VPI University Program

Photonics Curriculum Version 7.0

Lecture Series

VPIphotonics™

Introduction to Optical Transmitters

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Module Prerequisites

- Introduction to Fiber-Optic Communications I & II
- Recommended - Fibers I

Module Objectives

- Semiconductor lasers as sources for optical transmitters
- How a laser works
  - Functional view: gain medium, energy pump, cavity, losses
  - Basic structure: Fabry-Perot laser
  - Optical absorption and emission processes
- Gain Curve, Lasing conditions (gain and phase)
- Rate Equations, Dynamic Effects of Lasers
- Introduction to DFB Lasers

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Sources for Optical Transmitters

- Many types of optical sources are available
  - Light Emitting Diodes (LEDs)
  - Solid state lasers
  - Gas lasers
  - Semiconductor lasers
  - Fiber lasers

- Semiconductor Lasers are preferred
  - Powered by electrical energy
  - Directly converts electrical signals to optical signals
  - Generate coherent light source unlike LEDs

Semiconductor Laser Features

- High modulation bandwidth (> 10 Gbit/s)
- Small size
  - Packaged: ~ 2 × 1 × 1 cm
  - Unpackaged: ~ grain of salt, 0.5mm × 200μm × 100μm
- Intense single spatial mode
- Energy efficient
- Narrow spectral linewidth
- Can be single longitudinal mode (monochromatic)
- Reliable operation
- Can be integrated

What does LASER stand for?

LASER is an acronym for:

LIGHT

AMPLIFICATION by

STIMULATED

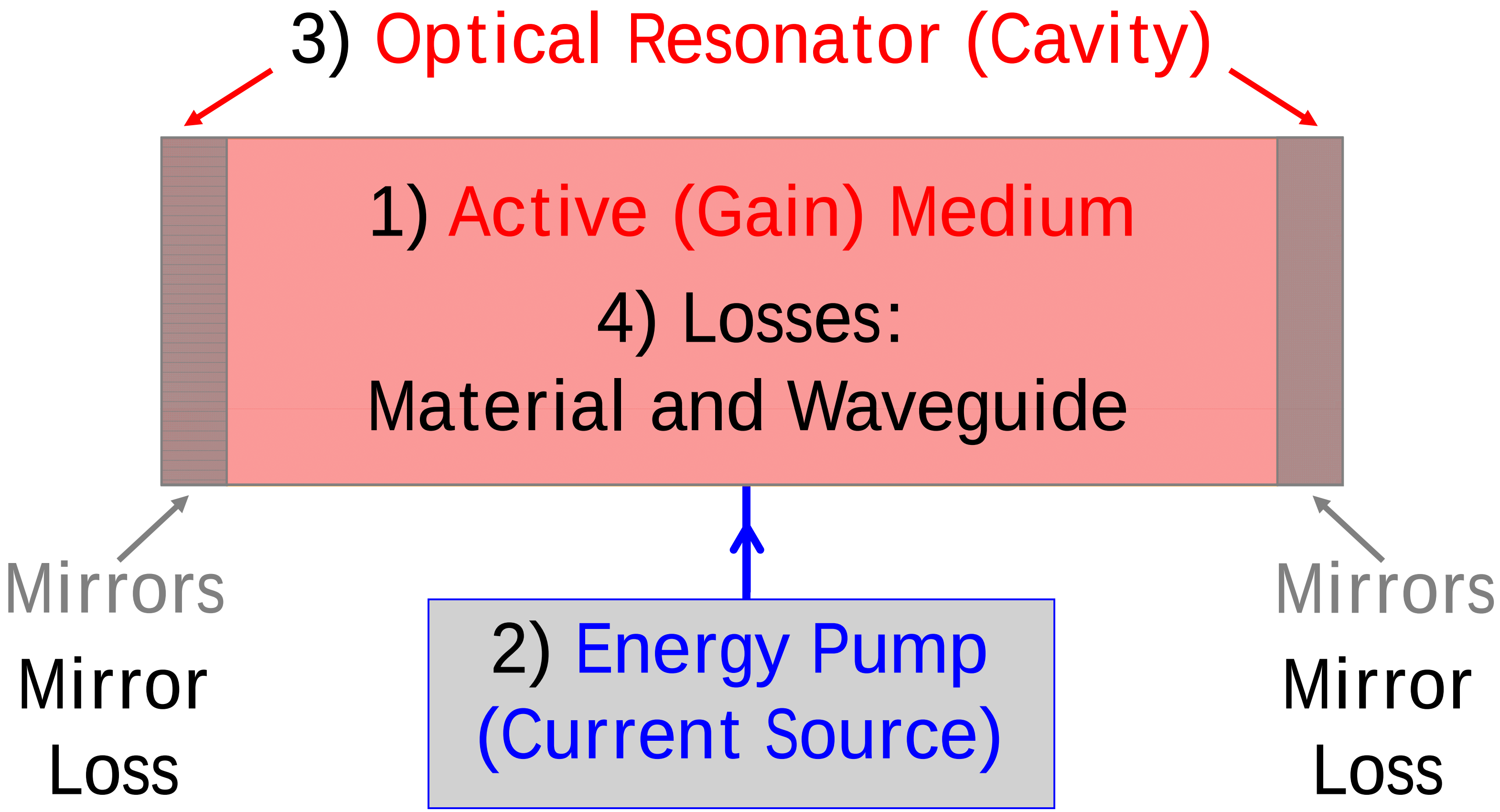
EMISSION of

RADIATION

- How does it work?
- Why amplification?
- What is stimulated emission?

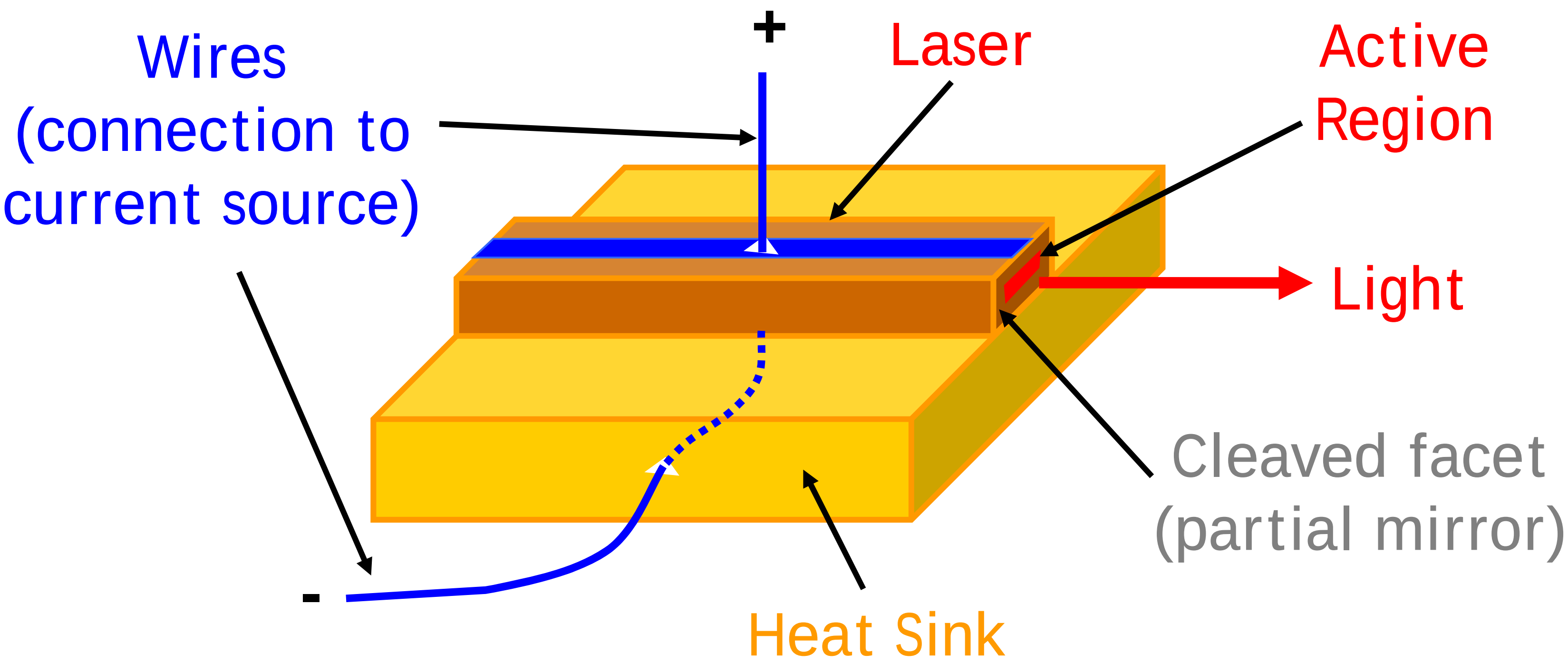
How does a Laser work?

A functional view of a laser: 4 main parts



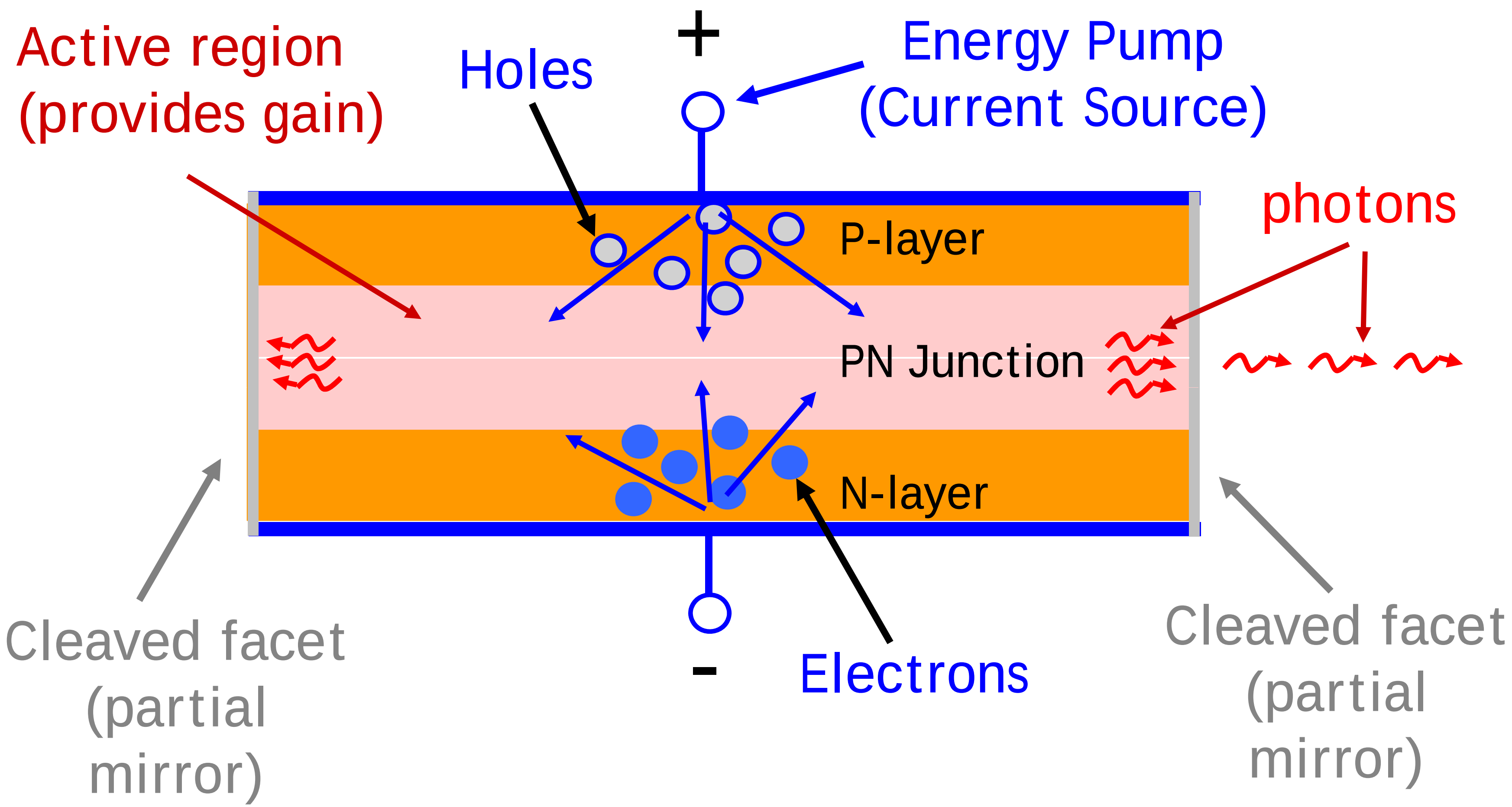
Basic Laser Structure

Fabry-Perot Laser



A Basic Laser Structure

Fabry-Perot Laser (longitudinal section)



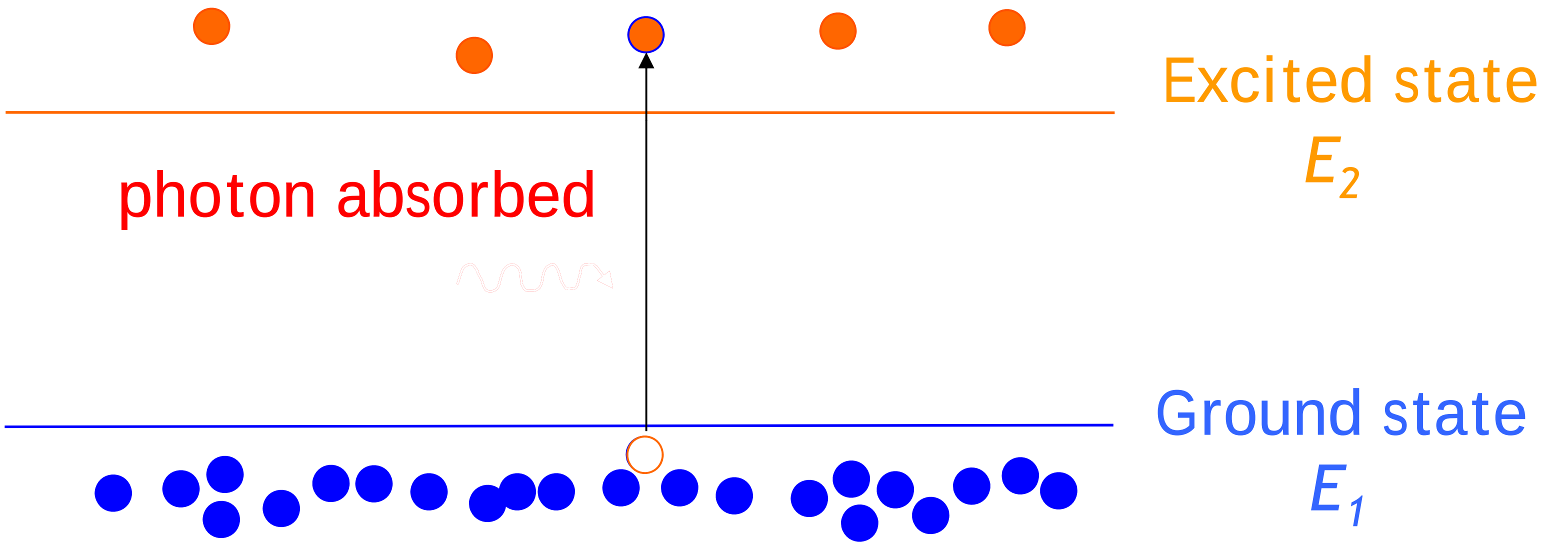
How does a Laser produce Light?

- Need to consider three optical transition processes:
  - Absorption
  - Spontaneous emission
  - Stimulated emission

Energy level diagrams for electrons in the active medium

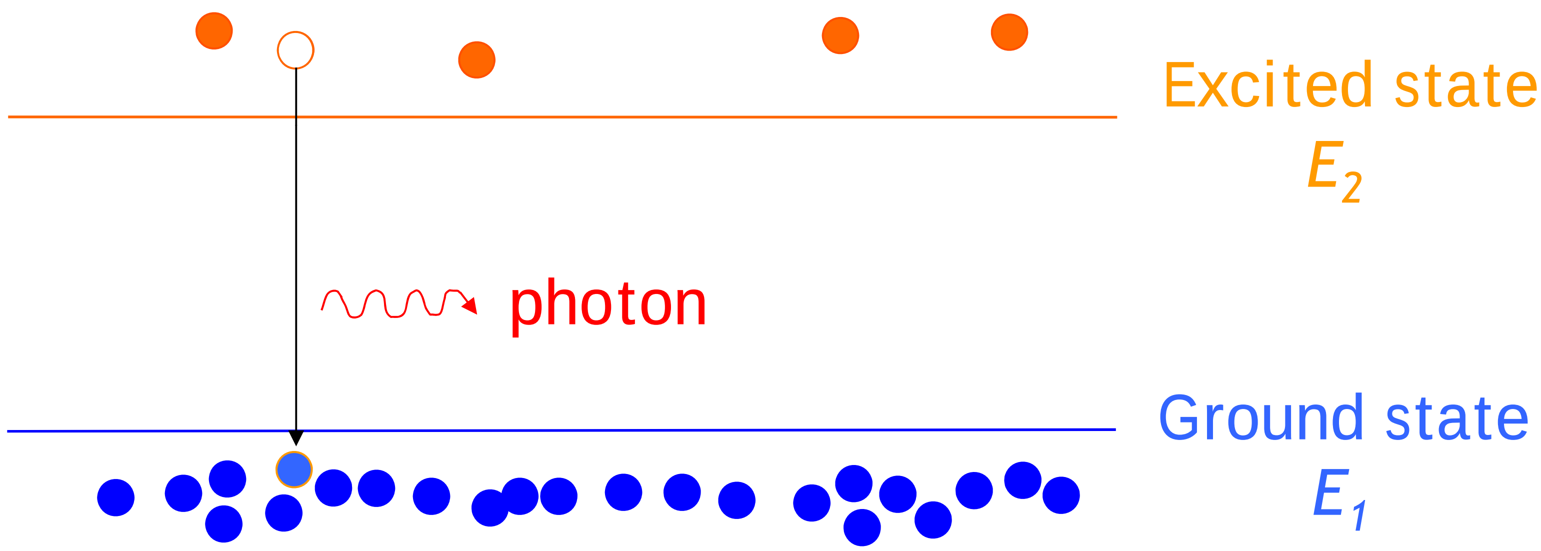
Optical Absorption Process

- Absorption: a photon with energy > (E_2 - E_1)
- The photon's energy can be absorbed by an electron in state E_1, thus exciting it to state E_2



Optical Emission Processes

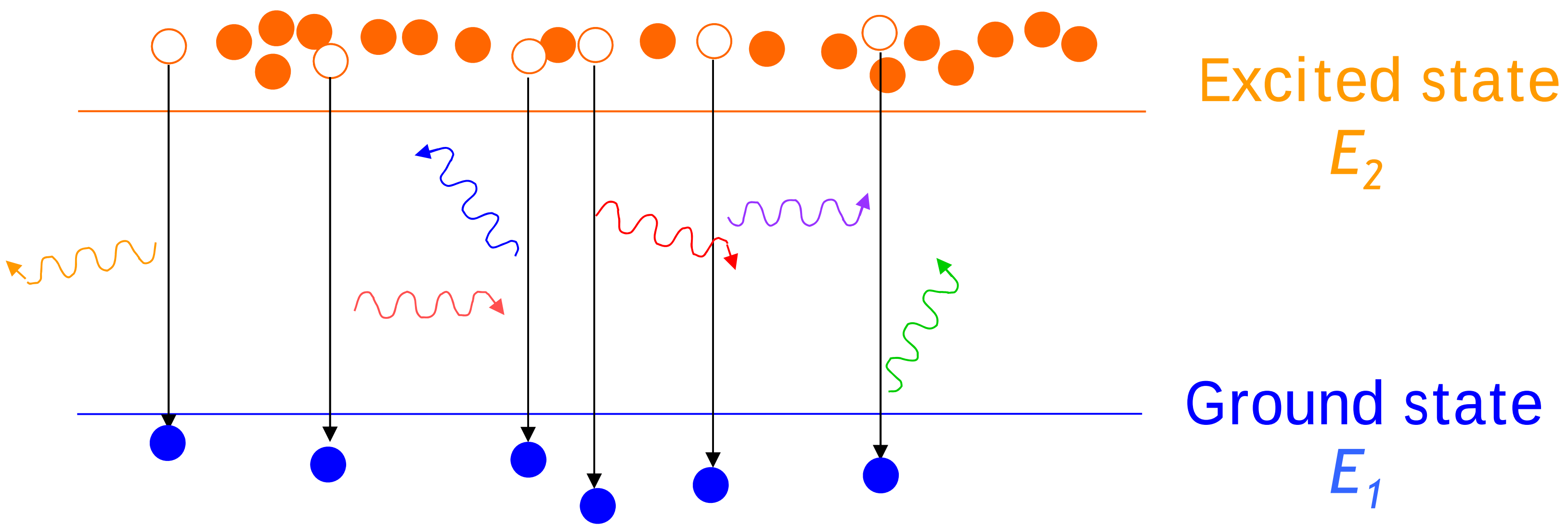
- Spontaneous Emission: electron in excited state E_2 can spontaneously decay to state E_1
- A photon with energy hf > (E_2 - E_1) is emitted



Optical Emission Processes

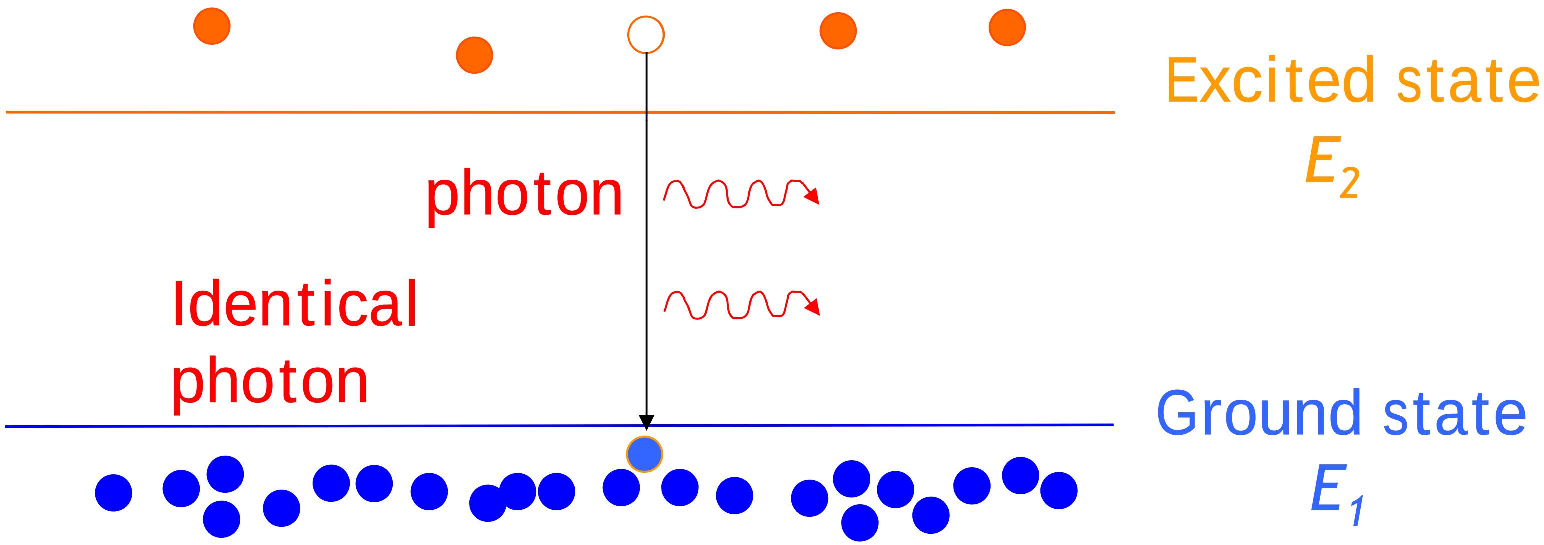
Light produced by spontaneous emission:

- Random propagation direction
- Random phase
- Random frequency
- is incoherent (broad linewidth)



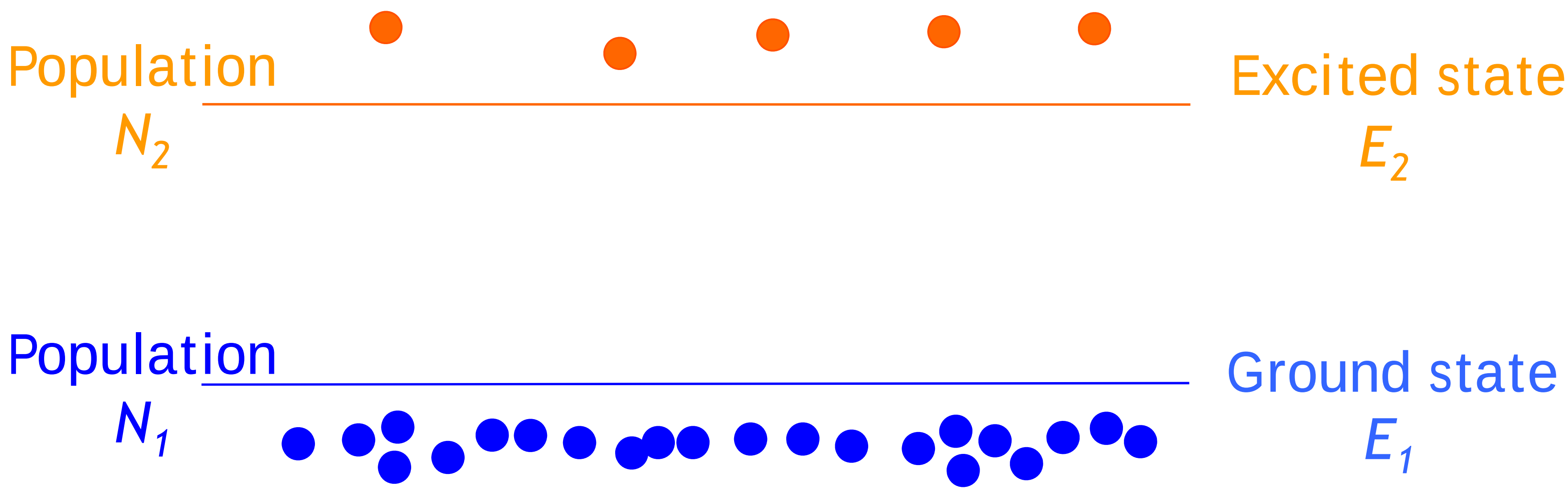
Optical Emission Processes

- Stimulated Emission
- A photon with energy > (E_2 - E_1): triggers transition of an excited electron → identical photon is emitted
- Produced light is coherent (desirable)



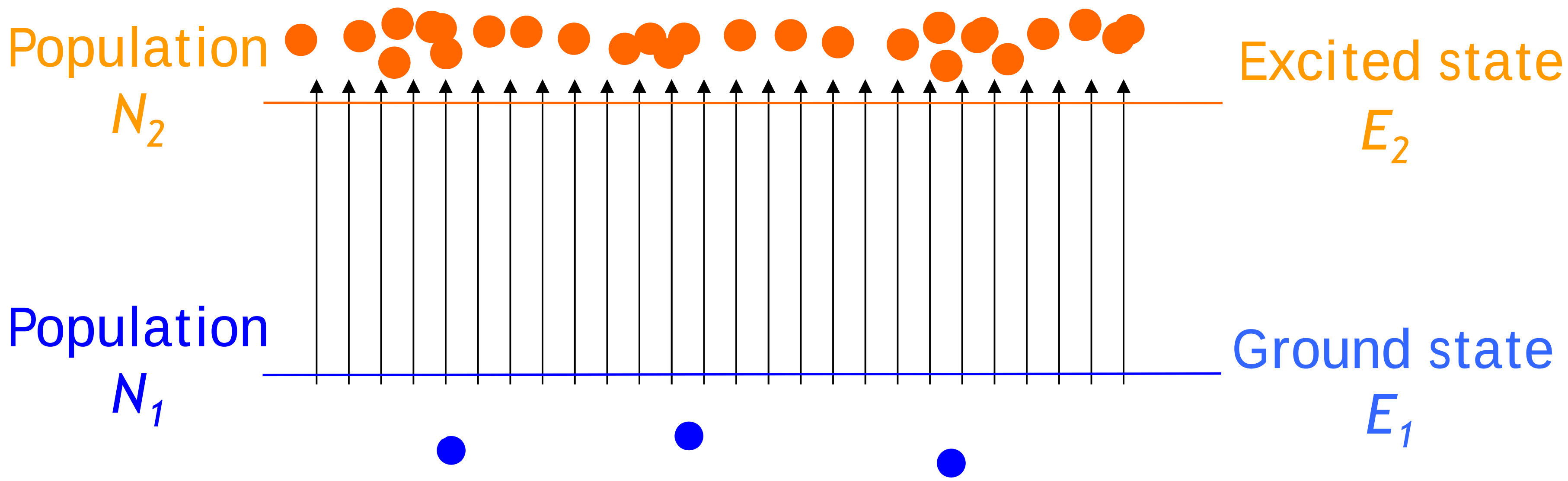
Optical Transition Processes

- All three processes related (Einstein Relations)
- At thermal equilibrium, absorption = emission
- Electrons mostly in state E_1: $(N_2 << N_1)$
- Spontaneous emission dominates



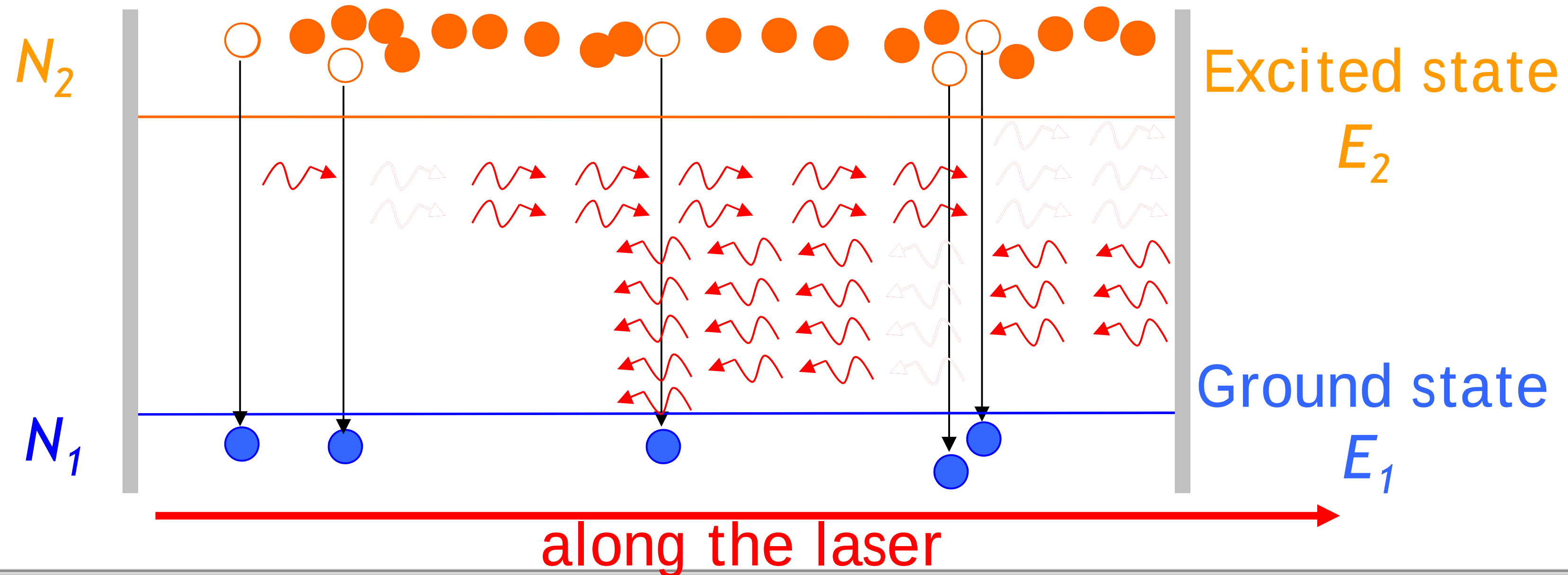
Population Inversion

- Stimulated emission – coherent light, desirable
- Need electrons to be mostly in state E_2
- Population inversion achieved by electrical pumping
- $N_2 >> N_1$, stimulated emission dominates



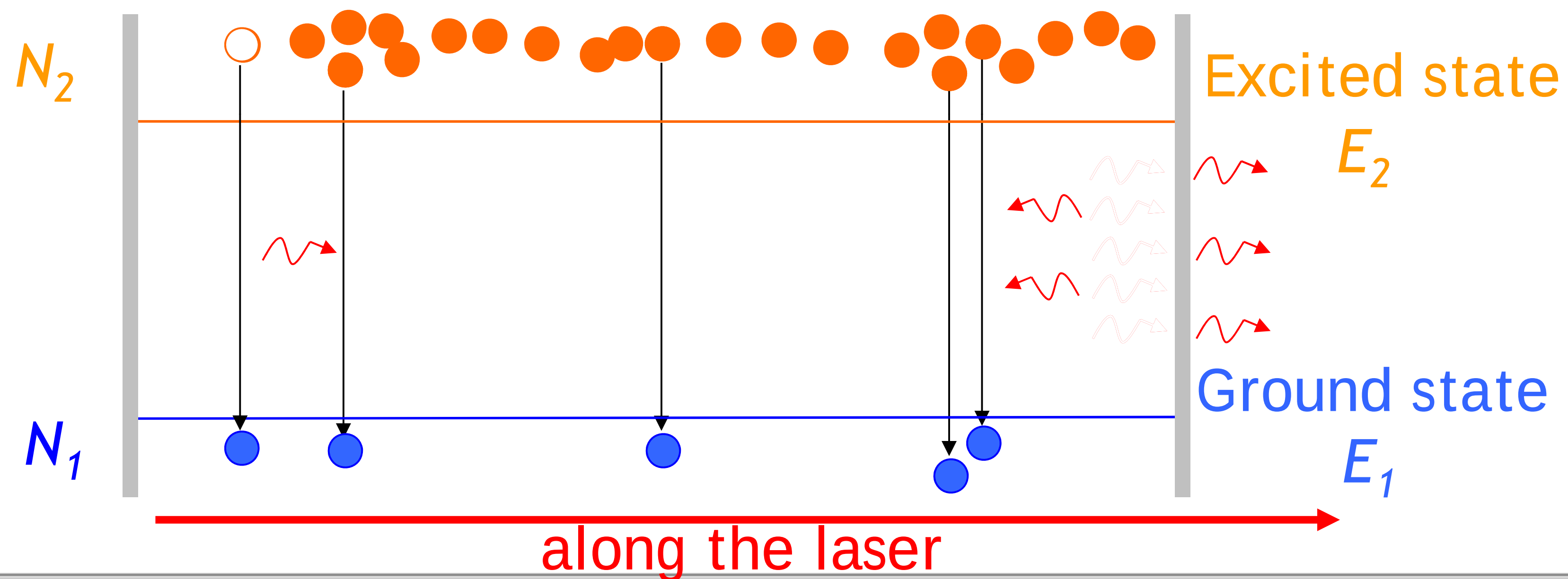
Optical Cavity and Feedback

- Light amplification by stimulated emission… is not strong, especially if the active region is short
- Optical cavity provides feedback into active region
- Light is reflected repeatedly and greatly amplified



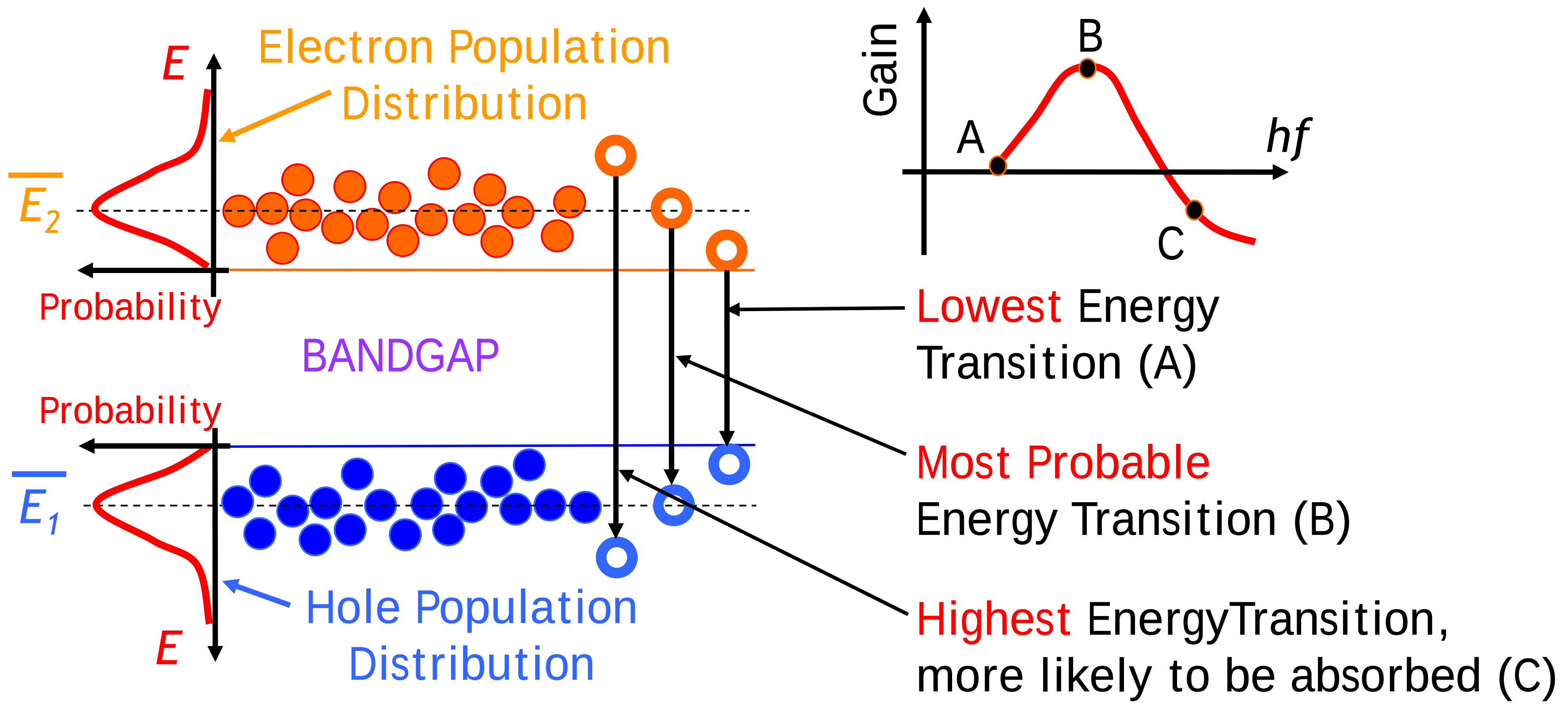
Optical Losses and Laser Output

- One mirror is partially transmitting, to get output
- Photons transmitted out are lost (mirror loss)
- Other losses: scattering in the material, nonradiative processes



Laser Spectrum (Gain vs. λ Curve)

- Laser oscillation (lasing) occurs over a range of λ
- Due to distribution of E_2 and E_1 around mean values



Lasing Conditions

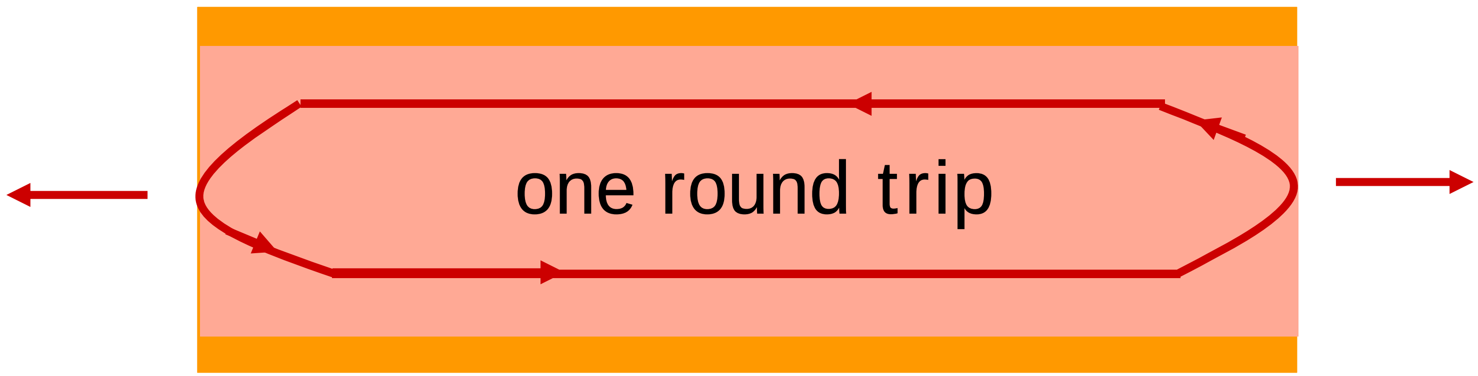
For lasing to initiate in a cavity, two conditions need to be satisfied:

- Gain condition:

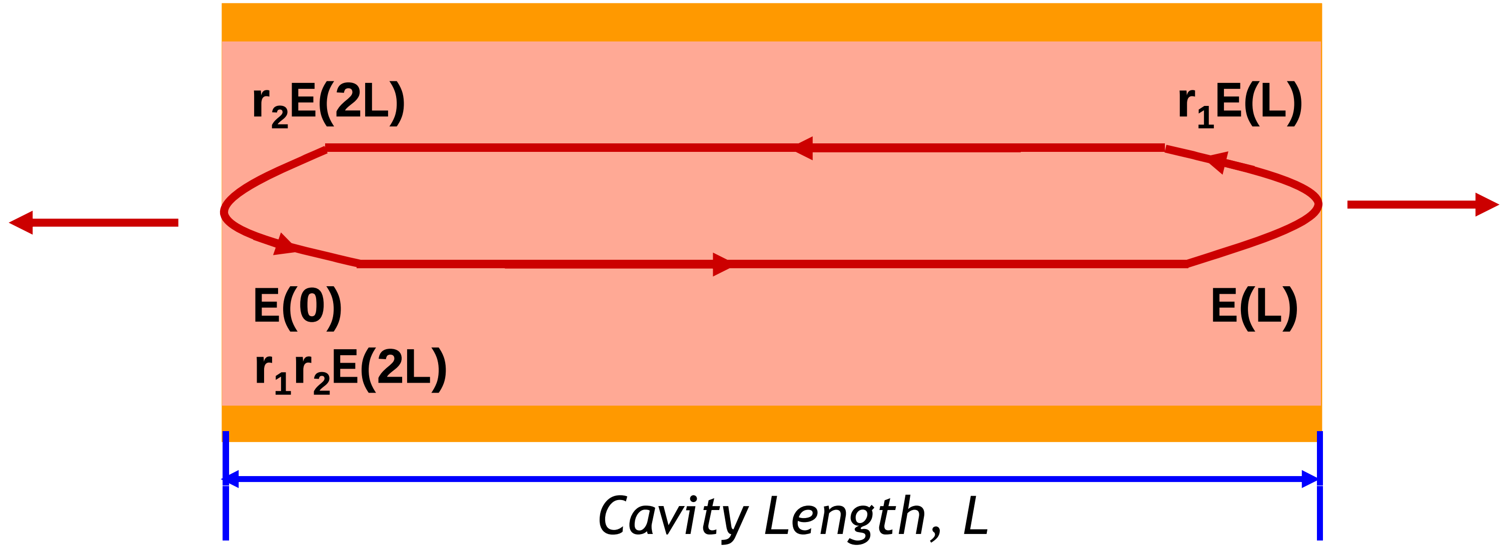
  The electric field of the light, after completing one round trip inside the cavity, should have the same amplitude

- Phase condition:

  The electric field of the light, after completing one round trip inside the cavity, should have the same phase



Gain Condition



Gain Condition: $E(t,0) = E(t,2L)$

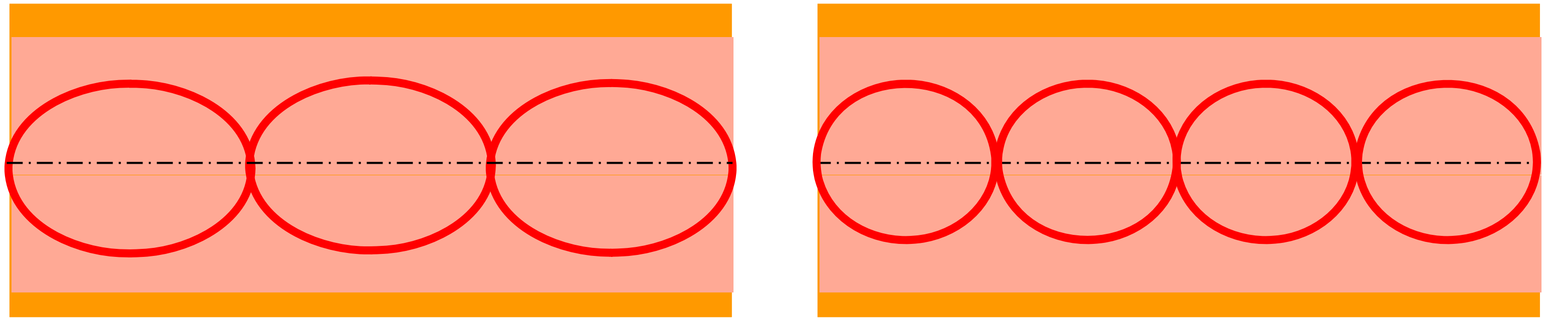
$$E(t,0) = A\,exp(j\omega t);\ E(t,\ 2L) = Ar_1r_2exp[2L(g-\alpha i)]exp[j(\omega t-2\beta L)]$$

To satisfy the Gain Condition: $r_1r_2exp[(g-\ \alpha_i)2L] = 1$

The threshold gain: $$g_{th} = \alpha_i + \frac{1}{2L}ln\frac{1}{r_1r_2}$$

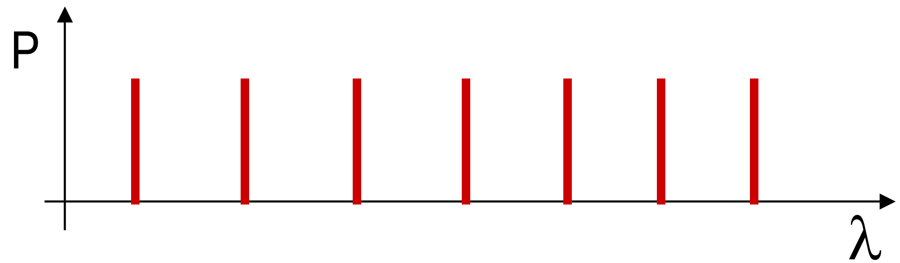
Phase Condition

Integral number of cycles must fit within the cavity



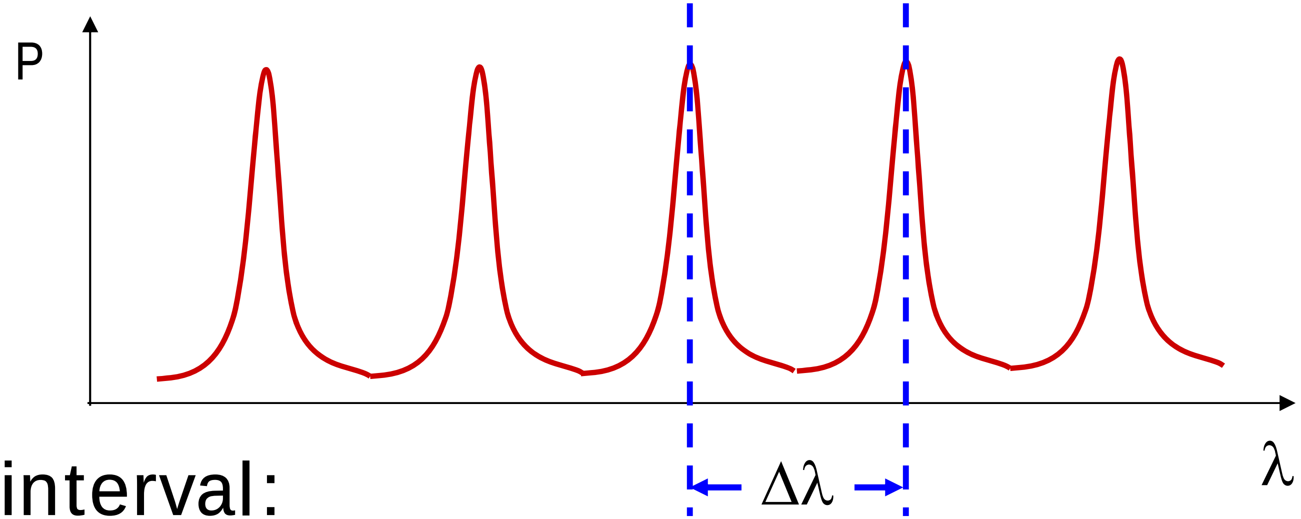
Phase: $$exp(-2j\beta L) = exp\,(-\frac{4j\pi nL}{\lambda}) = 1, \quad \frac{4j\pi nL}{\lambda} = 2m\pi$$

Resonant cavity – discrete set of spectral lines



Phase Condition

Discrete modes that can be supported by the cavity are called longitudinal modes

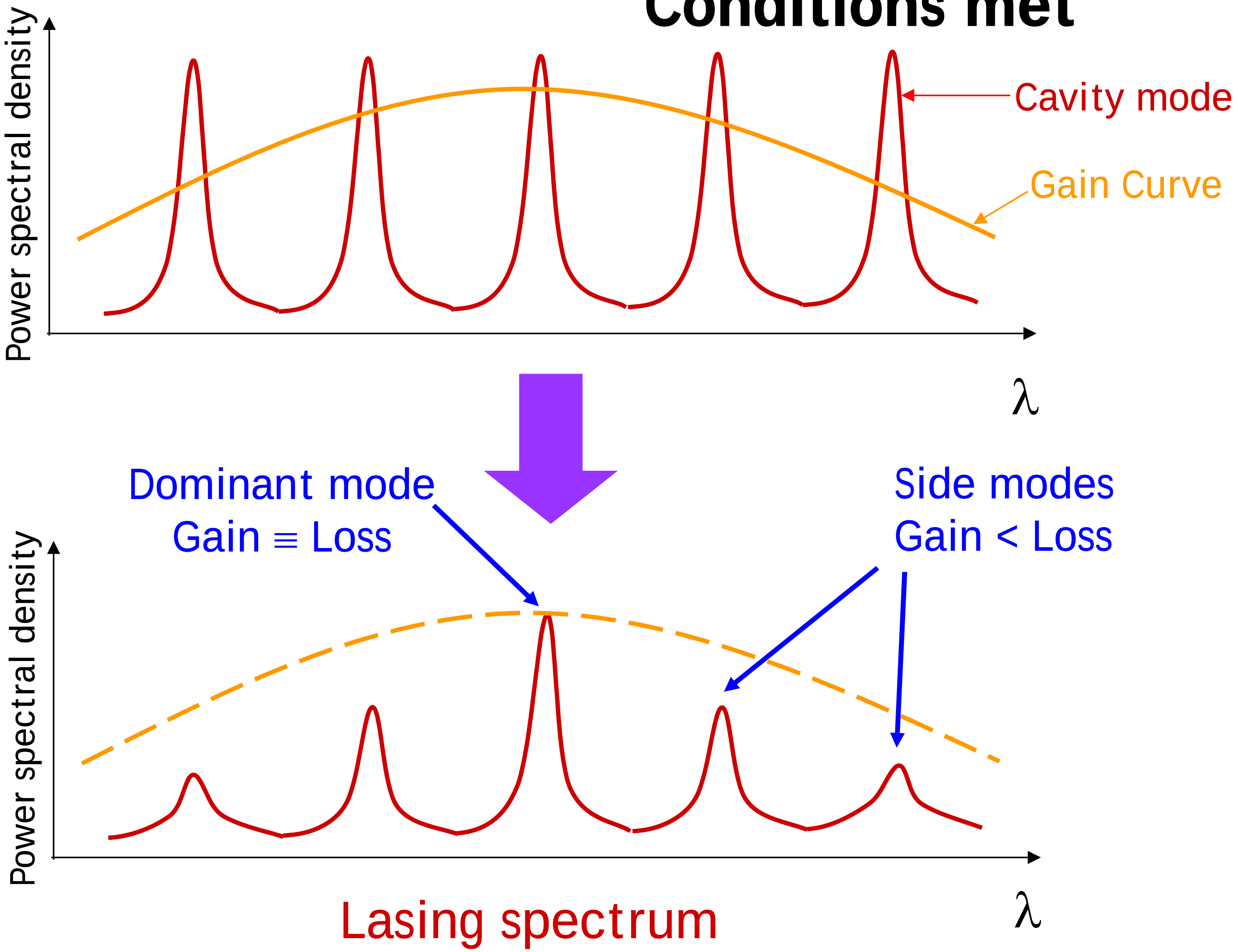


Mode interval:

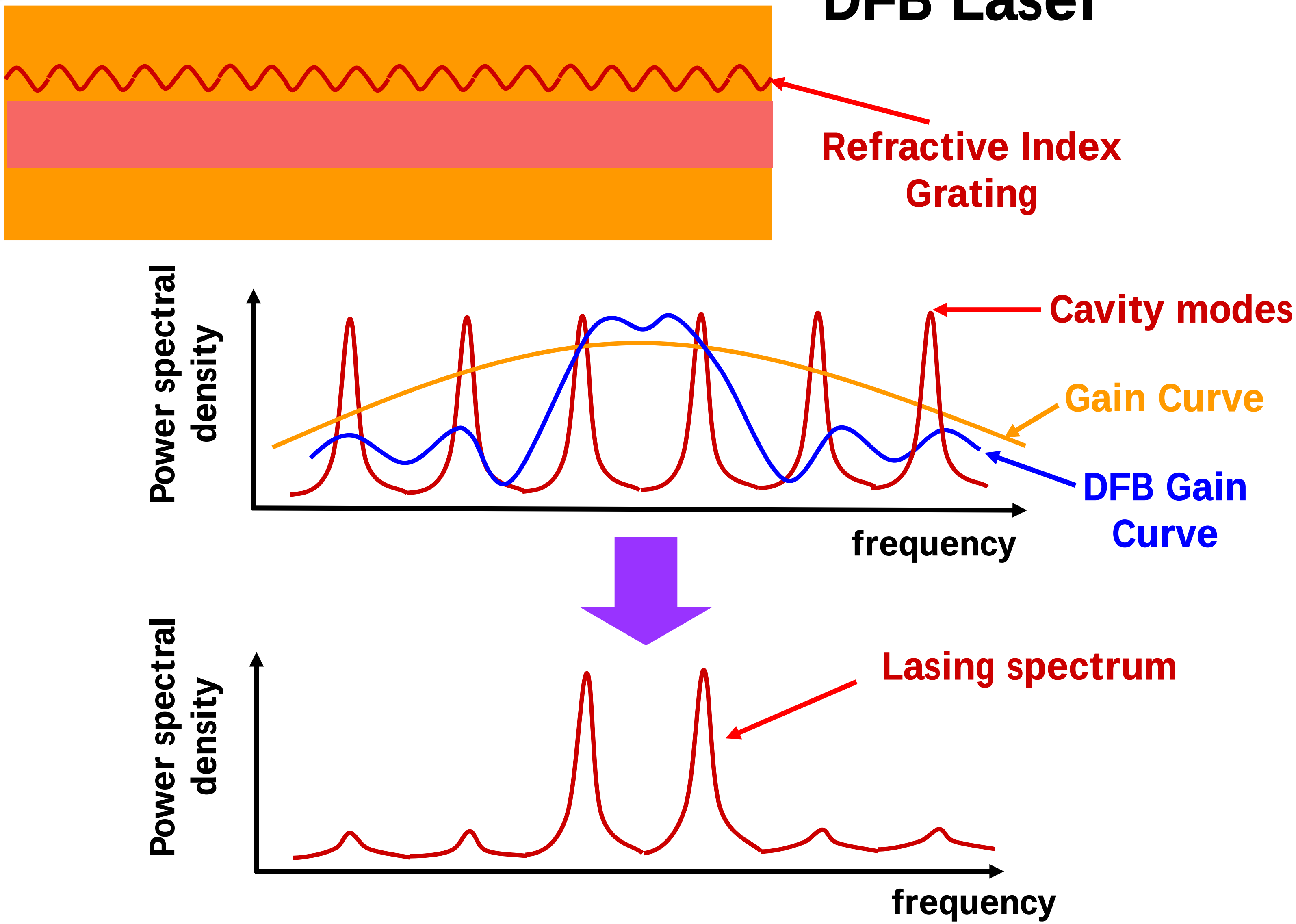
Phase condition: $\dfrac{2nL}{\lambda} = m$

Thus: $\Delta\lambda = \dfrac{\lambda^2}{2nL}$

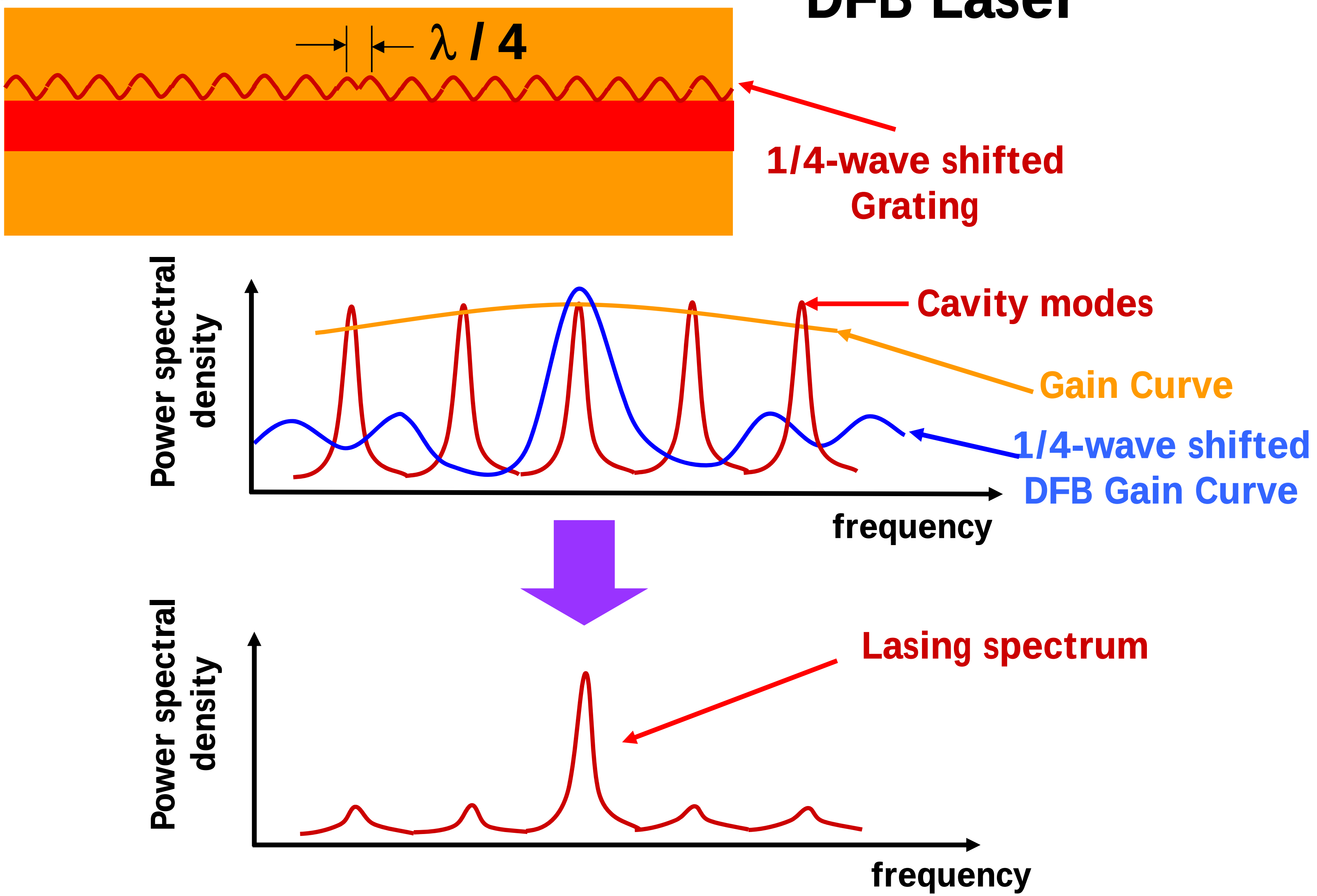
Laser Spectrum: Gain & Phase Conditions met



Another Laser Structure: DFB Laser



Another Laser Structure: DFB Laser



Rate Equation

Rate equation describe the dynamic interaction between excited electrons and photons

Change in carrier density:

$$\frac{dn}{dt} = \frac{I}{qV} - \frac{n}{\tau} - v_g g s$$

Contribute from Current

Decay of electrons

Usage of electron by Stimulated emission

Change in photon density:

$$\frac{ds}{dt} = \Gamma v_g a(n-n_0)s - \frac{s}{\tau_p} + \Gamma\beta\frac{n}{\tau}$$

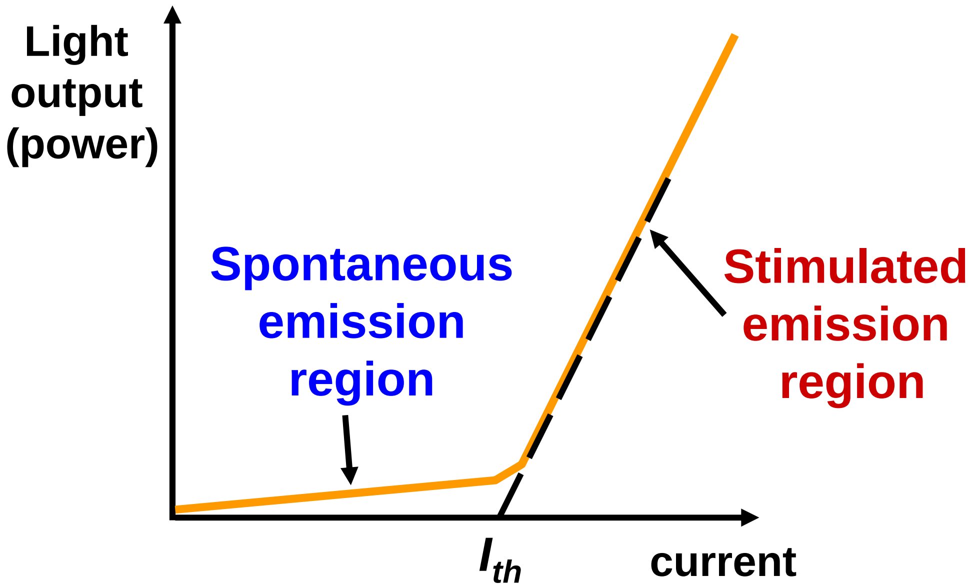
Photon generated by stimulated emission

Decay of photon

Photon generated by Spontaneous emission

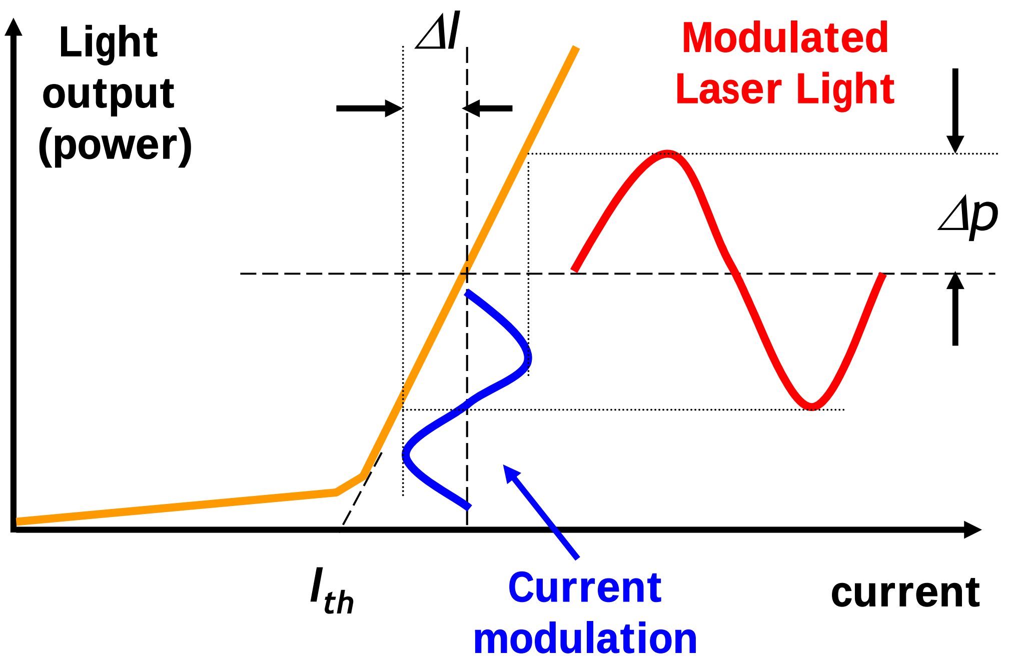
Light-Current Characteristics

- The *L-I* curve: output light power vs. input current
- Diode characteristics, threshold current I_{th}
- For $I > I_{th}$, light power increases linearly with I



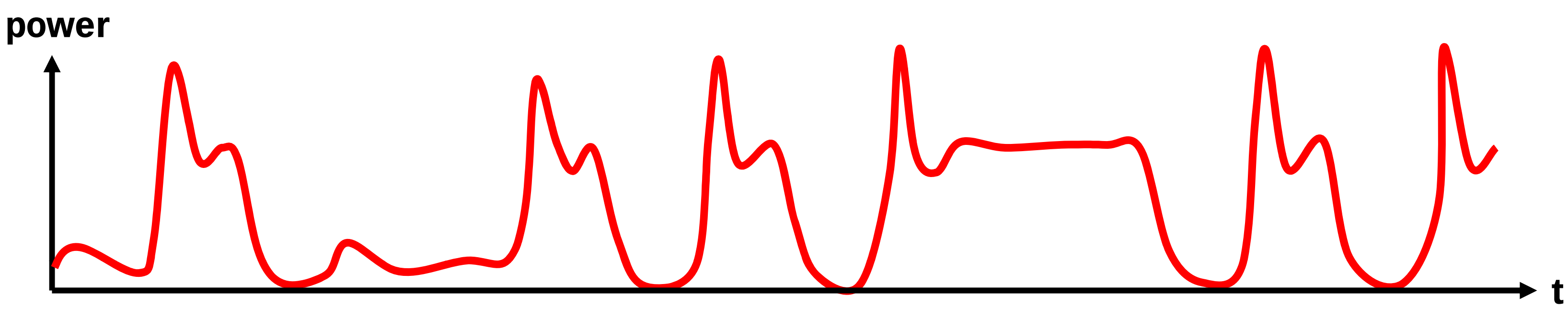
Direct-Current Modulation

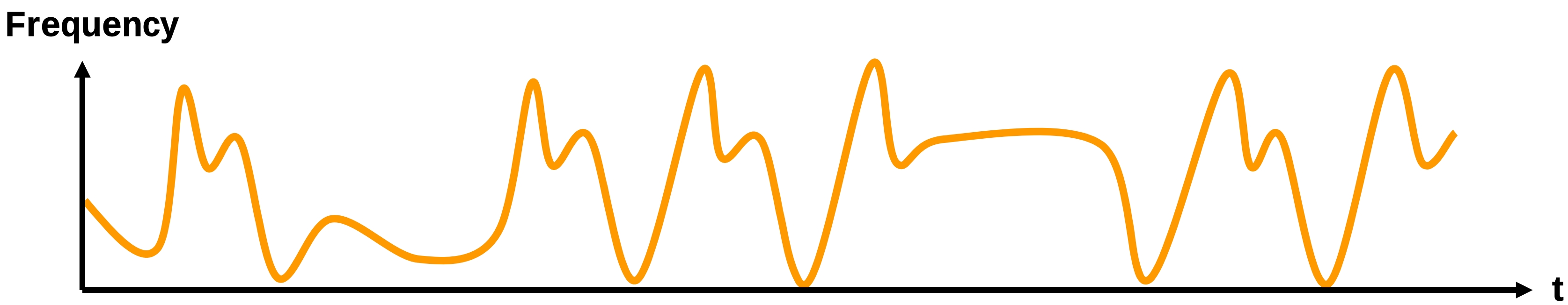
The information is encoded on semiconductor lasers by current modulation



Laser Dynamics: Chirp

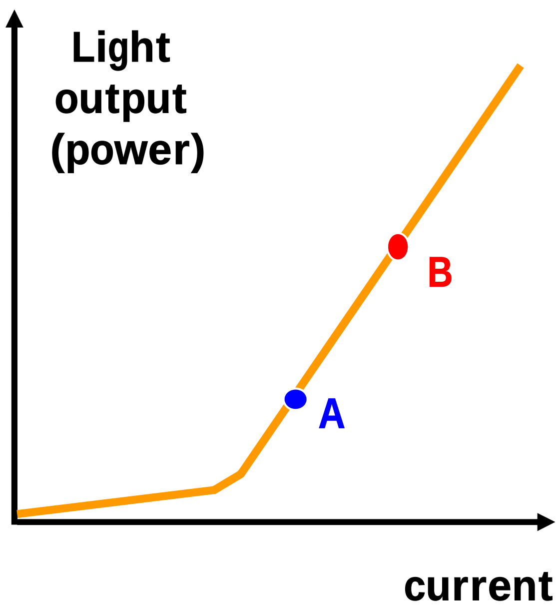
- Chirping of the laser output signal (pulses)
- Instantaneous frequency of the signal changes
- Leads to increased dispersion (broadening)

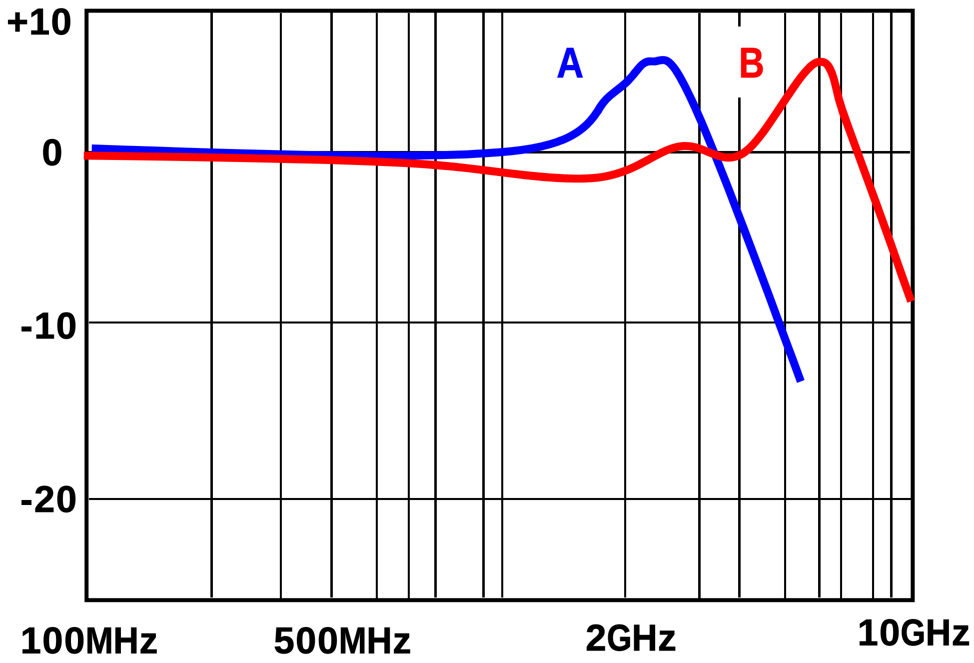




Laser Dynamics: Modulation Bandwidth

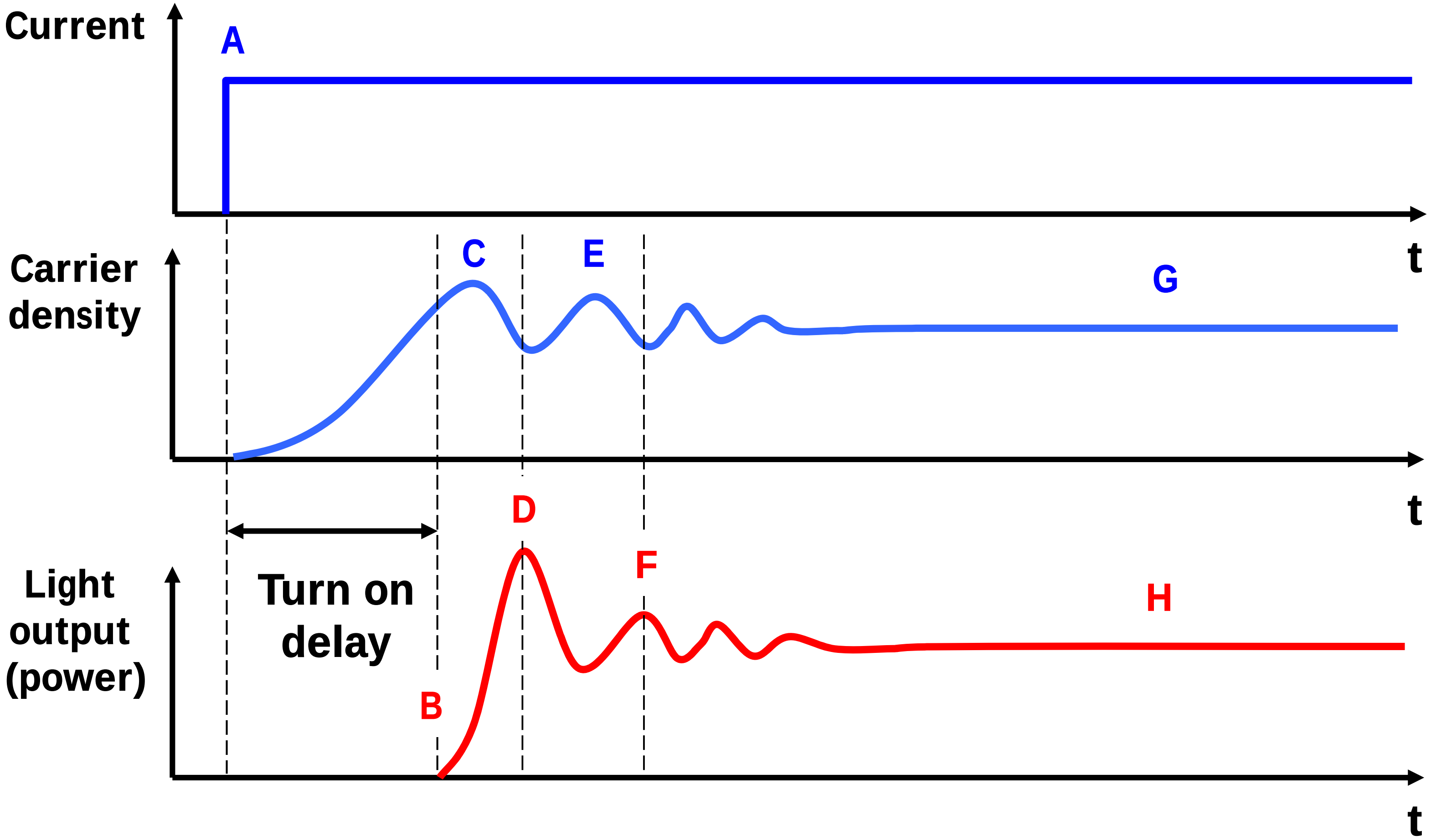
- Determines maximum direct modulation speed
- Increases with increasing drive (bias) current
- Within practical limits, get multi-GHz modulation





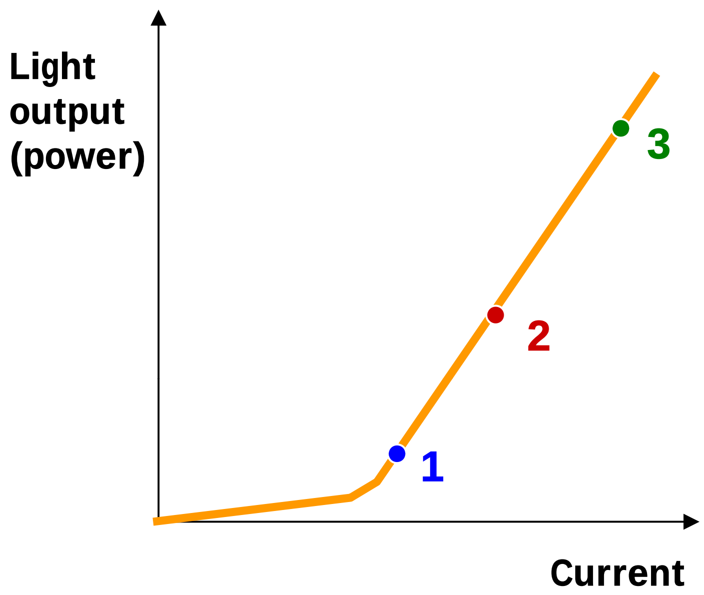
Laser Dynamics: Turn On Delay

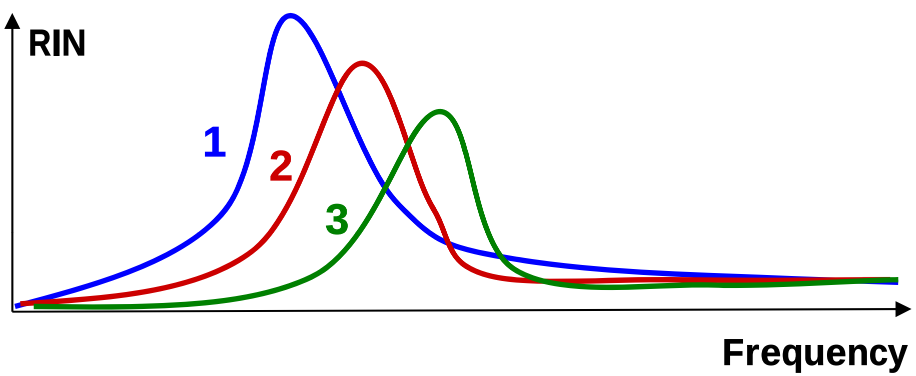
Delay between injection of current and generation of light



Laser Dynamics: Relative Intensity Noise

Frequency shape of RIN depends on laser driving conditions





Summary

- Semiconductor lasers optical transmitters
  - Gain medium, energy pump, cavity, losses
  - Basic structure: Fabry-Perot laser
  - Optical absorption and emission processes
  - Einstein Relations
- Gain Curve, Lasing conditions (gain and phase)
- Introduction to Dynamic Effects of Lasers
  - Rate equations, *L-I* curve, direct modulation, chirp
  - Modulation bandwidth, turn on delay, RIN

Proceed with the *Interactive Learning Module*