Lecture 21 - Laser Diodes - II - Outline

• In-plane laser diodes, cont.

  Cavity design (in-plane geometries)
  Vertical structure:  homojunction
double heterojunction
quantum well
wide guides
quantum cascade

  Lateral definition:  stripe contact
buried heterostructure
shallow rib

  End-mirror design:  cleaved facet
etched facet
DFB, DBR

(cont. here from Lect. 20)

• In-plane surface emitting lasers

  Deflecting, etched mirrors
Second order gratings; holographic elements

• Vertical cavity, surface emitting lasers (VCSELs)

  Basic concept, design and fabrication issues
Structures, technologies

(today's material)
Laser diodes: vertical design evolution

Double heterostructure:

The first major advance in laser diode design was the double heterostructure geometry which confines the carriers and the light to the same region.

The threshold current density is approximately

$$ J_{th} = \frac{q n_{crit} d}{\tau_{min}} $$

As predicted, and shown to the right, $J_{th}$ decreases linearly with $d$ until the guide layer is too thin to confine the light, at which point the overlap decreases and the threshold increases.

Ref: Yariv, Optical Electronics, Fig. 15-13(a).
**Laser diodes: vertical design evolution**

**Double heterostructure:**
carriers and light are confined by the same narrow bandgap layer. The threshold decreases with d until the optical mode spills out.

**Separate confinement DH:**
the waveguide and carrier confinement functions are done by different layers. The overlap is less, but the threshold is still reduced.

**Quantum well:** the overlap is less than in SCDH, but there is a net win because the quantum well transitions are stronger.
Laser diodes: Separate confinement DH issues

Overlap estimate: because the optical mode is peaked in the center of the waveguide the overlap of the mode and the inverted carrier population is greater than might first be expected. In the situation illustrated below, the inner layer is 1/3 the thickness, but the overlap integral is only reduced by 1/2.

Waveguide portion options: the optical confinement/waveguide layer is often graded by some means so the carriers can fall into the active or QW layers more easily and to shape the mode:

- Simple SCDH structure
- Linearly grading
- Parabolic grading
- Step grading

\[ \cos \frac{\pi x}{0.15} \]
**Laser diodes: Vertical design - beam shaping**

In all of the edge-emitting designs we have been discussing, the guide is only a few tenths of a micron thick vertically. This, coupled with the high refractive indices of the component semiconductors, leads to a large divergence normal to the junction plane:

The challenge is to increase the width of the mode vertically, while still retaining single-mode operation.

Two examples of structures that do this are the slab-coupled optical waveguide laser (SCOWL) and the ARROW laser.

See next few foils.
Laser diodes: Vertical design - beam shaping, cont.

SCOWL

Slab coupled guide:
Recall that a slab-coupled optical waveguide, pictured below, is designed so that the higher order modes under the guiding stripe couple to the modes of the slab guide in the structure. These modes are therefore very lossy, and only the lowest order mode, which does not couple to the slab, is a low-loss mode.

Slab coupled optical waveguide laser:
The slab-coupled optical waveguide laser (SCOWL) uses the high loss of the higher order modes in a slab coupled guide to achieve lasing in a single mode with a large vertical width, and thus to get low beam divergence.
Laser diodes:  **Vertical design - beam shaping, cont.**  

**SCOWL, cont:**  

The slab-coupled optical waveguide laser, SCOWL. An example of a vertical design intended to increase the guide thickness vertically and obtain a more symmetrical beam profile.

**Laser diodes:** Vertical design - beam shaping, cont.

**ARROW:**

The anti-resonant reflecting optical waveguide, ARROW, an example of another design frequently used to increase the guide thickness and thereby obtain a more symmetrical beam profile.

Additional features are (1) that higher order modes are suppressed, and (2) that an active (gain) layer can be incorporated into one of the low index layers.

Referenced: Above - Coldren and Corzine, Fig. 7.22; Right - A. Bhattacharya, et al., "High power narrow beam singlemode ARROW-type InGaAs/InGaAsP/InGaP diode lasers," Elect. Lett. 31 (1995) 1837-1838.

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Waveguiding operation: Note that $n_0 < n_1 < n_2$ so the guiding is not in the highest index layer(s)!
**Laser diodes:** Vertical design - beam shaping, cont.

**ARROW, cont.:**

Additional ARROW laser results showing the actual layer profile used and beam profiles illustrating the enhanced beam profile.


C. G. Fonstad, 5/07
Laser diodes: Further active layer evolution

Quantum wire and dot: Most of the work quantization beyond the quantum well has focused on quantum dots. An example applied to a VCSEL is shown to the right. The record low QD laser thresholds current densities are a few 10's of A/cm².

Ref: S-F Tang, et al, APL 78, No. 17 (2001), Fig. 1.

Strained quantum wells: As we saw earlier in the term, tensile and compressive strain modify the valence band energy levels and can enhance the transition strengths. Strained quantum wells are often used in laser diodes. The QWs are thin enough that the layers are pseudomorphic.

Ref: Singh Fig. 7.19b

InGaAs QW (10% In) on GaAs
The well is in compression.
**Laser diodes:** Further active layer evolution

**Quantum cascade lasers:** To obtain lasing at long wavelengths people have historically relied on the use of very narrow bandgap lead-tin salts in traditional laser diode geometries. A more recent advance has been the use of the transitions between the levels in a quantum well.

Cascase laser diodes operate at wavelengths from 5 to well over 20 µm

Many periods of an injector and active region multi-quantum well structure are used to obtain lasing of the n=2 to n=1 layer transition. In practice, complex superlattice structures like that shown to the left are used to optimize the performance.

Ref: R. Colombelli, et al, APL 78, No. 18 (2001), Fig. 1.
Laser diodes: Active layer variations

Quantum cascade lasers:
An example of a novel materials combination and 10 \( \mu \)m lasing.

Laser diodes: lateral design

Stripe contact geometries:

A laser diode where the lateral cavity is defined by the sides of the chip is called a "broad area" diode.

A step of importance in increasing laser diode operating temperatures that was comparable to the introduction of the DH laser was the introduction of stripes to define the cavity laterally.

A wide variety of stripe structures have been used as the figures show.

The idea is that the threshold current is reduced by the lateral confinement, which reduces power dissipation. At the same time, the heat will be conducted away to the package through the whole chip width, effectively improving the heat sinking.
Adding lateral optical confinement improves the overlap of the optical field and the inverted population, and also makes it possible to get single mode operation.
Laser diodes: longitudinal design

Fabry-Perot cavity:
The traditional way of forming the primary laser cavity has been by cleaving the crystal to get parallel facets (see right), and using the reflection at the semiconductor-air interface.

Most modern in-plane lasers still use cleaved end-mirrors, often with coatings.

Mirrors can also be made by dry etching, but it is difficult to get them as vertical and parallel as is achieved by cleaving.

Ref: Sze, Physics of Semiconductor Devices
Laser diodes: longitudinal design, cont.

Fabry-Perot modes

Comparison of spectra taken just below, and well above, threshold. The subthreshold spectrum gives information on the Fabry-Perot mode spacing, and on the shape of the gain curve.

Calculated gain spectrum as a function of pumping level. Note shift of peak to higher energy.
Laser diodes: longitudinal design, cont.

Mode evolution above threshold:

It is interesting to note how the modes evolve in a cleaved-facet laser at currents near to, and well above threshold. Near threshold Fabry-Perot cavity modes appear on the output spectrum. As the current is raised well above threshold, one mode will ideally grow rapidly and dominate the spectrum.

In the figure on the right there is not one dominate mode, which is not the desired situation.

Ref:
Laser diodes: longitudinal design, cont.

Distributed Feedback:
Improved wavelength stability and control can be obtained using a distributed Bragg reflectors. By convention, when the distributed reflectors are within the active laser cavity the laser is called a DFB laser and when they are outside the active region on either end of the device the laser is called a DBR laser. Examples of each are shown below:

Distributed Feedback (DFB) Laser

Distributed Bragg Reflector (DBR) Laser
Laser diodes: longitudinal design, cont.

Distributed Feedback, cont:

The resonances of a DFB structure show the picket-fence Fabry-Perot structure, but the strength of the resonances are not the same as in a traditional FP cavity. Instead, the two modes on either side of the Bragg resonance are the strongest and thus are favored. This stabilizes the emission at one of these modes when the gain curve overlaps them. Adding a quarter wavelength shift between the two halves of the DFB structure can remove this degeneracy.

Forward and backward modes (above)

Spectral modes (right)
Laser diodes: longitudinal design, cont.

Fabry-Perot and DFB resonances

**Fabry-Perot Cavities:**
- Cavity defined by parallel mirrors (can be either partially transmitting or totally reflecting)
- Resonances occur when an integral number of half wavelengths fit between end mirrors

<table>
<thead>
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<th>n_1</th>
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\[ L = m \cdot \frac{\lambda_r}{2n_1} \Rightarrow \lambda_r = 2n_1L/m \]

**Note:** resonant spectrum is a series of modes separated by approximately

\[ \Delta \lambda \approx \frac{\lambda_r^2}{2n_1L} \Rightarrow \Delta \lambda \uparrow \text{ when } L \downarrow \]
Fabry-Perot Cavities, cont:
• Resonant spectrum:

\[ \lambda_r = 2n_1L/m \]
\[ \Delta \lambda \approx \lambda_r^2/2n_1L \implies \Delta \lambda \uparrow \text{ when } L \downarrow \]

Distributed Bragg Reflector (DBR) Cavities:
• Cavity defined by two DBR's separated by distance L
• Resonances occur when an integral number of half wavelengths fit between ends of cavity defined by L and the effective lengths of the DBR mirrors.
Distributed Bragg Reflector (DBR) Cavities, cont:

- Cavity:

![Diagram of DBR cavity]

- When the grating reflection is moderate, $L_{\text{eff}} \approx L_g/2$.
- If the grating is continuous, $L = \Lambda/2 = \lambda_{BR}/4$
- In this case, the total length of the cavity, $L_{\text{TOT}}$, is

$$L_{\text{TOT}} = 2L_{\text{eff}} + L = L_g + L = r\Lambda + \frac{\Lambda}{2} = (r + \frac{1}{2})\frac{\lambda_{BR}}{2}$$

and the resonances are found to be:

$$L_{\text{TOT}} = m \cdot \frac{\lambda_r}{2} = \left(r + \frac{1}{2}\right)\frac{\lambda_{BR}}{2} \Rightarrow \lambda_r = \frac{\left(r + 1/2\right)\lambda_{BR}}{m}$$
Distributed Bragg Reflector (DBR) Cavities, cont:

\[ \Lambda = \frac{\lambda_{BR}}{2} \]

\[ L_g = \frac{\Lambda}{2} \]

\[ L_g = r \Lambda \]

\[ L_{TOT} = \Lambda (r + 1/2) \]

\[ \lambda_r = \frac{(r + 1/2)}{m} \lambda_{BR} \]

- The mirrors are only effective in the vicinity of \( \lambda_{BR} \), and thus the only \( \lambda_r \)'s for which there will be strong resonances will be those around \( \lambda_{BR} \):

  \[ m = r : \quad \lambda_r = \left[ \frac{(r + 1/2)}{r} \right] \lambda_{BR} \approx (1 + 1/2r) \lambda_{BR} \]

  \[ m = r + 1 : \quad \lambda_r = \left[ \frac{(r + 1 - 1/2)}{(r + 1)} \right] \lambda_{BR} \approx (1 - 1/2r) \lambda_{BR} \]

  \[ m = r - 1 : \quad \lambda_r \approx (1 + 3/2r) \lambda_{BR} \]

  \[ m = r + 2 : \quad \lambda_r \approx (1 - 3/2r) \lambda_{BR} \]
Distributed Bragg Reflector (DBR) Cavities, cont.

- The resonances nearest $\lambda_{BR}$ are the strongest and the mode spectrum is thus:

  $$\Delta \lambda \approx \lambda_{BR} / r$$

- To get a resonance right at $\lambda_{BR}$, the spacing, $L$, between the gratings must be increased by another quarter wavelength, $\lambda_{BR}/4$ or, equivalently, $\Lambda/2$. This is shown on the next foil.
Distributed Bragg Reflector (DBR) Cavities, cont.

- Adding an addition quarter wavelength separation:

\[ \Delta \lambda = \lambda_m = (r-1) \Lambda \]

\[ m = \frac{(r+1)}{r} \lambda_{BR} \quad \Rightarrow \quad \lambda_r = \lambda_{BR} \]

- We now have:

\[
\begin{align*}
L_g &= \Lambda \\
L_g &= r \Lambda \\
L_{TOT} &= \Lambda (r + 1)
\end{align*}
\]
Distributed Bragg Reflector (DBR) Cavities, cont.

- See Coldren and Corzine for more detailed and complete analyses.

(from Figs. 3.17 and 3.18)

The objective: A unique lowest order resonance.
Distributed Bragg Reflector (DBR) Cavities, cont.

- **Final comments:** This all looks wonderful, and it seems like you should be able to pre-select the lasing wavelength simply by controlling $\Lambda$, but there are complications in real life:
  - The effective index of the guide, $n_{\text{eff}}$, is not precisely known so controlling the physical period of the grating, $\Lambda$, is not enough to determine its optical period, $\lambda_{\text{BR}}$.
  - The DBR's are often highly reflective and their effective depths are then not a simple multiple of $\Lambda$.

- **The bottom line:** DBR's give you mode selectivity around the Bragg frequency and are extremely useful, especially in VCSELs (as we'll see next time), **but the idea that you can design the resonant wavelength with precision using a DBR** (which was the big hope when they were first introduced) **is not correct, and is not the reason to use a DBR.**
Laser diodes: longitudinal design, cont.

Distributed Feedback, cont.: Data taken on Pb-salt lasers comparing temperature tuning characteristics of Fabry-Perot and DFB laser diodes

Temperature tuning curves

Device structure

**Laser diodes:** longitudinal design, cont.

**Distributed Feedback, cont.:**

Data taken on Pb-salt lasers comparing temperature tuning characteristics of Fabry-Perot and DFB laser diodes

- Variation of emission spectra with temperature.
- Device structure

Laser diodes: longitudinal design, cont.

DFB laser with a $\lambda/4$ section, (i.e. with the DBR separation being an integral number of half wavelengths)

Example in VCSEL cavity design

- In Lecture 21 we will look at techniques for obtaining emission normal to the junction. The most successful of these techniques is the VCSEL, or vertical-cavity surface-emitting laser, shown here.