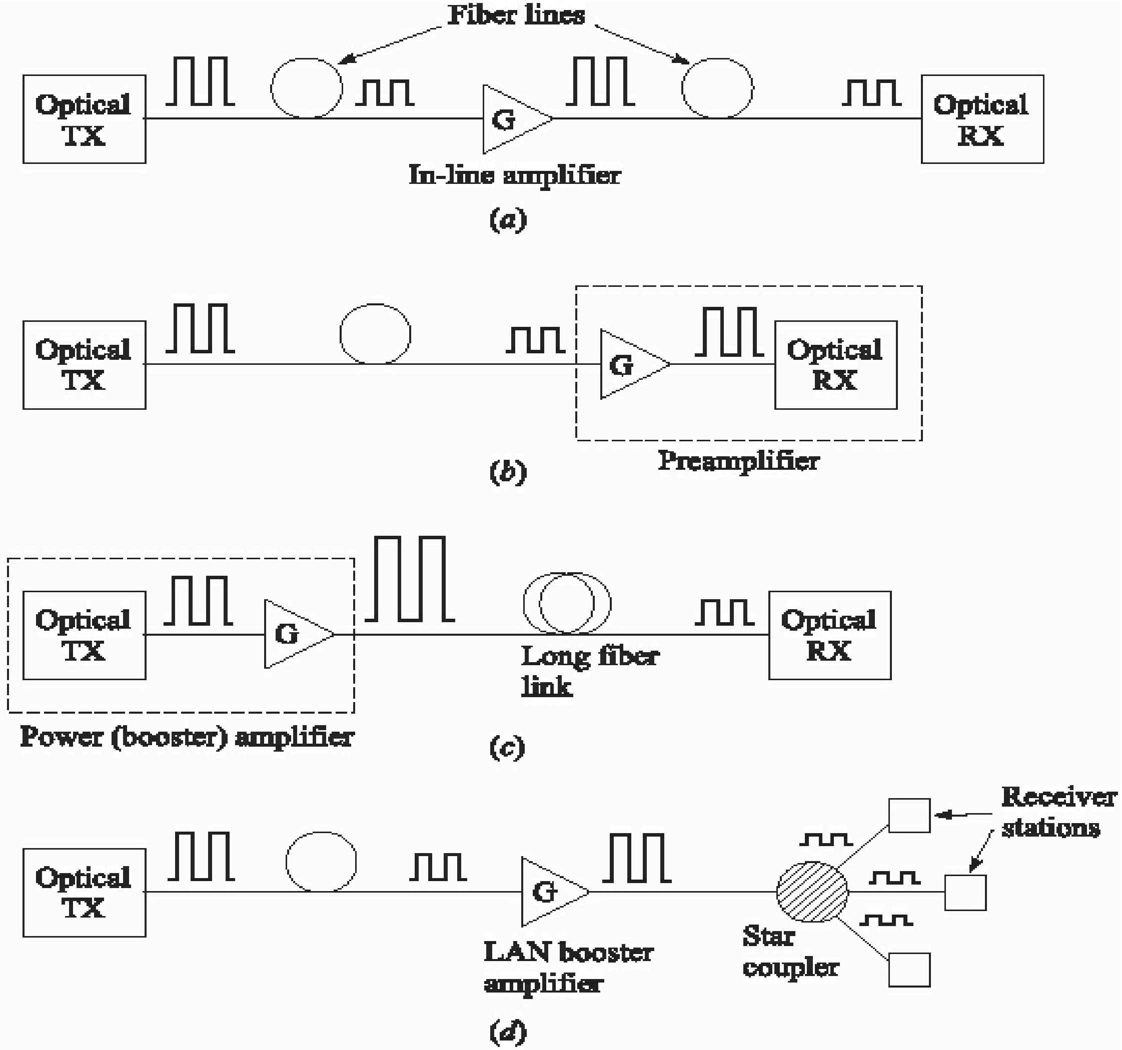
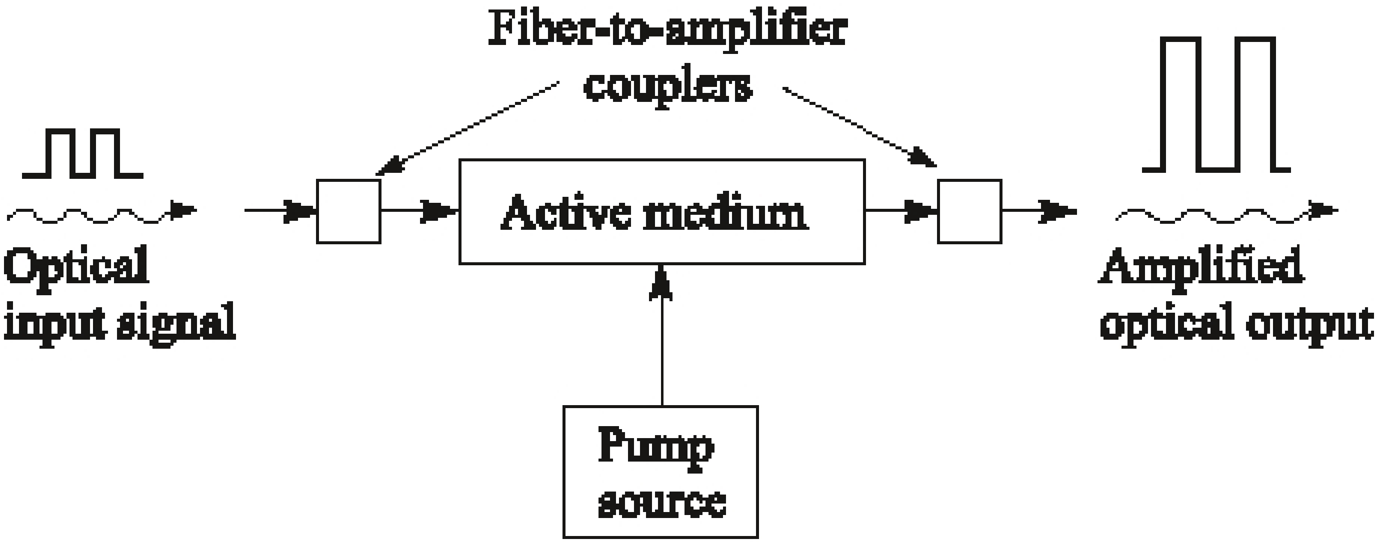
Optical amplifiers and their applications

Ref: *Optical Fiber Communications by:*
G. Keiser; 3rd edition

Depend on
Source of Losses:



Basic operation of optical amplifiers



Optical Amplifiers

Two main classes of optical amplifiers include:

Semiconductor Optical Amplifiers (SOA)

Doped Fiber Amplifiers (DFA)

Semiconductor Optical Amplifiers

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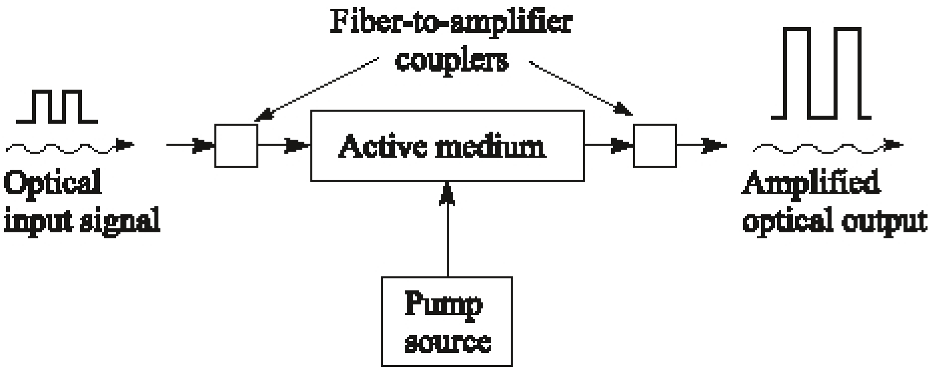
There are two types of SOAs:

--- Fabry- Perot amplifiers (FPA)
When the light enters FPA it gets amplified as it reflects back and forth between the mirrors until emitted at a higher intensity.
It is sensitive to temperature and input optical frequency.

---Non-resonant traveling-wave amplifiers (TWA)
It is the same as FPA except that the end facets are either antireflection coated or cleaved at an angle so that internal reflection does not take place and the input signal gets amplified only once during a single pass through the device. They widely used because they have a large optical bandwidth, and low polarization sensitivity.

Non-resonant traveling-wave amplifiers (TWA)



External Pumping

External pumping injection creates population inversion similar to LASERs.
The rate equations can be defined as:

$$\frac{\partial n(t)}{\partial t} = R_p(t) - R_{st}(t) - \frac{n(t)}{\tau_r}$$

$$R_p(t) = \frac{J(t)}{qd}$$

is the external pumping rate, J(t) is the current density, d is the active layer thickness, and τ_r is the combined time constant coming from spontaneous-carrier recombination mechanism. *Rst(t)* is the stimulated emission and it is equal to:

$$R_{st}(t) = \Gamma a v_g (n - n_{th}) N_{ph} \equiv g v_g N_{ph}$$

External Pumping (Cont…)

where v_g is the group velocity of the incident light, Γ, optical confinement factor, *a* is the gain constant, n_{th} is threshold carrier density, N_{ph} is the photon density and g is the overall gain per unit of length.

$$N_{ph} = \frac{P_s}{v_g (hv)(wd)}$$

where *Ps* is the power of optical signal, w and d are width and the thickness of active area respectively.
Example…

Under steady state condition, variation of n vs time is zero, therefore:

$$R_p = R_{st} + \frac{n}{\tau_r}$$

External Pumping (cont…)

Substituting for R_p and R_{st} and solving for g yields:

$$g = \frac{\dfrac{J}{qd} - \dfrac{n_{th}}{\tau_r}}{v_g N_{ph} + 1/(\Gamma a \tau_r)} = \frac{g_0}{1 + N_{ph}/N_{ph;sat}}$$

Steady state gain per unit length

$$N_{ph;sat} = \frac{1}{\Gamma a v_g \tau_r}$$

Saturation photon density

$$g_0 = \Gamma a \tau_r \left(\frac{J}{qd} - \frac{n_{th}}{\tau_r} \right)$$

g_o is the zero or small-signal gain

per unit of length (in the absence of the signal input)

Typical values: I = 100 mA, L x W x d=500 x 5 x 0.5 μm^3, Γ = o.3 – 0.5, $n_{th}=10^{18}$ cm^{-3},
a= 2 x 10^{-16} cm^2, life time = 1 nS, group velocity = 2 x 10^8 m/s,
optical signal power = 1µW

Amplifier Gain

Amplifier gain or signal gain G is defined as:

An important parameter

$$G = \frac{P_{s,out}}{P_{s,in}}$$

or as we saw in the case of laser:

$$G = \exp\left[\Gamma\left(g_m - \bar{\alpha}\right)L\right] \equiv \exp\left[g(z)L\right]$$

G is increasing with device length, however, the internal gain is limited by gain saturation. G is depended on the optical input intensity, as it increases EHP depleted from the active region. For sufficiently large optical input, there will not be enough EHP to be stimulated.

where, g_m , α, and L are the material gain coefficient, the effective absorption coefficient of the material and amplifier length respectively. g(z) is the overall gain per unit of length. It is depends on the carrier density and signal wavelength.

g(z) can written as:

$$g(z) = \frac{g_0}{1 + \frac{P_s(z)}{P_{amp,sat}}}$$

g_o, the unsaturated medium gain per unit of length in the absence of signal input,

Amplifier Gain

P_s is the internal signal power at point z. $P_{amp.sat}$ is the amplifier saturation power defined as: internal power level at which the gain/(unit length) has been halved.

The increase in the light power in incremental length of *dz* can be expressed as:

$$dP = g(z)P_s(z)dz$$

Which can show:

$$g_0 dz = \left(\frac{1}{P_s(z)} + \frac{1}{P_{amp,sat}} \right) dP$$

now

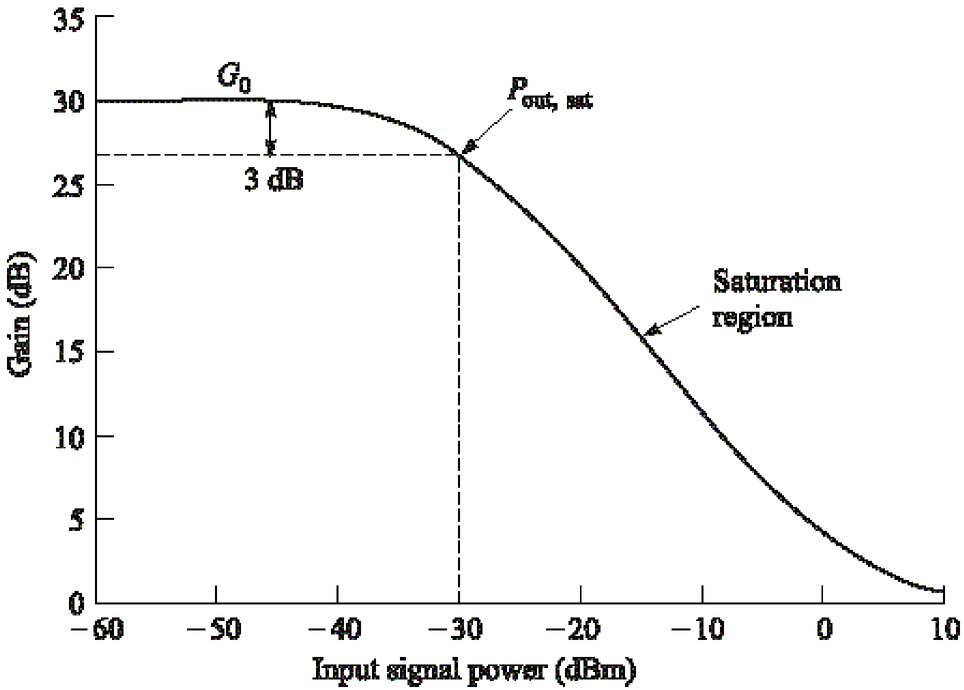
$$\int_0^L g_0 dz = \int_{Ps,in}^{Ps,out} \left(\frac{1}{P_s(z)} + \frac{1}{P_{amp,sat}} \right) dP$$

and finally one can see that:

$$G = 1 + \frac{P_{amp,sat}}{P_{s,in}} \ln\left(\frac{G_0}{G} \right)$$

where $G_o = \exp(g_o L)$ is the single-pass gain in the absence of light.

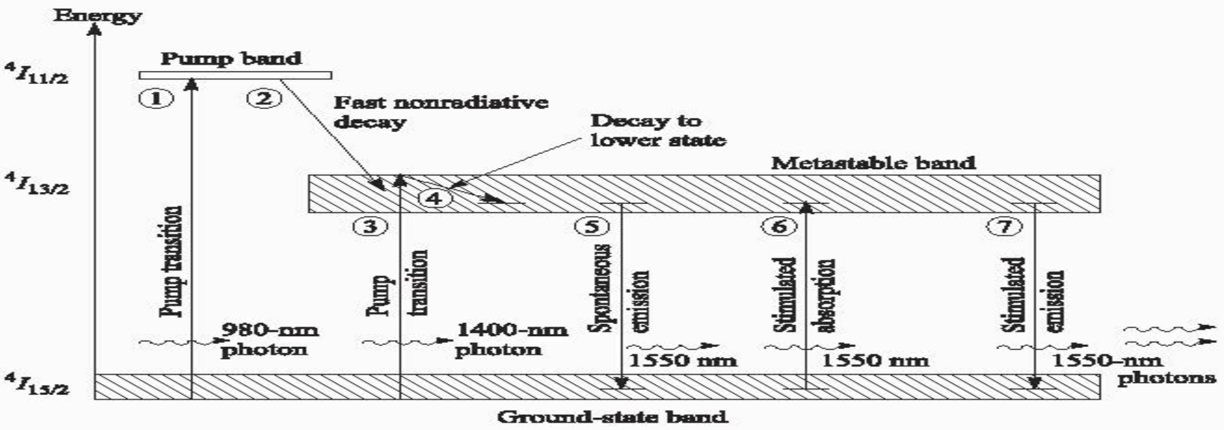
Amplifier gain versus power



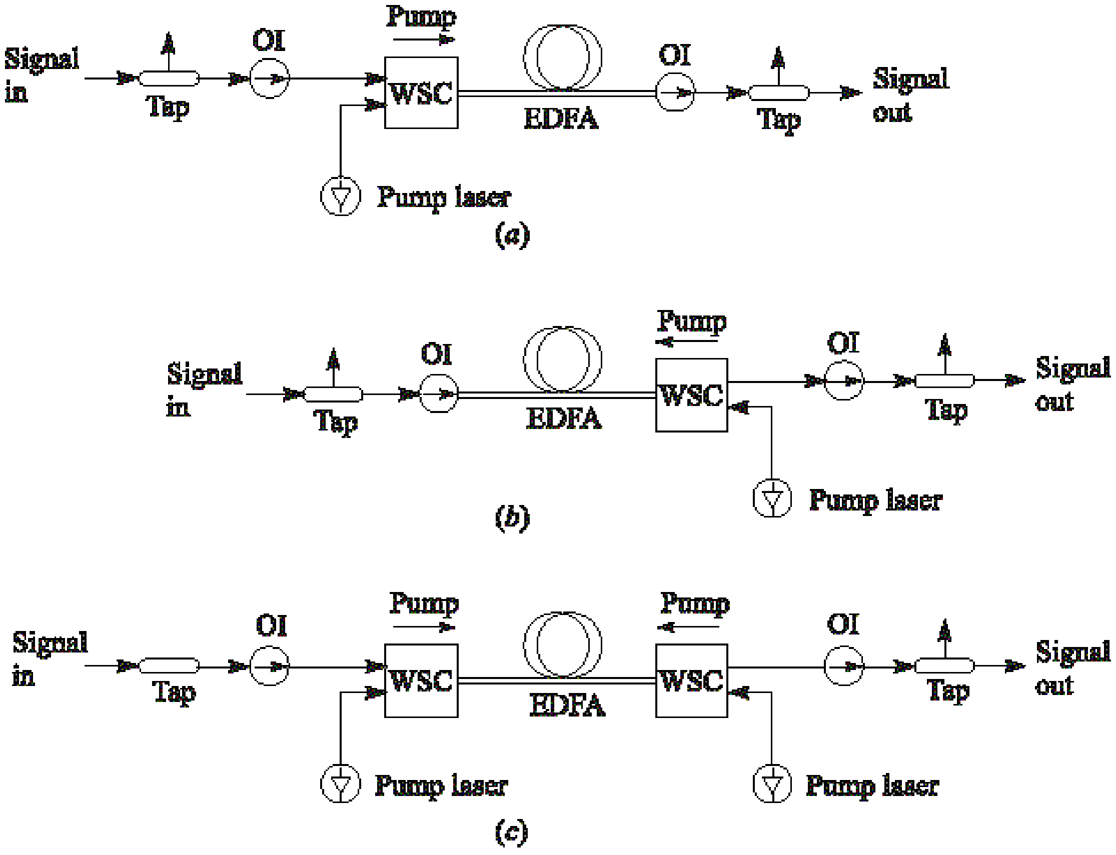
So, using the amplifier must be done at appropriate places where the optical power is really low.

Erbium-Doped Fiber Optic Amplifiers

Erbium energy-level diagram and amplification mechanism



EDFA configurations



OI: Optical isolator
WSC: Wavelength-selective coupler

EDFA Power-Conversion Efficiency (PCE) and Gain

The input and output power of an EDFA can be expressed:

$$P_{s,out} \le P_{s,in} + \frac{\lambda_p}{\lambda_s} P_{p,in}$$

Maximum output signal power depends on wavelength ratio of the pump to the signal. Pumping works only When λp< λs and for appropriate gain $P_{s,in} << P_{p,in}$

The Power Conversion Efficiency (PCE) is defined as (always less than unity)

$$PCE = \frac{P_{s,out} - P_{s,in}}{P_{p,in}} \approx \frac{P_{s,out}}{P_{p,in}} \le \frac{\lambda_p}{\lambda_s} \le 1$$

It is equal to 1 when all pump photons are converted to signal photons

Optical Amplifiers

We can also write the amplifier gain as:

$$G = \frac{P_{s,out}}{P_{s,in}} \leq 1 + \frac{\lambda_p}{\lambda_s}\frac{P_{p,in}}{P_{s,in}}$$

When input signal power is very large i.e. $P_{s,in} >> (\lambda_p / \lambda_s) P_{p,in}$

then the maximum G is unity

In order to achieve a specific maximum gain G, the input signal power can NOT exceed a value given by

$$P_{s,in} \leq \frac{\frac{\lambda_p}{\lambda_s} P_{p,in}}{G - 1}$$

Example…

Optical Amplifiers

EDFA Power-Conversion Efficiency (PCE) and Gain

The maximum gain in a 3 level laser medium of length L can also be given as follow (in addition to pump power, the gain depends on the fiber length)

$$G_{\max} = \exp\left(N\sigma_e L\right)$$

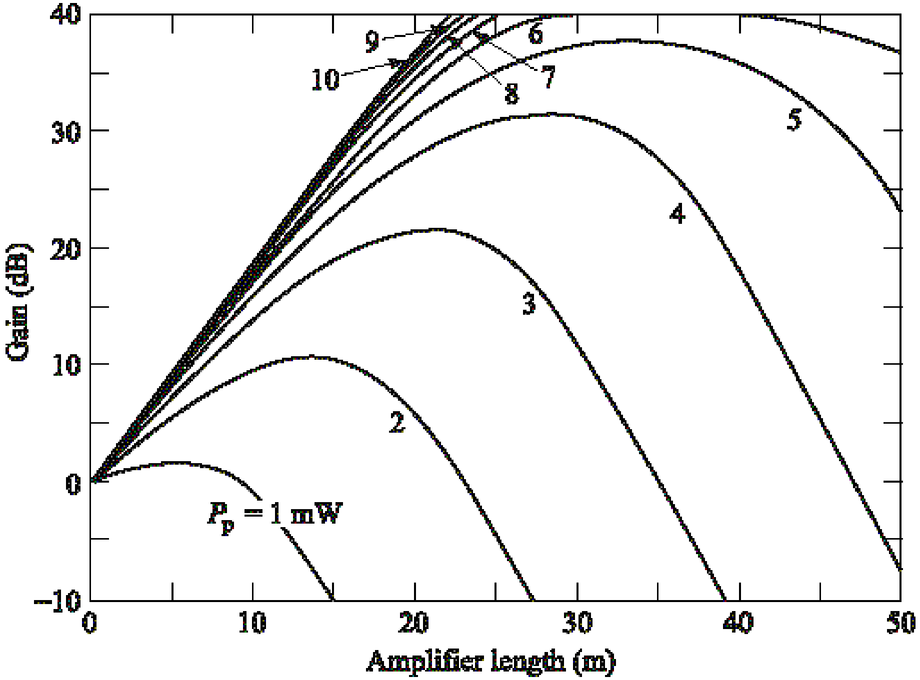
where N is the rare-earth element concentration and σ_e is the signal-emission cross section.

Therefore the maximum gain or power will be defined as:

$$G \leq \min\left\{\exp\left(\rho\sigma_e L\right), 1 + \frac{\lambda_p}{\lambda_s}\frac{P_{p,in}}{P_{s,in}}\right\}$$

$$P_{s,out} \leq \min\left\{P_{s,in}\exp\left(\rho\sigma_e L\right), P_{s,in} + \frac{\lambda_p}{\lambda_s}P_{p,in}\right\}$$

Gain versus EDFA length



Absorption and Emission Cross-Sections in EDFA

- The effect of absorption and emission efficiencies in external pumping in EDFA are realized by defining new parameters called *Absorption Cross-Section*, σ_a and *Emission Cross-Section*, σ_e respectively.
- σ_a determines the pumping rate. If the pumping power is P_p and Er ground state population is N_0, the pumping rate is W_pN_0 where,

$$W_p = \frac{\sigma_a P_p}{h\nu A}$$

- σ_e determines the medium gain, $g = \sigma_e N_2$. N_2 is metastable (inversion layer) population>N_0
- Stimulated emission rate, R_s is:

$$R_s = V_g g N_{ph} = \frac{\sigma_e P_{s-in} N_2}{h\nu A}$$

Where $P_{s\text{-}in}$ is the incident light power.

- Therefore the pumping gain will be:

$$G_p = \frac{P_{p-out}}{P_{p-in}} \cong e^{(\sigma_e N_2 - \sigma_a N_0)L}$$

L is the length of the pump.

Example

Let’s calculate the pump power needed per unit length of Er –doped optical fiber to establish a small-signal optical gain of 0.4 dB/m at 1.55 micron. Assume that the confinement factor is =0.7. Er^{3+} is doped at the center with a 2 micron diameter with concentration of 10^{18} ions/ cm^3. Assume a pump wavelength of 1.48 micron is used. The spontaneous emission lifetime is 10 msec.

Components for Optical Communications

Materials for self-studies

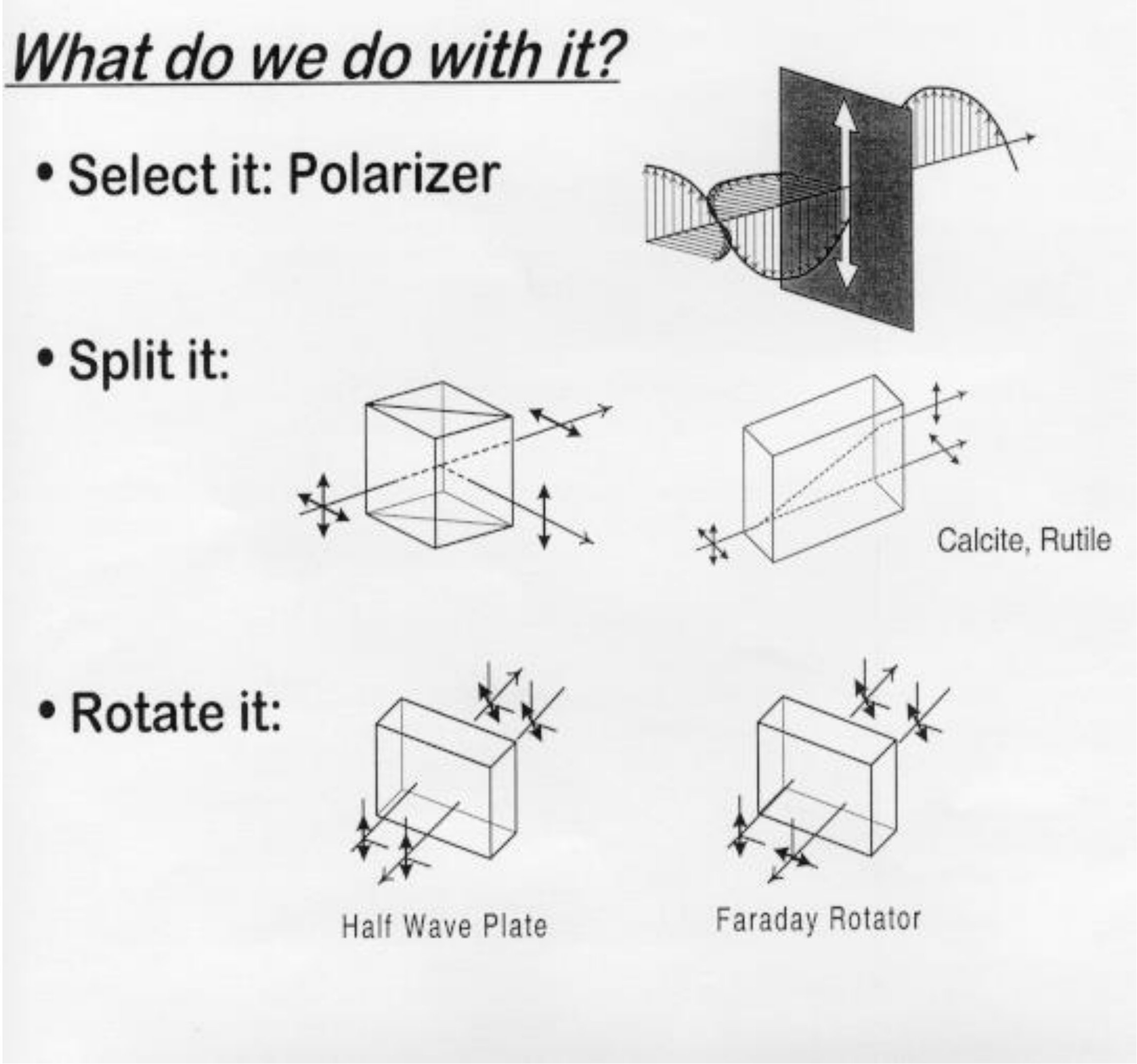
- Passive Components

Couplers,
Attenuators
Equalizers,
Isolators
WDM

- Active Components

Modulators,
Diodes,
Switches,
Routers

Some applications of Light polarization



What do we do with it?

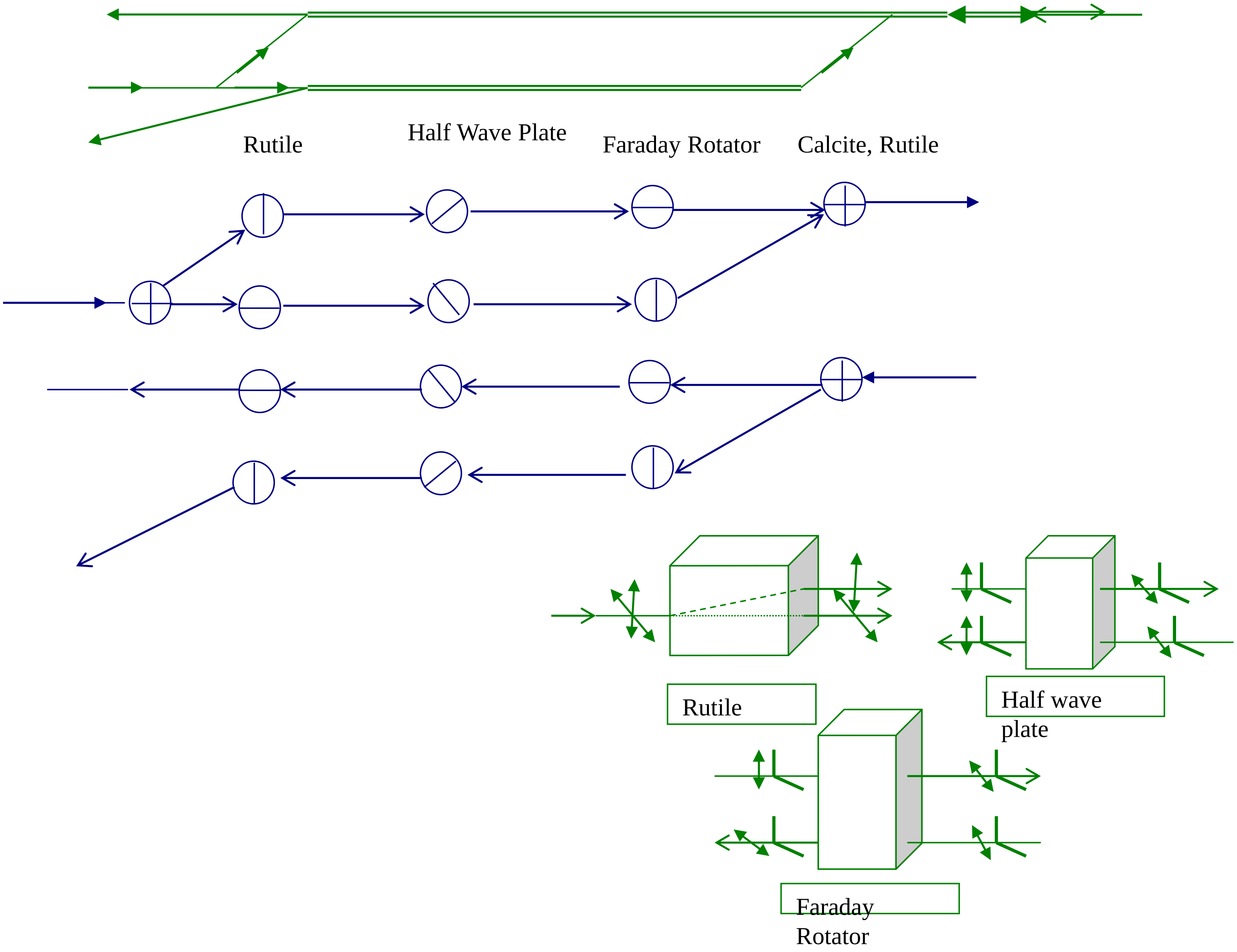
- Select it: Polarizer
- Split it:
- Rotate it:

Calcite, Rutile

Half Wave Plate

Faraday Rotator

Optical Diode



Rutile

Half Wave Plate

Faraday Rotator

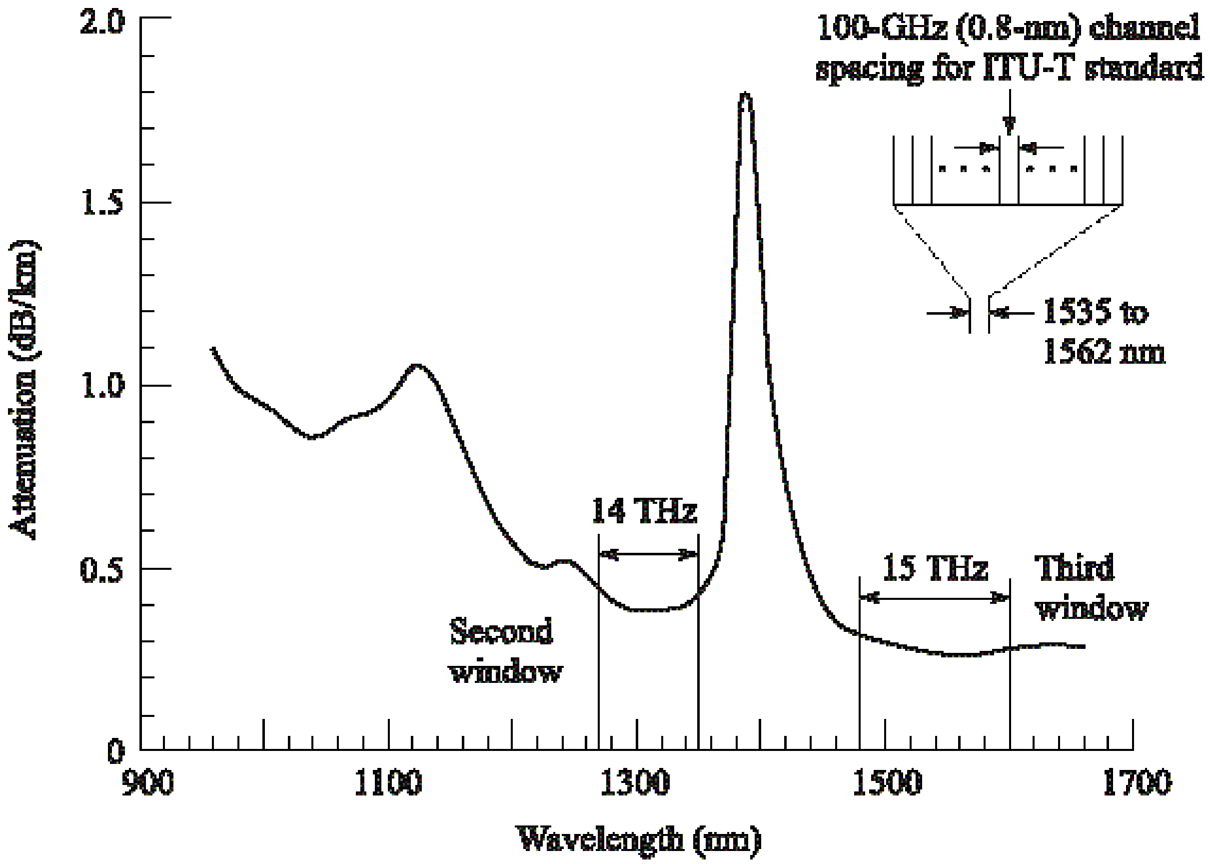
Calcite, Rutile

Rutile

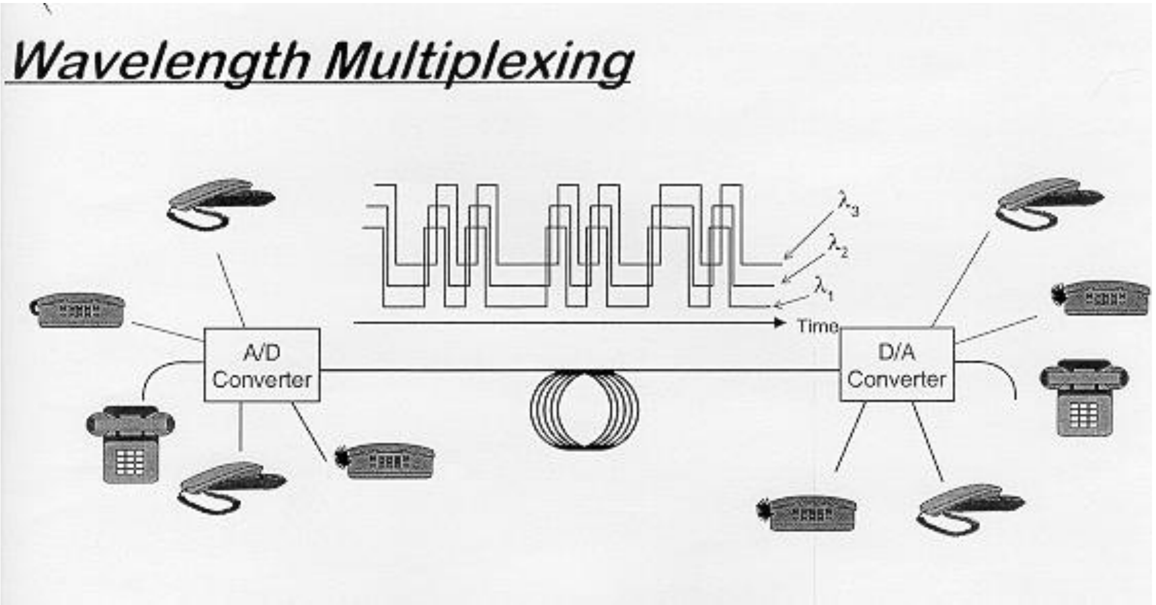
Half wave plate

Faraday Rotator

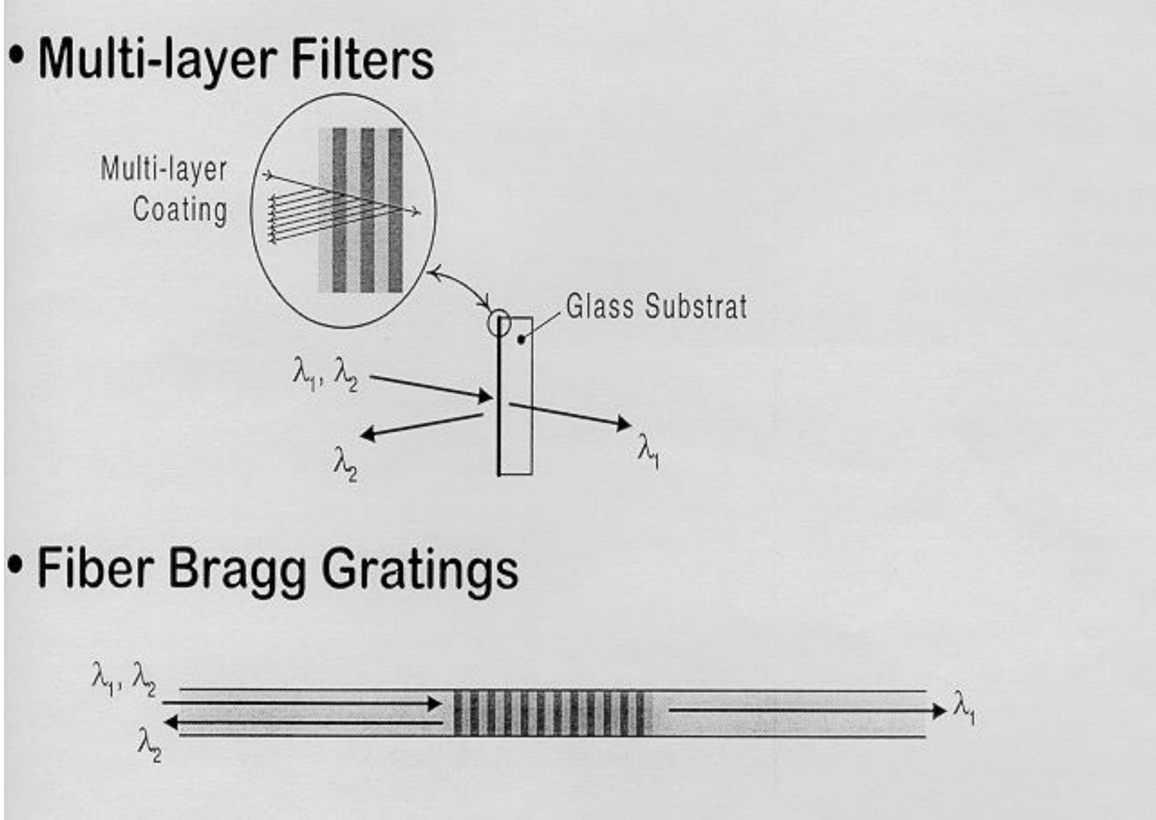
Transmission windows



WDM


Wavelength Multiplexing
λ_3
λ_2
λ_1
Time
A/D Converter
D/A Converter

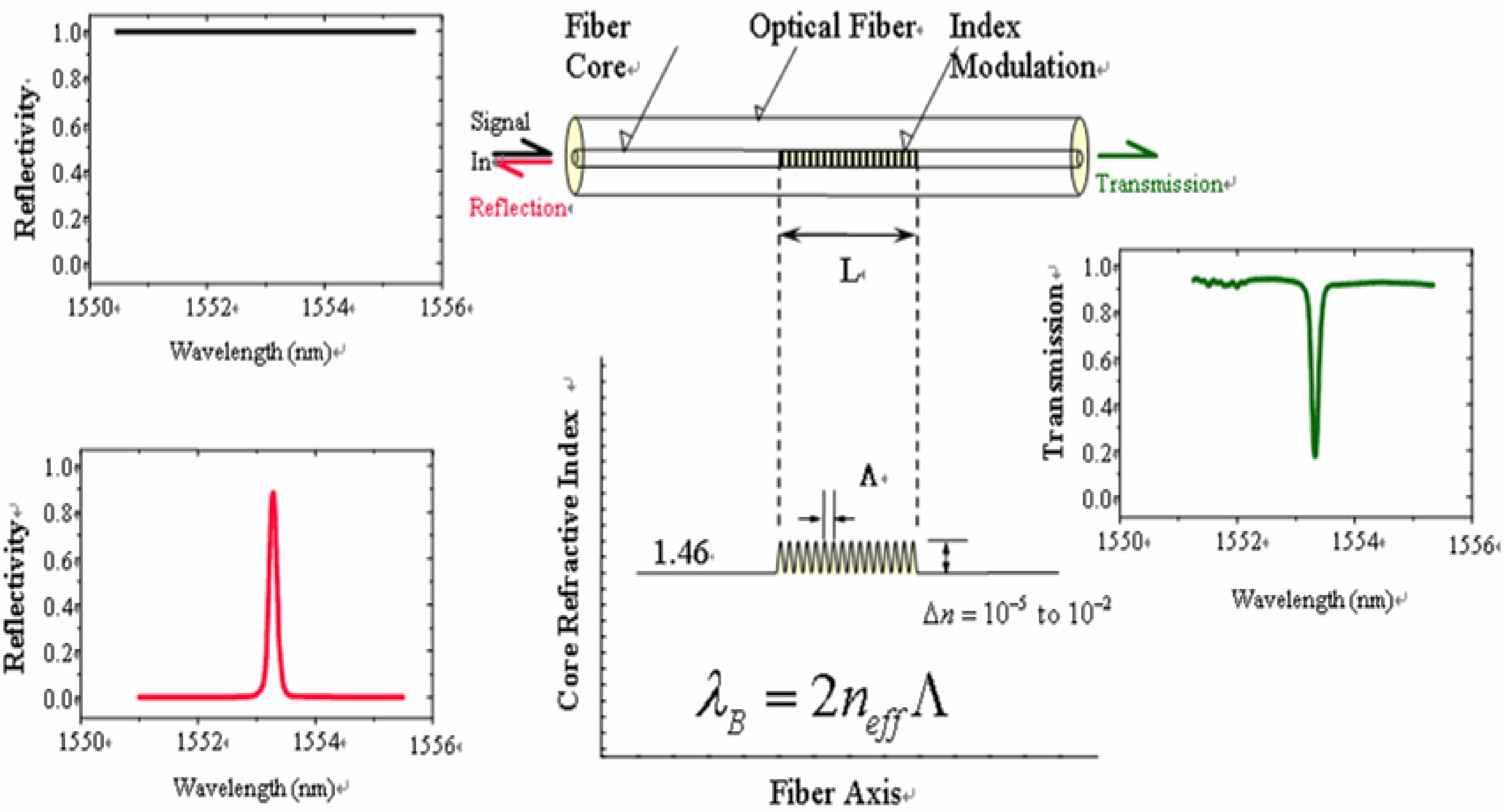
Optical Interference



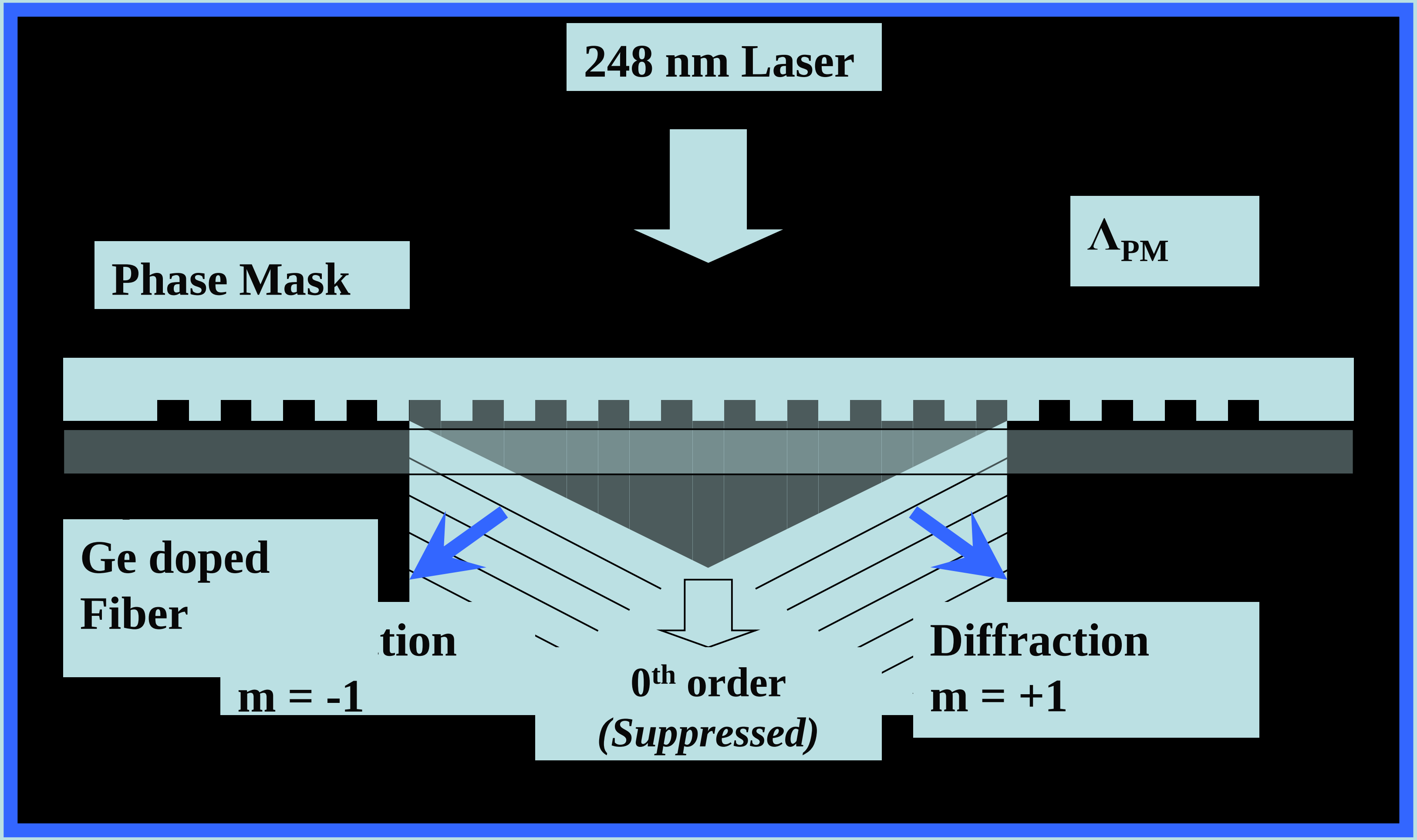
- **Multi-layer Filters**

- **Fiber Bragg Gratings**

Fiber Bragg grating



Fiber Bragg grating fabrication
Phase Mask: Direct Imprinting



248 nm Laser

Phase Mask

Λ_{PM}

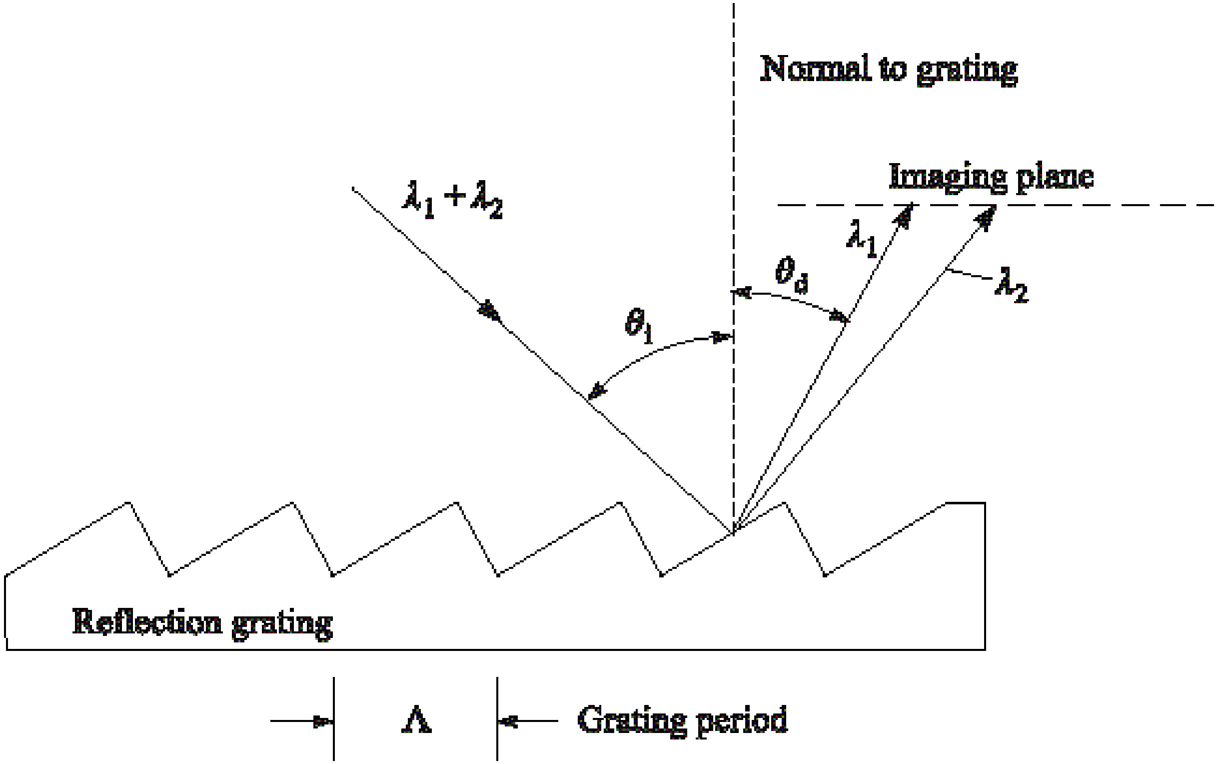
Ge doped Fiber

tion
m = -1

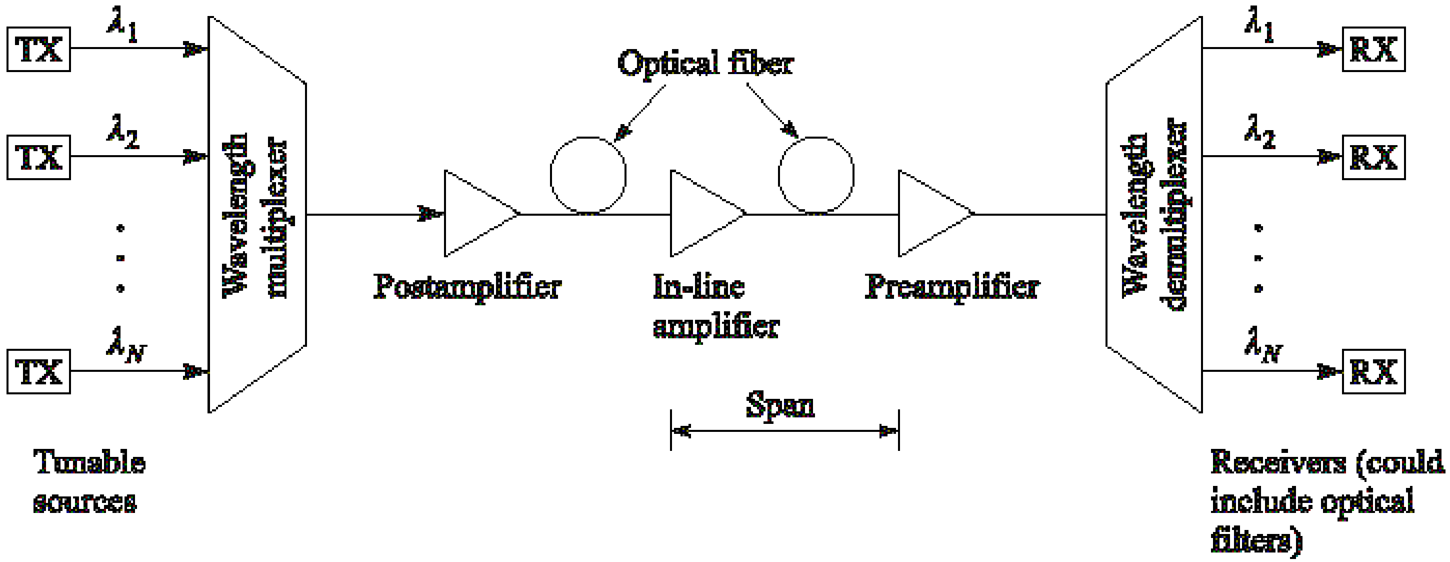
0^{th} order
(Suppressed)

Diffraction
m = +1

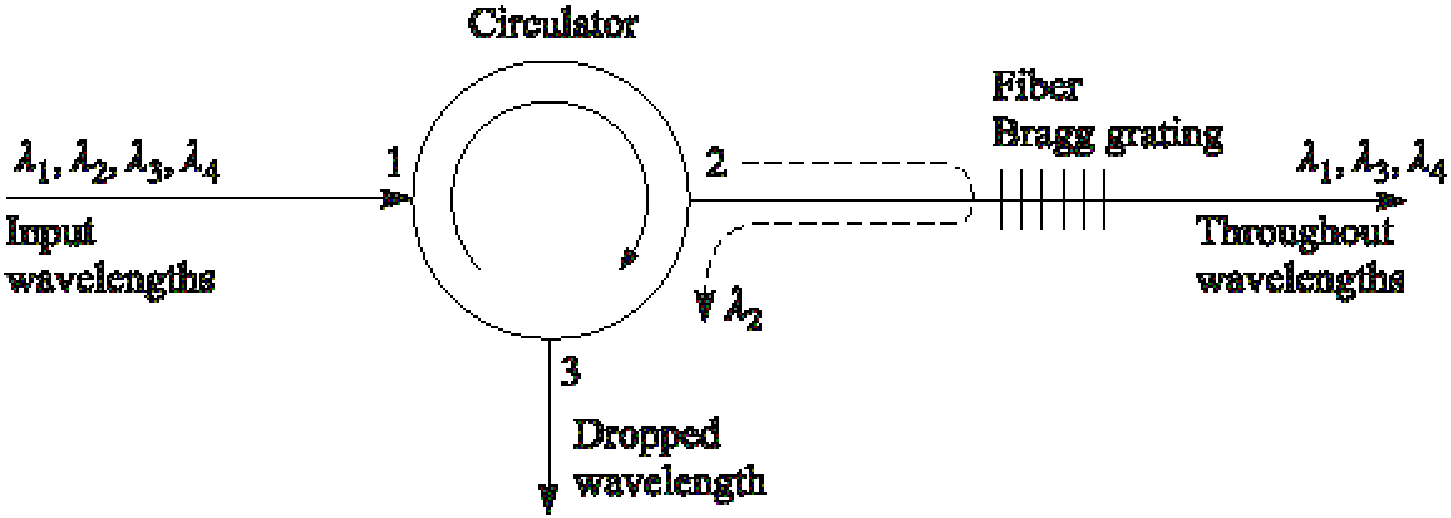
Reflection grating



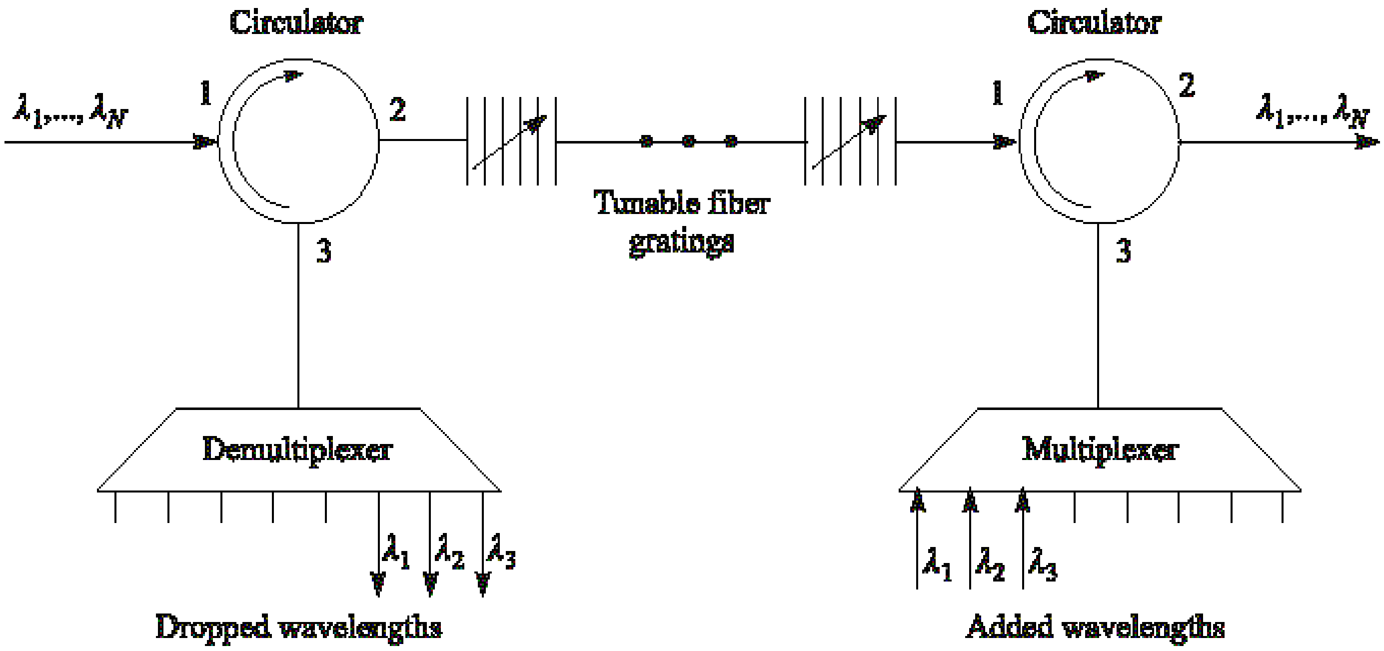
Typical WDM Network



Simple demultiplexer function



Extended add/drop multiplexer



Tunable optical filter