# Laser diode quantum efficiency revisited

from the worries of a beginner in 1983
to a contemporary problem

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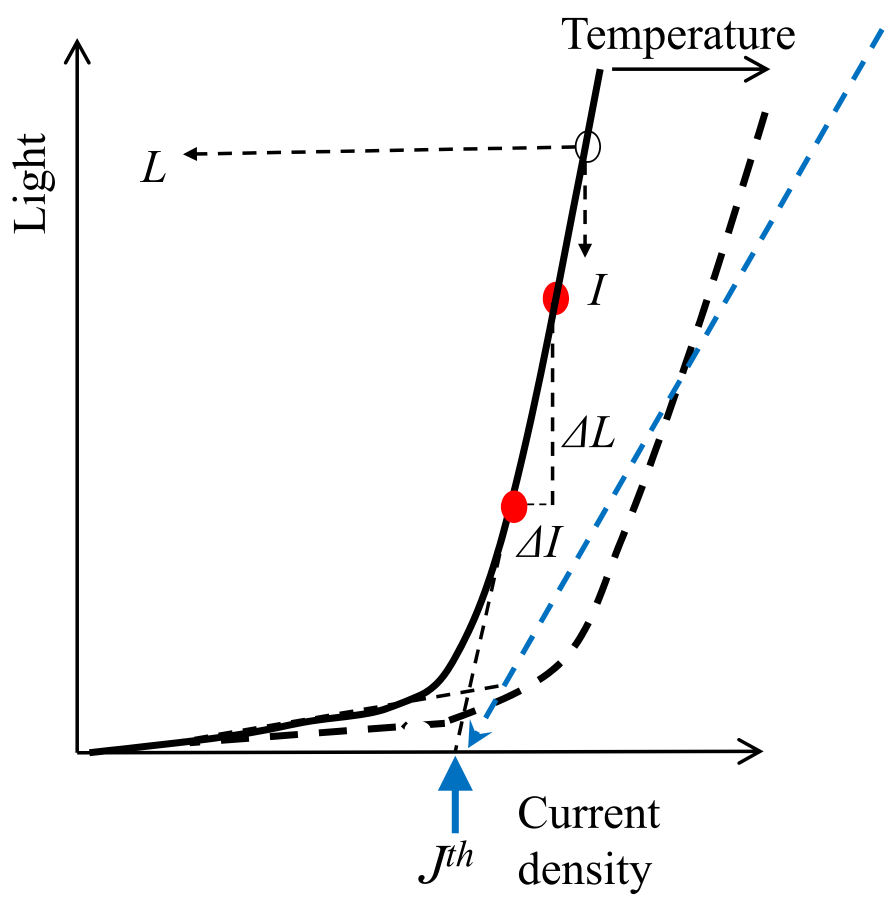
# Measured light-current characteristic




The **external current at threshold** $J_{ext}^{th}$:

- non-radiative recombination in the gain medium
- current lost by leakage and spreading
- intrinsic radiative (spontaneous) current, $J_{spon}^{th}$, which drives gain generation and can be calculated.

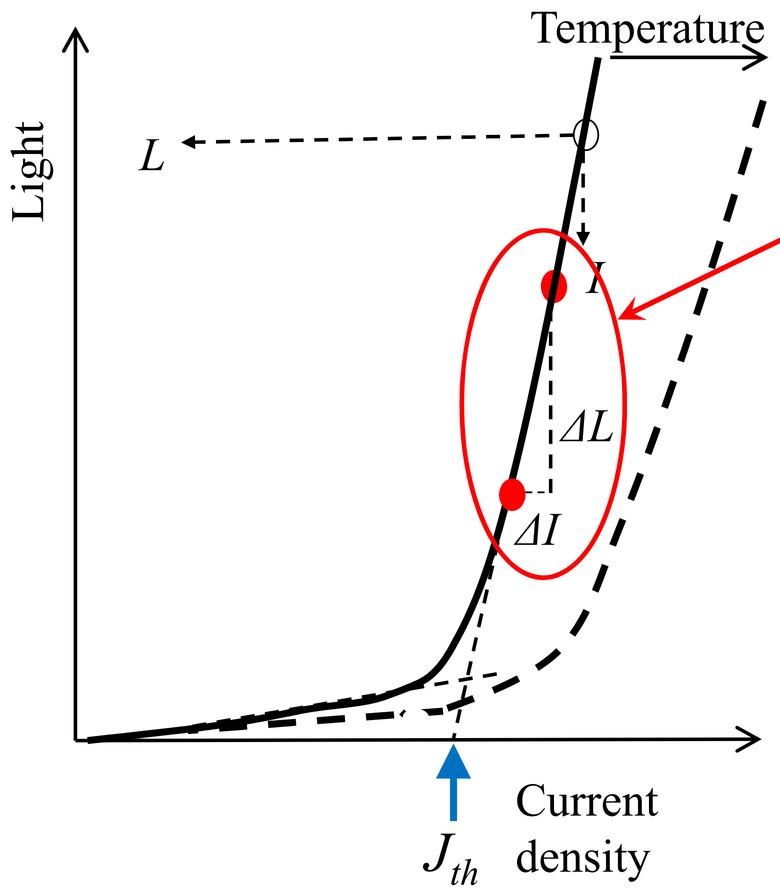
$$J_{spon}^{th} = \eta_0 J_{ext}^{th}$$

**Efficiency $\eta_0$ is not known:**

**sample and structure dependent**

➢ How can measurement and theory for threshold be compared?

# Measured light-current characteristic




**Above threshold**:
External **differential** quantum efficiency in the lasing mode:

$$\eta_{ext}^{d} = \frac{external\ photon\ emission\ rate\ increment}{external\ current\ increment/e}$$

$$\frac{1}{\eta_{ext}^{d}} = \left\{1 + \frac{\alpha_i}{ln(R^{-1})} L_c\right\} \frac{1}{\eta_0^d}$$

(Baird, Carr and Reed, 1964)

${}^{1}/_{\eta_{ext}^{d}}$ versus cavity length $L_c$ has intercept ${}^{1}/_{\eta_0^{d}}$

# Measurements

Typical experimental values give $\eta_0^d$ 0.6 to 0.9.

$\eta_0^d$ regarded as the "internal quantum efficiency".
Used to obtain spontaneous current at threshold to compare with theory.
Problem solved?

Two worries:

1. Why is $\eta_0^d$ from the intercept < 1?
   Fermi level pinning above threshold stimulated emission efficiency is 1.

2. Can we obtain *overall* efficiency at threshold from a *differential* efficiency above threshold?

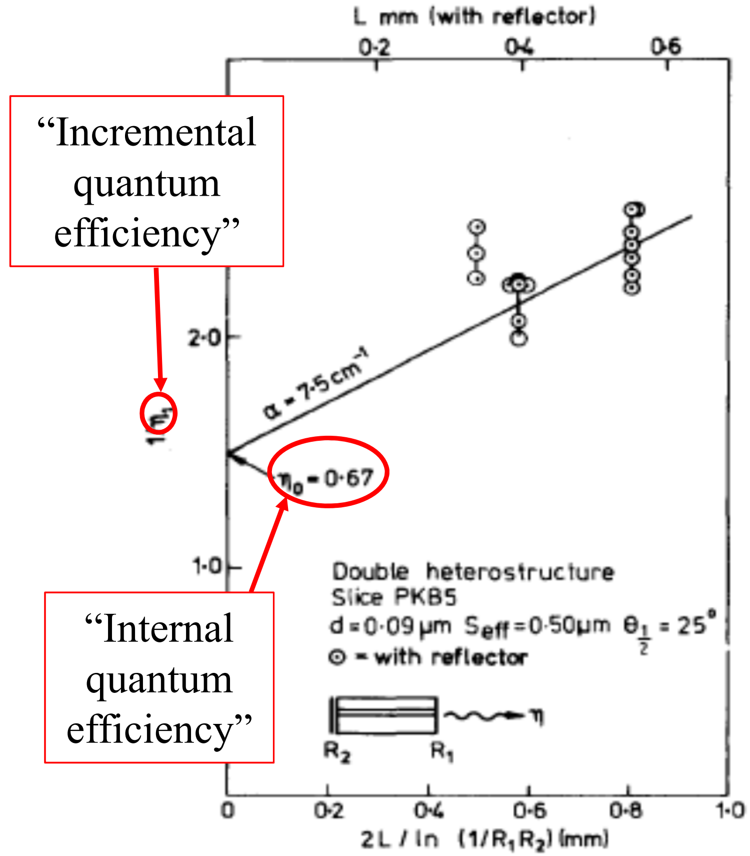



FIG. 11. Incremental quantum efficiency versus laser length for narrow-beam DH lasers.

Thompson et al 1976

# From a notebook

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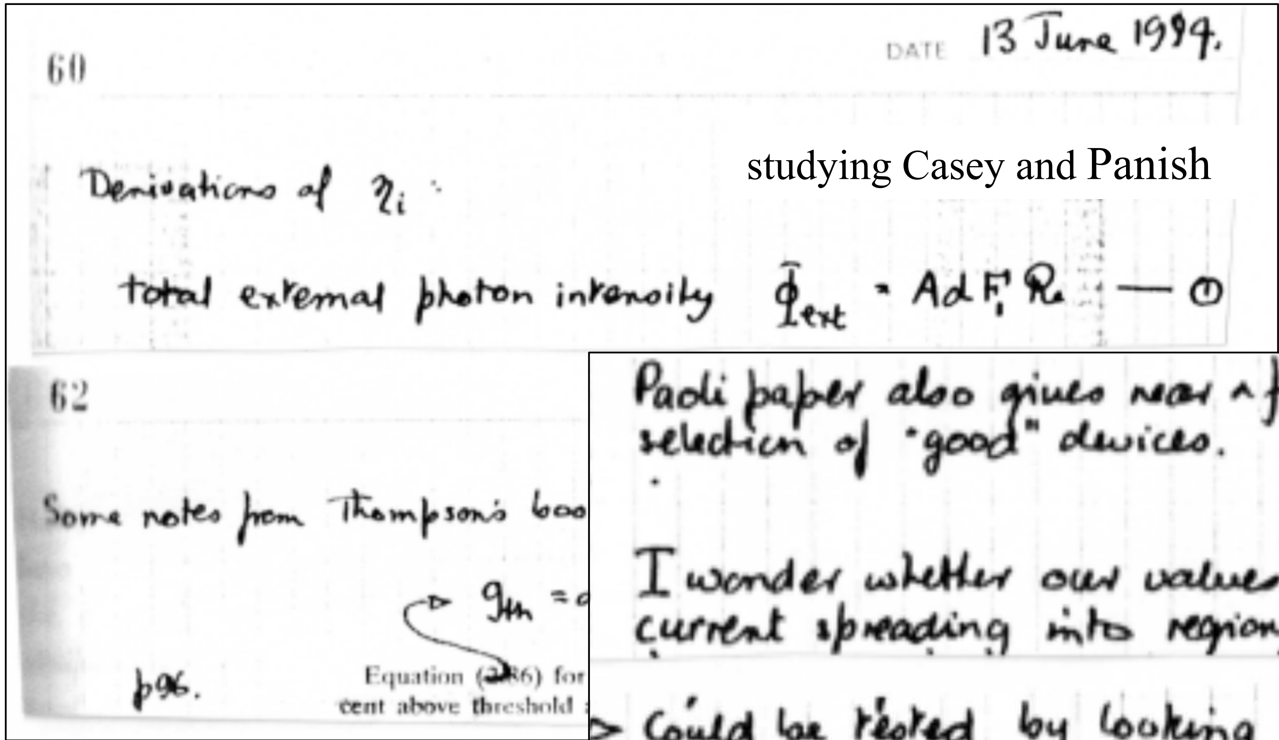

60 DATE 13 June 1994.

studying Casey and Panish

Derivations of $\eta_i$ :

total external photon intensity $\Phi_{ext} = A d F_1' R_e$ — (1)

62

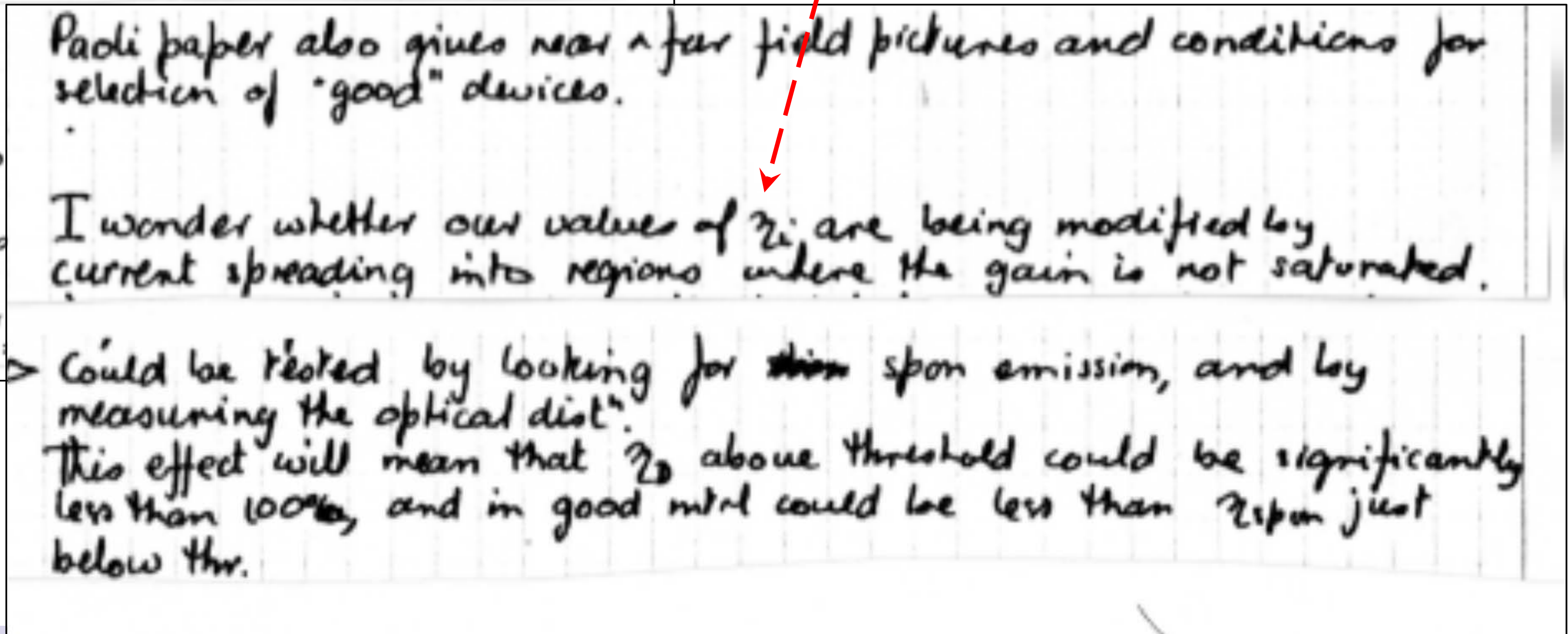
Some notes from Thompson's boo

$g_{th} =$

p96.

Equation (2.86) for
cent above threshold

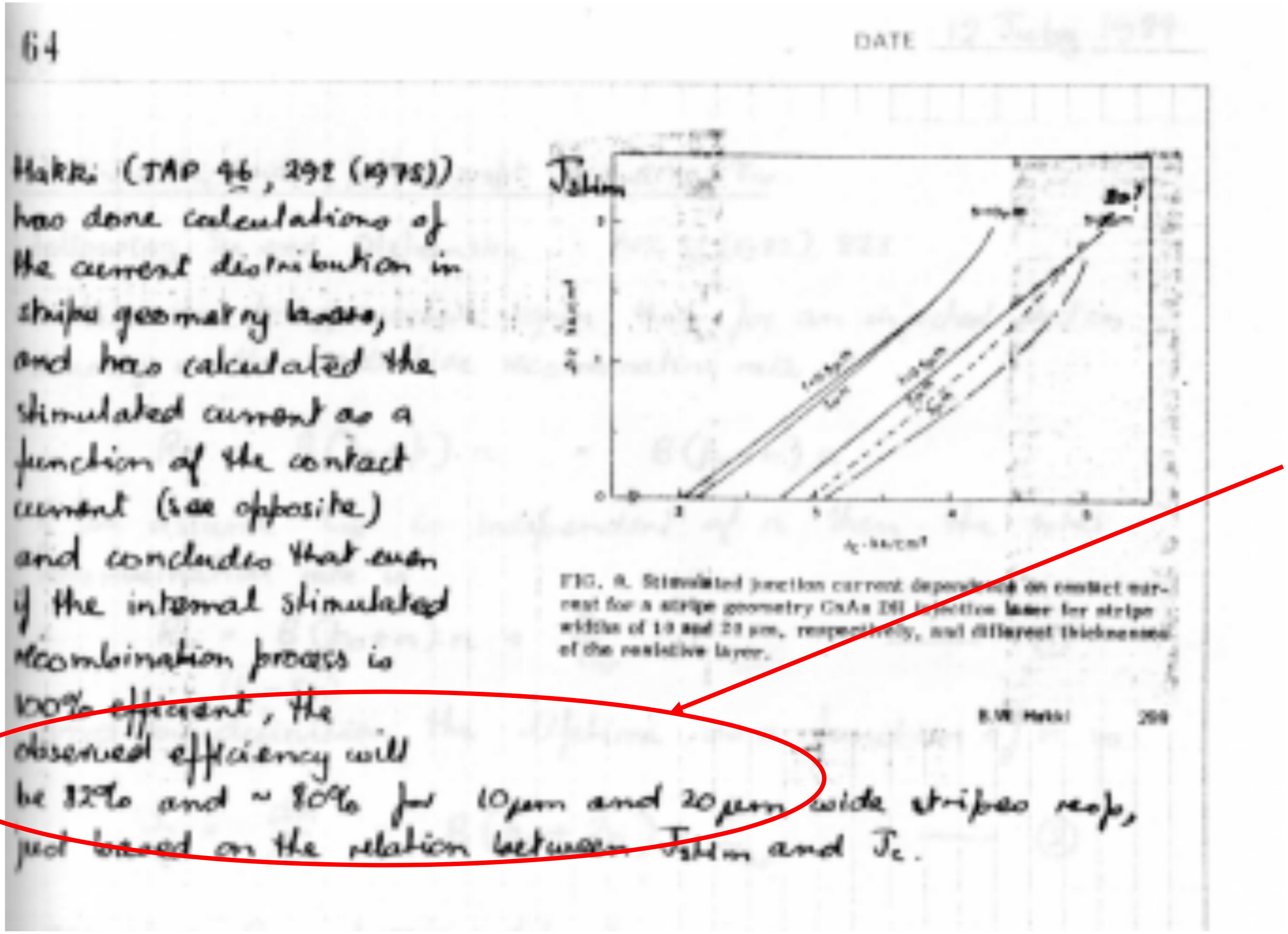
Notation not consistent


Paoli paper also gives near + far field pictures and conditions for selection of "good" devices.

I wonder whether our values of $\eta_i$ are being modified by current spreading into regions where the gain is not saturated.

→ Could be tested by looking for spon emission, and by measuring the optical distⁿ.
This effect will mean that $\eta_i$ above threshold could be significantly less than 100%, and in good mtrl could be less than $\eta_{i\,spon}$ just below thr.

# …on the next page…answer to Q1



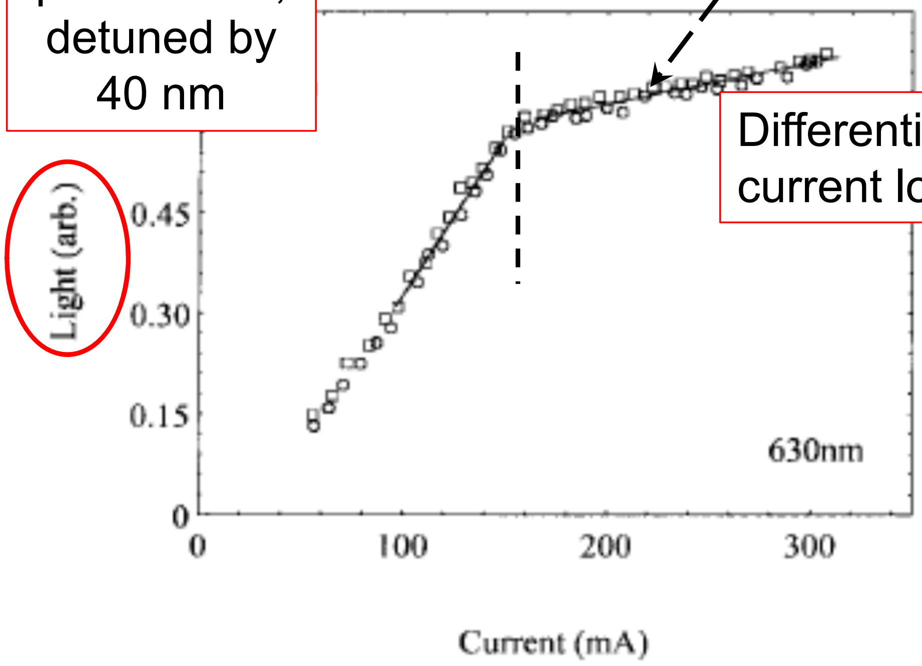

Calculated stimulated current versus external current for stripe laser by Hakki (1975)

Differential injection efficiency about 0.8 due to increasing current spreading above threshold.

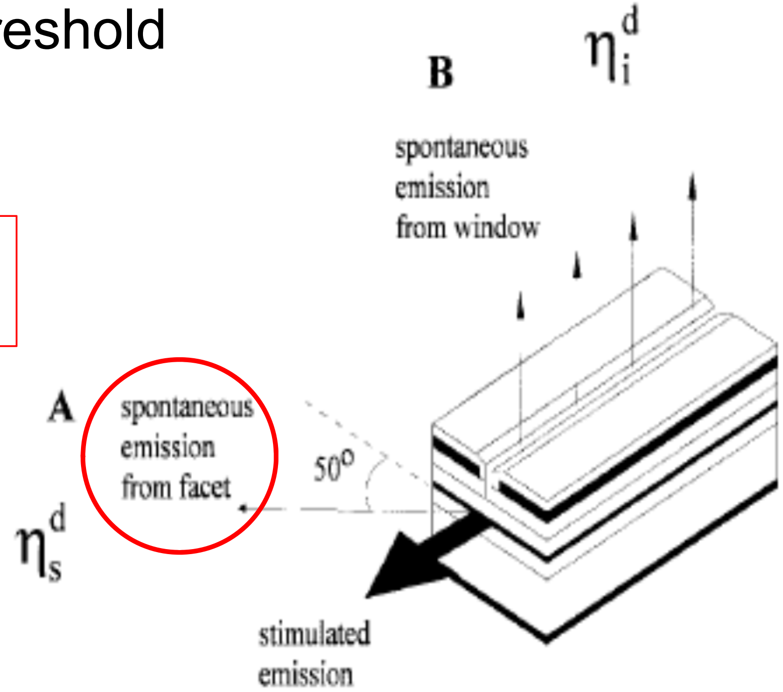
# Experiments, 10 years later!

Current spreading increasing above threshold

TM polarisation, detuned by 40 nm




Differential current loss 0.15.




Smowton and Blood, JSTQE 3 (1997) 491

# Current paths

**Above Threshold:**

- External differential efficiency:
  externally measured light and current

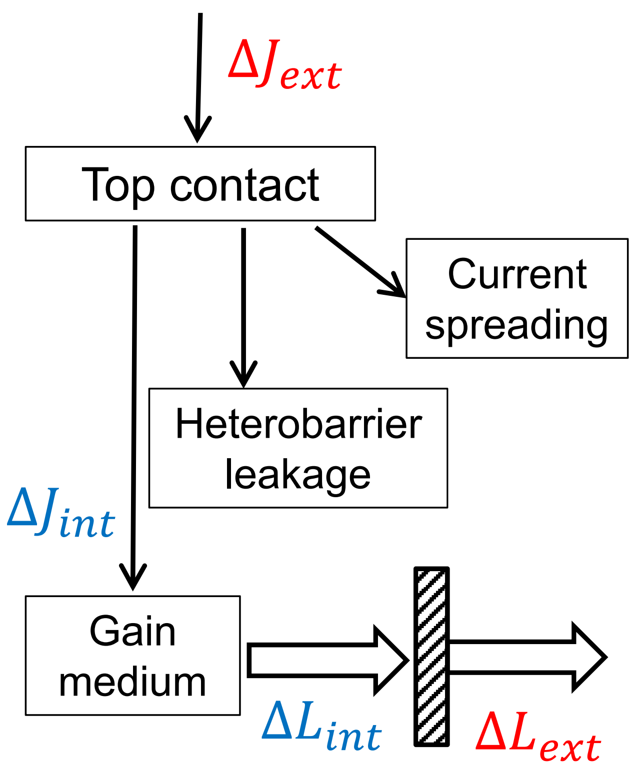
$$\eta_{ext}^{d} = \frac{e\Delta L_{ext}}{\Delta J_{ext}}$$

- Internal differential efficiency:
  Ratio of increments in rate of injection of electron-hole pairs (current) into gain region to the photon emission rate from this region.

$$\eta_{int}^{d} = \frac{e\Delta L_{int}}{\Delta J_{int}}$$

If Fermi levels pinned $\eta_{int}^{d} = \eta_{stim} = 1$

**Current paths**



# Differential efficiencies **above threshold**

Taking account of internal and external light and current:

$$\frac{e\Delta L_{ext}}{\Delta J_{ext}} = \frac{\Delta L_{ext}}{\Delta L_{int}} \times \frac{\Delta J_{int}}{\Delta J_{ext}} \times \frac{e\Delta L_{int}}{\Delta J_{int}}$$

External differential efficiency.

Light extraction factor

$$F = \frac{\alpha_m}{\alpha_m + \alpha_i}$$

Fractional increment in external current which enters the gain medium. **The differential current injection efficiency**

Internal differential efficiency **Stimulated emission**

$$\eta_{ext}^{d} = F \times \eta_{inj}^{d} \times \eta_{int}^{d}$$

If Fermi levels pinned in gain region intercept of plot gives $\eta_{inj}^{d}$ (<1).

# Overall efficiency at threshold

*Internal* spontaneous radiative efficiency is $\eta_{int}^{spon} = \frac{R_{spon}}{R_{spon}+R_{nr}} = \frac{eR_{spon}}{J_{int}}$

The overall injection efficiency is $\eta_{inj} = \frac{J_{int}}{J_{ext}}$

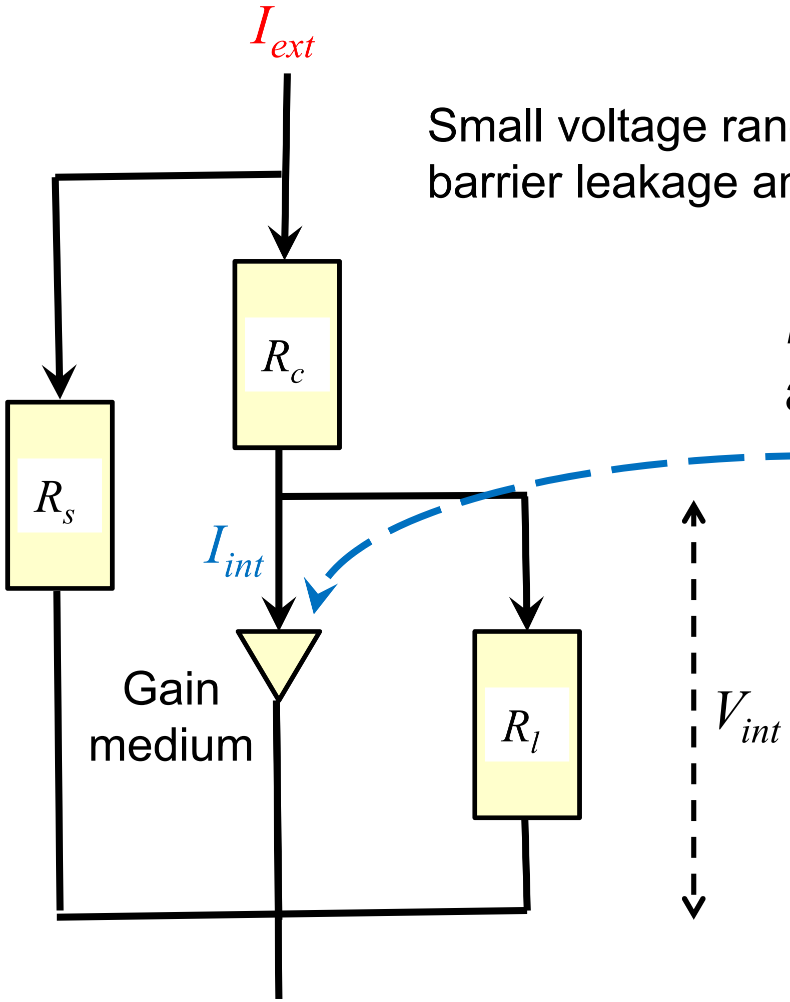
**Spontaneous Emission**
in all directions

$$J_{spon}^{th} = \eta_0 J_{ext}^{th} = [\eta_{int}^{spon} \times \eta_{inj}] J_{ext}^{th}$$

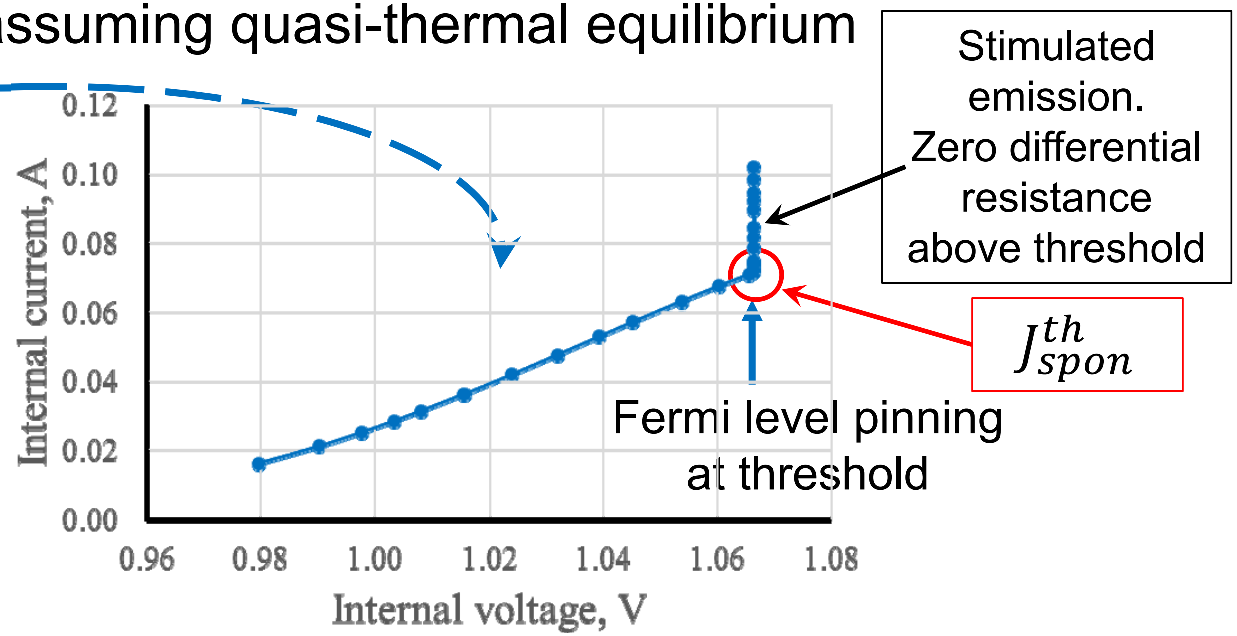
- **Question 2: Does overall injection efficiency at threshold = differential injection efficiency above threshold ?**

# External and internal current

Small voltage range around threshold, represent current spreading, hetero-barrier leakage and series resistance as linear resistive elements.

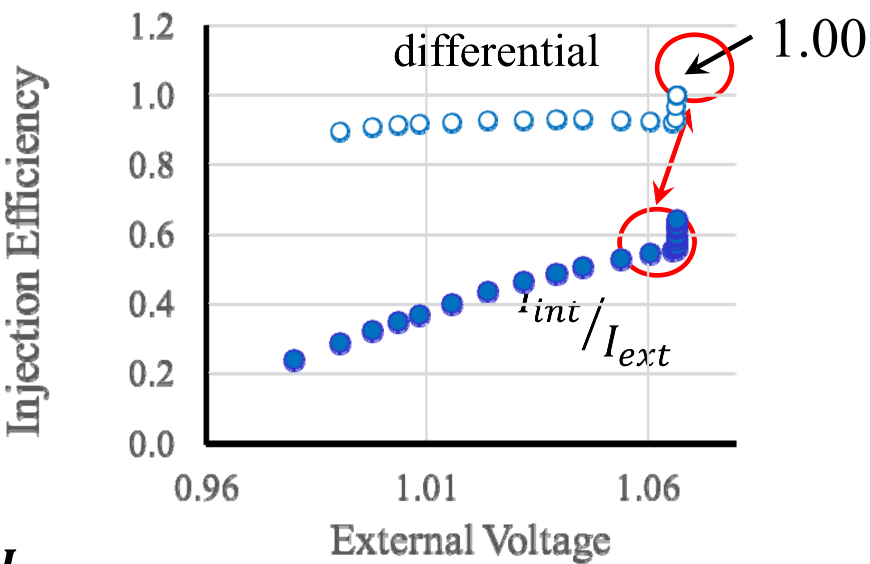



*Internal* I-V characteristic of gain medium assuming quasi-thermal equilibrium

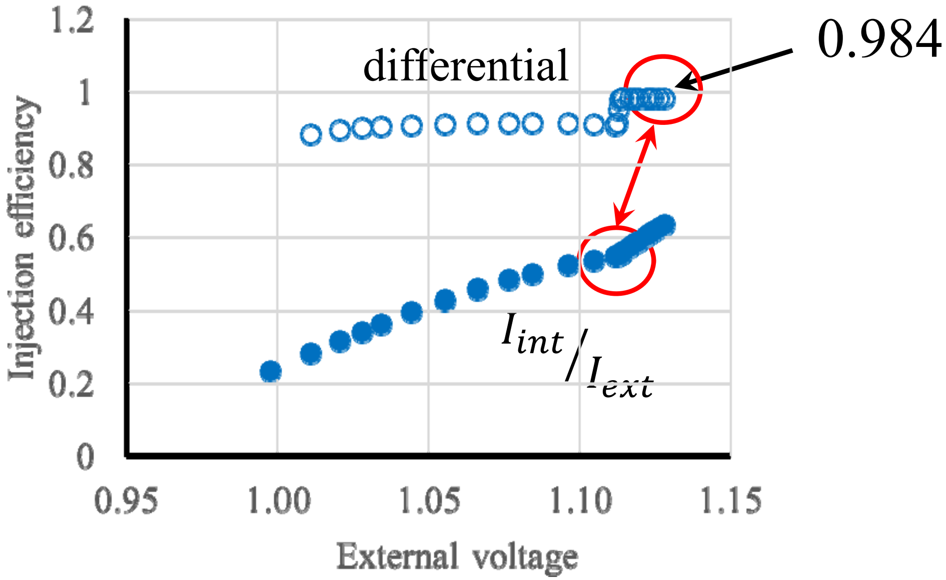


# Injection Efficiency

$R_c$= 0: Fermi level pinning everywhere




$R_c$ > 0: Current spreading and external voltage not pinned at threshold




**$I_{int}/I_{ext}$ at threshold is not equal to differential injection efficiency above threshold**

# An example: quantum dot active region

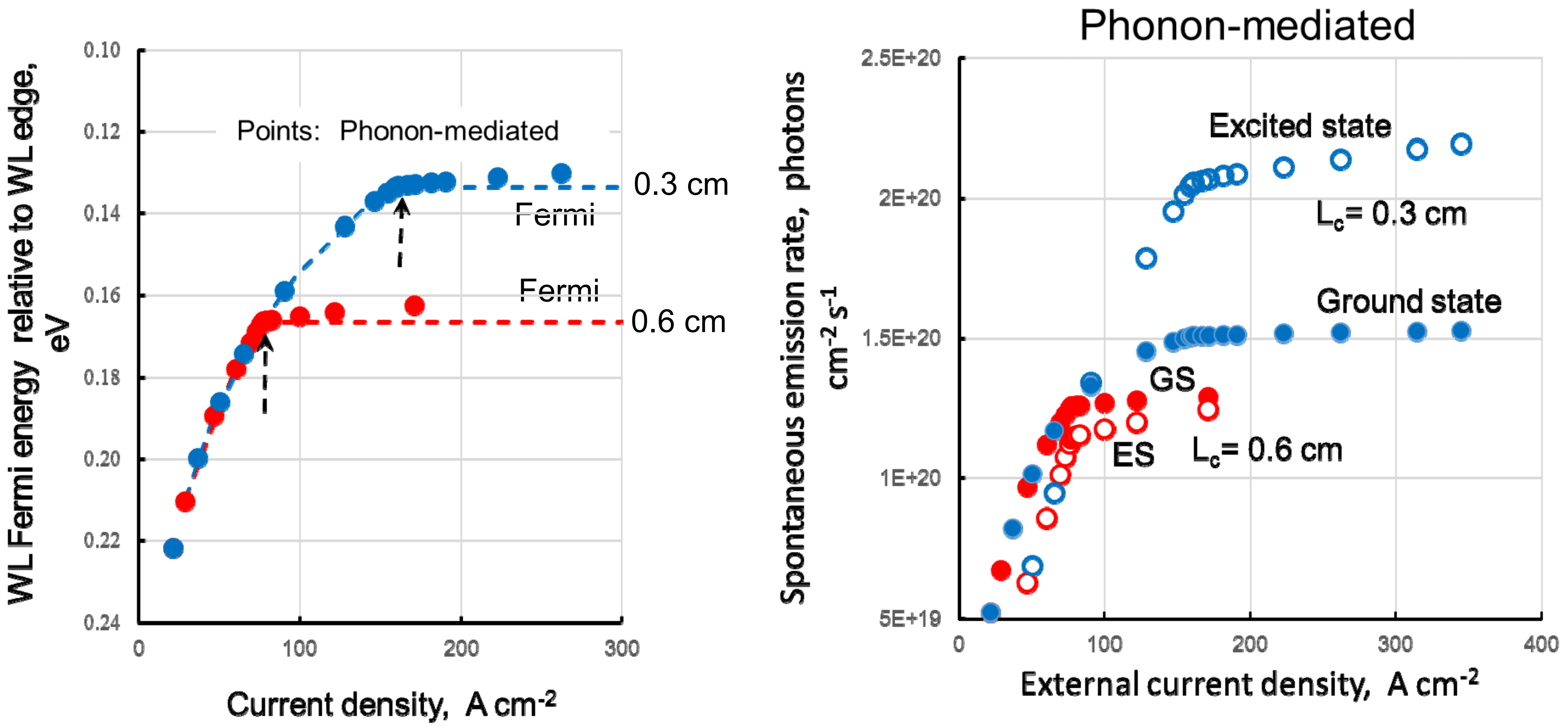
Random population at low temperature, probably thermal at threshold at room temperature, but…….
Spontaneous emission dots does not pin above threshold at room temperature.
(Smowton, unpublished, Marko et al, IET Opto, vol 8 (2014) 88-93).

Single mode laser rate equation model for

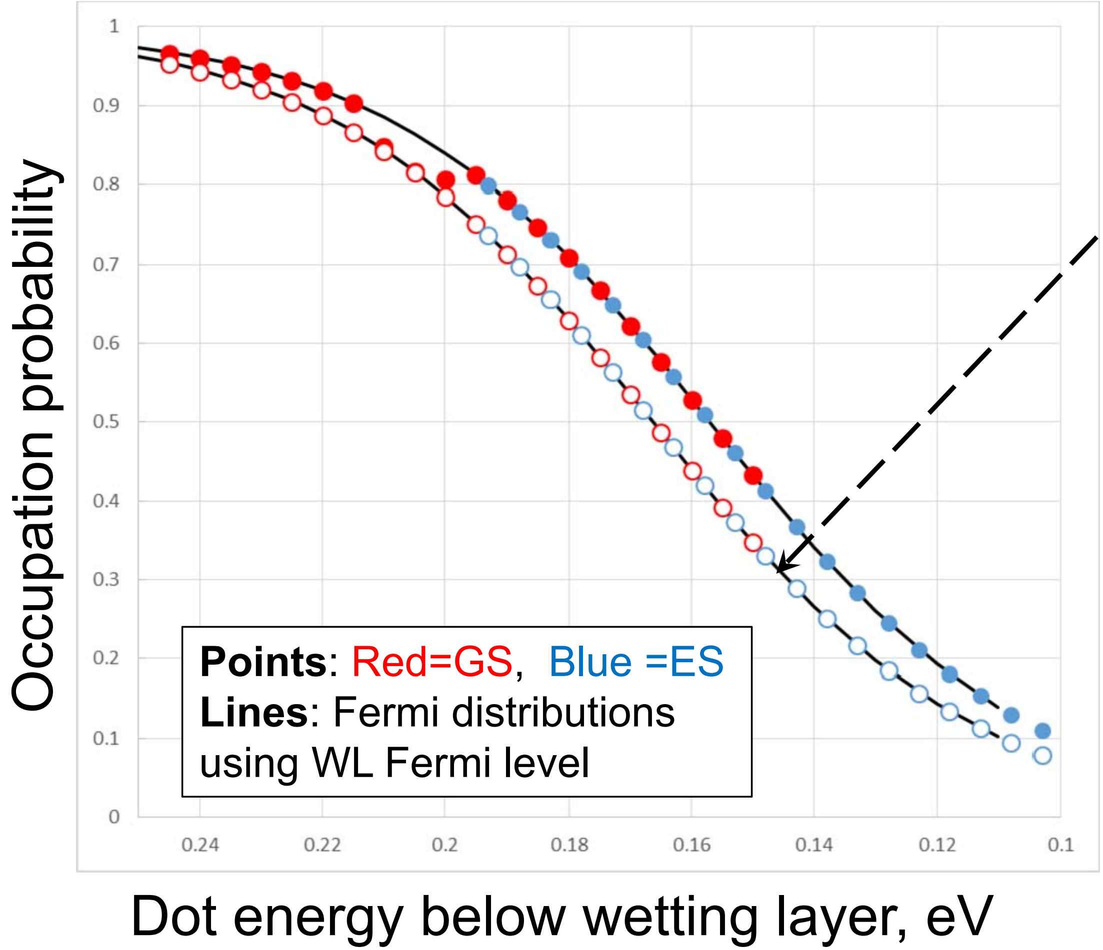
1. dots in thermal equilibrium with the wetting layer using Fermi-Dirac statistics (pinning in dots and WL),
2. dot occupation from interaction with wetting layer (WL) via a Bose-Einstein distribution of phonons without prior assumption of equilibrium. P Blood, Quantum Confined Laser Devices, OUP 2015, p 222; Finch et al J Sel Topics QE vol 21 (2015), 1900507

With heterobarrier leakage and current spreading.

# Wetting layer Fermi level,  dot spontaneous emission



# Dot occupation distributions: Phonon model



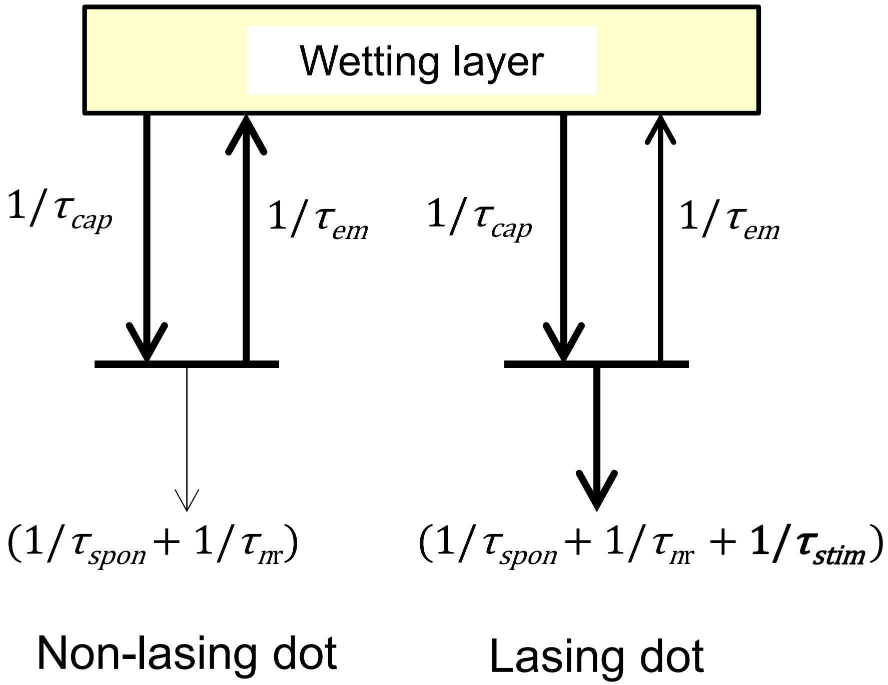

WL occupation at threshold is in thermal equilibrium with wetting layer.

WL carrier density and Fermi level not pinned above threshold

**Lasing dots**:
Gain and occupation pinned by laser action.

**Non-lasing dots**:
GS and ES in quasi-equilibrium with WL, but occupation not pinned. Spontaneous emission increases.

# Effect of stimulated emission




- All dots have the same capture rate from uniform carrier distribution in WL.
- Recombination rate in dot = non-rad +spon +stim.

➢ In **non-lasing dot**, no stim emission

$$\frac{1}{\tau_{em}} \gg \frac{1}{\tau_{spon}} + \frac{1}{\tau_{nr}} \qquad f_g = \frac{1}{1 + \frac{\tau_{cap}}{\tau_{em}}}$$

Occupation varies with energy of state: emission rate decreases with increasing energy separation.

➢ In **lasing dot**, strong stim emission

$$\frac{1}{\tau_{em}} \ll \frac{1}{\tau_{stim}} \qquad f_g = \frac{1}{1 + \frac{\tau_{cap}}{\tau_{stim}}}$$

Occupation determined by stim rate: photon density.
WL carrier density increases.

# Differential current components above threshold

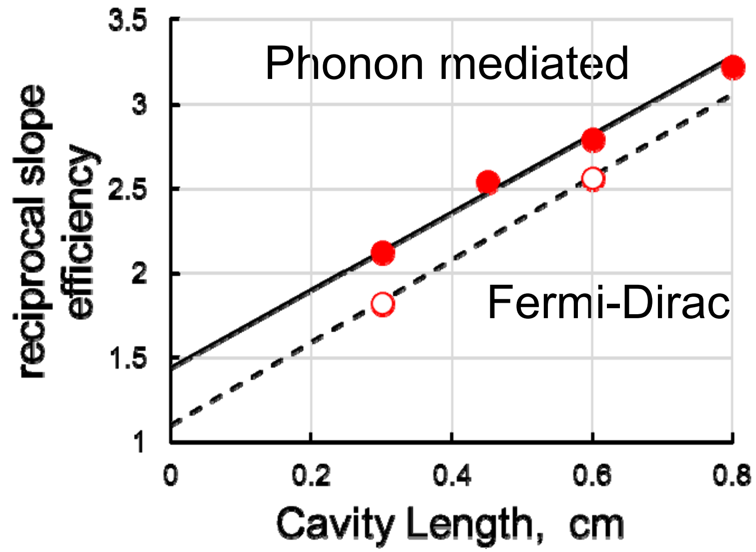
- Wetting layer carrier density not pinned:
  - Wetting layer recombination
  - Heterobarrier leakage
  - Current spreading

  not pinned.

**Differential Injection efficiency**
**into dots** $\eta_{inj}^{d}$ **= 0.86**
(Overall injection efficiency at threshold=0.45)

- Spontaneous emission of dots not pinned:

**Differential internal efficiency**
**of dot system** $\eta_{int}^{d}$**= 0.91**




Differential injection efficiencies length dependent.
Input value $\alpha_i$ = 3 cm$^{-1}$
From plot $\eta_{ext}^{d} - L_c$ plot = 1.92 cm$^{-1}$

# Summary

**In general** $\boldsymbol{\eta_{ext}^{d} = F \times \eta_{inj}^{d} \times \eta_{int}^{d}}$

- If Fermi levels pinned *everywhere* $\eta_{int}^{d} = 1$, $\eta_{inj}^{d} = 1$: intercept of plot = 1
- If Fermi levels pinned in gain medium only $\eta_{int}^{d} = 1$ but $\eta_{inj}^{d} < 1$

  But if $\eta_{inj}^{d}$ varies with $L_c$ plot has no meaning.

- Internal radiative efficiency at threshold difficult to measure directly
- Injection efficiency at threshold not equal to the differential injection efficiency above threshold.
- Quantitative comparison of experiment and theory still difficult.

Don't be afraid to challenge the accepted wisdom if you have good cause.