10.2. Structures and Properties of Injection Lasers
10.2.1. Stripe-Geometry Lasers - Transverse Mode Control

In broad area contact lasers, multiple transverse mode operation with filament-like near field emission pattern is normally observed. By narrowing stripe geometry contact, the number of transverse modes is reduced and finally a fundamental transverse mode operation is achieved. The added advantage is a lower operation current.
Gain guide laser utilizes uneven carrier density distribution induced index change to guide optical waves. Since the carrier density induced index value changes continuously, the gain and photon speed inside the waveguide also varies across the width of the active layer. This causes the wave front to warp and results in multiple longitudinal modes.
L-I Curve and Emission Spectra of Gain-Guided Lasers

‘Kinks’ are easily observed in the L-I curve of gain-guide lasers. The ‘kink’ indicates an optical mode change from a lower order to higher order one associated with the shift of gain peak.
(b) Index-Guided Stripe Lasers

By incorporating a real and uniform index change around the active region, an uniform photon velocity across the wave-front is achieved. A single transverse mode and single longitudinal mode operation are generally observed.
Performance of Index Guided Laser

- Using etch-and-regrowth method, a strong index guide buried-heterostructure (BH) laser is formed (shown on the right).
- The following L-I curve, far-field transverse mode and longitudinal mode are for a 0.78 µm AlGaAs BH laser.
10.2.2. Distributed Feedback (DFB) Laser - Longitudinal Mode Control

- Bragg condition:
  \[ 2\Lambda \sin \theta = l \frac{\lambda_b}{\bar{n}} \quad l = 1,2,3,.. \]

- For guided waves, \( \theta = 90^\circ \),
  \[ \Lambda = l \frac{\lambda_b}{2\bar{n}} \]
  Here, \( \lambda_b \) is the free space wave length that satisfies the Bragg condition.

- For a specific grating pitch, \( \Lambda \), the grating selectively reflects a certain wavelength, \( \lambda \), given by
  \[ \lambda_b = 2\bar{n}\Lambda/m \]
  The grating pitch corresponding to \( l = 1,2,.. \) is called the first-order grating, second-order grating, etc, respectively. This periodic index change produces a light reflection, and forms a distributed mirror.
• The reflected intensity is determined by the grating height and by the
distance between the grating and the active layer.
• The magnitude of optical feedback equals the product of cavity length, $L$, and a coupling constant, $\kappa$. The coupling constant is a structure parameter and is determined by the grating shape and height, and by the active and guide layer thickness.
• Near the Bragg wavelength, only two opposite traveling waves with significant amplitudes exist. These waves also in phase. Because of the presence of gain, these waves grow as they travel along the active layer and transfer energy between each other due to Bragg scattering.
• The exact solutions of the allowed resonance frequency and gain can be obtained by solving the coupled-wave equations concerning two opposite traveling waves.

$$ E_x(z) = R(z)\exp(-j\beta_b z) + S(z)\exp(+j\beta_b z) $$

where

$$ \beta_b = \frac{4\pi \bar{n}}{\lambda_b} $$

• The solutions determine a set of discrete eigen values $\gamma_c$ as

$$ \kappa_c = \pm \frac{j\gamma_c}{\sinh(\gamma_c L)} $$

For each $\gamma_c$ there is a corresponding threshold gain and resonant frequency.
• The resonance frequency of a DFB laser is given by
\[ \lambda_o = \lambda_b \pm \left[ (q + \frac{1}{2}) \lambda_b^2 / 2\bar{n}L \right] \quad \text{with } q = 0, \pm 1, \pm 2, \pm 3, \ldots \]
- \( \lambda_o \not= \lambda_b \)
- Resonance are spaced by \( \lambda_b^2 / 2\bar{n}L \)

• The gain (\(-\alpha_F\)) for the resonance frequency, \( \lambda_o \), can be calculated as
\[ 4\alpha_F^2 \equiv \left( \frac{\pi \bar{n}_a}{\lambda_o} \right)^2 \exp(-2\alpha_F L) \]
where \( n_a \) is the amplitude of the grating index variation.
Characteristics of Distributed Feedback (DFB) Laser

Matching of gain peak and grating pitch:
• DFB with $\lambda/4$ phase shifting region:
  There are two modes with the lowest threshold gain in a DFB laser. To remove this degeneracy, a $\lambda/4$ phase shift region is incorporated into the grating. There is only one mode at $\lambda_b$ with the lowest threshold gain.

• Distributed Bragg Reflector (DBR) Laser:
  A DBR laser is similar to a Fabry-Perot laser with a maximum mirror reflectivity determined by the gratings. The mirror reflectance $r_1$ and $r_2$ are complex numbers and are wavelength dependent.
10.3. Quantum Well Laser

**Progress of Laser Diode Performance**

- Threshold current density, $J_{th}$, is a good indicator of the efficiency of a laser diode.
- Heterostructures:
  - Improves carrier confinement
  - Improves optical confinement
- Bandgap Engineering:
  - Quantum size effect improves lasing conditions through volume (active region) reduction
  - Multi-dimensional quantum size effect allows extremely small cavity to form.
  - Strained layer further improves band structure for lasing
Comparison Between QW and DH Lasers

- $J_{th}$ reduction:
  - Difference in material gain between QW and DH lasers is small
  - The reduction of $J_{th}$ mainly from thickness reduction in the active region rather from the quantum size effect.
    \[
    J = \frac{qd}{\tau} n_{th} \propto d
    \]
  - Due to the step-like DOS, the differential gain is larger for QW lasers.
- Flexible wavelength selection:
  - Quantum size effect
  - Improving high-speed response due to large differential gain.
    \[
    \frac{dg}{dn} \propto f_r^2
    \]
Comparison Between QW and DH Lasers
Advantages of Using Low-Dimensional Active Region

- Flexible wavelength selection by adjusting QW thickness.
- Lower threshold current density due to much reduced active volume.
- Possible to include strain in QW layers, which also improves laser performance.
Quantum Well Laser Designs

Multiple QW (MQW)

Separate confinement heterostructure (SCH)

Graded-index separate confinement heterostructure (GRIN-SCH)
Quantum Well Laser Comparison

![Graph showing Quantum Well Laser Comparison]
Bandgap Engineering Using Strain

- Strain narrows the valence band:
  - Lighter effective mass on $J_{th}$
    » Small DOS in the valence band
    » $F_V$ moves faster to reach population inversion
    » Lower $J_{th}$
  - Lighter effective mass on gain and $n_{th}$
    » Larger material gain and differential gain
    » Smaller $n_{th}$ $\Rightarrow$ lower $J_{th}$
    
    $$g \propto |M_{CV}| \propto \frac{I}{m_h^*}$$
  - Reduced inter-valley absorption
    » Increased $T_o$ and $\eta_e$
  - Reduced Auger recombination

- Increased $\Delta E_C$ in compressive strain QW lasers:
  - lower $J_{th}$
Strained and Unstrained QWs

Unstrained AlGaAs/GaAs QW laser

Strained AlGaAs/InGaAs QW laser
- Enhanced reliability due to lattice hardening:

Unstrained AlGaAs/GaAs 0.89µm lasers

Strained InGaAs/GaAs 0.98µm lasers
10.4. Vertical Cavity Surface Emitting Laser (VCSEL)

**Photon Usage Enhancement in Micro-Cavities**

- Spontaneous emission factor:
  \[
  \beta \equiv \frac{\text{spontaneous emission coupled into the single lasing mode}}{\text{total spontaneous emission}}
  \]

\[
\beta \propto \frac{1}{\text{total optical mode}} \propto \frac{1}{L} = 10^{-5}
\]

in a Febry-Perot cavity.

Most of the spontaneous emissions are wasted and not participate in stimulated emission action.

![Diagram of VCSEL](image)
Photon Usage Enhancement in Micro-Cavities

- Micro-cavity:
  By shortening the cavity length, $\Delta \lambda$ (mode spacing) is increased and $\beta$ will be enhanced.

![Graphs showing PL intensity and power output vs current for different cavity lengths and VCSEL types.](image-url)
Attributes of VCSELs

• Large mode spacing (small active layer length)
  ⇒ Single longitudinal mode

• Low operation current (small cavity volume)
  ⇒ 2D integration

• Circular beam shape
  ⇒ Simple optics
  ⇒ Easy to couple

• Surface emitting
  ⇒ On wafer screening
  ⇒ Cost effective

• Highly reflective mirrors
  ⇒ Complex growth or fabrication process
10.4.1. Threshold current density

For VCSEL, the total gain at threshold is modified as

\[ \Gamma g_{th} = \alpha_i + \left(\frac{1}{2L}\right) \ln \left(\frac{1}{R_1 R_2}\right) \]

- For VCSEL, the total gain at threshold is modified as

\[ \Gamma g_{th} d = \Gamma \alpha_a d + \alpha_c (L - d) + \left(\frac{1}{2L}\right) \ln \left(\frac{1}{R_1 R_2}\right) \quad \text{and} \quad \Gamma = \Gamma_L \Gamma_T \approx \frac{d}{L} \]

then

\[ g_{th} = \alpha_a + \left(\frac{1}{\Gamma^2}\right) \left[ \alpha_c (1 - \Gamma) + \left(\frac{1}{2L}\right) \ln \left(\frac{1}{R_1 R_2}\right) \right] \]
Following the same argument for edge-emitting lasers,

\[ J_{th} = \frac{qdn_{ph}}{\tau_s} \]

\[ g_p = a(n - n_{tr}) \]

\[ B_r n_{th} = \frac{1}{\tau_s} \]

The threshold current density of a VCSEL is given by

\[ J_{th} = \frac{qdB_r}{a^2} \left\{ \alpha_a + an + \frac{1}{\Gamma^2} \left[ \alpha_c (1 - \Gamma) + \frac{1}{L} \ln \left( \frac{1}{R} \right) \right] \right\}^2 \]

\[ a = 4 \times 10^{16} \text{ cm}^2 \]

\[ B_r = 10^{-10} \text{ cm}^3/\text{s} \]

\[ \alpha_a = 25 \text{ cm}^{-1} \]

\[ \alpha_c = 10 \text{ cm}^{-1} \]

\[ \Rightarrow \]

Requires very high mirror reflectivities for low threshold!
10.4.2. Distributed Bragg Reflector (DBR) Mirrors

- The distributed Bragg reflector (DBR) mirror consists of \( N \) pairs of two alternating dielectric materials with refractive index \( \bar{n}_1 \) and \( \bar{n}_2 \).
- The thickness of the two layers are quarter wavelength long.
  \[
  L_1 = \frac{\lambda_b}{4\bar{n}_1} \quad \text{and} \quad L_2 = \frac{\lambda_b}{4\bar{n}_2}
  \]
- The reflectivity of the DBR at the Bragg wavelength is
  \[
  R_b = \left[ \frac{1 - (\bar{n}_1/\bar{n}_2)^{2N}}{1 + (\bar{n}_1/\bar{n}_2)^{2N}} \right]^2
  \]
• The high-reflectivity or stop band of the DBR depends on the refractive index difference of the two mirror materials.

\[ \Delta \lambda_b = \frac{2 \lambda_b \Delta \bar{n}}{\pi \bar{n}_{\text{eff}}} \]

\[ \bar{n}_{\text{eff}} = 2 \left( \frac{1}{\bar{n}_1} + \frac{1}{\bar{n}_2} \right)^{-1} \]

Reflectivity spectrum of six pair Si(100nm)/AlO\textsubscript{x}(235nm) DBR mirror

\( \bar{n}_{Si} = 3.3 \)

\( \bar{n}_{AlO_x} = 1.57 \)
DBR Mirror Systems

Mirror stack materials:

- **Dielectric**
  - A few pairs to reach >99% reflectivity
  - Transparent over a wide range
  - Low thermal conductance
  - Electrically non-conductive
- **Semiconductor**
  - A few tens pairs required for reflectivity >99%
  - Lattice match required
  - Electric conduction depends on junction design
  - Material dependent absorption
- **Metal**
  - Reflectance saturates at ~98%
  - Single layer and easy to make
  - Light absorption
- **Metal + dielectric**
  - Used on top of the electrode
  - Simple to fabricate
Dielectric Mirror Material Properties (1.55 µm)

<table>
<thead>
<tr>
<th>Material</th>
<th>α-Si</th>
<th>SiC</th>
<th>ZnSe</th>
<th>TiO₂</th>
<th>Si₃N₄</th>
<th>Al₂O₃</th>
<th>MgO</th>
<th>MgF</th>
<th>CaF₂</th>
<th>SiO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity (W/cm-K)</td>
<td>0.026</td>
<td>2.5</td>
<td>0.19</td>
<td>0.09</td>
<td>0.16</td>
<td>0.36</td>
<td>0.53</td>
<td>–</td>
<td>0.1</td>
<td>0.012</td>
</tr>
<tr>
<td>Refractive Index</td>
<td>3.6</td>
<td>2.57</td>
<td>2.46</td>
<td>2.44</td>
<td>2.0</td>
<td>1.74</td>
<td>1.71</td>
<td>1.35</td>
<td>1.43</td>
<td>1.45</td>
</tr>
</tbody>
</table>
10.4.3. Resonant Periodic Gain in VCSELs

- Forward traveling wave
  \[ E^+ = E_o \exp[-j(\omega t - \beta z)] \]
- Reverse traveling wave
  \[ E^- = E_o \exp[-j(\omega t + \beta z)] \]
- Net electric field
  \[ E = E^+ + E^- = 2E_o \exp(-j\omega t)\cos(\beta z) \]  
(b)
- Time average energy density
  \[ P = \frac{n}{2} \sqrt{\varepsilon_o E^* E} = 2n \sqrt{\varepsilon_o E_o^2 \cos^2(\beta z)} \]
  \[ P \] has a maximum value at antinodes situated at \( \beta z = m\pi; \) \( m = 0, 1, 2, \ldots \)
(c)
- Needs to put gain medium at the antinodes of the optical wave

\[ \Rightarrow \text{Resonant periodic gain} \]
10.4.4. Current and Optical Confinement in VCSELs

- Ion implanted

- Etched air-post

- Intra-cavity contacts

- Selectively wet oxidation
Semiconductor DBR Mirrors

Different composition profile designs at the hetero-interface are used to eliminate the band discontinuity induced carrier blocking effect.

- Step grading
- Chirped grading
- Linear grading
- Parabolic grading

Problems:
- Lattice matching for materials other than AlGaAs.
Wet-Oxidation of Al-Based Semiconductors

AlGaAs QW hydrolyzed in air for 1521 and 2808 days, respectively.

AlAs/GaAs superlattice disks defined by Zn-diffusion disordering subjected to wet (water vapor) oxidation at 400°C for 3 hours.

Native Oxide DBR Mirror by Wet-Oxidation

Native-oxide vertical cavity confinement in edge-emitting QW laser:
- Demonstrated optical confinement by Al-oxide/GaAs SL structure
- Wet oxidation process converting AlAs into Al-oxides
- Detuned Al-oxide/GaAs SL forms a DBR mirror stack
- DBR mirror enhance optical confinement within the n-Al$_{0.2}$Ga$_{0.8}$As waveguide.

Intra-cavity Tunnel Junction Design

- Take advantage of the high electron mobility to lower contact resistance of p-layer in intracavity VCSELs.
- Holes are provided by a thin p++ tunnel junction (TJ) layer for light generation.

Intracavity VCSELs utilizing TJ design with native-oxide DBR was demonstrated in 1997 in Dr. Holonyak’s lab.
- The native-oxide DBR mirror was defined by wet oxidation of AlAs/GaAs SL.
Fabrication of Micro-Cavity VCSELs

(a) Epitaxial growth
(b) Device patterning
(c) Dry etching for laser post
(d) Wet etching and oxidization
(e) Regrowth or planarization
(f) Metal contact.
10.4.5. Characteristics of VCSELs

Optical output power roll-off:
- Junction heating shifts the gain spectrum at a different rate from the cavity resonance wavelength.
- It calls for more current to reach threshold and generates more heat.
- VCSEL cease to lase.

[Diagram showing Cavity Resonance and Gain Bandwidth with a plot of Threshold Current vs. Temperature]
Optical Mode of VCSELs

cw operation of 15 µm square VCSEL at different power level
Major Challenges

• Long wavelength (1.3 and 1.55 µm) VCSELs:
  ➢ Inefficient DBR mirror due to small refractive index difference.
  ➢ Lattice-match control for InP-based materials.

• Short wavelength (< 0.7 µm) VCSELs:
  ➢ Inefficient DBR mirror using AlN/GaN
  ➢ Material growth problems

• Polarization control:
  ➢ Polarization selection is poor in the emitting surface

• Output power roll-off:
  ➢ Gain-cavity resonance peak mismatch.