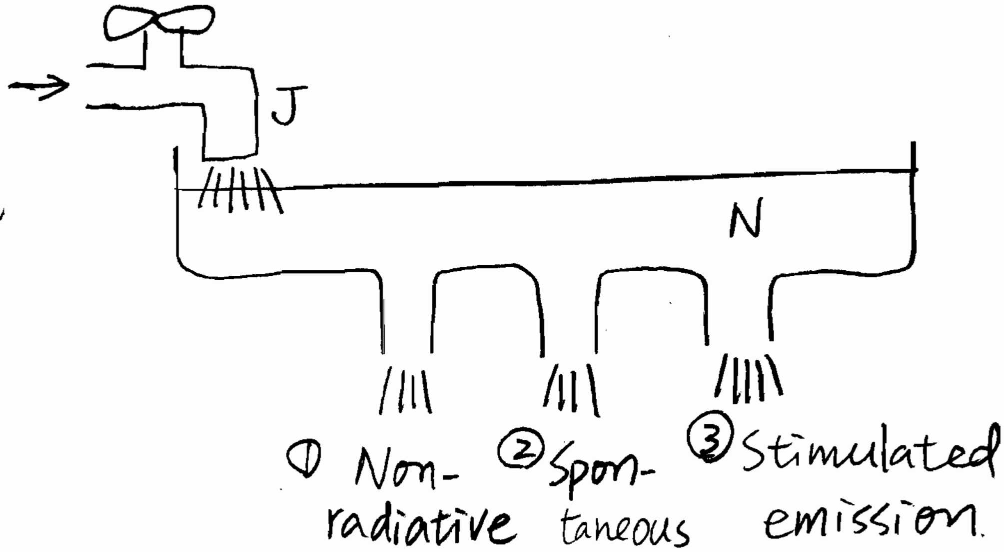


Rate Equations

$$\begin{cases} \dfrac{dN}{dt} = \dfrac{\eta_i J}{qd} - \dfrac{N}{\tau} - \dfrac{c}{n_r} g(N) \cdot S \\[2em] \dfrac{dS}{dt} = \dfrac{c}{n_r} \Gamma g(N) \cdot S - \dfrac{S}{\tau_p} + \beta R_{sp} \end{cases}$$

η_i: Internal quantum efficiency

$\dfrac{N}{\tau}$ ← ① ②; $\dfrac{c}{n_r} g(N) \cdot S$ ← ③

R_{sp} ← ②

N: carrier density
S: photon "
$[\frac{1}{cm^3}]$

τ_p = Photon lifetime

β: spontaneous emission factor (fraction of spon. coupled to laser mode)

$\beta \sim 10^{-3}$ to 10^{-4} for DH

Steady State

$$\frac{dN}{dt} = 0, \quad \frac{dS}{dt} = 0$$

At threshold:

$S = 0$

$N = N_{th}$

$J = J_{th}$

First Eq: $\eta_i \frac{J_{th}}{qd} = \frac{N_{th}}{\tau} \Rightarrow J_{th} = \frac{N_{th}}{\eta_i \tau} \cdot qd$

Second Eq: Neglect βR_{sp}

$$\frac{c}{n_r} \Gamma g_{th} = \frac{1}{\tau_p} = \frac{c}{n_r}(\alpha_i + \alpha_m)$$

$$\tau_p = \frac{1}{\frac{c}{n_r}(\alpha_i + \alpha_m)}$$

Above threshold:

gain is clamped $\Rightarrow g(N) = g(N_{th}) = g_{th}$

$\Rightarrow$ carrier conc is clamped $\Rightarrow N = N_{th}$

$$\frac{dN}{dt} = 0 = \frac{\eta_i J}{qd} - \frac{N_{th}}{\tau} - \frac{c}{n_r} g(N_{th}) \cdot S$$

$$\frac{N_{th}}{\tau} = \frac{\eta_i J_{th}}{qd}$$

$$\frac{\eta_i (J - J_{th})}{q d} = \frac{c}{n_r} g_{th} \cdot S = \frac{1}{\Gamma}(\alpha_i + \alpha_m) \frac{c}{n_r} \cdot S$$

$$g_{th} = \frac{1}{\Gamma}(\alpha_i + \alpha_m)$$

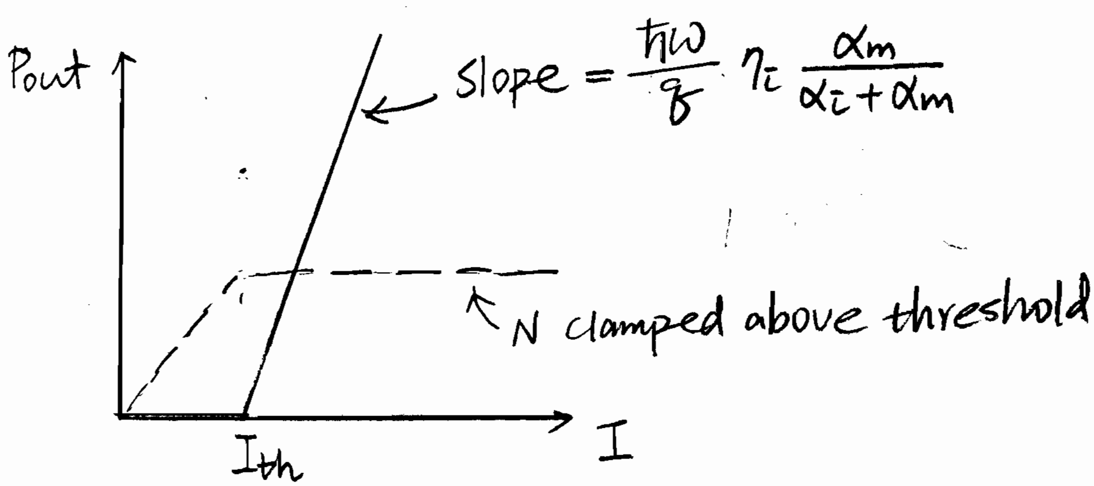
Output power

$$P_{out} = (\hbar\omega)\, S \cdot \frac{L \cdot W \cdot d}{\Gamma} \cdot \underbrace{\frac{c}{n_r} \cdot \overset{cm^{-1}}{\alpha_m}}_{\frac{1}{sec}}$$

$$\Rightarrow P_{out} = (\hbar\omega) \frac{LWd}{\Gamma} \cdot \alpha_m \left(\frac{c}{n_r} \cdot S\right)$$

$$= (\hbar\omega) \frac{LWd}{\Gamma} \alpha_m \cdot \frac{\eta_i (J - J_{th})}{q d} \cdot \frac{\Gamma}{\alpha_i + \alpha_m}, \qquad LW \cdot J = I$$

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



L-I curve

$$\text{Quantum Efficiency (QE)} = \frac{\#\ \text{Photons}}{\#\ \text{Electrons}}$$

$$\eta_e = \eta_i \cdot \frac{\alpha_m}{\alpha_i + \alpha_m}$$ measured QE is usually referred to as "external" QE

I_{th} and η_{ext} can be measured from the L-I curve.

What about η_i and α_i ?

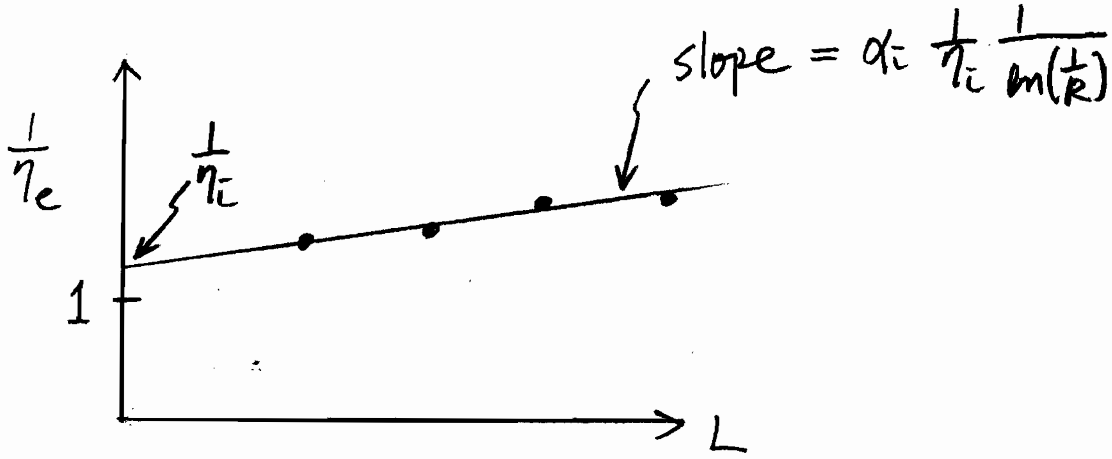
Note that

$$\frac{1}{\eta_e} = \frac{1}{\eta_i}\left(1 + \frac{\alpha_i}{\alpha_m}\right)$$

$$\alpha_m = \frac{1}{2L}\ln\frac{1}{R_1R_2} = \frac{1}{L}\ln\frac{1}{R} \quad , \quad R_1 = R_2 = R$$

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

⇒ Measure η_e for many similar lasers with different L



η_i can be determined from intercept

α_i can be determined from slope.