ECE 6323

OPTICAL AMPLIFICATION, WAVELENGTH CONVERSION AND REGENERATION

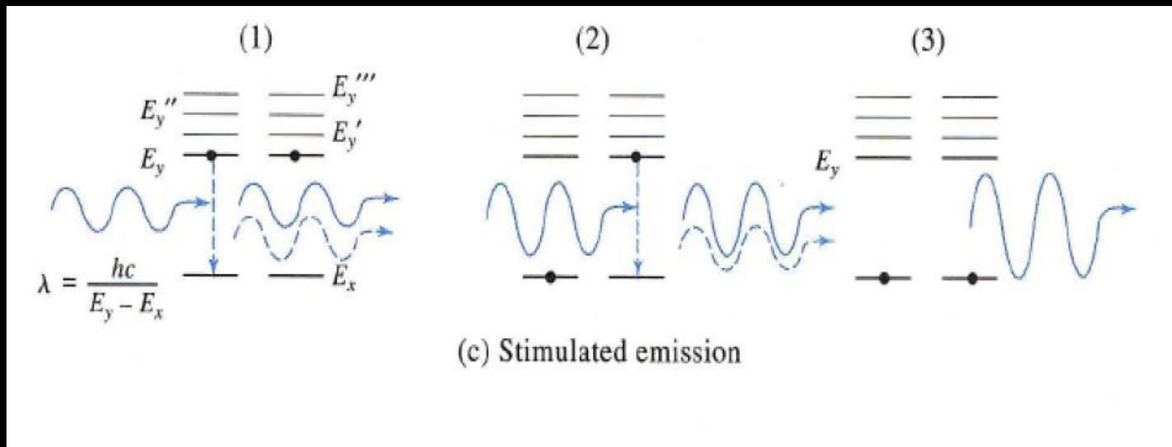
Outline

- Introduction
- Fundamental of optical amplifiers
- Types of optical amplifiers
  - Erbium-doped fiber amplifiers
  - Semiconductor optical amplifier
  - Others: stimulated Raman, optical parametric
- Advanced application: wavelength conversion
- Advanced application: optical regeneration

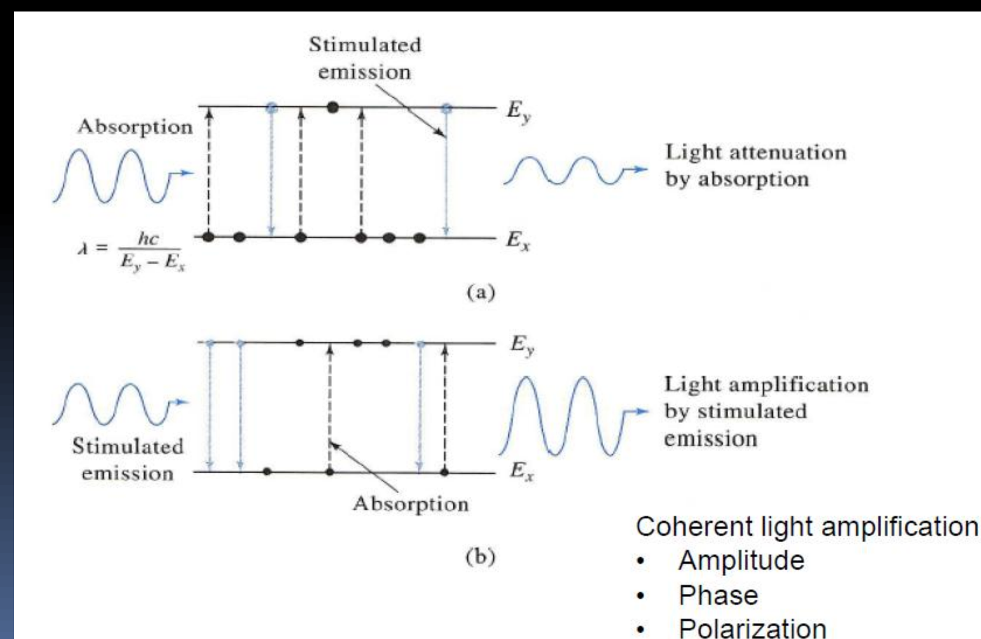
Introduction

- What is optical amplification?
- What use is optical amplification?

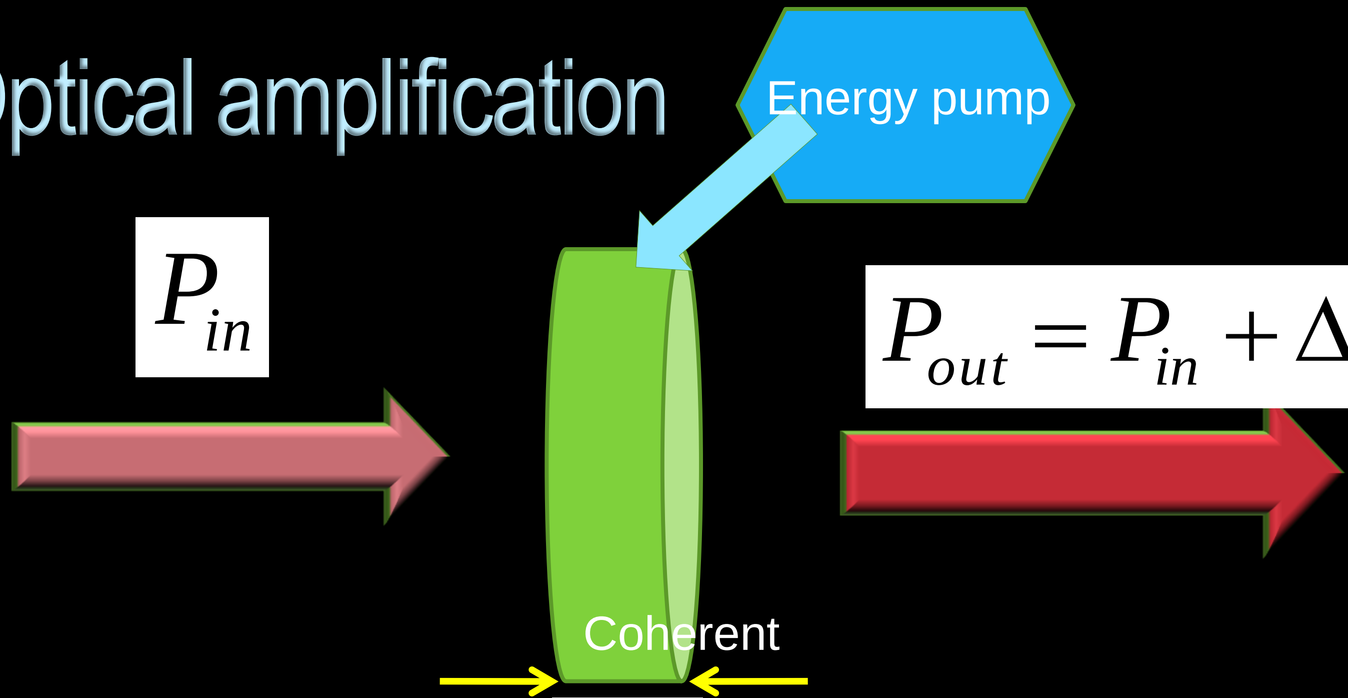
Review: stimulated emission



- Through a population, net gain occurs when there are more stimulated photons than photons absorbed
- Require population inversion from input pump
- Amplified output light is coherent with input light



Optical amplification



$$P_{in}$$

$$P_{out} = P_{in} + \Delta P$$

$$\Delta z$$

$$\Delta P = P_{in}\, \gamma (N_2 - N_1)\, \Delta z$$

$$\frac{dP}{dz} = gP$$

If g>0: Optical gain (else, loss)

Optically amplified signal: coherent with input: temporally, spatially, and with polarization

Introduction

- What is optical amplification?
- What use is optical amplification?
  - The most obvious: to strengthen a weakened signal (compensate for loss through fibers)
  - …But why not just detect the signal electronically and regenerate the signal?
    - System advantage: boosting signals of many wavelengths: key to DWDM technology
    - System advantage: signal boosting through many stages without the trouble of re-timing the signal
    - There are intrinsic advantages with OA based on noise considerations
    - Can even be used for pre-amplification of the signal before detected electronically

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Optical amplification fundamental

Summary of OA fundamental

Key concepts in optical amplification process:

1- The signal is amplified with gain as in the following equation:

$$(d\, I[z])/(d\, z) = g[z]\, I[z]$$

but gain g[z] can be saturated:

$$g[z] = g_0/(1 + I(z)/I_{sat})$$

where g_0 is a characteristic value, and I_{sat} , the saturation intensity is:

$$I_{sat} = (\gamma_{spont}/(2\, \gamma_{stim}))\, h\, \nu$$

where γ_{spont} and γ_{stim} are the amplifier stimulated emission and spontaneous emission coefficients, respectively.

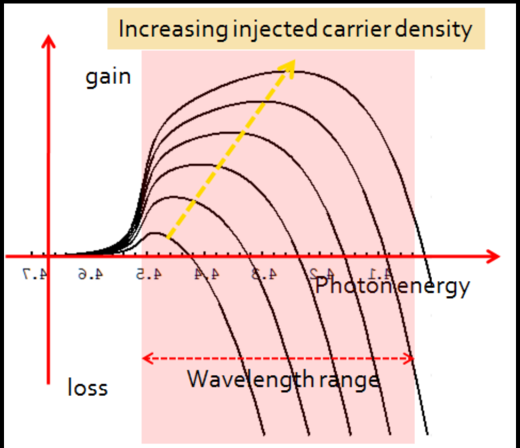
The main features are:

1.a power (or intensity) gain is exponential at small signal

1.b but becomes linear when the power (or intensity) is large

Summary of OA fundamental (cont.)

2- Just like a laser has certain spectral range, gain can occur only over certain range of wavelength that depends on the medium. The variation of gain vs. wavelength is called gain spectrum, g[λ]



3- The light coming out of an OA is not just the amplified input signal (*what if we don't have any input*?) but also includes Amplified Spontaneous Emission (ASE): very important effect on the OA noise characteristics,

4- There are 2 key noise terms of an OA:
- Signal--spontaneous beat noise
- Spontaneous--spontaneous beat noise

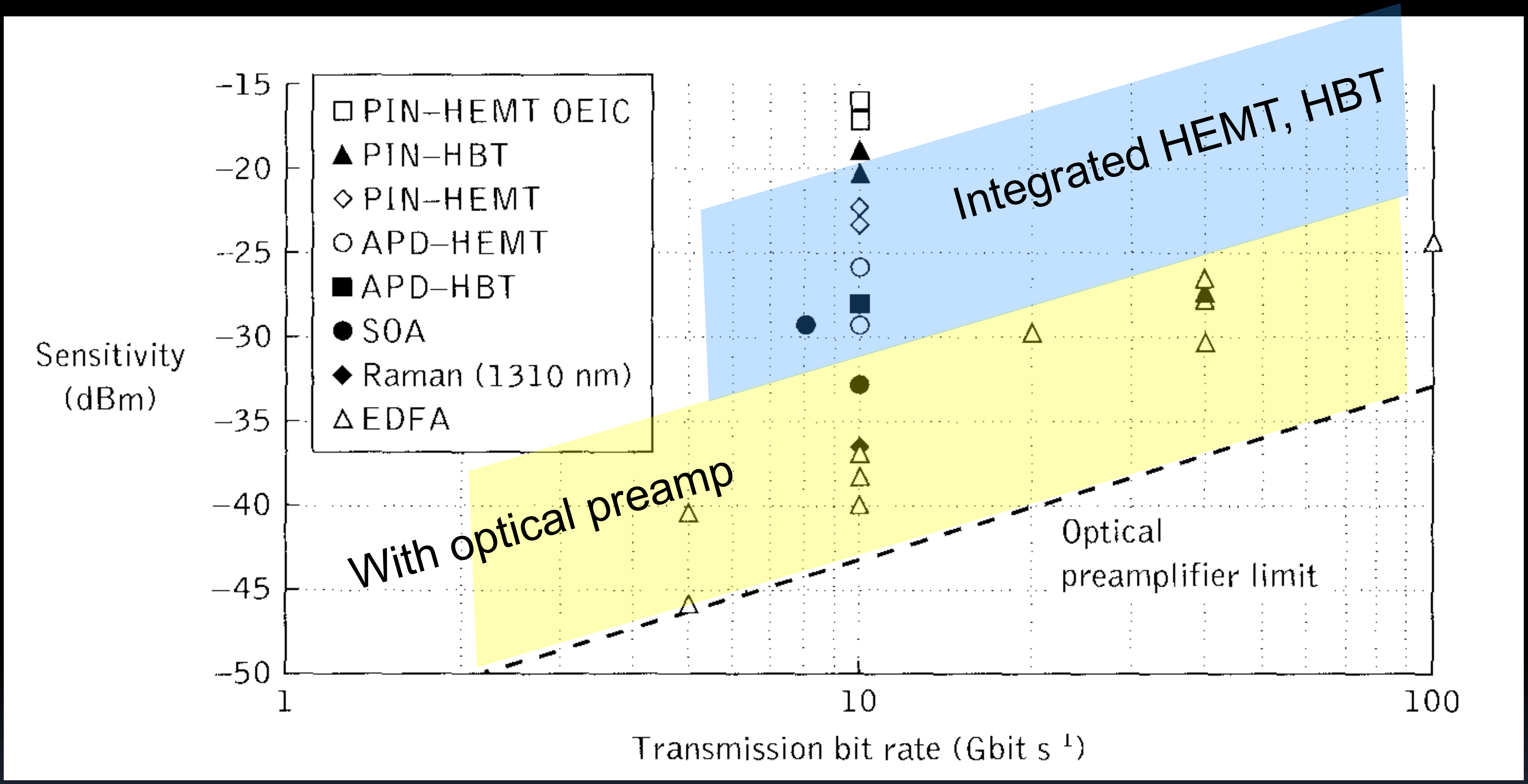
Both are critical to the performance of OA.

Example of optical amplifier research

Key points

- Optical amplifier can be:
  - Booster: boosts the signal power that is loss through transmission
  - Pre-amplifier: enhance the signal to overcome detector noise
- Gain behavior is:
  - Linear for booster application (high power gain)
  - Exponential for small signals (pre-amp)
- Noise source from ASE:
  - Signal-ASE beat noise
  - ASE-ASE beat noise

Some Receiver Performance Data



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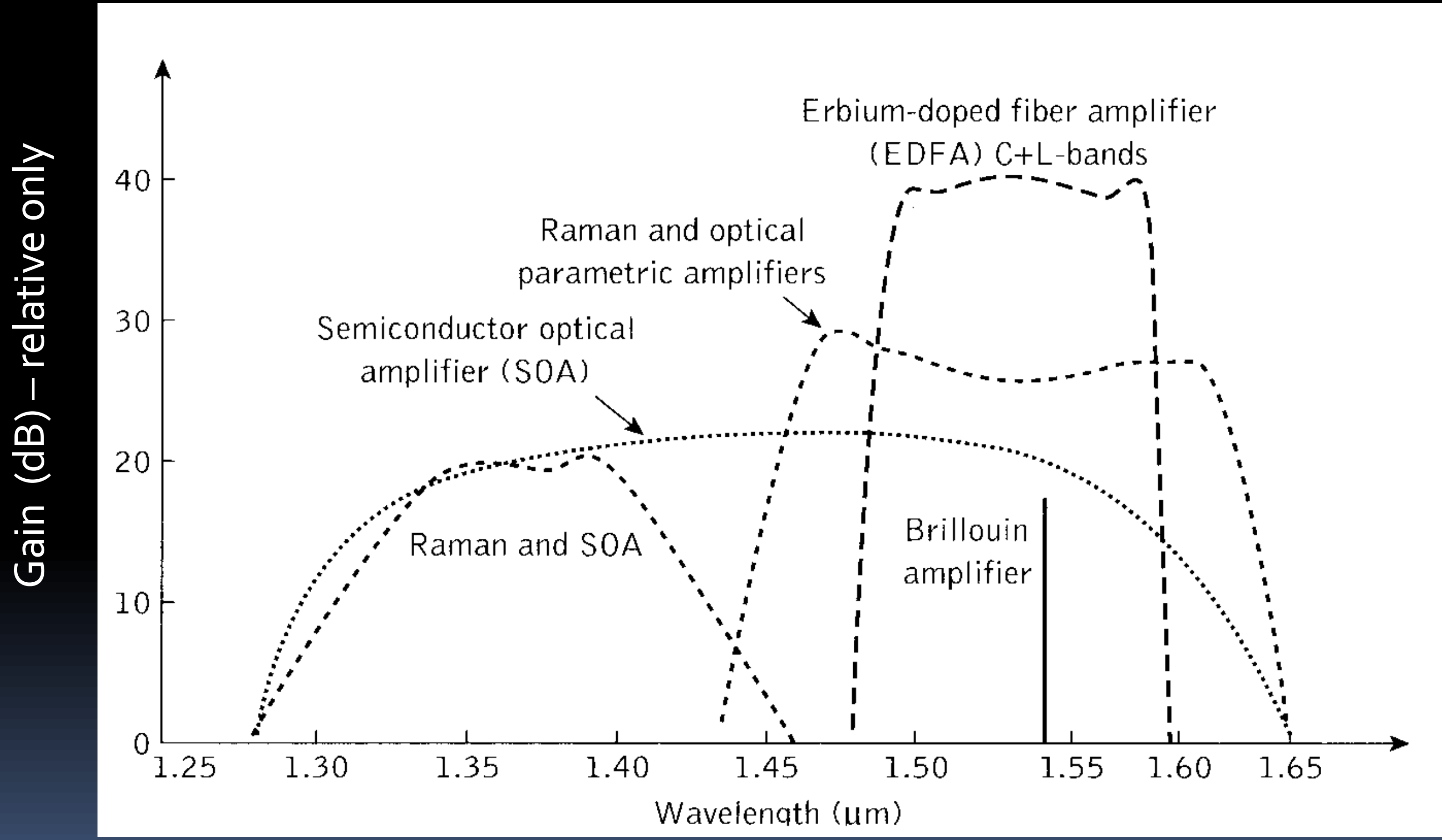
Spectra of various type of amplifiers

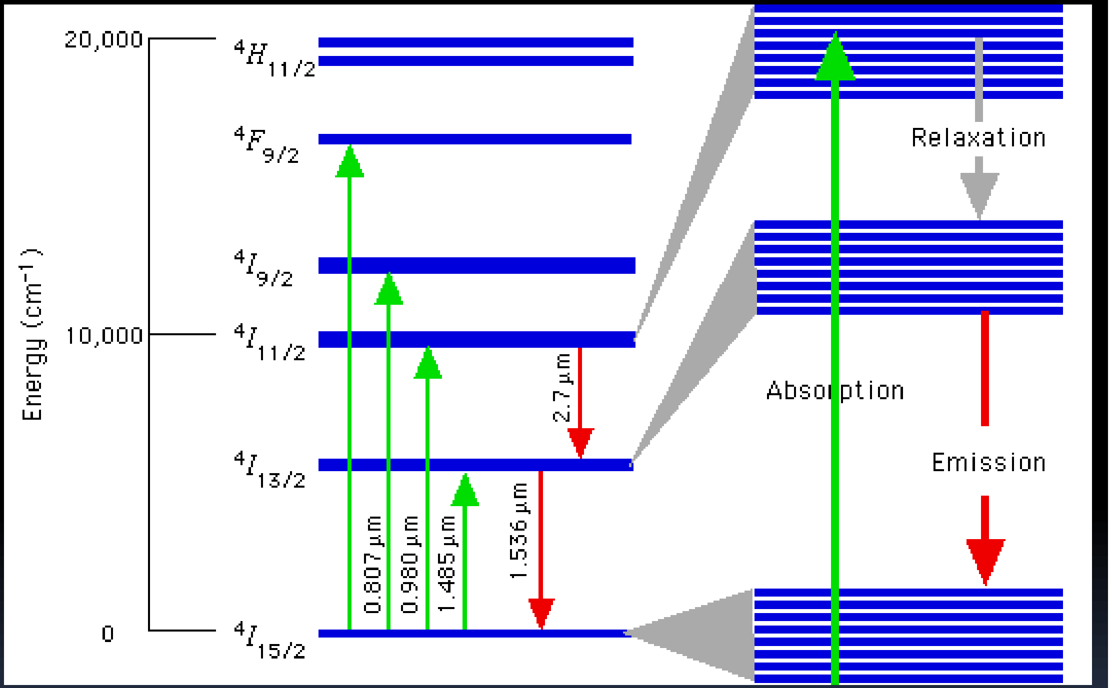


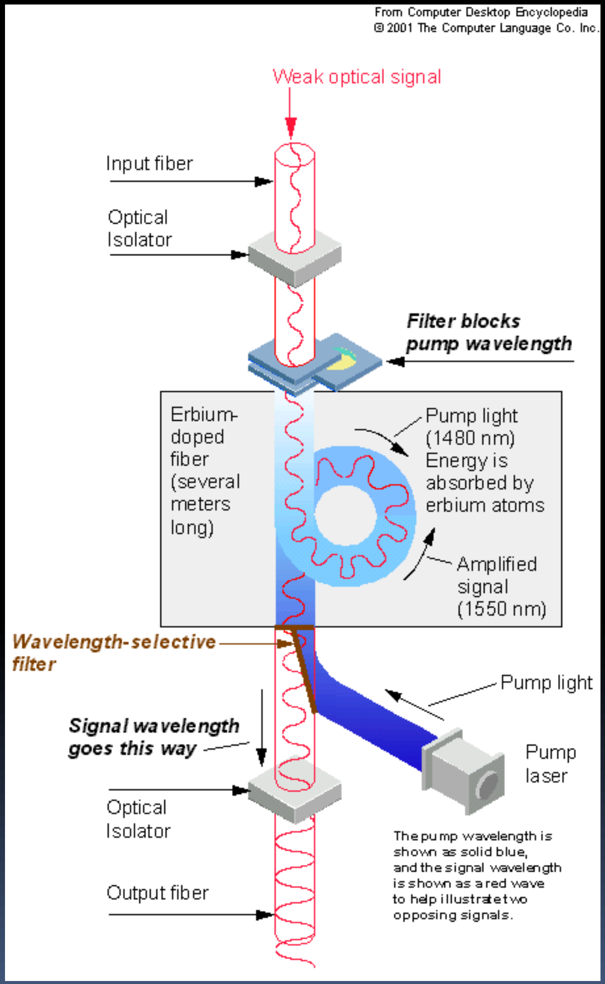
Functional properties of various OAs

- Different OA types serve different operational needs:
  - Some for high power booster
  - Some for mid-range power
  - Some for pre-amplification
  - Some for processing on chip (to compensate for loss)
  - Some for optical signal processing in photonic circuit
  - For optical communication applications, virtually all are in waveguide form.
  - Cost-performance are also major factor

Erbium doped fiber amplifier (EDFA)

Energy structure of Er^{3+} ion in glass

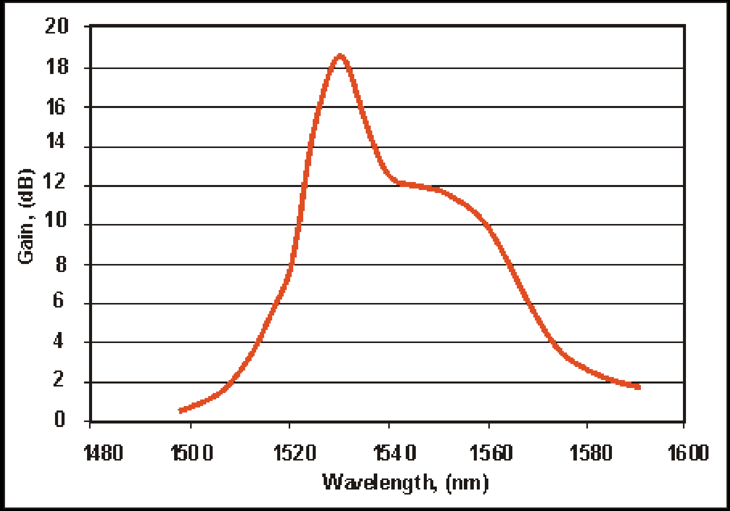


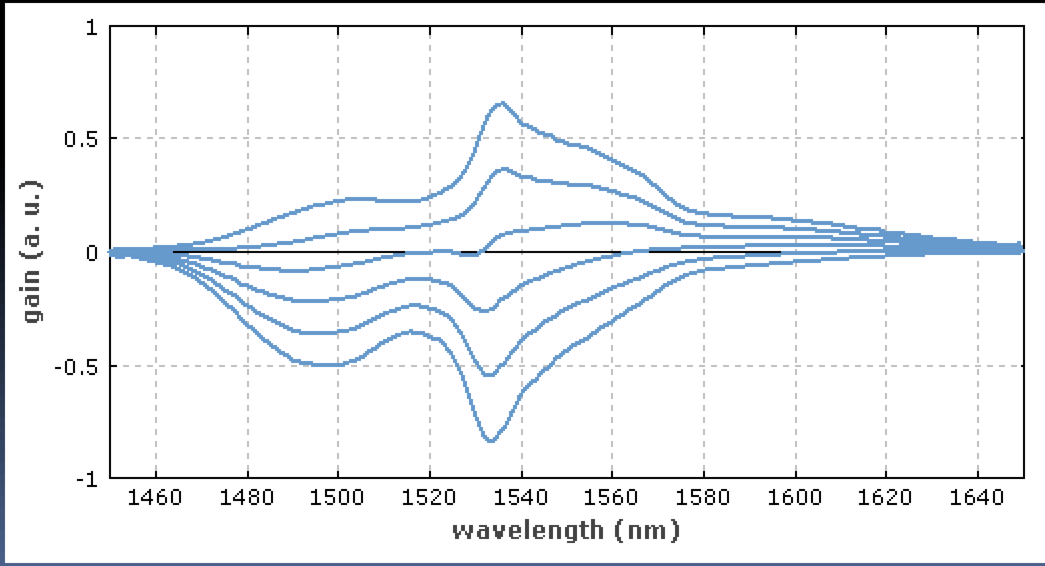


EDFA gain spectrum characteristics

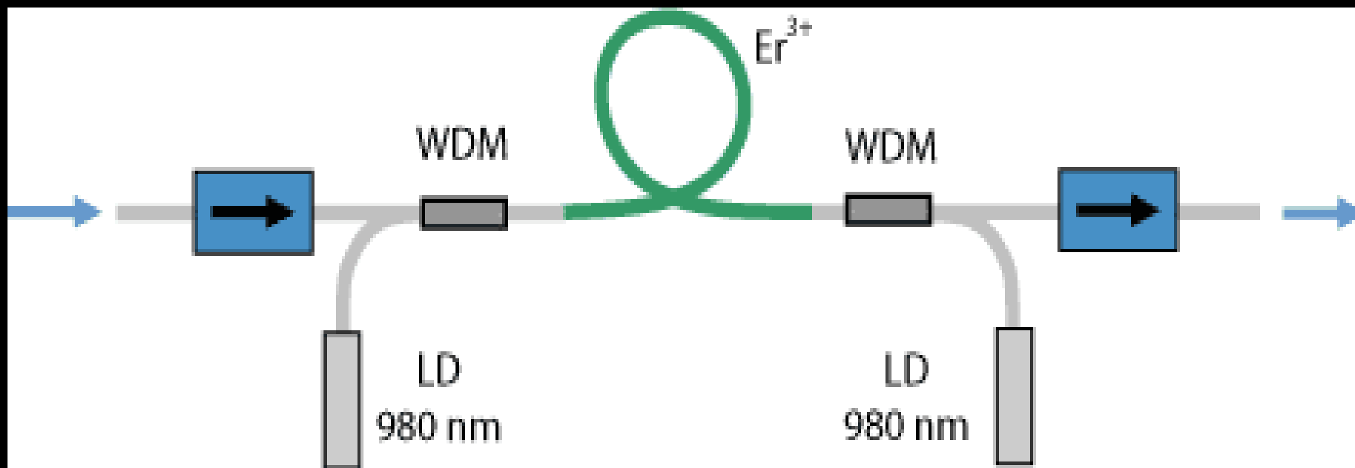
- Intrinsic gain is NOT flat over the C and L band
- Must be engineered to flatten the effective gain

- System application sometimes require equalizer





Typical EDFA module



Semiconductor Optical Amplifiers (SOA)

- Most versatile: spectrum, gain, size, and integratability
- Remember the semiconductor laser: any semiconductor laser structure without optical cavity can function as an OA:
  - Edge emitting ridge waveguide
  - Vertical amplification, multiple pass design
- Cost competitive, especially for pre-amp

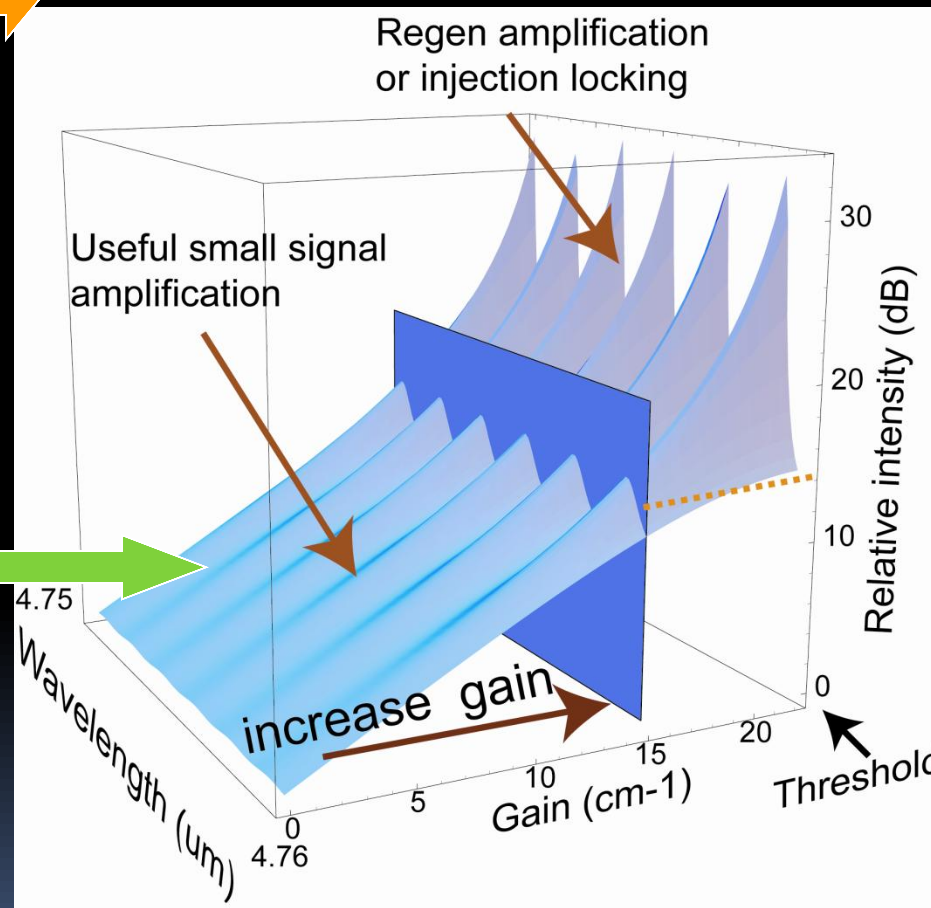
EXAMPLE OF A SEMICONDUCTOR OPTICAL AMPLIFIER

Problems with Straight Waveguide Amplifier

20 dB
(not included input coupling loss)

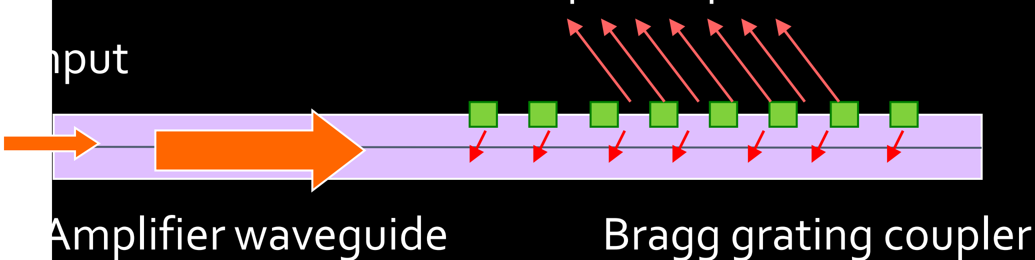
0.01

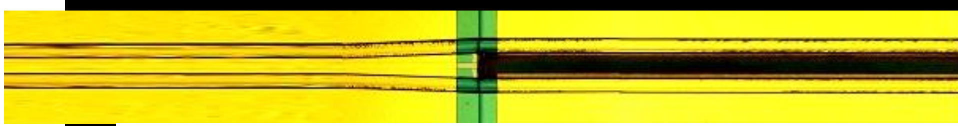
Real useful gain

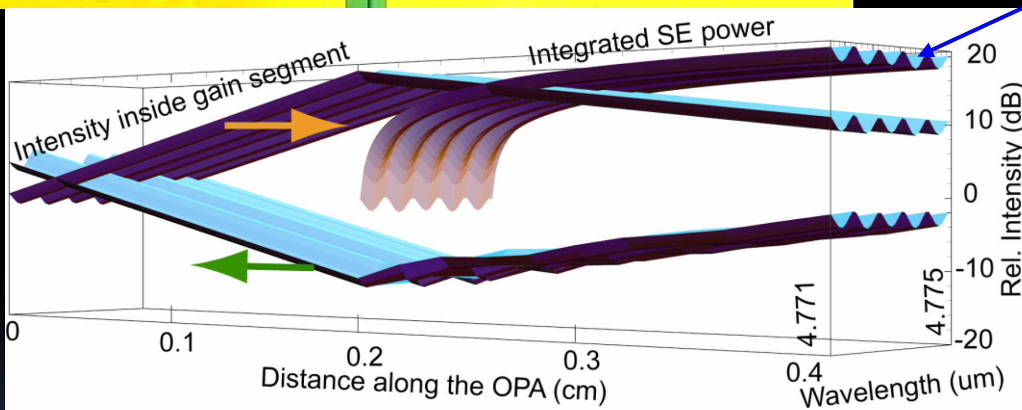


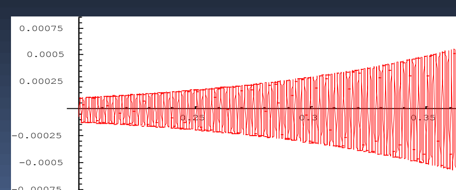
~10-11 dB with coupling loss

Why Bragg Grating Coupled OPA?



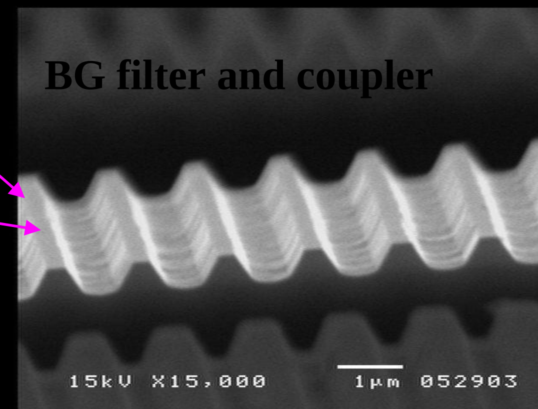


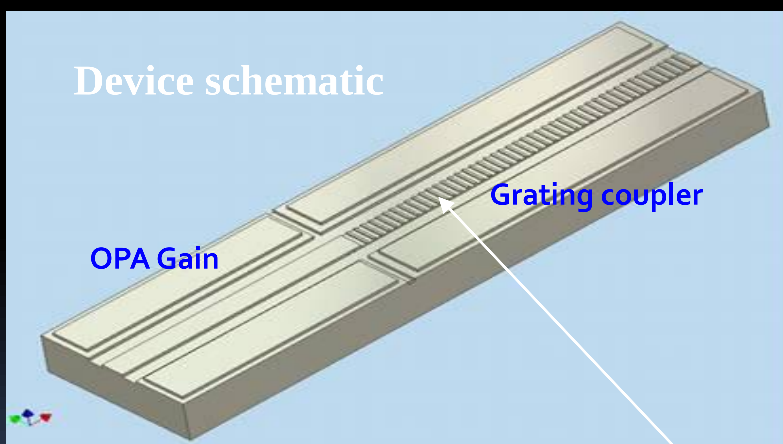




- **Surface emitting BG is a large-loss element:**
  - Lasing suppression
  - AR coating tolerance
  - Low gain FP ripple
- **Wavelength dispersion**
  - WDM, multi-spectral applications
  - ASE filtering for low noise
- **Low numerical aperture output (flat wavefront); distributed output for high power applications**

Device Structure and Fabrication



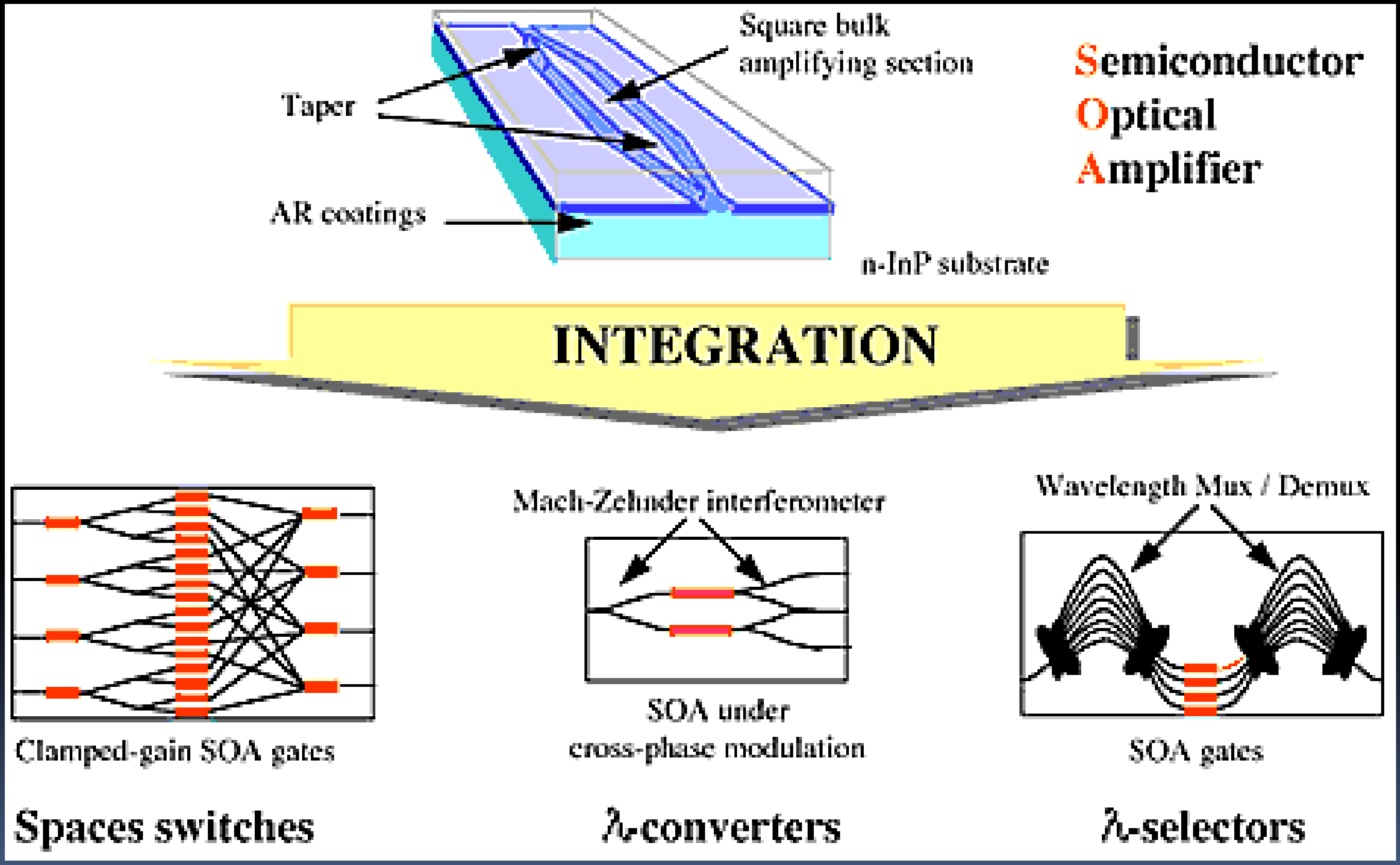


BG: Λ=1.42μm, 50% dc, 0.5μm deep

Device: width 17 μm; Gain length 1.8mm; BG length 1.5mm.

(can be tilted, but insignificant improvement)

Some photonic circuit designs with SOA



Others: Raman, Optical Parametric Amp

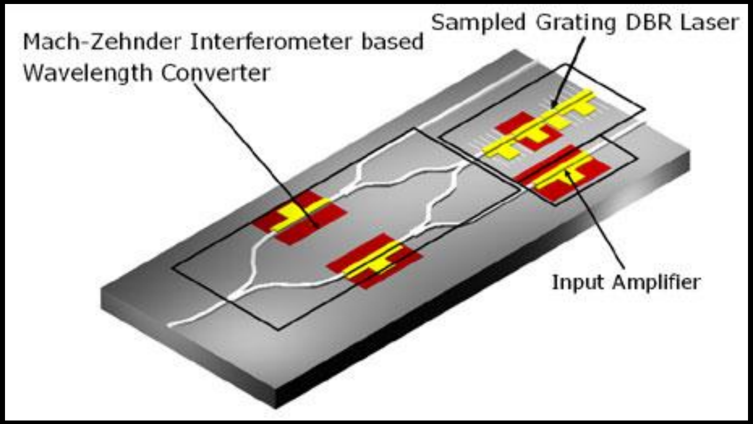
- Stimulated Raman emission: can be used for gain
  - Lower gain, requires higher pump power than EDFA and SOA
  - But offer wider gain spectrum than EDFA
  - Specialized application
- OPA: A nonlinear process, require materials with high optical nonlinearity. Require very high peak power. Less practical

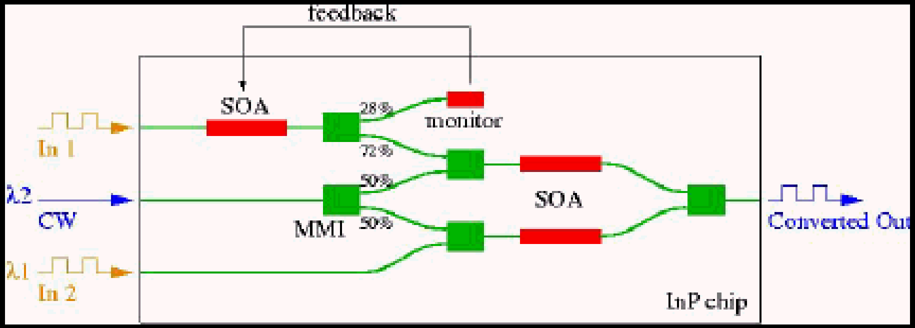
Wavelength Conversion

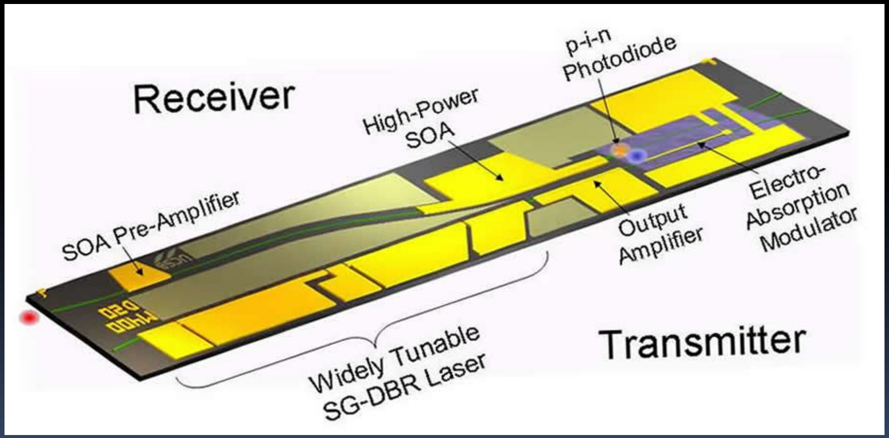
Sometimes, it’s useful to change the carrier wavelength of a signal

- For network management, a signal may need to change its wavelength from one segment to another
- There are many ways to achieve this, some preferred ways is NOT to convert the signal back to electrical: direct optical conversion
- There are a number of approaches, but all with some limits

Some wavelength converter concepts

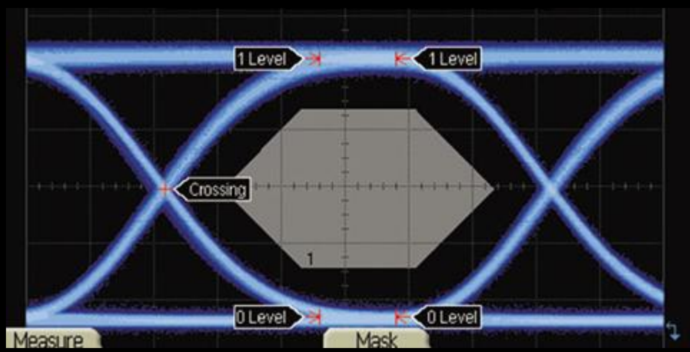




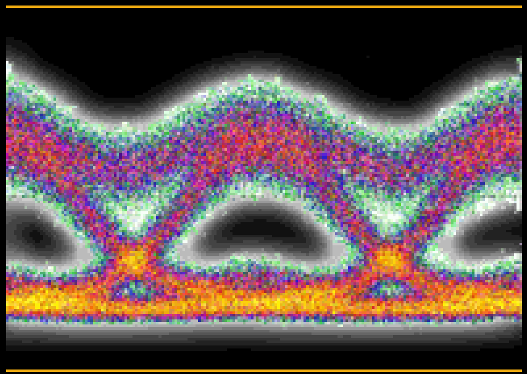


Signal Regeneration

Input

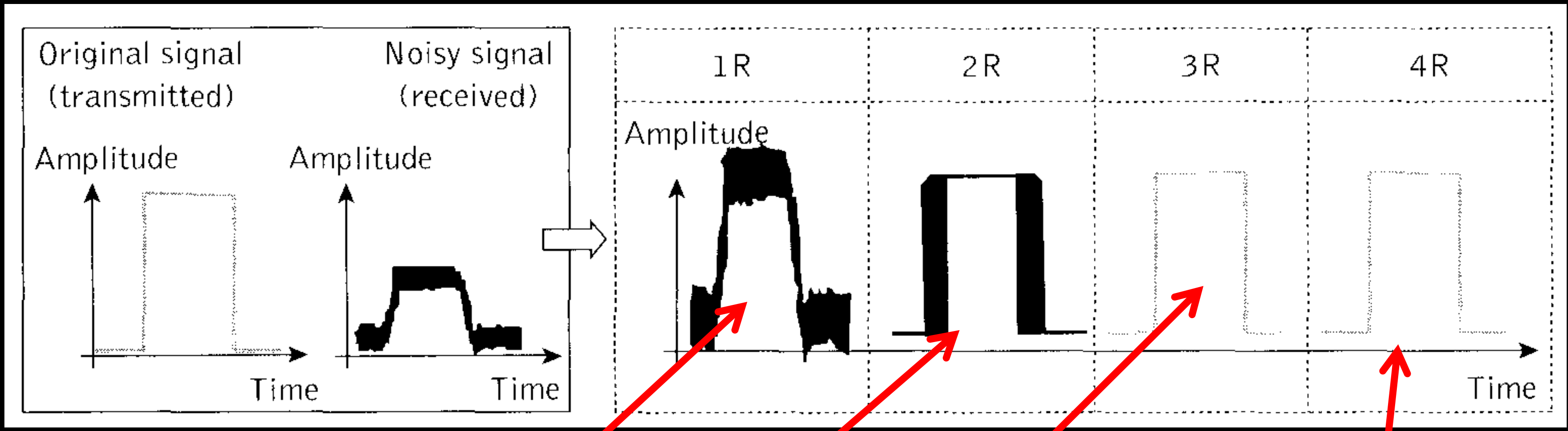


Output



- A signal can be degraded in different ways:
  - weaker (amplitude) – need re-amplification
  - distorted (shape) – need re-shaping
  - jittered – need re-timing
  - This is the concept of 3R
- Sometimes, there is one more R to make 4R: need wavelength conversion: re-allocation of wavelength

Signal regeneration concepts



Amplification to overcome loss

Reshape to overcome distortion due to dispersion and loss

Re-time to overcome jitter due to dispersion and random fiber vibration

Re-allocation of wavelengths (for network efficiency)

Technology for 3R or 4R

- While it is highly desirable, it is still a big technical challenge to come up with an efficient device for 3R and 4R, a few exists but not quite widespread usage
- Nevertheless, it is likely will be integrated in future system, depending on the demand
- It would make network more efficient