

Fiber Optics Communications

Week 10

Optical Amplifiers

Lecturer: Zelalem Hailu (Assistant Prof.)

***Addis Ababa Science and Technology University
Addis Ababa, Ethiopia***

Topics of Previous Lecture (Week-9)

Optical Detectors

- Semiconductor Photodiodes
- Photodiode Materials Choices
- PIN Photodiodes
- Avalanche Photodiodes (APD)
- Noise Sources in Photodetectors

Week-10: Lecture Learning Outcomes

1. Define what an optical amplifier is and explain its role in optical communication systems.
2. Describe the general operation principle of optical amplifiers
3. Identify the major types of optical amplifiers and their applications
4. Explain the working mechanisms, advantages, and limitations of Semiconductor Optical Amplifiers (SOA), Erbium-Doped Fiber Amplifiers (EDFA), and Raman Amplifiers (RA)
5. Compare the performance characteristics of different optical amplifier types

Week-10: Optical Amplifiers

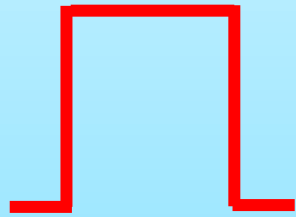
Outline

- Introduction to Optical Amplifiers
- General Operation Principle of Optical Amplifier
- Types of Optical Amplifiers
- Semiconductor Optical Amplifiers (SOA)
- Erbium Doped Fiber Amplifiers (EDFA)
- Raman Amplifiers (RA)

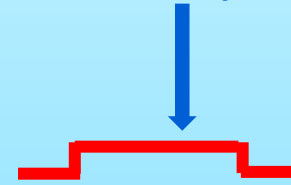
Introduction to Optical Amplifiers

- To enable signal transmission over long distances (E.g. greater than 100 km), attenuation losses in the fiber must be compensated.

Optical pulse carrying
information bit



The optical signal
becomes too weak to
be effectively detected



Needs Amplification



Figure 1: Optical power reduction in Optical fiber transmission line

- An **optical amplifier** or **3R repeater** can be used to amplify the weak optical signal.

Introduction to Optical Amplifiers

- **Optical amplifier (OA)** is a device that boosts the strength of an optical signal directly, without need of optical-to electrical conversion
- **3R Repeater:** amplifies the signal in electrical domain after converting the weak optical signal in to electrical signal.

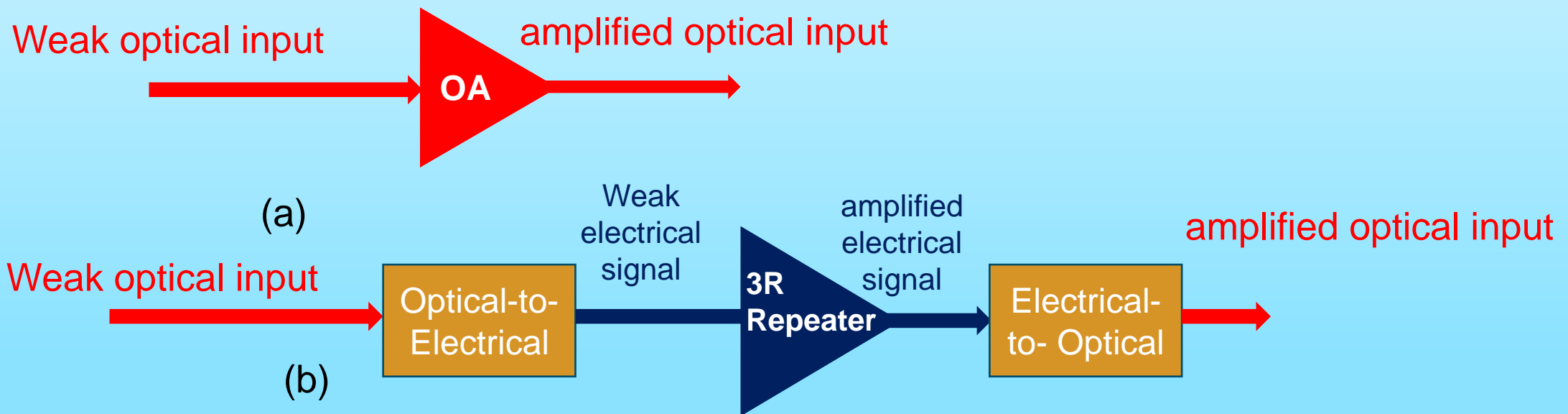


Figure 2: (a) Optical amplifier (b) 3R repeater

Optical Amplifiers Application Scenarios

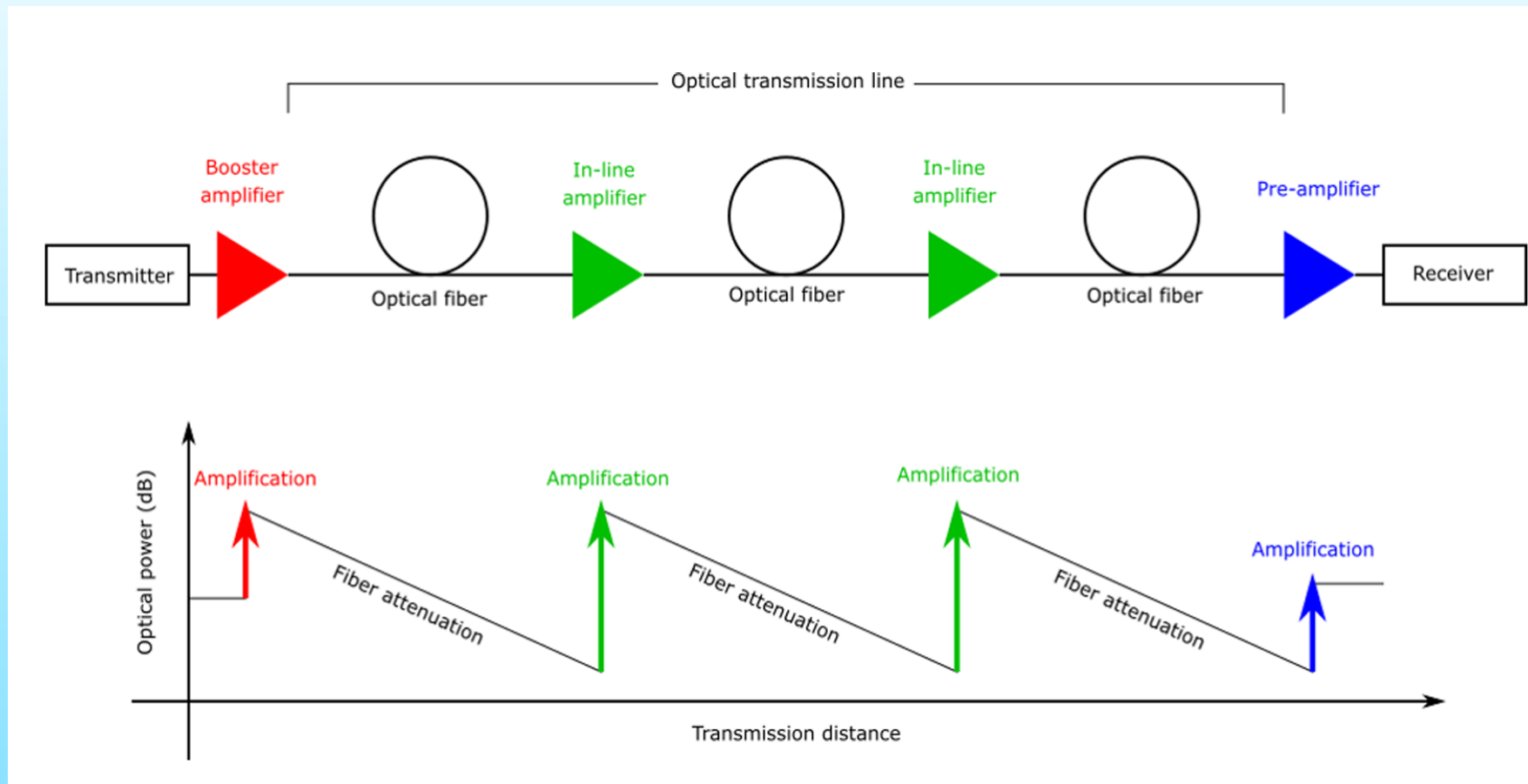


Figure 3: Optical amplifiers application scenarios

Source: A. Biswas, "Telemetry and Data Collection for Artificial Intelligence in Optical Systems," M.S. thesis, The University of Arizona, Sep. 2020. <https://www.researchgate.net/profile/Aishik-Biswas/publication/344391031/figure/fig3/AS:940114880524290@1601152262278/Schematic-depiction-of-Booster-In-line-and-Pre-amp-EDFAs-original-figure-from.ppm>

General Operation Principle of Optical Amplifier

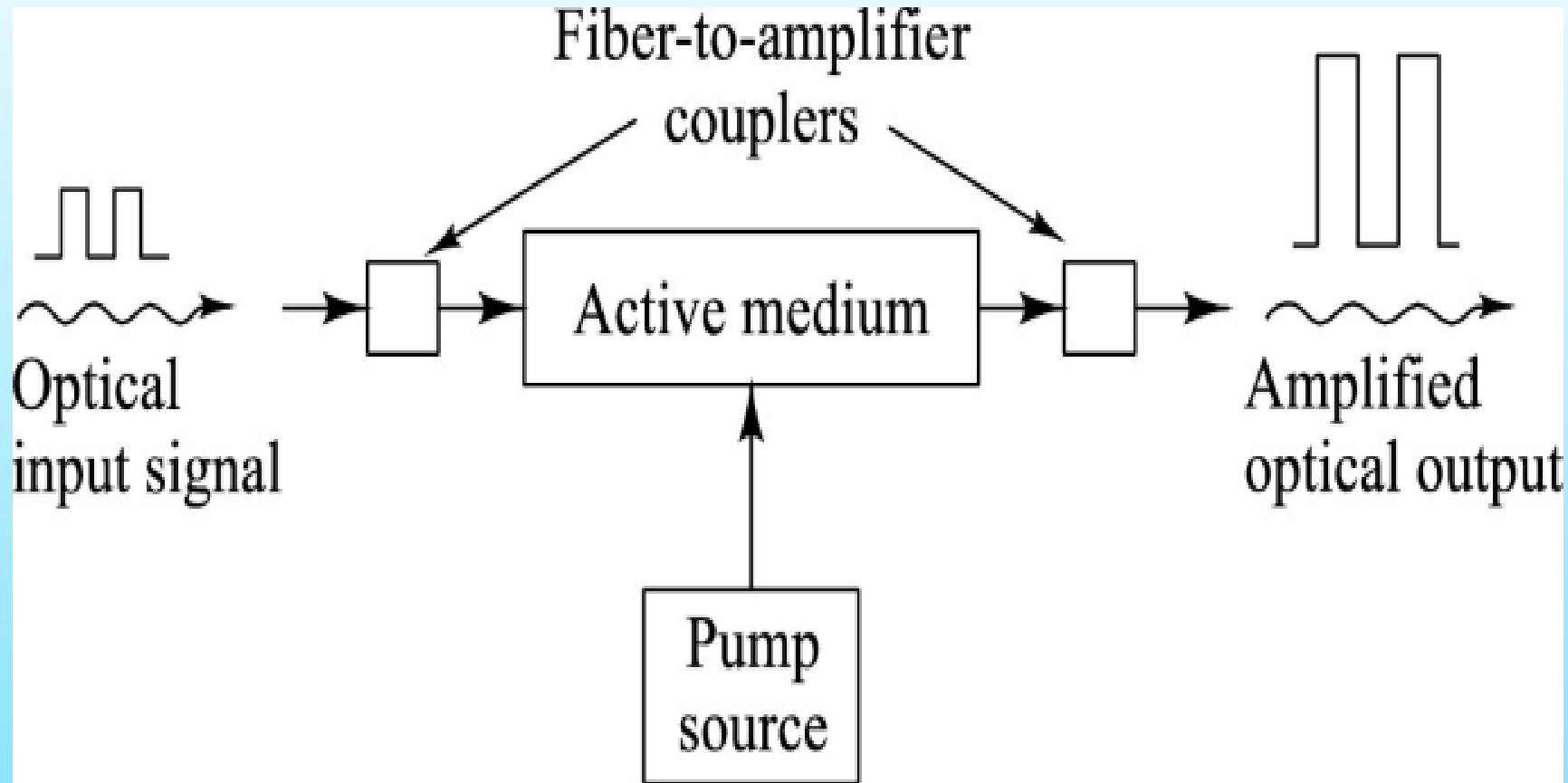


Figure 4: Generic optical amplifiers

Source: K. S. Kim, "Optical Fiber Communications – Components, Subsystems & Systems," Springer, 2021, ch. 11. https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-981-33-4665-9_11/MediaObjects/495048_1_En_11_Fig2_HTML.png

Types of Optical Amplifiers

Semiconductor Optical Amplifiers (SOA)

- ❖ Small package
- ❖ Low cost

Erbium Doped Fiber Amplifiers (EDFA)

- ❖ Best performance
- ❖ Low cost and widely used

Raman Amplifiers (RA)

- ❖ Better noise performance compared to EDFA



Semiconductor Optical Amplifiers (SOA)

Semiconductor Optical Amplifiers (SOA)

- Operates the same way as Semiconductor laser by the virtue of stimulated emission using gain cavity
- External current injection or Electrical pump is used to create population inversion
- As photons pass through the active region, they stimulate excited electrons to release their excess energy as additional photons with the same wavelength as the original ones through stimulated emission.

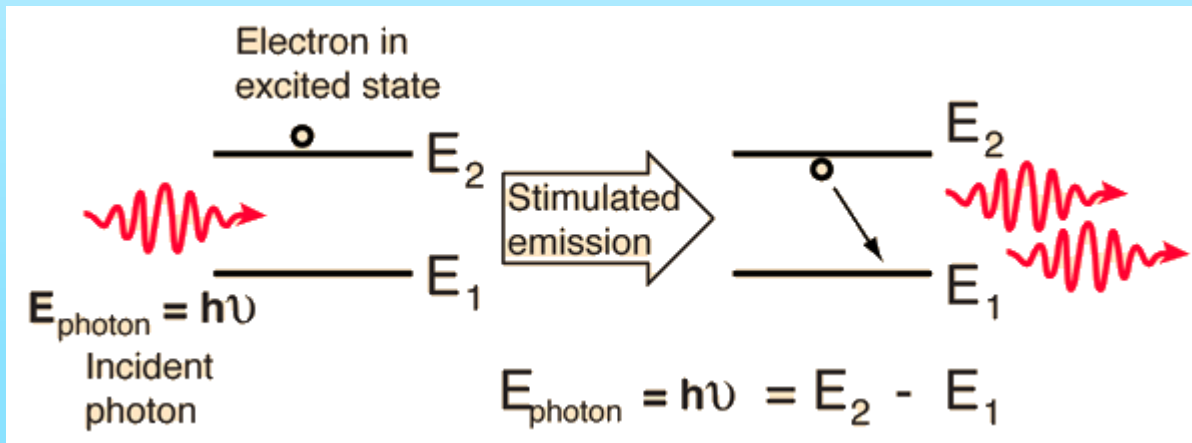


Figure 5: Stimulated emission

Source: "Interaction of radiation with matter," HyperPhysics, Georgia State University Physics & Astronomy. <http://hyperphysics.phy-astr.gsu.edu/hbase/imgmod/qpro2.gif>

Semiconductor Optical Amplifiers (SOA)

- After population inversion, the number of excited electrons become large and the number of generated photons through stimulated emission also becomes large

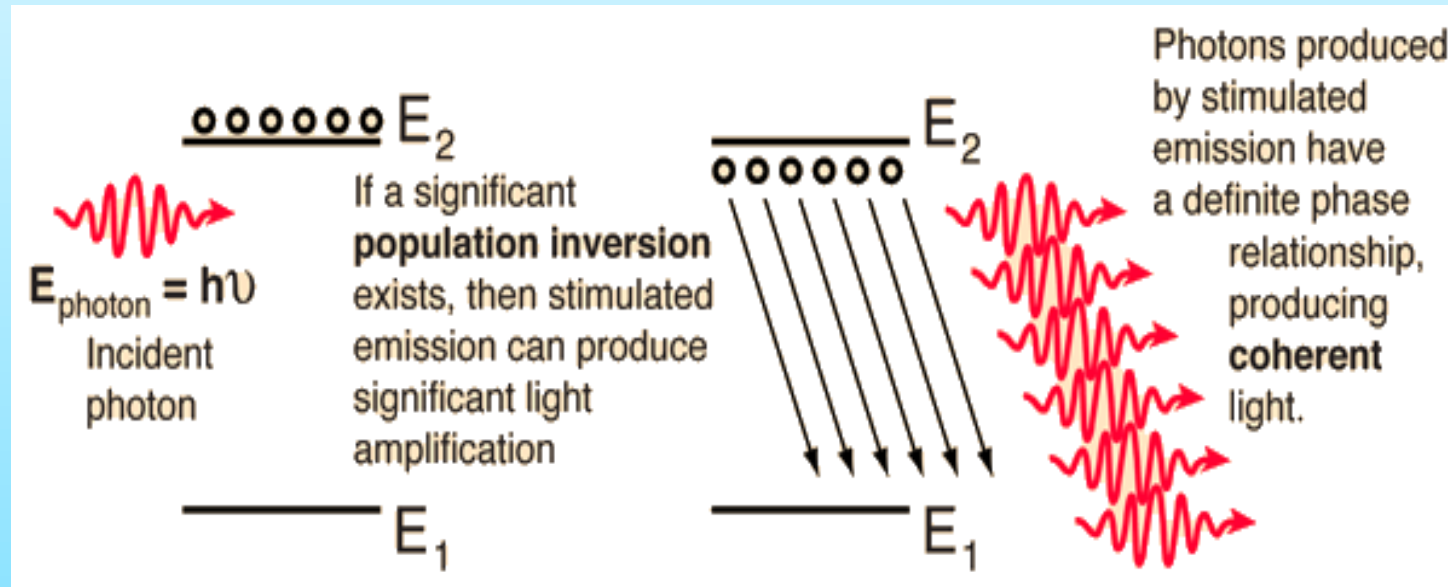


Figure 5: Stimulated emission when population inversion exist

Source: "Interaction of radiation with matter," HyperPhysics, Georgia State University Physics & Astronomy. <http://hyperphysics.phy-astr.gsu.edu/hbase/imgmod/qpro3.gif>

Semiconductor Optical Amplifiers (SOA)

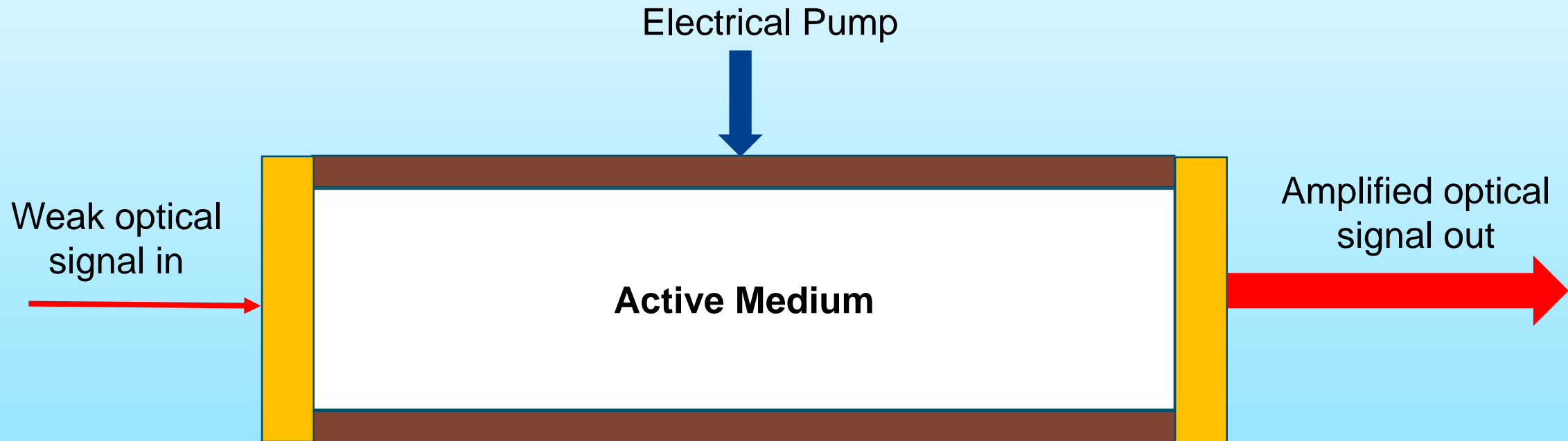


Figure 6: Semiconductor optical amplifier (SOA)

Characteristics of SOA

- The most common characteristics of semiconductor amplifier (SOA) are as follows:

- ❖ Relatively high gain ~20 dB
- ❖ Output saturation power 5-10 dBm
- ❖ Large BW
- ❖ Can operate at 800, 1300, and 1500 nm wavelength regions
- ❖ Compact and easily integrated with other devices
- ❖ Potential use for low-cost applications

Types of Semiconductor Optical Amplifiers (SOA)

- There are two types of SOA:

1. Fabry-Perot Amplifier (FPA)

- ❖ Uses resonant cavity as a laser do
- ❖ Offer lower optical bandwidth
- ❖ Needs careful temperature stabilization

2. Traveling Wave Semiconductor optical Amplifier

- ❖ Non resonant
- ❖ Offer higher optical bandwidth
- ❖ Widely used

Types of Semiconductor Optical Amplifiers (SOA)

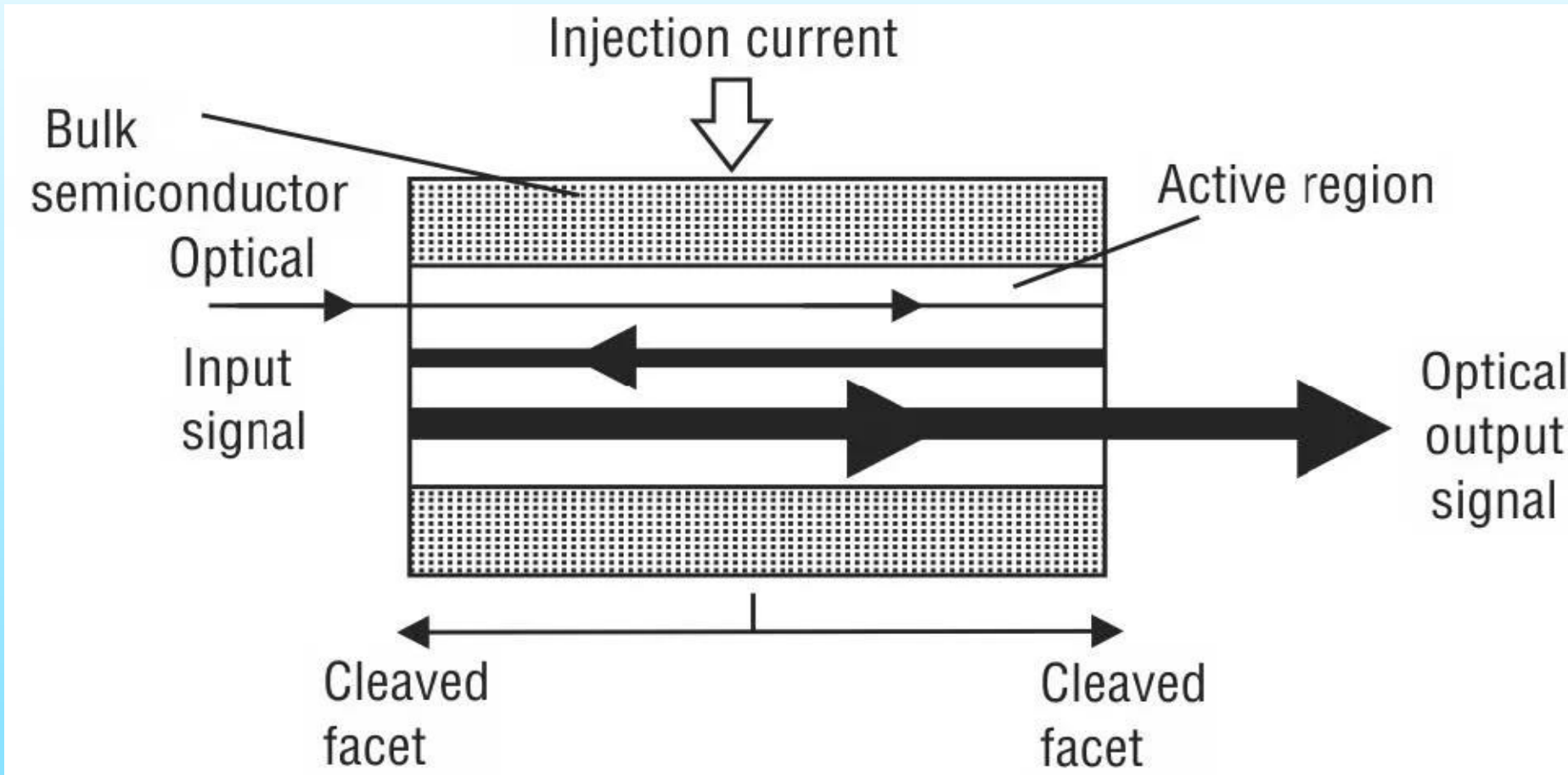


Figure 6: Fabry-Perot Amplifier (FPA)

Source: "Semiconductor Optical Amplifiers (SOA)," Electronics Club. <https://electronics-club.com/wp-content/uploads/2021/04/Principle-of-operation-of-Fabry%E2%80%93Perot-laser-amplifier.jpg>

Types of Semiconductor Optical Amplifiers (SOA)

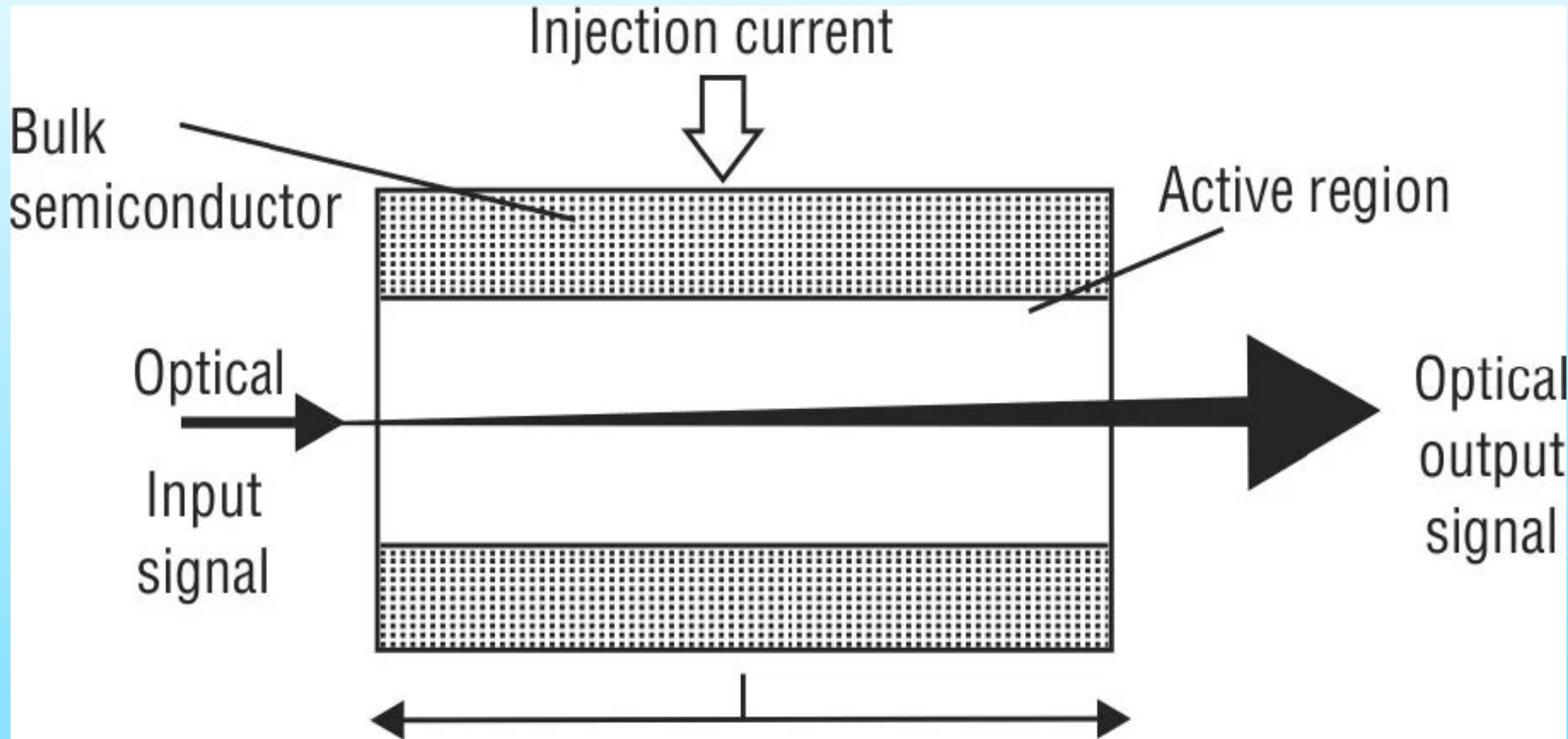


Figure 7: Traveling Wave Semiconductor optical Amplifier

Source: "Semiconductor Optical Amplifiers (SOA)," Electronics Club. <https://electronics-club.com/wp-content/uploads/2021/04/Principle-of-operation-of-TWSLA.jpg>

Important Parameters of SOA

- **External pump:** used to create population inversion
- **Gain:** ratio of output power to input power (in dB)
- **Gain efficiency:** gain as a function of input power (dB/mW)
- **Gain bandwidth:** range of wavelengths over which the amplifier is effective
- **Gain saturation:** maximum output power, beyond which no amplification is reached
- **Saturation Output Power:** the maximum output power an amplifier can produce and beyond which the amplifier can no longer amplify the power linearly

SOA Rate Equation

- In SOA, external current injection is used to create population inversion
- The rate equation that governs the rate of change of carrier density in the active region is given by [1]:

$$\frac{\partial n(t)}{\partial t} = \frac{J(t)}{qd} - R_{st} - \frac{n(t)}{\tau_{sp}} \quad (1)$$

Current injected
from external pump

Rate of stimulated
emission

Rate of spontaneous
emission

SOA Rate Equation

- The rate of stimulated emission (R_{st}) is given by:

$$\begin{aligned} R_{st} &= \Gamma a(n - n_{th})v_g N_{ph} \\ &= gv_g N_{ph} \end{aligned} \quad (2)$$

Where:

- v_g Group velocity of incident light
- Γ Optical confinement factor
- a Gain constant
- n_{th} Threshold carrier density
- N_{ph} Photon density
- g Overall gain per unit length

SOA Rate Equation

- Using Eq (1) and Eq (2) for steady state condition ($\frac{\partial n}{\partial t} = 0$), the steady state gain per unit length :

$$g = \frac{\frac{J}{qd} - \frac{n_{th}}{\tau_{sp}}}{v_g N_{ph} + \frac{1}{\Gamma a \tau_{sp}}} = \frac{g_0}{1 + \frac{N_{ph}}{N_{ph,sat}}} \quad (3)$$

Where:

$$g_0 = \Gamma a \tau_{sp} \left(\frac{J}{qd} - \frac{n_{th}}{\tau_{sp}} \right) \rightarrow \text{Small signal gain per unit length}$$

$$N_{ph,sat} = \frac{1}{\Gamma a v_g \tau_{sp}} \rightarrow \text{Saturation photon density}$$

SOA Gain

- The single pass signal gain (G) of SOA having length L can be written in terms of Input signal power ($P_{s,in}$) and output signal power ($P_{s,out}$):

$$G = \frac{P_{s,out}}{P_{s,in}} = \frac{P_{s,in} (e^{g(z)L})}{P_{s,in}} = e^{g(z)L} \quad (4)$$

Where:

$$g(z) = \frac{g_0}{1 + \frac{P_s(z)}{P_{amp,sat}}} \rightarrow \text{overall gain per unit length}$$

$P_s(z) \rightarrow$ internal signal power at point z

$P_{amp,sat}(z) \rightarrow$ amplifier saturation power



Erbium Doped Fiber Amplifiers (EDFA)

Erbium Doped Fiber Amplifiers (EDFA)

- Fiber amplifier and the core of an EDFA is an optical fiber doped with erbium, a rare-earth element.
- Optical pump (980nm, 1480nm) is used to create population inversion in EDFA to amplify optical signal (1550nm)

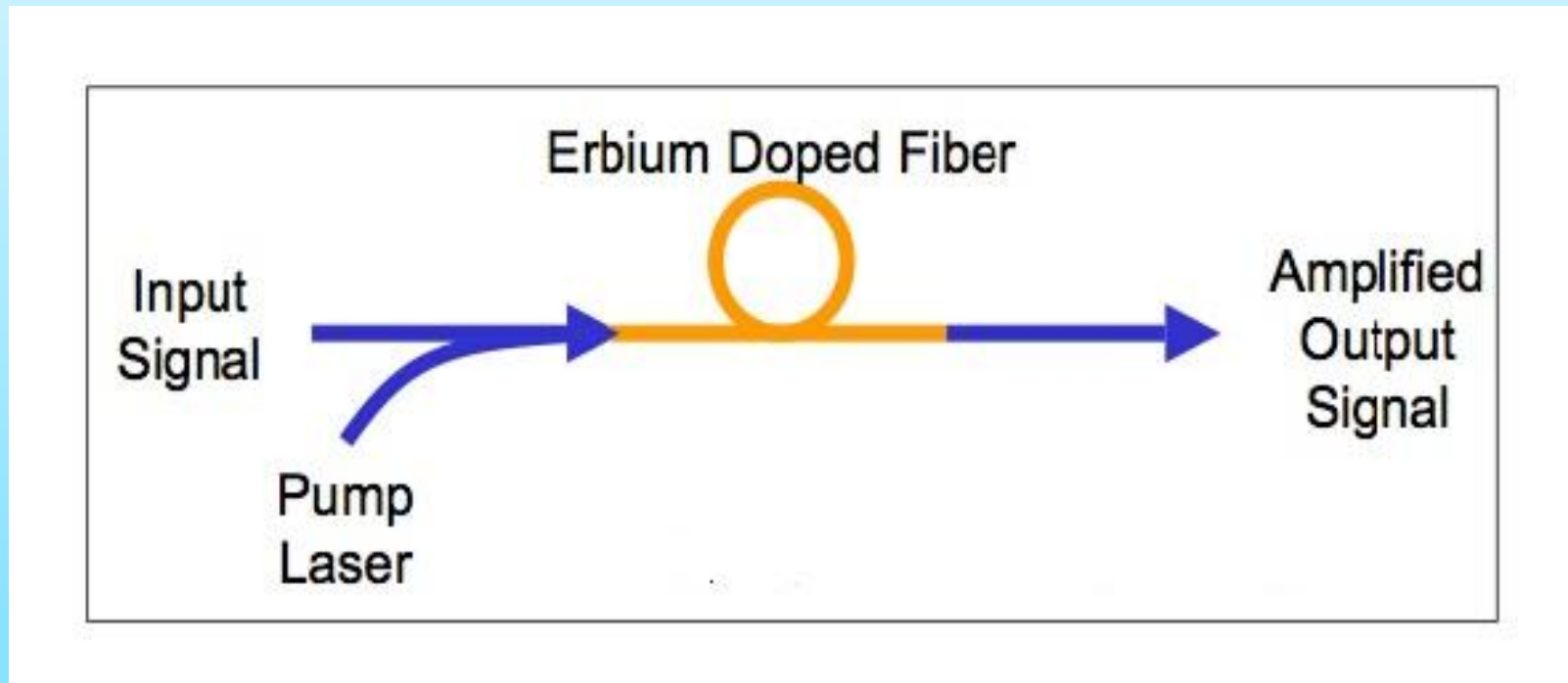


Figure 8: EDFA

Source: "EDFA vs Raman amplifier," Telecomate, Mar. 22, 2023.

<https://www.telecomate.com/wp-content/uploads/2023/03/EDFA-vs-Raman-amplifier-2.jpg>

Erbium Ion Energy Band and EDFA Operation

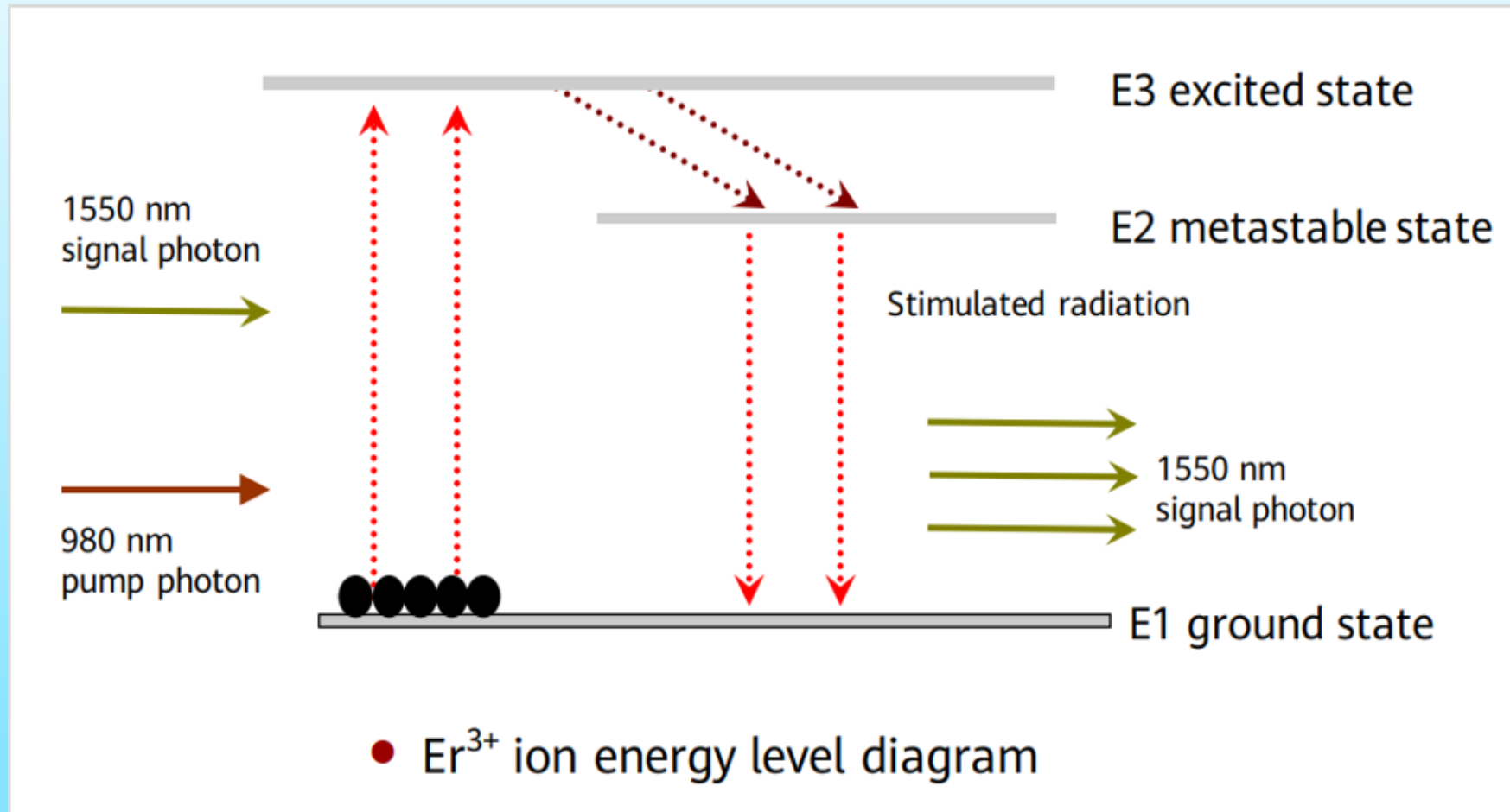


Figure 9: Erbium energy band and EDFA operation

Source: "Erbium-doped fiber amplifier (EDFA)," Telecomate Blog, Mar. 22, 2023.

<https://www.telecomate.com/wp-content/uploads/2023/03/Erbium-doped-fiber-amplifierEDFA-1.png>

Types of EDFA Configurations

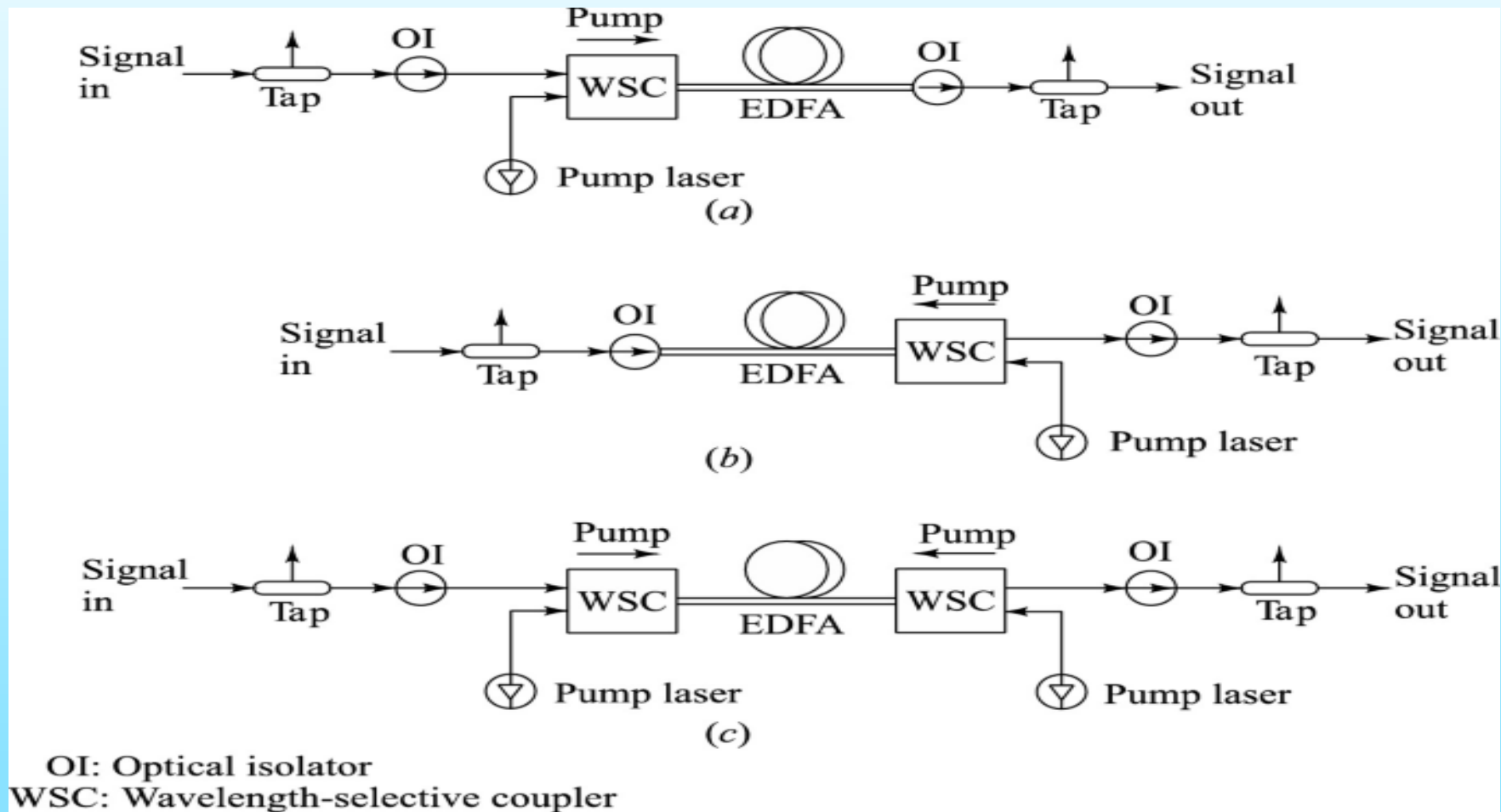


Figure 10: pumping configuration (a) co-directional (b) counter directional (c) dual

Source: G. Keiser, "Basics of Optical Amplifiers," in Fiber Optic Communications, Springer Singapore, 2021, p. 437–475, Fig. 6. https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-981-33-4665-9_11/MediaObjects/495048_1_En_11_Fig6_HTML.png



Raman Amplifiers (RA)

Raman Amplifiers (RA)

- RA uses intrinsic optical nonlinearity characteristics of silica fiber optics particularly stimulated Raman scattering [2].
- Special doping is not required in Raman amplification
- RA is distributed amplifier since the signal amplification takes place through the entire length of the fiber.
- High energy pump optical wave is co-launched into the fiber
- Raman gain depends on the pump optical power and frequency shift between pump and signal optical signal
- The energy of pump photon reduced their wavelength will be aligned to the signal photon wave length

Raman Amplifiers Operation

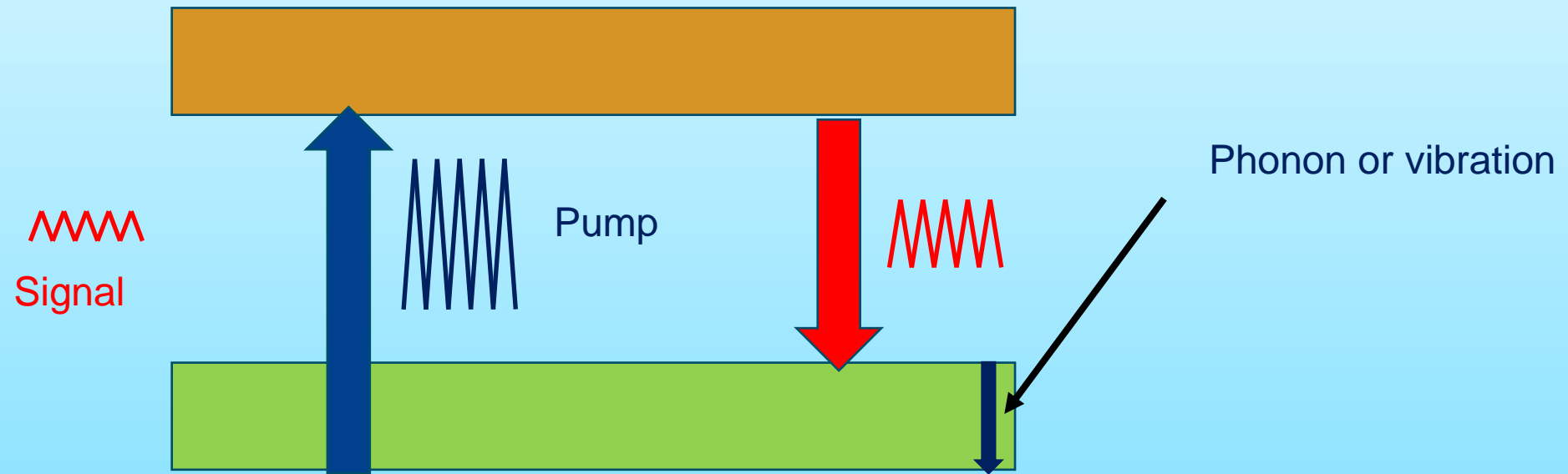


Figure 11: Raman Amplifier operation

Raman Amplifiers Configurations

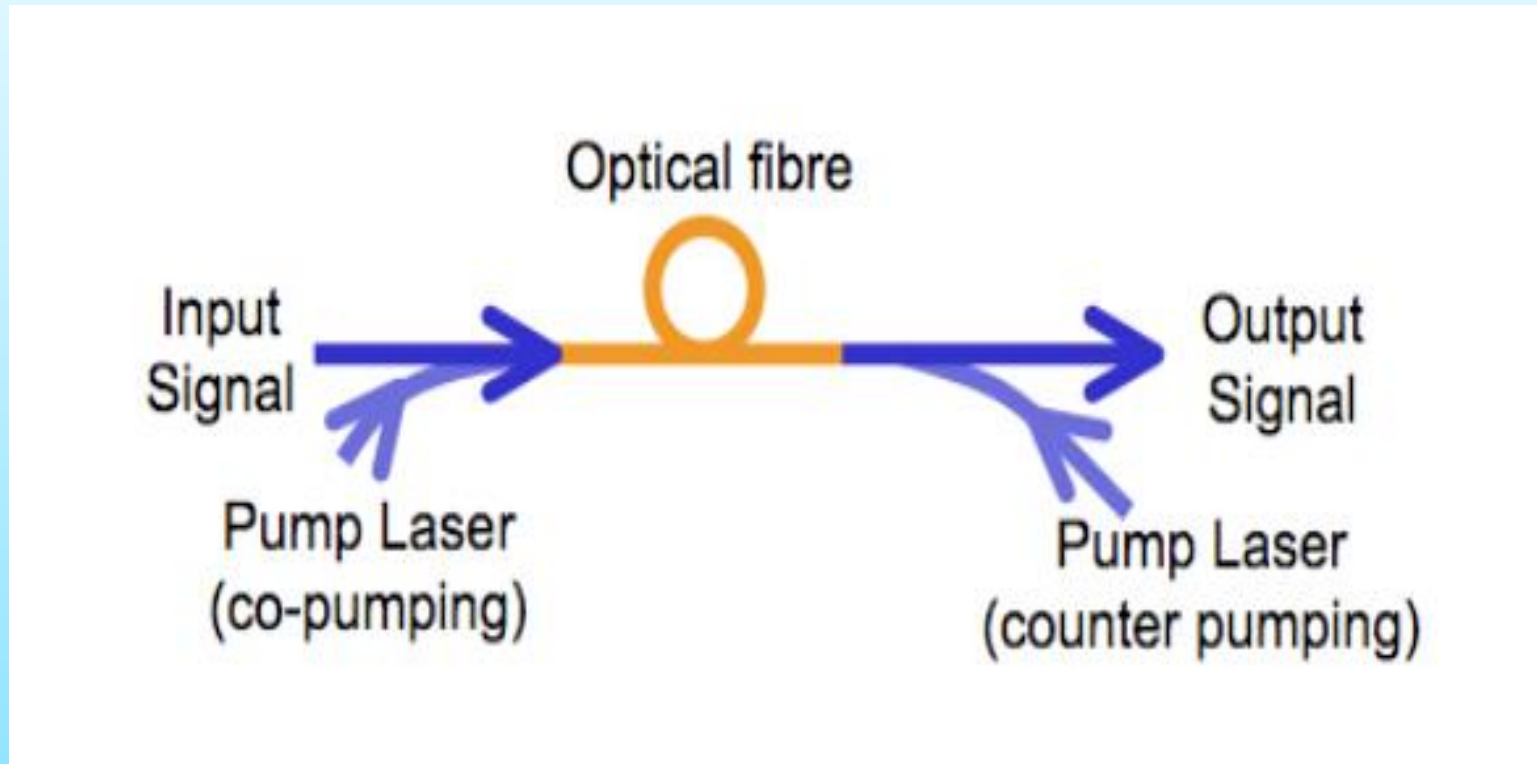


Figure 11: Raman Amplifier pump configuration

Source: "EDFA vs Raman amplifier," Telecomate, Mar. 22, 2023.
<https://www.telecomate.com/wp-content/uploads/2023/03/EDFA-vs-Raman-amplifier-3.png>

Summary

- **Significance of Optical Amplifier:**
 - ✓ To compensate optical power reduction due to attenuation
- **General Operation principle:**
 - ✓ Using external pumping to achieve population inversion
 - ✓ Signal amplification through stimulated emission
- **Common Types of Optical Amplifiers:**
 - ✓ **SOA:** laser like operation, electrical pump, amplification in gain cavity
 - ✓ **EDFA:** Erbium doped fiber, use optical pump
 - ✓ **Raman Amplifier:** exploit the nonlinearity of silica fiber, use optical pump

References

- [1] Gerd Keiser, "*Fiber Optic Communications*", Springer, Pp.442, 2021.
- [2] Govind P. Agrawal, "Fiber-Optic Communication Systems", John Wiley & Sons, Pp.243, 2002.



Thank You !