1}\left(\frac{n_2}{n_1}\right)$$



NA ↑ ⇒ 2θ ↑

Figure 4.14 Core-cladding structure of optical fiber.

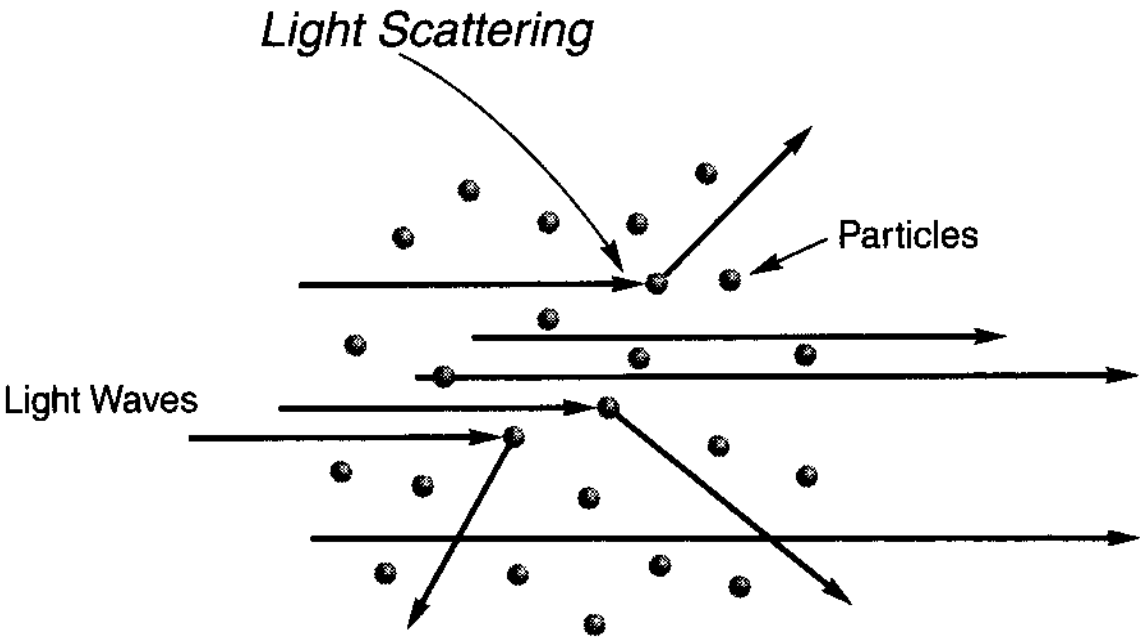
Bending Losses – light can leak out of a bent fiber



Rayleigh Scattering and Infrared Absorption in Silica Fiber

- The attenuation of a laser light in the silica (SiO_2) fiber is not the same for all wavelengths. The absorption spectrum of the silica fiber shows that dips in attenuation curve near 1.31 μm and 1.55 μm provide "windows" in the attenuation.
- The overall decrease in attenuation with increasing wavelength is due to the reduced scattering from small random inhomogeneity which results in fluctuations of the refractive index on a scale comparable to the wavelength. This type of attenuation, called *Rayleigh scattering*, decreases with the fourth power of wavelength.
- Obviously, Rayleigh scattering encourages operation at long wavelengths in fiber optic systems. However, a competing process of *infrared absorption* dominates for wavelengths longer than about 1.7 μm, due to vibrational excitation of the atoms making up the glass. Therefore, a useful minimum in absorption for silica fibers occurs at about 1.55 μm, where epitaxial layers in the InGaAsP system can be grown lattice-mated to the InP substrate.

Rayleigh Scattering of Light

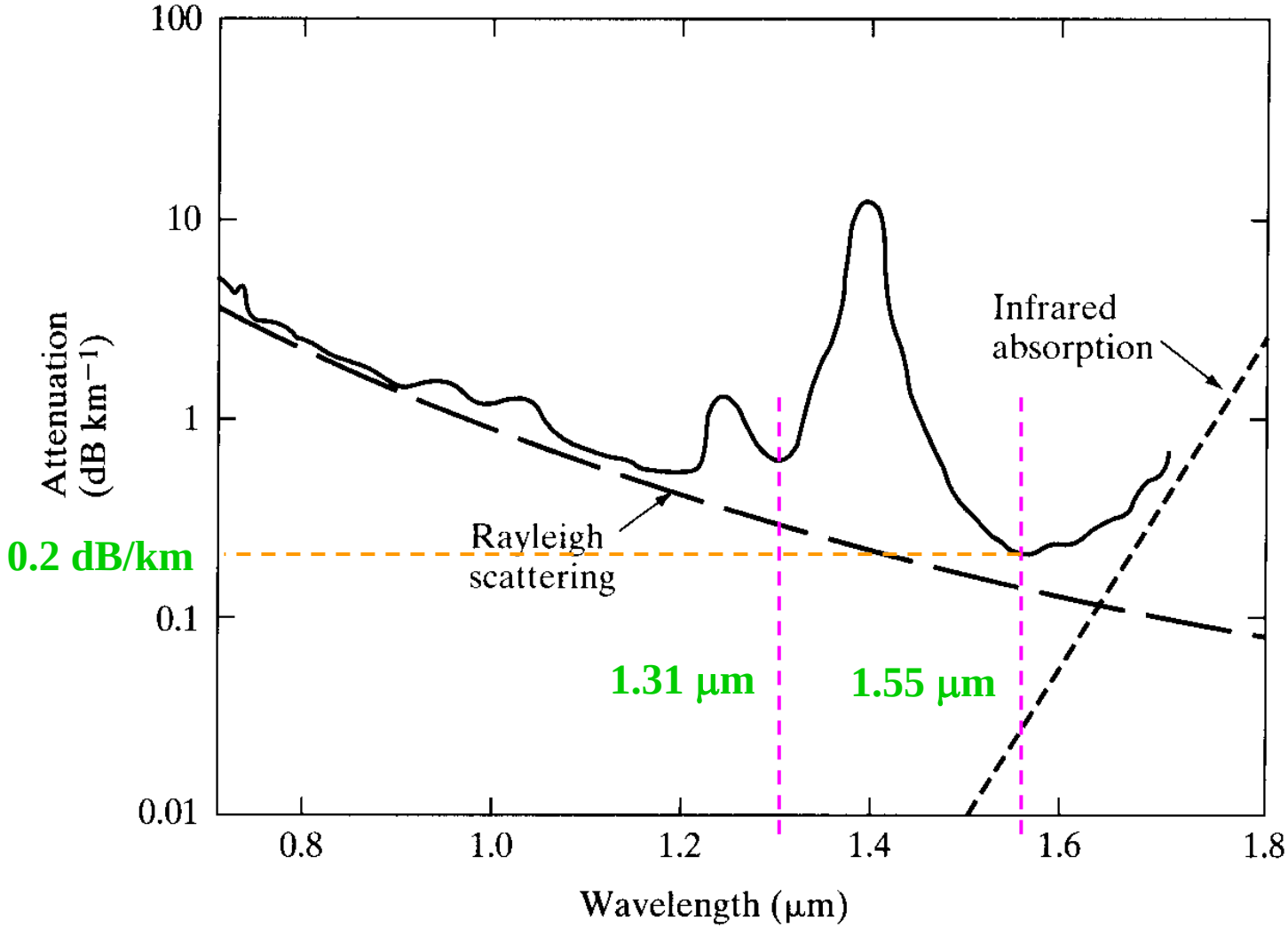


For a transparent solid, the scattering loss in decibels (dB) per kilometer is given by **(分貝)**

$$\text{Scattering} = A\lambda^{-4}\ (\text{dB/km})$$

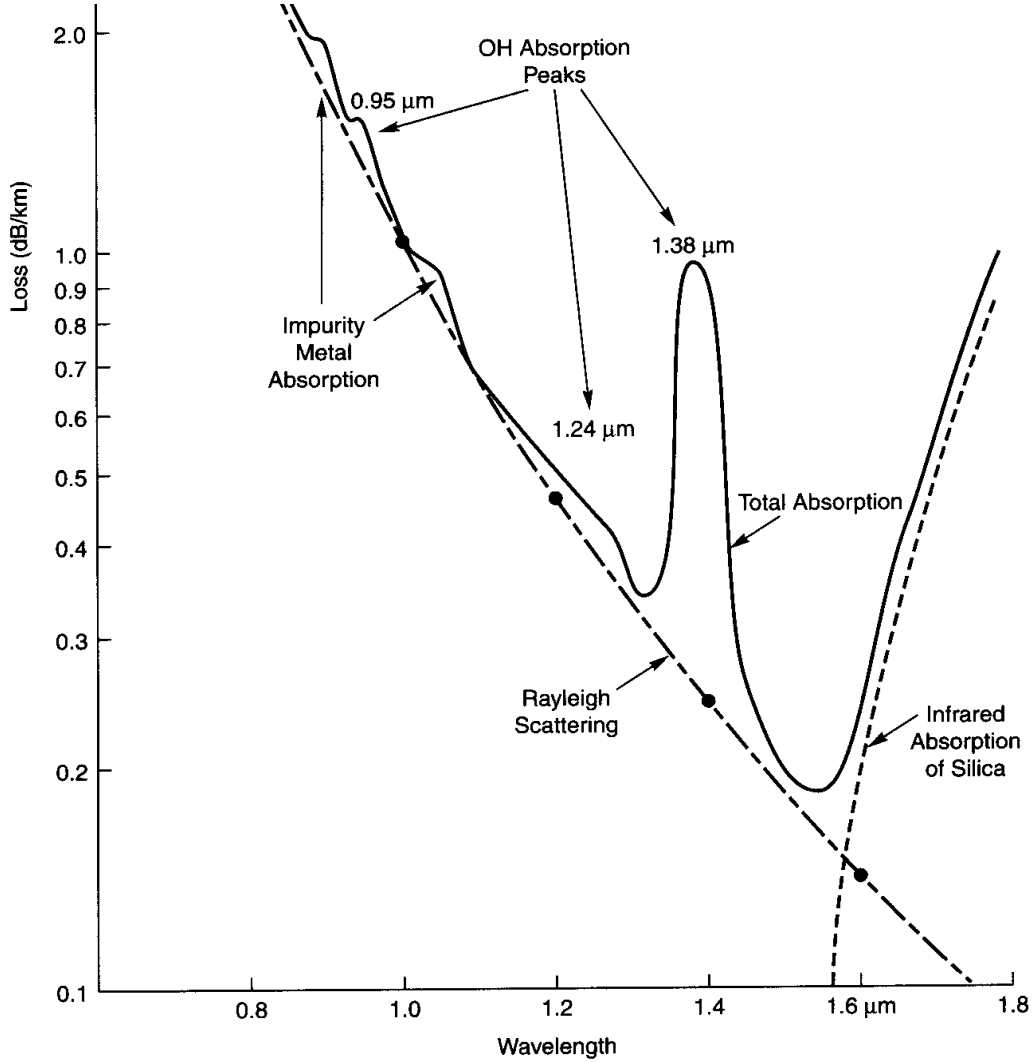
where *A* is a constant depending on the material.

Attenuation Coefficient vs. Wavelength for a Fused Silica Optical Fiber

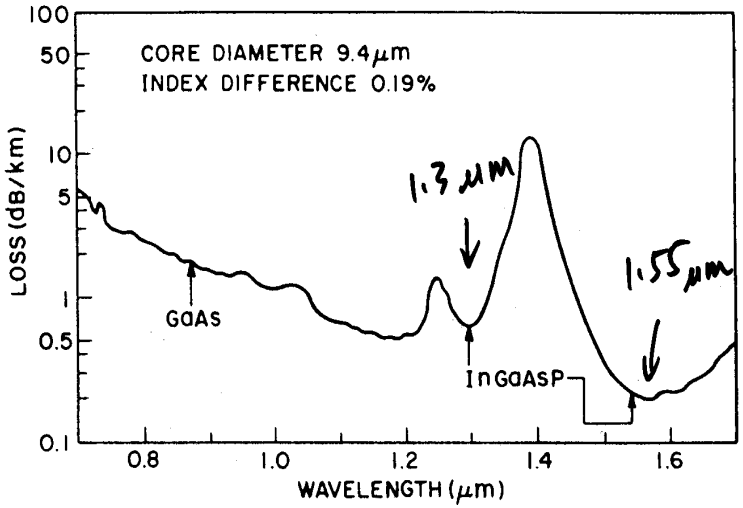


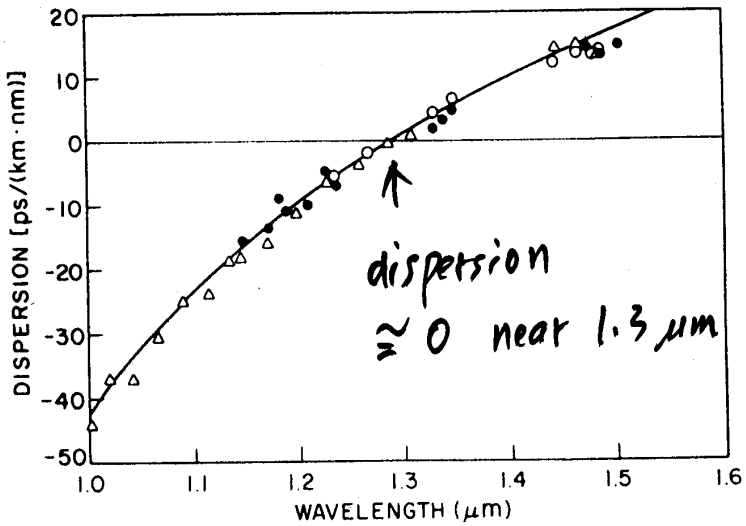
Loss vs. Wavelength in a Fiber

(Reference: J. Hecht, *Understanding Fiber Optics*, 4th Edition, 2002)



Semiconductor Lasers for Fiber Communications

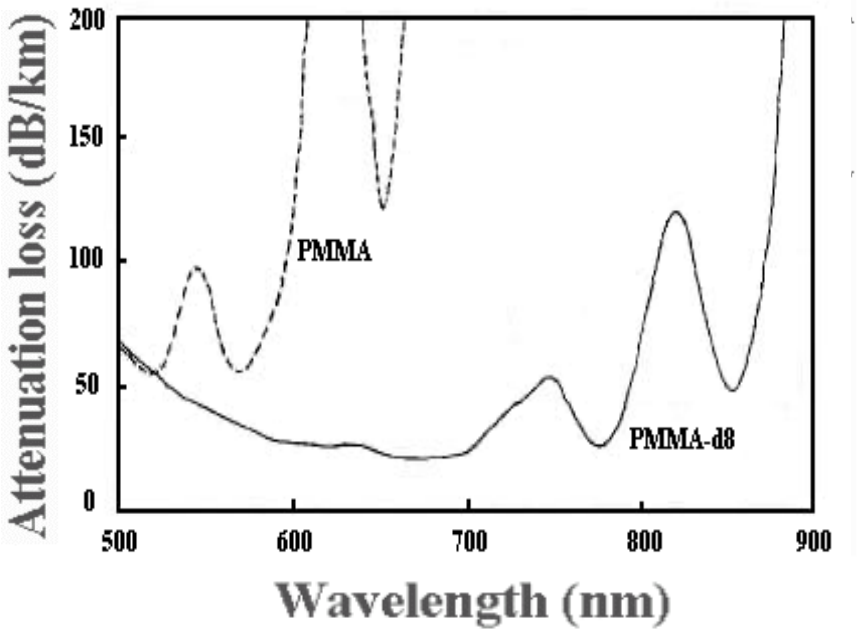


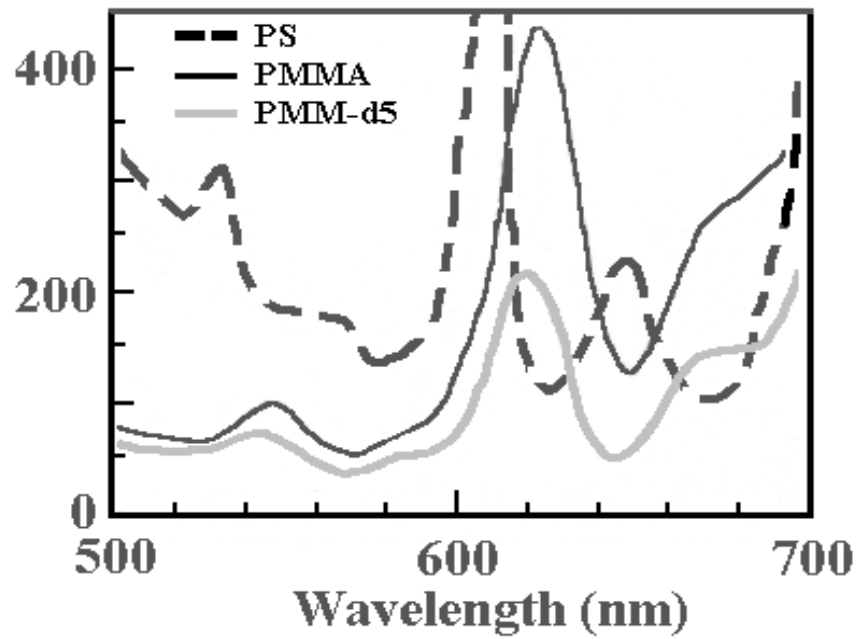


- **Optical fiber (SiO_2) has low-loss windows at 1.3 μm and 1.55 μm.**
- **Loss ≅ 0.2 dB/km at 1.55 μm (Loss ≅ 3 dB after 15 km; i.e., the signal will attenuate to one half of its original amplitude in 15 km).**

  Note: dB ≡ 10 log (P_1/P_2) = 20 log (E_1/E_2)
- **Dispersion is minimum near 1.3 μm. (Distortion of signals is minimized near 1.3 μm.) Best candidate for long-range fiber communication: $In_xGa_{1-x}As_yP_{1-y}$ / InP**

Materials for Short-Range Optical Fiber Communication





- **PMMA (Polymethylmethacrylate) related optical fibers have low-loss windows near 570 nm, 650 nm, and 850 nm.**
- **Plastic fibers and short-wavelength (edge-emitting and vertical-cavity surface-emitting) semiconductor lasers are better options for short-range optical fiber communication if cost is a major concern.**

Application of AlGaInP & InGaN LED and Laser Diode

- **Application of AlGaInP & InGaN LED:**

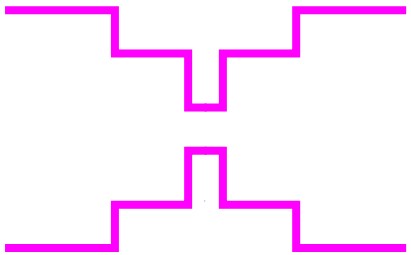
  Full-color LED display, Outdoor panel display, Traffic lights, LED light bulb (including white light source), Full-color scanner, Automobile lighting, etc.

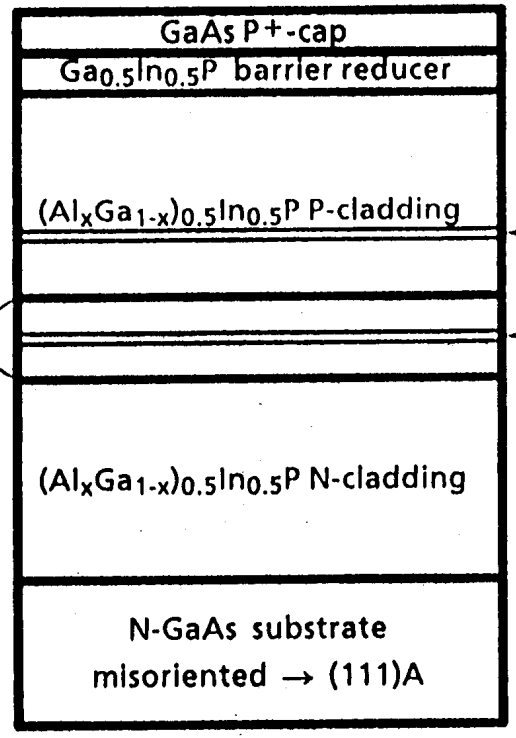
- **Application of AlGaInP & InGaN LD:**

  DVD, High-density DVD, Laser pointer, Local communication, Laser printer, Bar code reader, Medicine, Sold-state laser pumping, Material processing, Entertainment, Instrumentation, etc.

Typical Structure of AlGaInP Semiconductor Lasers

SCH Structure





$(Al_xGa_{1-x})_{0.5}In_{0.5}P$ SCH

Saparate Confinement Heterojunction Structure

$Al_{0.5}In_{0.5}P$ cladding layers:

x_{clad} = 1.0

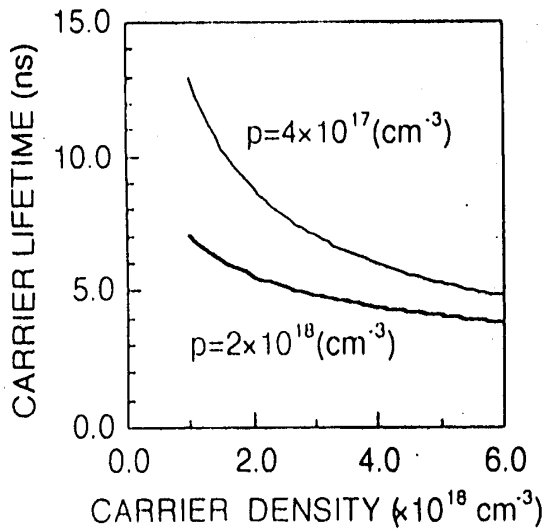
x_{SCH} = 0.5 -0.8

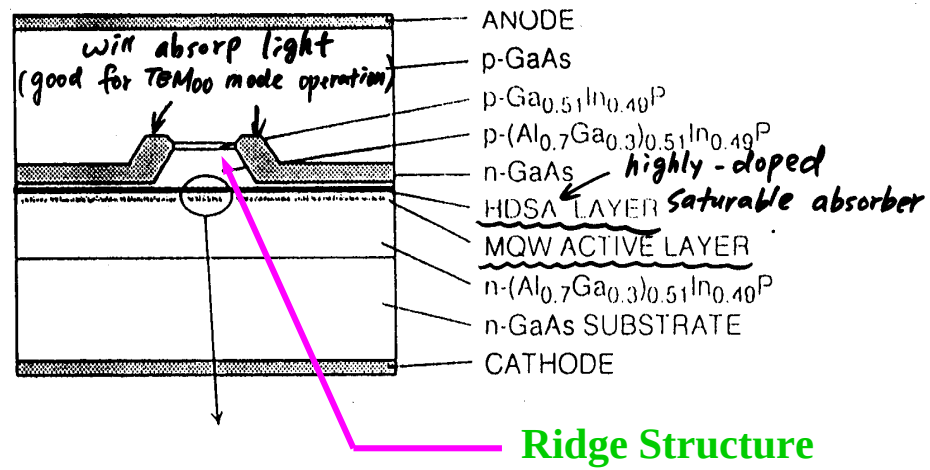
$(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ cladding layers:

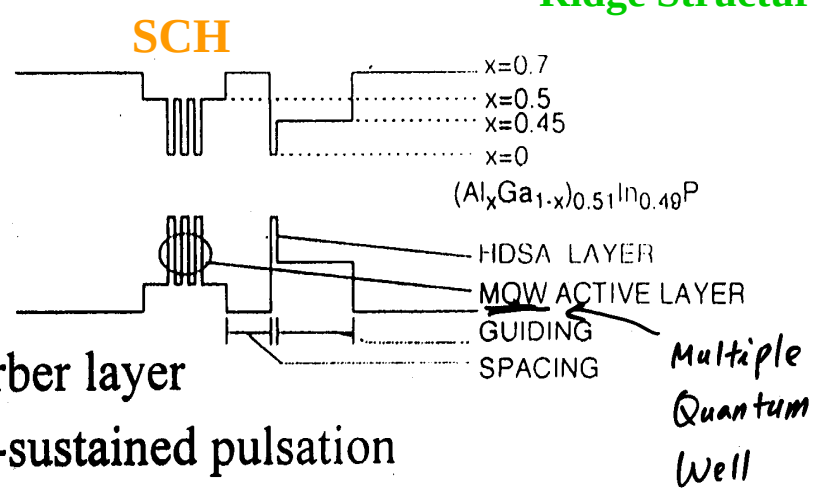
x_{clad} = 0.7

x_{SCH} = 0.3 - 0.5

Self-Pulsation Semiconductor Lasers with Saturable Absorber







pulse-mode operation (for DVD)

⇒ Low Intensity Noise

(Signal-to-noise ratio, S/N ↑)

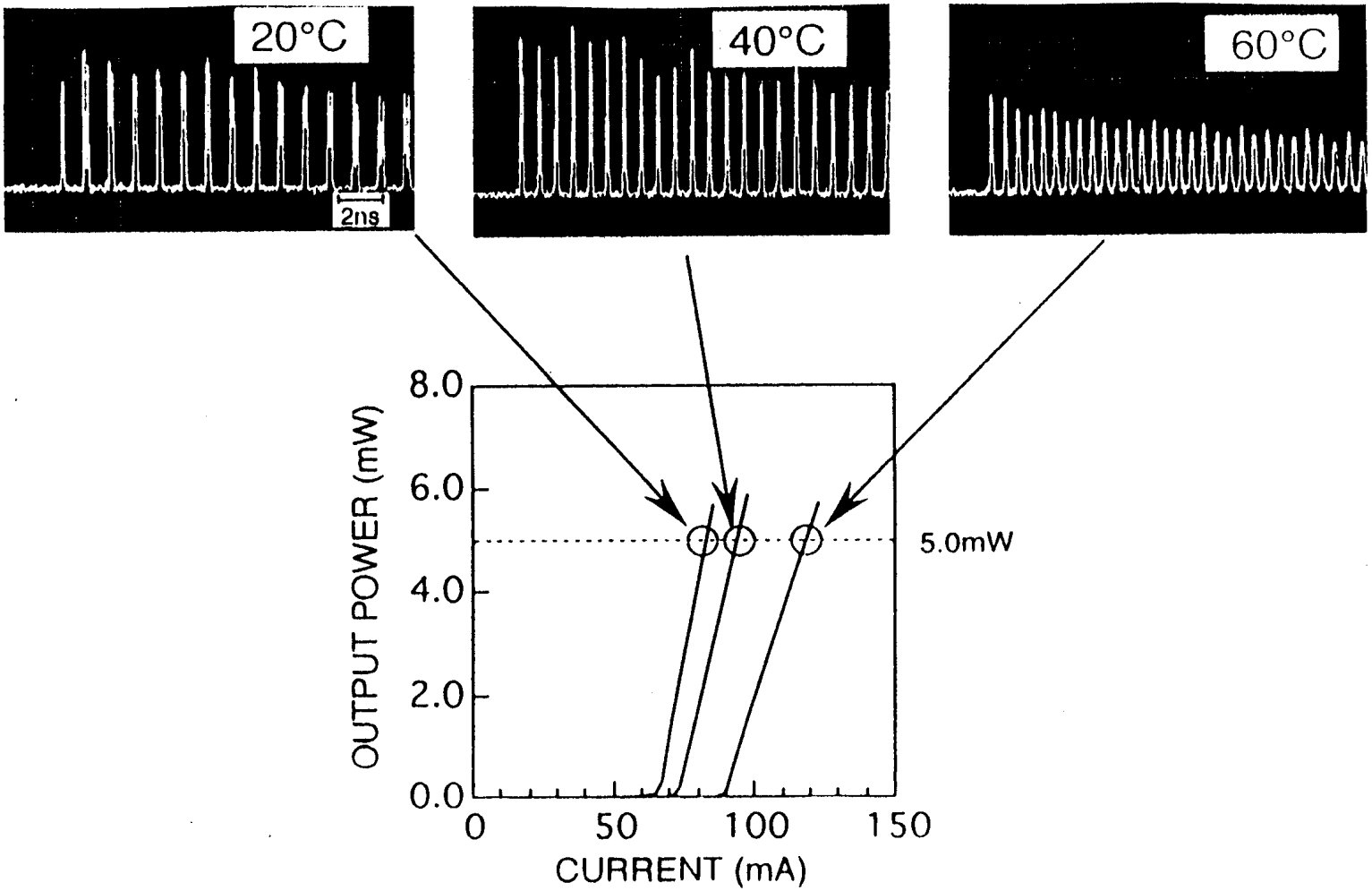
- High doping in saturable absorber layer

⇒ Short carrier lifetime ⇒ self-sustained pulsation

* After Kidoguchi et al., Appl. Phys. Lett., vol. 68, no. 25, p. 3543, 1996.

Temperature Dependence of Laser Output for Self-Pulsation Laser Diode

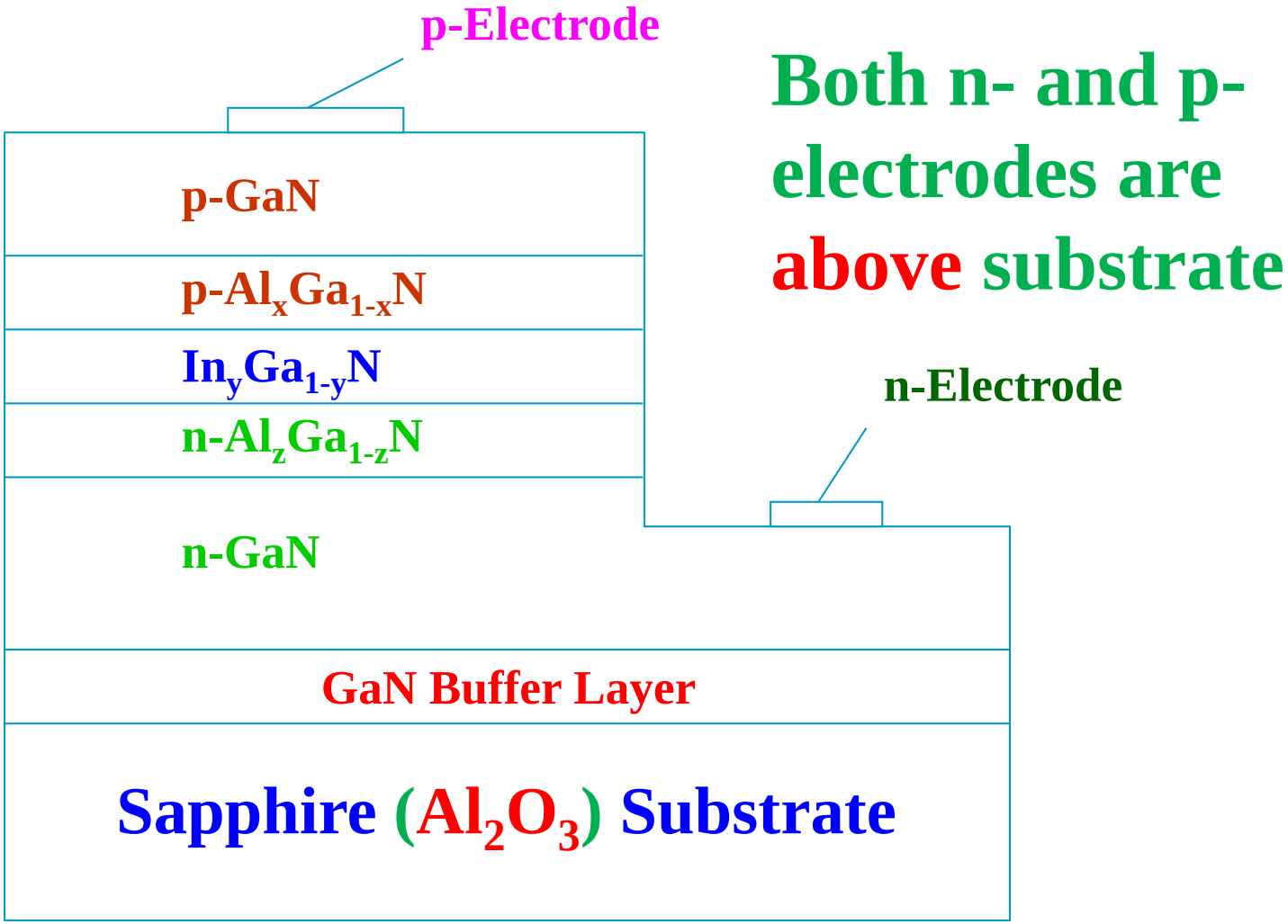
(From S. Kamiyama, Matsushita Elec. Co.)



Development of InGaN LED and Laser Diode

- 1971：Pankove (RCA) Develop first blue GaN LED
- 1989：Nakamura Start research on GaN
- 1991：Nakamura Develop first GaN pn-LED
- 1992：Akasaki Develop first room-temperature GaN LED
- 1993：Nakamura Develop first 1-Cd GaN blue LED
- 1995：Nakamura Develop first commercialized green GaN LED
- 1996/1：Nichia Inc. Develop first pulsed GaN blue LD
- 1996/12：Nichia Inc. Develop first CW GaN LD (life = 1 sec)
- 1997/8：Nichia Inc. CW GaN LD (life = 300 hours)
- 1997/9：Nichia Inc. CW GaN LD (life = 1,150 hours)
- 1997/10：Nichia Inc. CW GaN LD (life = 3,000 hours)
- 1997/11：Nichia Inc. CW GaN LD (life > 10,000 hours) (2 mW, 20 °C)
- 1999/1：Nichia Inc. Blue and green LDs are commercialized

InGaN/AlGaN LED/LD Grown on Sapphire Substrate



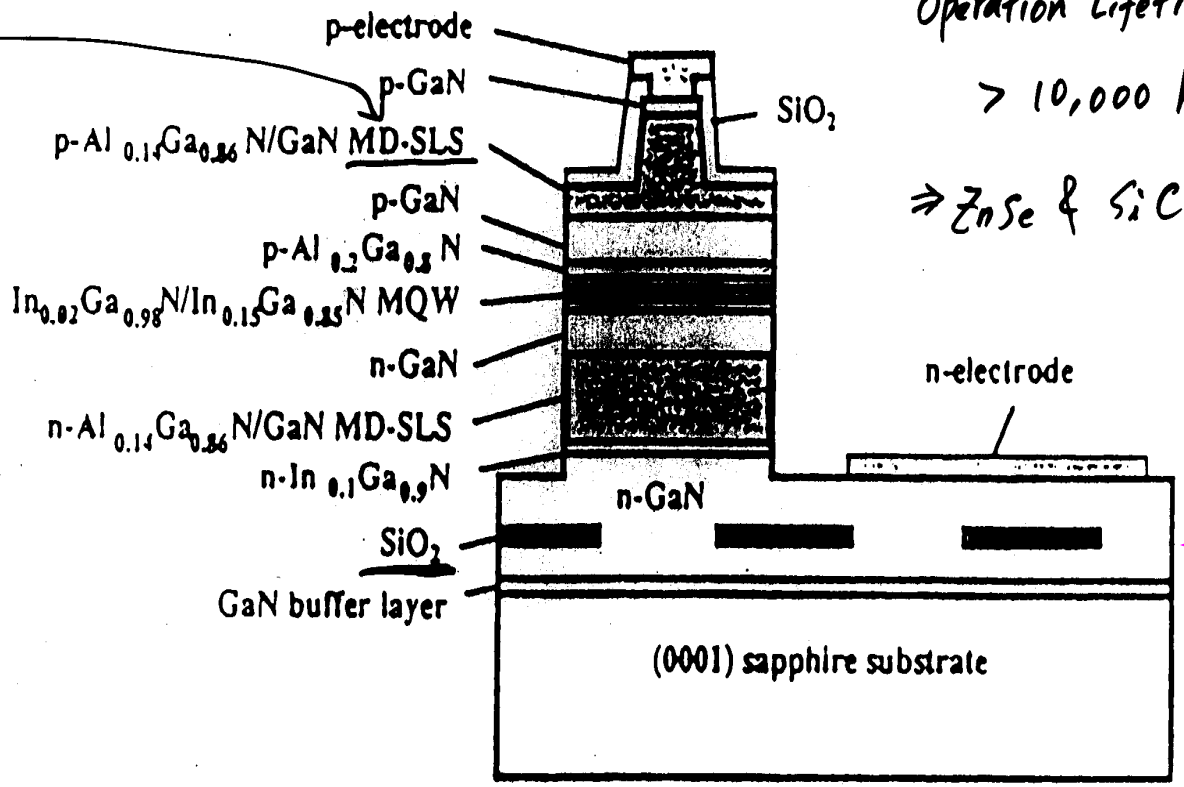
InGaN Semiconductor Laser Fabricated by Nichia Inc.

modulation-doped Strained-layer Superlattice

Operation Lifetime

> 10,000 hours !

⇒ ZnSe & SiC can't survive !!



ELOG Substrate

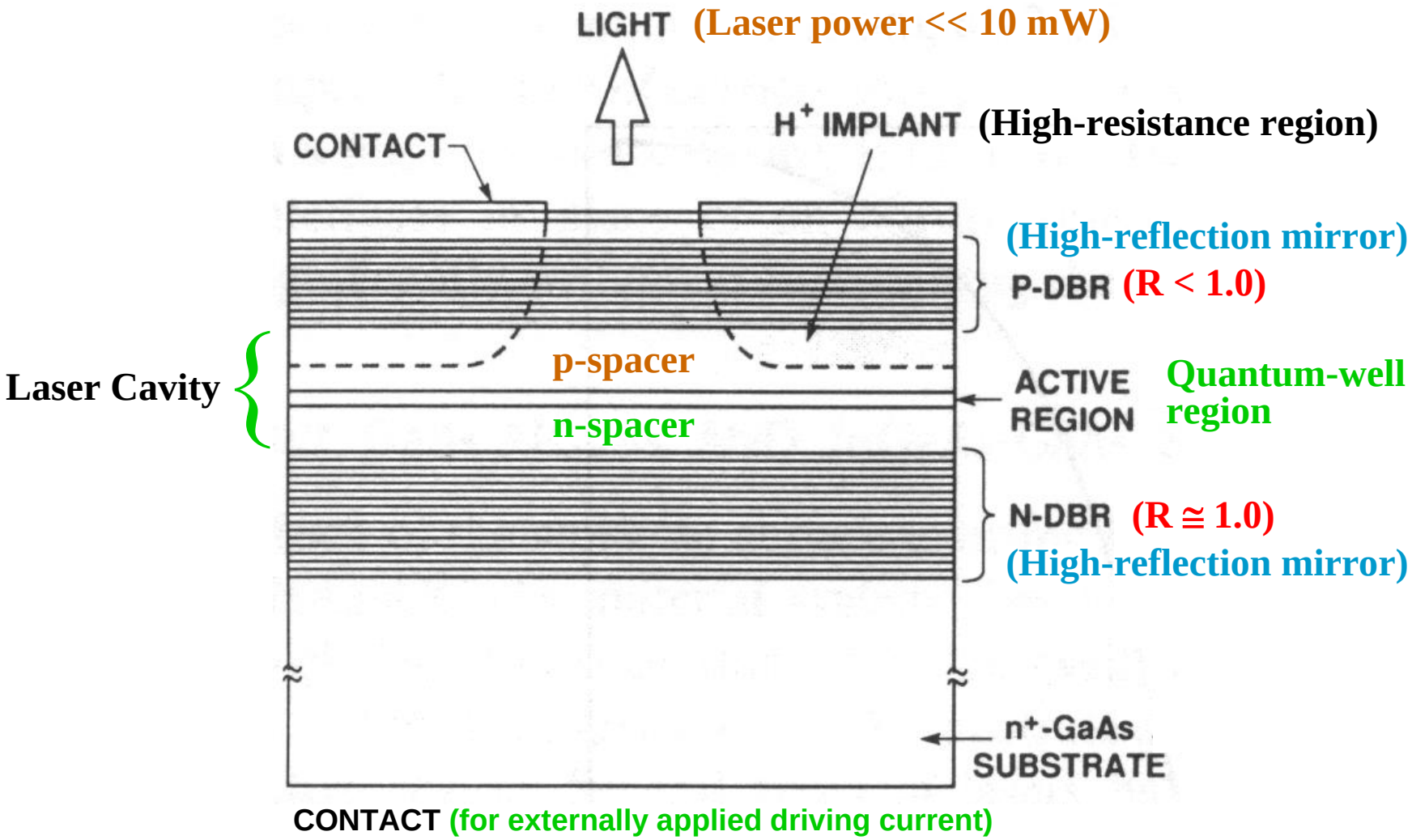
(Epitaxially Laterally Overgrown GaN Substrate)

(LEOS'97 Postdeadline PD1.1 (11/12/'97) San Francisco)

Vertical-Cavity Surface-Emitting Laser (VCSEL)

- The major difference between a vertical-cavity surface-emitting laser (VCSEL) and an edge-emitting laser (EEL) lies in the fact that a VCSEL emits light in the direction along the axis of crystal growth.
- The VCSELs have symmetrical laser beams that have small divergent angles. Hence, when compared to the EEL, the light emitted by a VCSEL may be coupled into an optical fiber more effectively.
- VCSELs are of advantage in the application of 2D arrays for communication.
- There is no need for the VCSEL wafers to be cleaved and coated for device performance testing, which saves a lot of time in device characterization.
- Light-emitting diode (LED) have been used in some short-distance optical fiber communication systems. If the LED light source were replaced by a VCSEL, the operating distance and data transmission rate would be greatly enhanced. Since the packaging for both LED and VCSEL are almost identical, the substitution of a LED by a VCSEL in an optical fiber communication system is very cost effective.

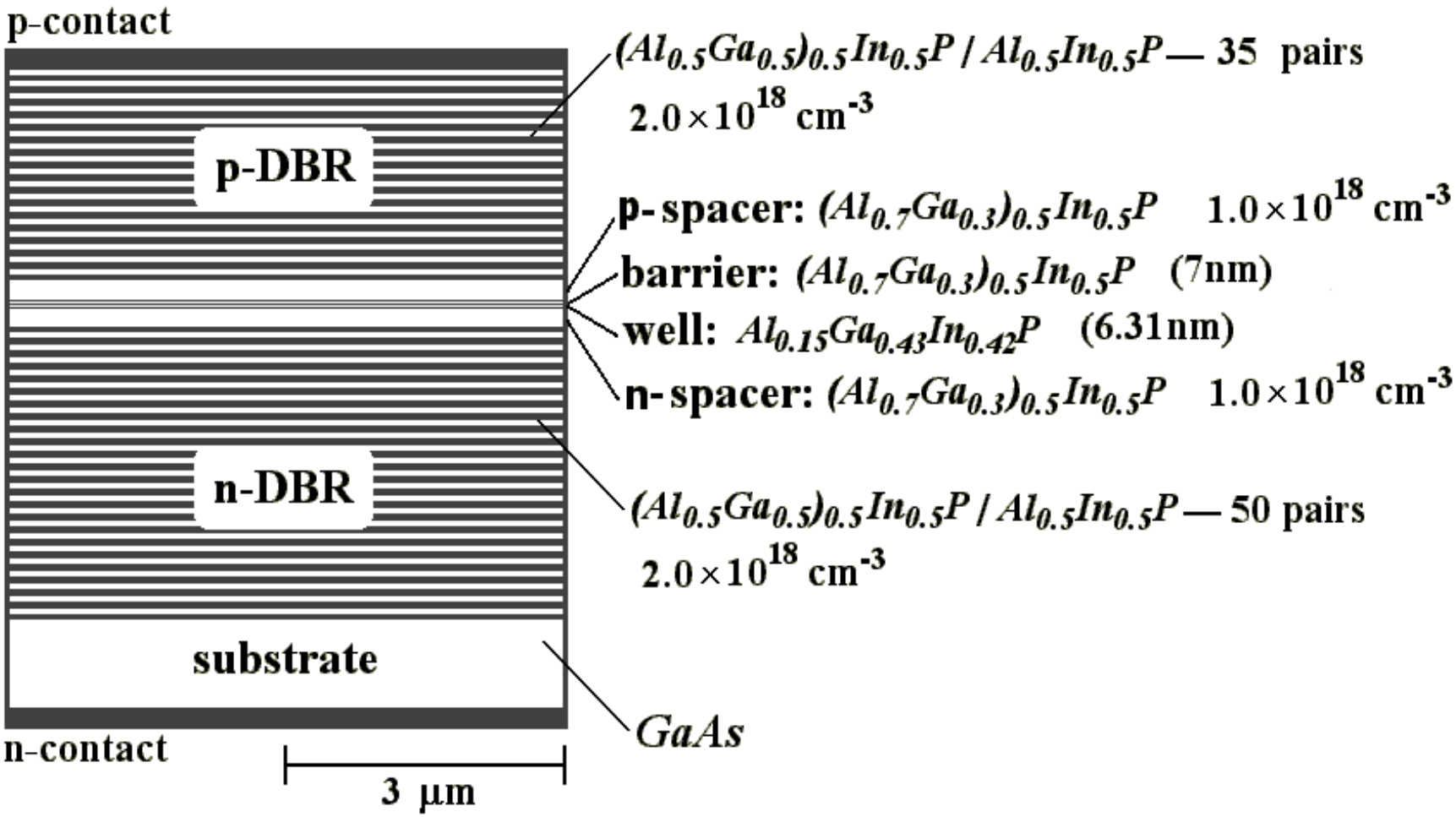
Structure of Vertical-Cavity Surface-Emitting Laser



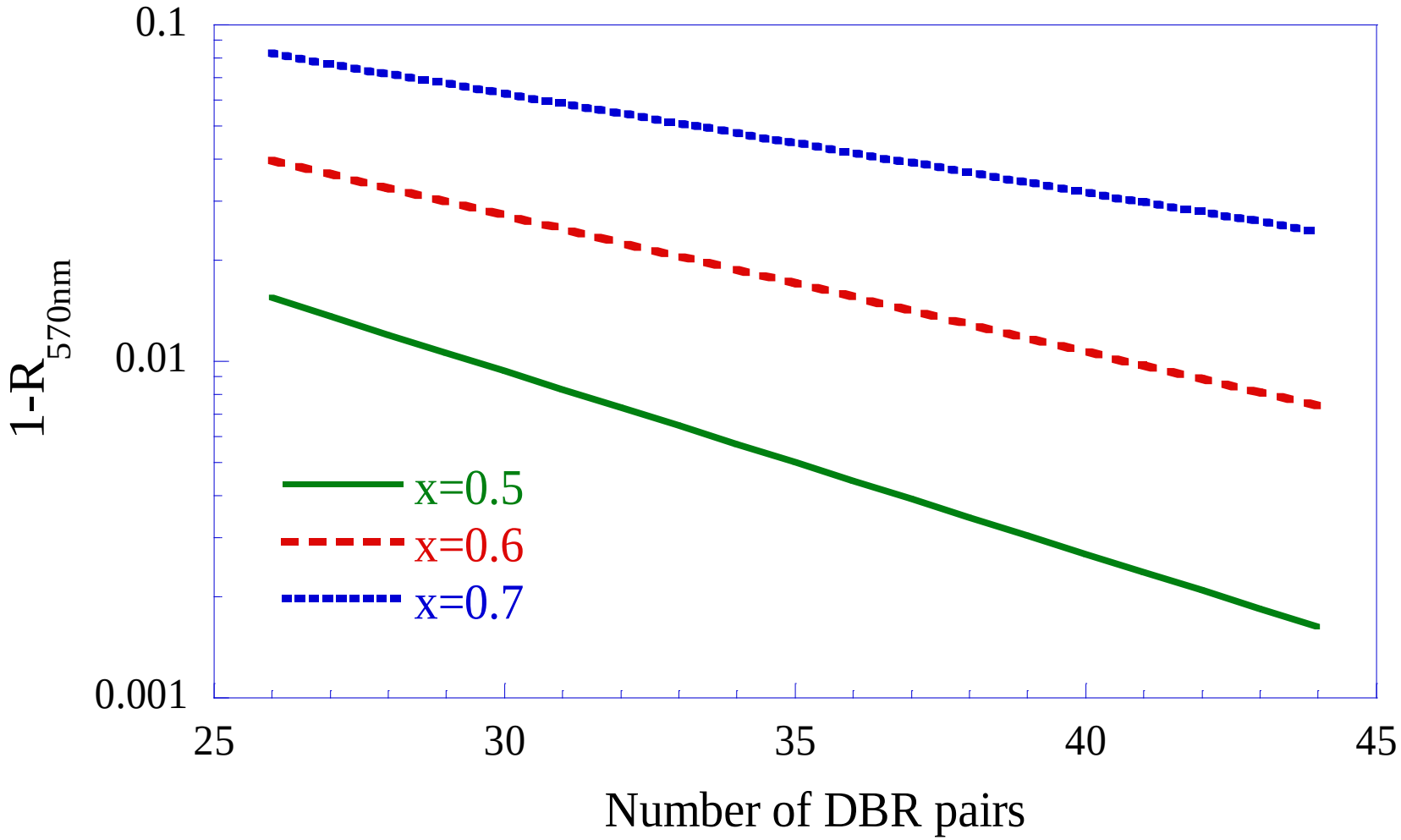
Optical Properties of 570-nm Yellowish Green AlGaInP VCSEL

- **Reference:** 黃雅蓮、郭艷光, 2002年9月, "黃綠光磷化鋁鎵銦面射型半導體雷射光學特性之模擬分析," 光學工程, 第79期, 第87至100頁.
- The emission efficiency of the AlGaInP semiconductor materials becomes poor when the emitting wavelength is shorter than 555 nm due to its indirect bandgap characteristics. However, the AlGaInP still has good emission efficiency when its emitting wavelength is near 570 nm.
- In this simulation, the optical properties of the 570-nm VCSEL are investigated with a PICS3D simulation program. Specifically, we intend to design an optimized structure that could be used as a reference for those researchers who wish to grow this specific VCSEL.

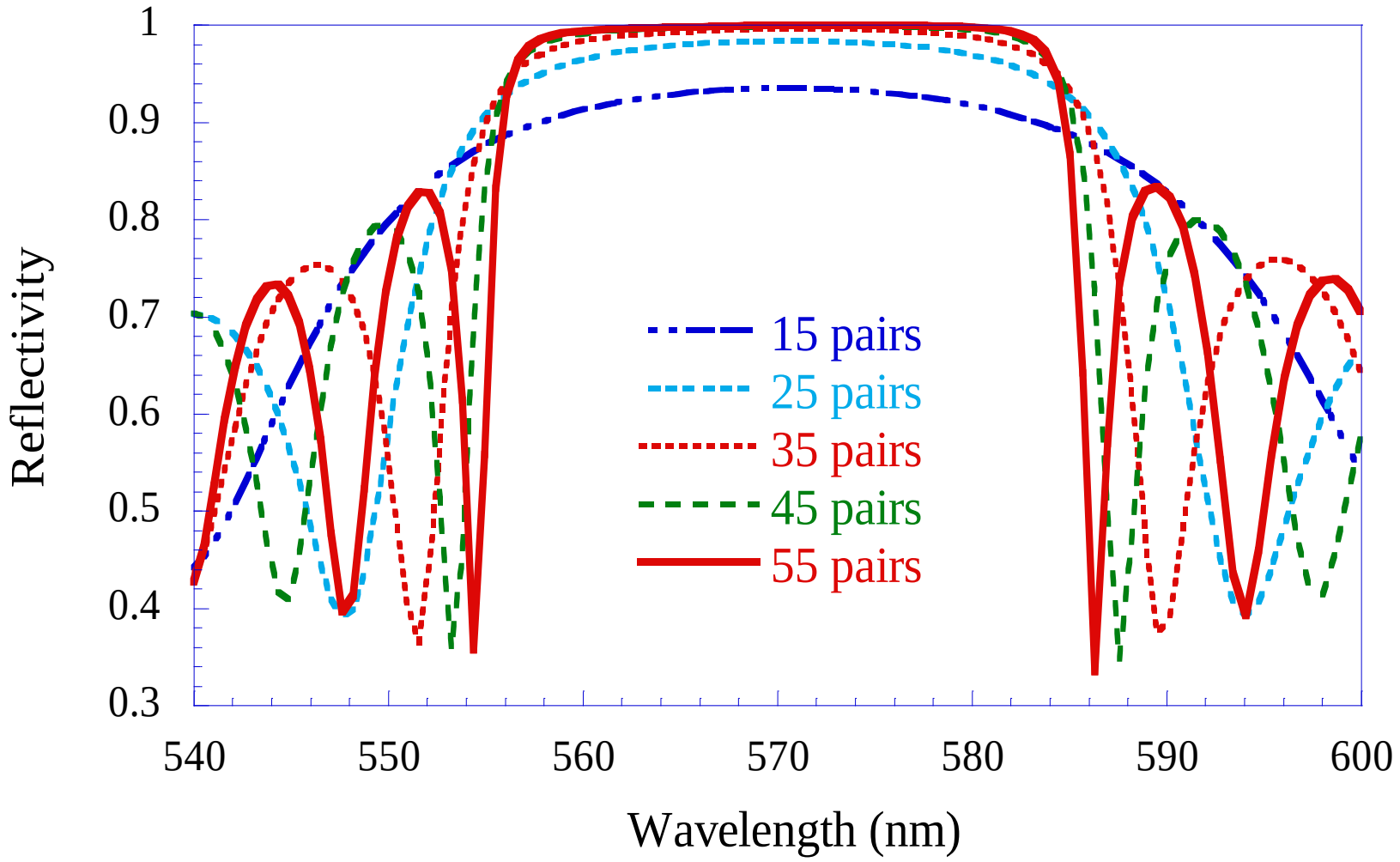
Structure of a 570-nm Yellowish Green AlGaInP VCSEL



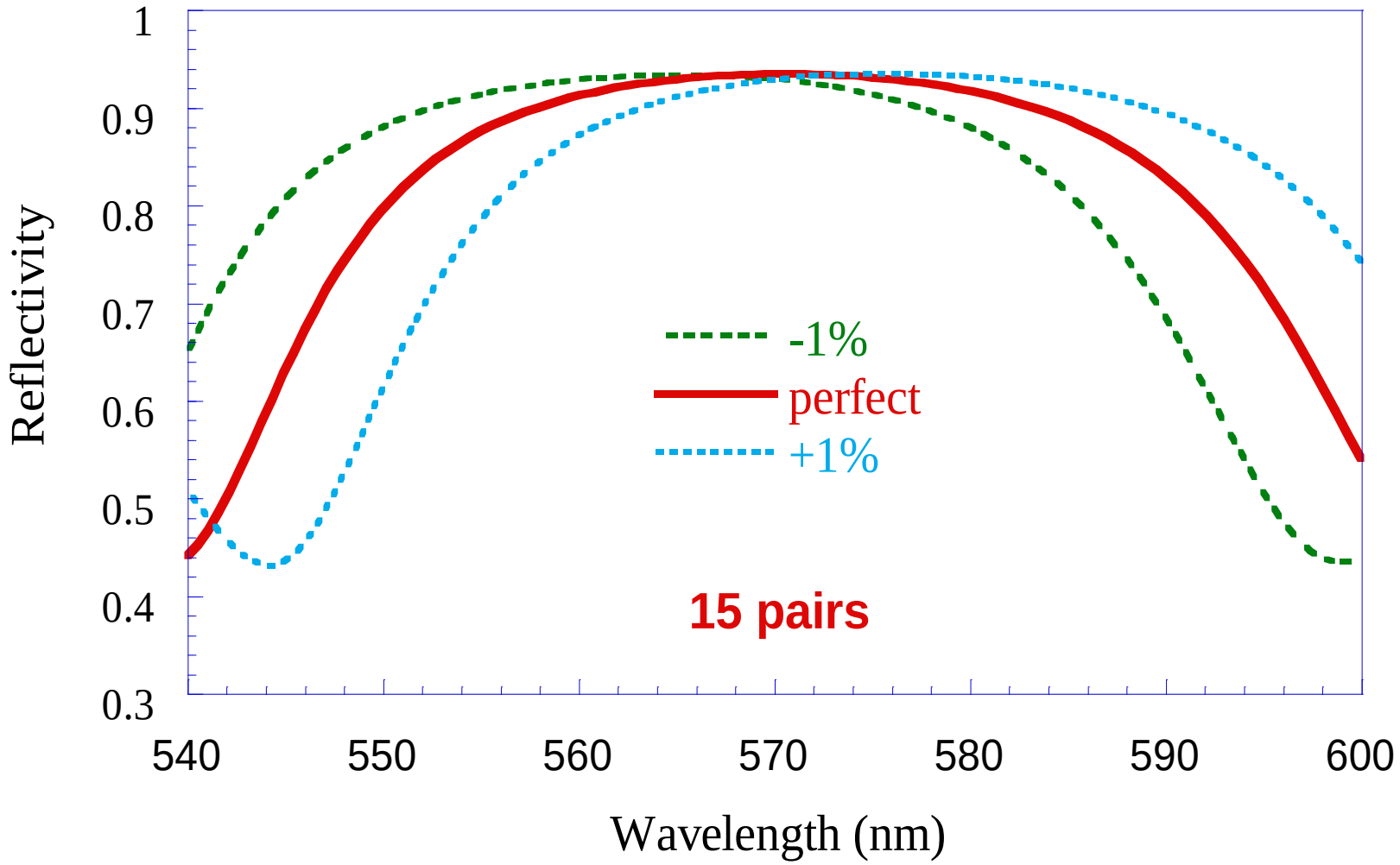
Transmission of $(Al_xGa_{1-x})_{0.5}In_{0.5}P/Al_{0.5}In_{0.5}P$ DBR at 570 nm Versus Number of DBR Pairs



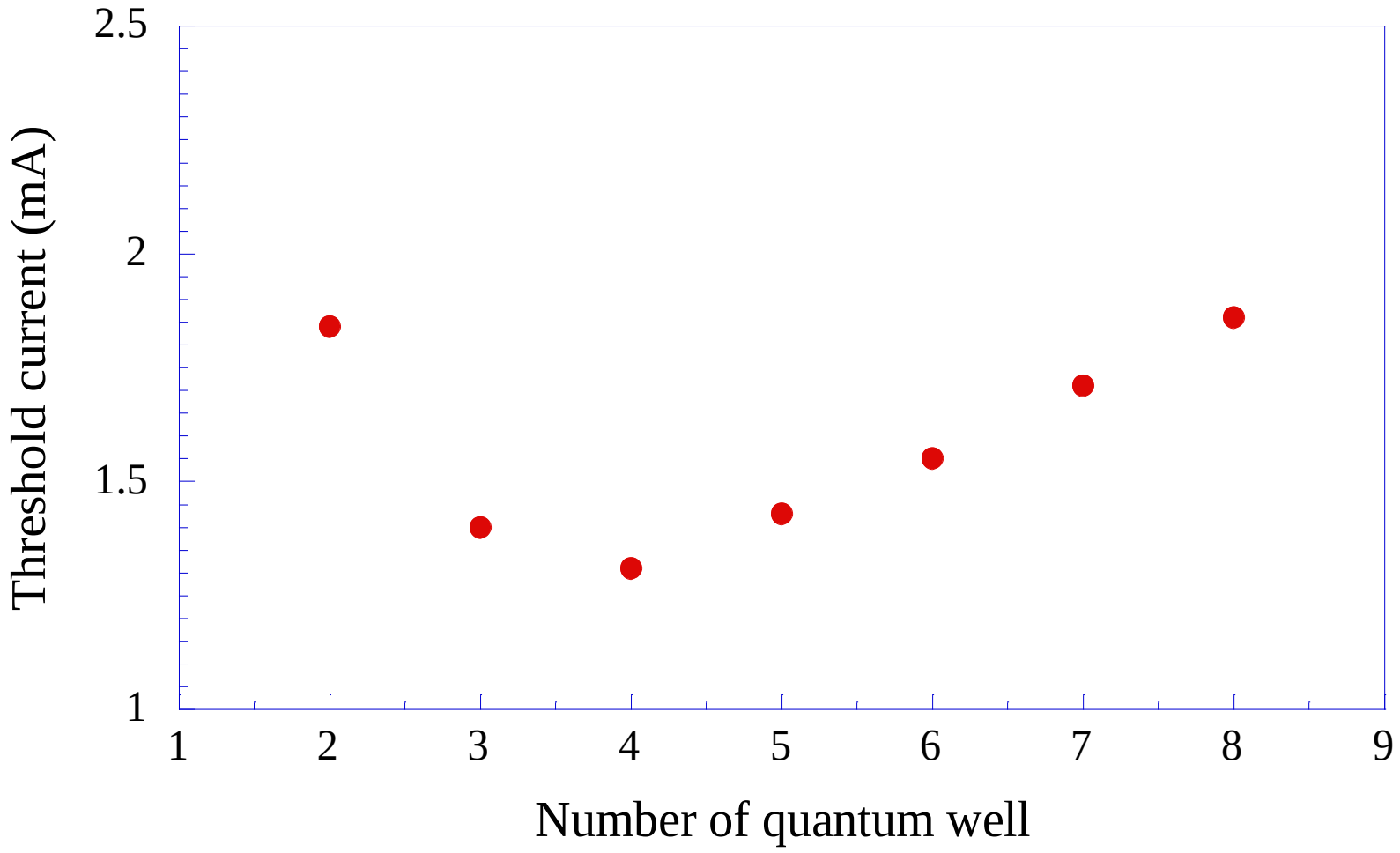
$(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P/Al_{0.5}In_{0.5}P$ DBR



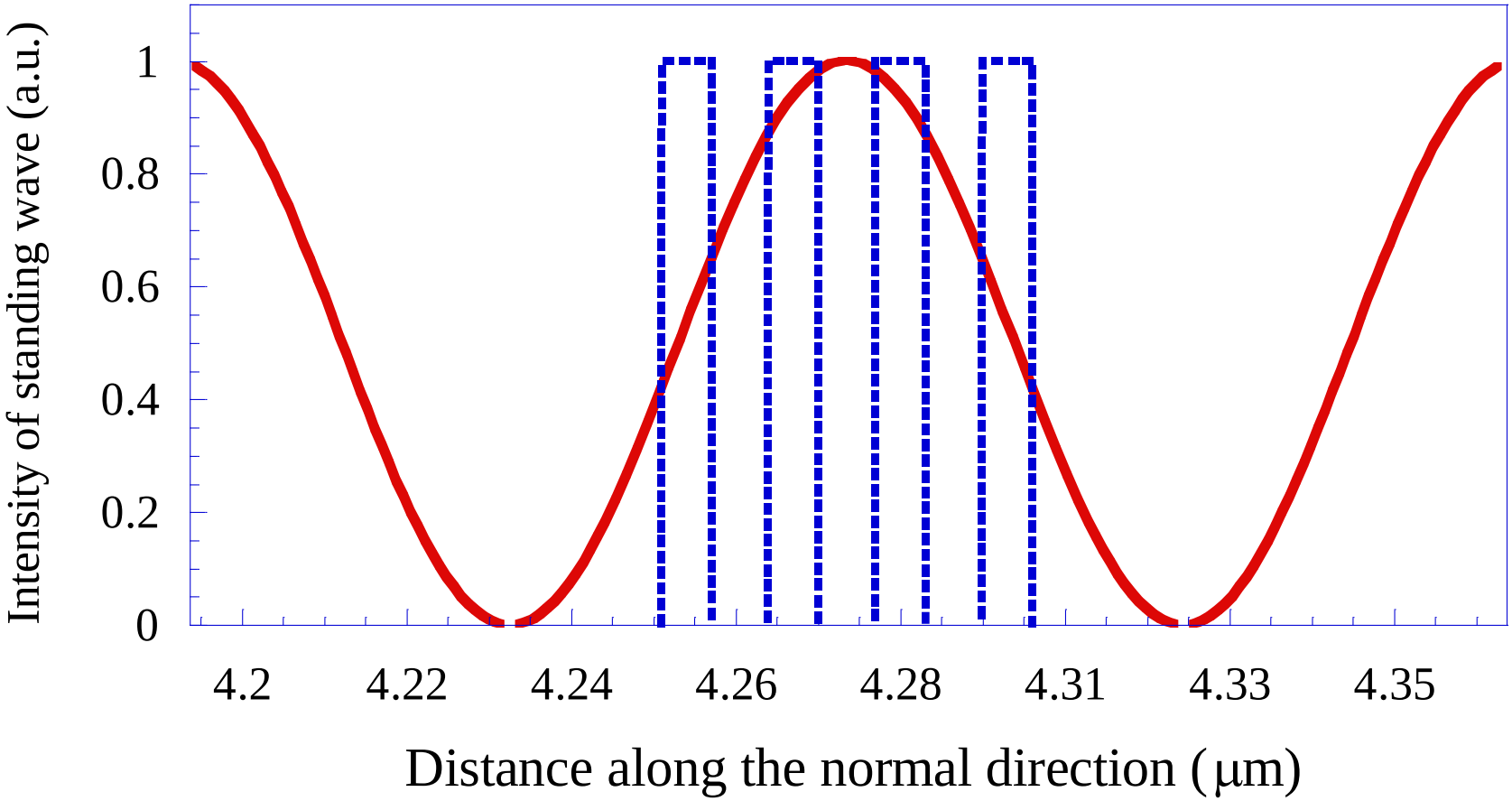
Reflectivity Spectra of $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P/Al_{0.5}In_{0.5}P$ DBR When the Thickness of Each Layer Has an Error of 1%



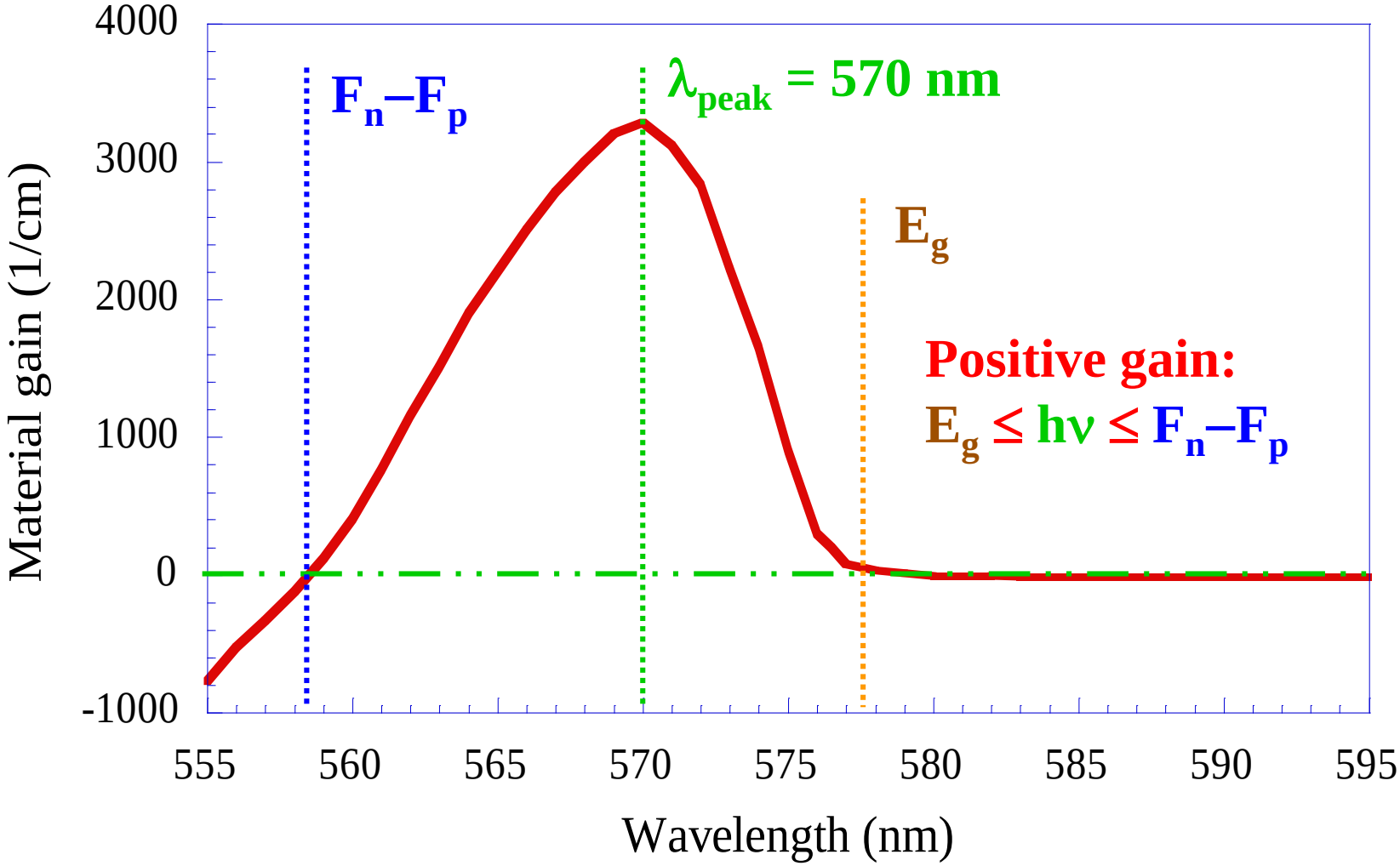
Threshold Currents vs. Number of Quantum Wells



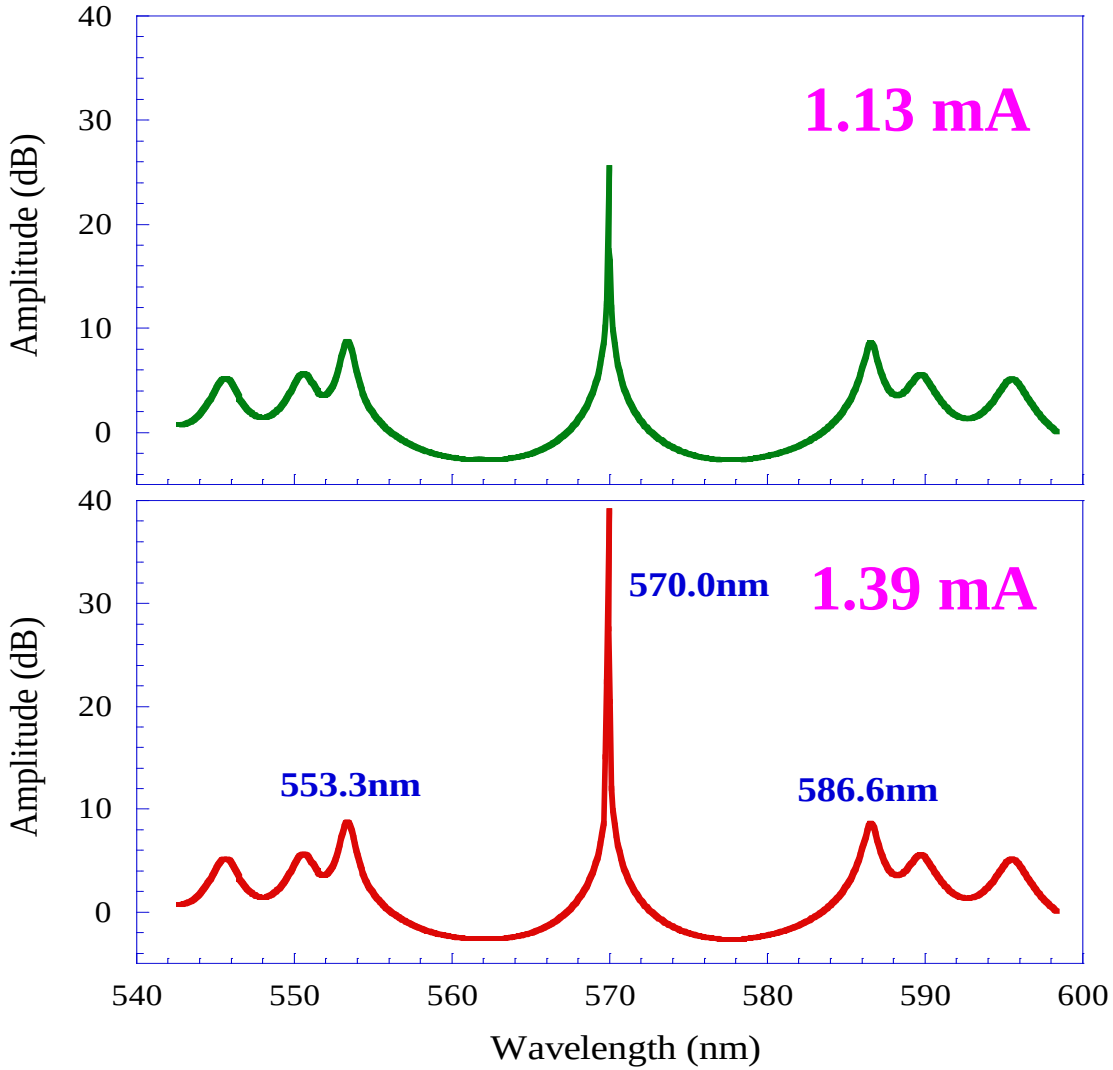
Overlap Between Quantum Wells and Standing Wave for 4 Quantum Wells



Material Gain When Carrier Density Is 5×10^{18} cm^{-3}

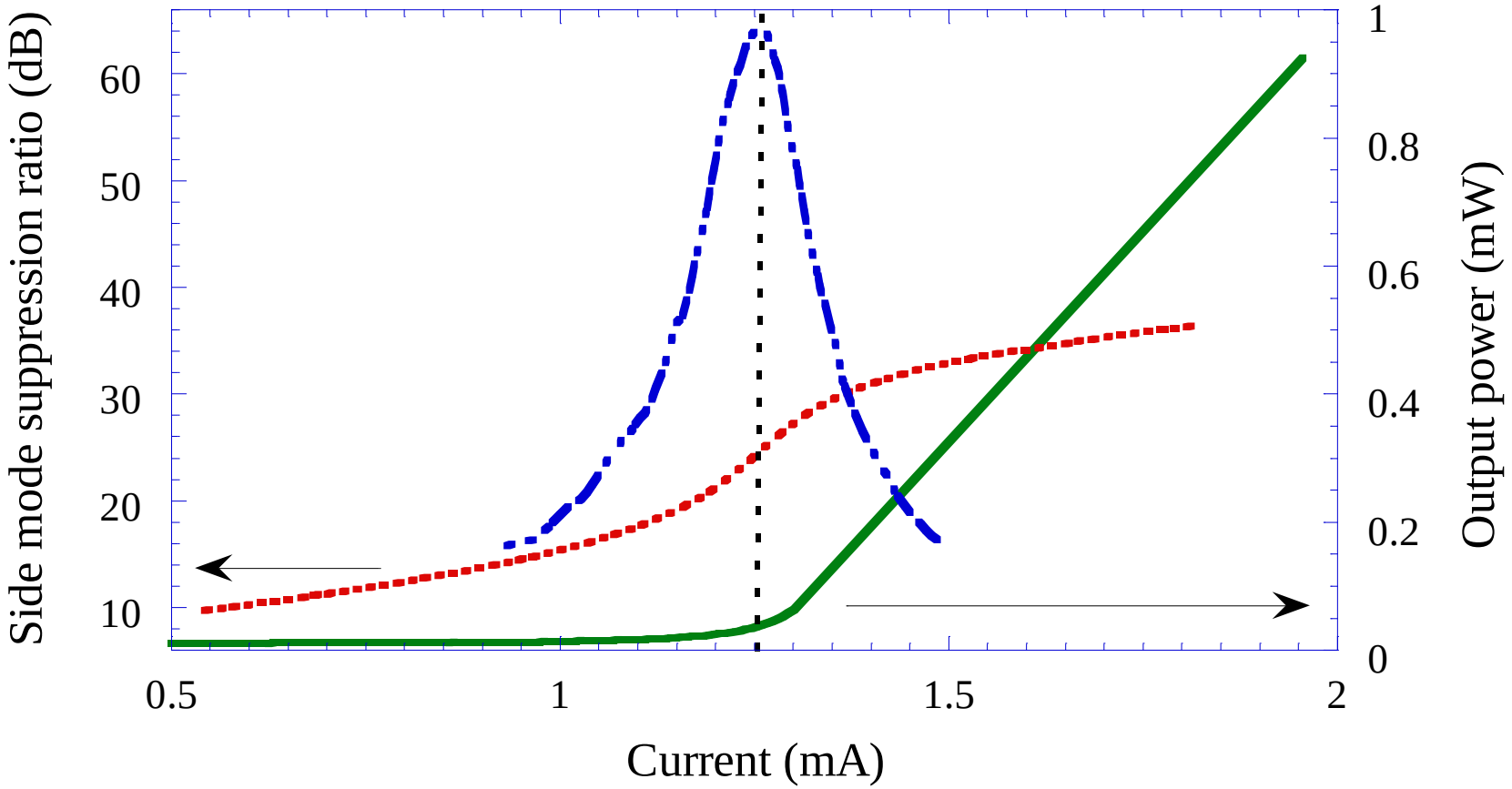


Laser Spectra When Current Is 1.13 mA ($0.9I_{th}$) and 1.39 mA ($1.1I_{th}$)



Threshold Current ≈ 1.26 mA

Side Mode Suppression Ratio as a Function of the Injection Current



The blue curve is the result of differentiation of the function of side mode suppression ratio.