EE 443 Optical Fiber Communications
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Answers to Class Questions
(Session 1)

http://www.wiretechworld.com/the-future-of-optical-fibres/
1. Clarify Numerical Aperature and Acceptance Angle

From Lecture 4 in EE 443

Numerical Aperature $NA = n \cdot \sin \alpha$

$NA = \sqrt{n_1^2 - n_2^2}$

2. Why is the critical angle not always 90 degrees?

See next slide
Critical Angle in Optical Fibers

http://macao.communications.museum/eng/exhibition/secondfloor/MoreInfo/2_8_4_TotalInternalReflection.html
What is Mode Dispersion?

Chromatic Dispersion

Modal Dispersion

https://chinafiberoptics.blog.hu/2016/05/18/limiting_factors_in_fiber_optic_transmissions
What is redundancy in optical fiber communications?

Fiber network redundancy describes the situation in which multiple, geographically diverse cable routes provide service to the same client site. This creates a safety net so that if something were to happen to the primary fiber cable, service to the client would not be interrupted.

How do you know when to use multimode or single-mode?

Single Mode vs. Multimode Fibers

**Single-Mode**
- Small core
- Less dispersion
- Carry a single ray of light, usually generated from a laser.
- Employ for long distance applications (100Km)
- Uses as Backbone and distances of several thousands meters.

**Multimode**
- Larger core than single mode cable.
- Allows greater dispersion and therefore, loss of signal.
- Used for shorter distance application, but shorter than single-mode (up to 2Km)
- It uses LED source that generates different angles along cable.
- Often uses in LANs or small distances such as campus networks.

How do you know if a fiber is multimode?

Most Silica-based optical fibers have a 125 microns outer diameter (cladding). The single-mode fiber core is around 6 to 9 microns diameter, whereas, multimode fiber core is typically 50 microns or 62.5 microns.
What is the use of the heterojunction?

A heterojunction (HJ) is the interface that occurs between two layers or regions of dissimilar crystalline semiconductors. These semiconducting materials have unequal band gaps as opposed to a homojunction.

- **HJ lasers** (> population inversion, carrier confinement & index guiding)
- **HJ photodiodes** (engineered bandgaps & higher drift velocities)
- **HJ LEDs** (engineered bandgaps for different wavelengths & colors; internal gratings)
- **HJ Solar cells** (engineered bandgaps for greater collection of solar radiation; > $\eta$)
- **HJ bipolar transistors** (Wide bandgap emitters; higher gain and emitter efficiency; lower base resistance and enhanced base transport yielding higher $f_{\text{max}}$)
- **HJ field-effect transistors** (HEMT & MODFET; > mobility in quantum well channels; lower noise; higher $f_{\text{max}}$)
- **Nanostructures** (quantum dots; search for higher density electronic circuits to keep Moore’s Law active)

[https://www.mdpi.com/2073-4352/7/10/307/htm](https://www.mdpi.com/2073-4352/7/10/307/htm)
What are multiple heterojunctions used for?

Multiple heterojunctions can be used to form quantum wells and alternating quantum wells for carrier confinement and for photon confinement, for Bragg reflection gratings and cavities (such as the VCSEL). They can also be used for solar cells to create multiple pn-junctions to select portions of the solar spectrum to collect a greater amount of solar radiation. This can also be applied to detectors for particles.

How does a heterojunction affect power dissipation?

This depends upon the device and how much the performance is enhanced. Many compound semiconductors can operate at higher temperatures than silicon, have higher thermal conductivity, so power dissipation must look at all of the variables to draw a conclusion.
Is there anything other than lasers used in Fiber Optic Communications?

Yes, there are LEDs, which are also used as sources for multimode fibers, and photodiodes for optical receivers (and even in a few cases optical transistors are used for detection transducers).

Phototransistors have current gain which is somewhat like avalanche photodiodes. Phototransistors are light sensitive bipolar transistors and can be more sensitive than photodiodes.

![Phototransistor Diagrams](https://www.electrical4u.com/phototransistor/)

**Figure 1** Phototransistor (a) Homojunction Structure (b) Heterojunction Structure

https://www.electrical4u.com/phototransistor/
What even is voltage?

VOLTAGE – potential difference (electrical pressure) is the difference in electrical potential between two points → establishes a static electric field And is defined as the work needed per unit electrical charge to move a test Charge between the two points. [Work per unit charge has units of joule/coulomb.]

SI definition for volt: 1 volt = 1 watt (power) per 1 ampere (current)

Electrical potential difference between two points is caused by
1. Separated electric charge
2. Electric current through a magnetic field (like the Hall effect)
3. Time-varying magnetic field

Reference: R. P. Feynman’s lecture on AC circuits

www.feynmanlectures.Caltech.edu/II_22.html
How do the bandgaps look like in multiple degrees of freedom of the crystal structure?

First Brillouin zone

Consists of quantum states

E-k diagram

https://www.researchgate.net/figure/Simplified-Si-band-structure-The-lowest-band-gap-is-not-positioned-directly-at-G-point_fig3_322927864
Are there lasers that do not produce heat?

NO. Lasers get warmer because not all of the energy input to pump the laser is emitted in its coherent light beam. Photons are absorbed by the materials forming the laser and this energy turns into thermal energy. The harder you pump, the hotter it becomes.
How does temperature affect the index of refraction?

For silica optical fibers the temperature variation in its index of refraction is very small. This is not true for most plastic optical fibers, however.

Finished here on October 1st
Our interest in direct bandgap versus indirect bandgap is primarily limited to electron transition time in recombination (i.e., electron annihilates hole and emits a photon and perhaps a phonon). The response time of lasers and other devices is dependent upon the transition times.

Also, the emission of phonons heats the lattice which means the heat needs to be removed in actual receiver circuits.

Indirect bandgap materials tend to have longer transition times because it is harder to balance the energy and crystal momentum changes in band-to-band transitions.
How does the unit A/W work?

From Lecture 11: The responsivity $R$ is more useful in characterizing the performance of a photodiode. It is defined by

$$R = \frac{I_p}{P_0} \text{ [A/W]}$$

where $I_p$ is the output photocurrent in amperes and $P_0$ 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).

That means that the photodiode outputs a current for an optical input power (i.e., output current in amperes for an optical input power in watts).
Why was it difficult to create the Blue LED?

First blue LED demonstrated at Stanford University in 1972. This device used GaN that was magnesium-doped.

Rhines and Maruska

In 1993, Nakamura, Akasaki and Amano demonstrated high output blue LEDs with GaN grown on sapphire substrates. Basis of the 2014 Nobel prize.

By the way, now GaN can be grown on silicon substrates.

http://large.stanford.edu/courses/2014/ph240/rolston1/
Gallium nitride (GaN) is a binary III/V direct bandgap semiconductor commonly used in light-emitting diodes since the 1990s. The compound is a very hard material that has a Wurtzite crystal structure.

Why was it difficult to create the Blue LED?

https://en.wikipedia.org/wiki/Gallium_nitride
Why was it difficult to create the blue LED? 
GaN Band structure

![GaN Band Structure Diagram]

\[ \lambda = \frac{1.24}{E_G \text{ [eV]}} \text{ [μm]} \]

\[ \lambda = \frac{1.24}{3.39 \text{ eV}} = 0.366 \text{ μm} \]

That is UV
Blue light is 0.450 to 0.500 μm
Violet is 0.385 to 0.450 μm

http://www.ioffe.ru/SVA/NSM/Semicond/GaN/bandstr.html
Why was it difficult to create the blue LED?
GaN Grown on sapphire

Lattice mismatches create areas where the LED is less efficient.

Al₂O₃
Why was it difficult to create the blue LED?
The LED MQW structure
The formation of an $\text{In}_x\text{Ga}_{1-x}\text{N}$ recombination region in the device defines the emission wavelength. Controlling the indium mole fraction ($x$) of the InGaN active layer is done by changing the growth temperature or indium source flow rate during InGaN growth. As a quantum well, it need not be doped. The quantum well acts like a “bucket,” where holes are poured in from the p-type layers, and electrons are injected from the n-type layers on the other side. The recombination is band-to-band in the well. Nakamura’s team reported the first actual blue InGaN quantum well laser diode device in 1996. There is just a single emission peak at 417 nm.

The Royal Swedish Academy of Sciences has decided to award the

2014 NOBEL PRIZE IN PHYSICS

Isamau Akasaki, Hiroshi Amano
and Shuji Nakamura

“for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources”
Can you build a photodiode that absorbs multiple frequencies of light?

But, can we use multiple materials in stacked junctions to cover a wider spectrum?

See solar cell Example.

http://km2000.us/solar/readings.html
I would like to understand the concept of radiation.

https://www.pinterest.com/pin/573997914999859701/

https://www.sciencedirect.com/topics/neuroscience/electromagnetic-radiation
I would like to understand the concept of radiation.

https://www.tes.com/lessons/NkJjWTsBQVmz9w/nuclear-chemistry
I would like to understand the concept of radiation.

https://phys.libretexts.org/Bookshelves/University_Physics/Book%3A_University_Physics_(OpenStax)/Map%3A_University_Physics_III_-_Optics_and_Modern_Physics_(OpenStax)/6%3A_Photons_and_Matter_Waves/6.1%3A_Blackbody_Radiation
I would like to understand the concept of radiation. 
Wave-particle duality

\[ \lambda = \frac{h}{p} = \frac{h}{mv} \]

The wave properties of matter are only observable for very small objects. de Broglie wavelength of …

• a human being running at top speed: $1 \times 10^{-36}$ m
• a 10 eV electron: $3.9 \times 10^{-10}$ m, comparable to the spacing between atoms, so a crystal acts as a diffraction grating for electrons.

http://www.feynmanlectures.caltech.edu/III_01.html
What is the difference between spontaneous and stimulated emission?

http://semesters.in/spontaneous-emission-of-radiation-for-btech-1st-year-physics/
Could you go over the importance of Einstein’s A & B Coefficients

Review: Section 6.2.2 (pp. 299 to 302) in Senior 3rd ed. and Lecture 7, slides 7 through 13
Why is the laser gain the sum of the two losses?

The laser cavity has losses which must be overcome to oscillate. The gain of the laser medium has gain at the wavelength of stimulated emission, therefore, When the gain is equal to the losses in the cavity, we have the threshold of oscillation.

For a laser to emit a coherent beam with power, the gain must exceed the losses at the gain threshold and row in magnitude until it reaches saturation where the gain will exactly equal the loss of the cavity.
Why do electrons not lose momentum in direct bandgap materials?

No momentum is transferred to the crystal when the k-values line up between the conduction band and the valence band.

There can be small momentum emissions of phonons for such electron-hole recombination events.
How does the forward/reverse bias affect photodetector response?

Photodiodes are always operated in reverse bias. Forward bias would generate a current greatly exceeding the dark current (reduced sensitivity) and would slow down the photodiode’s response time.
Does quantum tunneling occur in photo-optical communications?

Yes. For example, photodiodes are combined with resonant tunnel diodes to make IR and THz radiation detectors. An example is the reference:

http://physics.gsu.edu/perera/pdf/resonant.pdf

Tunneling is the basic principle behind the tunnel diodes (Esaki diode) and the less common backward diode. The lower voltage Zener diode uses the tunneling principle – these are widely used for voltage reference applications.
Now Ask More Questions

One more question?