VPI University Program

Photonics Curriculum Version 7.0

Lecture Series

VPIphotonics™

Introduction to Optical Amplifiers

OA1

Module Prerequisites

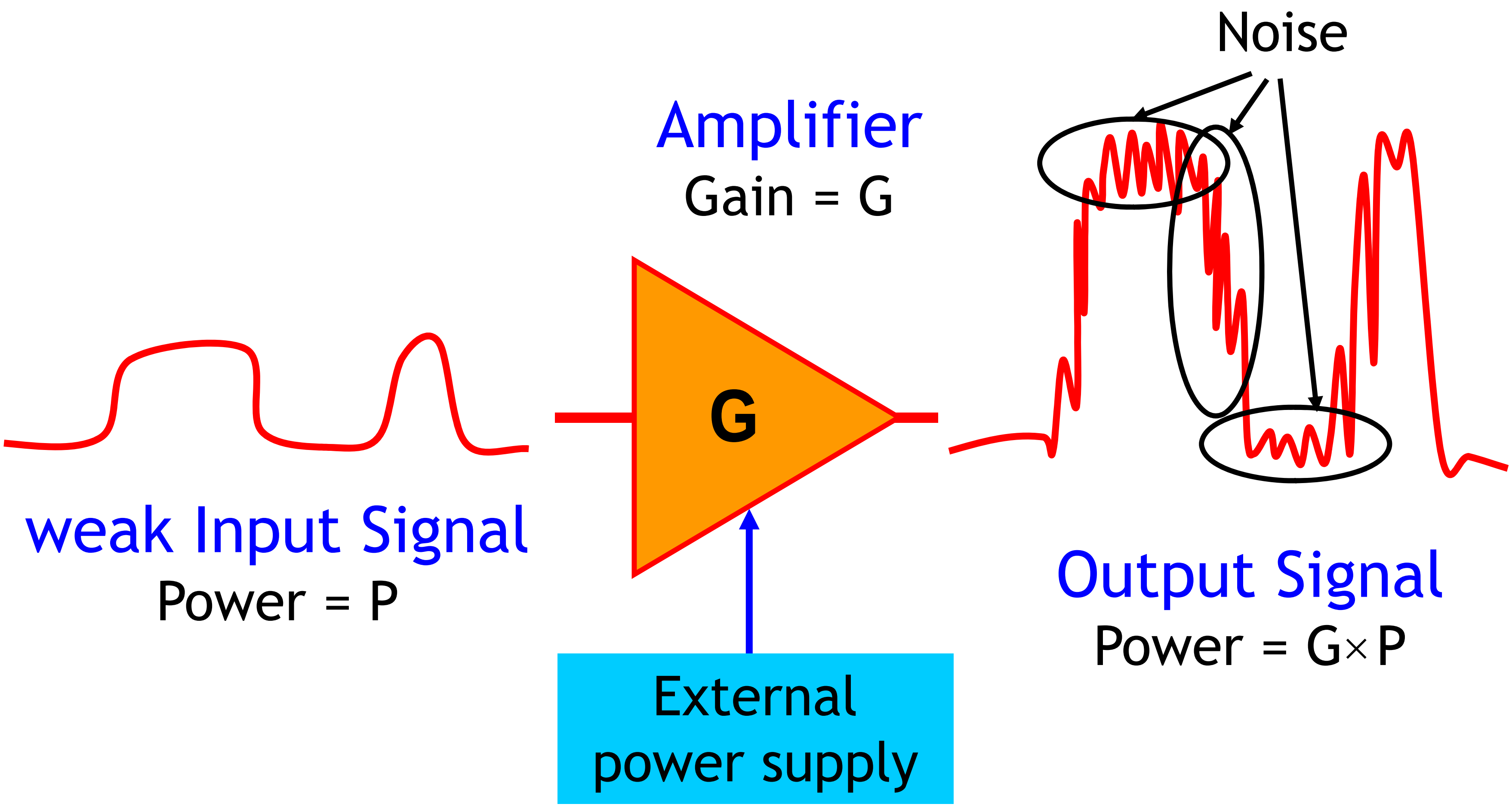
- **Introduction to Fiber-Optic Communications I & II**
- **Recommended – Transmitters I and Receivers I**

Module Objectives

- **Introduction to optical amplifiers**
- **How they work:**
  Gain, Stimulated and Spontaneous Emission
- **Performance Measures:**
  Gain, Noise, SNR, Noise Figure
- **Performance Limitations and Applications**
- **Summary**

Introduction

Share some similarities with electrical amplifiers



Introduction

Similarities between optical and electrical amplifiers:

- Signal amplification
- Noise added to amplified signal
- Gain and noise can be measured and calculated

Differences between optical and electrical amplifiers:

- Large gain bandwidth

  3 THz – 25 THz (optical)

  2 GHz – 50 GHz (electrical)

- Noise spans the same bandwidth

How Optical Amplifiers work

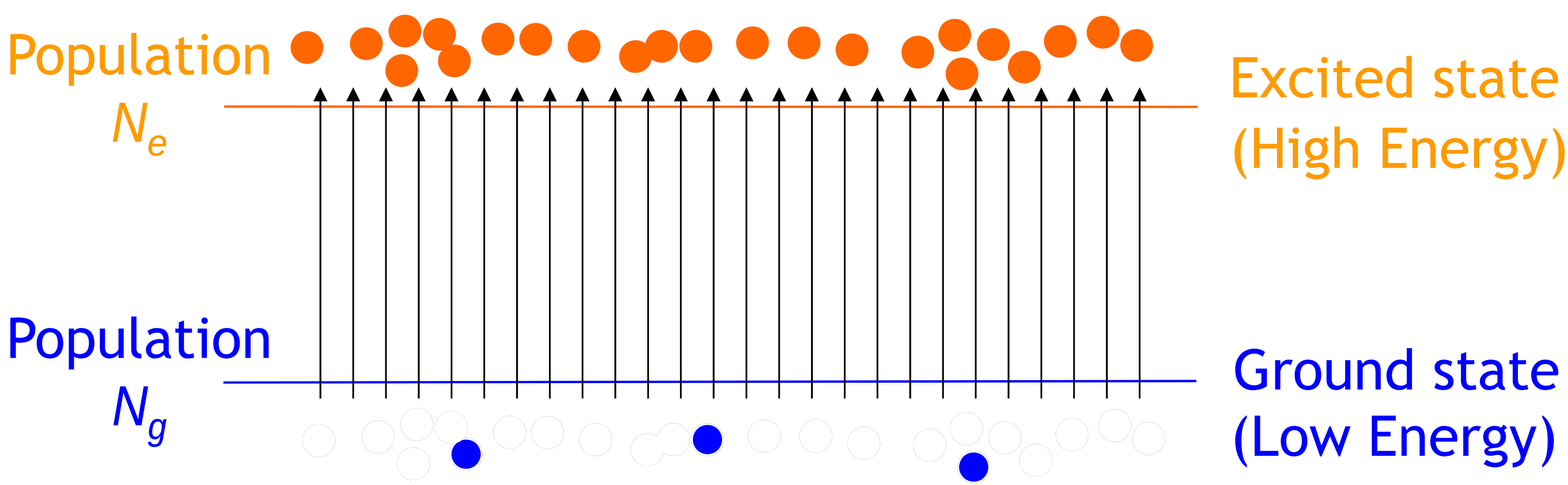
LASER is a good starting point

LIGHT
AMPLIFICATION by
STIMULATED
EMISSION of
RADIATION

Energy Level diagram

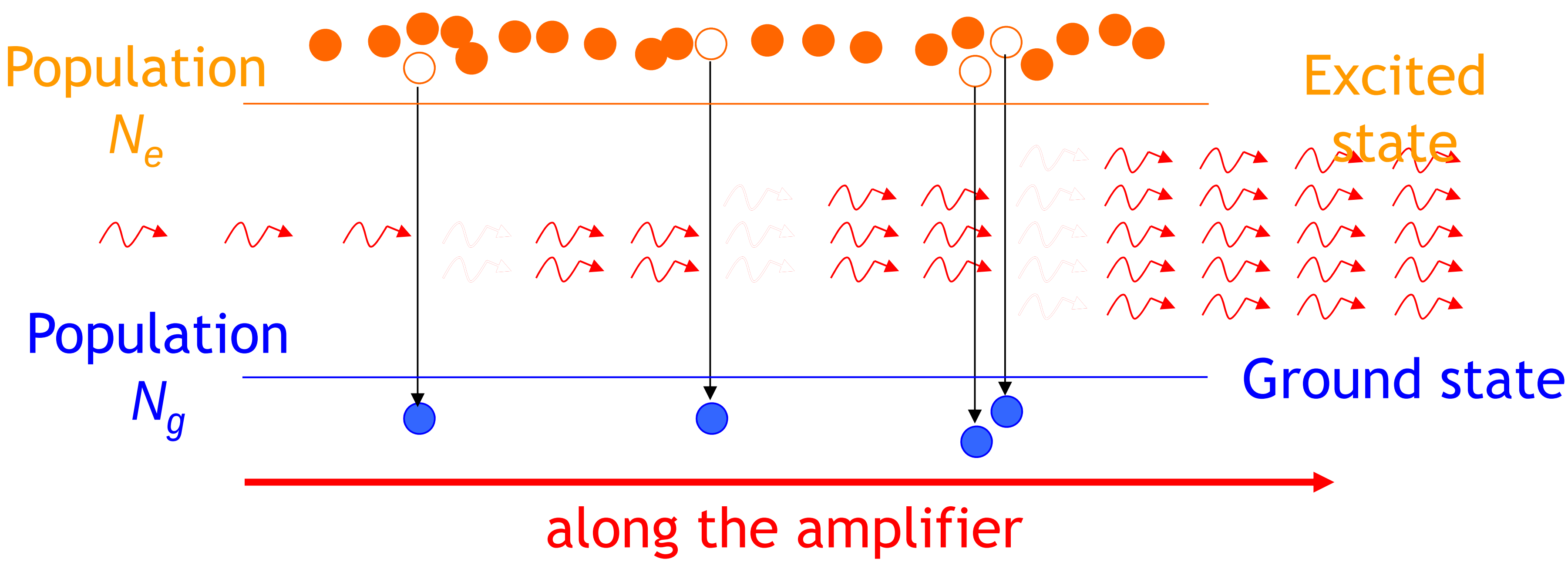
How Optical Amplifiers work

- First, “Population Inversion” is needed
- “Normal”, N_g = number in ground state
- “Population Inversion”: $N_e > N_g$



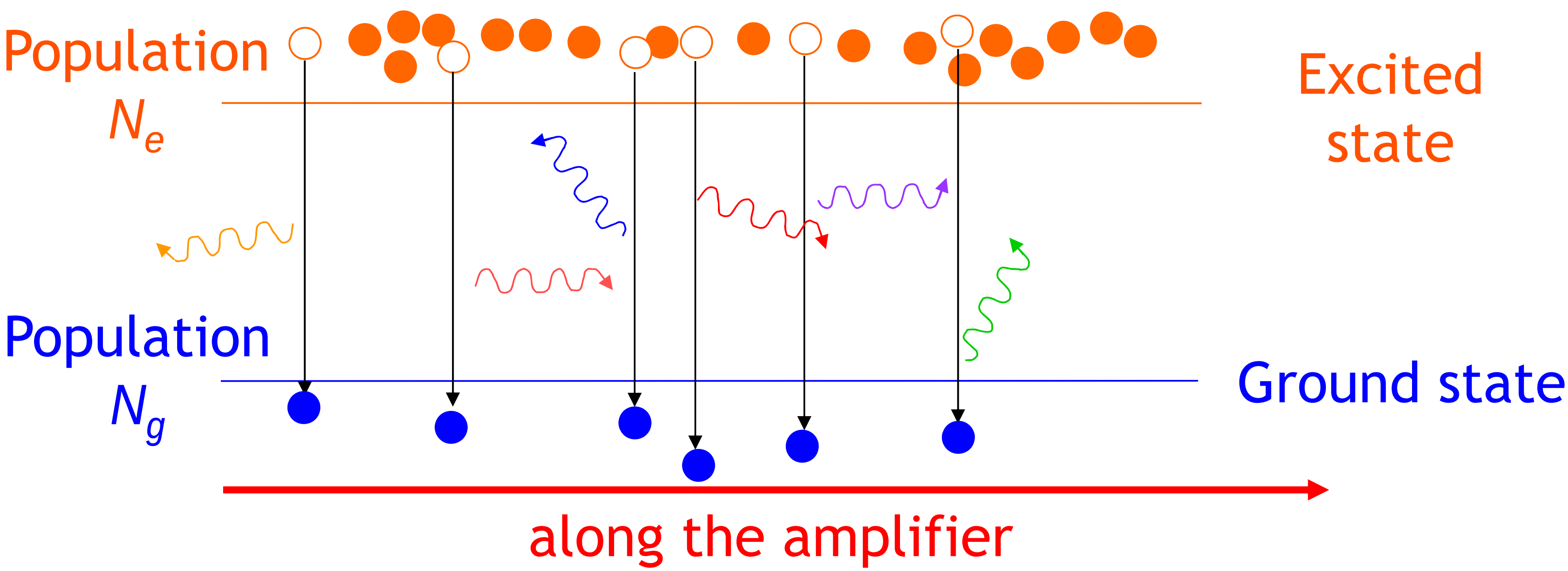
How Optical Amplifiers work

- Signal photon enters the amplifier
- It stimulates an electron to decay to ground state, which emits an identical photon.
- This process repeats… and the signal is amplified (Gain)



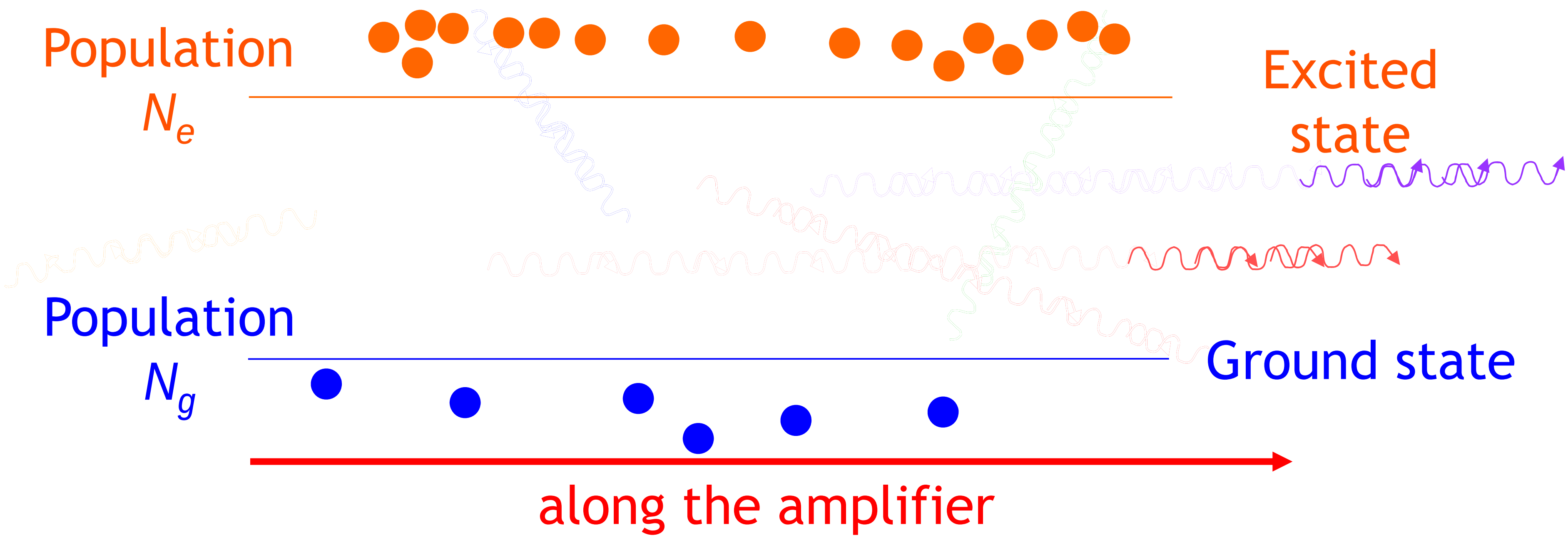
Spontaneous Emission

- Electrons can decay to ground state spontaneously
- Photons emitted, random orientation, phase and λ
- "Spontaneous Emission"



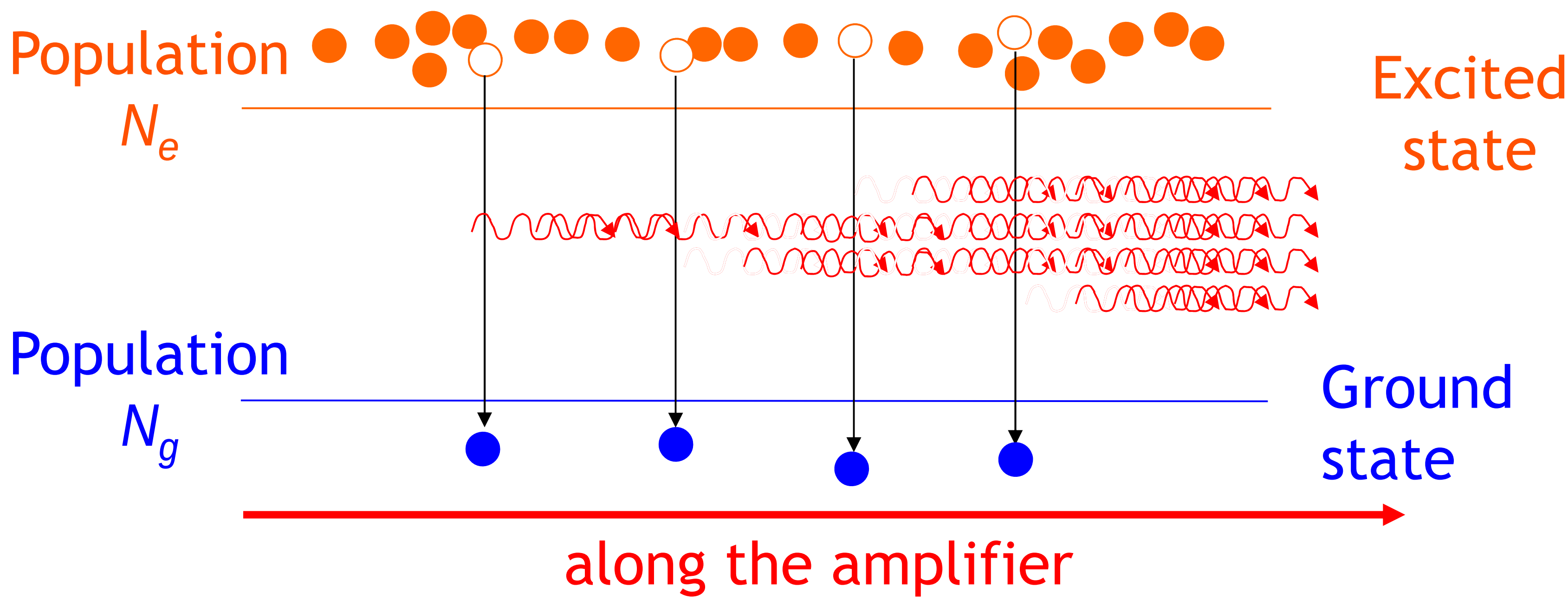
Spontaneous Emission and Guided Modes

- Most of the spontaneously emitted photons are lost
- Only a portion is transmitted: those that become guided modes of the amplifier's waveguide structure



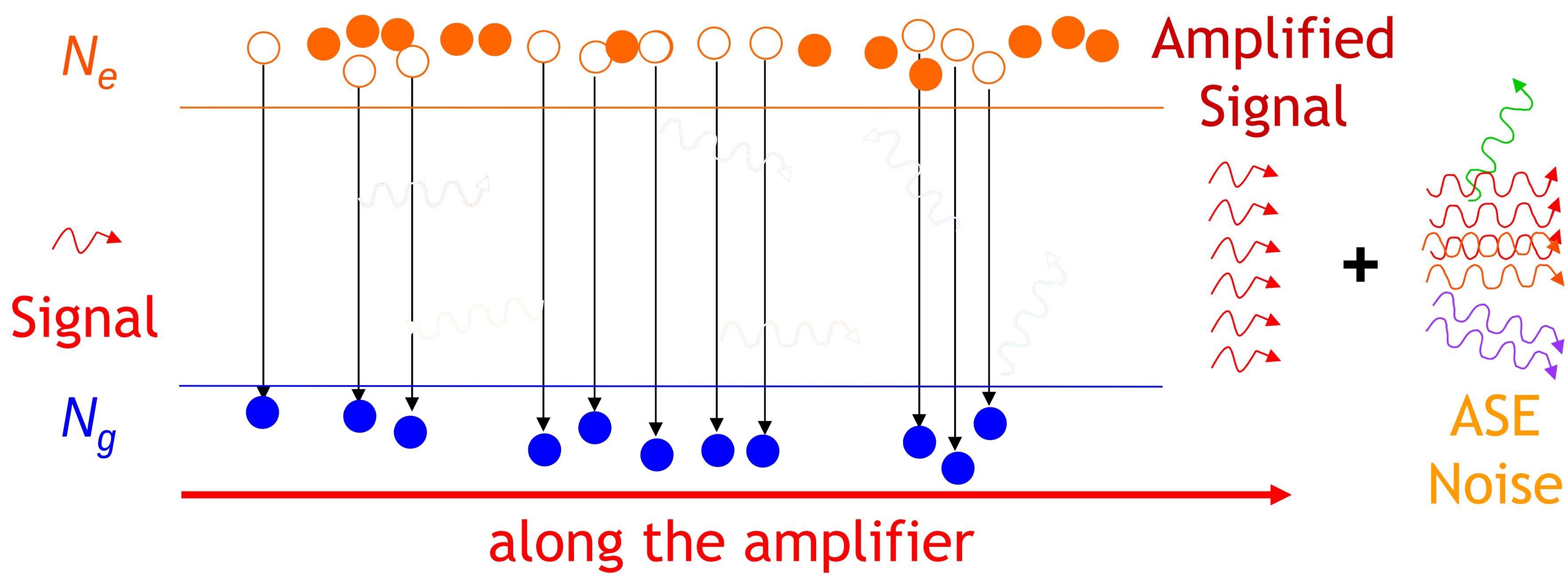
Amplified Spontaneous Emission

- Spontaneously emitted photons can (and will) get amplified
- "Amplified Spontaneous Emission" (ASE)
- Significant source of Noise



How (Noisy) Optical Amplifiers work

- A signal entering an optical amplifier will…
  emerge amplified…
  and is accompanied by ASE noise.



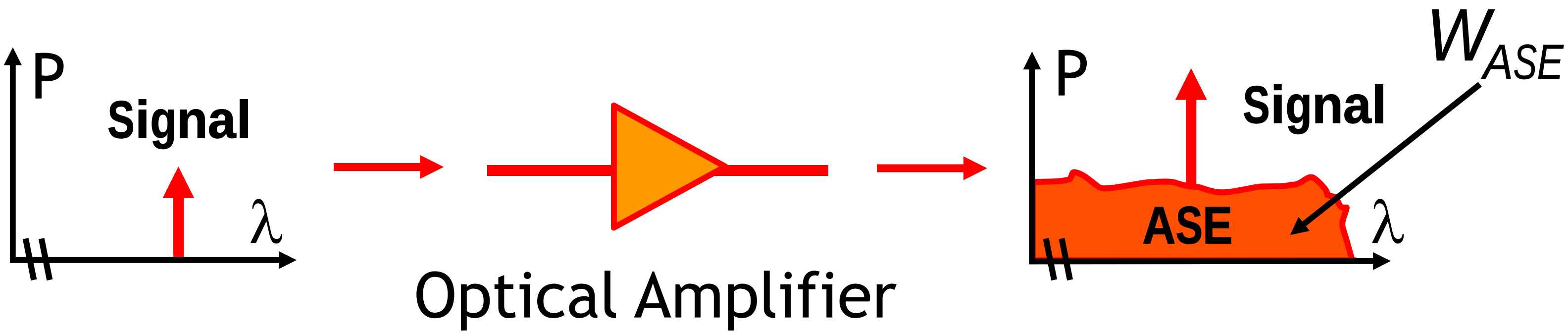
Optical Amplifier Performance: Gain

$$G\ [dB] = 10\ \log_{10}\left(\frac{P_{signal\_out}}{P_{signal\_in}}\right) \quad dB$$

- Ratio of signal power at amplifier output to signal power at amplifier input
- Expressed in decibels (dB)

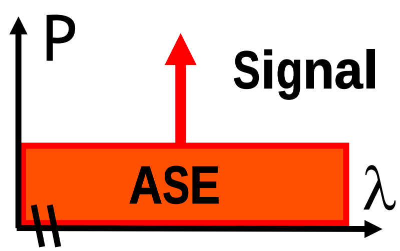
Optical Amplifier Performance: Noise

- An optical amplifier will produce ASE noise



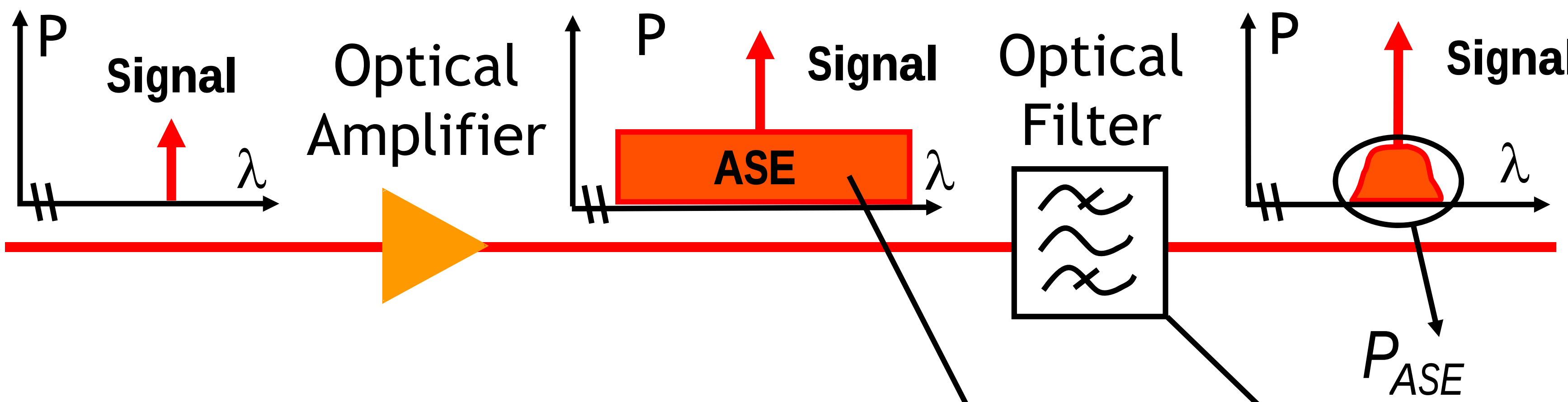
- W_{ASE} = ASE noise Power Spectral Density (PSD)

- W_{ASE} is approximately flat



Optical Amplifier Performance: Noise

- ASE noise is usually reduced by optical filtering



Average Noise Power : $P_{ASE} = W_{ASE} \times B_0$

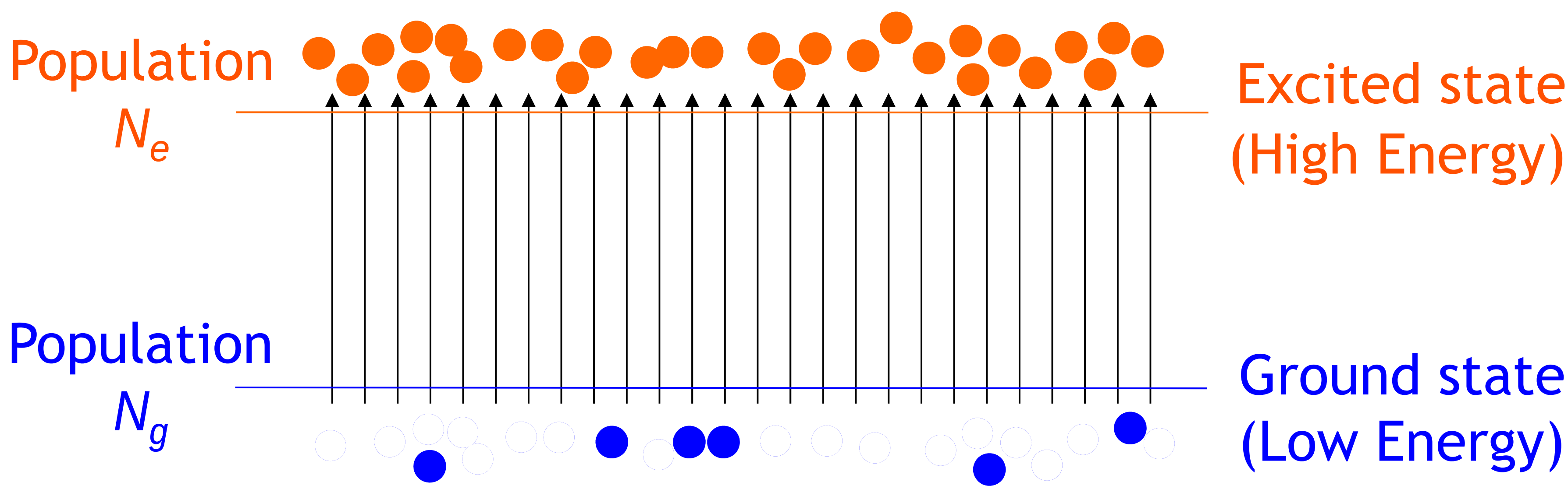
- B_0 is the optical filter bandwidth
- Expression valid for a brickwall filter and flat W_{ASE}

Relationship between Gain and Noise

- Gain & Noise depend on Population Inversion

Population Inversion or Spontaneous Emission Factor

$$n_{sp} = \frac{N_e}{N_e - N_g} > 1$$



Relationship between Gain and Noise

- n_{sp} is defined only when $N_e > N_g$ (i.e. inversion)
- Noise $\propto N_e$, higher N_e ⇨ more spont. emission
- Absorption $\propto N_g$, higher N_g ⇨ greater absorption
- Gain $(G) \propto N_e - N_g$, can only have gain if emission is greater than absorption
- An interpretation of n_{sp}: $n_{sp} \approx \dfrac{\text{Noise}}{\text{Gain}}$
- Low inversion ⇨ low gain ⇨ noise dominates

Relationship between Gain and Noise

- Noise PSD (W_{ASE}) depends on n_{sp}

$$W_{ASE} = hfn_{sp}(G - 1)$$

- High inversion ⇨ $N_g \to 0$ ⇨ $n_{sp} \approx N_e / N_e \to 1$

  amplifier less noisy as $n_{sp} \to 1$

- High inversion also desirable because $G \propto N_e - N_g$,

  $N_g \to 0$ ⇨ $n_{sp} \to 1$ ⇨ $\mathrm{G} \to$ *maximum value*

- For optical amplifiers, high inversion and high gain is the best.

Noise Performance Measures

Besides n_{sp} and Noise Power …

commonly used performance measures are:

1. Electrical Signal-to-Noise Ratio (SNR)
2. Noise Figure

- Why not n_{sp}?

  Impossible to count number of excited atoms …

- Why not Noise Power ?

  Not useful without knowing signal power …

SNR in Optically Amplified Systems

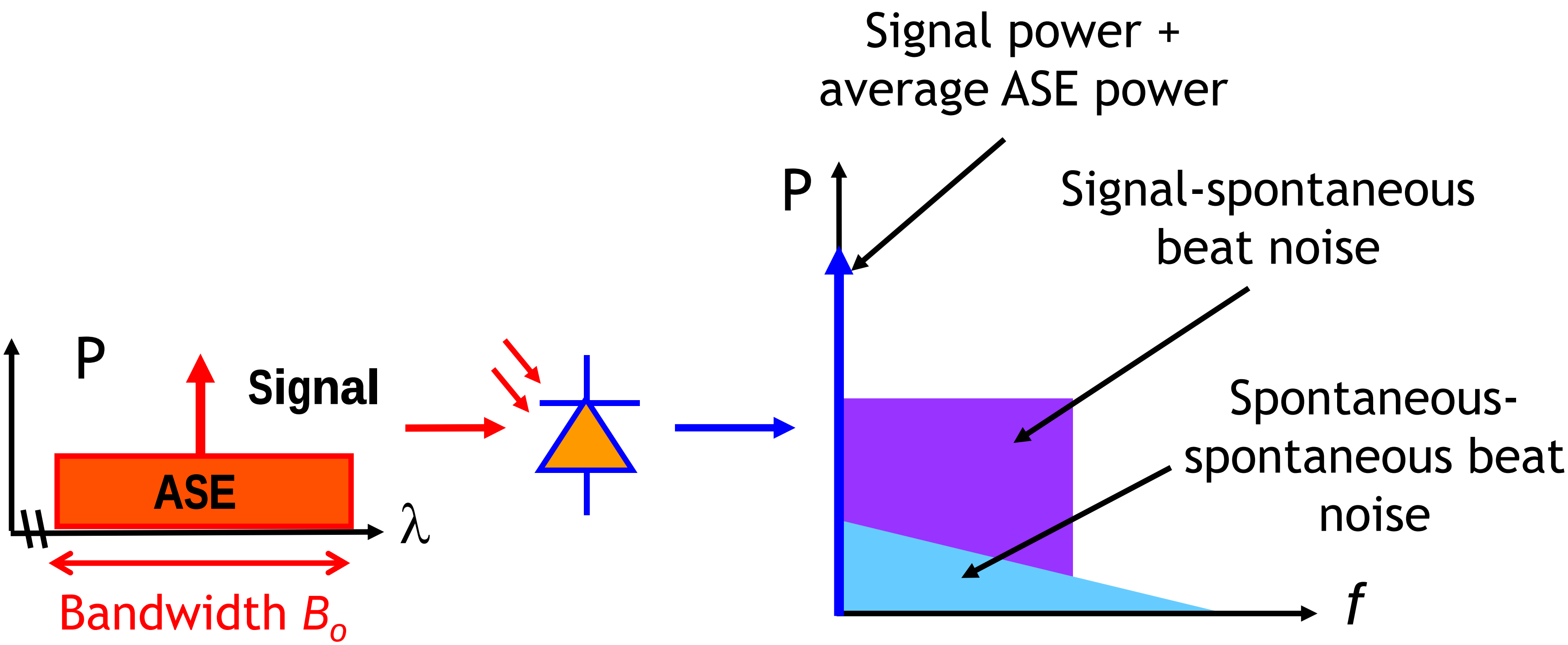
Two more important differences
(between optical and electrical amplifiers):

1. SNR meaningful only after the signal has been detected (converted to electrical)

2. Optical detectors are square law devices
   - Mixing (or beating) between various frequency components of the optical signal
   - Detected electrical spectrum contains frequency difference components!

SNR in Optically Amplified Systems

Mixing of various optical spectral components:



Optical Spectrum

Electrical Spectrum

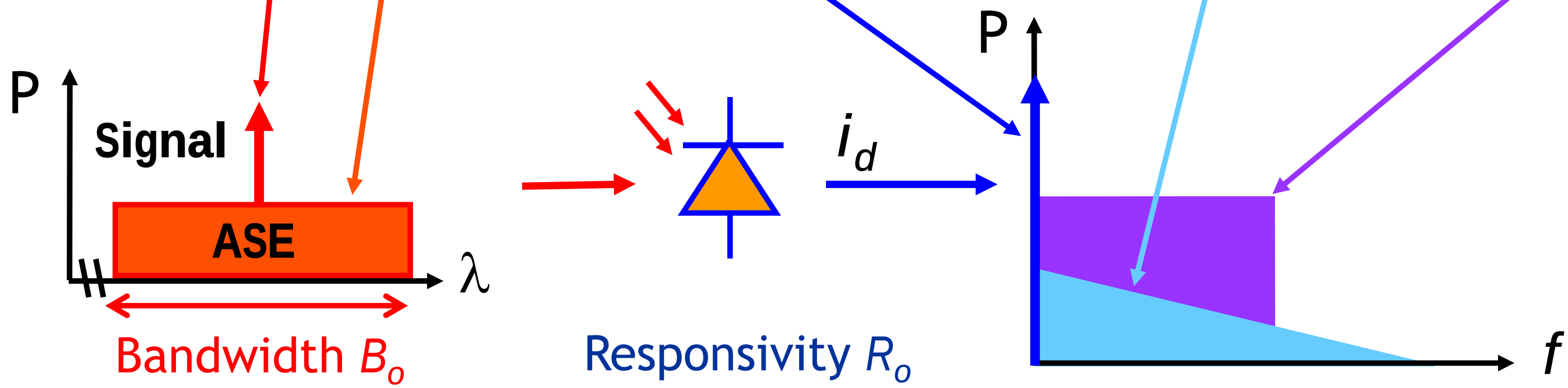
SNR in Optically Amplified Systems

Mixing products in the detected photocurrent:

$$i_d \propto R_o |E_s + E_{ASE}|^2 = R_o(|E_s|^2 + |E_{ASE}|^2 + 2Re[E_s E_{ASE}])$$

$$= R_o P_s + R_o P_{ASE} + R_o P_{ASE\text{-}ASE} + R_o P_{s\text{-}ASE}$$

$$\Rightarrow i_d = i_s + i_{ASE} + i_{sp\text{-}sp} + i_{s\text{-}sp}$$



Optical Spectrum | Detector | Electrical Spectrum

SNR in Optically Amplified Systems

The SNR at a receiver with responsivity R_o, and electrical bandwidth B_e :

$$SNR = \frac{i_s^2}{\left(\overline{i_{s\text{-}sp}}^2 + \overline{i_{sp\text{-}sp}}^2 + \overline{i_{shot}}^2 + \overline{i_{th}}^2\right) B_e}$$

signal-spontaneous beat noise

spontaneous-spontaneous beat noise

shot noise

thermal noise

contribution from optical amplifier

contribution from detector

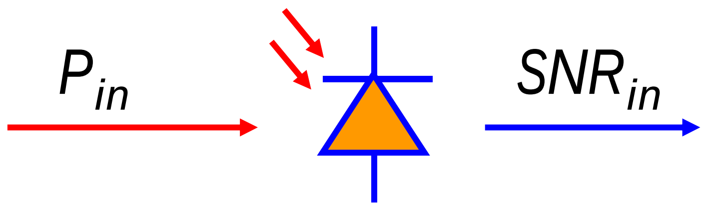
The Noise Figure of a device is defined as follows:

SNR at the input — **device** — SNR at the output

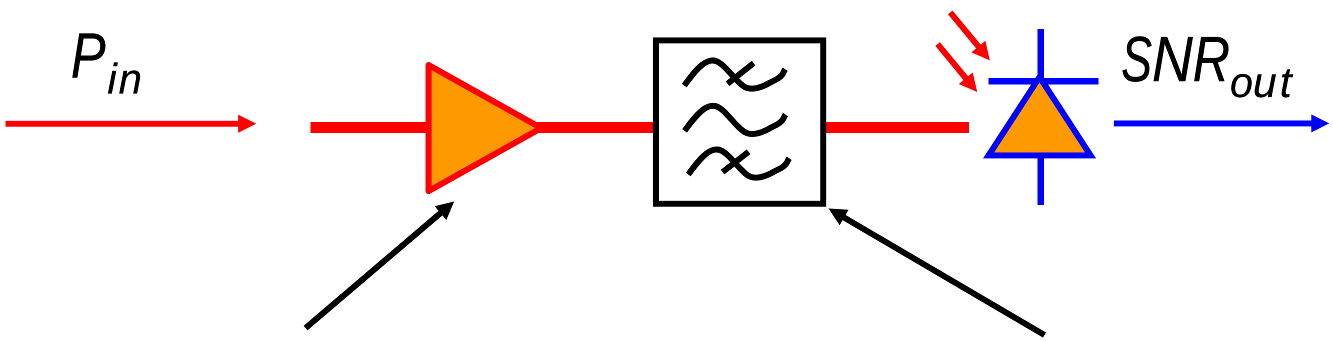
$$\text{Noise Figure, } F = \frac{\text{SNR at the input}}{\text{SNR at the output}}$$

Noise Figure of an Optical Amplifier

SNR at the input of the Optical Amplifier, SNR_{in}



SNR at the output of the Optical Amplifier, SNR_{out}

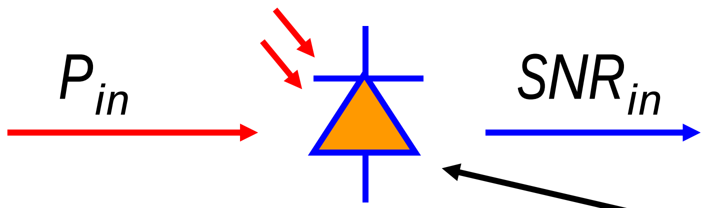


Optical Amplifier
Gain = G, Noise Figure = F

Optical Bandpass Filter
Bandwidth = B_o

Noise Figure of an Optical Amplifier

SNR_{in}:



Receiver,
Responsivity = R_0
Electrical Bandwidth = B_e

$$SNR_{in} = \frac{(R_o P_{in})^2}{2eR_o P_{in} B_e}$$

assuming shot noise limited detector

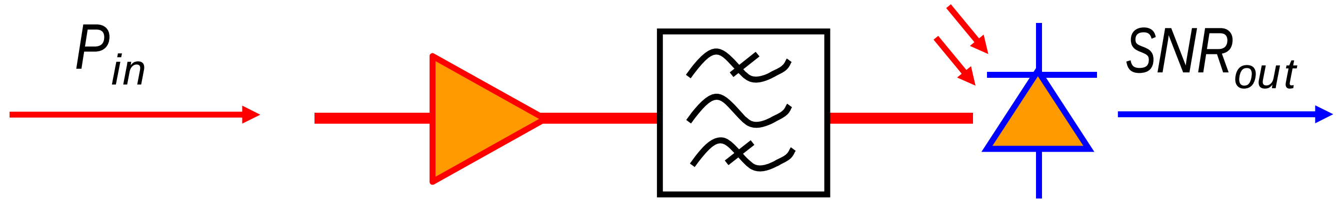
For a "perfect" detector with 100% Quantum Efficiency,

$$R_o = \frac{e}{hf}$$

$$SNR_{in} = \frac{P_{in}}{2hfB_e}$$

Noise Figure of an Optical Amplifier

SNR_{out}:



$$SNR_{out} \approx \frac{(R_o P_{out})^2}{4R_o^2 P_{out} hf n_{sp}(G-1)B_e + 2eR_o P_{in} B_e}$$

$$= \frac{GP_{in}}{4hfn_{sp}(G-1)B_e + 2hfB_e} \longleftarrow \text{after simplification}$$

Noise Figure, F:

$$F = \frac{SNR_{in}}{SNR_{out}} = \frac{4hfn_{sp}(G-1)B_e + 2hfB_e}{2hfB_e\,G} = \frac{2n_{sp}(G-1)+1}{G}$$

Quantum-limited Noise Figure

- Any worthwhile amplifier will have high gain, and

$$F = \frac{SNR_{\text{in}}}{SNR_{\text{out}}} = \frac{2n_{sp}(G-1) + 1}{G}$$

- For an amplifier with high inversion, $n_{sp} \rightarrow 1$

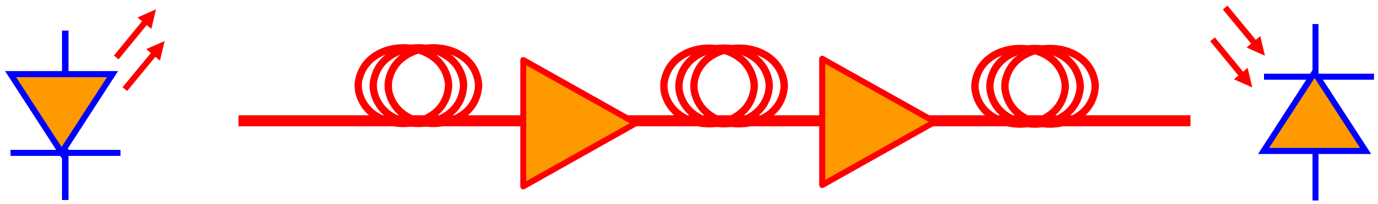
$$F \approx \frac{2n_{sp}G}{G} = 2 \Rightarrow 3\text{ dB}$$

- 3 dB is the quantum limited noise figure

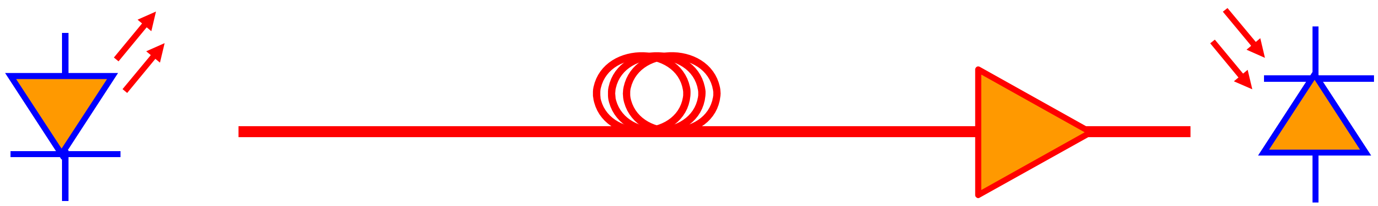
Applications

- Power amplifier

- Line amplifier



- Receiver preamplifier



Summary

- Fundamental characteristics:
  - stimulated emission, amplification, spontaneous emission, ASE
- Performance measures:
  - Inversion Factor, gain, noise power, SNR and noise figure
- Performance Limitations
  - Mixing products, Quantum limit
- Basic mathematical analysis
- Applications

Proceed with the *Interactive Learning Module*