Semiconductor Optical Communication Components and Devices

Lecture 22: Threshold Current

Prof. Utpal Das
Professor, Department of Electrical Engineering, Laser Technology Program, Indian Institute of Technology, Kanpur

http://www.iitk.ac.in/ee/faculty/det_resume/utpal.html
Calculation of Laser Threshold Current - I

In presence of Photons, Stimulated Emission starts, specially in the case where the bands are loaded with carriers (rule of thumb: the Fermi Energy is above kT over the band edge).

If a line connects the peaks of the Gain profile as a function of carrier concentration, the red curve is obtained (~linear at larger gain). The extrapolated carrier conc. at zero gain is the minimum carrier conc. required for gain (N_T).

InGaAs
λ=1.3μm
Calculation of Laser Threshold Current - II

Fabry-Perot (FP) Laser

Rate equations for the carrier concentration and the photon concentration in an elemental spectrum, where $\tau_c$ and $\tau_{ph}$ are the carrier and photon lifetimes, and $d$ the active layer thickness.

For steady state $\frac{d}{dt}=0$ and solving for $N_0$ and $\rho_{\nu_o} \delta \nu$

$$\frac{dN}{dt} = \frac{J}{qd} - \frac{N}{\tau_c} - g_1 (N - N_T) \rho_{\nu} \delta \nu$$

$$\frac{d(\rho_{\nu} \delta \nu)}{dt} = g_1 (N - N_T) \rho_{\nu} \delta \nu - \frac{\rho_{\nu} \delta \nu}{\tau_{ph}} + \gamma \frac{N}{\tau_c} = 0$$

$$\frac{J_o}{qd} - \frac{N_o}{\tau_c} - g_1 (N_o - N_T) \rho_{\nu} \delta \nu = 0$$

$$g_1 (N_o - N_T) \rho_{\nu_o} \delta \nu - \frac{\rho_{\nu_o} \delta \nu}{\tau_{ph}} + \gamma \frac{N_o}{\tau_c} = 0$$

$g_1 (N_o - N_T) \rho_{\nu_o} \delta \nu$ eliminated

$$\frac{J_o}{qd} - (1 - \gamma) \frac{N_o}{\tau_c} - \frac{\rho_{\nu_o} \delta \nu}{\tau_{ph}} = 0$$

$$\frac{J_o}{qd} = \left[ \frac{g_1 N_T + \frac{1}{\tau_{ph}}}{\frac{g_1 \rho_{\nu_o} \delta \nu + \frac{1}{\tau_c}}{\tau_c} \cdot \frac{1}{\tau_{ph}} + \frac{1}{\tau_c}} \right] \rho_{\nu_o} \delta \nu = \left[ \frac{N_T + \frac{1}{g_1 \tau_{ph}}}{\rho_{\nu_o} \delta \nu + \frac{1}{g_1 \tau_c}} \cdot \frac{1}{\tau_c} \cdot \frac{1}{\tau_{ph}} \right] \rho_{\nu_o} \delta \nu$$
Threshold Current - III

**Fabry-Perot (FP) Laser**

\[
\frac{J_o}{qd} = \left[ \frac{N_T + \frac{1}{g_1\tau_{ph}}}{\rho_v \delta v + \frac{\gamma}{g_1\tau_c}} \cdot \frac{1 - \gamma}{\tau_c + \frac{1}{\tau_{ph}}} \right] \rho_v \delta v
\]

Solve for \( N_o \) and \( \rho_v \delta v \) in terms of \( J_o \)

**OR** \( \rho_v \delta v \) as an independent variable, and \( J_o \) and \( N_o \) as dependant variables.

**Case-1: LED** \( \rho_v \delta v \ll \gamma/(g_1\tau_c) \)

\[
\frac{J_o}{qd} \approx \left[ \left( g_1 N_T + \frac{1}{\tau_{ph}} \right) \cdot \frac{1 - \gamma}{\tau_c} + \frac{1}{\tau_{ph}} \right] \rho_v \delta v
\]

**Case-2: LASER** \( \rho_v \delta v \gg \gamma/(g_1\tau_c) \)

\[
\frac{J_o}{qd} \approx \frac{g_1 N_T + \frac{1}{\tau_{ph}}}{g_1} \cdot \frac{1 - \gamma}{\tau_c} + \frac{1}{\tau_{ph}} \rho_v \delta v
\]

\[
\frac{J_{th}}{qd} = \frac{g_1 N_T + \frac{1}{\tau_{ph}}}{g_1} \cdot \frac{1 - \gamma}{\tau_c} \approx \frac{1}{\tau_c} \left( N_T + \frac{1}{g_1\tau_{ph}} \right)
\]

\[
\rho_v \delta v = \frac{\tau_{ph}}{qd} \left( J_o - J_{th} \right)
\]

**Case-2:** \( \rho_v \delta v \) proportional to \( J_o - J_{th} \)
Laser Threshold

Fabry-Perot (FP) Laser

\[ N_{\text{th}} = \frac{g_1 N_T + \frac{1}{\tau_{\text{ph}}}}{g_1 \rho_{\nu_0} \delta \nu + \frac{\gamma}{\tau_c}} \rho_{\nu_0} \delta \nu \]

\[ \phi_0 \delta f \gg \frac{\gamma}{(g_1 \tau_c)} \]

\[ N_{\text{th}} = N_T + \frac{1}{(g_1 \tau_{\text{ph}})} \]

= Constant

\[ \approx \frac{\tau_c J_{\text{th}}}{qd} \]

Diagram showing the behavior of laser threshold with varying parameters.
Diode Laser Emission Pattern

Fabry-Perot (FP) Laser

Far field radiant intensity pattern

Near field intensity pattern

Active Junction

s

+ Current

d

w

\( \theta \parallel \)

\( \theta \perp \)

Far field radiant intensity pattern
1. The threshold current density for a stripe-geometry AlGaAs laser is 3kA.cm\(^{-2}\) at a temperature of 15\(^{\circ}\)C. Estimate the required threshold current at a temperature of 60\(^{\circ}\)C when \(T_o\) for the device is 180\(^{\circ}\)K, and the contact stripe is 20 x 100 (mm)\(^2\).


2. Explain why in steady state the carrier concentration in the injection laser active region remains constant even when the current is increased above threshold.

3. The output power of a junction laser above threshold is proportional to \(R_b/\tau_{ph}\) as \(R_{bias}= [G\tau_{ph}/qw](J_{bias}-J_{th})\).

Where \(\tau_{ph}\) is the photon lifetime in the cavity. Show that, above threshold, the output power still depends on \(\tau_{ph}\) and is proportional to \(\{J-(qw/\tau_{tot})[N_T + (g_1G\tau_{ph})^{-1}]\}\). Where \(g_1\) is the constant of Stimulated emission, \(N_T\) is the carrier concentration for which transparency is obtained, and \(G\) is the fraction of injected carrier distribution and mode overlap.