EE 443/CS 543 Optical Fiber Communications
Dr. Donald Estreich
Fall Semester

Lecture 11

Semiconductor Lasers & Photodiodes

http://www.wiretechworld.com/the-future-of-optical-fibres/
Highlights from Lecture 10

1. Direct bandgap semiconductors are best for LEDs and lasers
2. Compound semiconductors allow for many direct bandgap options
3. Different compound semiconductors allow for bandgap and refractive index choice, but under the restriction of matching lattice spacings
4. Heterojunction is the interface between layers or regions of different crystalline semiconductors (with different bandgaps)
5. Double heterojunctions allow for quantum wells where electrons and holes can reside in greater concentrations
6. MBE and MOCVD are used to grow heterostructures
7. Rate equations for both electrons and photons were presented (refer to Lecture 10, slides 21 through 24)
8. A static analysis using the rate equations show that the light output is proportional the diode current beyond the laser threshold current
Highlights from Lecture 10 (continued)

9. Differential external quantum efficiency is the slope of the P-I characteristic
10. Stripe lasers have significant diffraction of their optical beam output
11. Stripe lasers use both gain-guiding or index-guiding for confinement in their laser cavity
12. Double heterostructures are used in many semiconductor lasers
13. Distributed feedback lasers use Bragg reflectors (periodic modulation of index of refraction)
14. Both standard and quarter-wave shifted distributed structures are used in distributed feedback (DFB) lasers
Review From Last Lecture: DFB Lasers

Review

Fabry-Pérot Laser

Distributed Feedback Laser
Distributed Bragg Reflector Laser

Bragg grating

Cleaved Facet
Active Layer

Distributed Feedback Laser
Distributed Bragg Reflector (DBR)

**Distributed Bragg reflector** (DBR) is a reflector used in waveguides, such as optical fibers. It is a structure formed from multiple layers of alternating materials with varying refractive index, or by periodic variation of some characteristic (such as height) of a dielectric waveguide, resulting in periodic variation in the effective refractive index in the guide.

**Quarter-wave stack**

![Quarter-wave stack diagram](https://www.batop.de/information/r_Bragg.html)

**Photon**

![Photon diagram](https://en.wikipedia.org/wiki/Distributed_Bragg_reflector)

---

**References**

- [Distributed Bragg Reflector](https://en.wikipedia.org/wiki/Distributed_Bragg_reflector)
- [Photon](https://en.wikipedia.org/wiki/Distributed_Bragg_reflector)

---

**Links**

- [Distributed Bragg Reflector](https://www.batop.de/information/r_Bragg.html)
If $2\Lambda$ is the period of the refractive index variations, the Bragg grating acts as a reflector with reflection maxima occurring at Bragg frequencies,

$$f_{\text{Bragg}} = \frac{mc}{2n\Lambda}, \text{ for integer } m = 1, 2, 3, \ldots,$$

where $n$ is the material index of refraction. This is known as the *Bragg Condition*. The longitudinal modes of the cavity of length $L$ that do not satisfy the Bragg condition do not survive in the cavity. The longitudinal modes are given by

$$f_q = \frac{qc}{2nL}, \text{ for integer } q = 1, 2, 3, \ldots,$$
Standard & Quarter-Wave Shifted DBF Laser Configurations

Bragg reflectors consist of periodically changing of the index of refraction

From: Coldren, Corzine and Mašanović, Diode Lasers and Photonic Integrated Circuits, 2nd ed., J. Wiley & Sons, Inc., New York, 2012; Section 3.7.1, Figure 3.25, page 142. © Wiley
Distributed Feedback Semiconductor Laser

Suppose we have a laser with $L = 300 \, \mu m$, $n = 3.3$, and the frequency separation between the longitudinal modes is 0.15 THz. If the primary mode frequency is 190 THz, the frequency of two neighboring modes is 189.85 THz and 190.15 THz. The reflection is the strongest for the first-order gratings ($m = 1$). Choosing the grating period so that $f = 190 \, \text{THz}$ (for $m = 1$), then $2\Lambda = 0.24 \, \mu m$.

The neighboring modes do not satisfy the Bragg condition, and so they suffer high losses. That is what we want to happen.

However, the DBR with the corrugated region being part of the cavity has higher photon losses and that lowers its efficiency. The solution to that is to use the distributed feedback laser where the grating is positioned above the cavity region. This modulates the effective index of refraction periodically and is equivalent to a waveguide with periodic index variation in the cavity.
A quantum well laser is a laser diode in which the active region of the device is so narrow that quantum confinement occurs. The wavelength of the light emitted by a quantum well laser is determined by the thickness of the active region rather than just the bandgap of the material from which it is constructed. Thus, much shorter wavelengths are emitted from quantum well lasers than from conventional laser diodes.

https://www.wias-berlin.de/people/kaiser/projects/efa/efa.html
1.4 μm InGaAsP/InP Strained Lattice Multiple-Quantum-Well Laser

Example

0.1 μm p-InP $4 \times 10^{17}$ cm$^{-3}$ (Be doped)

0.07 μm In$_{0.92}$Ga$_{0.08}$As$_{0.17}$P$_{0.83}$ (undoped)

0.07 μm In$_{0.89}$Ga$_{0.11}$As$_{0.23}$P$_{0.77}$ (undoped)

In$_{0.83}$Ga$_{0.17}$As$_{0.70}$P$_{0.30}$ (undoped wells)

0.01 μm In$_{0.83}$Ga$_{0.17}$As$_{0.24}$P$_{0.76}$ (undoped barriers)

0.07 μm In$_{0.89}$Ga$_{0.11}$As$_{0.23}$P$_{0.77}$ (undoped)

0.07 μm In$_{0.92}$Ga$_{0.08}$As$_{0.17}$P$_{0.83}$ (undoped)

1.5 μm n-InP $2 \times 10^{18}$ cm$^{-3}$ (Si doped)

https://www.semanticscholar.org/paper/1.4-μm-InGaAsP-InP-strained-multiple-quantum-well-Zhu-Cassidy/d287c38324c37ddaed6eac19944c143dc2ab2d12/figure/0
Quantum cascade lasers are comprised of dozens of alternating layers of semiconductor material, forming quantum energy wells that confine the electrons to particular energy states. The electron continues through the structure and when it encounters the next active region it transitions again and emits another photon.

Refer to Section 6.11.1, Pages 381-383, in Senior, 3rd ed.

Quantum Cascade Laser (QCL)

Vertical Cavity Surface Emitting Laser (VCSEL)

DBR = distributed Bragg reflector

https://www.21semiconductors.com/innovation/laser-concepts/
Physical Structure of a Vertical Cavity Surface Emitting Laser

Fact: Low-threshold current VCSELs need DBRs that are 99.9% reflective.

https://www.researchgate.net/figure/A-mesa-structure-of-the-13-mm-top-emitting-oxide-confined-OC-InGaAs-GaAs-quantum-dot_fig2_235443851
Advantages & Applications of Vertical Cavity Surface Emitting Lasers

Applications:

(1) Optical fiber data transmission sources (such as in Gigabit Ethernet and Fiber Channel)
(2) Laser printers
(3) Computer mouse

Advantages:

(1) Low threshold current for onset of laser operation
(2) Manufacturable in quantity (as arrays)
(3) VCSELs can be tested in the manufacturing flow before they are completed
(4) Very small size
(5) Tunable wavelength

https://www.myvcSEL.com/small-footprint
Smaller apertures (*e.g.*, 2 x 2 μm²) can give single mode operation.

Vertical Cavity Surface Emitting Laser (VCSEL)

- Emission $\lambda = 850$ nm & 940nm
- 10 mW to 2 W output power/chip
- Scalable

[Link to VCSEL article](https://www.laserfocusworld.com/lasers-sources/article/16550169/vcsels-for-manufacturing-highpower-vcsel-arrays-make-ideal-industrial-heating-systems)

[Link to High Power VCSEL product](http://www.milli-tech.com/product-117.html)
VCSEL Source and Photodetector Arrays

## Comparing LASER Parameters for LED, EE-LASER and VCSEL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>LED</th>
<th>Edge Emitter</th>
<th>VCSEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold current</td>
<td>mA</td>
<td>--</td>
<td>20</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Operating current</td>
<td>mA</td>
<td>100</td>
<td>30</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>mW</td>
<td>200</td>
<td>100</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Modulation bandwidth</td>
<td>GHz</td>
<td>0.1</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Beam Divergence (FWHM)</td>
<td>degrees</td>
<td>&gt; 0.01</td>
<td>0.3</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>Spectral width</td>
<td>nm</td>
<td>50</td>
<td>0.3</td>
<td>0.01</td>
</tr>
<tr>
<td>Astigmatism</td>
<td>--</td>
<td></td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>
Using VCSEL Arrays for Achieving Higher Optical Power

https://www.ricoh.com/technology/institute/research/tech_high_power_vcsel
Recall From Optics: Anti-Reflection Coatings

Anti-reflection coatings work by producing two reflections which interfere destructively with each other.

Works only at one wavelength

http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/antiref.html
Multi-Layer Anti-Reflection Coatings

Multiple layers are more effective over a wider range of wavelengths.

Typical Material

\[ \frac{\lambda}{4} \]

Optimum coating:

\[ n_{\text{coating}} = \sqrt{n_{\text{glass}}} \]

\[ n_0 = \frac{n_1^2 n_{\text{glass}}^2}{n_2^2} \] (optimum coating)

http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/antiref.html
Coupling Laser Output Into an Optical Fiber

To couple the laser radiation into the fiber, the laser radiation must be transformed to a spot with a precisely specified size and must hit the fiber core as precisely as possible.

https://www.beamxpert.com/applications
Laser Beam Divergence

Elliptical Gaussian Beam Spreading (Diffraction)

https://micro.magnet.fsu.edu/primer/techniques/microscopylasers.html
Various Ways to Couple Lasers to Optical Fibers

Coupling Laser Output to input of Fiber

https://www.newport.com/t/fiber-optic-basics
Ball lenses have several unique optical properties which make them highly desirable for use as micro-optical elements, with the most significant advantage being their short focal lengths and huge numerical apertures. The mechanical symmetry of the ball lens also makes them extremely easy to align and center.
Coupling Laser Output Into Fiber

Typical 1 Watt Fiber-Coupled Diode Laser Showing Interior Construction

https://www.repairfaq.org/sam/laserdio.htm
Coupling VCSEL Optical Output Into a Fiber

https://www.researchgate.net/figure/a-Hybrid-assembly-of-a-movable-silicon-45-micromirror-for-VCSEL-fiber-active-alignment_fig5_258380120
Laser Diode Biasing Circuit

Recall: Fourth Generation of Optical Fiber Systems

Fourth generation (Optical amplifiers)

- Year implemented: 1996
- Bit rate: 10 Tbps
- Regenerator spacing: > 10,000 km
- Operating wavelength: 1450 nm to 1620 nm

Fourth generation lead to the use of wavelength division multiplexing (WDM) and the introduction of optical amplifiers (such as erbium-doped fiber amplifiers (EDFA)). With fourth generation chromatic dispersion becomes the major limitation.

https://sites.google.com/site/csapgroupc/home/history-of-optical-fibers
Fiber Laser Amplifiers

What if the optical fiber could perform amplification?

A fiber laser is a laser in which the active gain medium is an optical fiber doped with rare-earth elements such as erbium, ytterbium, neodymium, dysprosium, praseodymium, thulium and holmium.

https://www.fiberlabs.com/glossary/fiber-laser/
Energy Level Diagram of Er$^{3+}$ Ions

Er$^{3+}$ Energy Levels

Simplified energy levels of Er$^{3+}$ ions in Erbium doped fibers

- E3 $^{4}I_{11/2}$
- E2 $^{4}I_{13/2}$
- E1 $^{4}I_{15/2}$

Pump Laser 980 nm

- Fast Decay (non-radiative emission)
- Stimulated absorption
- Stimulated emission (1520-1570 nm)

Lifetime ~ 10 ms

The Stark effect splits the atomic energy levels by an electric field.

Atomic number is 68

Erbium-Doped Fiber Amplifiers

https://www.fiberoptictel.com/understanding-dwdm-system-components-minutes/erbium-doped-fiber-amplifier-edfa/
Amonics Optical Fiber Laser Amplifier

Output up to 10 Watts
1535 nm to 1563 nm
Gain > +30 dB
Saturated power > 40 dBm

https://www.solidstatelasersource.com/shop/High-Power-1550nm-EDFA-Fiber-Amplifier
Advantages of EDFAs

• Commercially available (C-band and L-band)
• Insensitivity to light polarization state
• High optical power gain
• Low noise figure (4.5 dB to 6 dB)
• Negligible distortion at high bit rates
• Simultaneous amplification of WDM signals
• Immunity to cross-talk among WDM signals
• Does not need high-speed electronics
• Independent of bit rate (transparency)

https://www.slideshare.net/jayanshugundaniya9/erbium-doped-fiber-amplifier-edfa
Disadvantages of EDFAs

• Large pump power is required
• Need to use a gain equalizer for multistate amplification
• Difficult to integrate with other components
• Large physical size (doped fiber is 10 to 50 m)
• Limited signal wavelength range (C-band and L-band)

https://www.slideshare.net/jayanshugundaniya9/erbium-doped-fiber-amplifier-edfa
Next Major Topic: Optical Detectors

See Chapter 8 (starting on page 444) in Senior, 3rd ed.

Optical Fiber System Link

Transmitter

- Message Origin
- Modulator
- Carrier Source
- Channel Coupler

Fiber

- Fiber
- Repeater or Optical Amplifier

Fiber

- Fiber
- Information Channel

LEDs & Diode Lasers

EDFA Amplifiers

Receiver

- Detector
- Amplifier
- Processing

Fiber

Message Output

Next topic: Photodetectors

Photoconductors Have Been Around For a Long Time

A photoconductor is a light-controlled variable resistor

Selenium discovered to be photoconductor in 1873

https://www.researchgate.net/figure/Geometry-and-bias-of-a-photoconductor_fig4_224485590
Photoresistors

A photoresistor (or light-dependent resistor, LDR, or photo-conductive cell) is a light-controlled variable resistor. The resistance of a photoresistor decreases with increasing incident light intensity; in other words, it exhibits photoconductivity.

Photoresistors come in many types. Inexpensive cadmium sulfide cells can be found in many consumer items such as camera light meters, clock radios, alarm devices (as the detector for a light beam), nightlights, outdoor clocks, conventional and solar street-lamps, etc.

https://www.wikiwand.com/en/Photoresistor
https://www.sciencedirect.com/topics/engineering/photoresistors
Better Solution: Photodiodes

Commonly used semiconductors used for photodiodes are silicon, germanium and III-V compound semiconductors. Silicon is sensitive from 800 nm to 900 nm. Smaller bandgap semiconductors are required for longer wavelengths ranging from 1200 nm to 1600 nm (that includes 1300 nm and 1550 nm). Germanium and some III-V semiconductors fill this need.

Optical Detection Principle:

An optical detector is a transducer that converts an optical signal into an electrical signal. It does this by generating an electrical current proportional to the intensity of incident optical radiation.
Basic Concept: Photons Shining Upon a PN-Junction Photodiode
Attenuation of Light Penetrating a Semiconductor

Absorption Coefficient $\alpha_0$

Photogeneration: Electron-hole pairs are created as photons are randomly annihilated as they penetrate the semiconductor body. Each photon carries energy $hf$.

Let $N_{ph}(x)$ be the number photons per unit area into the body of the semiconductor, then

$$N_{ph}(x) = N_{ph}(x = 0) \cdot \exp[-\alpha_0 x]$$

$$I(\lambda, x) = I_0(\lambda) \exp(-\alpha_0 x)$$

$$I(\lambda, x) = (1 - R(\lambda)) \cdot I_0(\lambda) \exp(-\alpha_0 x)$$

Reference: Section 8.4, pp. 448 to 450, in Senior, 3rd ed.

https://www.asu.edu/courses/phs208/pat ternsbb/PiN/rdg/mechanism/index.html
Absorption of Photons in a Photodiode

Photons focused upon a photodiode travel through the diode thereby creating electron-hole pairs as they decay in intensity. The semiconductor has an absorption coefficient $\alpha_0$ at the wavelength of the light. Assuming only band-to-band transitions (intrinsic absorber) the photocurrent $I_p$ produced by the light of optical power $P_0$ is given by

$$I_p = \frac{P_0 q(1-r)}{h \nu} \left[ 1 - \exp(-\alpha_0 d) \right]$$

where $q$ is the electronic charge, $r$ is the Fresnel reflection coefficient at the semiconductor-air interface, and $d$ is the width (depth) of the absorption region.

Absorption coefficients are strongly dependent upon wavelength as shown on the next slide.
Absorption Coefficient $\alpha_0$ as a Function of Wavelength

$$\lambda_c = \frac{hc}{E_G} = \frac{1.24}{E_G[\text{eV}]} \, [\mu\text{m}]$$

Corresponds to Figure 8.2, p. 449 in Senior, 3rd ed.

Quantum Efficiency

The quantum efficiency $\eta$ is defined as the fraction of incident photons absorbed by the photodetector and generate electrons which are collected at its terminals:

$$\eta = \frac{\text{number of electrons collected}}{\text{number of incident photons}}$$  \hfill (8.2)

$$\eta = \frac{r_e}{r_p}$$  \hfill (8.3)

where $r_p$ is the incident photon rate (photons per second) and $r_e$ is the corresponding electron collection rate (electrons per second).

Thus, the absorption coefficient is important in determining $\eta$. The quantum efficiency is always less than unity (< 100%) because not all photons are absorbed to create electron-hole pairs.

Power Absorbed in Semiconductor

\[ P_{\text{absorbed}}(d) = \int_0^d \alpha_0 P_{\text{input}} \times \exp(-\alpha_0 z) \, dz = P_{\text{input}} \left(1 - \exp(-\alpha_0 d)\right) \]

If reflectivity \( r \) at the interface, then

\[ P_{\text{absorbed}}(d) = P_{\text{input}} \times (1 - r) \left(1 - \exp(-\alpha_0 d)\right) \]

The photocurrent \( I_p \) is then given by

\[ I_p = \frac{q}{h\nu} P_{\text{input}} \times (1 - r) \left(1 - \exp(-\alpha_0 d)\right) \]
External Quantum Efficiency

$$\eta = \frac{\text{number of electron-hole pairs generated}}{\text{number of incident-absorbed photons}}$$

$$\eta = \frac{(I_p / q)}{(P_{\text{input}} / hf)}$$

The external quantum efficiency of a photodiode (width $d$) is

$$\eta_{\text{ext}} = \frac{(I_p / q)}{(P_0 / hf)} (1 - r) \times [1 - \exp(-\alpha_0 d)]$$

The internal quantum efficiency is then

$$\eta_{\text{int}} = \frac{\eta_{\text{ext}}}{(1 - r)} = [1 - \exp(-\alpha_0 d)]$$
Responsivity \( R \)

The quantum efficiency \( \eta \) does not depend upon the photon energy and, hence, the responsivity \( R \) is more useful in characterizing the performance of a photodiode. It is defined as

\[
R = \frac{I_p}{P_{\text{input}}} \quad [\text{A/W}] \tag{8.4}
\]

where \( I_p \) is the output photocurrent in amperes and \( P_{\text{input}} \) is the incident optical power in watts (i.e., the output optical power from the fiber).

The responsivity is a useful parameter as it gives the transfer characteristic of the detector (photodiode).

\[
R = \frac{\eta q}{hf} = \frac{\eta q \lambda}{hc} \tag{8.9} \quad \text{and} \quad \tag{8.11}
\]

Reference: Section 8.6, pp. 451 to 455, in Senior, 3rd ed.
Responsivity versus Wavelength for Silicon P-I-N Diodes

\[ R = \eta \frac{q}{h} = \eta \frac{q \lambda}{hc} \]

See Fig. 8.3 on page 453 of Senior, 3rd edition.

https://users.physics.ox.ac.uk/~rtaylor/teaching/Opto_lecture5.pdf
Optical Responsivity versus Wavelength For Si, Ge & InGaAs

Figure 8.3 (b) on p. 453

https://www.fiberoptics4sale.com/blogs/archive-posts/95046662-pin-photodetector-characteristics-for-optical-fiber-communication
Responsivity $R$ (continued)

The equation for the responsivity $R$ can be expressed as a function of the quantum efficiency $\eta$. Starting with $E = hf$, the incident photon rate $r_p$ can be written as

$$r_p = \frac{P_0}{hf} \quad (8.5)$$

and so the electron rate $r_e$ is given by

$$r_e = \eta r_p \quad (8.6)$$

Upon substitution we next obtain,

$$r_e = \frac{\eta P_0}{hf} \quad \text{and} \quad I_p = \frac{\eta P_0 q}{hf} \quad (8.7) \text{ & (8.8)}$$

$$\therefore \quad R = \frac{\eta q}{hf} \quad (8.9)$$

Also, $R = \frac{\eta \lambda}{1.24}$

Reference: Section 8.6, pp. 451 to 455, in Senior, 3rd ed.
Long-Wavelength Cutoff

For the intrinsic absorption process requires the energy of the photons must be greater than the bandgap energy $E_G$ of the material. Thus, the photon energy:

$$\frac{hc}{\lambda} > E_G$$

which gives

$$\lambda < \frac{hc}{E_G} \quad (8.12) \& (8.13)$$

The threshold for detection, often called the “long-wavelength cutoff point” $\lambda_c$

$$\lambda_c = \frac{hc}{E_G} \quad (8.14)$$

This gives the longest wavelength that the light will result in photodetection.

Reference: Section 8.7, pp. 455 to 456, in Senior, 3rd ed.
https://www.skipprichard.com/ask-questions-to-improve-your-leadership/