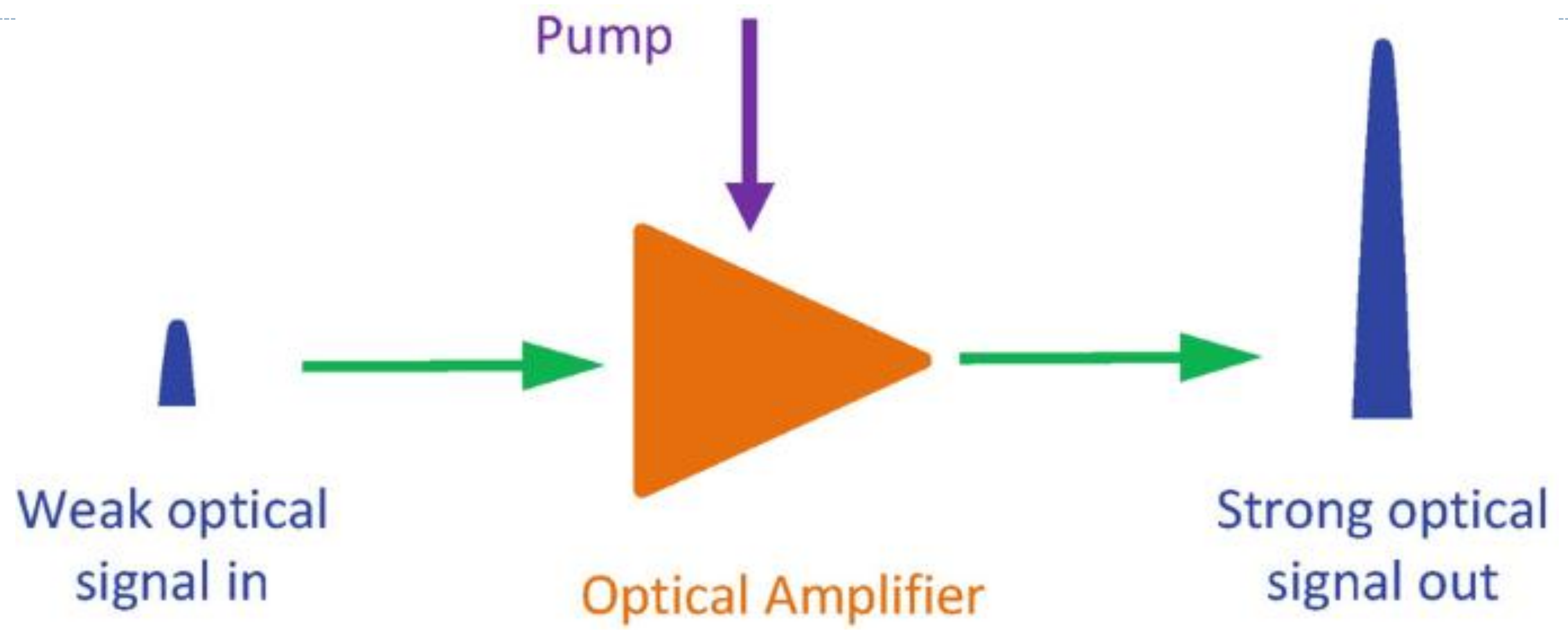


Module – 7
Optical Amplifiers

Semiconductor Optical/Laser Amplifiers (SOAs/SLAs)

- Semiconductor optical amplifiers (SOAs) are based on the same technology as laser diodes.

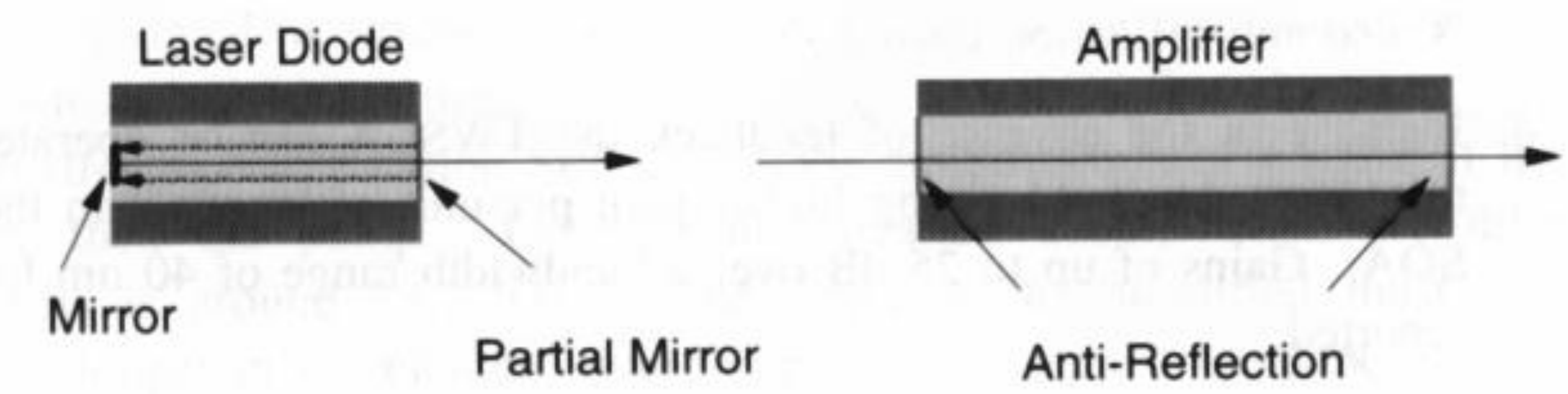
- The attractiveness of this is that SOAs can operate in every fiber wavelength band extending from 1280 nm in the O-band to 1650nm in the U-band.

- Furthermore, since they are based on standard semiconductor technology, they can be integrated easily on the same substrate as other optical devices and circuits

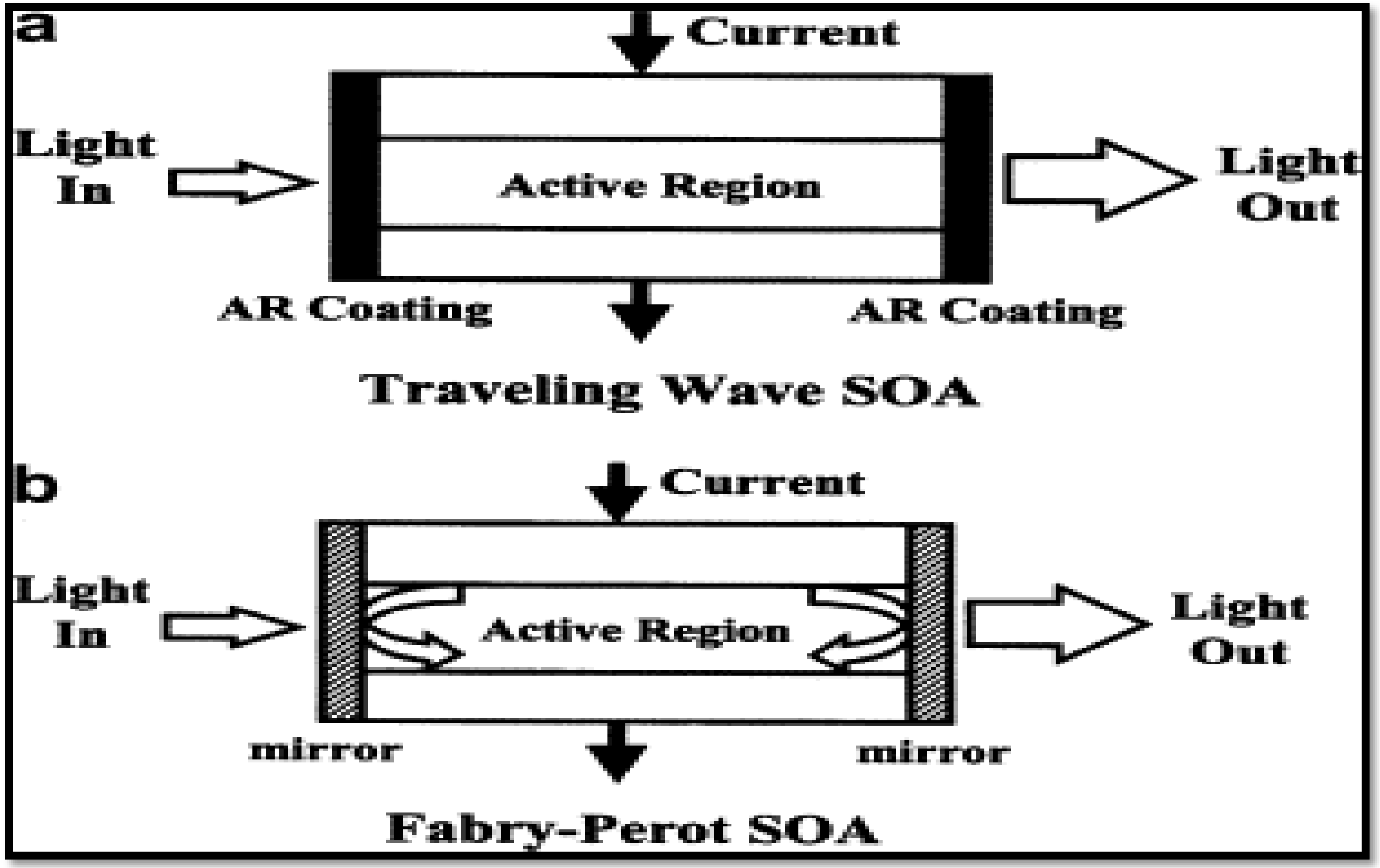
- The major types SOAs are
  - ➢ Resonant Fabry Perot Amplifier (FPA)
  - ➢ Non resonant Travelling Wave Amplifier (TWA)

LASER vs SOA

- LASER & SOA - Stimulated emission process - but difference is that;
- LASER diode => amplifier gain medium + facet mirrors
- SOA – gain medium & facets (anti-reflection coating coupled to both fibre ends => so light amplified travelling just one time(single pass) in gain medium



FPA & TWA


a
Current
Light
In
Active Region
Light
Out
AR Coating
AR Coating
Traveling Wave SOA
b
Current
Light
In
Active Region
Light
Out
mirror
mirror
Fabry-Perot SOA

FPA & TWA

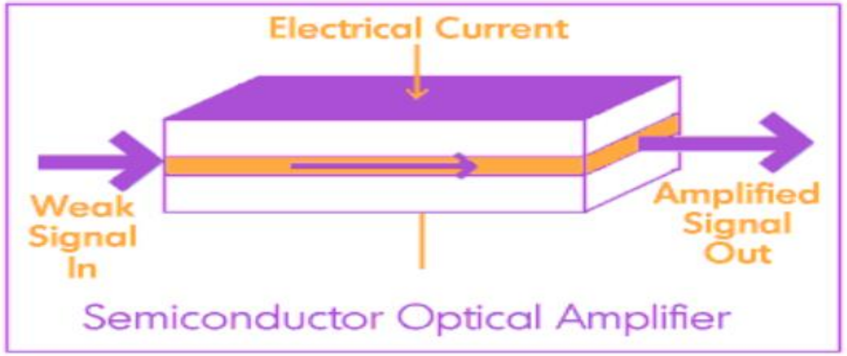
Fabry-Perot amplifiers (FPA)

- When the light enters, 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.

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 low polarization sensitivity.

Construction and working



- Stimulated emission to amplify an optical signal.
- Active region of the semiconductor.
- Injection current to pump electrons at the conduction band.
- The input signal stimulates the transition of electrons down to the valence band to acquire an amplification.
- Similar to laser diodes, external current injection is the pumping method used to create the population inversion needed for the operation of the gain mechanism in semiconductor optical amplifiers.

Amplifier Gain

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

$P_{s,in}$ = Input power of optical signal

$P_{s,out}$ = Output power of amplified optical signal

Same as that of LASER,

$$G = e^{(\Gamma g_m - \bar{\alpha})L} = e^{(g(z))L}$$

Where,

- G = single pass gain in active medium of SOA
- gm = The material gain coefficient
- α = Effective absorption coefficient of the material
- L = Amplifier length respectively

- G, gain ↑ with device length & the internal gain is limited by gain saturation.
- i/p power ↑ => G ↑ => EHP depleted from the active region => will not have enough EHP in the active region to be stimulated=> gain saturation

large optical input => Gain saturates

Amplifier Gain

g(z) can written as $\dfrac{g_0}{1+\dfrac{P_S(Z)}{P_{amp,sat}}}$

g_0= unsaturated medium gain per unit of length in the absence of signal input

$P_S(z)$ = internal signal power at point z.

$P_{amp,sat}$ = amplifier saturation power

Amplifier Gain

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

$$dP = g(z)\, P_S(Z)dz = \frac{g_0}{1+\frac{P_S(Z)}{P_{amp,sat}}} P_S(z)\ dz$$

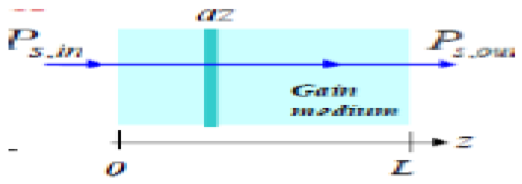
Solving for g_0,

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

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

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

Amplifier Gain



Now integrating both sides with

$$\int_0^L g_0 \mathrm{dz} = \int_{P_{s,in}}^{P_{s,out}} \left\{\frac{1}{P_S(Z)} + \frac{1}{P_{amp,sat}}\right\} \mathrm{dz}$$

$$\int_0^L g_0 \mathrm{dz} = g_0 \int_0^L \mathrm{dz} = g_0 [z]_0^L = g_0 [L-0] = g_0 L \ldots \ldots \ldots ()$$

$$\int_{P_{s,in}}^{P_{s,out}} \left\{\frac{1}{P_S(Z)} + \frac{1}{P_{amp,sat}}\right\} dz$$

$$=> \int_{P_{s,in}}^{P_{s,out}} \left\{\frac{1}{P_S(Z)}\right\} dz + \int_{P_{s,in}}^{P_{s,out}} \left\{\frac{1}{P_{amp,sat}}\right\} dz$$

$$= [ln P_S(Z)]_{P_{s,in}}^{P_{s,out}} + \frac{1}{P_{amp,sat}} [z]_{P_{s,in}}^{P_{s,out}}$$

$$= \ln(P_{s,out}) - ln(P_{s,in}) + \{\frac{P_{s,out} - P_{s,in}}{P_{amp,sat}}\}$$

Amplifier Gain

$$\ln\left(\frac{P_{s,out}}{P_{s,in}}\right) + \left\{\frac{P_{s,out} - P_{s,in}}{P_{amp,sat}}\right\} = g_0 L$$

$$single\ pass\ gain\ in\ absence\ of\ light = e^{(g_0 L)}$$

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

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

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

Solving for G,

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

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

Amplifier Gain

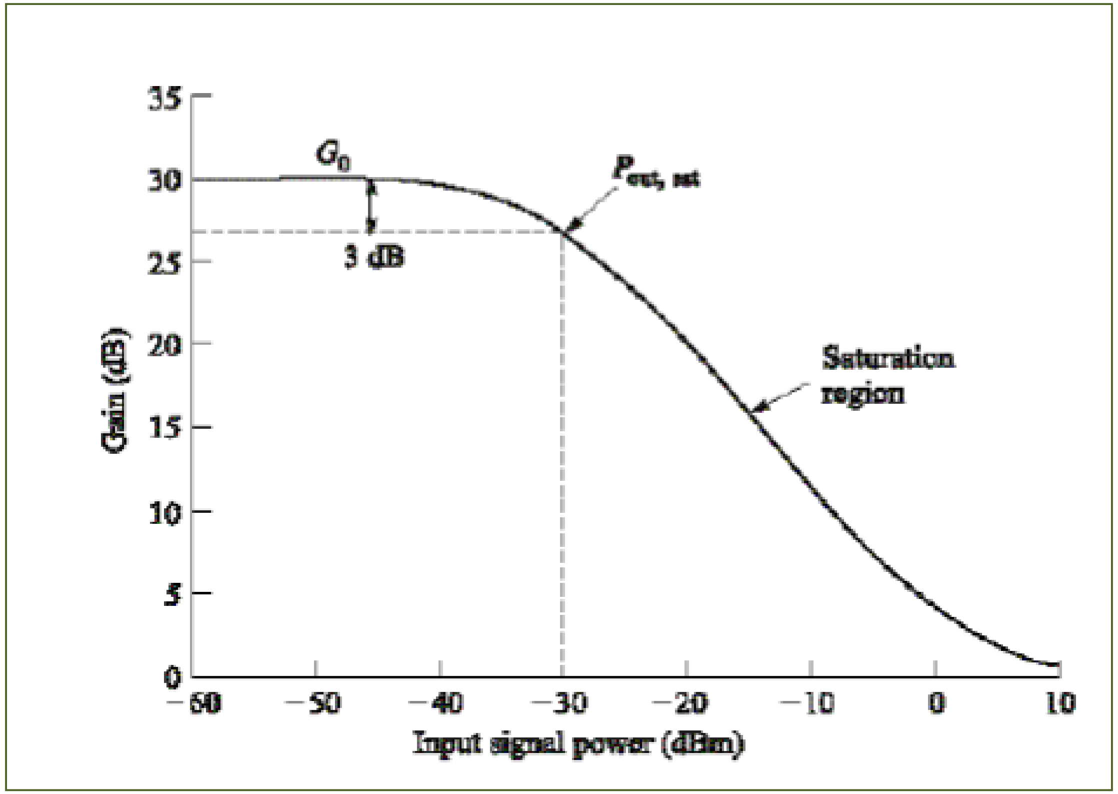


fig: single pass gain vs input power

- From fig, G depended on the optical input power

- Here G is reduced by 3dB from unsaturated amplifier gain (G0)

Merits and Demerits

Advantages

- The semiconductor optical amplifier is of small size and electrically pumped.
- It can be potentially less expensive than the EDFA and can be integrated with semiconductor lasers, modulators, etc.
- All four types of nonlinear operations (cross gain modulation, cross phase modulation, wavelength conversion and four wave mixing) can beconducted.
- SOA can be run with a low power laser. This originates from the short nanosecond or less upper state lifetime, so that the gain reacts rapidly tochanges of pump or signal power and the changes of gain also cause phase changes which can distort the signals.

Disadvantages

- The performance of SOA is still not comparable with the EDFA. The SOA has higher noise, lower gain, moderate polarization dependence and high nonlinearity with fast transient time.

Summary

- They are polarization dependent
- They have relatively high gain (20 dB).
- Their output saturation power is in the range of 5-10 dBm.
- They have a large bandwidth.
- They operate at the wavelength regions of 1300 and 1500nm.
- They are compact semiconductors easily integrable with other devices, which can also be used as wavelength converter.
- Because of nonlinear phenomena, have a high noise figure and high cross-talk level
- Technological difficulties in fabricating SOAs with low (up to 10-4) reflectance's.

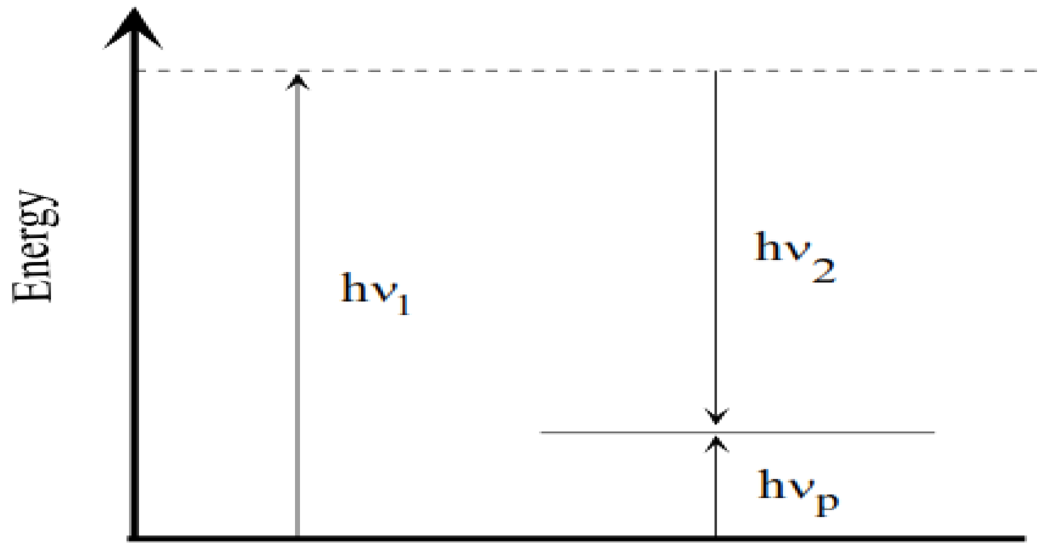
Raman Amplifier

- Raman Amplifier was demonstrated in the 1980s
- Uses the principle of SRS
- Low ASE
- Unavailability of low cost high-power diode laser pump source
- Innovation of FBGs in 1997
- Why do you need it :
  - amplify signals from 1270 to 1670 nm
  - any optical fiber can serve as the amplifying medium

Stimulated Raman Scattering

- Raman scattering is an elastic scattering mechanism

$$\nu_2 = \nu_1 - \nu_p$$

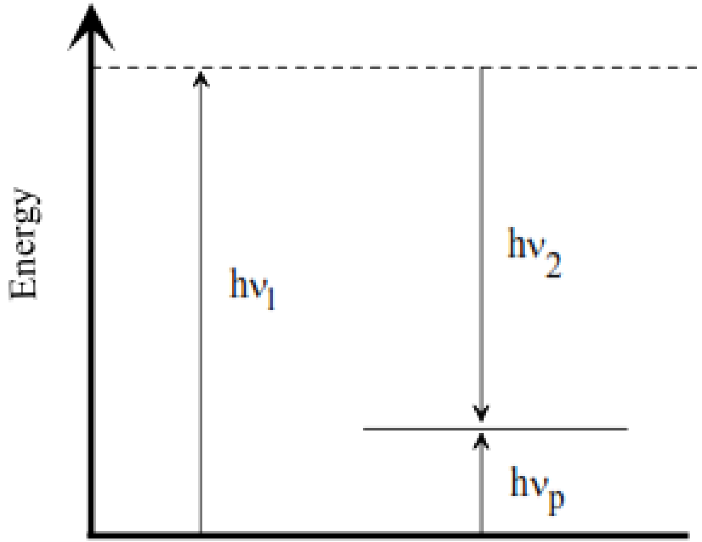


Stokes and Anti stokes

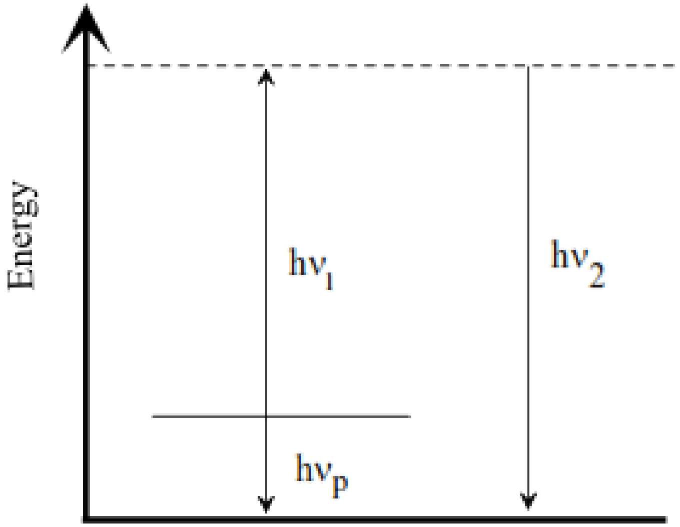
- Scattered light with lower energy - Stokes

- Scattered light with higher energy – Anti stokes

Stokes

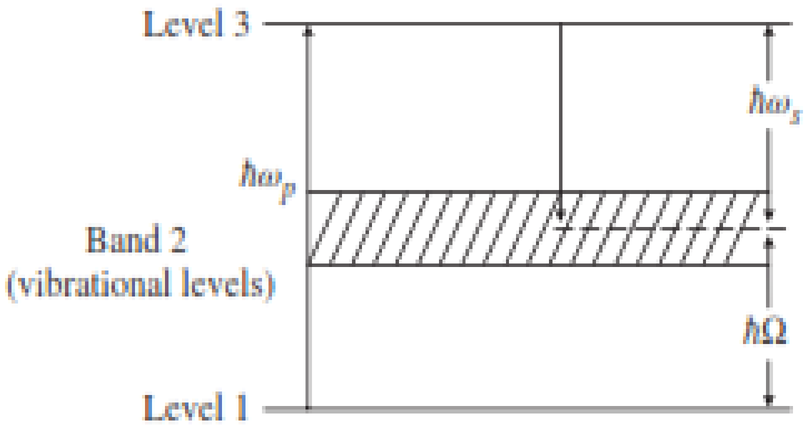


Anti-Stokes



Energy levels of silica

- Pump signal frequency - ω_p
- Optical signal frequency - ω_s
- Difference between ω_p and ω_s – Stokes shift
- Stimulated Raman Scattering
- Spontaneous Raman Scattering

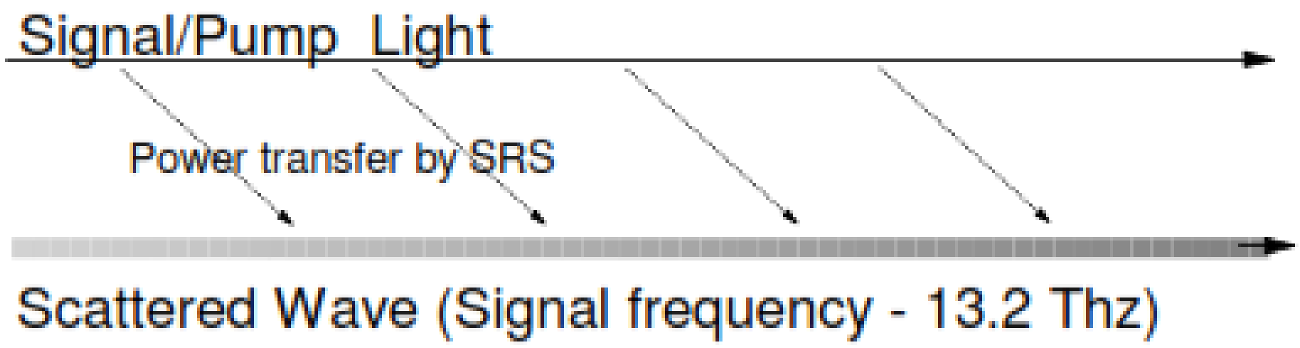


Stimulated Raman Scattering

- New signal is generated in the same direction as the pump wave
- Frequency is down shifted by 13.2 THz
- Amplification of signal if its lower than pump frequency
- Raman amplifier – Take a fiber and couple into a signal and pump of around 13.2 THz higher in frequency (1550 nm signal 1450 nm pump)
- Problem with the high power pump source

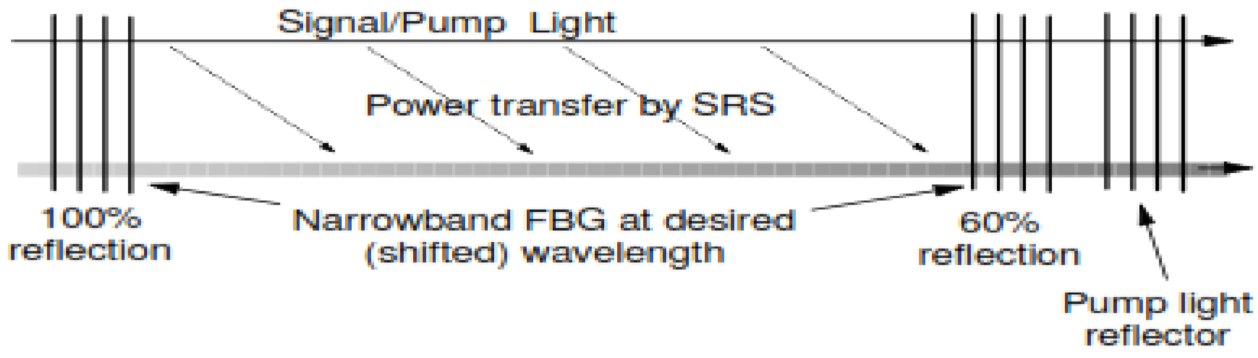
Wavelength changing in SRS

- Solution to get proper pump wavelength is wavelength shifting
- At high power level some light is shifted by the SRS to new wavelength (higher)
- Shifted light is amplified by SRS
- Transfer of power takes place from signal to stokes wave



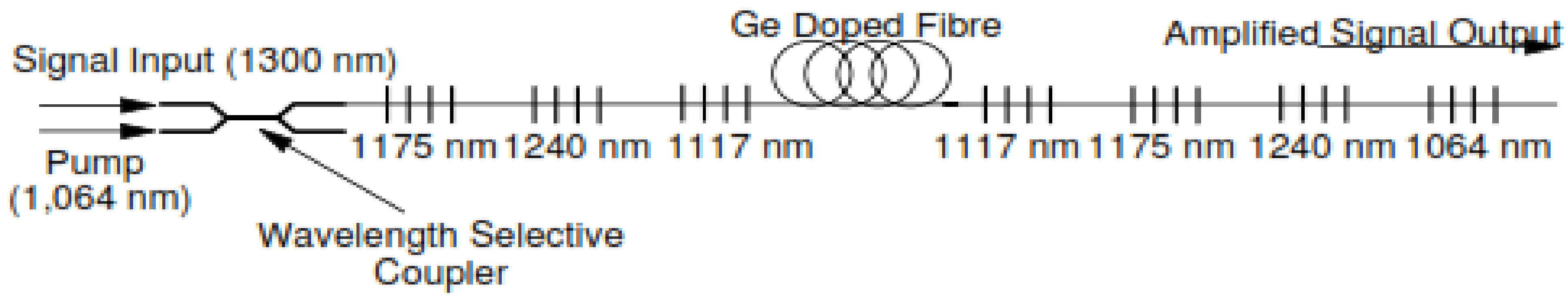
Wavelength shifter using FBG

- Wavelength shifting can be improved by FBG
- Shifted light will reflect between two FBGs
- Unwanted wavelength will exit the device
- Efficiency is improved by adding the FBG reflector for pump wavelength

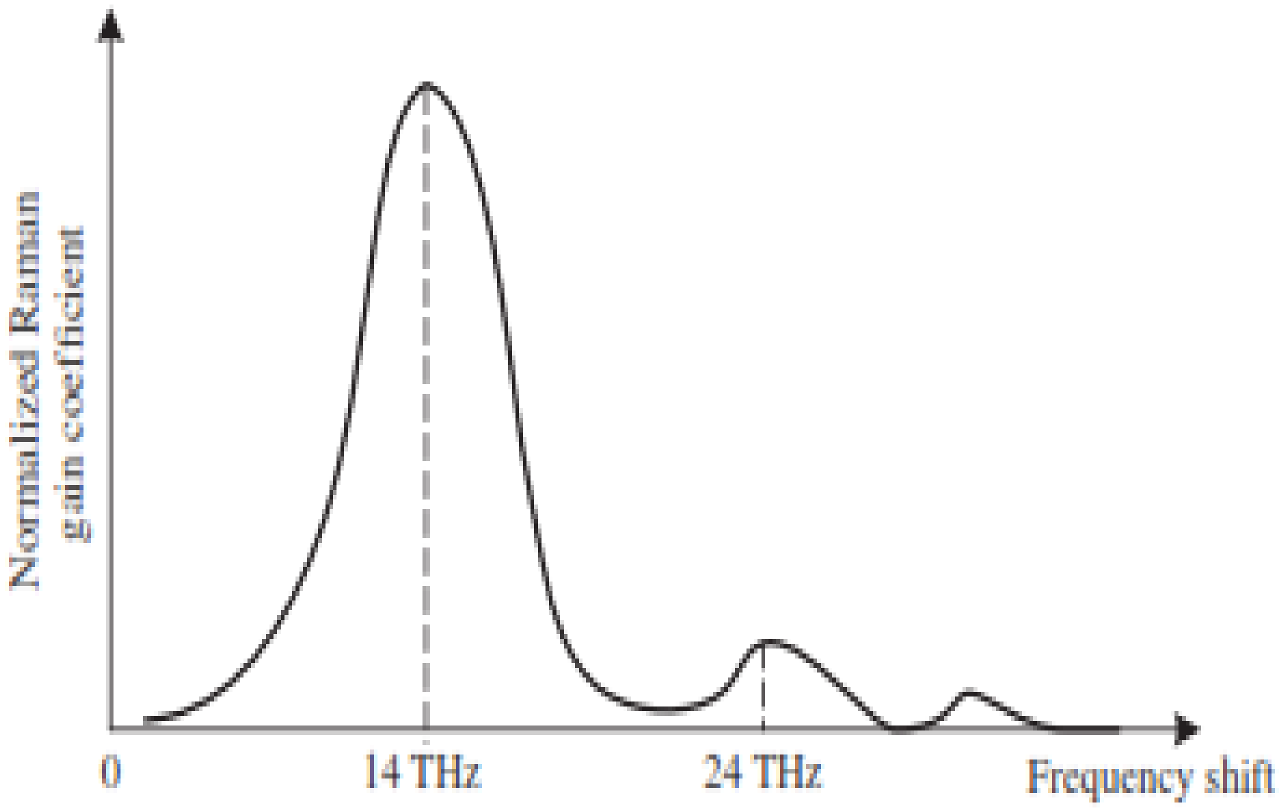


1310 nm band Raman amplifier

- Signal light and pump light enter the device together through a wavelength selective coupler
- The pump light at 1064 nm is shifted to 1117 nm and then in stages to 1240 nm
- The 1240 nm light then pumps the 1310 band signal and amplification is obtained



Raman gain spectrum



Comparison of different optical amplifiers

Property	EDFA	Raman	SOA
Gain (dB)	> 40	> 25	>30
Wavelength (nm)	1530-1560	1280-1650	1280-1650
Bandwidth (3dB)	30-60	Pump dependent	60
Max. Saturation (dBm)	22	0.75 × pump	18
Polarization Sensitivity	No	No	Yes
Noise Figure (dB)	5	5	8
Pump Power	25 dBm	>30 dBm	< 400 mA
Time Constant	10^{-2} s	10^{-15} s	2×10^{-9}
Size	Rack mounted	Bulk module	Compact
Switchable	No	No	Yes
Cost Factor	Medium	High	Low