Semiconductor Lasers

Class: Integrated Photonic Devices
Time: Fri. 8:00am ~ 11:00am.
Classroom: 資電206
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Principles of Laser Operation

- Amplifier is the gain medium (population inversion)
- Positive feedback is provided by a resonator (Fabry-Perot Etalon, Bragg Grating, Ring Resonator,...)
- Initial stimulus comes from spontaneous emission (noise)
- Saturation is reached when gain = loss

Laser = Gain medium + Cavity
Basic Structure of p-n Junction Laser Diode

- Epitaxial growth of a p-type layer on an n-type substrate
- GaAs, GaAlAs, GaInAsP are often used for different wavelengths
- Ohmic contacts
- Two parallel end faces are used as partially reflected mirrors

Fabry-Perot Etalon for Optical Feedback

- Only the fundamental longitudinal modes have high quality factors (low loss) which can be utilized for laser modes
- The mode number $m$ is given by the number of half-wavelengths

$$m = \frac{2ln}{\lambda_0}$$
**Fabry-Perot Etalon for Optical Feedback**

The mode spacing (free spectrum range) is determined by

\[
\frac{dm}{d\lambda_0} = -\frac{2L n}{\lambda_0^2} + \frac{2L}{\lambda_0} \frac{dn}{d\lambda_0}
\]

The mode spacing \( d\lambda_0 \) is given by taking \( dm = -1 \)

\[
d\lambda_0 = \frac{\lambda_0^2}{2L (n - \lambda_0 \frac{dn}{d\lambda_0})}
\]

- Usually several longitudinal modes will coexist. (multiple modes)

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**Lasing Threshold Conditions (Threshold Current)**

- For oscillation (lasing), the net gain of a single loop should be equal to 1 (stationary Ps)

\[
\text{Loss} = \text{Gain}
\]

- Loss is due to propagation loss (scattering, absorption) and optical transmission through mirror
- Gain is due to population inversion at the p-n junction
Lasing Threshold Conditions (Threshold Current)

Power variation during propagation: \( P = P_i \exp\left(\frac{d}{D} \alpha Z\right) \)

Gain Medium

Partially Reflected Mirror

Partially Reflected Mirror

Transverse Spatial Energy Distribution in a Diode Laser

- The photon distribution extends or spread into the inactive regions on each side of the junction (optical mode width)
- The index is a little high in depletion region
- only a fraction \( d/D \) remain in the active region and can generate additional photons by stimulated emission
Lasing Threshold Conditions (Threshold Current)

To maintain the loop gain equal to 1, 

\[ P_i = R P_s \exp \left( g \frac{d}{D} \alpha \right) L \]

or 

\[ \ln \frac{1}{R} = \left( g \frac{d}{D} - \alpha \right) L \]

where \( R \) is the reflectance. Thus, 

\[ g \frac{d}{D} = \alpha + \frac{1}{L} \ln \frac{1}{R} \]

Lasing Threshold Conditions (Threshold Current)

The gain coefficient \( g \) is related to the injected current density of holes and electrons. It can be given by

\[ g = \frac{\eta \lambda^2 J}{8\pi en^2 \Delta \nu} \]

where 

- \( \eta \): internal quantum efficiency
- \( \lambda_p \): vacuum wavelength emitted
- \( n \): index of refraction at \( \lambda_0 \)
- \( \Delta \nu \): linewidth of spontaneous emission
- \( e \): electron charge
- \( d \): thickness of active region
- \( J \): injected current density

Therefore, the threshold condition for lasing is 

\[ \frac{\eta \lambda_p^2 J_n}{8\pi en^2 \Delta \nu D} = \alpha + \frac{1}{L} \ln \frac{1}{R} \]

or 

\[ J_n = \frac{8\pi en^2 \Delta \nu D}{\eta \lambda_p^2} \left( \alpha + \frac{1}{L} \ln \frac{1}{R} \right) \]
Lasing Threshold Conditions (Threshold Current)

The threshold current is that which is necessary to produce just enough gain to overcome the losses.

Note that, from the standpoint of threshold, the light output of a laser at the end faces must be counted as a loss.

\[
\frac{1}{L} \ln \left( \frac{1}{R} \right) = \frac{1}{L} \ln \left( \frac{1}{1 - T} \right)
\]

\[
= \frac{1}{L} \left( T - \frac{T^2}{2} + \frac{T^3}{3} - \frac{T^4}{4} + \ldots \right)
\]

\[
\frac{1}{L} \ln \left( \frac{1}{R} \right) \equiv \frac{T}{L}
\]

\( T \): transmittance

Propagation loss coefficient

\[
\alpha \cong + \frac{T}{L}
\]

Output Laser Power and Efficiency

The power provided by external injected current should be equal to the emitting laser power as well as loss inside the cavity.

The ratio of the emitting power is defined by

\[
\eta = \frac{\frac{1}{L} \ln \frac{1}{R}}{\alpha + \frac{1}{L} \ln \frac{1}{R}}
\]

\( R \): reflectance

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The emitted power is then given by

\[ P_{out} = \eta P_{in} = \eta \left( \frac{J}{e} \eta_i (L \times W) h \nu \right) \quad (P_{out} \text{ is power out of both end faces}) \]

which is,

\[ P_{out} = \frac{1}{\alpha + \frac{1}{L} \ln \frac{1}{R}} \frac{1}{L} \ln \frac{1}{R} \frac{J \eta_i (L \times W) h \nu}{e} \]

The overall power efficiency including the effect of series resistance in the devices is thus given by

\[ \eta_{out} = \frac{P_{out}}{P_{in, tot}} = \frac{\frac{1}{\alpha + \frac{1}{L} \ln \frac{1}{R}} \frac{1}{L} \ln \frac{1}{R} \frac{J \eta_i (L \times W) h \nu}{e}}{\frac{J}{e} (L \times W) h \nu + \left[ \frac{J (L \times W)}{e} \right]^2 R_{series}} \]
Tunnel-Injection Laser

- No junction is required
- Electrons are injected from low-work-function metal by diffusion current
- Holes are injected from high-work-function metal by tunnelling current
- Holes and Electrons are recombined in the semiconductor region

The tunnel-injected laser was one of the first of the confined-field type lasers (such as heterojunction lasers)
- The optical field is well confined in the semiconductor region due to metal reflection. That is, \( D = d \)

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