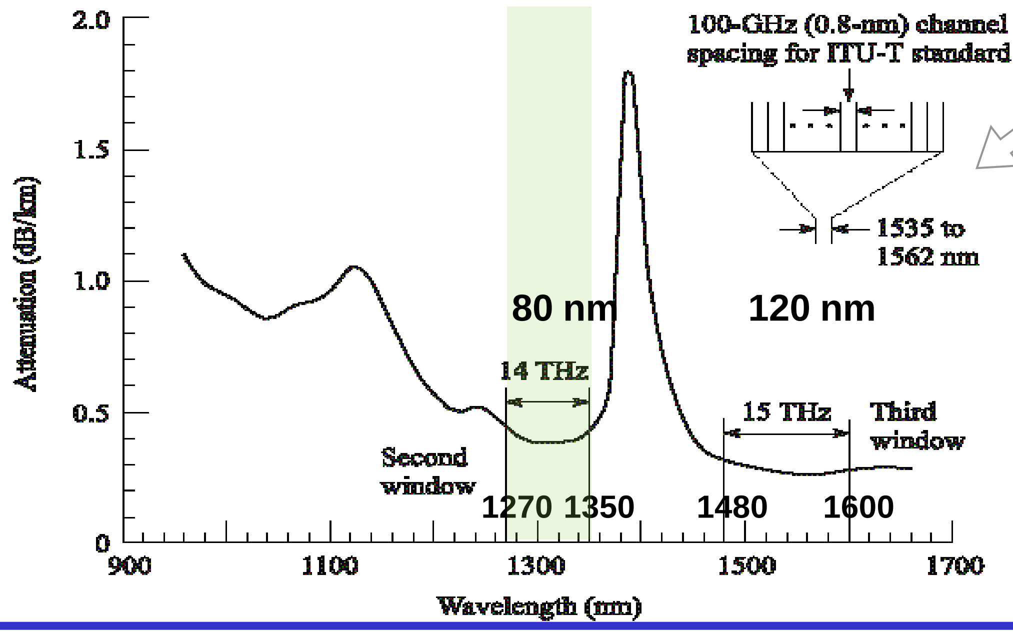
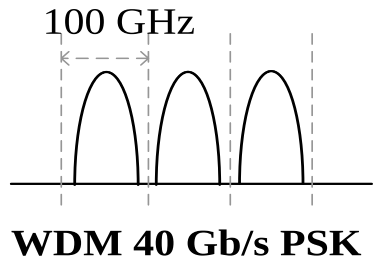
Topic 8

8 Wavelength Division Multiplexing (WDM)

Introduction (i)





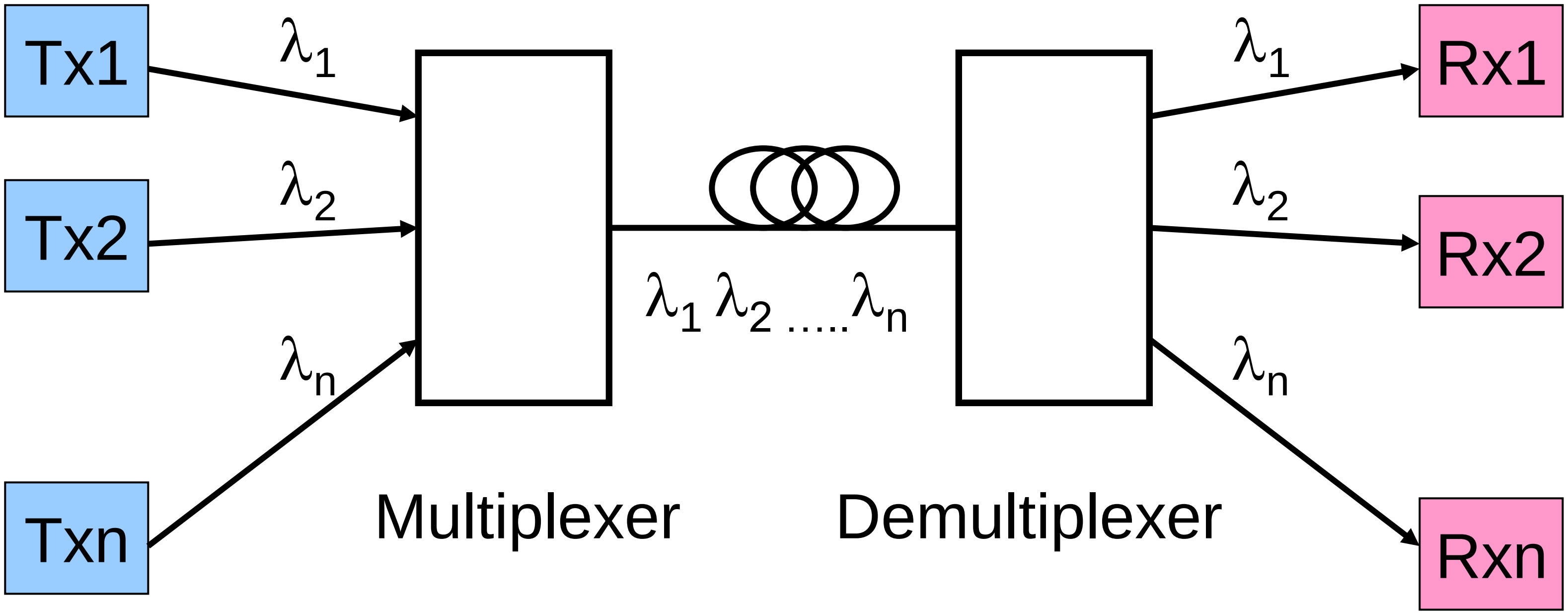
- Optical Band width $$\boxed{|\Delta \nu| = \left(\frac{c}{\lambda^2}\right)|\Delta \lambda|}$$

- Optical windows in 1300~1600 nm: **200nm~30THz**
  C band: 1525–1565 nm; and **L band**: 1570–1610 nm

- Laser requirement: Band allocated for each channel is very narrow ; laser spectral linewidth is 0.8 nm **(~100 GHz**); a single optical fiber can carry different signals in **50 channels.** Each channel has to be transmitted at a different wavelength

A highly stabilized laser with a narrow line width is required.

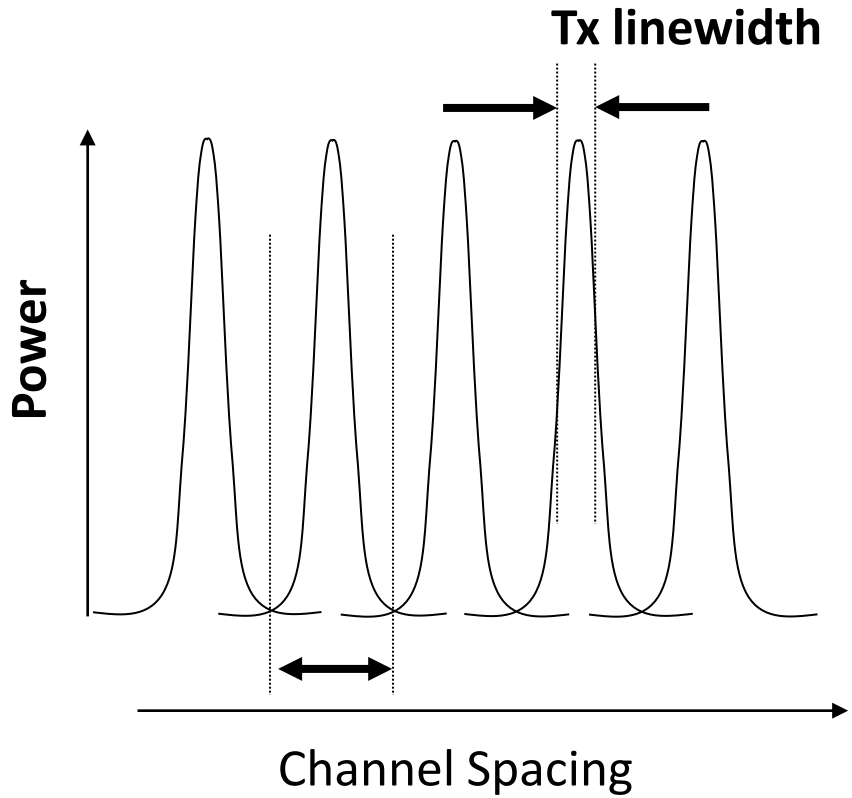
Introduction (ii)



Wavelength Division Multiplexing

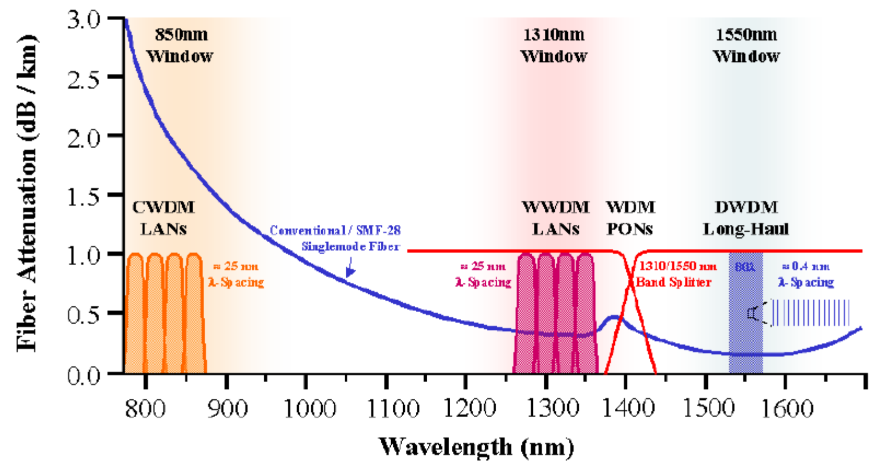
- **WDM**: a technology which **multiplexes** a number of optical carrier signals onto a single optical fiber by using different wavelengths of laser, and then **demultiplexes** them into individual signals
- This allows to transmit signals in many channels through a single fibre

Wavelength Division Multiplexing



•Coarse – CWDM: (for 850 nm windows) large spacing between channels compared to laser linewidth (~10nm), used for short distance

•Dense – DWDM: small spacing between channels (~<nm), used for long distance



•Many channels can be deployed, massively increasing the available bandwidth of one fibre:

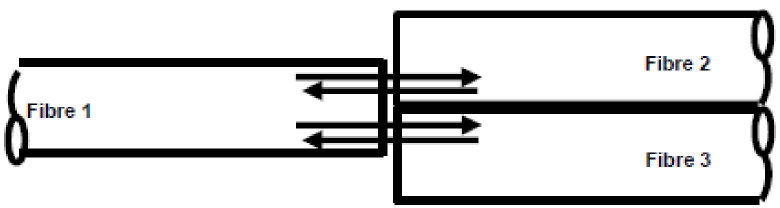
•Optical coupler: **multiplexes**/**demultiplexes** (into) many signals

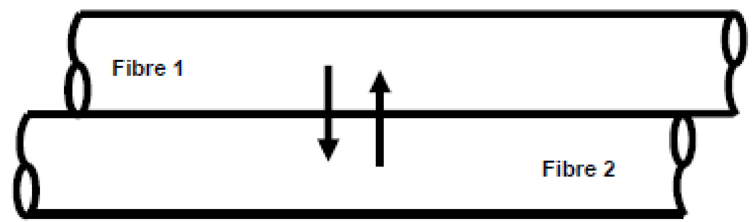
Optical Coupler-1

- **Definition:** a device which can combine multiple input channels in one path or split into multiple paths

- **Classification of Fibre Couplers**

(i) Core interaction type; (ii) Surface interaction type

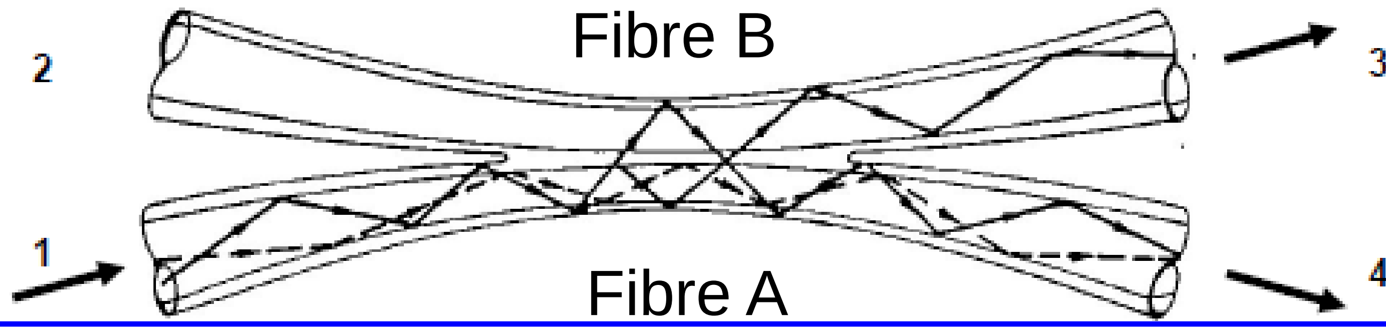




- **Depending on precision of fibre jointing**
- **Easy to understand: coupling depends on the overlap between fibres**

- **Most common technique**
- **Basis of the FBT fibre coupler**

Optical Coupler-2



•Fused biconical fibre taper (FBT) technique: the most common way of manufacturing couplers.

•Fibre twisted together, then fused under tension to form an elongated "biconical taper structure".

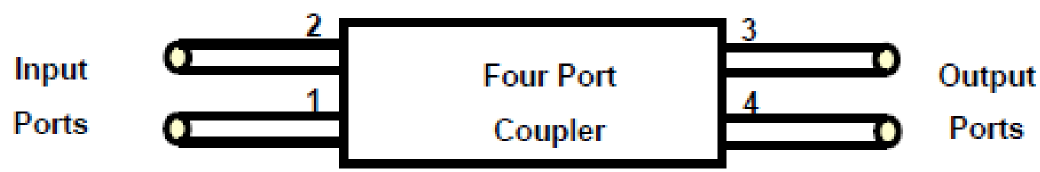
•Coupling process happens when the twisting destroys the conditions for total internal reflection, and core diameters are reduced, allowing some light to leave from Fibre A to Fibre B.

- **Some power from port 1 is transferred over the taper to port 3**
- **The transferred power: a function of taper length and coupling degree**

Optical Coupler-3

Characteristics of an optical coupler:

(i) Split Ratio; (ii) Insertion Loss; (iii) Excess Loss; (iv) Crosstalk

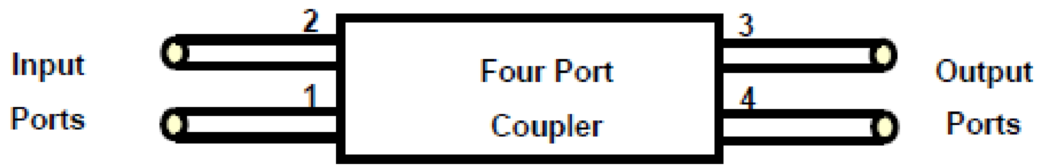


Split Ratio (Coupling Ratio): percentage division of optical power between output and Input

$$\text{Split Ratio} = \frac{P3}{P3 + P4} \times 100\%$$

- Most cases: split ratio is 50%, i.e. P3 = P4
- Simply expressed as X/Y; for example, for P3 = P4, it is called a 50/50 splitter

Optical Coupler-4



- **Insertion Loss (dB):** loss between two particular ports

$$\text{Insertion Loss} = 10 \log \frac{P1}{P4} \text{ dB}$$

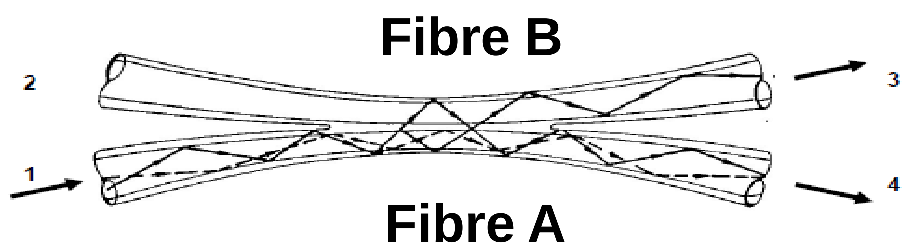
- For a 50/50 splitter, insertion loss is ~ 3 dB

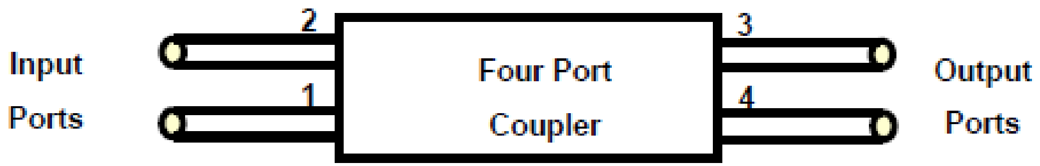
- **Excess Loss (dB):** due to scattering, absorption and imperfections

$$\text{Excess Loss} = 10 \log \frac{Pin}{Pout} \text{ dB}$$

- For example, for a 50/50 splitter, a reasonable excess loss is < 0.4 dB

Optical Coupler-5





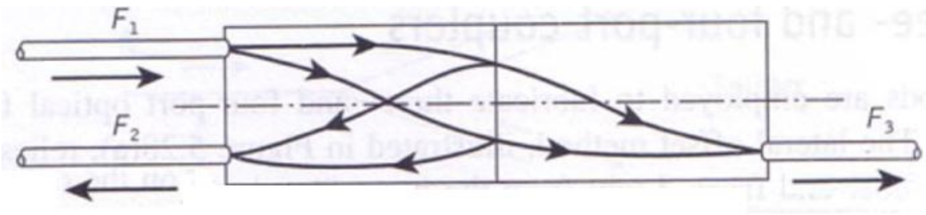
•**Crosstalk (dB):** a measure of the isolation between two input or two output ports; i.e, power from one input may be backscattered to another input

$$\text{Crosstalk} = 10 \log \frac{P2}{P1} \text{ dB}$$

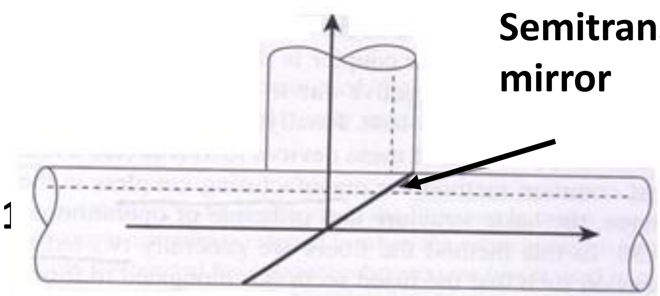
•Important issue in high speed systems (reflection needs to be reduced)

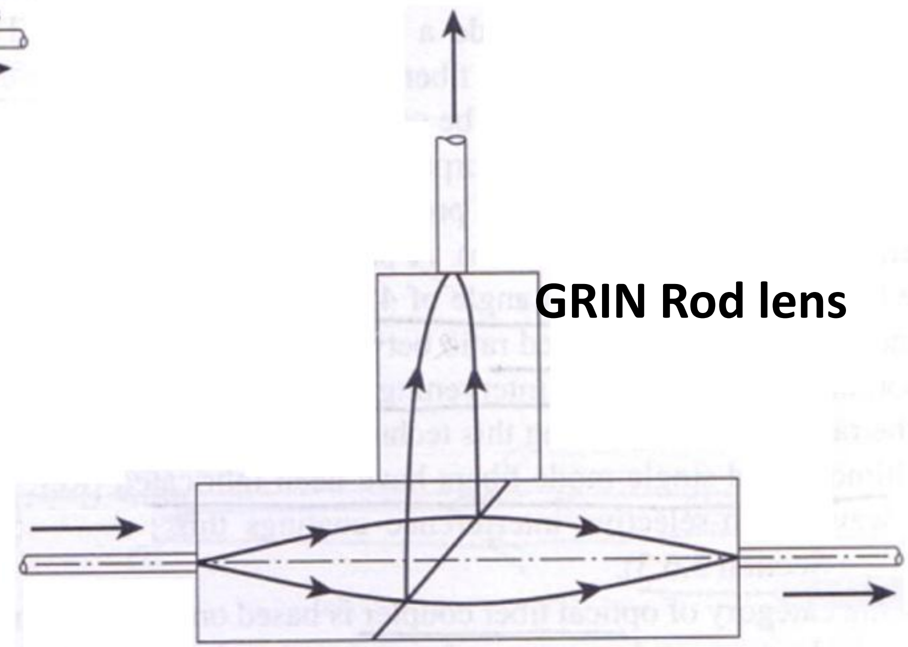
•For a quality 50/50 splitter, a typical crosstalk is <- 60 dB.

Optical Coupler-6



GRIN Rod lens





A few examples using mirror-based beam splitter

WDM coupler

- The above optical couplers have **high losses**;
- WDM requires combining or splitting **a large number of optical channels.**

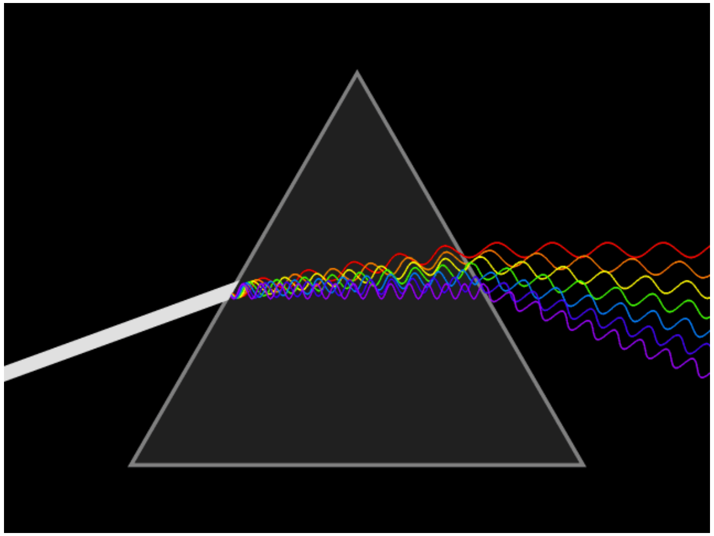
$\Rightarrow$ It is difficult to use them for applications in WDM

- A specially designed coupler is required for WDM, which can be realised based on **optical gratings**.

Three major kinds of optical gratings:

(i) diffraction grating; (ii) Fiber Bragg gratings; (iii) arrayed waveguide gratings.

Diffraction Grating

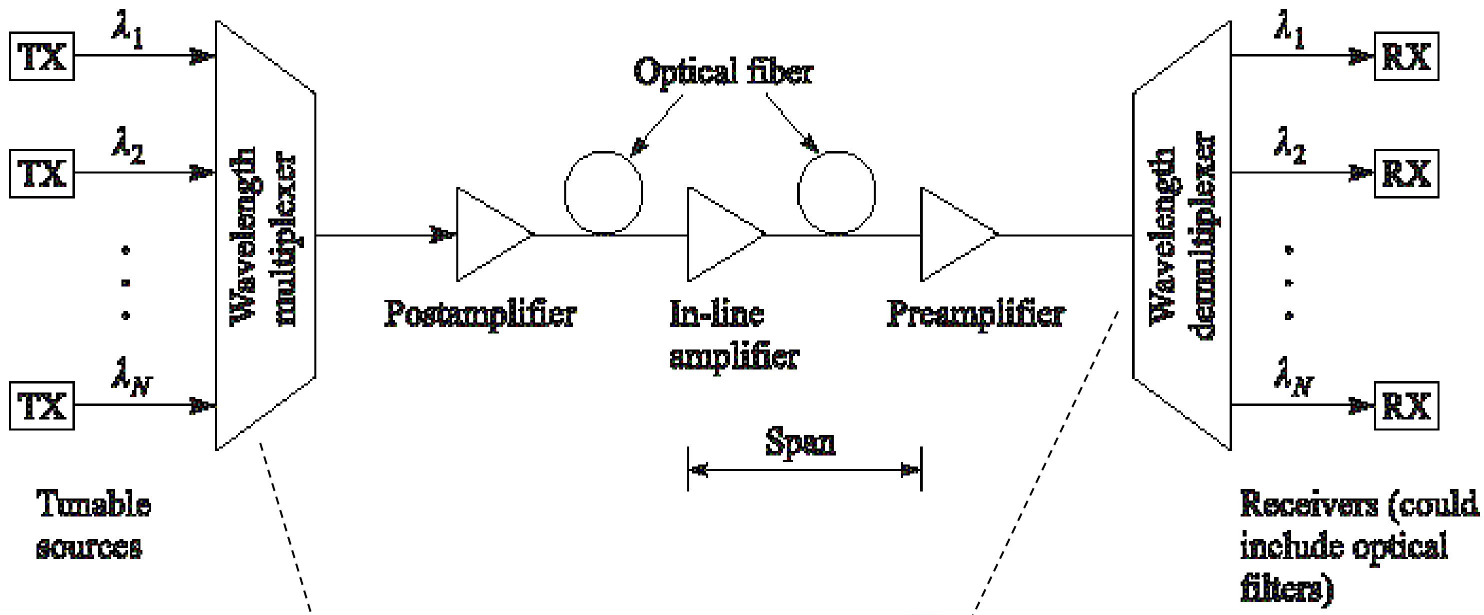


It is easy to understand WDM as long as you know how **rainbow** forms.

$\Rightarrow$

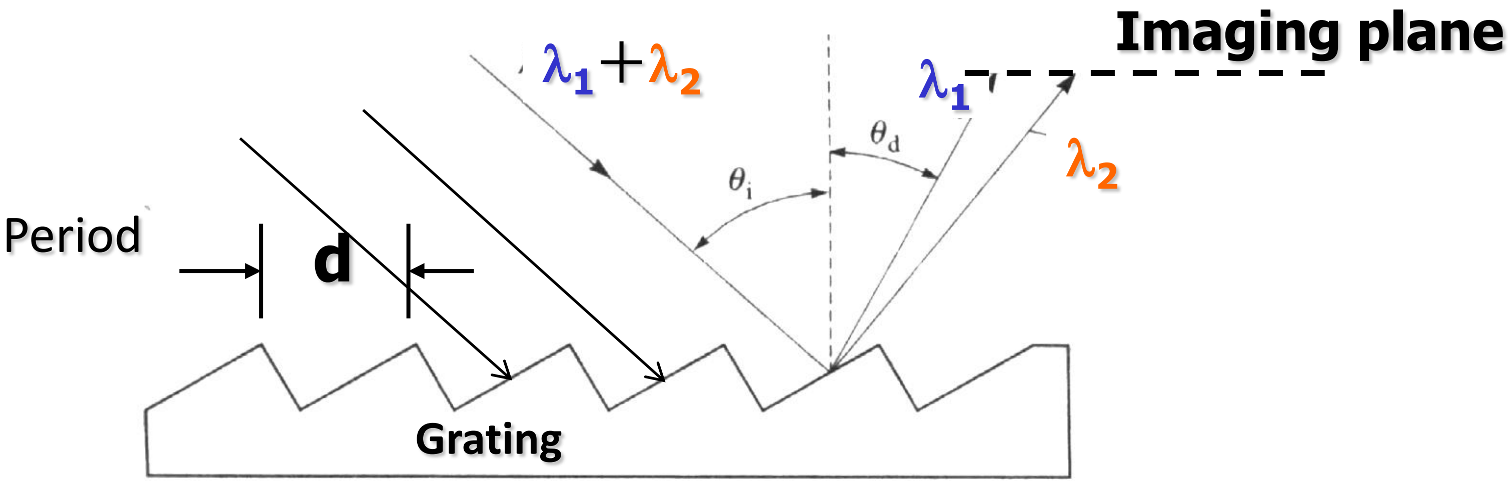
It works in an identical way as a **prism**, and it can decouple white light consisting of red, green, yellow, blue, etc. into individual colours **all at once**. In a reverse direction, all these colour can and mix or couple into white color when they pass through the **prism**.

WDM Communication System



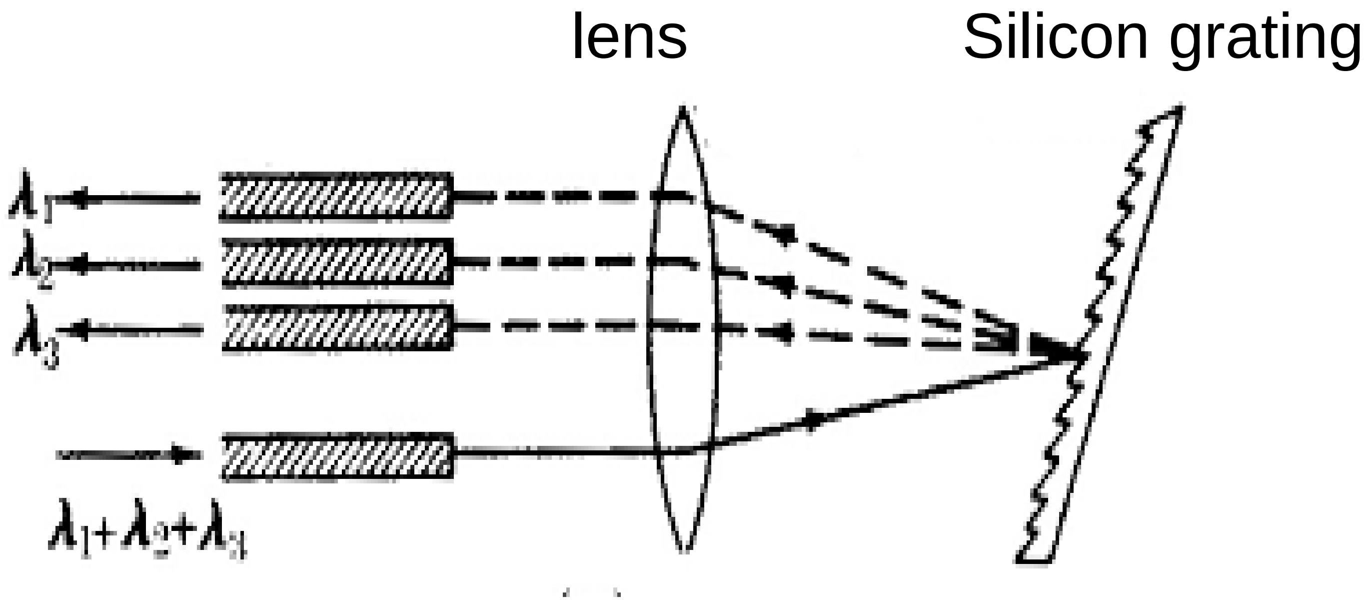
WDM

Diffraction Grating-1



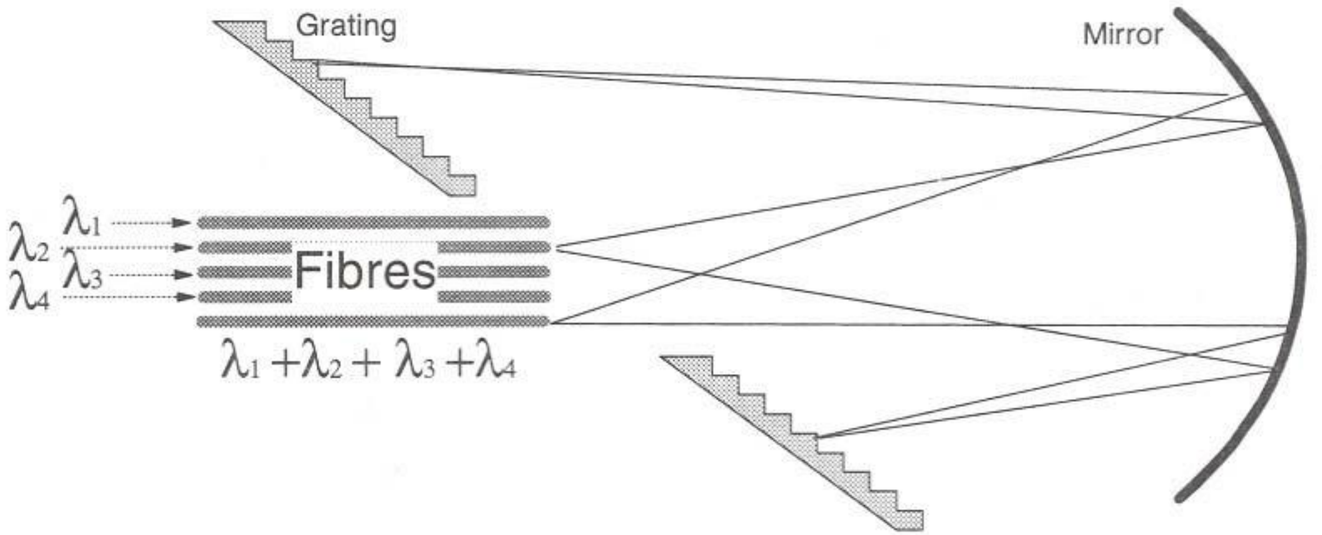
- Constructive interference, showing blazing light under condition $d(\sin\theta_i - \sin\theta_d) = m\lambda$
- On imaging plane: different wavelength can meet the above requirement at a different angle (blazing angle)

Diffraction Grating-2



In practical applications, we would like all individual optical pulses to transmit in a parallel direction after diffraction grating, where the individual optical pulses will be coupled into their individual optical fibres for their further transmission.

Summary of Diffraction Grating



- Diffraction gratings: **multiplex and demultiplex** wavelengths or optical channels.
- All setups are based on fiber bundle, one or more diffraction gratings and additional optics to couple light out of the fibers and back into the fibers.
- The light can be focused by a **lens or a concave mirror**

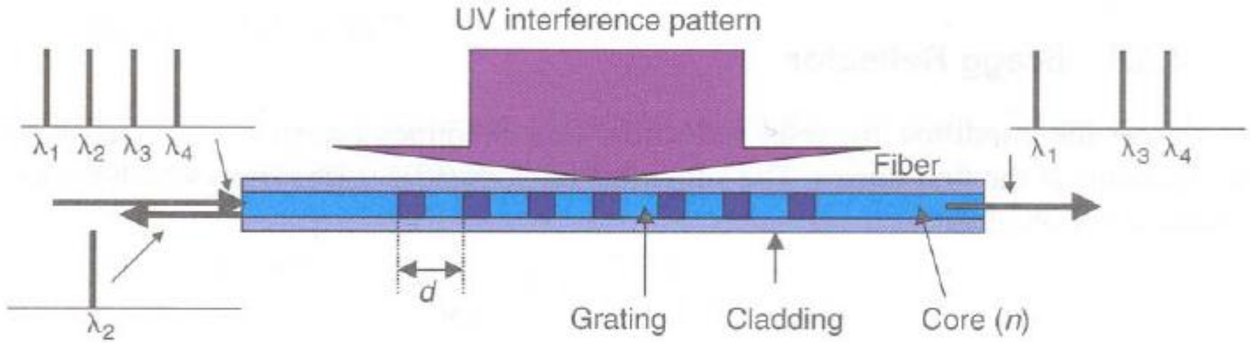
Fiber Bragg Gratings-1

• **Fiber Bragg gratings**: can be incorporated in an optical fiber. This is a **wavelength selective filter**.

• Adding Ge into SiO_2 : achieve contrast in refractive index between core and cladding layer

•These Ge related chemical bonds are sensitive to UV light, (broken by the UV light)

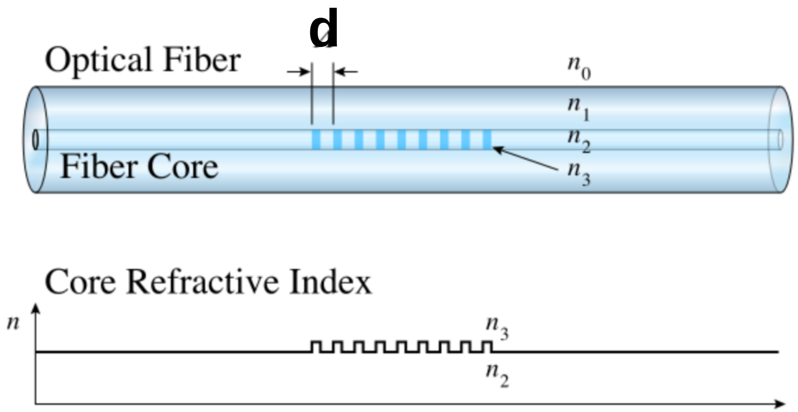
•A standard lithography technique can be used for manufacturing the grating: by the exposure of the fiber through a mask (phase mask) with 244 nm UV light, allowing for modification of the refractive index of the fibre core

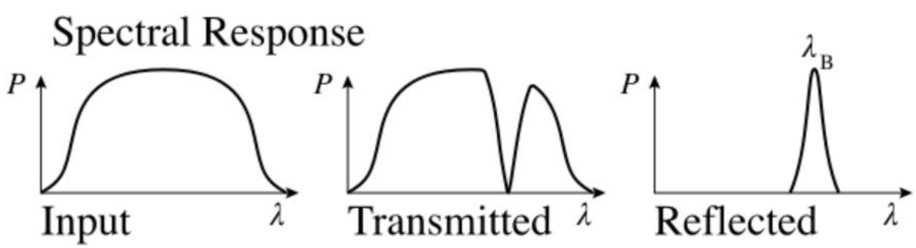


The wavelength (λ) of the reflected band: $\boxed{\lambda = 2 \cdot n_{eff} \cdot d}$

n_{eff}: the average refractive index of the material; d: is grating period.

Fiber Bragg Gratings-2





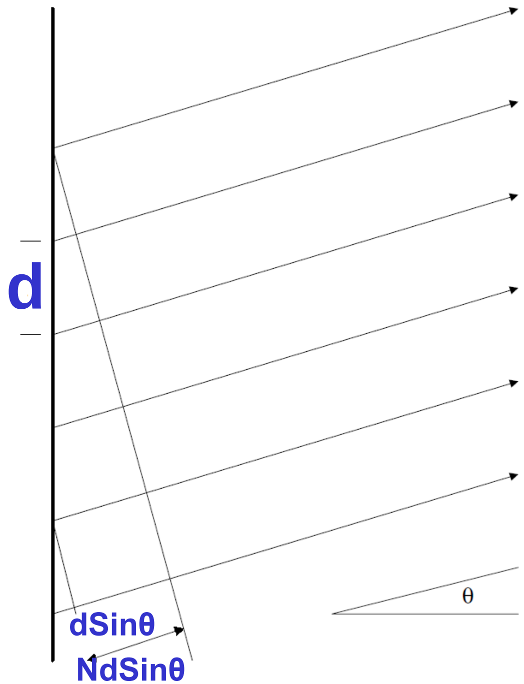
- The devices operate in reflection rather than transmission (not ideal)

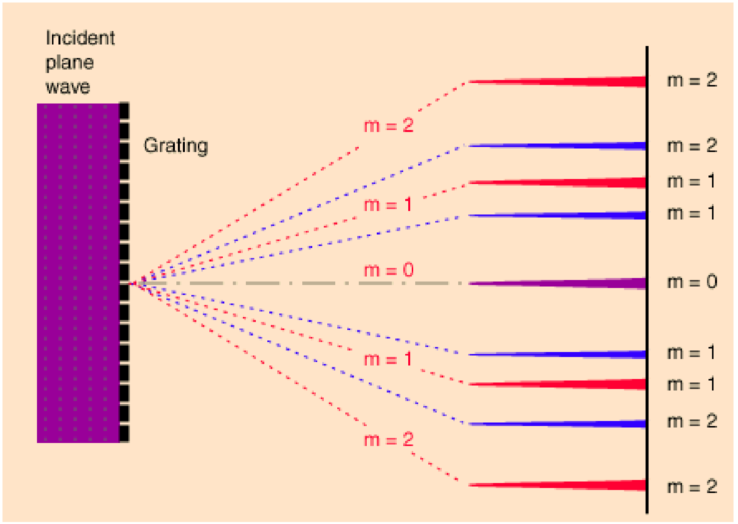
- Resolution (sensitivity) of **Fiber Bragg gratings** depends on the **contrast in refractive index** (area exposed to UV and the area without being exposed to UV), and also **number of grating periods**.

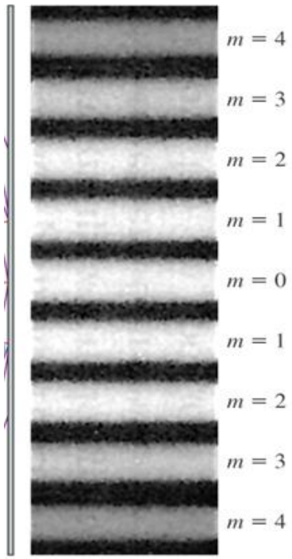
- The **contrast in refractive index:** ~ **0.001**. Therefore, a large number of periods have to be used for an efficient grating.

The fiber grating is typically 1cm long, and 10,000 periods are used to form the grating

Review on operation principles of diffraction gratings







- Phase change: due to a difference in transmission distance, **determined by incident angle**
- **Constructive interference**:

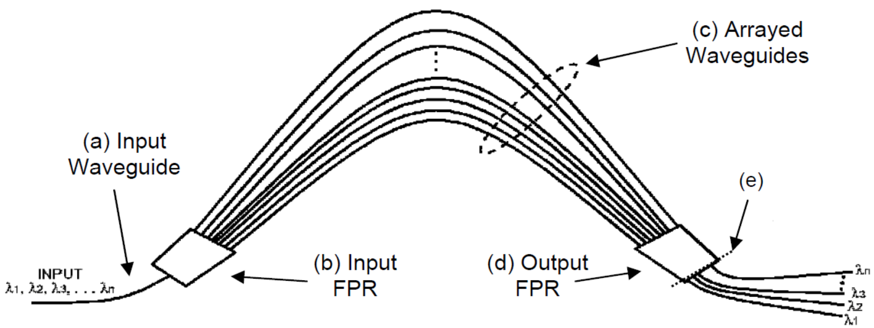
$\mathrm{Sin}\theta_m = m\lambda_m / d$, (d: period of grating).

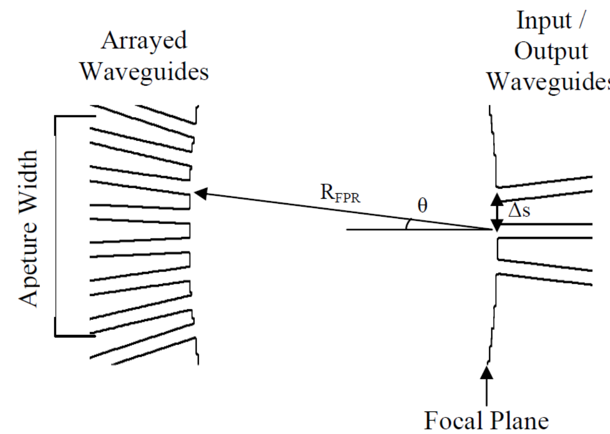
For zero order: different λ_m has different θ_m

Arrayed waveguide grating-1

(Waveguide Grating Routers)

Operation mechanism: similar to diffraction grating, and the „grating“ introduces a phase difference for each signal, as all waveguides have a different length



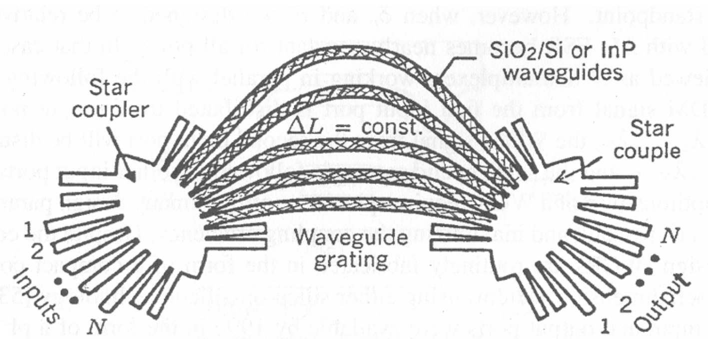


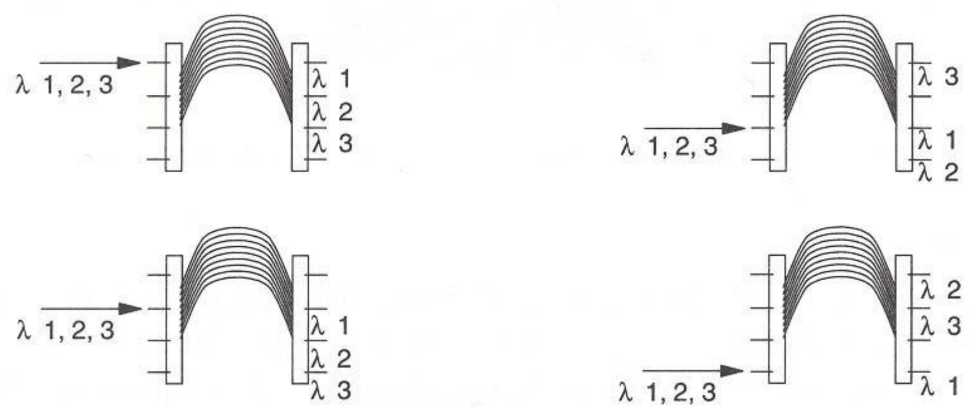
- Each AW increases in length by ΔL compared to the previous one in the array; **$\Delta L = m\,\lambda /n$, where m is an integer**
- Focal plane: an output waveguide is **positioned to capture the focused light**.
- Different wavelengths of light: Different phases change along the AW output plane, causing the focal point to **move along the focal plane**
- An output waveguide is positioned on the output plane to pick up each input frequency.

Wavelength Routers-2

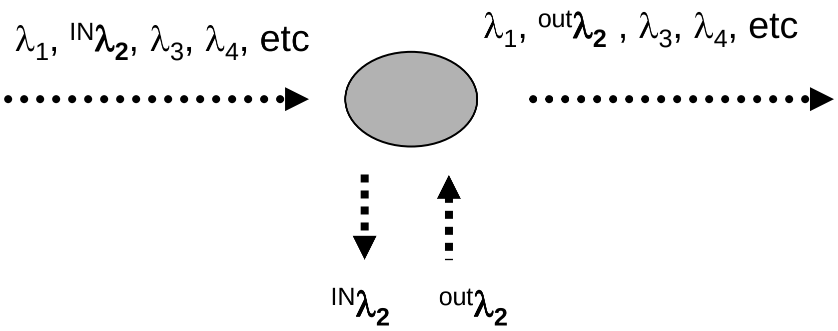
Advantages of arrayed gratings:

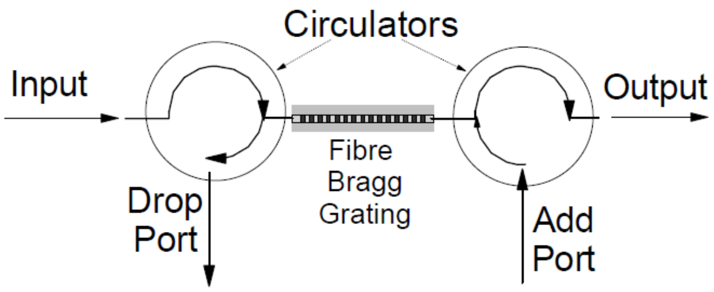
• Multi-channels (multi-wavelength) appearing as a single input can be separated so that each channel is fed in different output ports.
• Combine many inputs from different input ports onto the same output port.
• A arrayed waveguide can operate bi-directionally
• The device can be used as a multiplexer and demultiplexer.
• It can be connected as an optical add-drop multiplexer





Add / Drop multiplexer





- **Key element: FBG.**

$$\lambda = 2 \cdot n_{eff} \cdot d$$

- Operation procedure:

(1) The **non-selected wavelengths** pass through the FBG to the next circulator, but the **selected wavelength** (λ_2) is reflected by the FBG and then drop out of the circulator port.

(2) The wavelength to be added (**the same as the one just dropped, λ_2**) enters through the "add-port" of the right circulator.

(3) It travels around to the FBG and is reflected back to the circulator, and then process mixes the added channel with the multiplexed stream.

Maximum Link Capacity

What is data capacity of a WDM Link?

DWDM –

Channel spacing 0.4nm (50GHz)
40GBit/s per channel

Use 1250 – 1650nm (may need dry fibre)

Gives ~30TBit/s

Using amplifiers etc – can transmit this over 1000km……..

Practical Limiting Factors

Amplifiers don't cover all this spectral range – EDFAs only cover ~40nm

Number of channels limited by
(1) Wavelength stability of laser (DFB)
(2) Signal degradation – non-linear effects (not discussed)
(3) Interchannel crosstalk at DEMUX

Research Groups have demonstrated

~6 Tbit/s over 3000km
~4 Tbit/s over 11000km

Commercially available
160 channels each at 10Gbit/s

Summary WDM

- Photons do not easily interact with other photons – we can transmit many optical channels (different wavelengths) down one physical channel

- The optical spectrum may be sliced into a number of channels, and we require the transmitter wavelength to sit centrally in this band, and any demultiplexing components to have a high rejection of neighbouring wavelengths

- There are many forms of filters, demux, routers, allowing many possible functions within a network – additional noise (crosstalk) in a WDM system may be from within the same optical channel or from neighbouring channels. A power penalty is paid to achieve required BER if these noise sources are present

Summary WDM - Wavelength Continuity

For a WDM system, wavelength continuity results in difficulties in wavelength allocation within the system

One solution is to prioritise certain routes (fixed alternate routing), or determine a function (cost) which must be minimised at all times within the system (adaptive routing).

Another solution is to allow the wavelength of a signal to be changed (ideally entirely in the optical domain). This alleviates the requirement for wavelength continuity

Summary WDM - Components

In addition to loss, dispersion effects on components discussed previously….

Channel spacing getting narrower in wavelength

Transmitters

– need wavelength selectable, wavelength tuneable

Filters, Routers,

-need to have high finesse/Q factor (or pay power penalty)

Amplifiers

Need high saturated gain, broadband

EDFA is good but 40nm wide band and limited gain

Tutorial Questions – T8

T8.1 Describe the physical concept of wavelength division multiplexing, using diagrams if necessary.

T8.2 Dry Fibres have low loss over a spectral region 1.3 to 1.6 μm. Estimate the capacity of a WDM system covering this entire region using 40 Gb/s optical channels spaced apart by 0.4nm.

Tutorial Questions – T8

T8.3 The C and L spectral bands cover a wavelength range from 1.53 to 1.61 μm. How many channels can be transmitted when the channel spacing is 0.8nm? What is the effective bit rate – distance product when a WDM signal covering the two bands using 10 Gb/s channels I transmitted over 2000km?

T8.4 What limits the number of optical channels which may be operated?

Tutorial Questions – T8

T8.5 Describe the operation of an add-drop multiplexer, and provide and example of how one may be constructed.

T8.6 What is meant by wavelength continuity? Describe why this makes wavelength assignment across a network complex.