Semiconductor Lasers

Explorations in silicon photonics laser modelling, design, fabrication and challenges for industry

ELEC 413

January 11, 2022

Dr. Lukas Chrostowski

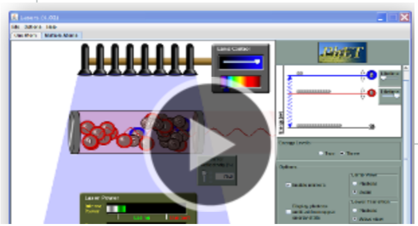

In terms of Lasers – What is “right” and what is “wrong” with this picture?

Why are you in this class?

Week overview

- BEFORE CLASS
- DURING CLASS
- AFTER CLASS

Pre-Lecture Activity	**Week starting**	**Activities during Class**	**Assignment** (due before the following week's class, unless otherwise noted)
Introduce yourself in discussion forum Download, install, and play with it for 5 minutes: the PhET Laser animation	January 10	Lectures: • Course introduction • What is a laser? • Project Design 1 & 2	PhET Laser Animation questions Install the Lumerical tools and KLayout + SiEPIC tools. The Photonic Components module (Waveguides, Waveguide modelling, Fibre Grating Coupler).



- Course logistics, outline
- Register on the edX and Piazza course pages
- Introduction to semiconductor lasers

413 - Course Information

Instructor:	Dr. Lukas Chrostowski (contact via Piazza)
Teaching Assistant:	Iman Taghavi <staghavi3@ece.ubc.ca> Alex Tofini <atofini@ece.ubc.ca>
Web Page:	https://edge.edx.org/courses/course-v1:UBC+ELEC413-201+2021W2/about
Discussion Forum	piazza.com/ubc.ca/winterterm22021/elec413
Text:	**Silicon photonics design** (book download link from UBC Library**)** by L. Chrostowski; M. Hochberg **Lecture notes**
Suggested Text:	Photonics: Optical Electronics in Modern Communications by A. Yariv and P. Yeh, 6th Ed, 2007 S.O. Kasap, “Principles of Electronic Materials and Devices”, 2005 (chapter on LEDs, lasers)

413 - Course Information

Semiconductor Lasers

Pick up where you left off

Resume course

Expand all

ELEC 413 Introduction

- Course Overview & Project
- Course Schedule & Lecture Notes
- Software Installation
- [Optional] MATLAB Tutorials

Semiconductor Laser Introduction

- PhET Laser Animation (6 Questions)
  Homework due Jan 18, 2022, 12:30 PM PST
- Laser types
- Fabry Perot cavities (3 Questions)
- VCSEL Design, Transfer Matrix Method (2 Questions)

Introduction to Silicon Photonics

Photonic Components

- Section Overview
- Waveguides (12 Questions)
- Waveguide modelling - Lumerical MODE (4 Questions)
- Y-Branch (2 Questions)
- Fibre Grating Coupler (1 Question)

413 - Course Information

Marking:	Projects	***50%***	Midterm	***10%***	Homework	***30%***
	Lab Report	***10%***	Final Exam	***0%***		

Prerequisites
- Background in electromagnetics
  - plane waves, reflections, transmission lines
- Background in semiconductors
  - band structure diagrams, doping, pn junctions
- Mathematics (calculus, algebra)
- Basic programming (Python, MATLAB, etc)

Computer: In-class activities and homework using a laptop; software will be provided.

Midterm / Exam: 1 Midterm: online
Exam: none

Homework: Assignments (modelling, analytic, and numerical)

Project 1: “Bragg grating resonator Design-Fabrication-Test”

Project 2: “Laser modelling”

Lab Report: 1 experiment (laser characterization)

Co-Creating the Syllabus

- What do you want to know about lasers?

- What skills do you want to acquire?
  -

Material to be Covered

- Applications of lasers
  - Communications (data, voice)
  - Computing
  - Biophotonics and sensors
  - Quantum computing
- Silicon Photonics
  - laser integration challenge
- Mirrors, resonators
  - Design, fabrication, test, data analysis – Project
- Semiconductors
  - Band structure engineering
  - recombination
  - optical gain
- Laser model & performance
  - Rate equations (Matlab or Python)
  - Lumerical INTERCONNECT
  - DC, digital modulation, stability, feedback, noise, optical links
- Laser characterization
  - Lab

Course Outline

Semiconductor Theory

Band Diagrams
Carrier Density Distributions
Quasi-Fermi Levels

Maxwells Equations

Light confinement
Optical Modes
Fabry-Perot Resonators

Design,
Fabrication,
Test Project

Light-Matter Interaction

Optical Transitions
(Emission, Absorption)
Semiconductor Optical Gain
Pumping (Current Injection)

Compact models:
- Laser: Rate Equations

Semiconductor Optoelectronic Devices

Lasers, Detectors, Amplifiers, LEDs

Applications

Optical / Lightwave
Communication Systems
Biomedical

Learning Objectives

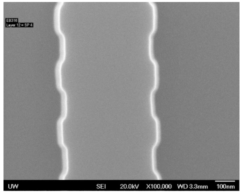
- At the end of this course, the student will be able to:
  - Predict laser characteristics quantitatively and qualitatively
  - Perform calculations predicting the optical properties of laser cavities
  - Design and test a laser cavity, using an integrated photonics platform (silicon)
  - Perform simulations of the laser to predict laser characteristics
  - Experimentally characterize a laser

Project 1 – Bragg grating Cavity Design-Fabrication-Test

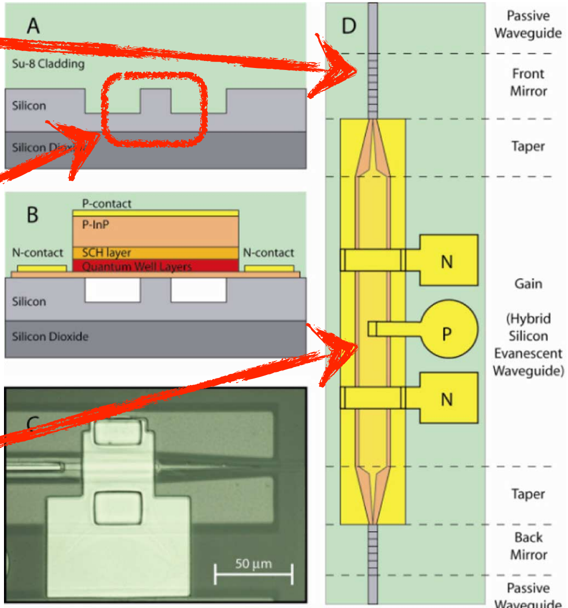
- Design a laser resonator cavity
  - Objective: Design the highest possible Q factor cavity – class competition
  - Winning student who 1) gets the highest Q in the class, and 2) beats my design (which I will share with you).
- Parts
  - Optical modelling and design: Waveguide, Bragg gratings, Fabry Perot resonator/cavity
  - Layout
  - Peer feedback & Design review
  - Fabrication – done by e-beam lithography at UBC by Staff (Applied Nanotools Inc.)
    - February 13th, 2022.
  - Measurements – done by TA
  - Data analysis
  - Report
- Different this year:
  - Wavelength = 1.3 μm (instead of 1.5 μm), and 2nd fabrication run with an on-chip laser!

Silicon Laser – used by Intel

- Bragg grating for:
  - Front mirror & back mirrors



- Waveguide
  - Rib waveguide
- Cavity
  - with semiconductor for optical gain
  - electrical contacts



IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 20, NO. 20, OCTOBER 15, 2008

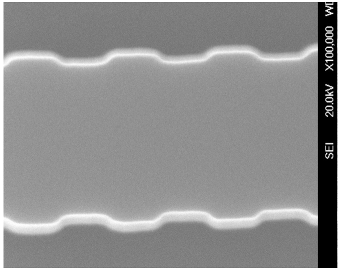
Fig. 1. (a) Passive silicon rib and (b) hybrid silicon evanescent waveguide cross section. (c) Microscope image of a hybrid to passive taper. (d) DBR-SEL top-view topographical structure.

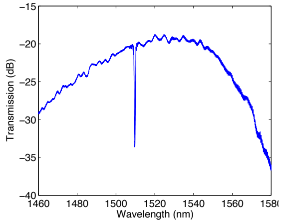
Waveguide Bragg Gratings

Thesis: https://circle.ubc.ca/handle/2429/45687

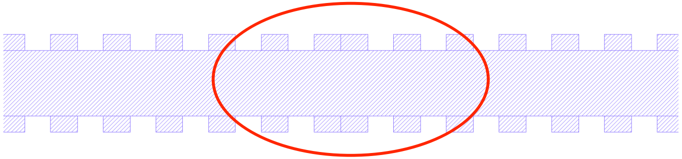
- Bragg gratings – in waveguides

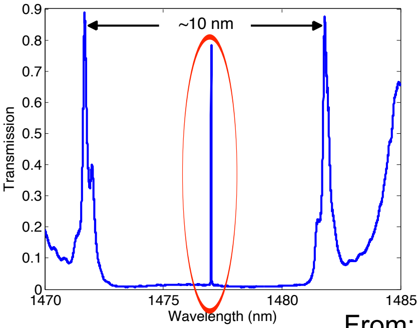
Single-mode
BW: 0.5 – 35 nm





- Phase shifted gratings



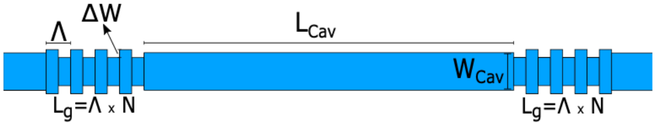


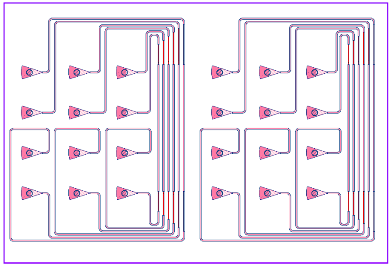
From: Xu Wang

Waveguide Bragg Gratings

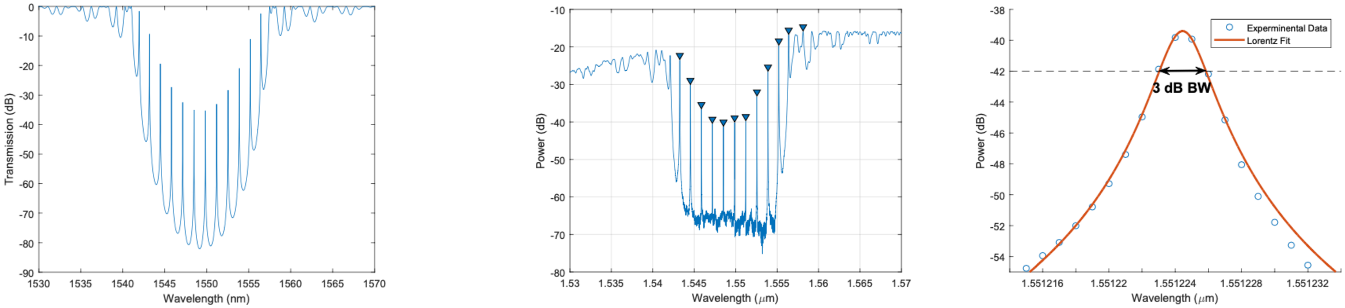
Report by Ajay Mistry

- Bragg gratings – resonator design:





- Simulated and experimental results:



Peak quality factor of 499,700 at 1551 nm

Project 2 – TBD

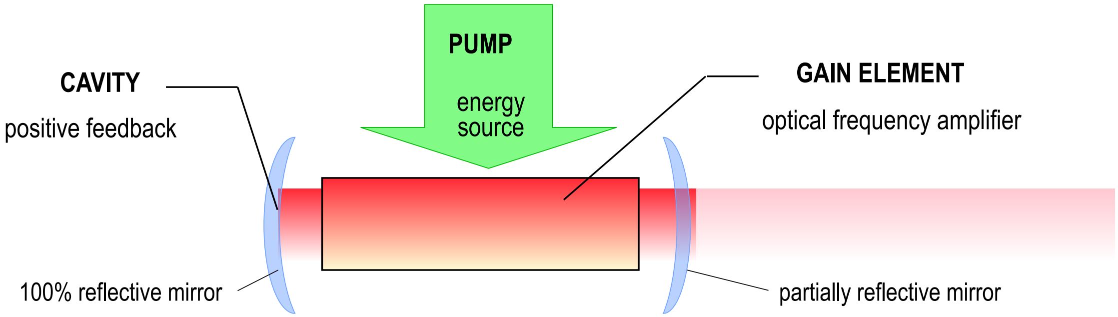
- To be determined. Possibilities:
- External Cavity Laser (ECL) design
  - Design, simulate, and layout an external cavity laser (ECL) based on a commercial semiconductor optical amplifier (SOA) and one or more silicon photonic reflectors (Bragg grating)
  - Target specifications. Simulations. Summary of performance parameters. Report. Presentations.
- Ideas for a Laser integration product
  - Students will develop a concept of a product that uses lasers and integration with silicon photonics. We want ideas that are feasible, grounded in science and engineering, and which are novel. Furthermore each idea must be unique within the class cohort.
  - Definition of Novel: not available in the marketplace. Early TRL 1 ideas ok.
  - Example: smart watch with an integrated laser to measure the concentration of CO_2.
  - Report. Presentation.
- Advanced Model for DFB laser integrated with silicon
  - Build an advanced laser model for the laser used in Project 1 Design 2. Including optical feedback. Choice of implementation software (Matlab, Python, Lumerical, Cadence VerilogA).

What is a LASER?

- Break-out room, discuss – 2 minutes
  - Draw a diagram, sketch?
- Share with the class – 5-10 minutes
  -

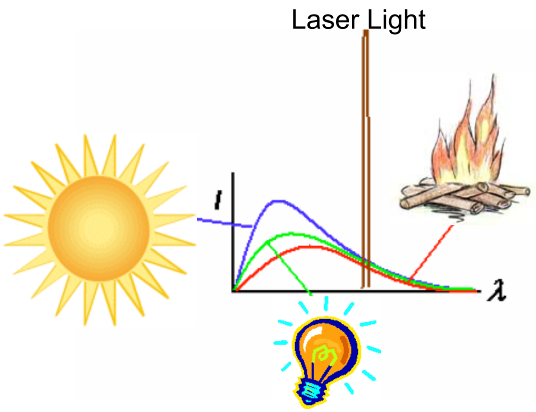
What’s a laser?

- **LASER** = **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.
- A laser is an *oscillator* that operates at very high (optical) frequencies (usually in the range 10^{13} - 10^{15} Hz, e.g. 192 THz).
- In common with an electronic circuit oscillator, a laser is constructed from an amplifier with positive feedback.
- Lasers are constructed using three essential elements:

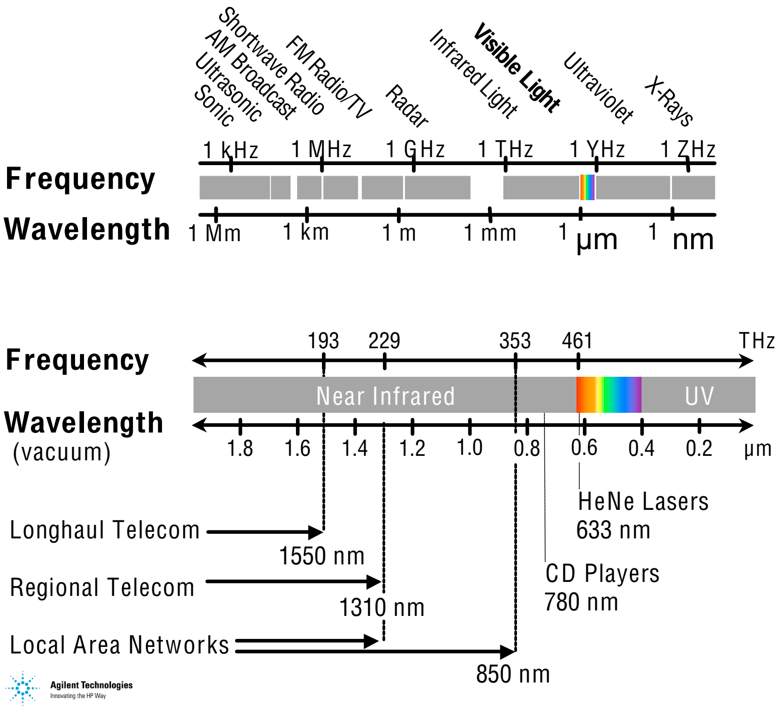


Laser Properties

- Laser light is "monochromatic"
  - i.e. single colour
  - In contrast to rainbows, white light, etc
- Laser light is in the form a *beam*



Optical Spectrum



Semiconductor Laser Applications

Internet

- Optical communications
  - Telecom
  - Datacom (millions)
  - Computercom (billions)

Bio-Med Applications

- Surgery
- Disease detection
- Environmental sensing
- Drug discovery

Other

- CD players
- Entertainment
- Machining
- LIDAR

Chrostowski's research involving Lasers

- Laser integration for biosensors (COVID-19)
- Laser linewidth reduction silicon photonic circuits for LIDAR and coherent communications
- Lasers as pumps for single photon sources for quantum computing and quantum communications
- Lasers for optical computing
- Design, fabrication, test of VCSELs for LIDAR and data communications

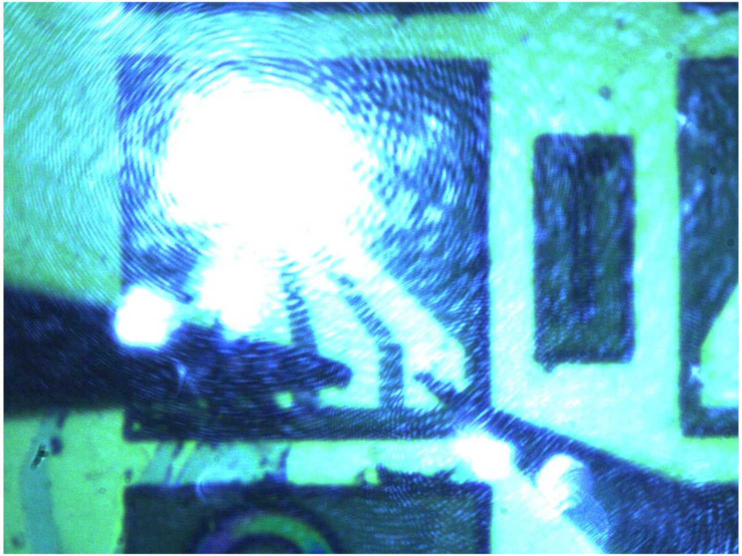
iPhoneX

- Uses VCSELs for facial recognition

Source: Bloomberg reporting

Bloomberg

850 nm Vertical Cavity Laser (VCSEL)

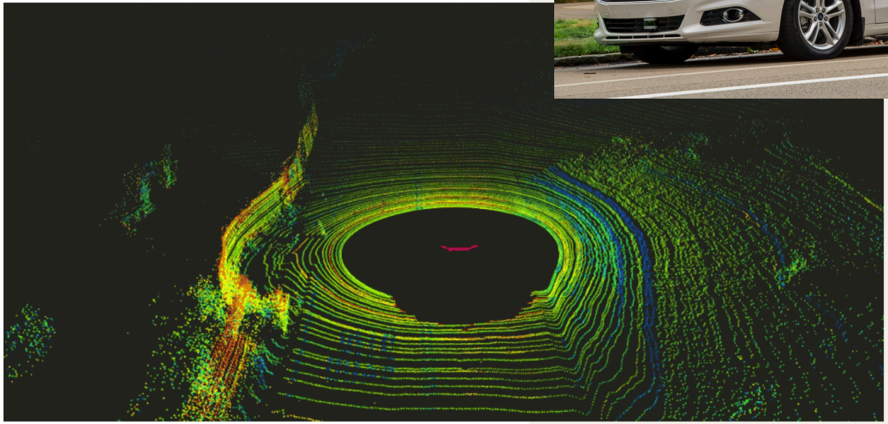


- Lasers fabricated at UBC in the AMPEL Nanofab

LIDAR

https://news.voyage.auto/an-introduction-to-lidar-the-key-self-driving-car-sensor-a7e405590cff

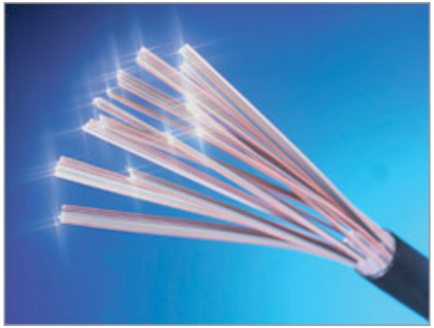
- for self-driving cars



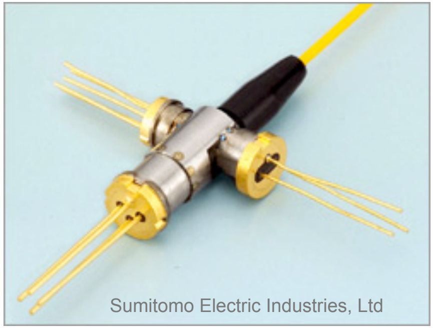
LIDAR

- Numerous silicon photonics & lasers start-up companies working on LIDAR
  - Start-ups: LightIC – in Canada, SiLC, Analog Photonics
  - Larger: AEVA, Blackmore
    - $2B valuation for AEVA: https://techcrunch.com/2020/11/02/lidar-startup-aeva-to-go-public-via-2-1-billion-spac-merger/
    - $0.5B raise for Blackmore then acquisition: https://techcrunch.com/2019/05/23/fresh-off-a-530m-round-aurora-acquires-lidar-startup-blackmore/
- iPhone "LIDAR"
  - https://www.cnet.com/how-to/lidar-sensor-on-iphone-12-pro-and-ipad-pro-2020-what-it-can-do-now-and-future/
  - https://www.howtogeek.com/695823/what-is-lidar-and-how-will-it-work-on-the-iphone/

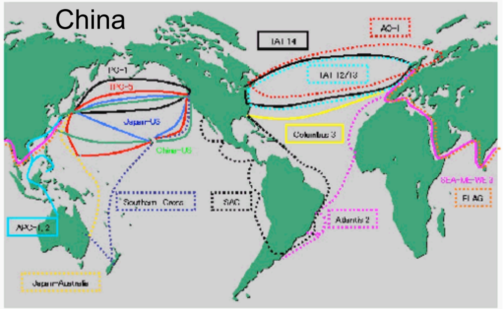
Optical Telecommunications



Lucent



Sumitomo Electric Industries, Ltd

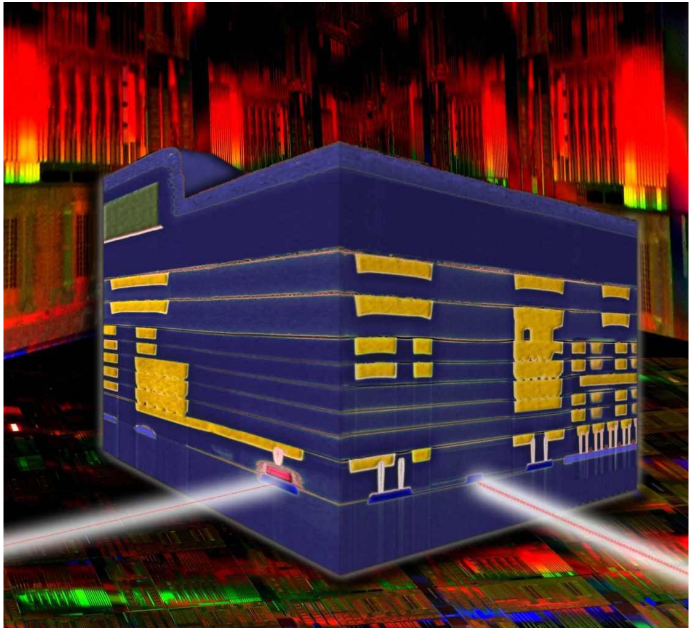


Lasers in Data and Computer Comm

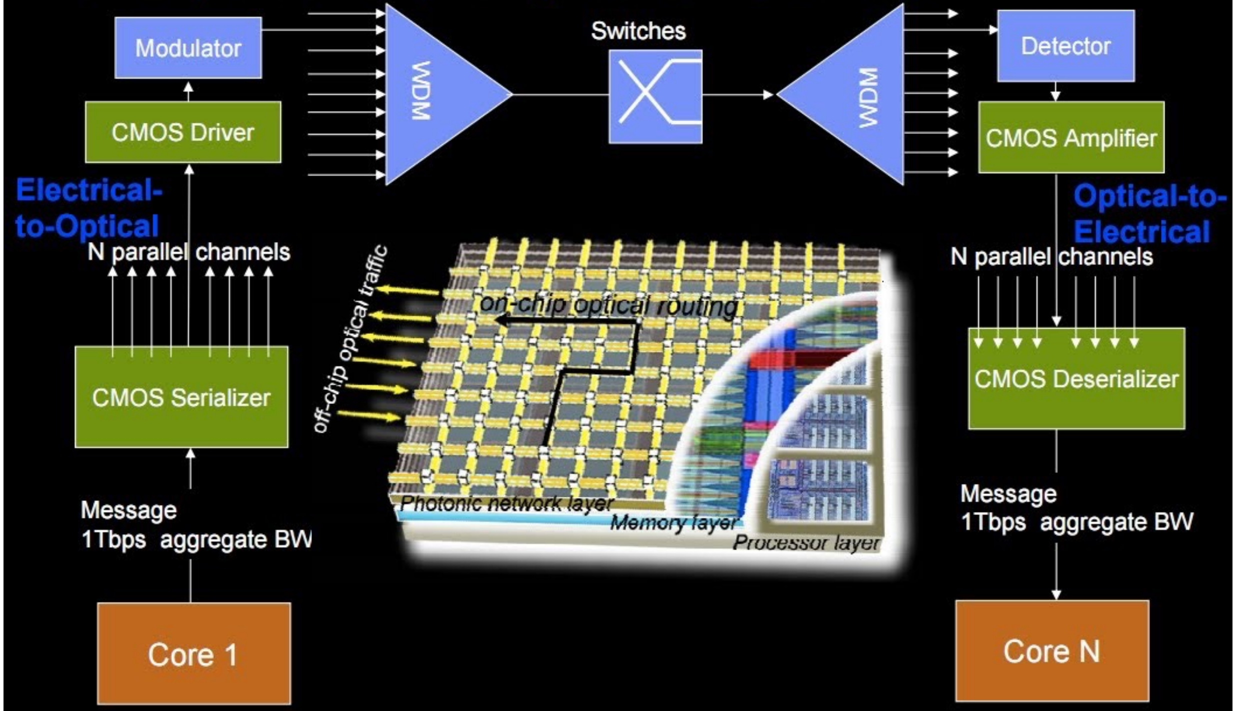
- Intel, IBM, Oracle, Cisco, etc.

IBM

- http://researcher.watson.ibm.com/researcher/view_group.php?id=2757
- CMOS + photonics



Off-Chip and On-Chip Nanophotonics Interconnects

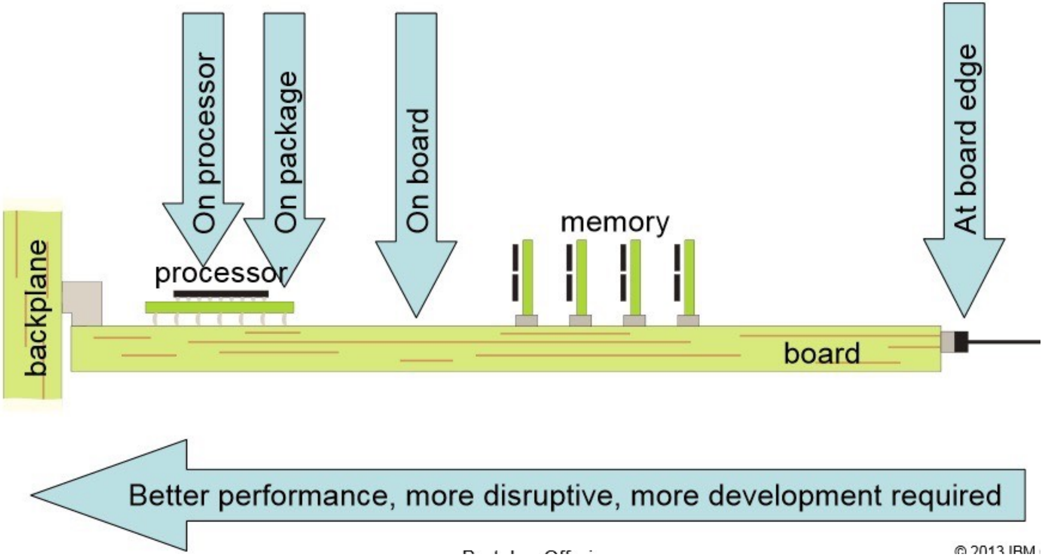


Goal: Integrate Ultra-dense Nanophotonics Circuits with CMOS chip

IBM

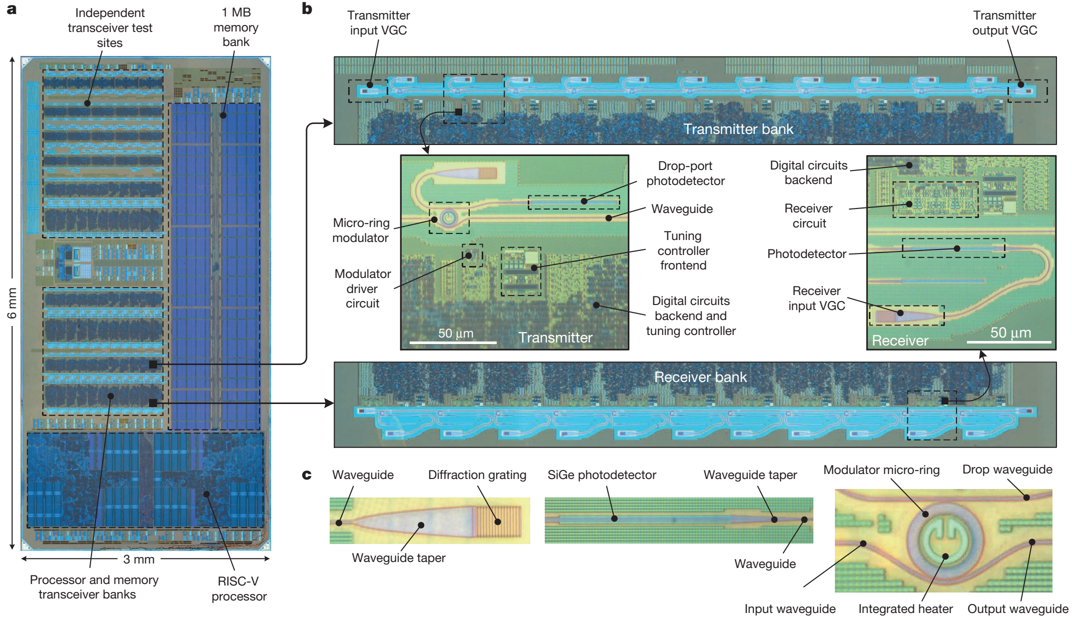
The point where electro-optical conversion takes place moves closer to the processor

– Card edge optics → Board-level optics → Optics on processor package



Microprocessors with Optical Comm

- UC Berkeley, December 2015
- http://www.nature.com/nature/journal/v528/n7583/full/nature16454.html



Jobs in silicon photonics?

- Numerous IT companies involved in SiP R&D
  - in Canada: TeraXion, Quebec, Canada (Coherent receiver); Huawei, Ottawa, Canada (World's largest telecom company; Silicon photonics in Ottawa); Ranovus, Ottawa (data comm); LuxMux, Calgary (oil & gas industry); IBM, Bromont, QC (SiP packaging); INO, Quebec (SiP packaging); ACAMP, Alberta (SiP packaging); Optelian, Ottawa (optical communications); Cisco, Ottawa, US (Acquired Lightwire Inc.); Ciena, Ottawa; PMC Sierra, Inc., Vancouver, BC; Ericsson, Canada; Tornado Medical, Toronto;
  - Design software, Canada: Lumerical Solutions Inc., Vancouver, BC; Optiwave, Ottawa; Crosslight Software, Inc., Vancouver, BC; Apollo Photonics Inc., Ontario;
  - International: Intel; IBM, Yorktown Heights, US; Kotura, US; Oracle, US; Luxtera, US; Alcatel-Lucent, US; Scorpios, US; FiBest, Japan; Hewlett Packard, US; Infinera, US; Excelitas, US; Enablance, US; Morton Photonics, US; Photonic Control, US; Rambus, US; Samsung; Genolyte, US (medical); Chiral Photonics; PLC Connections; Synopsis; Mentor Graphics; Cadence; Ayerlabs, US
- Integrating a laser with silicon photonics is one of the most difficult remaining challenges
- (almost) all companies will need a laser!

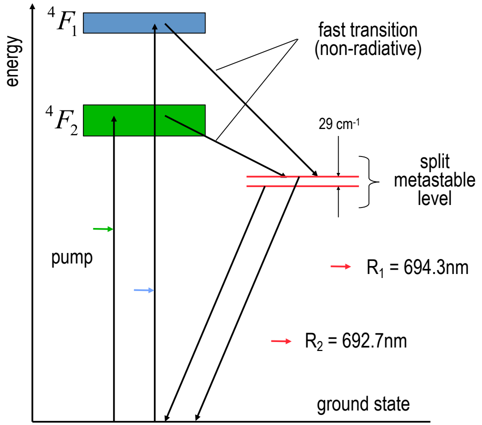
History

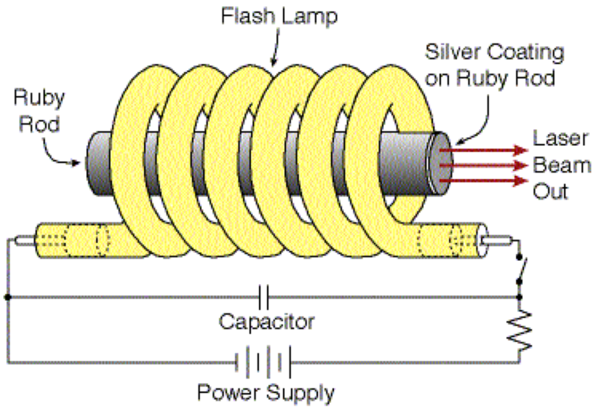
1916	Albert Einstein	Foundations for laser - spontaneous and stimulated emission
1953	Charles Townes	1st MASER demonstrated
1957	Gordon Gould (graduate student) Schalow & Townes	Optical wavelength LASER name, theory
1964	Charles Townes, Nikolay Basov Aleksandr Prokhorov	Nobel Prize in Physics "for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle."
1960	Theodore H. Maiman	*1st laser. Used a solid-state flashlamp-pumped synthetic ruby crystal to produce red laser light*
1960	Ali Javan, et. al.	1st gas laser - HeNe. continuous operation.
1962	Basov, Javan	**semiconductor laser diode proposed**
	Robert Hall	1st NIR GaAs laser
	Nick Holonyak, Jr	1st visible laser
1970	Zhores Alfrerov	heterojunction structure - semiconductor laser Room Temperature operation

http://en.wikipedia.org/wiki/Laser#History

The Ruby Laser

- First man made laser (built by Theodore Maiman in 1960).
- Optical pumping usually achieved with a xenon flashlamp (pulsed operation).

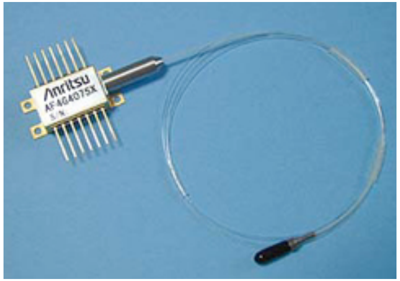




- Theodore Maiman lived in Vancouver in the last part of his life, and died in 2007.
- 2010 was the 50th anniversary of the laser

Semiconductor Lasers

- Laser designs:
  - DFB laser
    - Theory, Kogelnik and Shank (1972)
    - Demonstration, A. Yariv et al. (1973)
  - VCSEL (Surface emitting Laser)
    - invention, K. Iga (1977)
    - Room temperature operation (1988)
    - Mass production (started in 1999)
- Materials
  - Heterostructures, Quantum Wells, Quantum Dots
  - Growth uniformity, composition, doping
  - Work towards — higher efficiency, higher power, higher speed, many wavelengths, etc.

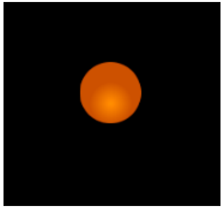


What is an electron? A photon?

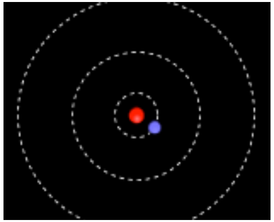
- Both are required for lasers, LEDs…
  - Electron
  - Photon
  - Both are fundamental **particles**
    - Different masses: electrons have mass, photons do not
    - Charge difference: electrons have charge (Fermion), photons do not (Bosons)
  - Both have **wave properties**
    - Electrons: de Broegli wavelength - 0.1 nm
    - Photons: 500 nm visible, 1550 nm infrared
  - Momentum
  - **Energy**
    - Photons: E = h v, v = c / lambda
    - Electrons: E = mc^2 (that's not how a laser works). How does e- carry energy?
      - Energy levels, difference in energy = excited states minus ground states.

Atom Models

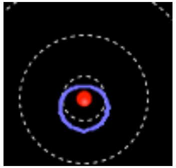
- Classical (Billiard ball)



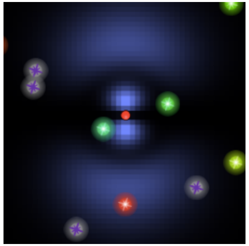
Bohr



- deBroglie (shell model)



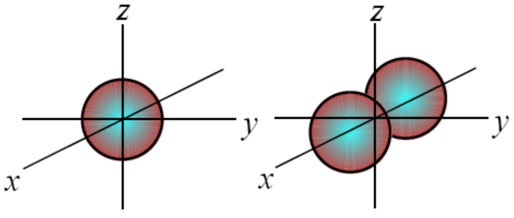
Schroedinger



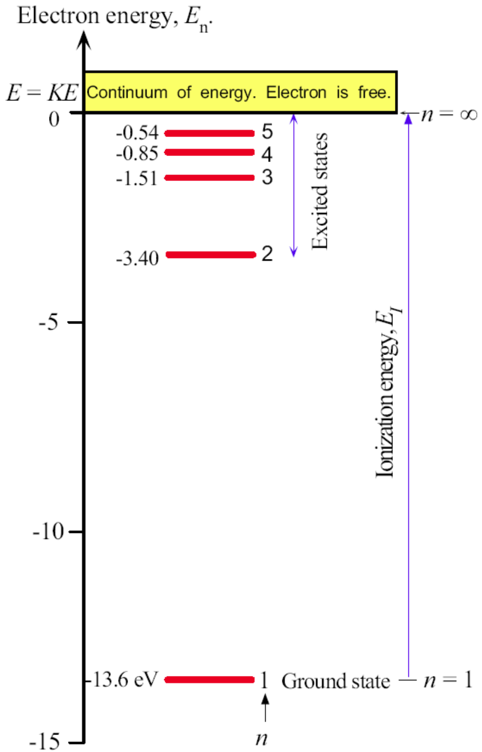
[PhET.colorado.edu "hydrogen-atom"](PhET.colorado.edu)

Hydrogen Atom

- Electron energy in the hydrogen atom is quantized.
- *n* is a quantum number:
  - 1, 2, 3, 4 …
- Each defined state has a wave-function



Y for a $1s$ orbital Y for a $2p_x$ orbital

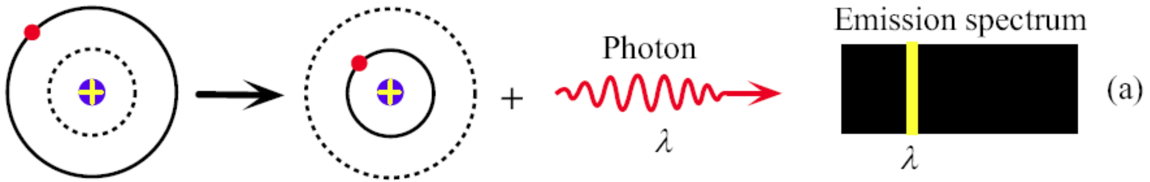


From Principles of Electronic Materials and Devices, Third Edition, S.O. Kasap (© McGraw-Hill, 2005)

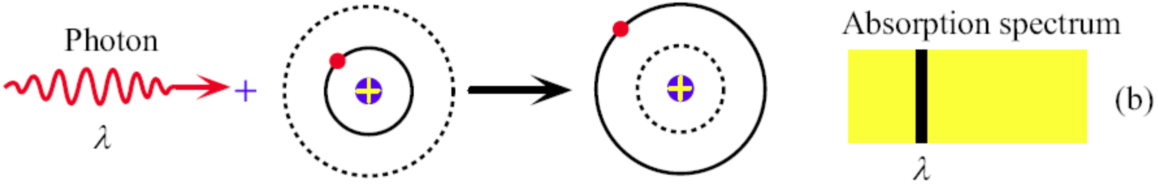
Hydrogen Atom – Electronic transitions

- Transitions from one energy level to another occur via energy loss or gain (e.g., via *photons*)

Spontaneous Emission:



Stimulated Absorption:

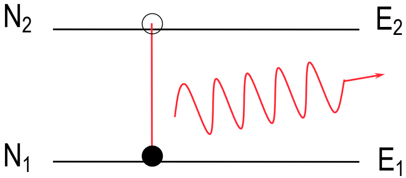


From Principles of Electronic Materials and Devices, Third Edition, S.O. Kasap (© McGraw-Hill, 2005)

Concept of Spontaneous Emission

N_2 = population density of energy level 2.

(i.e. # of electrons per cm^3)



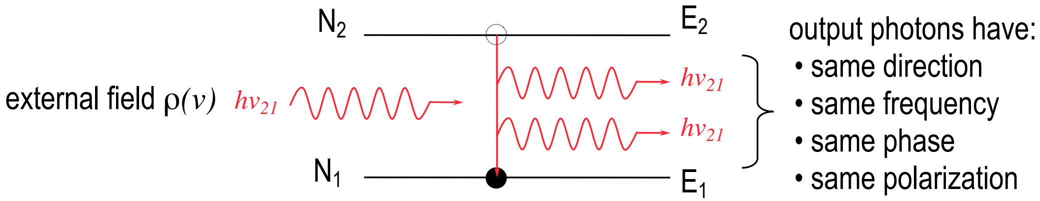
$$\nu_{photon} = \frac{E_2 - E_1}{h} = \frac{c}{\lambda_{photon}}$$

(h = 6.626 x 10^{-34} J.s)

- An electron can spontaneously fall from energy level E_2 to E_1. A photon of wavelength λ_{photon} is emitted in the process.
- The photon is emitted in a random direction.
- The probability of a spontaneous jump is given quantitively by the so-called Einstein "A" coefficient.
- A_{21} = probability per second of a spontaneous jump from level 2 to level 1
  - $A_{21} = 1 / t_{sp}$ (spontaneous emission lifetime)

Process of Stimulated Emission

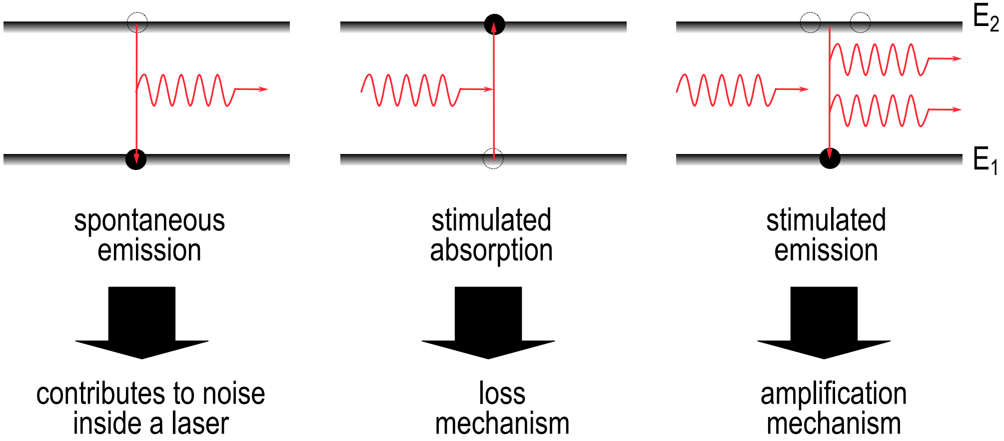
- Electron transitions can be stimulated by the action of an external radiation field.



- $\rho(v)$ = energy density of the applied radiation field at frequency v. (energy per unit volume per unit frequency interval: J.m^{-3}.Hz^{-1}).

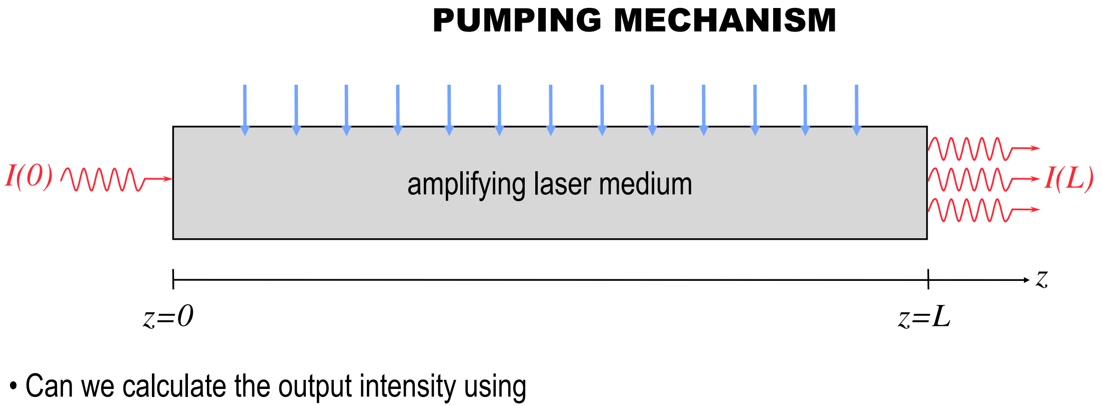
Summary: three types of transitions

- C



- All three processes occur simultaneously inside a laser.
- What about LEDs? Detectors? Optical Amplifiers?

Optical Amplification

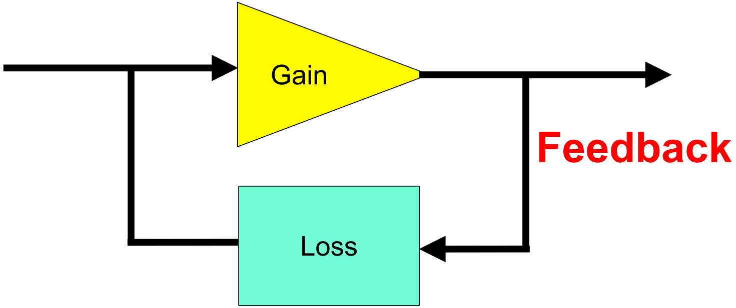


- ***Stimulated emission*** provides optical amplification.
- We can calculate the intensity at position L, given the gain function γ_0:

$$I(L) = I(0)\, e^{\gamma_0(v)L}$$

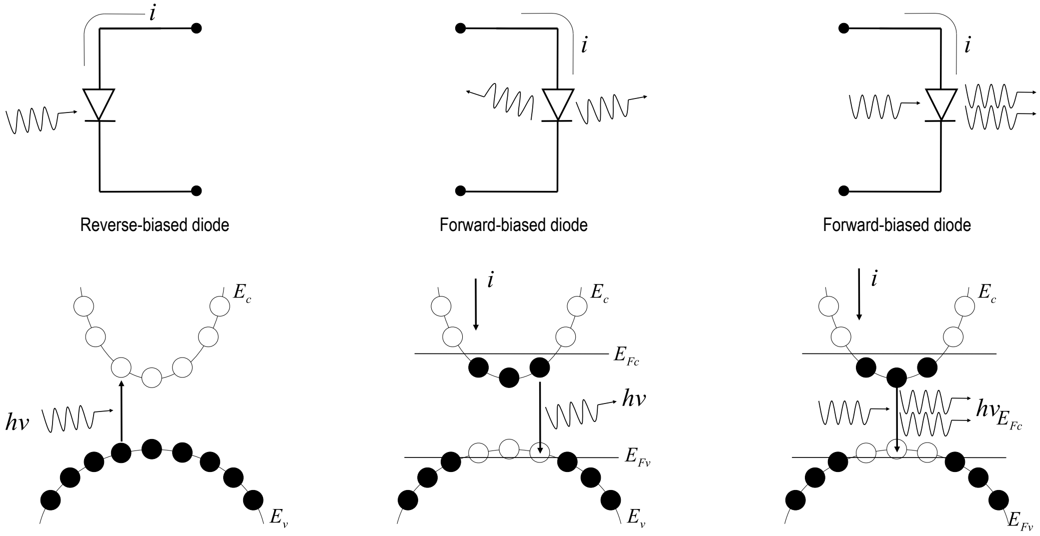
Condition for Lasing

- Gain = Loss
  - For self-sustaining oscillations, the optical power lost through the mirrors must be replenished by the gain medium.



e.g., Electronic Oscillator

Absorption & Emission – Semiconductors



Stimulated absorption (direct or indirect gap)

PHOTODETECTOR

Spontaneous emission (only direct gap)

LIGHT EMITTING DIODE

Stimulated emission (only direct gap)

SEMICONDUCTOR LASER

Simplified Semiconductor Laser