ECE 536 – Integrated Optics and Optoelectronics Lecture 14 – March 3, 2022

Spring 2022

Tu-Th 11:00am-12:20pm

Prof. Umberto Ravaioli

ECE Department, University of Illinois

Lecture 14 Outline

- Power in Lasers

- LED vs. Laser

- Measurements

Light Output Intensity

$$P_{out} = \begin{bmatrix} \text{Photon} \\ \text{Energy} \end{bmatrix} \times \begin{bmatrix} \text{Photon} \\ \text{Density} \end{bmatrix} \times \begin{bmatrix} \text{Effective Volume} \\ \text{of Optical Mode} \end{bmatrix} \times \begin{bmatrix} \text{Photon} \\ \text{Escape Rate} \end{bmatrix}$$

$$= [\hbar\omega] \times [S] \times [wL\, d_{op}] \times [v_g\, \alpha_m]$$

Since
$$d_{op} = \frac{d}{\Gamma}$$
$$I = w\, L\, J$$

$$P_{out} = \eta_i \frac{\hbar\omega}{q} \frac{\alpha_m}{\alpha_i + \alpha_m} (I - I_{th})$$

External Quantum Efficiency

$$\eta_e = \frac{dP_{out}/dI}{\hbar\omega/q} = \eta_i \frac{\alpha_m}{\alpha_i + \alpha_m} = \eta_i \frac{\ln(1/R)}{\alpha_i L + \ln(1/R)}$$
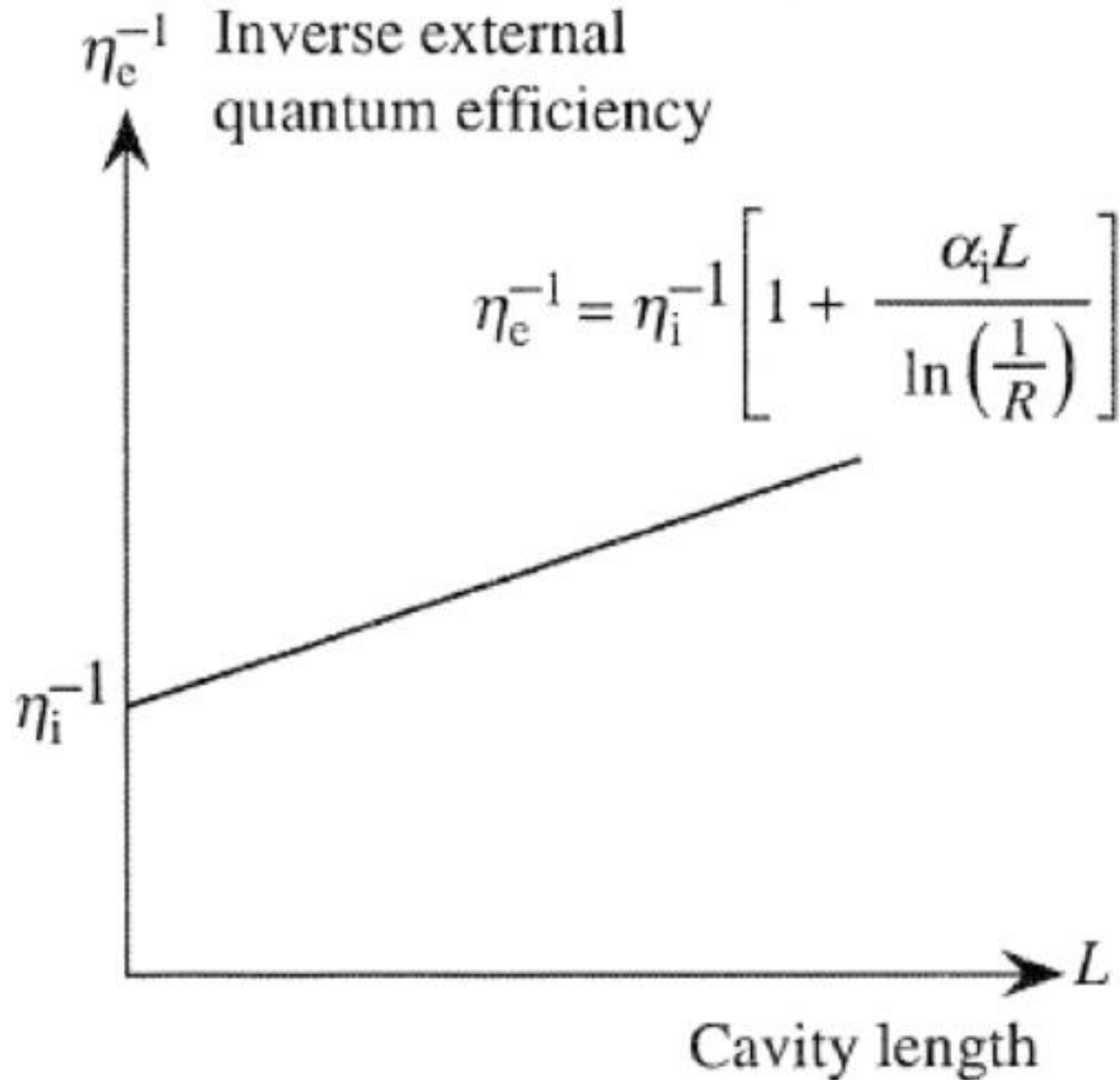
also
$$\eta_e^{-1} = \eta_i^{-1} \left[1 + \frac{\alpha_i L}{\ln(1/R)}\right]$$

Plotting η_i^{-1} versus L is a line with a y-intercept of η_i^{-1}

The slope divided by the y-intercept is

$$\frac{\alpha_i}{\ln(1/R)}$$ and can determine α_i

External Quantum Efficiency

$$\eta_e^{-1} = \eta_i^{-1} \left[1 + \frac{\alpha_i L}{\ln\left(\frac{1}{R}\right)} \right]$$

η_e^{-1} Inverse external quantum efficiency

η_i^{-1}

L

Cavity length

Leakage Current

$$I = I_A + I_L = JwL + I_L$$

$$I_{th} = J_{th}wL + I_{L@th} = \frac{qn_{th}(wLd)}{\eta_i \tau_e(n_{th})} + I_{L@th}$$

Revised Expression for P_{out}

$$P_{out} = \eta_i \frac{\hbar\omega}{q} \frac{\alpha_m}{\alpha_m + \alpha_i}(I - I_{th} - \Delta I_L)$$

Temperature Dependence

Laser threshold and efficiency vary with temperature since $g(\hbar\omega)$, Auger recombination, and other processes are temperature dependent

$$\uparrow T \qquad \uparrow I_{th}(T) \qquad \downarrow \eta_e(T)$$

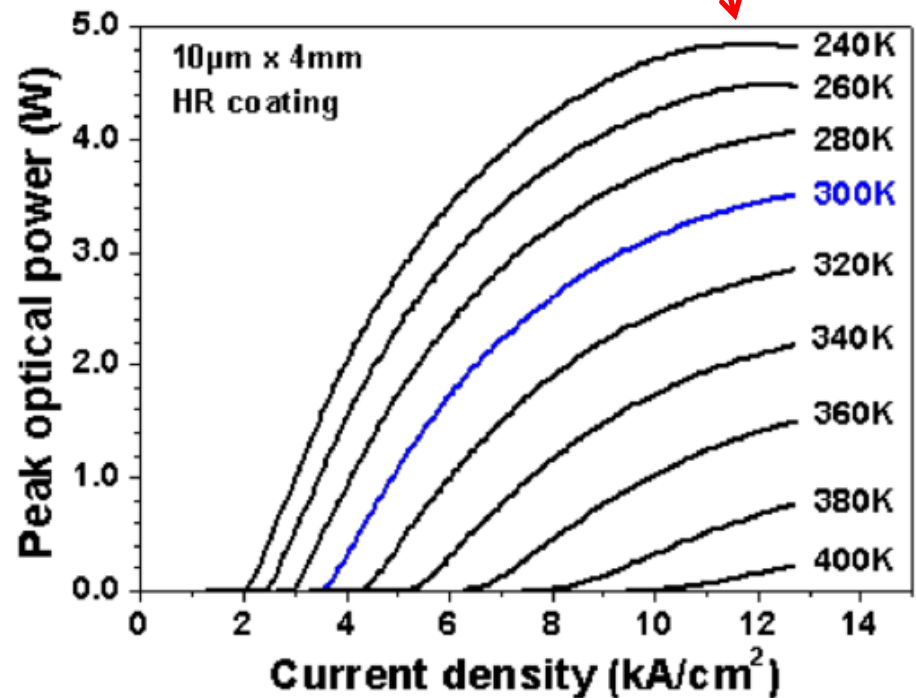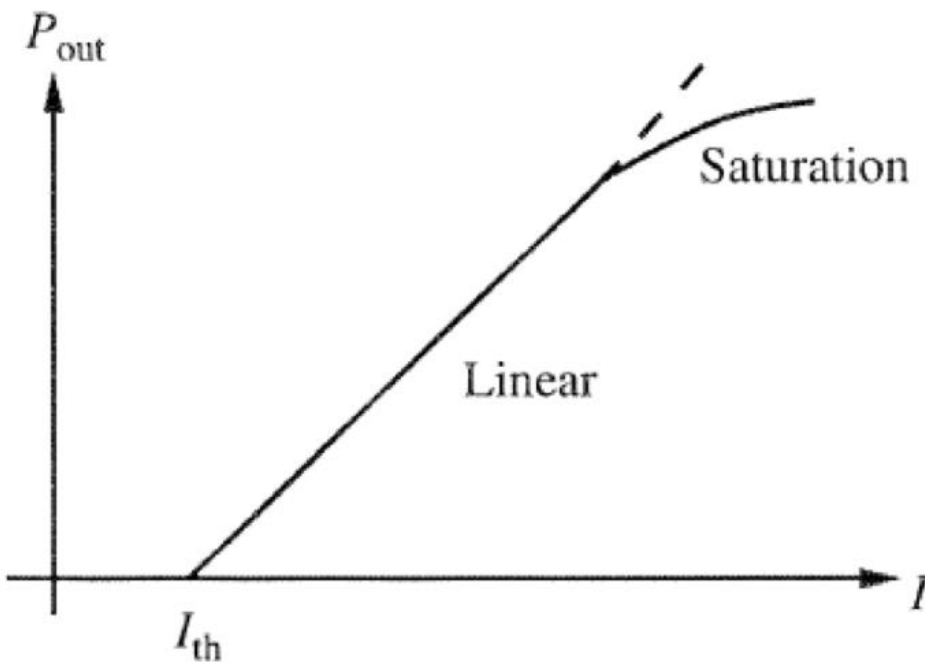$$I_{th}(T) = \{\text{constant}\} e^{T/T_0} = I_{th}(T_a) e^{(T-T_a)/T_0}$$

$$\eta_e(T) = \{\text{constant}\} e^{-T/T_1} = \eta_e(T_a) e^{-(T-T_a)/T_1}$$

Saturation of Laser Output Power

Possible causes are:

- increasing leakage current
- Junction heating
- Increasing internal absorption α_i

In continuous wave (CW) regime there is typically a maximum power $P_{max}(T)$

Saturation of Laser Output Power

$$P_{in} = IV$$

$$P_{out} = P_{in}\,\eta_{wp}$$

$$\eta_{wp} = \frac{P_{out}}{P_{in}} = \frac{\dfrac{\hbar\omega}{q}\,\dfrac{\alpha_m}{\alpha_i + \alpha_m}\,\eta_i(I - I_{th})}{IV}$$

Power conversion efficiency is high in lasers when compared to other light emitter, but it typically does not exceed 60%. The power which is not converted into light is dissipated as heat, which needs to be removed by a heatsink.

The heatsink is characterized by a ***thermal resistance R_T***

$$R_T = \frac{\Delta T}{P_{in} - P_{out}}$$

$$\Delta T = R_T(P_{in} - P_{out}) = R_T\big(1 - \eta_{wp}\big)P_{in}$$

ΔT = laser overheating

Improving P_{max}

**To decrease overheating ΔT**
- Develop better heatsink and laser mounting to reduce R_T
- Improve laser *"wall-plug efficiency"*
    - Reduce voltage drop across heterostructure
    - Reduce internal loss α_i
    - Increase injection efficiency η_i
    - Reduce threshold current I_{th}

To decrease temperature sensitivity
- Suppress carrier leakage which affects external quantum efficiency
- Minimize non-radiative recombination which reduces the concentration at threshold

Improving P_{max}

Laser substrate is thick and has high thermal resistance. High power lasers are mounted upside down with the *p*-layer in contact with the heatsink.

p-cladding ~ 1 – 2 μm
active layer ~ 1 μm
n-cladding ~ 1 – 2 μm
substrate *n*-type ~ 100 μm
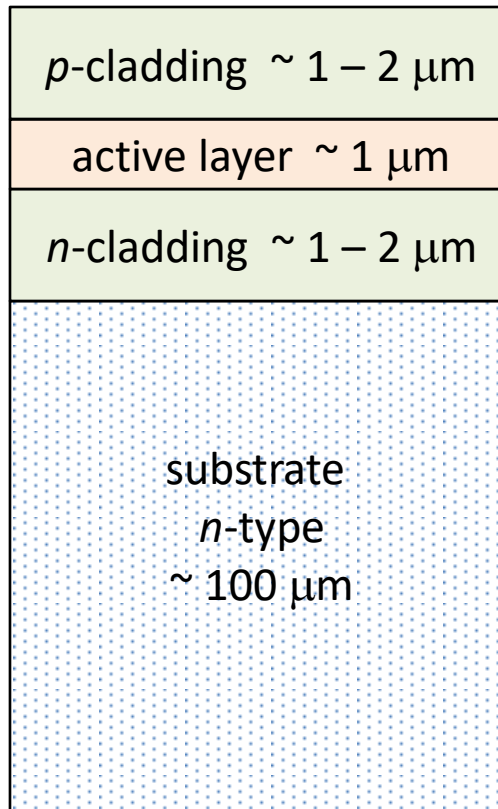
Improving P_{max}

The thermal resistance is inversely proportional to the cavity length. For high power operation, a long cavity is better as long as laser efficiency is not affected too much.

$$\alpha_m = \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)$$

$$\eta_e = \eta_i \frac{\alpha_m}{\alpha_i + \alpha_m}$$

$$\uparrow L \qquad \downarrow \alpha_m \qquad \downarrow \eta_e$$

As mirror losses are lower with increasing cavity length, the relative role of internal loss increases. This causes quantum efficiency to drop.

Internal loss α_i

Much of the internal loss is due to free carrier absorption. Transitions between HH and SH valence bands, known as "intervalence band absorption" are an important component.

The main contribution to net internal loss is absorption in highly doped cladding regions.

The confinement factor is somewhat reduced in a *broadened waveguide* but losses in the cladding regions are greatly reduced, leading to a reduced threshold current density.

Efficiency of the broadened waveguide is less sensitive to cavity length, so this structure is suitable for power applications, increasing maximum CW power.

Broadened waveguide
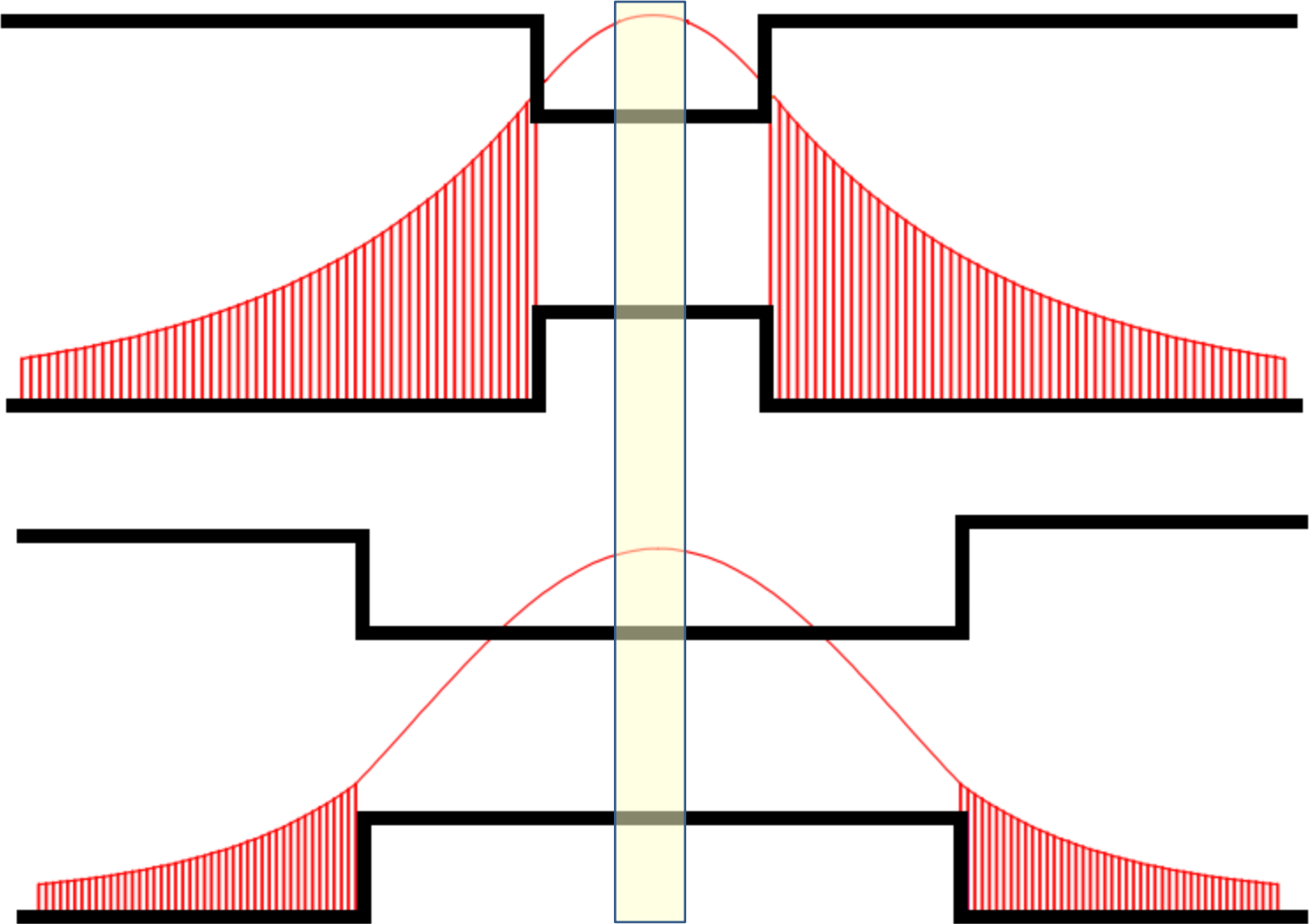
active quantum
region

Minimize threshold current to increase power output

$$P_{out} = \eta_i \frac{\hbar}{\omega} \frac{\alpha_m}{\alpha_i + \alpha_m} (I - I_{th})$$
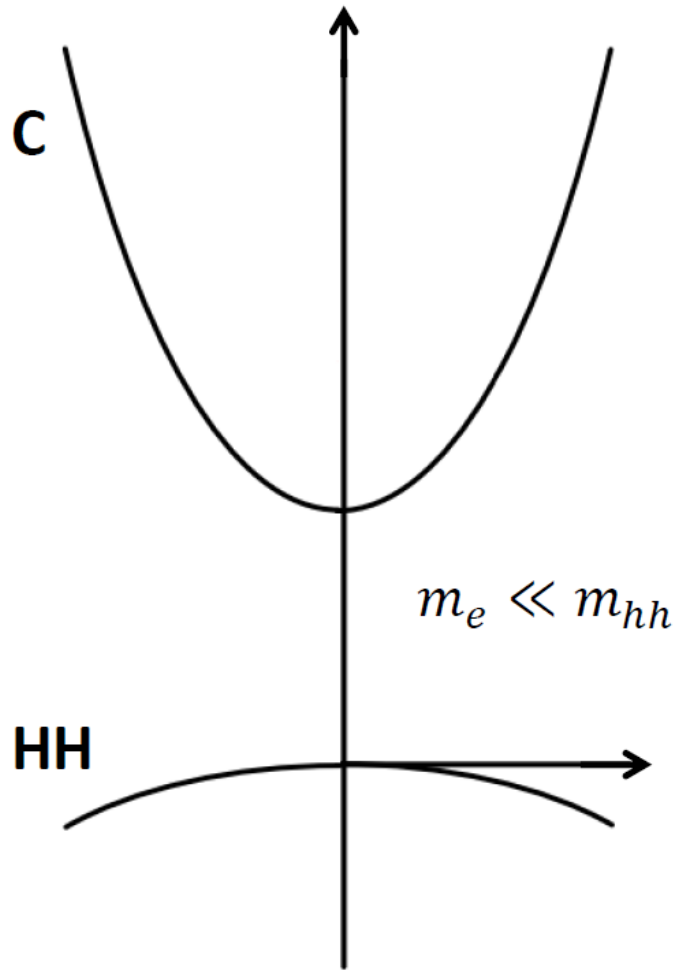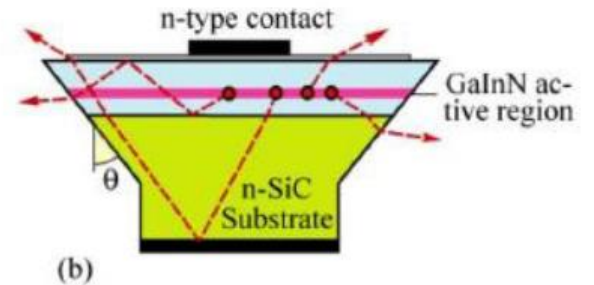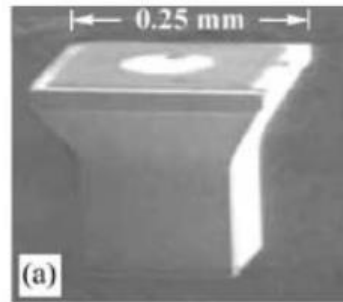
$$I_{th} = I_{tr} + I_{loss}$$

To minimize I_{tr}
- Reduce number of quantum wells to a minimum
- Compressive strain in QW reduces difference in effective mass between C and HH bands

To minimize I_{loss}
- Compressive strain in QW reduces difference in effective masses and increases differential gain

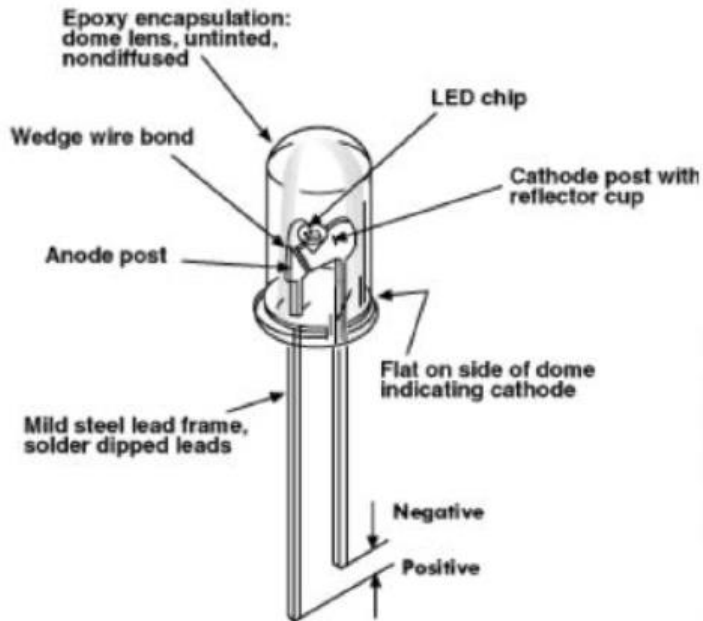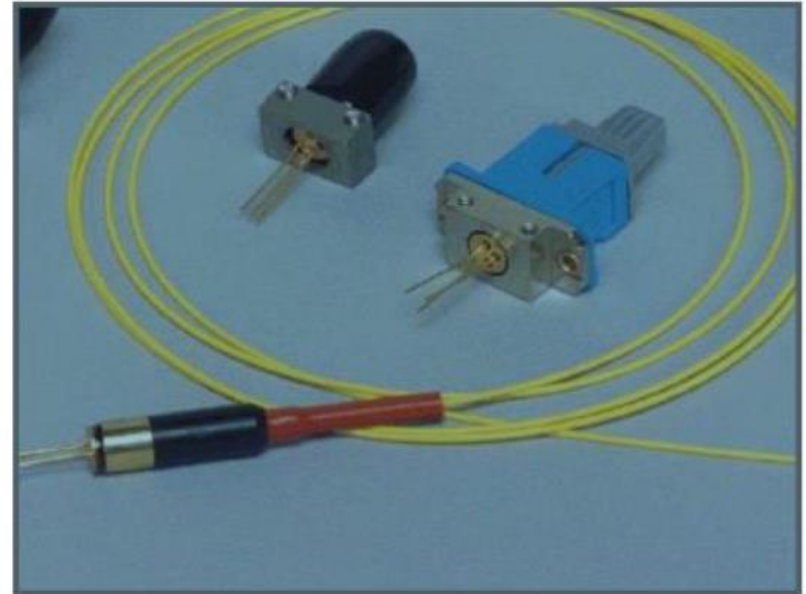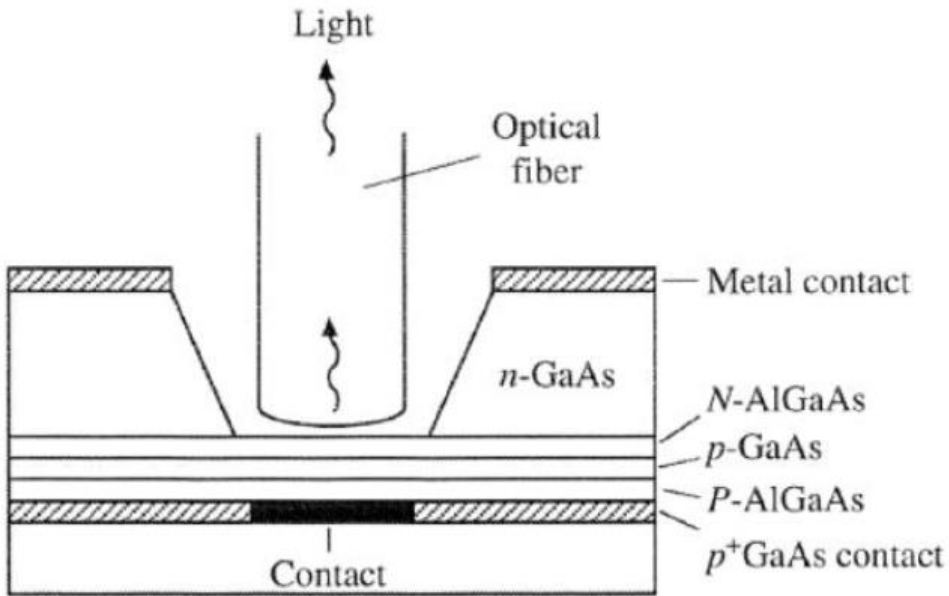# Minimize threshold current to increase power output

C

$m_e \ll m_{hh}$

HH

C

$m_e \approx m_{hh}$

HH
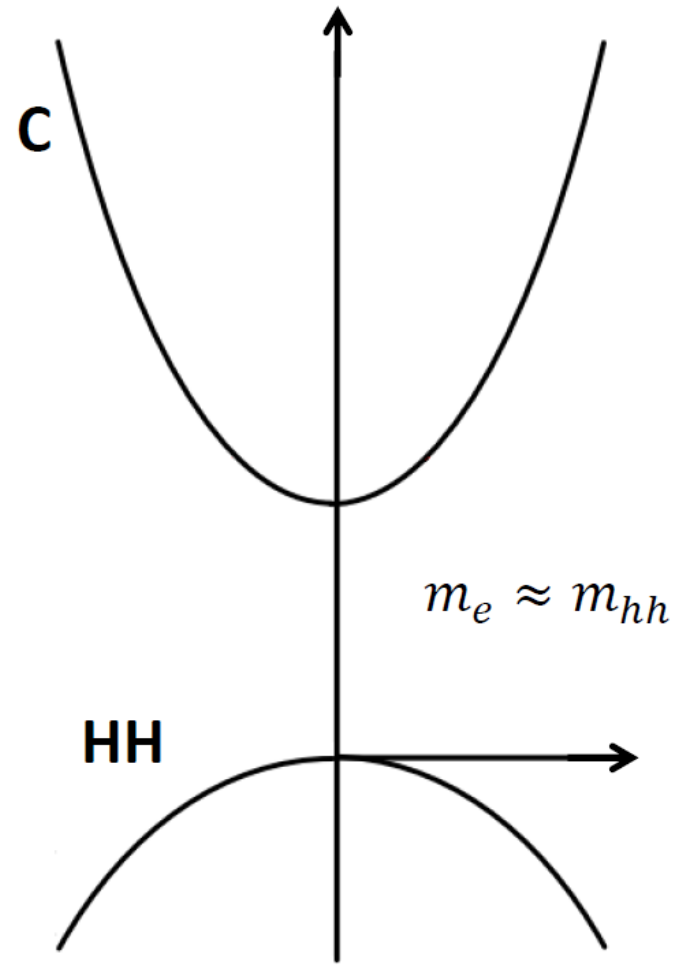
LED versus Lasers

Spontaneous Emission and
Amplified Spontaneous Emission (ASE)

LEDs for Display

(a) air

Metal contact

$2\theta_c$

θ_c θ_c

P

Active region

N

Critical Angle

(b) P N

Metal contacts

Epoxy encapsulation: dome lens, untinted, nondiffused

Wedge wire bond

LED chip

Anode post

Cathode post with reflector cup

Flat on side of dome indicating cathode

Mild steel lead frame, solder dipped leads

Negative

Positive

(a) 0.25 mm

(c) 1.0 mm

(b) n-type contact

GaInN active region

θ

n-SiC Substrate

(d) n-type contact

n-GaP Substrate

θ

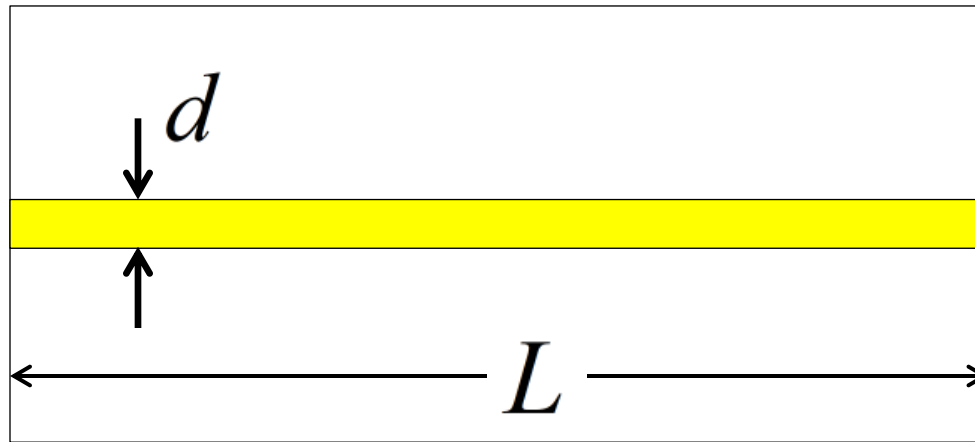AlGaInP active region

p-type GaP

18

LEDs for Communications

$$L_W(\hbar\omega)$$

spontaneous emission rate per unit volume
(broader spectrum)

$$L_F(\hbar\omega)$$

d

L

amplified spontaneous emission
rate per unit volume
(narrower spectrum)

$$L_W(\hbar\omega)$$

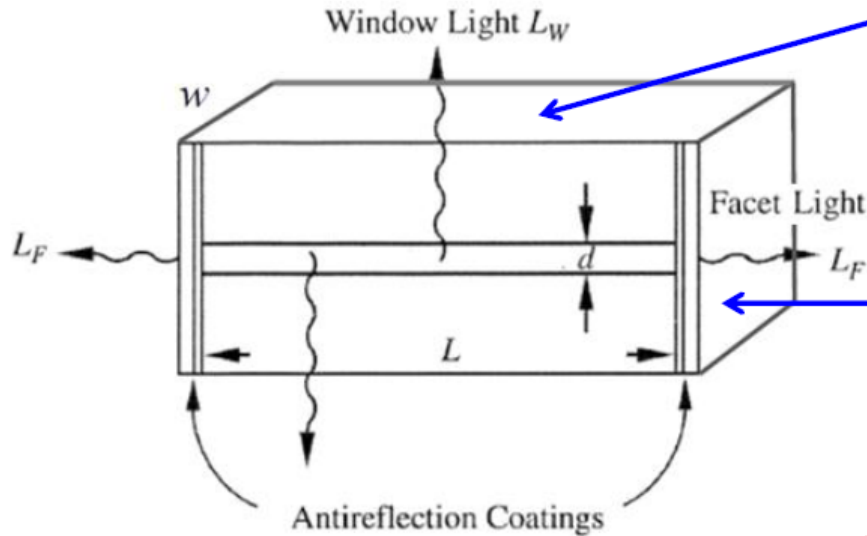spontaneous emission rate per unit volume
(broader spectrum)

At transparency $\boxed{L_W(\hbar\omega_{tr}) = L_F(\hbar\omega_{tr})}$

LED versus Laser

LED

Window Light

$$L_w(\hbar\omega) = \hbar\omega\, r^{spon}(\hbar\omega)wdL$$
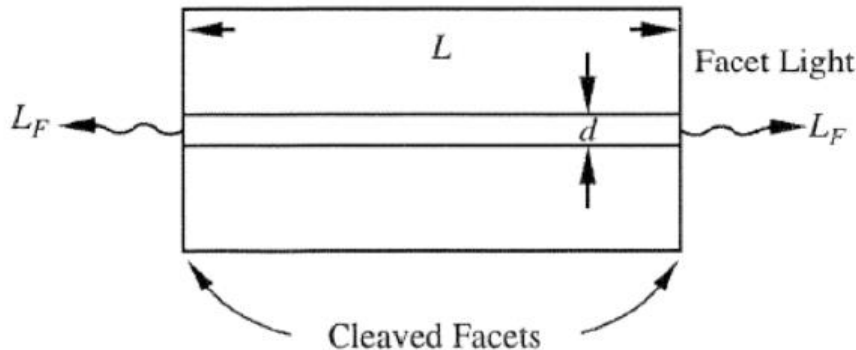
Facet Light (ASE)

$$L_F(\hbar\omega) = \hbar\omega wd \int_{z=0}^{L} r^{spon}(\hbar\omega)e^{G_n(\hbar\omega)z}\, dz$$

$$= \hbar\omega wd\, r^{spon}(\hbar\omega)\left[\frac{e^{G_n(\hbar\omega)L} - 1}{G_n(\hbar\omega)}\right]$$

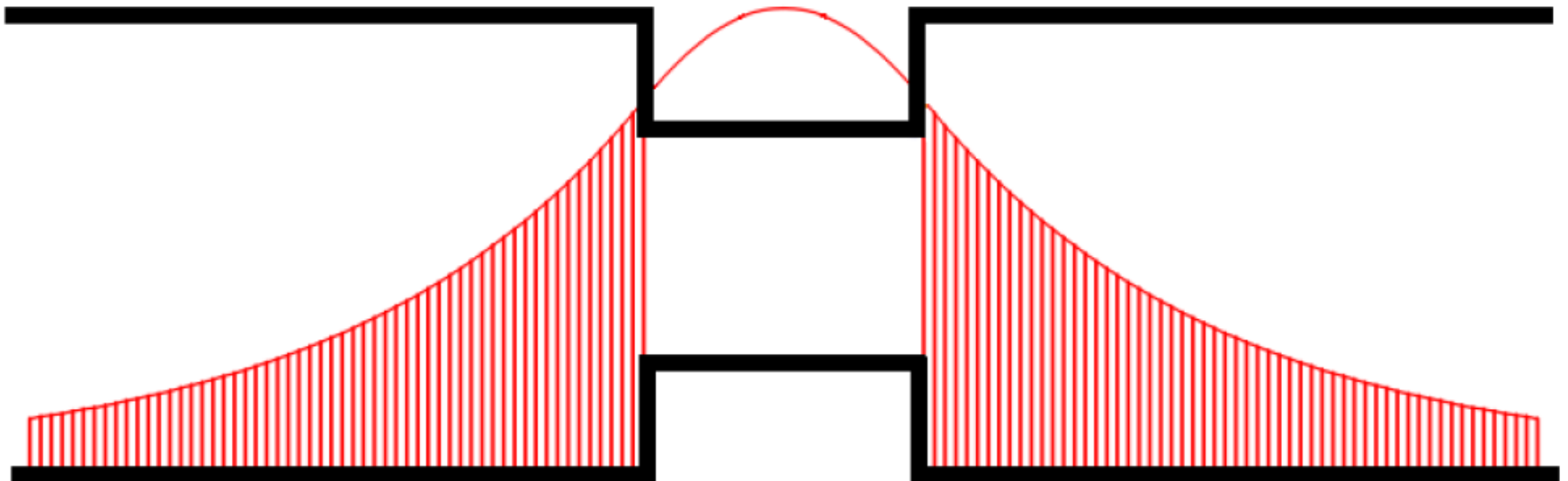**net modal gain** $\quad G_n(\hbar\omega) = \Gamma g - \alpha_i$

LASER

$$r^{spon}(\hbar\omega) \equiv \frac{\text{Spontaneous Emission}}{\text{Rate per Unit Volume}}$$
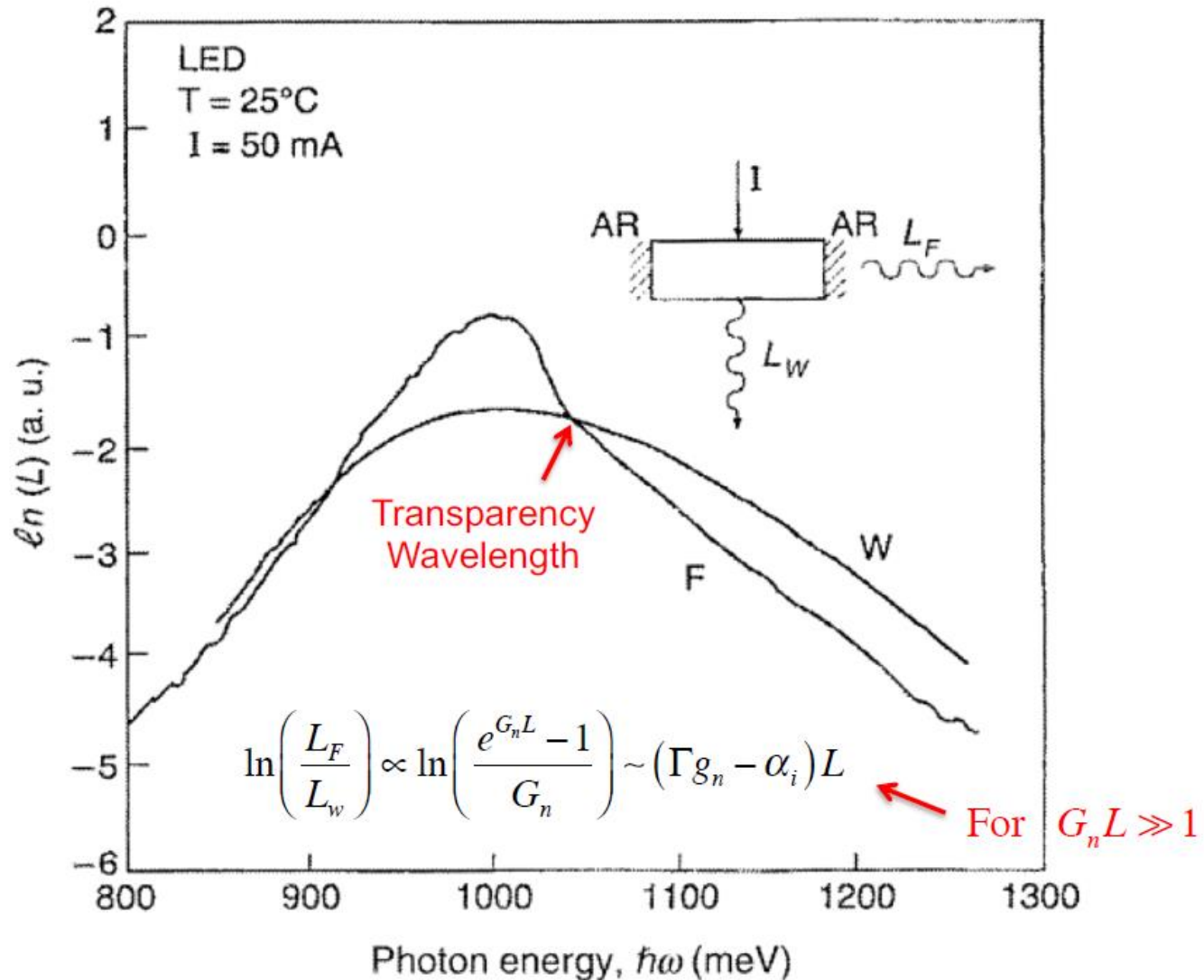
21

Definition: Net Modal Gain

This term typically indicates the net gain in the laser cavity structure, adjusted to take into account the partial overlap between the optical field and the active region occupied by carriers, through the confinement factor Γ.

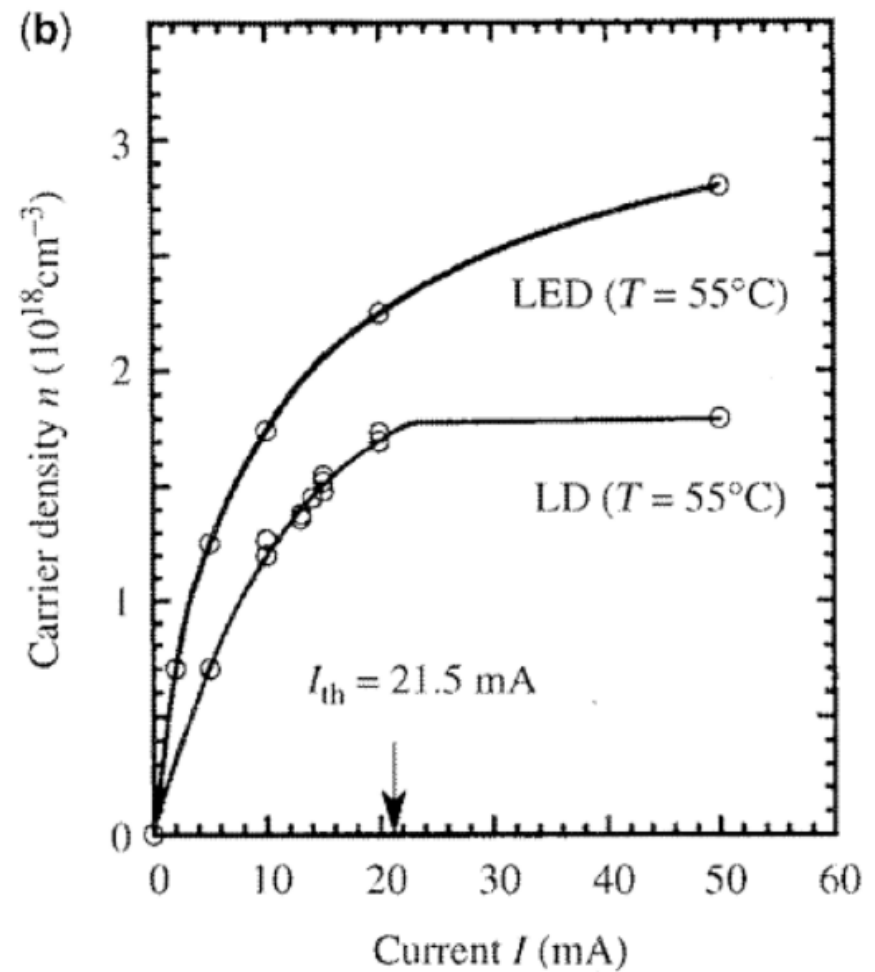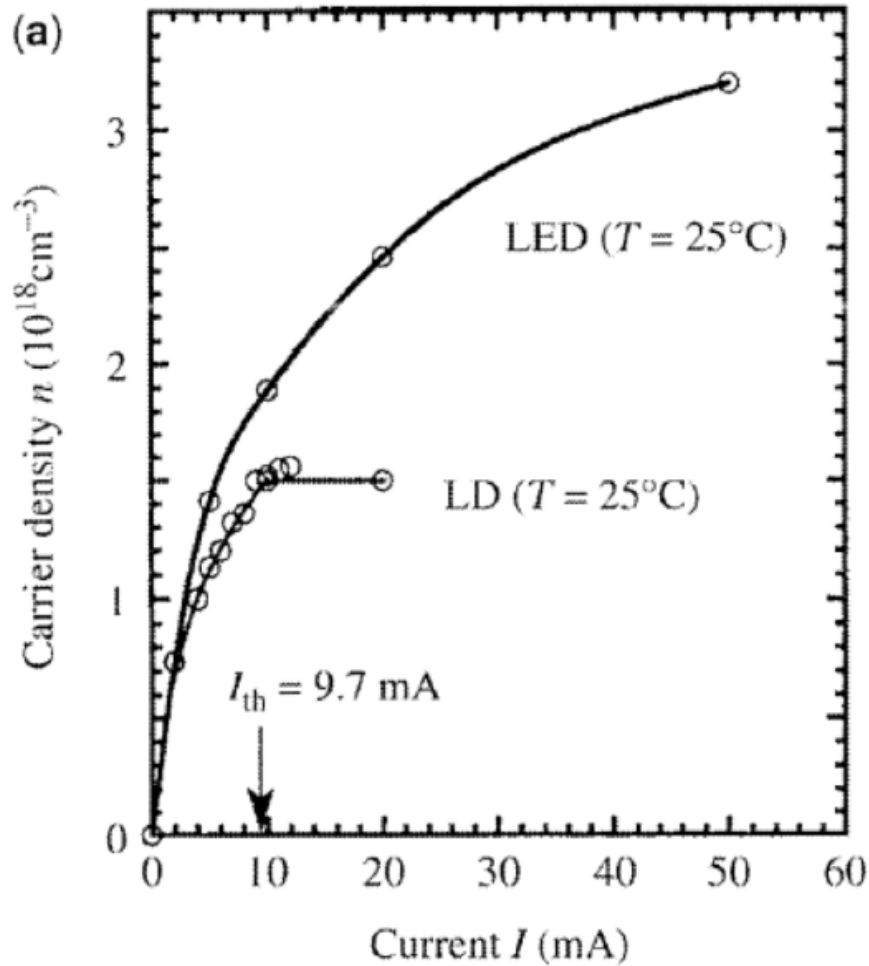$$G_n(\hbar\omega) = \Gamma g - \alpha_i$$

ASE versus Window Light

Chuang, O'Gorman, Levi, IEEE J. Quantum Electronics, vol. 29, no. 6, p. 1631, 1993. Active region is a InGaAsP layer, lattice matched and sandwiched by InP layers in a buried bulk double heterostructure device (d = 0.14 μm, L = 260 μm, W = 1 μm, E$_g$ = 968.4 meV).

23

Carrier Pinning

(a) Carrier density n (10^{18} cm^{-3}) vs Current I (mA): LED ($T = 25°C$), LD ($T = 25°C$), $I_{th} = 9.7$ mA

(b) Carrier density n (10^{18} cm^{-3}) vs Current I (mA): LED ($T = 55°C$), LD ($T = 55°C$), $I_{th} = 21.5$ mA

Chuang, O'Gorman, Levi, IEEE J. Quantum Electronics, vol. 29, no. 6, p. 1631, 1993.

ASE and Optical Gain Measurements

Experimental Determination of Optical Gain

Measurements of gain continue to be an important component to validate and refine the design of a laser in order to meet desired performance specifications.

Optical stripe-length method

An external laser source is used to excite the sample under investigation. The laser beam is focused as a stripe with a cylindrical lens. The *amplified spontaneous emission* (ASE) is measured as a function of the stripe length and the gain is extracted from a fit of the data. This method is applied to a material which has not yet been processed into a complete laser structure.

Hakki-Paoli method – the laser is operated below threshold. If the length of the device and the facet reflectivity are known, the gain can be evaluated from maxima and minima of the Fabry-Pérot spectrum recorded with a spectrometer of sufficient resolution.
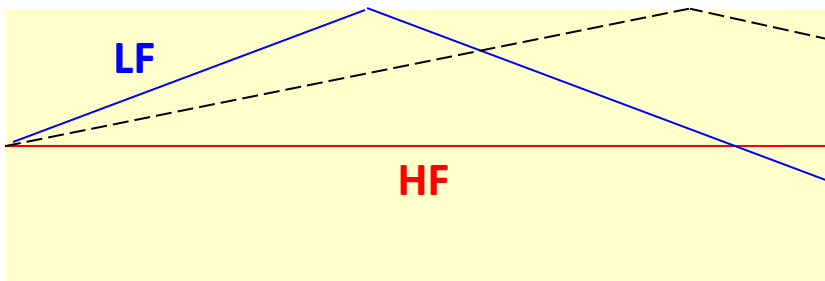
Transmission method – Requires a broadband weak light source, covering the spectral region of interest, transmitted through the device (which should operate in the fundamental mode with suppression of the Fabry-Pérot modes by deposition of anti-reflective coatings on the facets). The amplification of this broadband probe light in the diode is measured and it provides directly the gain spectra.
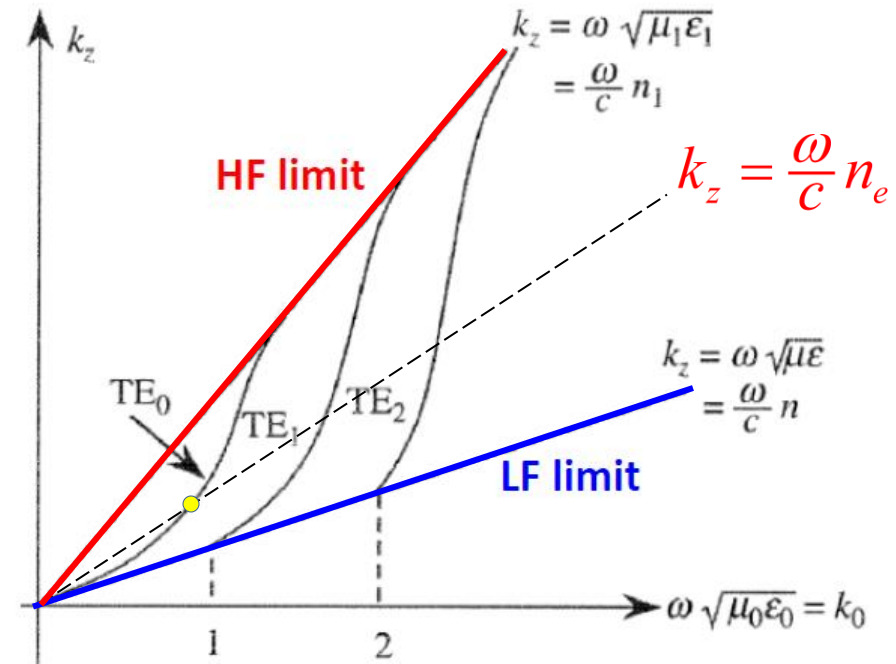
Review again: effective index n_e

$$k_z = \frac{2\pi}{\lambda_z} = n_e k = n_e \frac{2\pi}{\lambda}$$

$$n_e = \frac{2\pi}{\lambda_z} \frac{\lambda}{2\pi} = \frac{\lambda}{\lambda_z} = \frac{v_p}{f} \frac{f}{v_{pz}} = \frac{v_p}{v_{pz}}$$

$$n < n_e < n_1$$

$$k_z = \omega \sqrt{\mu_1 \varepsilon_1} = \frac{\omega}{c} n_1$$

HF limit

$$k_z = \frac{\omega}{c} n_e$$

TE_0 TE_1 TE_2

$$k_z = \omega \sqrt{\mu \varepsilon} = \frac{\omega}{c} n$$

LF limit

$$\omega \sqrt{\mu_0 \varepsilon_0} = k_0$$

Strictly, each mode is associated with a specific effective index at a given frequency

27

Optical Fields in Cavity with Gain

Fabry-Perot Cavity

Initial Field: $E_{sp}(\lambda)$

Field After Single Pass: $E'_{sp}(\lambda) = E_{sp}(\lambda) + E_{sp}(\lambda) r_1 r_2 e^{i2kL}$

General Expression: $E_{ASE}(\lambda) = E_{sp}(\lambda)\left[1 + r_1 r_2 e^{i2kL} + \left(r_1 r_2 e^{i2kL}\right)^2 + \left(r_1 r_2 e^{i2kL}\right)^3 + ...\right]$

$$\left[1 + a + a^2 + a^3 + ...\right] = \frac{1}{1-a} \longrightarrow E_{ASE}(\lambda) = \frac{E_{sp}(\lambda)}{1 - r_1 r_2 e^{i2kL}}$$

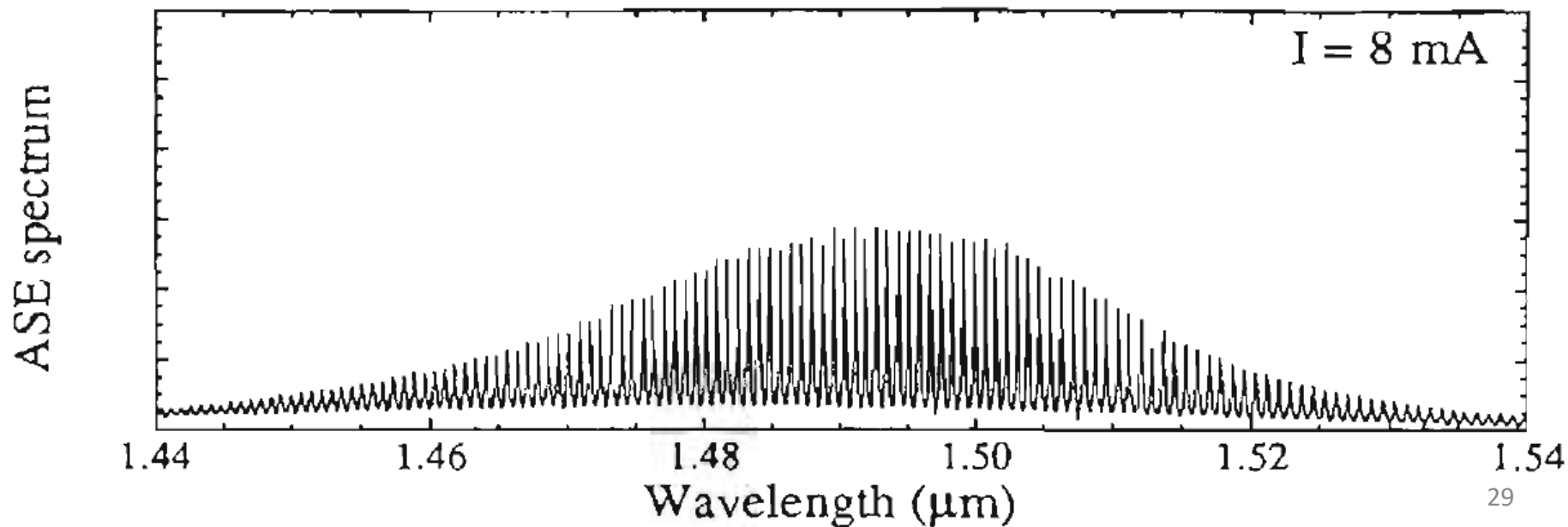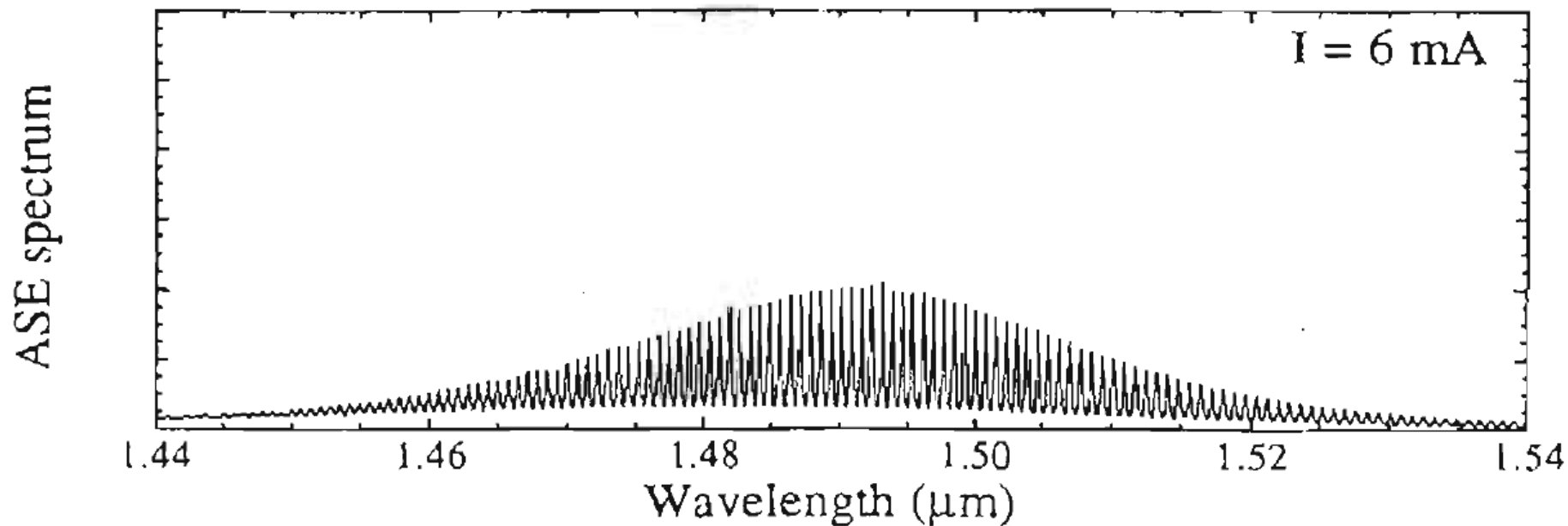n_e is the effective index
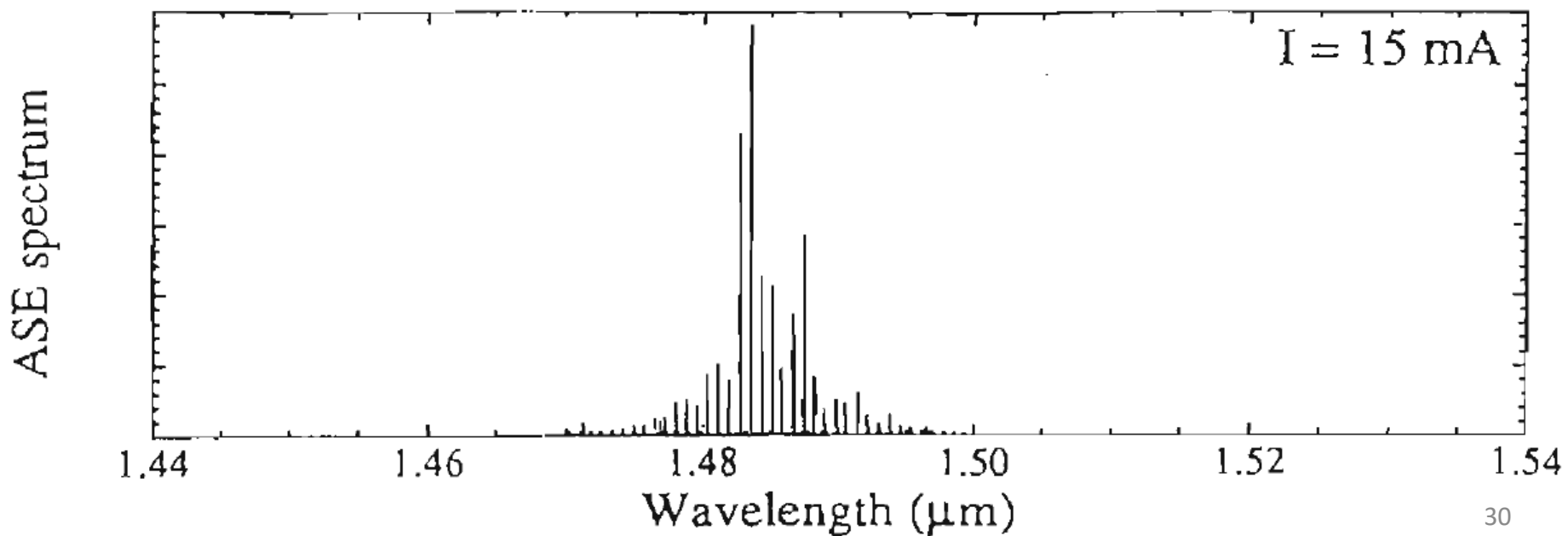
$G_n = \Gamma g - \alpha_i$ is the net modal gain

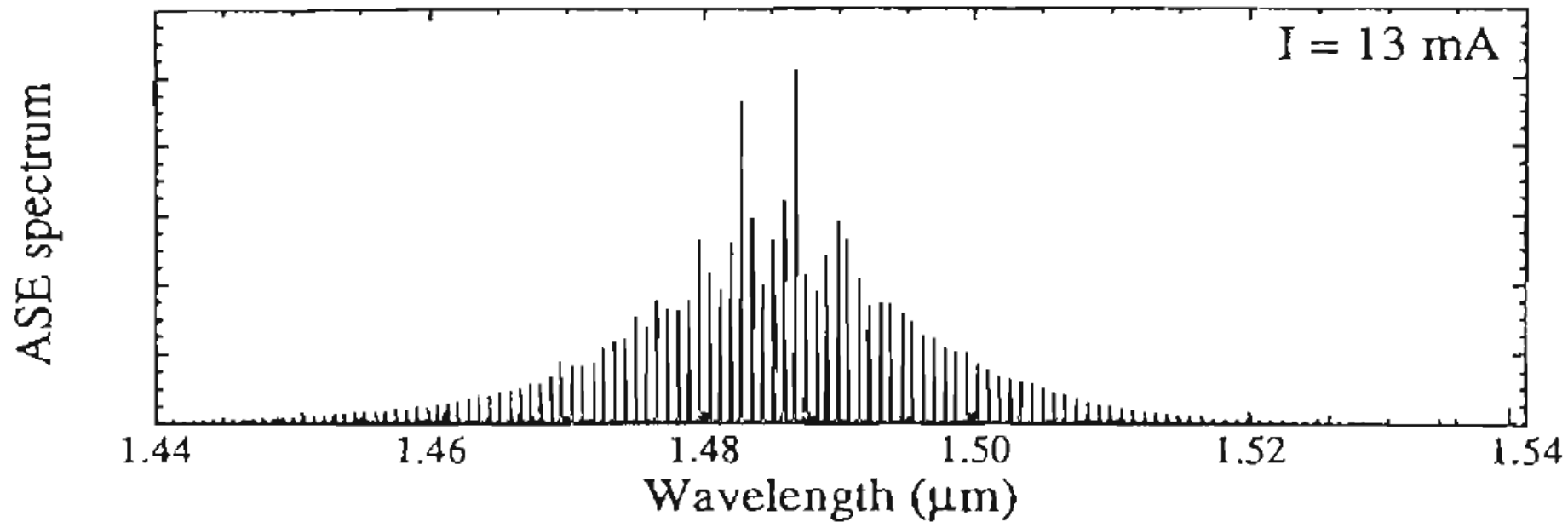$$k = k' - i\frac{G_n}{2} = \frac{2\pi}{\lambda} n_e - i\frac{G_n}{2}$$

$$G_n = \Gamma g - \alpha_i$$

28

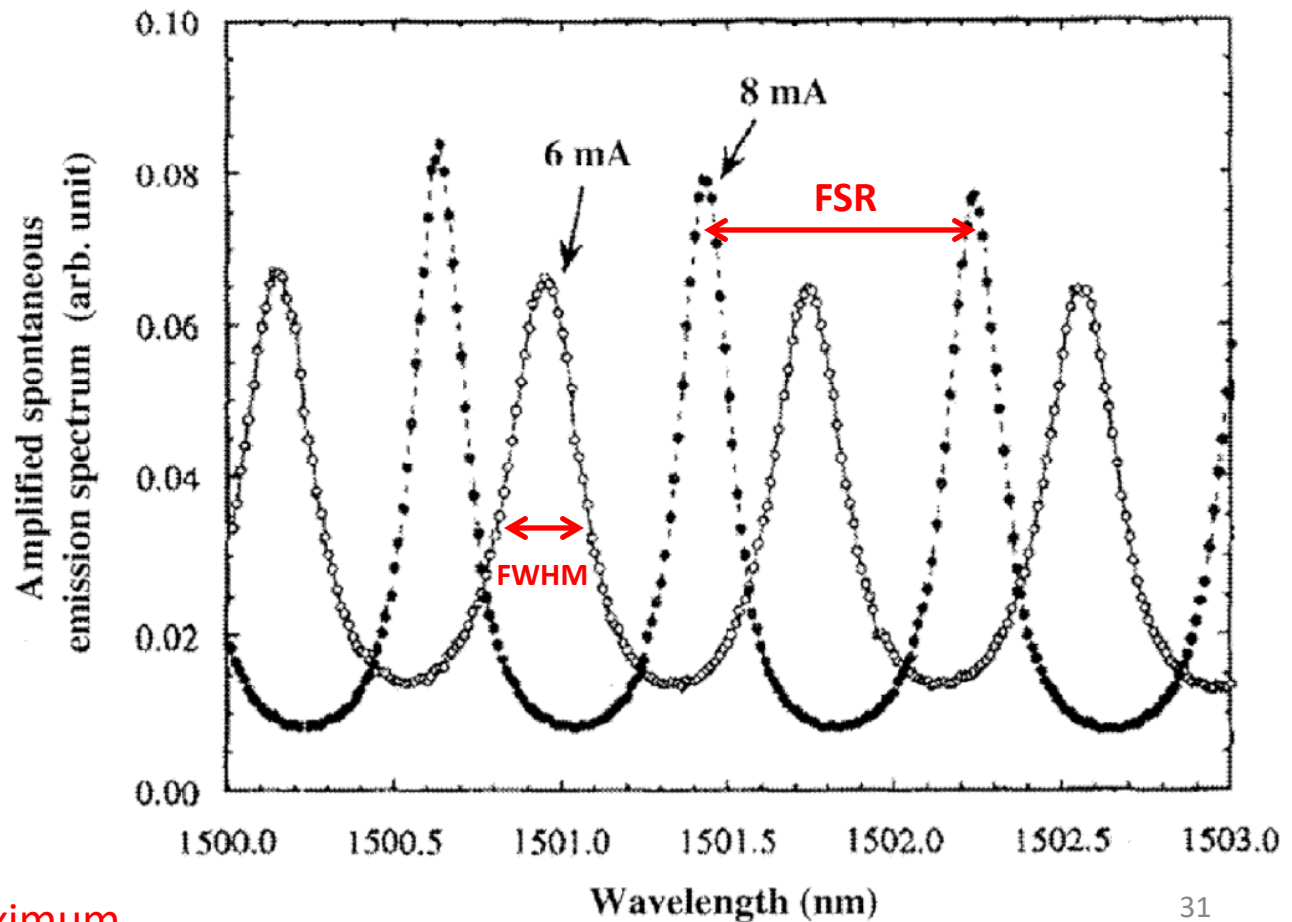# ASE Behavior below threshold

ASE Behavior below threshold

30

ASE Power Spectrum

$$P(\lambda) \propto \left| E_{ASE}(\lambda) \right|^2 = \frac{\left| E_{sp}(\lambda) \right|^2}{\left| 1 - r_1 r_2 e^{i2kL} \right|^2} = \frac{\left| E_{sp}(\lambda) \right|^2}{\left(1 - A \right)^2 + 4A \sin^2 \left(k'L \right)}$$

$$A = \sqrt{R_1 R_2}\, e^{G_n L}$$

$$R_1 = \left| r_1 \right|^2$$

$$R_2 = \left| r_2 \right|^2$$

FSR = Free Spectral Range
FWHM = Full Width Half Maximum

31

Modal Gain from ASE Spectra – 1

$$P(\lambda) \propto I(\lambda) = \left| E_{ASE}(\lambda) \right|^2 = \frac{\left| E_{sp}(\lambda) \right|^2}{\left| 1 - r_1 r_2 e^{i2kL} \right|^2} = \frac{\left| E_{sp}(\lambda) \right|^2}{(1-A)^2 + 4A\sin^2(k'L)}$$

Maximum of ASE Spectrum: $k'L = m\pi$ and $I_{max} = \dfrac{\left| E_{sp}(\lambda_{max}) \right|^2}{(1-A)^2}$

Minimum of ASE Spectrum: $k'L = \left(m + \dfrac{1}{2}\right)\pi$ and $I_{min} = \dfrac{\left| E_{sp}(\lambda_{min}) \right|^2}{(1+A)^2}$

Taking the ratio (nearby ASE peaks): $\dfrac{I_{max}}{I_{min}} = \dfrac{(1+A)^2}{(1-A)^2}$

Taking the ratio (nearby ASE peaks): $\dfrac{I_{max}}{I_{min}} = \dfrac{(1+A)^2}{(1-A)^2}$

Solving for A: $A = \dfrac{\sqrt{I_{max}/I_{min}}-1}{\sqrt{I_{max}/I_{min}}+1} = \sqrt{R_1 R_2}\, e^{G_n L}$

Solving for G: $G_n = \dfrac{1}{L}\ln\dfrac{\sqrt{I_{max}/I_{min}}-1}{\sqrt{I_{max}/I_{min}}+1} + \dfrac{1}{2L}\ln\dfrac{1}{R_1 R_2}$

G is the net modal gain.

Note: $G_n(\lambda) = \Gamma g(\lambda) - \alpha_i = Q_r + \alpha_m$ where $Q_r = \dfrac{1}{L}\ln\dfrac{\sqrt{I_{max}/I_{min}}-1}{\sqrt{I_{max}/I_{min}}+1}$

Hakki-Paoli Method for Gain Measurement

- Measure ASE spectrum

- Take the ratio of the magnitude of I_{max} and I_{min} for the peaks near the mth mode λ_m

- Calculate the mirror reflectivity and either measure the cavity length or calculate it from the measured mode spacing and the effective index n_e
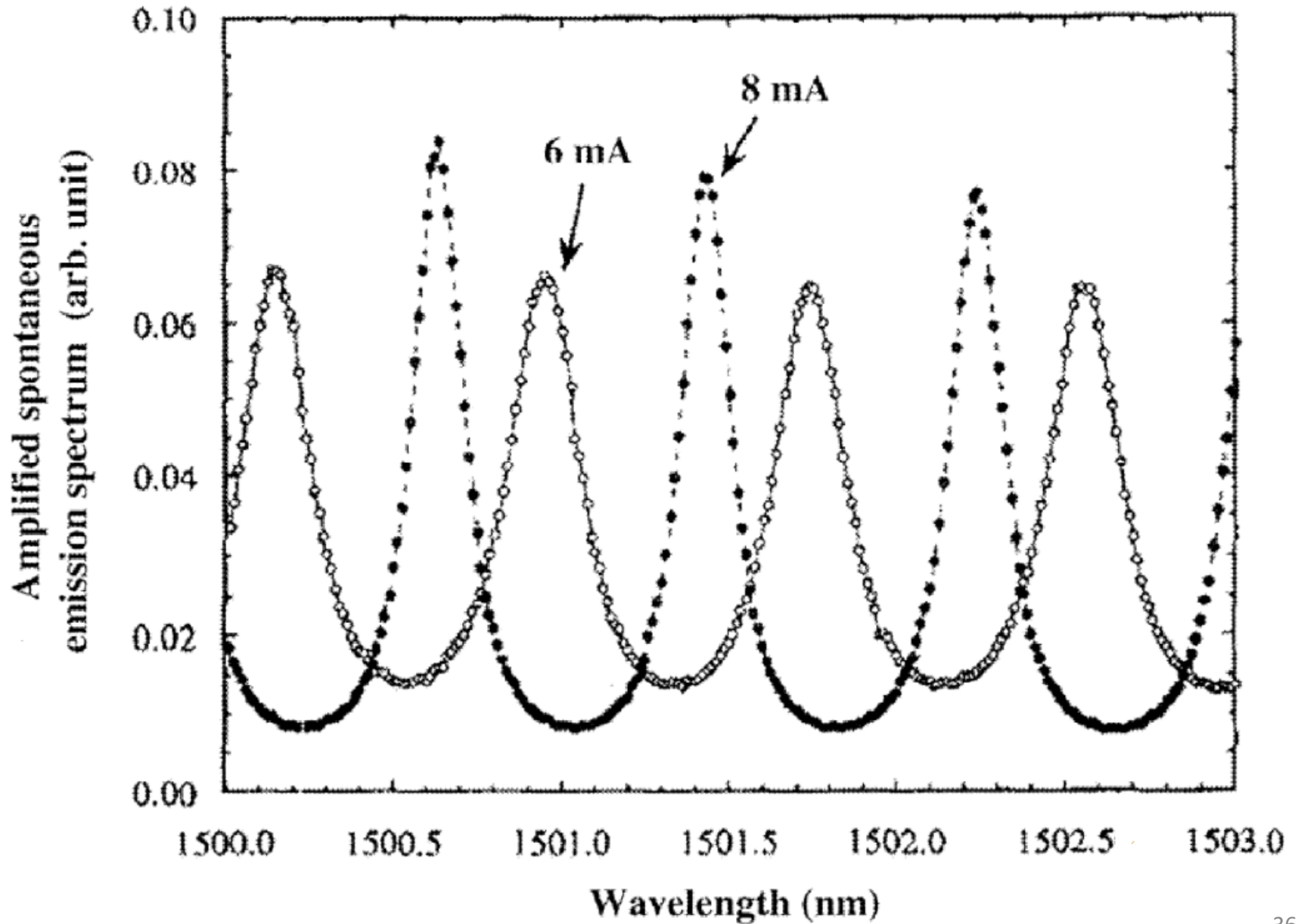
- Gain is calculated using

$$G_n(\lambda) = Q_r + \alpha_m$$

Hakki-Paoli Method for Gain Measurement
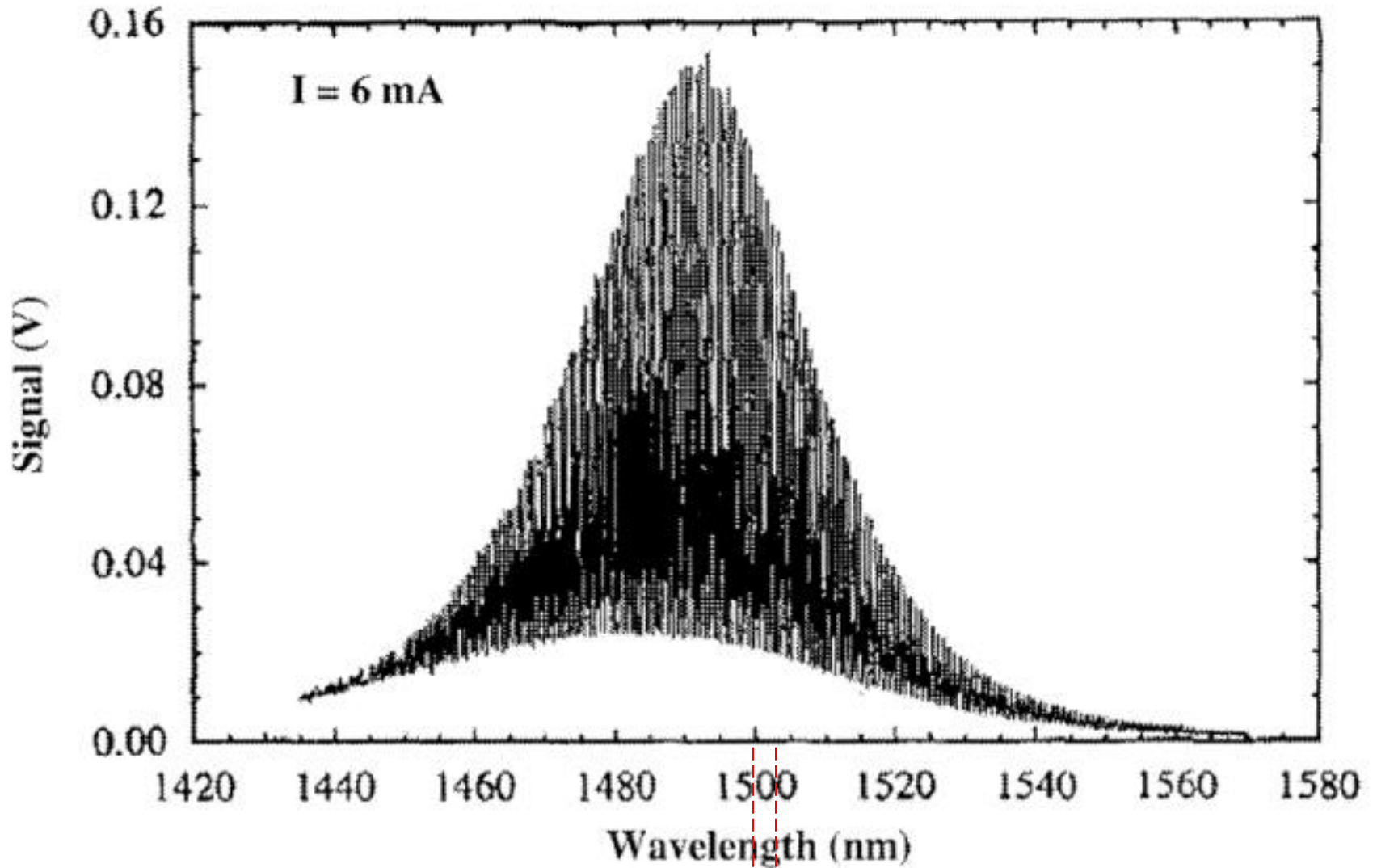
spectrum range enlarged in next slide
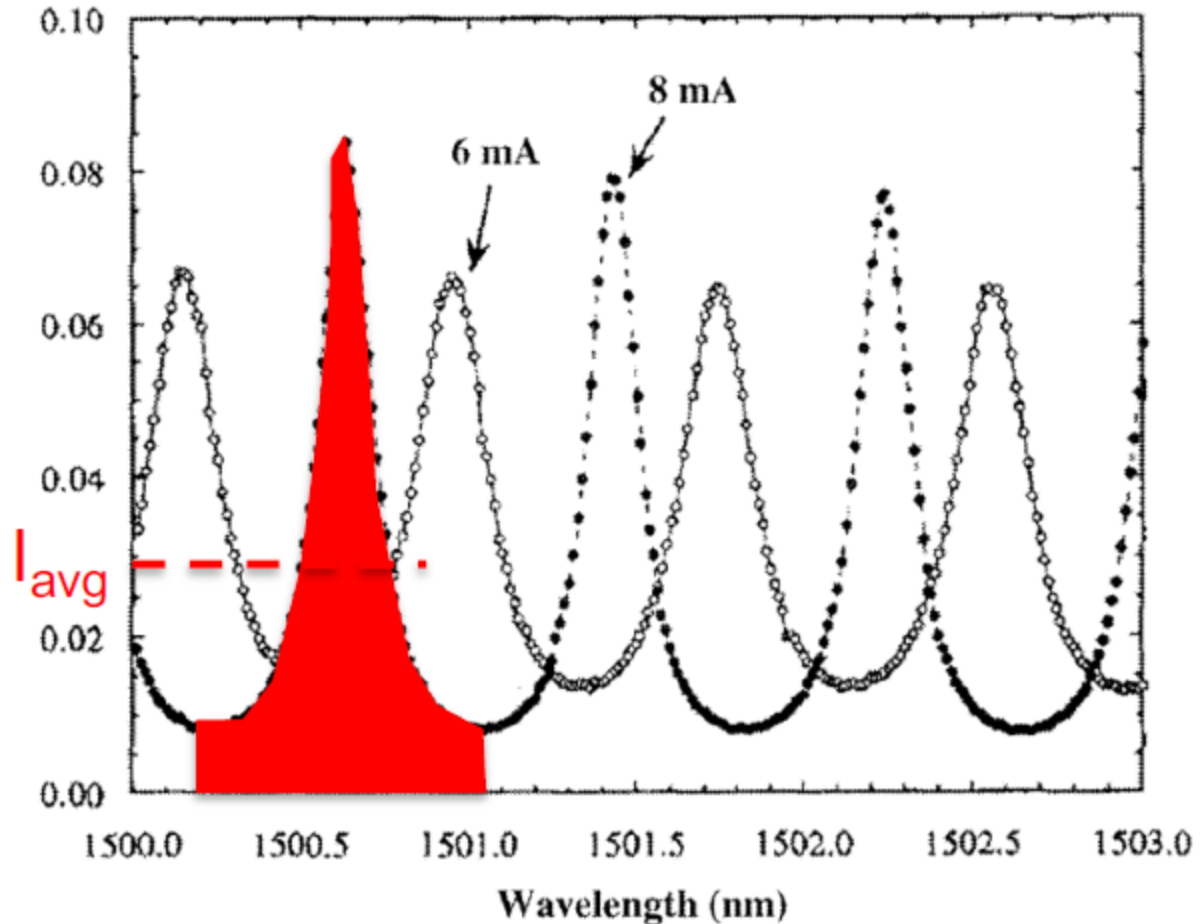
Hakki-Paoli Method for Gain Measurement

Cassidy's Method – Variant of Hakki-Paoli Method

Based on the Hakki-Paoli method, except that the ratio: I_{avg} / I_{min} is computed.

$$I_{avg} = \sqrt{I_{max} \cdot I_{min}}$$

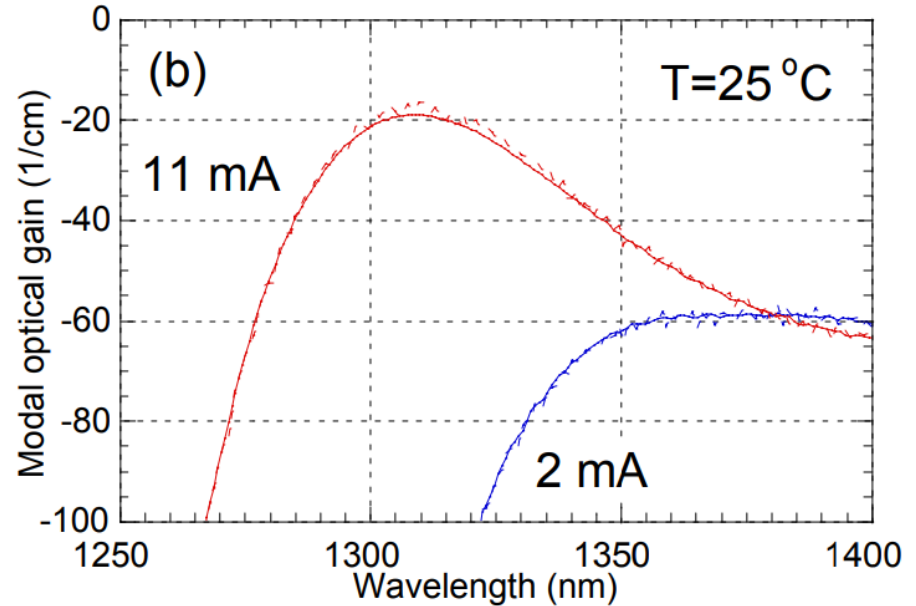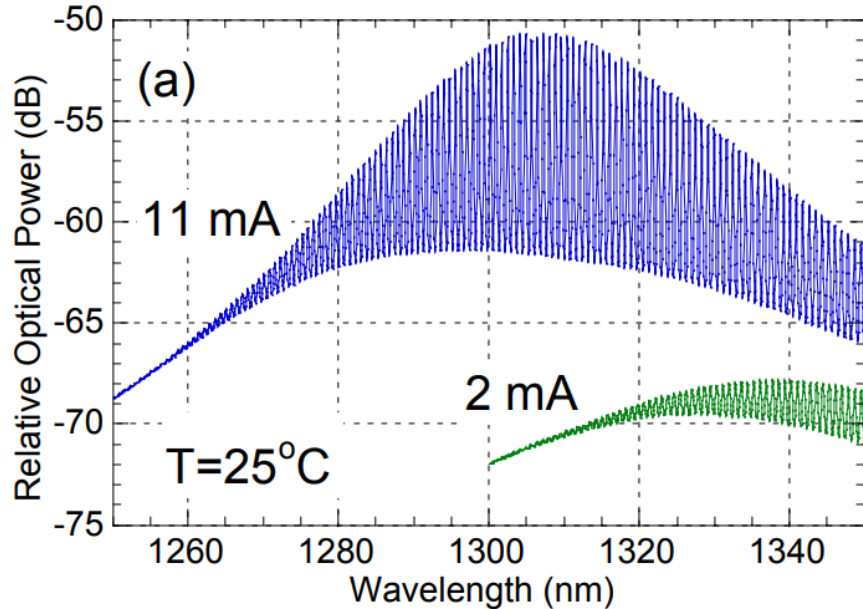I_{avg} is more accurate to measure than I_{max} which depends on resolution of the instrument.

In alternative one can use instead I_{max}/I_{avg} if data is noisy or I_{max} is more accurate than I_{min} .

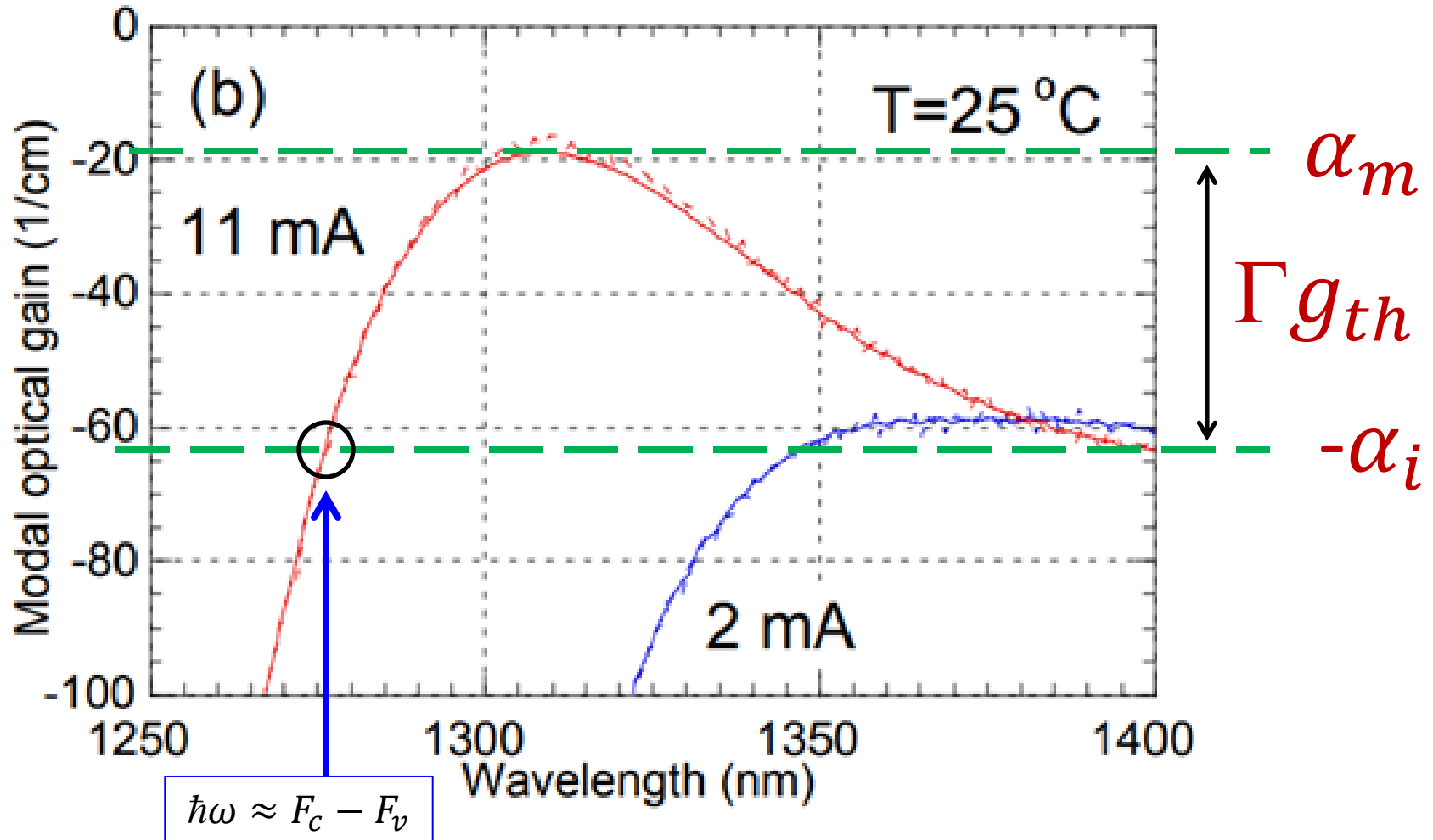JAP **56**, 3096 (1984)
JQE **41**, 532 (2005)

Example

Left: ASE spectra for a 1.3 μm laser with a bulk active region and uncoated mirror facets

Right: Modal optical gain measurements with Hakki-Paoli method (continuous lines) and with Cassidy method (dotted lines)

Characteristics of the G-λ Plot

(b)

T=25 °C

11 mA

2 mA

Modal optical gain (1/cm)

Wavelength (nm)

α_m

Γg_{th}

$-\alpha_i$

$\hbar\omega \approx F_c - F_v$

Below band edge (longer wavelengths) gain is negligible and the plot $G_n(\lambda)$ approaches $-\alpha_i$. The peak occurs at the laser threshold gain $G_n(\lambda) = \Gamma g_{th} - \alpha_i = \alpha_m$.

Reading Assignments:

Sections 10.1 and 10.2 of Chuang's book
Section 7.6 of Chuang's book (waves in lossy media)