# Lecture 5
# - passive and active optical components – part 2

Kaiser – cap 9

# Optical components classification:

## Outline

- Types of optical components
  - Passive (reciprocal & non-reciprocal)

  Lens, couplers, isolators, circulators, filters, multiplexer, demultiplexer
  - Active

  Modulator, switch, optical amplifier, wavelength converter, gain equalizer
- Wavelength Selectivity
  - Fixed
  - Tunable
- Parameters

  Temperature dependency, insertion loss (input→output loss)

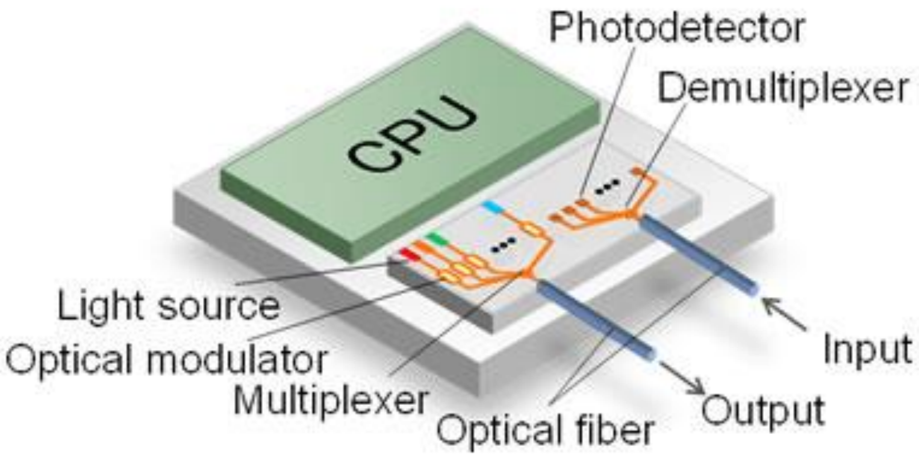
  inter-channel cross-talks, fast tunability, stability and polarization dependency

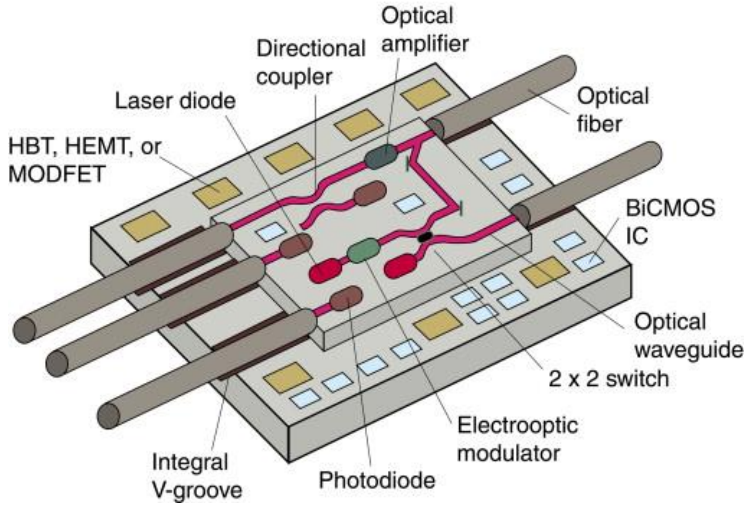
# Application examples

EXAMPLES

# Integrated silicon optical transmitter to carry large volumes of data between CPUs, modulators

Google keyword: photonic quantum computing chip

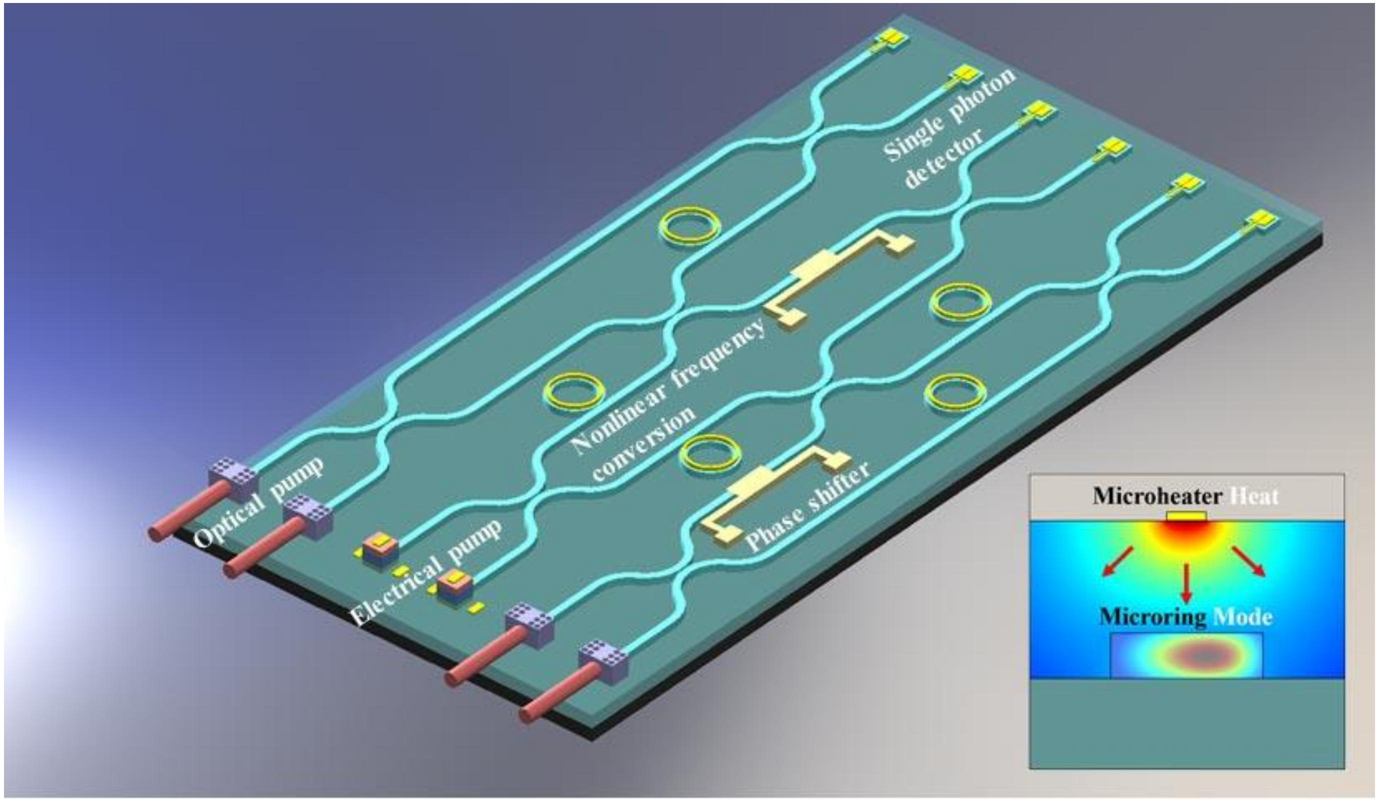



https://phys.org/news/2012-08-silicon-optical-transmitter-large-volumes.html

https://www.sciencedirect.com/science/article/pii/S1369702104006789

# New Tunable Optical Chips Can Be Used As Building-Blocks for Next Generation Quantum Computers




*School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia, USA*

https://scitechdaily.com/new-tunable-optical-chips-can-be-used-as-building-blocks-for-next-generation-quantum-computers/

"High-Q microresonators integrated with microheaters on a 3C-SiC-on-Insulator platform" by Xi Wu, Tianren Fan, Ali A. Eftekhar, and Ali Adibi, *Optics Letters*, 44, 20, 4941-4944 (2019).
DOI: 10.1364/OL.44.004941

# Two-qubits controlled-unitary quantum gates for quantum computing by silicon photonic chip (2017)

A **quantum state** provides a probability distribution for the value of each observable, i.e. for the outcome of each possible measurement on the system.

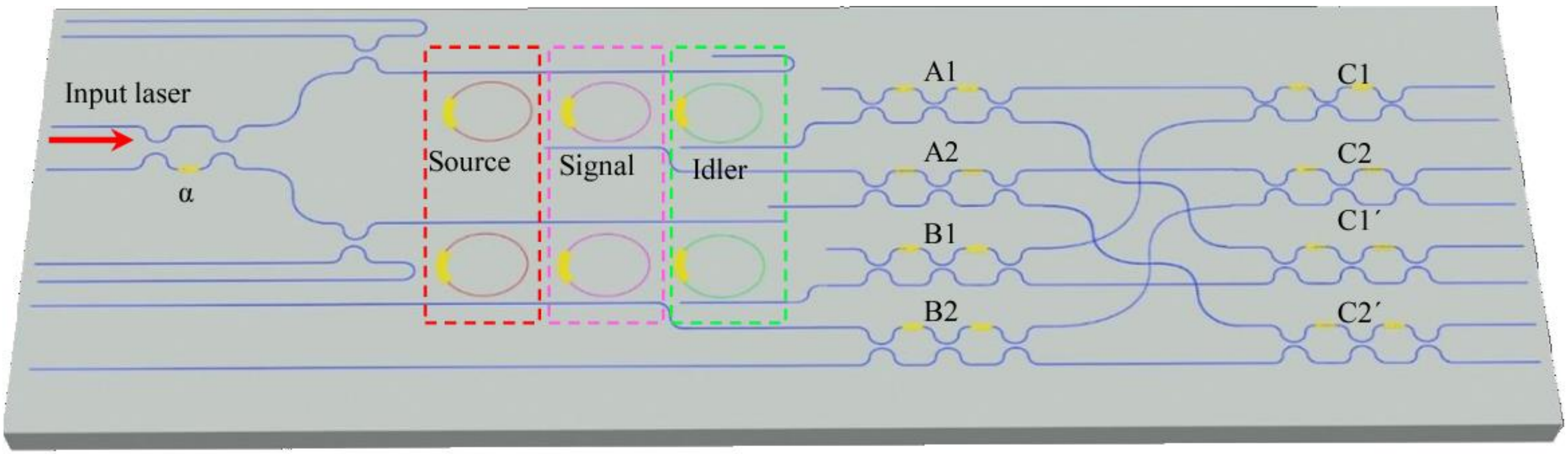



Fig. 1. Schematic illustration of the two-qubits gate operation on the photonic chips.

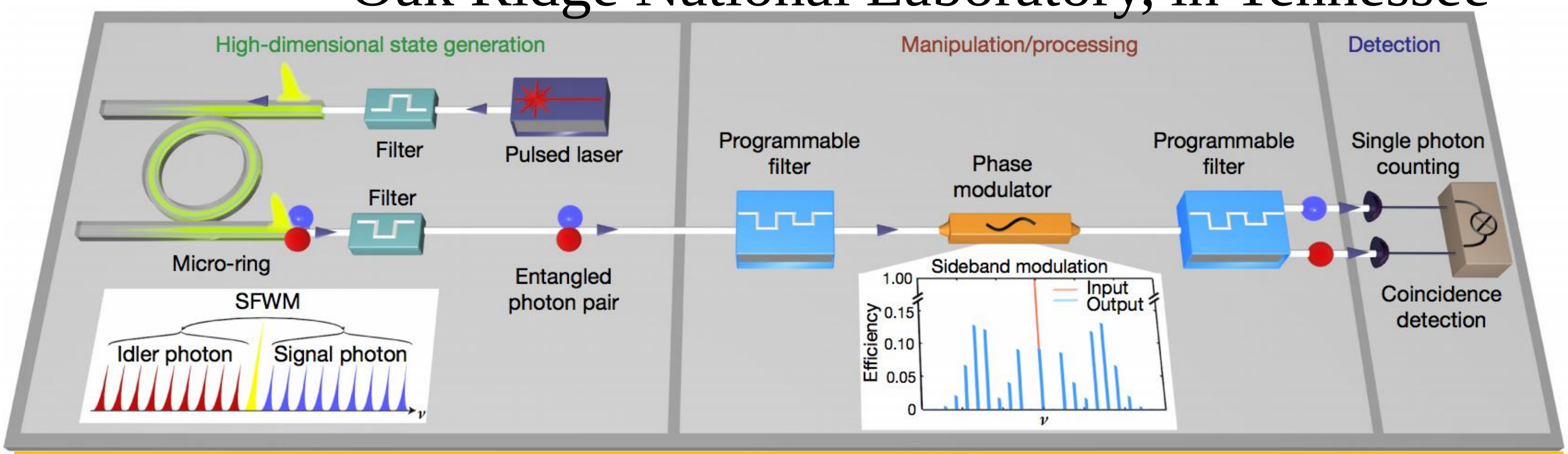
https://www.semanticscholar.org/paper/Two-qubits-controlled-unitary-quantum-gates-for-by-Huang-Kwek/d26dfb680657a5ea6821f5271d426acbb4620595

https://www.laserfocusworld.com/optics/article/16566918/new-dutch-silicon-nitride-photonics-company-quix-aims-at-quantum-computing

# Qudits: The Real Future of Quantum Computing? (2017)

**Qudits can have 10 or more quantum states simultaneously compared to just two for qubits**

Oak Ridge National Laboratory, in Tennessee




https://spectrum.ieee.org/tech-talk/computing/hardware/qudits-the-real-future-of-quantum-computing

Instead of creating quantum computers based on qubits that can each adopt only two possible options, scientists have now developed a microchip that can generate “qudits” that can each assume 10 or more states, potentially opening up a new way to creating incredibly powerful quantum computers, a new study finds.

Classical computers switch transistors either on or off to symbolize data as ones and zeroes. In contrast, quantum computers use quantum bits, or qubits that, because of the bizarre nature of quantum physics, can be in a state of superposition where they simultaneously act as both 1 and 0.

# Passive components – part 2

# How can we define a passive component?

A passive component is an optical device that modifies the propagation of the light at its inputs **completely in the optical domain without external power supply** or electrical signal

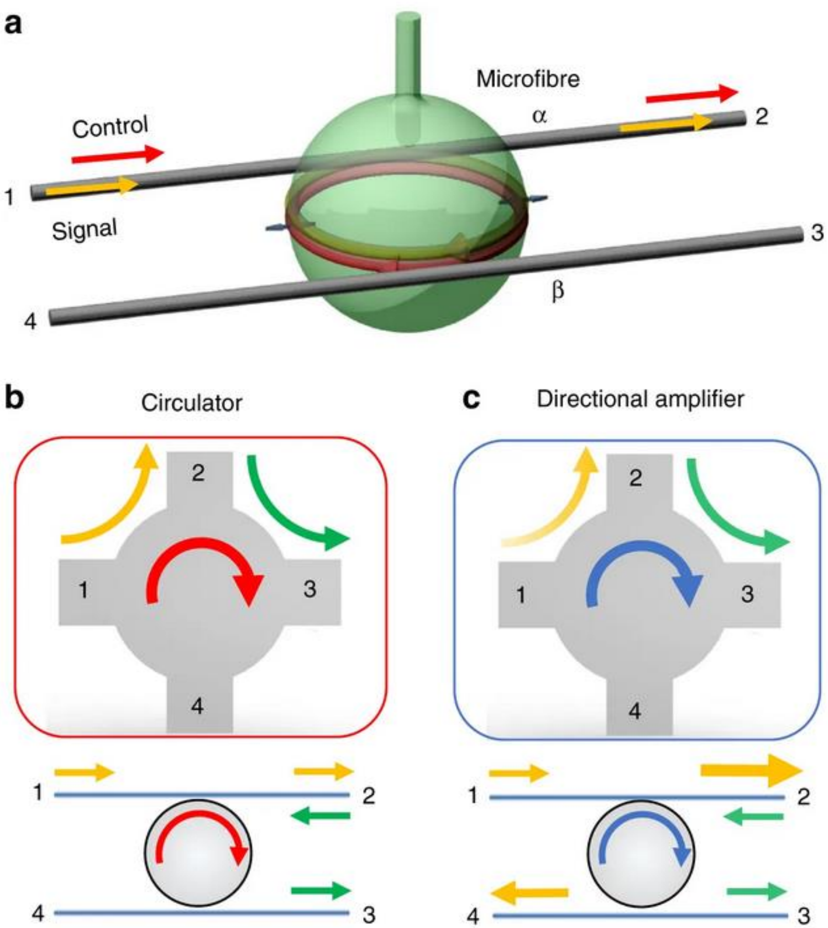
It can be classified by three different ways:

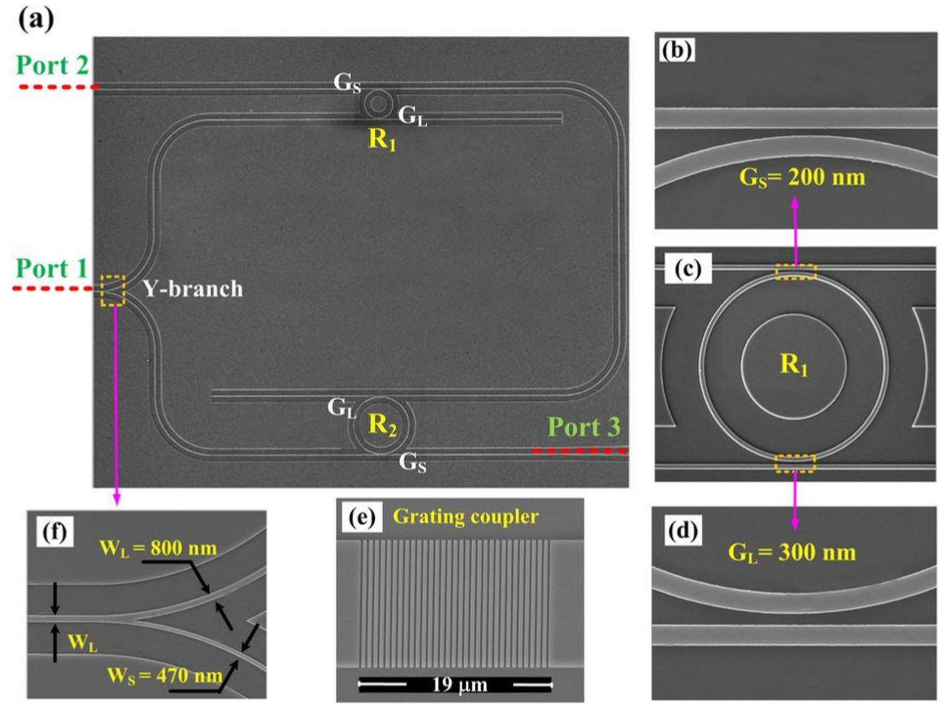
- According to their functionality
- According to their structure
- According to their port number

http://imedea.uib-csic.es/~salvador/docencia/coms_optiques/addicional/ibm/ewtoc.html

# Optical circulators

# Polarization independent-> Opto-mechanical circulator



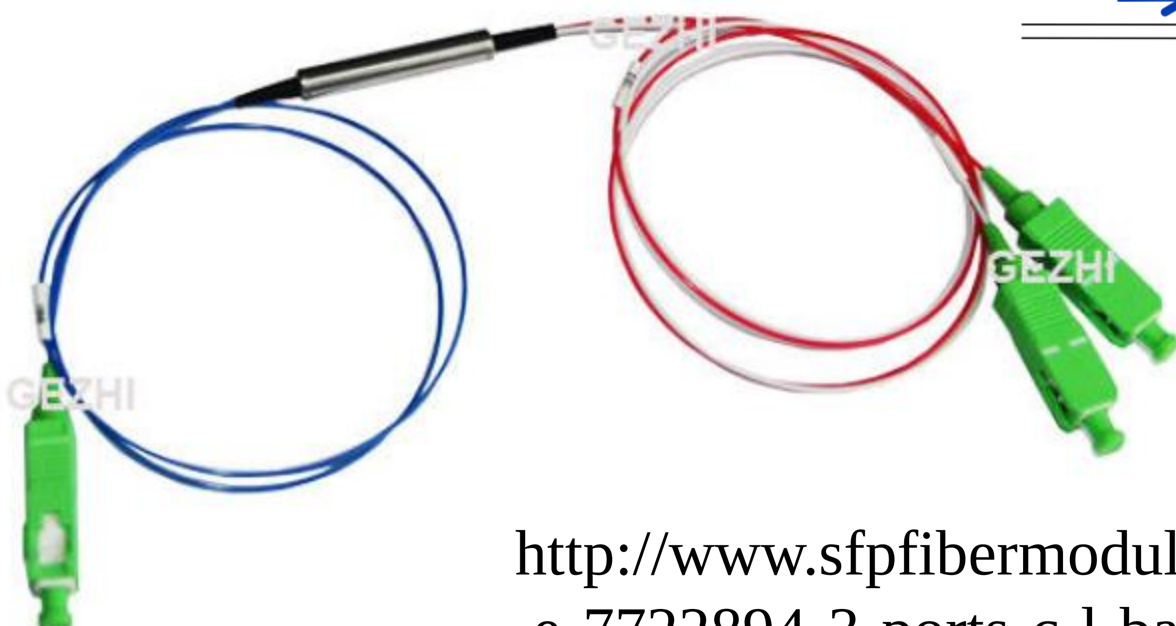



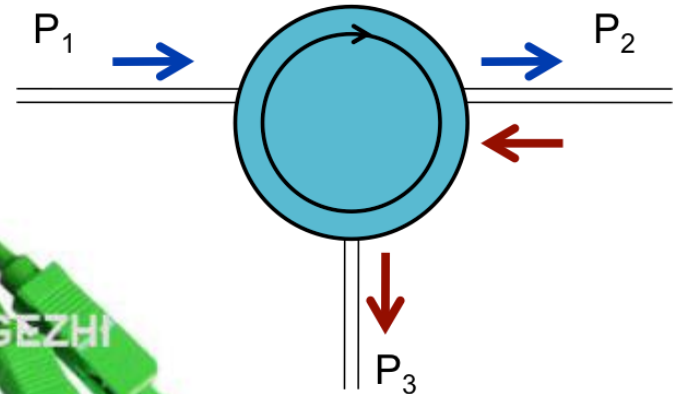

https://www.nature.com/articles/s41467-018-04187-8/figures/1

https://www.nature.com/articles/srep10190

# Component and symbol – implementation with optical fiber

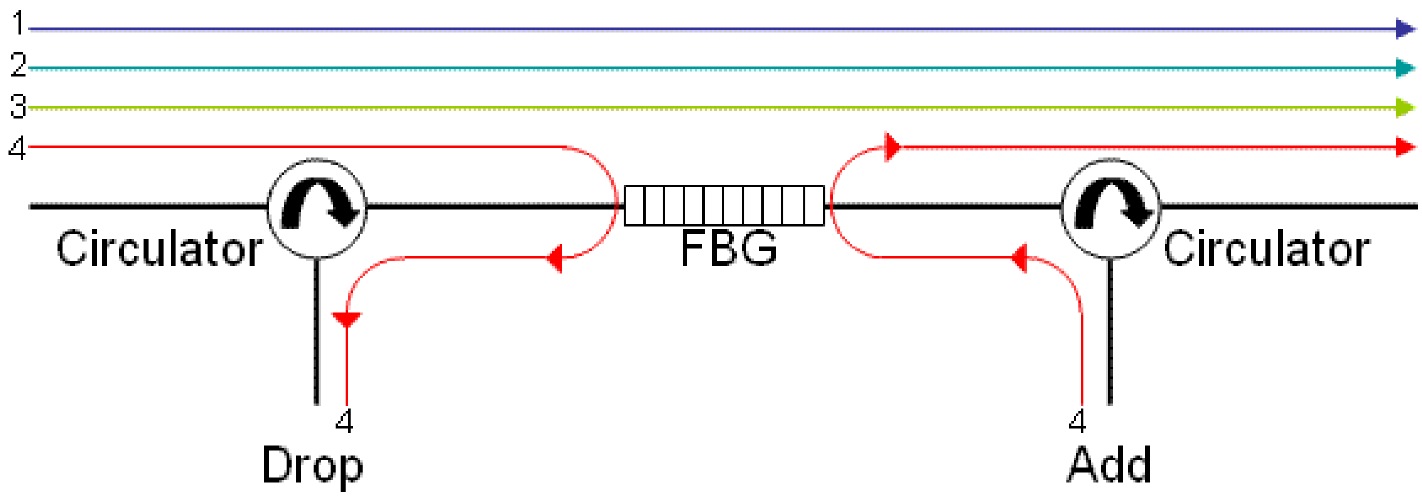
https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=373

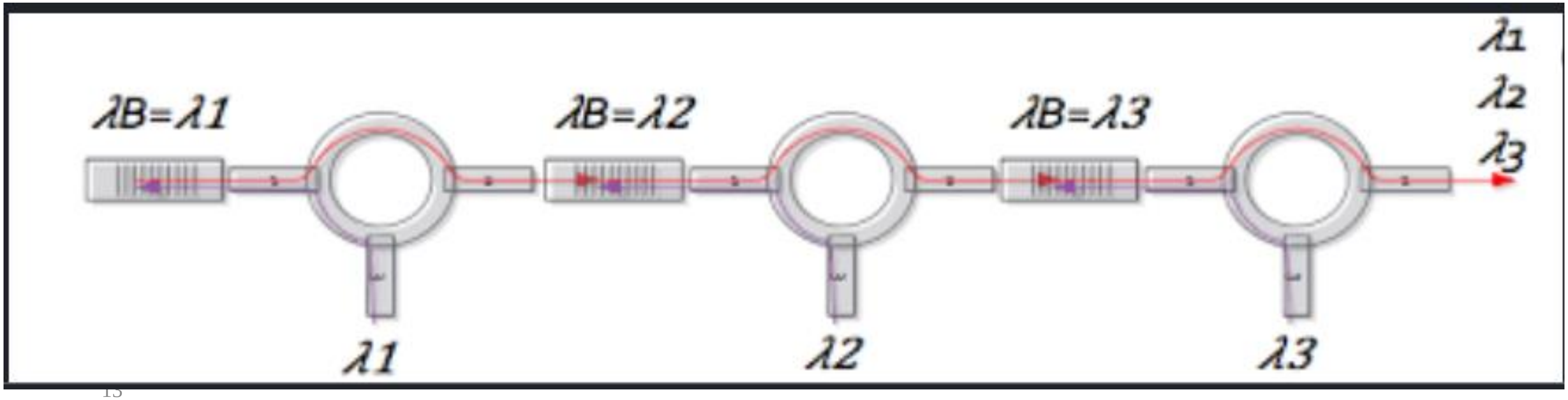



http://www.sfpfibermodule.com/sale-7722894-3-ports-c-l-band-fiber-optical-circulator-polarization-insensitive-components.html

# Application - OADM

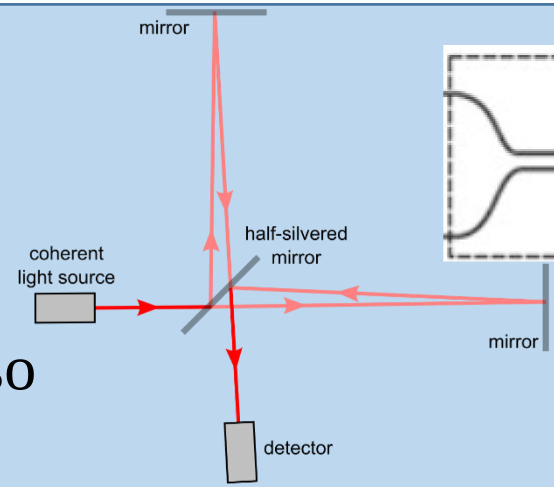


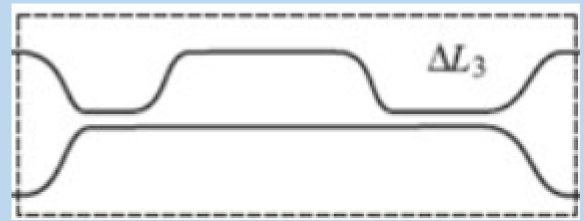



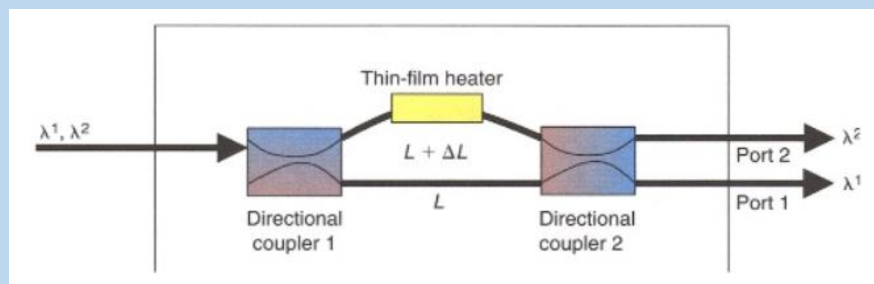
# Interferometer

# Interferometers- Fixed or tunable

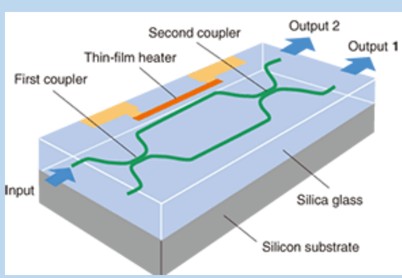
- Passive device but also

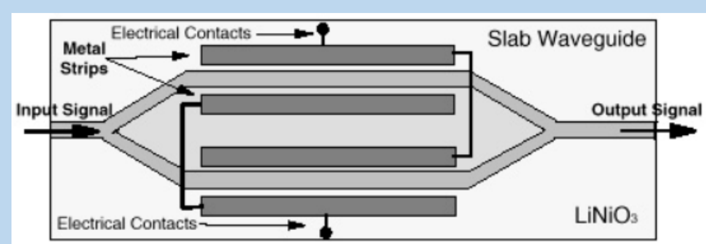


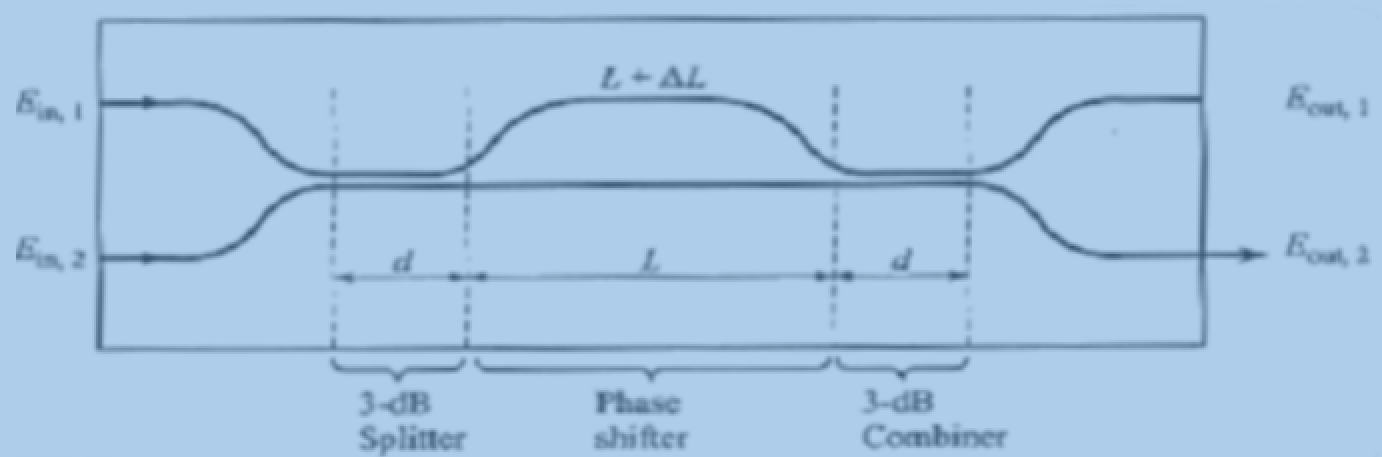

- Active device



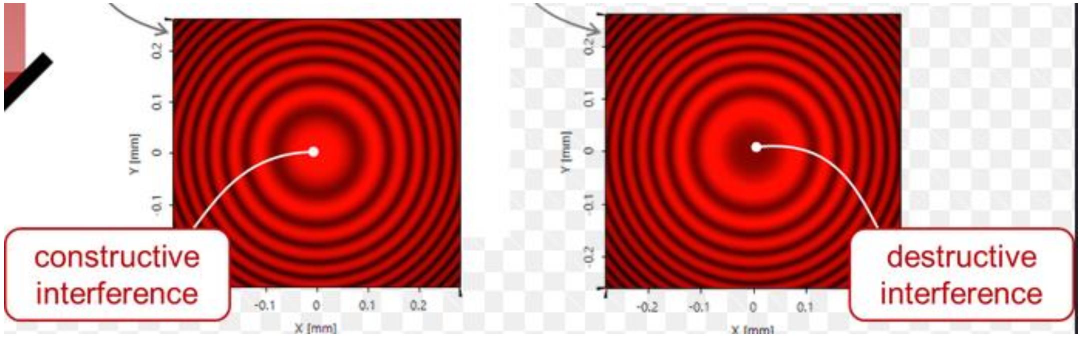
# Mach-Zehnder

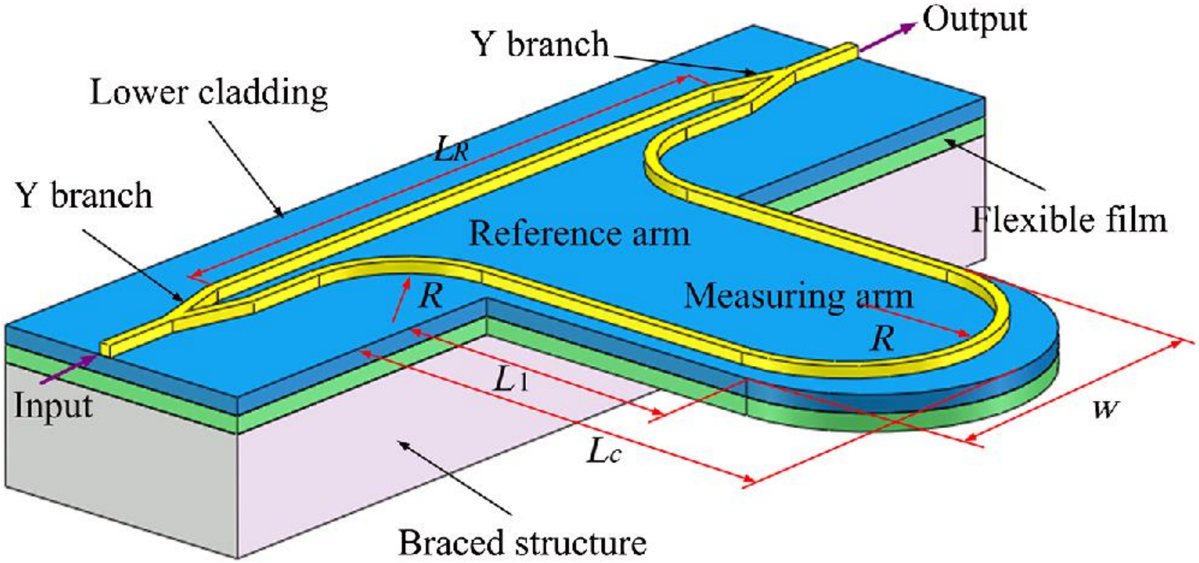
- **TheMach-Zehnder interferometer (MZI) consists of three stages:**
- **a 3-dB directional coupler which splits the input signals,**
- **a central section where one of the waveguides is longer by ΔL to give a wavelength-dependent phase shift between the two arms,**
- **and another 3-dB coupler which recombines the signals at the output.**



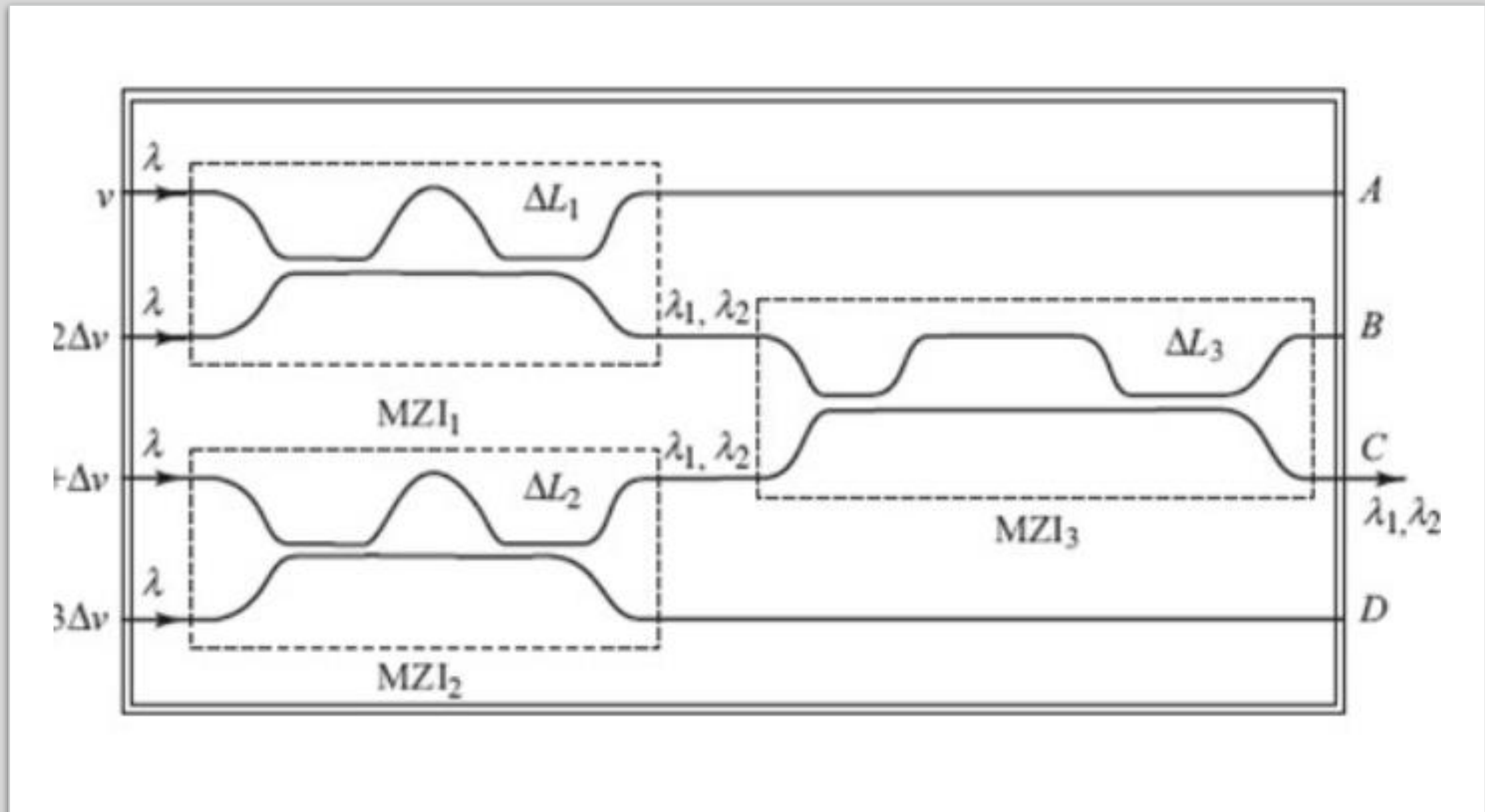

https://physics.stackexchange.com/questions/207810/mach-zehnder-interferometer-two-output-interference-pattern-question

# Passive interferometer



# Array of interferometers (cascaded) Multiplexer (MUX)



# Active interferometer

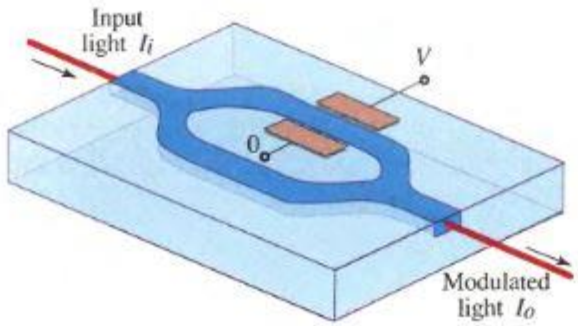
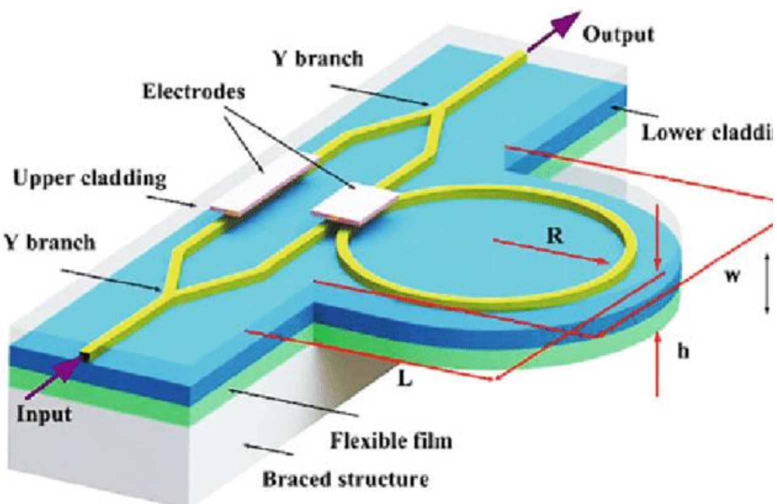
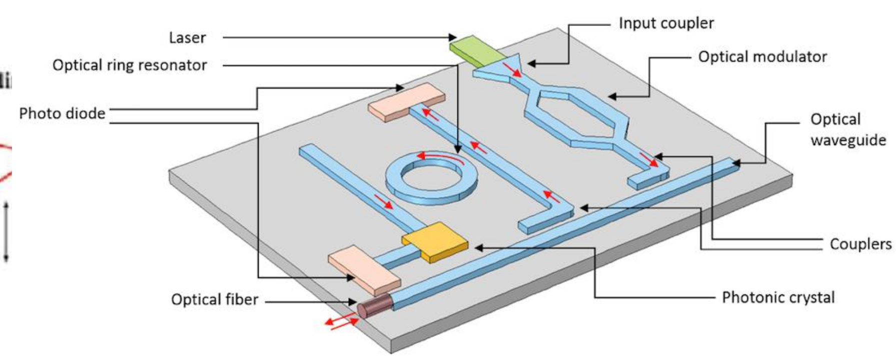


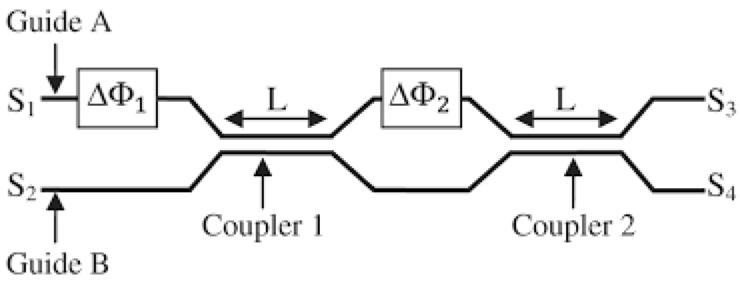

**Figure 20.1-5** An integrated-optical intensity modulator (or optical switch). A Mach–Zehnder interferometer and an electro-optic phase modulator are implemented using optical waveguides fabricated from a material such as $LiNbO_3$.

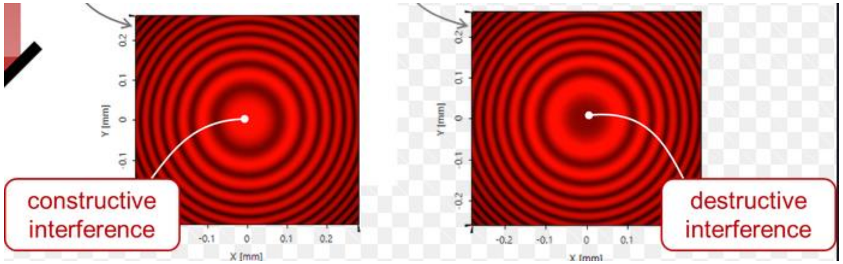


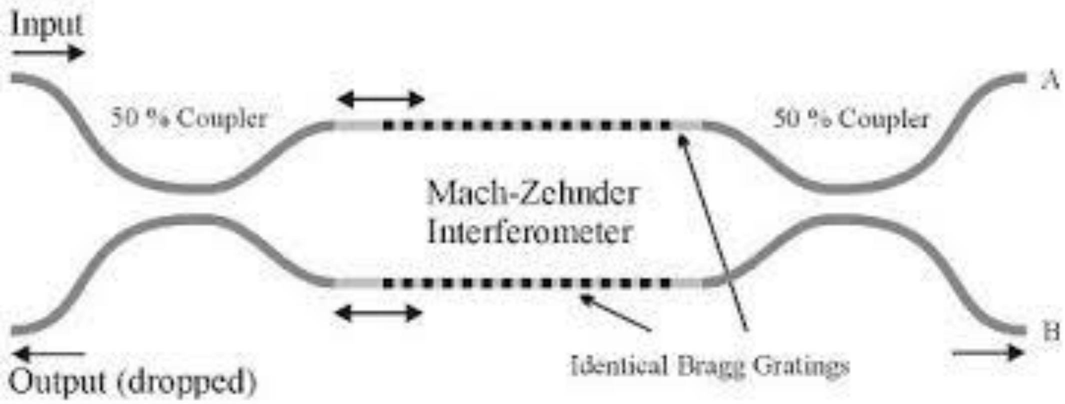




https://www.comsol.com/blogs/silicon-photonics-designing-and-prototyping-silicon-waveguides/

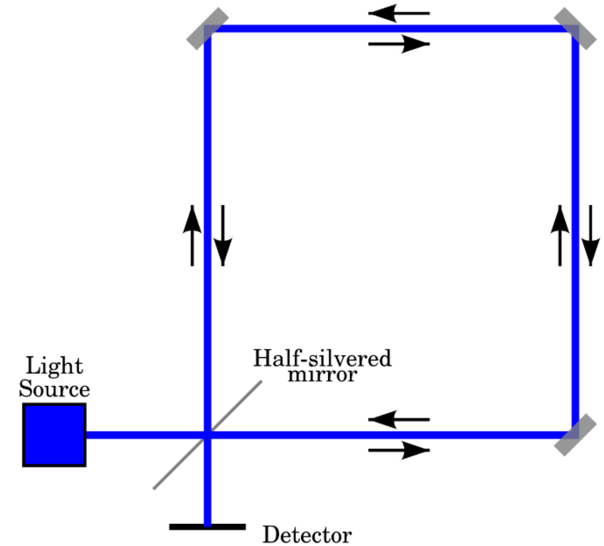
# Combination

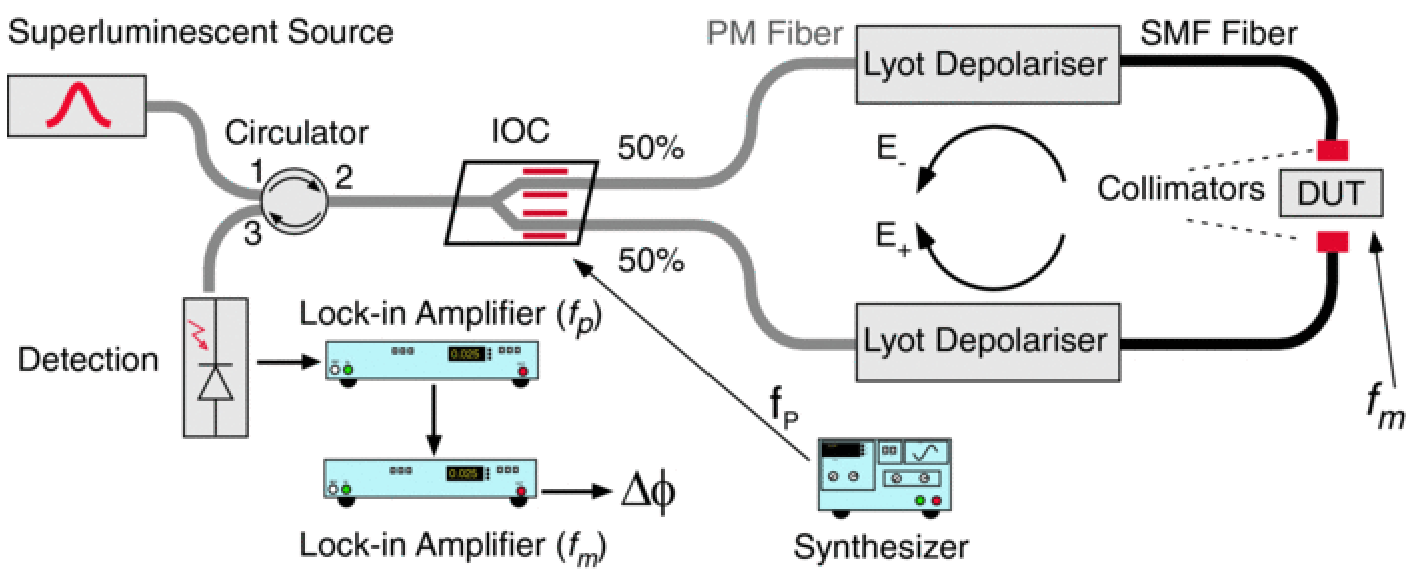


# Sagnac interferometer



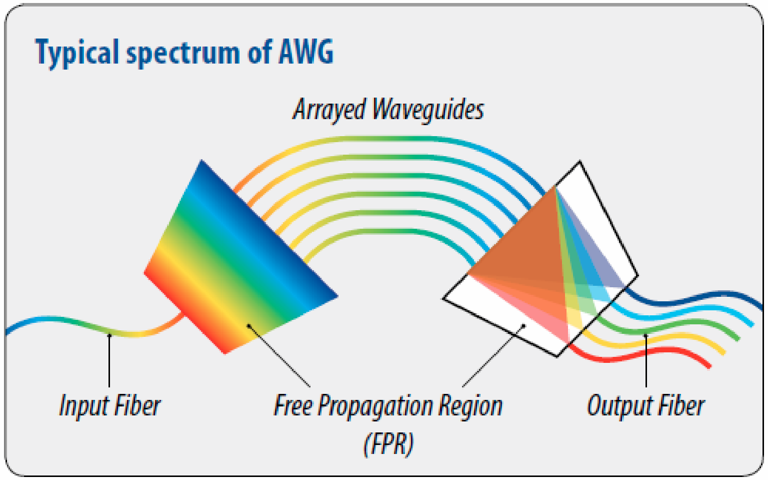



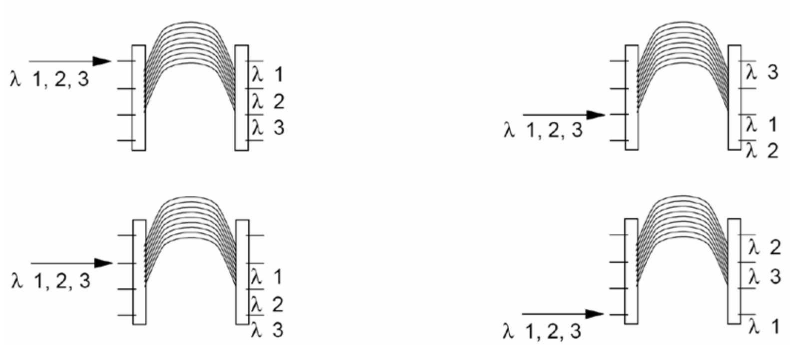

https://aip.scitation.org/doi/abs/10.1063/1.4871988?journalCode=rsi

# Optical filters

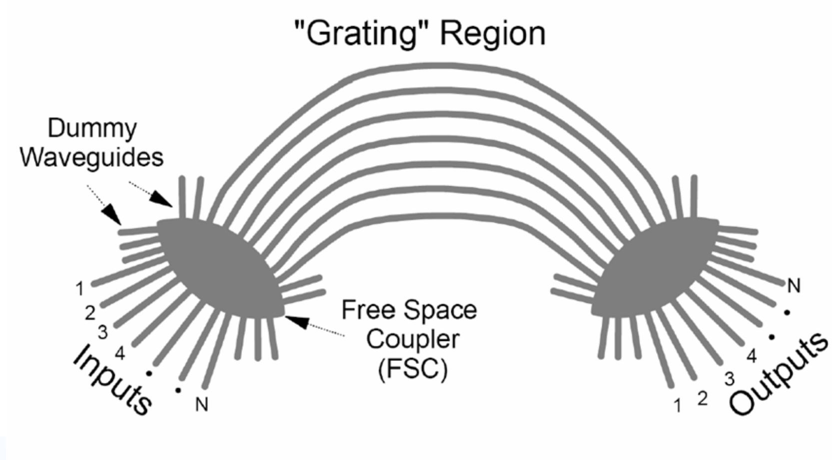
# Waveguide Grating Router (AWG)

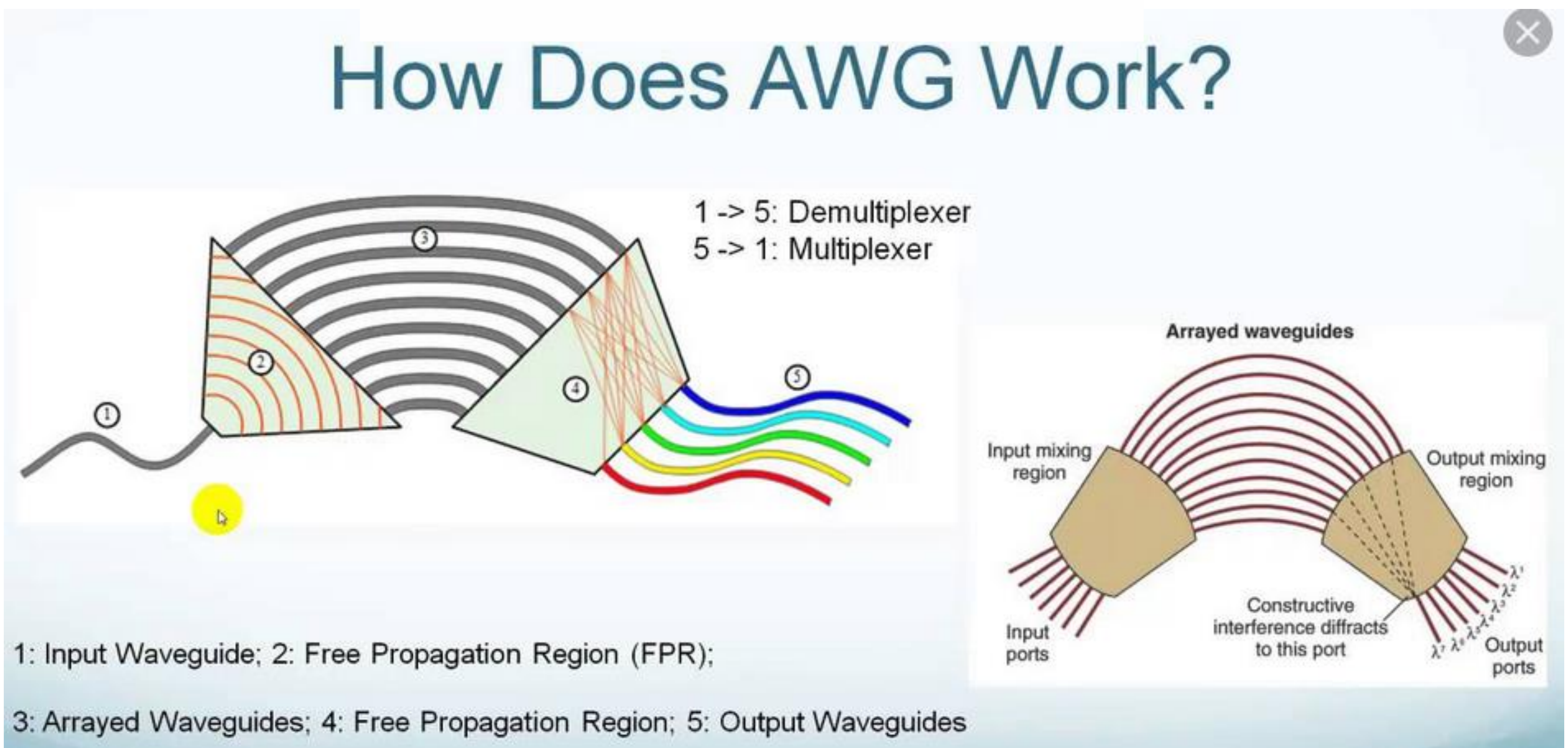
- The incoming light **(1)** traverses a free space **(2)** and enters a bundle of optical fibers or channel waveguides **(3)**. The fibers have different length and thus apply a different phase shift at the exit of the fibers. The light then traverses another free space **(4)** and interferes at the entries of the output waveguides **(5)** in such a way that each output channel receives only light of a certain wavelength. The orange lines only illustrate the light path. The light path from **(1)** to **(5)** is a demultiplexer, from **(5)** to **(1)** a multiplexer.



# Waveguide grating router-> all optical DMUX



# Active components

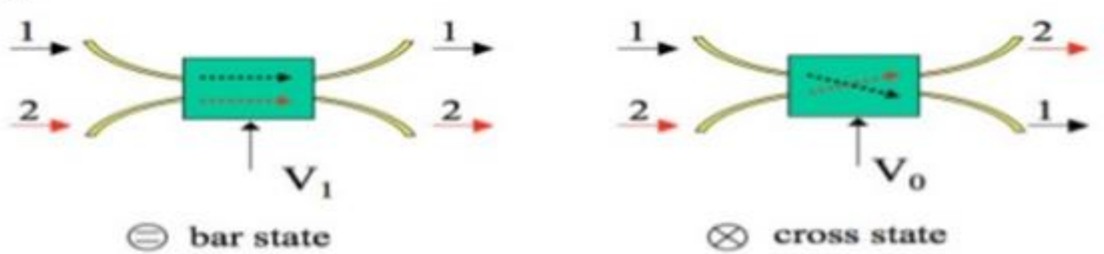
Gerd Keiser – Cap 10

# How can we define an active component?

-Active components require some type of external energy either to perform their functions or to be used over a wider operating range than a passive device, thereby offering greater application flexibility

- Modulator, switch, and router
- Optical amplifier (fiber amplifier, semiconductor amplifier)
- Wavelength converter
- Gain equalizer

Switch




Optical switch can be used for:
1) Light modulation(phase & intensity)
2) Routing optical data

# Type of Optical Modulators/Switches

| | tuning speed |
|---|---|
| • Mechanical or Micro-electro-mechanical system (MEMS) | (*ms*) |
| • Electro-absorption | (*ns/ps*) |
| • Electro-Optic | |
| – Lithium Niobate ($LiNbO_3$), Polymer | (*ns/ps*) |
| – Semiconductor Optical Amplifier (SOA) | (*ns/ps*) |
| • Acousto-Optic | ($\mu s$) |
| • Magneto-Optic | ($\mu s$) |
| • Thermal-Optic | ($ms/\mu s$) |
| • Liquid Crystal (Polarization switching) | (*ms*) |
| • All-Optical | (*ps/fs*) |

- *Tunable optical sources*, which are described in Chap. 6, allow their emission wavelength to be tuned precisely to a particular optical frequency (or, equivalently, to a particular wavelength) by some external control mechanism.
- *Wavelength lockers* are important devices in WDM systems to maintain the output from a laser diode at a predefined ITU-T frequency with a precision of ±1 GHz (or 8 pm). More details on this device are given in Chap. 12 on WDM.
- *External modulators* are described in Chap. 6. Such a device can be in the form of a separate external package, or it can be integrated into the laser diode package. These components allow the optical output to be modulated external to the light source at rates greater than 2.5 Gbps without significant distortion.
- *Photodetectors* are described in Chap. 7. A photodetector acts upon an optical signal by sensing the light signal falling on it and converting the variation of the optical power to a correspondingly varying electric current.
- *Optical amplifiers* are described in Chap. 11. These devices operate completely in the optical domain to boost the power level of optical signals. They work over a broad spectral range and boost the amplitudes of independent signals at all wavelengths in this band simultaneously. The fundamental optical amplification mechanisms are based on semiconductor devices, erbium-doped optical fibers, and the Raman effect in standard transmission fibers.
- *Variable optical attenuators* (VOAs) are used in multiple-wavelength links to adjust the power levels of individual wavelengths so that they closely have the same value. This chapter describes the construction and operation of VOAs.

- *Tunable optical filters* are key elements in a WDM system where one needs the flexibility to be able to select a specific wavelength for data receipt or performance monitoring. This chapter describes the construction and operation of tunable optical filters. Chapter 12 on WDM presents further details concerning the applications of these tunable filters.
- *Dynamic gain equalizers*, also called *dynamic channel equalizers* or *dynamic spectral equalizers*, provide dynamic gain equalization or blocking of individual channels across a given spectral band within a link in a WDM system. This chapter describes the construction and operation of some representative devices.
- *Optical add/drop multiplexers* (OADM) can be passive or active devices. Their function is to add or drop one or more selected wavelengths at a designated point in an optical network. This chapter describes an active OADM, and Chap. 17 describes switching applications in a network.
- *Polarization controllers* offer high-speed real-time polarization control in a closed-loop system that includes a polarization sensor and control logic. These devices dynamically adjust any incoming state of polarization to an arbitrary output state of polarization. This chapter describes their construction and operation.

- *Chromatic dispersion compensators* optically restore signals that have become degraded by chromatic dispersion, thereby significantly reducing bit error rates at the receiving end of a fiber span. This chapter describes the construction and operation of one representative device type. Chapter 15 illustrates further applications.
- *Optical performance monitors* track optical power, wavelength, and optical signal-to-noise ratio to check operational performance trends of a large number of optical channels and to identify impending failures. Chapter 18 looks at these devices in greater detail within the discipline of system maintenance and control.
- *Optical switches* that work completely in the optical domain have a variety of applications in optical networks, including optical add/drop multiplexing, optical cross-connects, dynamic traffic capacity provisioning, and test equipment. Chapter 17 looks at switching applications in greater detail.
- *Wavelength converters* are used in WDM networks to transform data from one incoming wavelength to a different outgoing wavelength without any intermediate optical-to-electrical conversion. Chapter 11 on optical amplifiers describes devices and techniques for doing this.

**TABLE 10.3. Summary of Some Tunable Devices, Their Functions, and in Which Chapter to Find Application Details**

| Tunable device | Function | Chapter |
|---|---|---|
| Tunable laser diode | Emits optical power at a precisely tunable frequency (wavelength) over a certain spectral band | 6 |
| Wavelength locker | Precisely maintains the output from a laser diode at a predefined ITU-T frequency | 12 |
| External modulator | Allows the optical output from a laser diode to be modulated external to the source at rates greater than 2.5 Gbps | 6 |
| Optical amplifier | Operates completely in the optical domain to boost the power level of optical signals | 11 |
| Variable optical attenuator | Used in multiple-wavelength links to adjust the power levels of individual wavelengths | 10 |
| Optical filter | Selects a specific narrow wavelength range for data receipt or performance monitoring | 9,10,12 |
| Dynamic gain equalizer | Provides dynamic gain equalization or blocking of individual channels | 10 |
| Optical add/drop multiplexer | Adds and/or drops selected wavelengths at a designated point in an optical network | 10,17 |
| Polarization controller | Dynamically adjusts any incoming state of polarization to an arbitrary output state | 10 |
| Chromatic dispersion compensator | Optically restores signals that have become degraded by chromatic dispersion | 10,15 |
| Optical performance monitor | Tracks optical power, wavelength, and optical signal-to-noise ratio to check operational performance trends | 18 |
| Optical switch | Operates completely in the optical domain to switch an incoming signal from an input to an output port | 17 |
| Wavelength converter | Transforms one incoming wavelength to a different outgoing wavelength in WDM links | 11 |

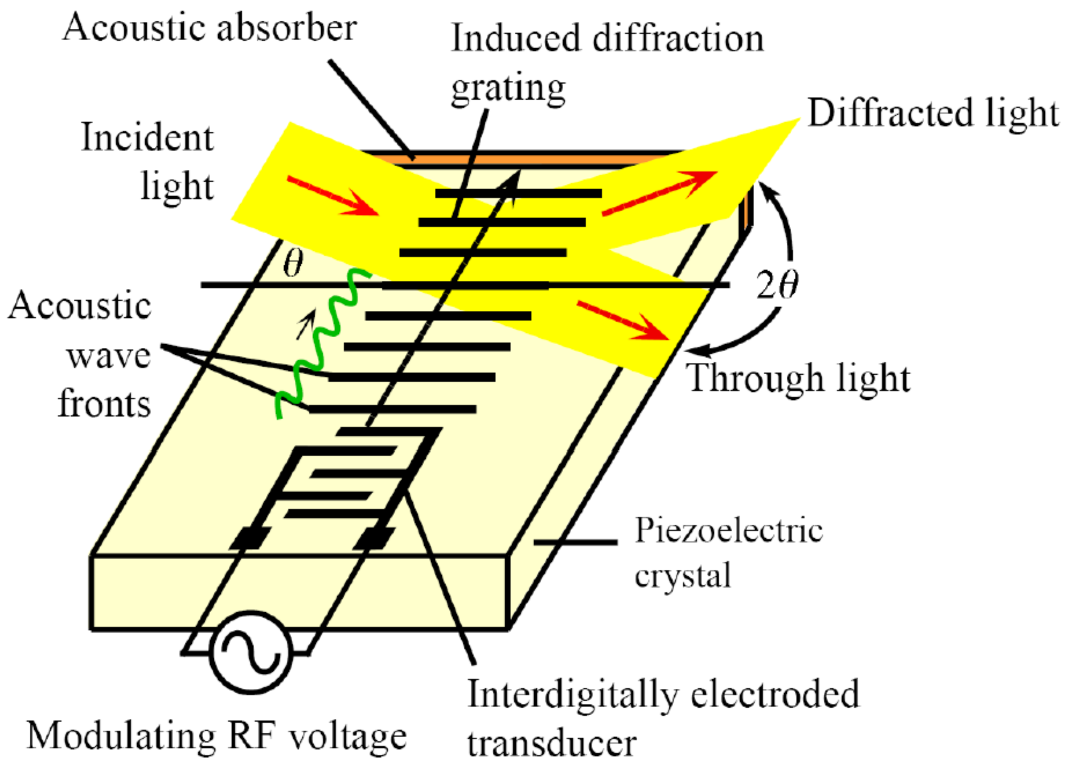


Gerd Keiser – page 172

# MEMS – *microelectromechanical systems*

- These are miniature devices that combine mechanical, electrical, and optical components to provide sensing and actuation functions.
- MEMS devices are fabricated using integrated-circuit compatible batch-processing techniques and range in size from micrometers to millimeters.
- The control or actuation of a MEMS device is done through electrical, thermal, or magnetic means such as microgears or movable levers, shutters, or mirrors.
- The devices are used widely for automobile air bag deployment systems, in ink-jet printer heads, for monitoring mechanical shock and vibration during transportation of sensitive goods, for monitoring the condition of moving machinery for preventive maintenance, and in biomedical applications, for patient activity monitoring and pacemakers.
- MEMS technologies also are finding applications in lightwave systems for variable optical attenuators, tunable optical filters, tunable lasers, optical add/drop multiplexers, optical performance monitors, dynamic gain equalizers, optical switches, and other optical components and modules.

# Active Grating – RF voltage




Traveling acoustic waves create a harmonic variation in the refractive index and thereby create a diffraction grating that diffracts the incident beam through an angle $2\theta$.

**Tunable Grating Technology** Before it is stretched, the center wavelength $\lambda_c$ of a fiber Bragg grating filter is given by $\lambda_c = 2n_{eff}\Lambda$, where $n_{eff}$ is the effective index of the fiber containing the grating and $\Lambda$ (lambda) is the period of the index variation of the grating. When the fiber grating is elongated by a distance $\Delta\Lambda$, the corresponding change in the center wavelength is $\Delta\lambda_c = 2n_{eff}\,\Delta\Lambda$.

The stretching can be done by thermomechanical, piezoelectric, acousto-optic or stepper-motor means

# Active components

*dynamic gain equalizer*

- A *dynamic gain equalizer* (DGE) is used to reduce the attenuation of the individual wavelengths within a spectral band. These devices also are called *dynamic channel equalizers* (DCEs) or *dynamic spectral equalizers*. The function of a DGE is equivalent to filtering out individual wavelengths and equalizing them on a channel-by-channel basis.

**TABLE 10.2. Some Typical Performance Parameters of a Tunable Optical Filter**

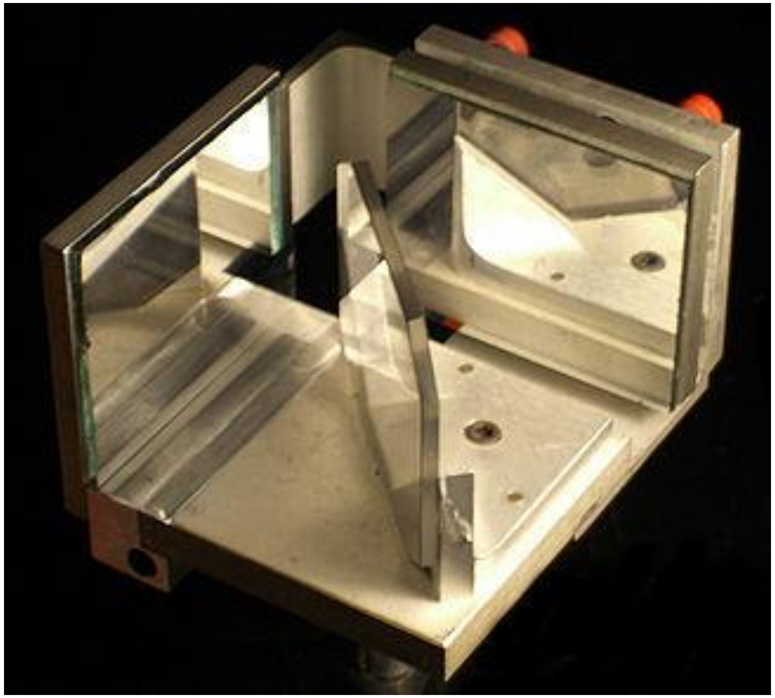
| Parameter | Specification |
|---|---|
| Tuning range | 100 nm typical |
| Free spectral range (FSR) | 150 nm typical |
| Channel selectivity | 100, 50, and 25 GHz |
| Bandwidth | <0.2 nm |
| Insertion loss | <3 dB across tuning range |
| Polarization-dependent loss (PDL) | <0.2 dB across tuning range |
| Tuning speed | 10 nm/μs in both C- and L-bands |
| Tuning voltage | 40 V |

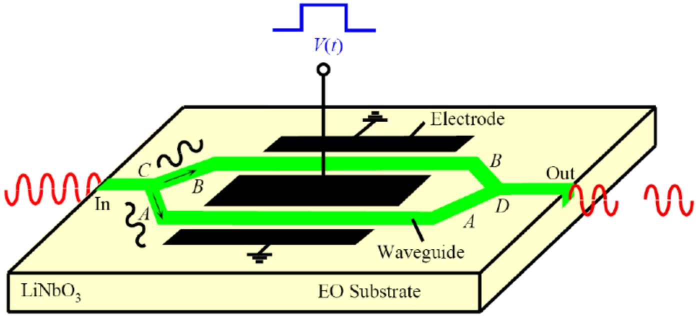
# Interferometer

## Electro-optic effect

Michelson

Mach-Zender






An integrated Mach-Zender optical intensity modulator. The input light is split into two coherent waves *A* and *B*, which are phase shifted by the applied voltage, and then the two are combined again at the output.

# Optic transceiver

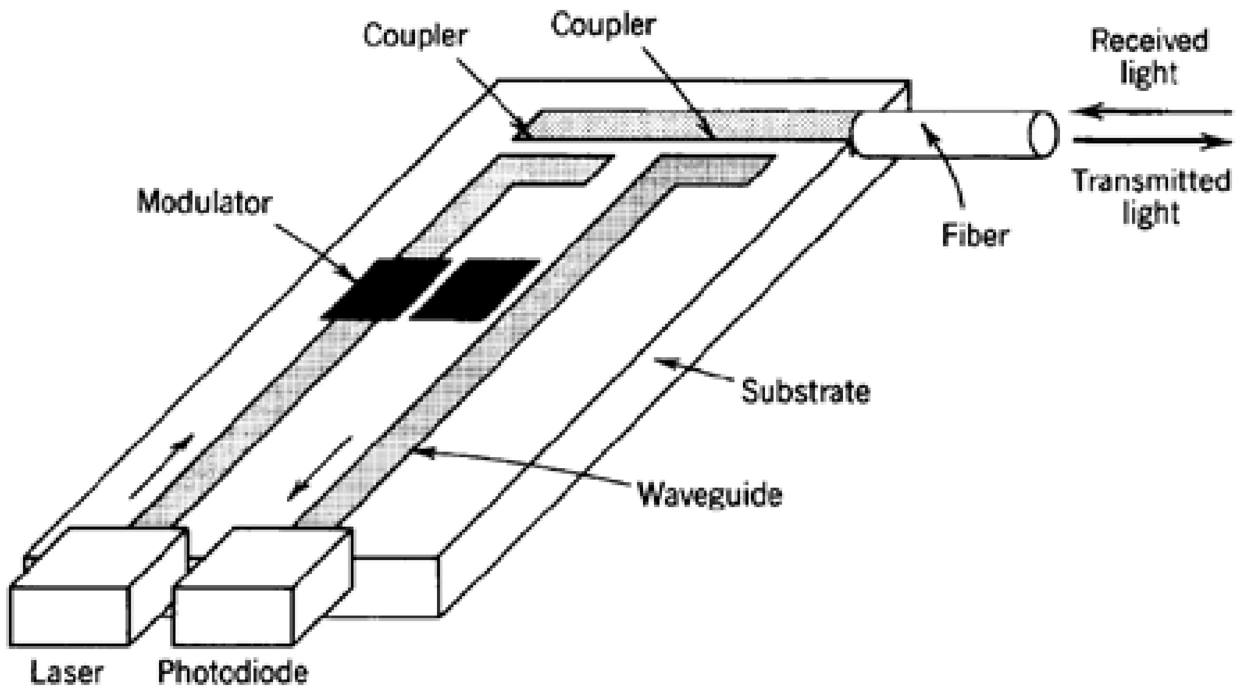
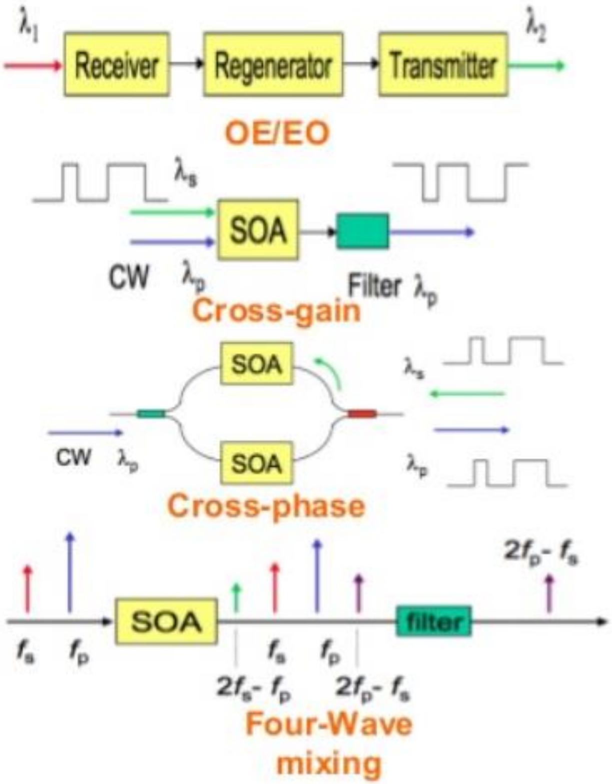



**Figure 7.0-2** An example of an integrated-optic device used as an optical receiver/transmitter. Received light is coupled into a waveguide and directed to a photodiode where it is detected. Light from a laser is guided, modulated, and coupled into a fiber.

# Different types of Wavelength Converter

- OE/EO regeneration
- SOA-based
  - Cross-gain modulation
  - Cross-phase modulation
  - Four-Wave mixing
- Fiber-based
  - Cross-phase modulation
  - Four-Wave mixing



# Optical amplifiers

Scattering and absorption mechanisms in an optical fiber cause a progressive attenuation of light signals as they travel along a fiber. At some point the signals need to be amplified so that the receiver can interpret them properly. Traditionally this was done by means of a regenerator that converted the optical signal to an electrical format, amplified this electric signal, and then reconverted it to an optical format for further transmission along the link. The development of an optical amplifier circumvented the time-consuming function of a regenerator by boosting the level of a light signal completely in the optical domain. Thus optical amplifiers now have become indispensable components in high-performance optical communication links.

Gerd Keiser – Cap 11

# Optical amplifiers

- Used routinely for loss compensation since 1995.
- Amplify input signal but also add some noise.
- Several kinds of amplifiers have been developed.
  - ⋆ Semiconductor optical amplifiers
  - ⋆ Erbium-doped fiber amplifiers
  - ⋆ Raman fiber amplifiers
  - ⋆ Fiber-Optic parametric amplifiers
- EDFAs are used most commonly for lightwave systems.
- Raman amplifiers work better for long-haul systems.
- Parametric amplifiers are still at the research stage.

# Optical amplifiers classes

**Semiconductor Optical Amplifiers (SOAs)**

- Alloys of semiconductor materials from groups III and V make up active medium for SOAs.
- They work in O-band and C-band and can be integrated on the same substrate as other optical devices.
- Compared with DFAs they consume less electrical power, have fewer components and are more compact.
- The rapid gain response give rise to crosstalk effects when a broad spectrum of wavelengths must be amplified.

**Active fiber or doped fiber amplifiers (DFAs)**

- The active medium is created by lightly doping silica or tellurite fiber core with rare earth elements such as thulium, erbium.
- They operate in S, C, L bands.
- They have the ability to pump devices at several wavelengths and possess low coupling loss for the given fiber transmission medium.
- They are immune from interference effects between different optical channels.

**Raman amplifiers**

- A fiber based Raman amplifier uses stimulated Raman scattering (SRS) occurring in silica fibers when an intense pump beam propagates through it.
- The incident pump photon gives up its energy to create another photon of reduced energy at lower frequency. The remaining energy is absorbed by the medium in the form of molecular vibrations. Thus Raman amplifiers

# Er dopped amplifiers

**Advantages:**

- High gain (40–50 dB),
- Low noise (3–5 dB),
- Low polarization sensitivity,
- EDFAs are fully compatible with the rest of the fiber optic transmission link.

**Limitations:**

- Large size,
- High pump power consumption (efficiency - 10dB/1 mW).

# Raman amplifiers

**Advantages:**

- Low noise (3–5 dB).
- Wide gain bandwidth (up to 10 nm).
- Distributed amplification within the transmission fiber.

**Limitations:**

- Low gain (10 dB).
- Requirement of high pump power.

# Optical amplifiers

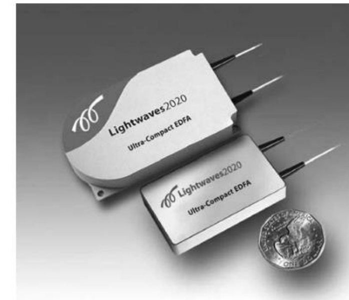



**Figure 10.8.** Two package sizes for compact optical amplifiers. (Photo courtesy of Lightwave 2020; www.lightwaves2020.com.)

## Two-Stage Doped-Fiber Amplifier: Pumped From Ends

The design shown in Figure 2-18 is similar to the previous design, except that pumping is from the ends. Mid-stage filtering may be used if desired, although this would stop pump power from the first stage being reused in the second stage.

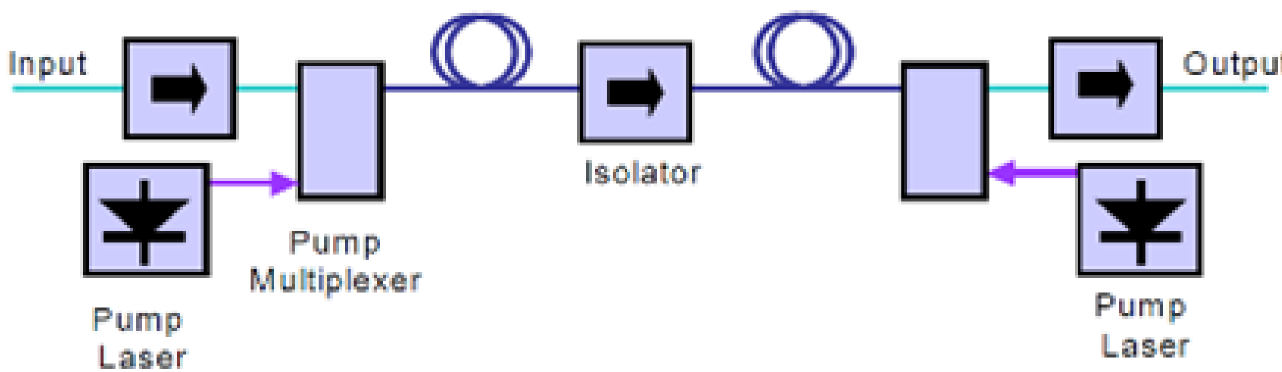
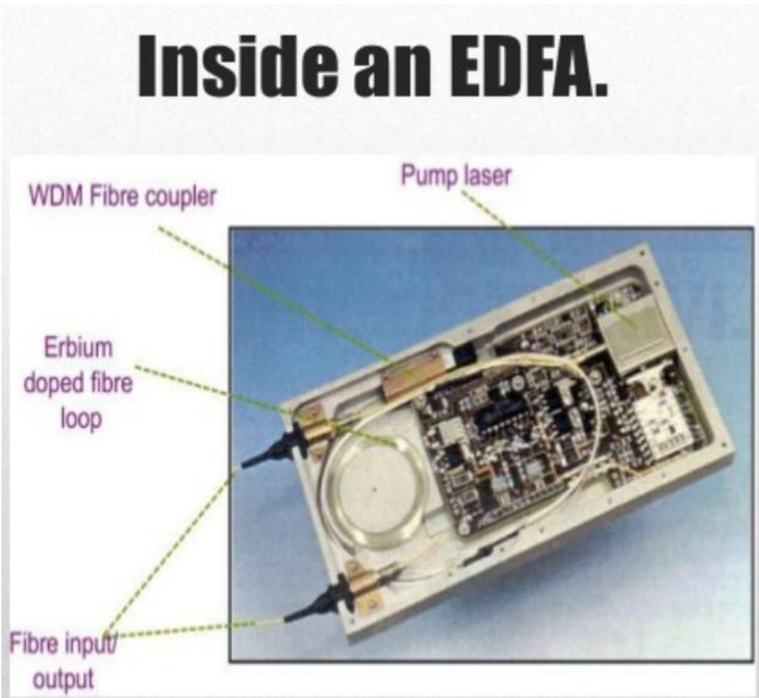
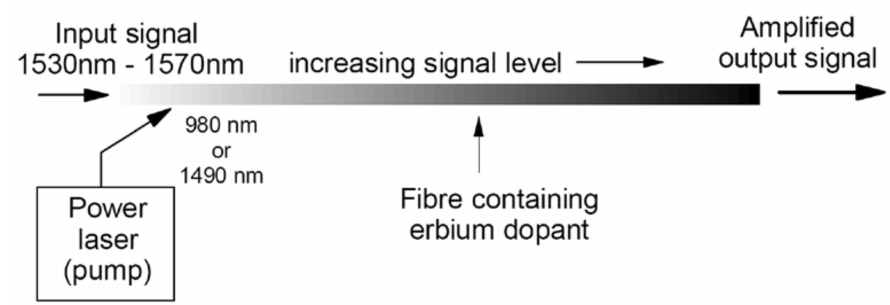



**Figure 2-18** *Two-stage doped-fiber amplifier with forward-backward pumping*




*3. Erbium Doped Fibre Amplifier (EDFA) - Function*

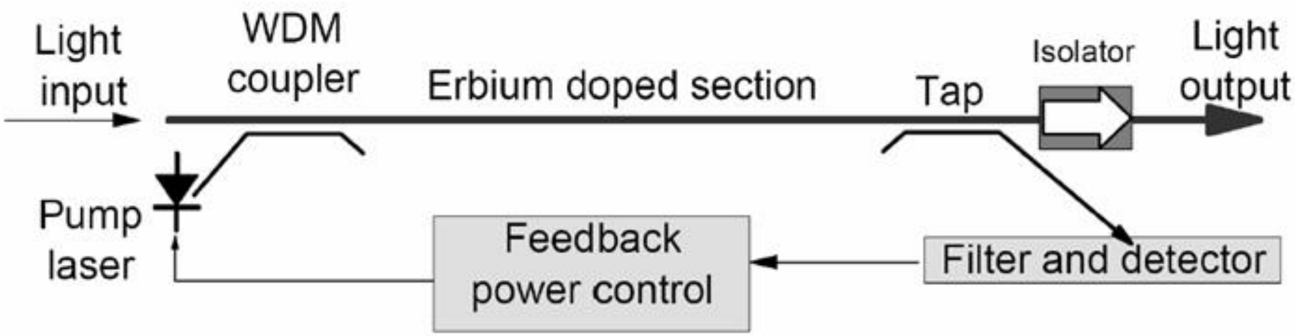



*Figure 114. Erbium Doped Optical Fibre Amplifier. Although the device is powered electrically, the amplification process is totally optical and takes place within a short of rare earth doped, single-mode fibre.*

AGC – Automatic Gain Control – Controlul Automat al Amplificării

Circuitul AGC nu numai că supraveghează (controlează) puterea optică generată, dar o şi stabilizează (Pout = const. ) reglând continuu puterea de pompaj

# Amplifier Wavelength Bands

The optical spectrum has been divided into 30 nm wide bands around the 1550 nm low-absorption window of silica fibers, defined as [5]:

- **S+ band**: 1450–1480 nm (*Extended Short*-Wavelength band)
- **S-band**: 1480–1530 nm (*Short*: not often used. Uses Raman amplifiers)
- **C-band** (or M-band): 1530–1570 nm (*Center*: the most mature band. Uses EDFAs)
- **L-band**: 1570–1610 nm (*Long*: first choice for extending bandwidth using gain-shifted EDFAs [6], Raman Amplifiers and EDTFAs)
- **L+ band**: 1610–1650 nm (*Longer*: limited amplification options).

## Doped-Fiber Amplifiers

If the signal power is increased, stimulated recombination will eventually start to impact on the population inversion of the fiber. This is because every photon created by stimulated emission removes one ion from the $^4I_{13/2}$ level to the $^4I_{15/2}$ level. This will happen first at the fiber output, where the power is maximum, as shown in Figure 2-10. Thus the gain will reduce until a balance is reached between pump absorption and stimulated recombination plus spontaneous recombination.

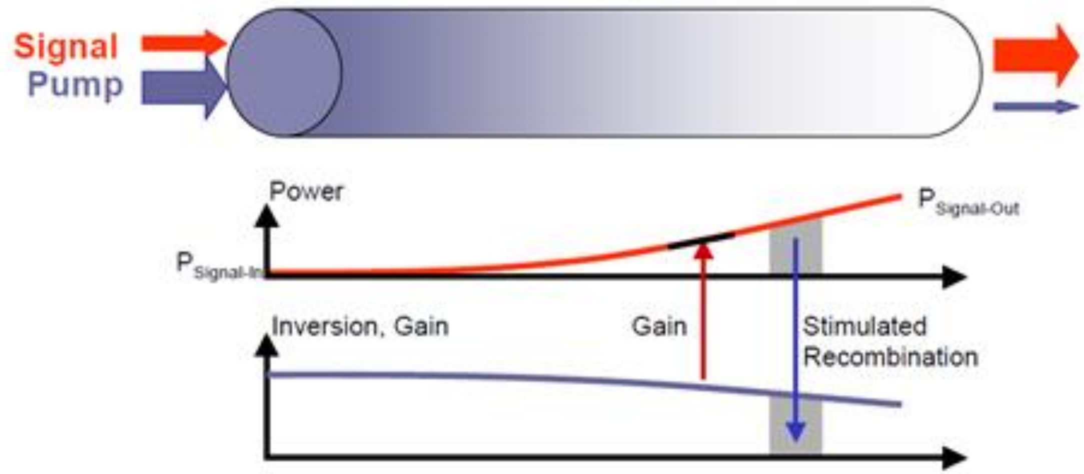



**Figure 2-10** *Illustration of the population inversion and signal strength along a fiber at moderate input powers when the inversion reduces at the output end of the fiber due to stimulated recombination becoming dominant over spontaneous*

# Amplification mechanism:-

- Optical amplifier uses optical pumping.
- Pumping gives energy to electrons to reach the excited state.
- After reaching its excited state, the electron must release some energy and drop to the lower level.
- Here a signal photon can then trigger the excited electron into stimulated emission. And electron releases its remaining energy in the form of new photon.

## EDFAs include the ability:-

- To pump the devices at several different wavelengths.
- Low coupling loss to the compatible-sized fiber transmission medium.
- Highly transparent to signal format and bit rate.
- Immune from interference effects( crosstalk and intermodulation distortion) when wavelength channels are injected simultaneously into amplifier.

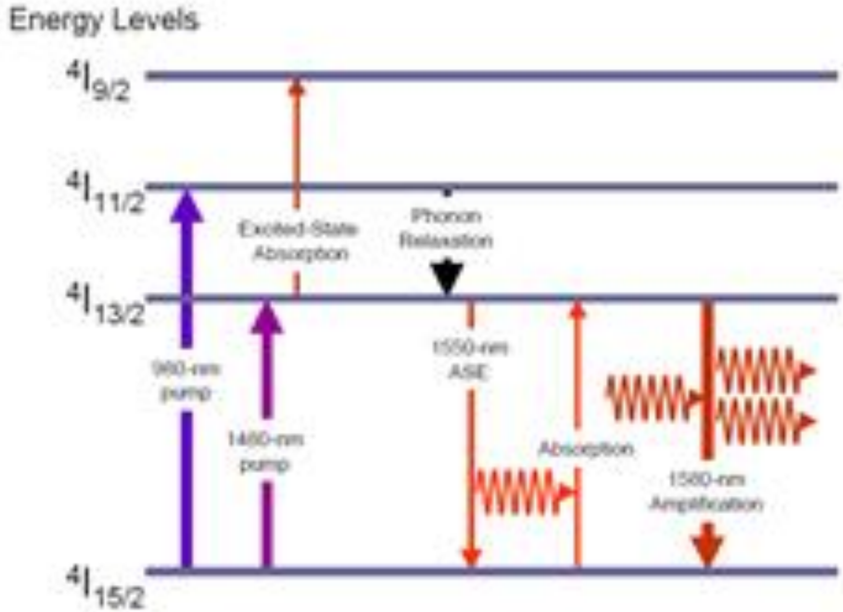



**Figure 2-3** *Transitions between energy levels in an Erbium-doped amplifier*

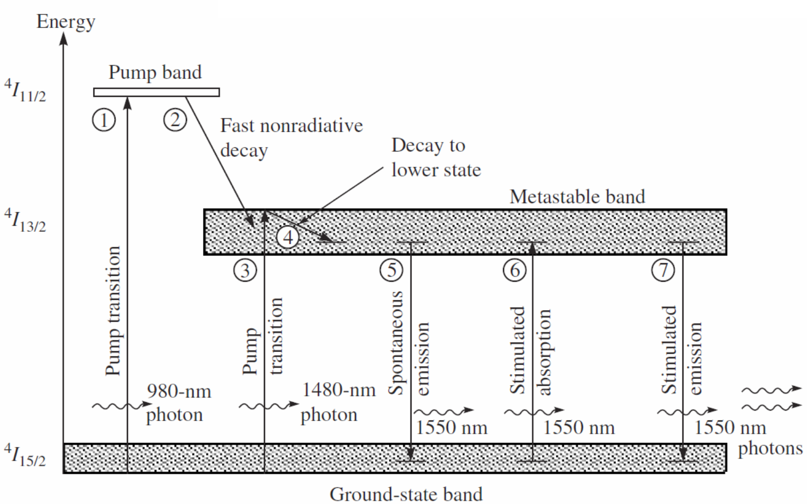



**Figure 11.7.** Simplified energy-level diagrams and various transition processes of $Er^{3+}$ ions in silica.

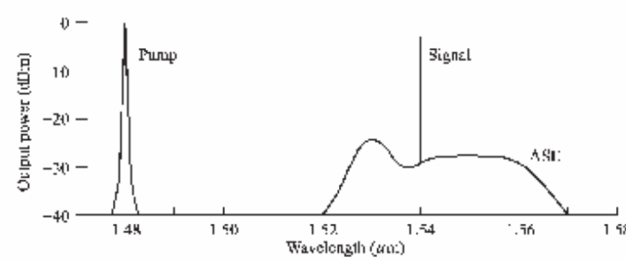
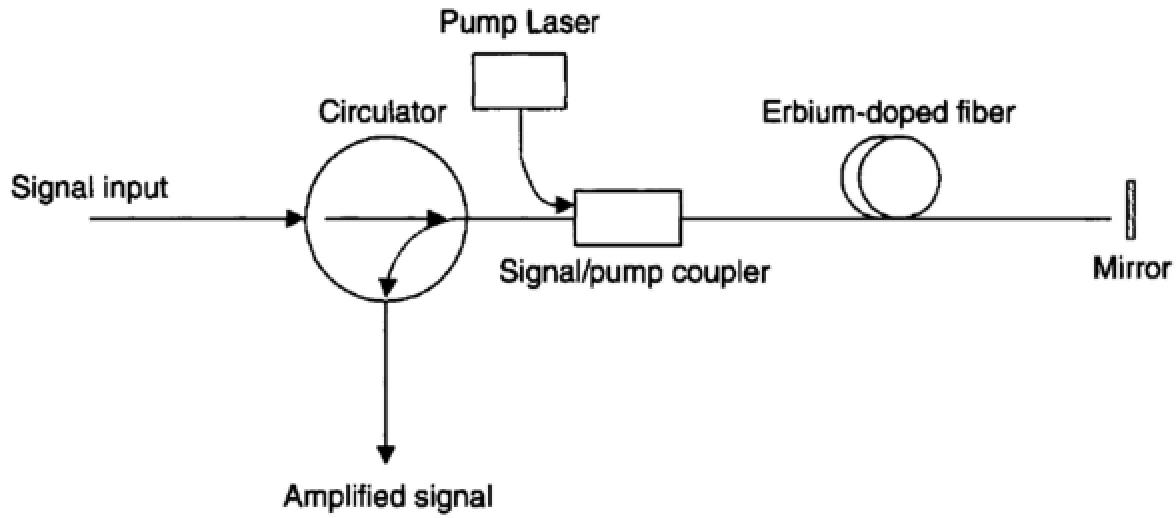



**Figure 11.11.** Representative 1480-nm pump spectrum and a typical output signal at 1540 nm with the associated ASE noise.

**Erbium Energy Bands** To get a phenomenological understanding of how an EDFA works, we need to look at the energy-level structure of erbium. The erbium atoms in silica are actually $Er^{3+}$ ions, which are erbium atoms that have lost three of their outer electrons. In describing the transitions of the outer electrons in these ions to higher energy states, it is common to refer to the process as "raising the ions to higher energy levels." Figure 11.7 shows a simplified energy-level diagram and various energy-level transition processes of these $Er^{3+}$ ions in silica glass. The two principal levels for telecommunication applications are a *metastable level* (the so-called $^4I_{13/2}$ level) and the $^4I_{11/2}$ *pump level*. The term *metastable* means that the lifetimes for transitions from this state to the ground state are very long compared to the lifetimes of the states that led to this level.

The metastable band is separated from the bottom of the $^4I_{15/2}$ ground-state level by an energy gap ranging from about 0.814 eV at the bottom of the band (corresponding to a 1527-nm photon) to 0.841 eV at the top of the band (corresponding to a 1477-nm photon). The energy band for the pump level exists at a 1.27-eV separation (corresponding to a 980-nm wavelength) from the ground state. The pump band is fairly narrow, so that the pump wavelength must be exact to within a few nanometers.

# Amplification




1.Signal light (1550nm) is launched into port 1 and passed through port 2 with minimum loss.
2.The signal is combined with the pump light (980nm) by a WDM coupler and both lights are launched into an erbium-doped fiber
3.The signal is amplified along the erbium-doped fiber
4.Both the signal and residual pump light are reflected by the mirror
5.The signal and residual pump light pass through the erbium-doped fiber again and the signal is amplified again by the residual pump light
6.At the WDM coupler, the signal light (1550nm) passes through while the pump light (980nm) is guided away into the pump laser (but absorbed by a built-in isolator)
7.The signal light is guided into port 3 by the circulator

# Pumping schematic view

## Forward

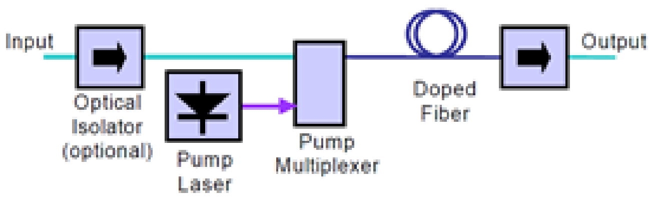
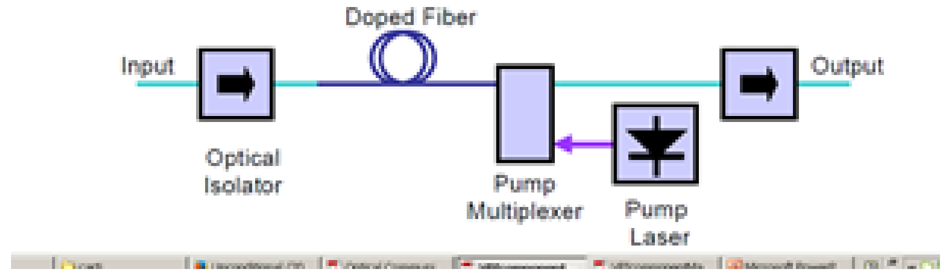



**Figure 2-12** *Forward-pumped doped-fiber amplifier*

## Backward




## Hybrid

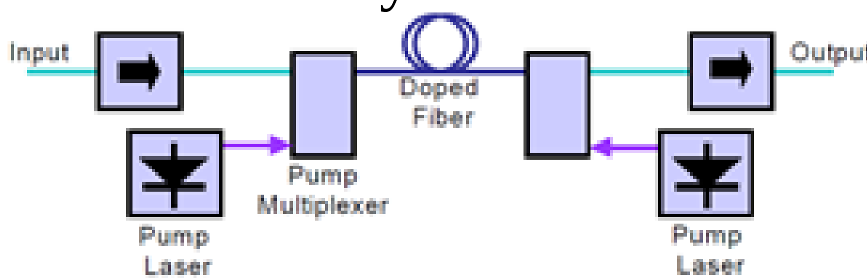
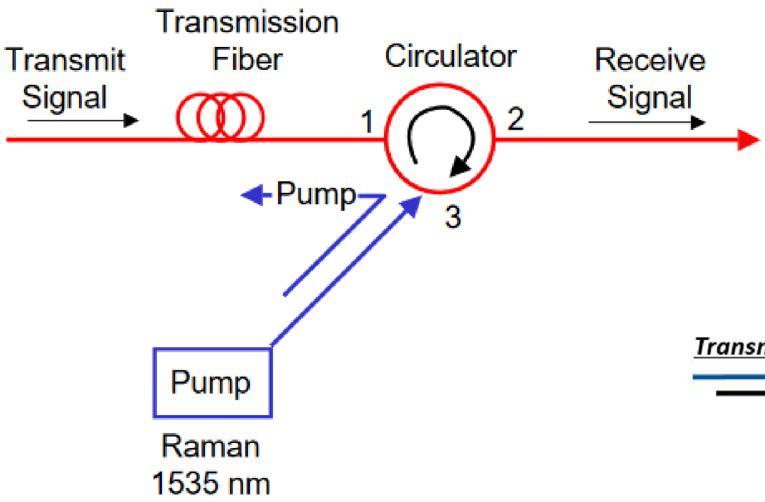
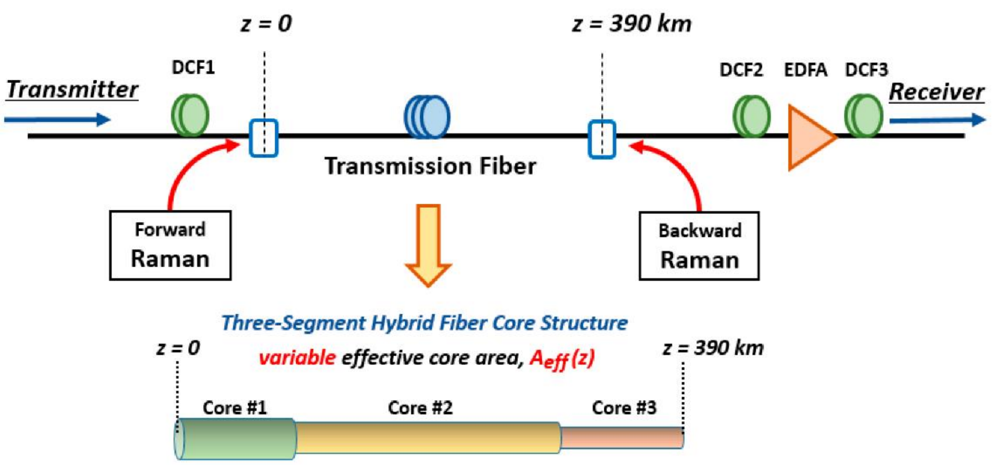



**Figure 2-14** *Forward- and backward-pumped doped-fiber amplifier*

# Amplification

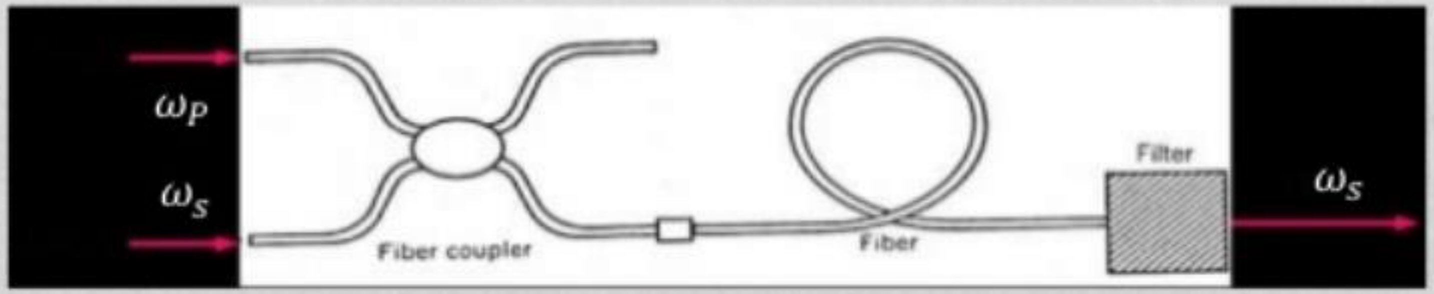



https://www.analogictips.com/optical-amplifiers-basic-implementations-faq/

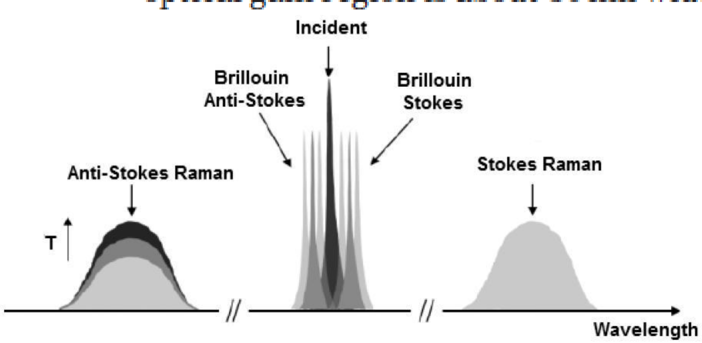
# Raman amplification

- Use stimulated Raman effect and pump laser whose frequency is equal to signal frequency plus frequency of chemical bond in the material
- Because it is a nonlinear process, requires very high pump powers (watts)
- A Raman amplifier is a device which takes input $\omega_s$ and amplified in the same direction or opposite direction with pump laser $\omega_P$.



Whereas an EDFA requires a specially constructed optical fiber for its operation, a *Raman amplifier* makes use of the transmission fiber itself as the amplification medium. A Raman amplifier is based on an effect called *stimulated Raman scattering* (SRS). This effect is due to an interaction between an optical energy field and the vibration modes of the lattice structure in a material. Basically what happens here is that an atom first absorbs a photon at one energy and then releases another photon at a lower energy, that is, at a wavelength longer than that of the absorbed photon. The energy difference between the absorbed and the released photons is transformed to a *phonon*, which is a vibration mode of the material. The power transfer results in an upward wavelength shift of 80 to 100 nm, and the shift to a longer wavelength is referred to as the *Stokes shift*. Figure illustrates the Stokes shift and the resulting Raman gain spectrum from a pump laser operating at 1445 nm. Here a signal at 1535 nm, which is 90 nm away from the pump wavelength, is amplified.

In a Raman amplifier this process transfers optical energy from a strong laser pump beam to a weaker transmission signal that has a wavelength which is 80 to 100 nm higher than the pumping wavelength. For example, pumping at 1450 nm will lead to a signal gain at approximately 1530 to 1550 nm. Owing to the molecular structure of glass, a number of vibration modes exist so that the optical gain region is about 30 nm wide. In practice one uses several pump lasers




Fiber Amplifiers and Fiber Lasers Based On Stimulated Raman Scattering: A Review
Micromachines2020,11, 247;
doi:10.3390/mi11030247

# Application: WDM systems

STANDARD WDM SPECTRAL GRIDS

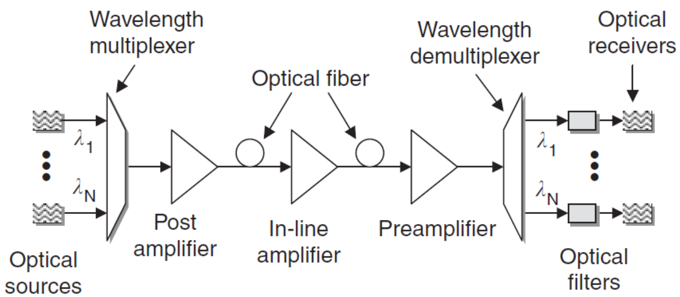



**Figure 3.2.** Implementation of a simple WDM link.

- Original band (O-band): 1260 to 1360 nm
- Extended band (E-band): 1360 to 1460 nm
- Short band (S-band): 1460 to 1530 nm
- Conventional band (C-band): 1530 to 1565 nm
- Long band (L-band): 1565 to 1625 nm
- Ultralong band (U-band): 1625 to 1675 nm

### 3.2.1 Dense WDM

The term *dense WDM* (DWDM) refers to the close optical frequency spacings denoted by ITU-T Recommendation G.694.1, which is aimed specifically at DWDM. This document specifies WDM operation in the S-, C-, and L-bands for high-quality, high-rate metro area network (MAN) and wide area network (WAN) services. It lists specifications for narrow frequency spacings of 100 to 12.5 GHz (or, equivalently, 0.8 to 0.1 nm at 1550 nm). This implementation requires the use of stable, high-quality, temperature- and wavelength-controlled (frequency-locked) laser diode light sources. For example, the wavelength-drift tolerances for 25-GHz channels are $\pm 0.02$ nm.

Table 3.1 lists part of the by ITU-T G.694.1 DWDM frequency grid for 100- and 50-GHz spacings in the L- and C-bands. The column labeled "50-GHz offset" means that for the 50-GHz grid one uses the 100-GHz spacings with these 50-GHz values interleaved. For example, the 50-GHz channels in the L-band would be at 186.00, 186.05, 186.10 THz, and so on. Note that when the frequency spacings are uniform, the wavelengths are not spaced uniformly because of the relationship given in Eq. (3.1).

To designate which channel is under consideration in 100-GHz applications, the ITU-T uses a *channel numbering convention*. For this, the frequency 19N.M THz is designated as ITU channel number NM. For example, the frequency 194.3 THz is ITU channel 43.

**TABLE 3.1 Sample Portion of the ITU-T G.694.1 DWDM Grid for 100- and 50-GHz Spacings in the L- and C-Bands**

| | L-Band | | | | C-Band | | | |
|---|---|---|---|---|---|---|---|---|
| | 100-GHz | | 50-GHz Offset | | 100-GHz | | 50-GHz Offset | |
| Unit | THz | nm | THz | nm | THz | nm | THz | nm |
| 1 | 186.00 | 1611.79 | 186.05 | 1611.35 | 191.00 | 1569.59 | 191.05 | 1569.18 |
| 2 | 186.10 | 1610.92 | 186.15 | 1610.49 | 191.10 | 1568.77 | 191.15 | 1568.36 |
| 3 | 186.20 | 1610.06 | 186.25 | 1609.62 | 191.20 | 1576.95 | 191.25 | 1567.54 |
| 4 | 186.30 | 1609.19 | 186.35 | 1608.76 | 191.30 | 1567.13 | 191.35 | 1566.72 |
| 5 | 186.40 | 1608.33 | 186.45 | 1607.90 | 191.40 | 1566.31 | 191.45 | 1565.90 |
| 6 | 186.50 | 1607.47 | 186.55 | 1607.04 | 191.50 | 1565.50 | 191.55 | 1565.09 |
| 7 | 186.60 | 1606.60 | 186.65 | 1606.17 | 191.60 | 1564.68 | 191.65 | 1564.27 |
| 8 | 186.70 | 1605.74 | 186.75 | 1605.31 | 191.70 | 1563.86 | 191.75 | 1563.45 |
| 9 | 186.80 | 1604.88 | 186.85 | 1604.46 | 191.80 | 1563.05 | 191.85 | 1562.64 |
| 10 | 186.90 | 1604.03 | 186.95 | 1603.60 | 191.90 | 1562.23 | 191.95 | 1561.83 |

### 3.2.2 Coarse WDM

With the production of full-spectrum (low-water-content) G.652C and G.652D fibers, the development of relatively inexpensive optical sources, and the desire to have low-cost optical links operating in access networks and local area networks, came the concept of *coarse WDM* (CWDM). In 2002 the ITU-T released

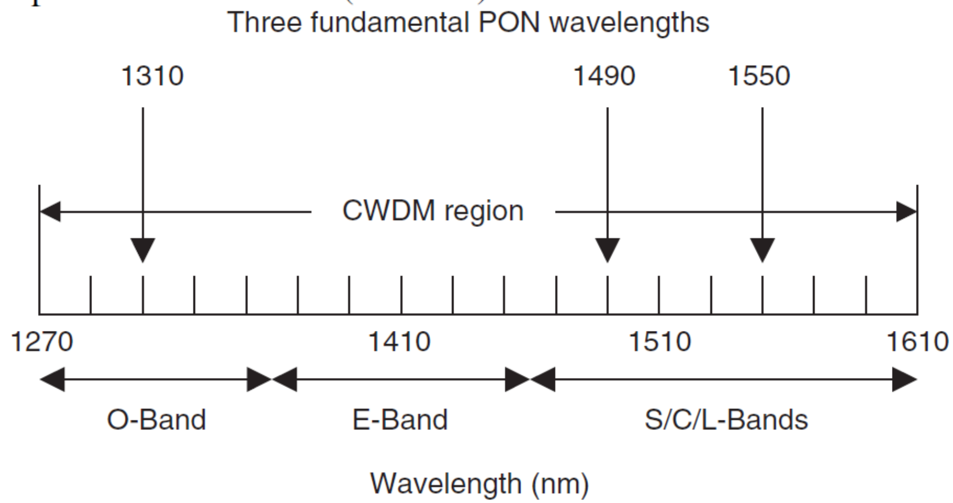



**Figure 3.3.** Spectral grid for CWDM.

Recommendation G.694.2 which defines the spectral grid for CWDM. As shown in Figure 3.3, the CWDM grid is made up of 18 wavelengths defined within the range 1270 to 1610 nm (O- through L-bands) spaced by 20 nm with wavelength-drift tolerances of ±2 nm. This can be achieved with inexpensive light sources that are not temperature controlled.

The ITU-T Recommendation G.695 released in 2003 outlines optical interface specifications for multichannel CWDM over distances of 40 and 80 km. Both unidirectional and bidirectional systems (such as used in PON applications) are included in the recommendation. The applications for G.695 cover all or part of the 1270- to 1610-nm wavelength range. The main deployments are for single-mode fibers, such as those specified in ITU-T Recommendations G.652 and G.655.

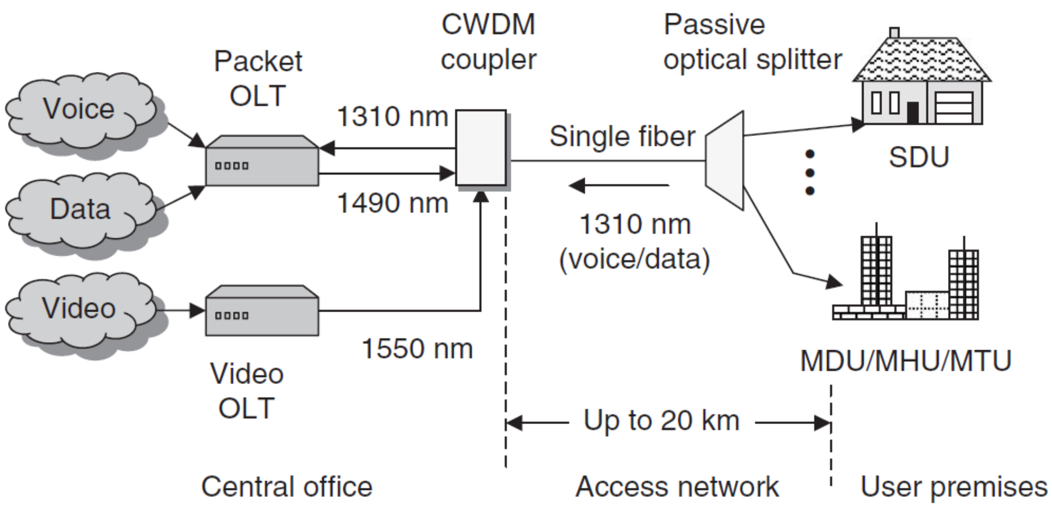



**Figure 6.1.** Basic architecture of a typical PON.

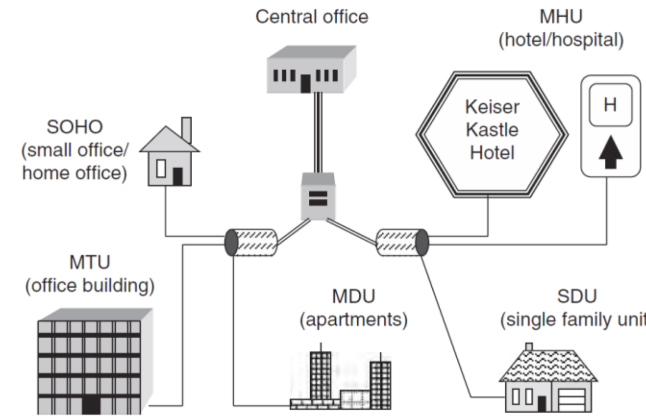



**Figure 1.7.** Acronyms used for various types of premises.

- A *multiple hospitality unit* (MHU) refers to premises such as hotels, hospitals, airports, or convention centers.
- A *single dwelling unit* (SDU) is a premises occupied by a single family.
- A *single family unit* (SFU) is an alternative designation of an SDU.
- A *small office/home office* is referred to by the acronym SOHO.

- A *multiple dwelling unit* (MDU) refers to apartment complexes, condominiums, or dormitories.
- A *multiple tenant unit* (MTU) designates an office building, an office campus, or an industrial campus with different business tenants.

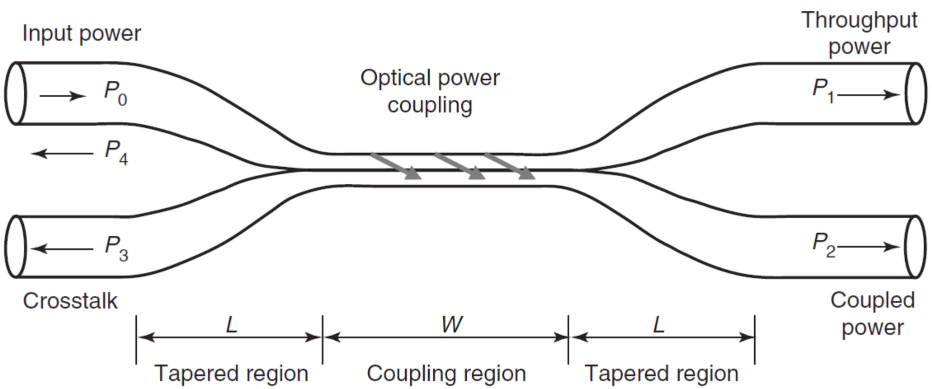



**Figure 3.4.** Cross-sectional view of a fused-fiber coupler and its operation concept.

**Figure 3.6.** Compact tap coupler consisting of a microtap and a pin photodiode. (Photo courtesy of Lightwaves2020; www.lightwaves2020.com.)

- FTTB, *fiber-to-the-business*, refers to the deployment of optical fiber from a central office switch directly into an enterprise.
- FTTC, *fiber-to-the-curb*, describes running optical fiber cables from central office equipment to a communication switch located within 1000 ft (about 300 m) of a home or enterprise. Coaxial cable, twisted-pair copper wires (e.g., for DSL), or some other transmission medium is used to connect the curbside equipment to customers in a building.
- FTTH, *fiber-to-the-home*, refers to the deployment of optical fiber from a central office switch directly into a home. The difference between FTTB and FTTH is that typically, businesses demand larger bandwidths over a greater part of the day than do home users. As a result, a network service provider can collect more revenues from FTTB networks and thus recover the installation costs sooner than for FTTH networks.
- FTTN, *fiber-to-the-neighborhood*, refers to a PON architecture in which optical fiber cables run to within 3000 ft (about 1 km) of homes and businesses being served by the network.
- FTTO, *fiber-to-the-office*, is analogous to FTTB in that an optical path is provided all the way to the premises of a business customer.
- FTTP, *fiber-to-the-premises*, has become the prevailing term that encompasses the various FTTx concepts. Thus FTTP architectures include FTTB and FTTH implementations. An FTTP network can use BPON, EPON, or GPON technology.
- FTTU, *fiber-to-the-user*, is the term used by Alcatel to describe their products for FTTB and FTTH applications.

# Questions