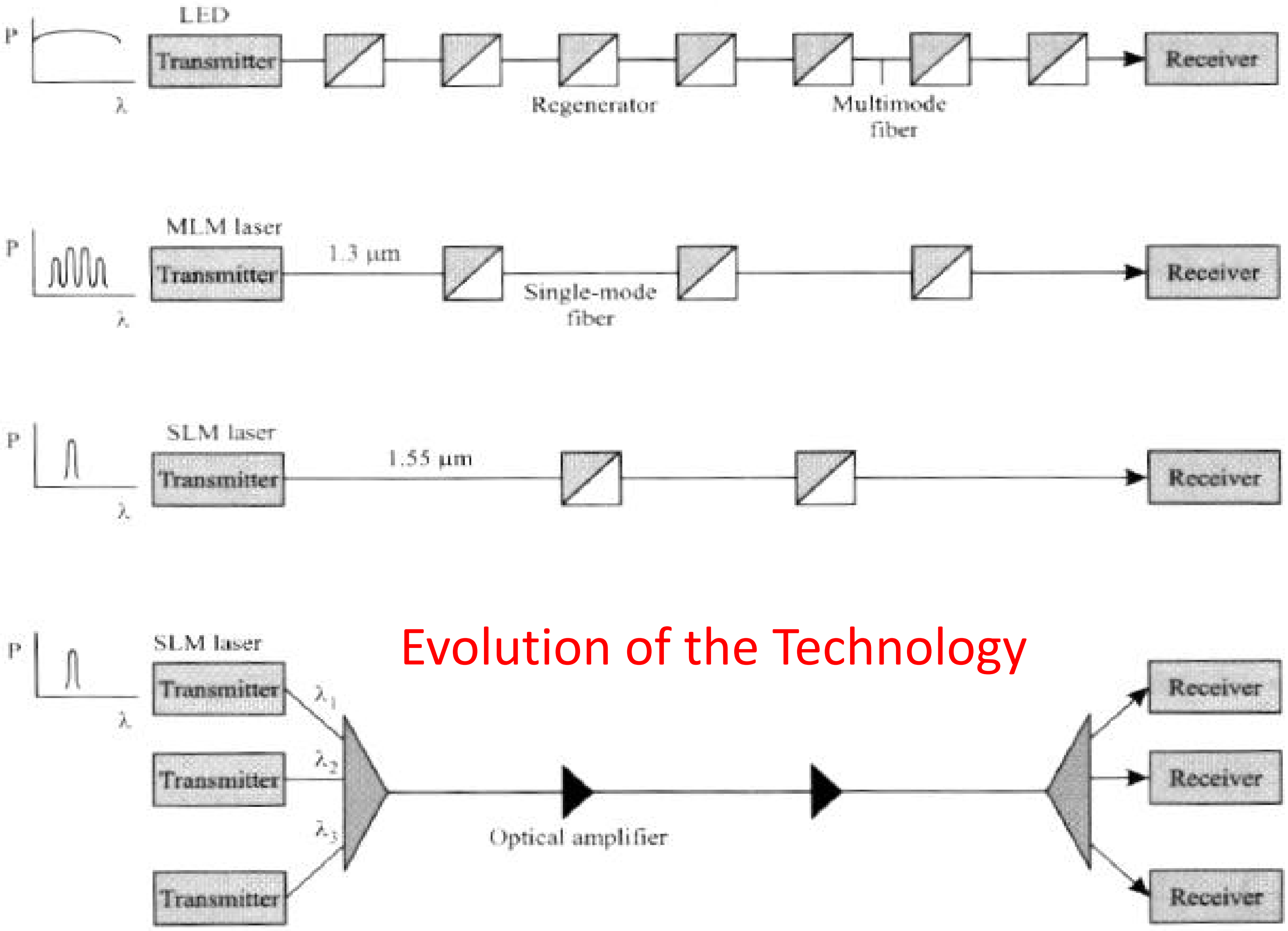
WDM Concept and Components

Part 1: WDM Concept

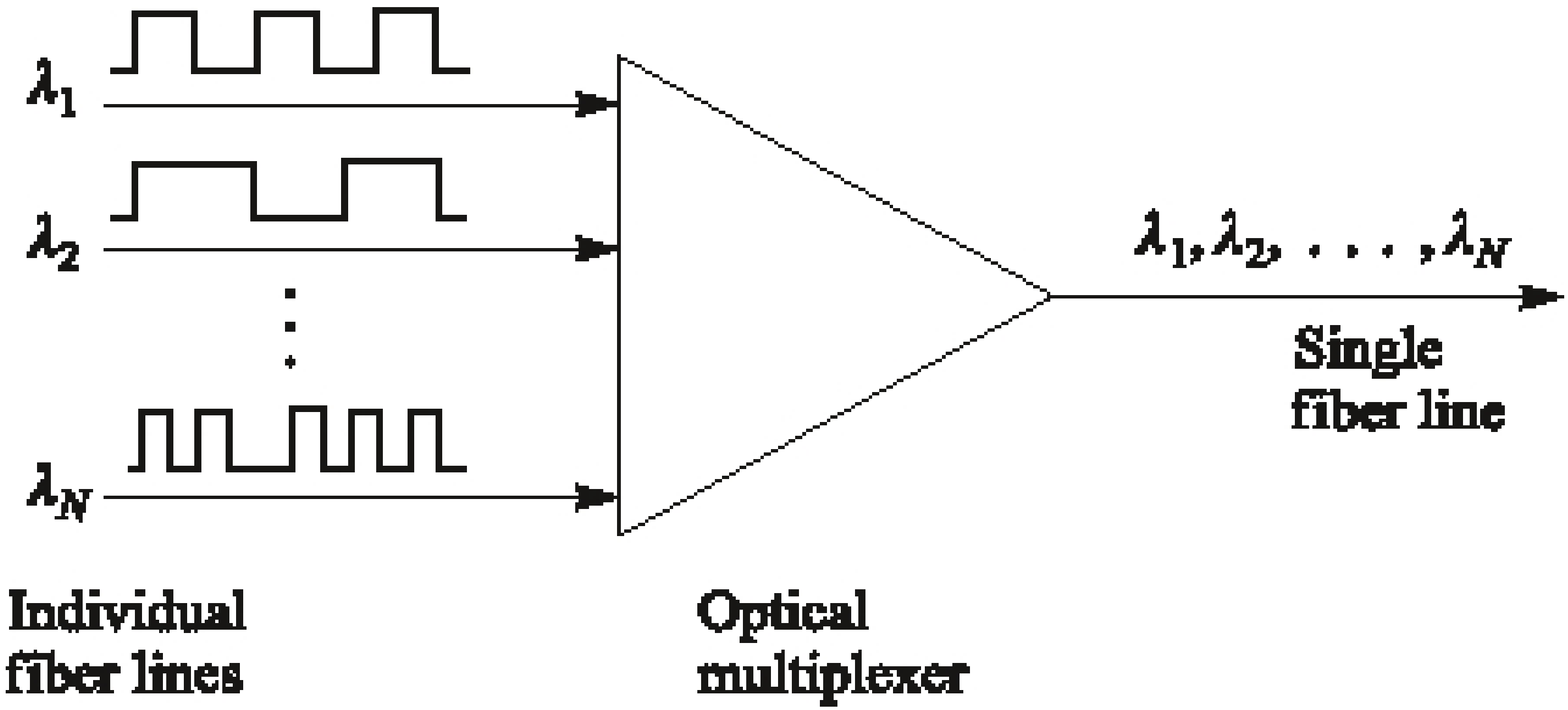
Evolution of the Technology



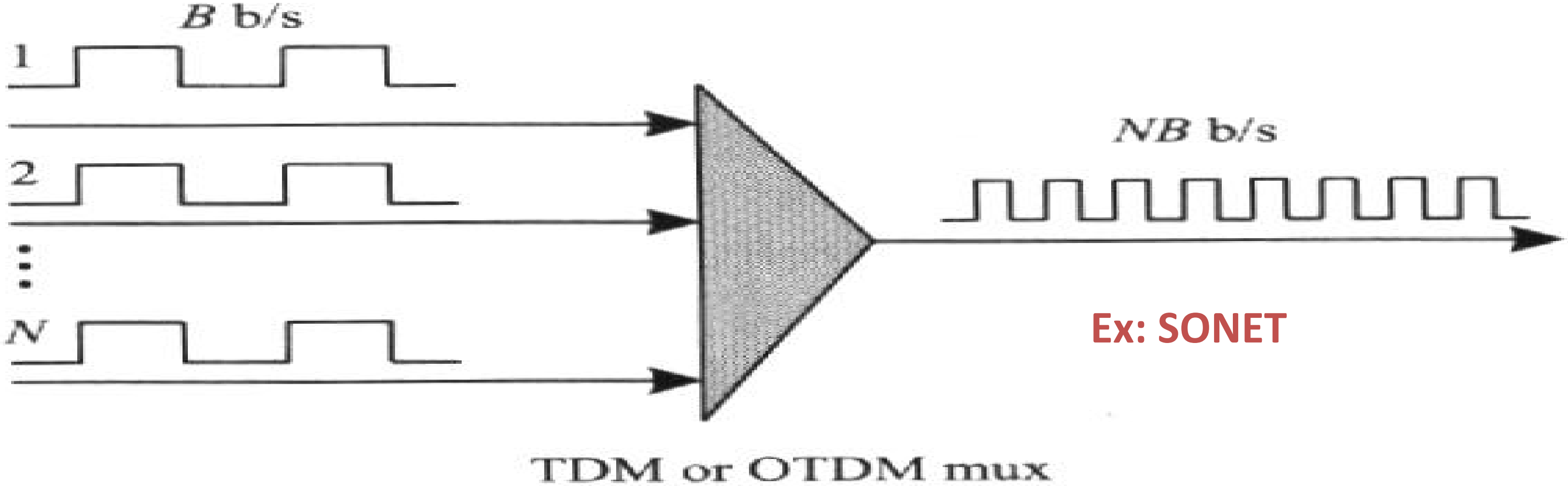
Why WDM?

- Capacity upgrade of existing fiber networks (without adding fibers)
- Transparency: Each optical channel can carry any transmission format (different asynchronous bit rates, analog or digital)
- Scalability– Buy and install equipment for additional demand as needed
- Wavelength routing and switching: Wavelength is used as another dimension to time and space

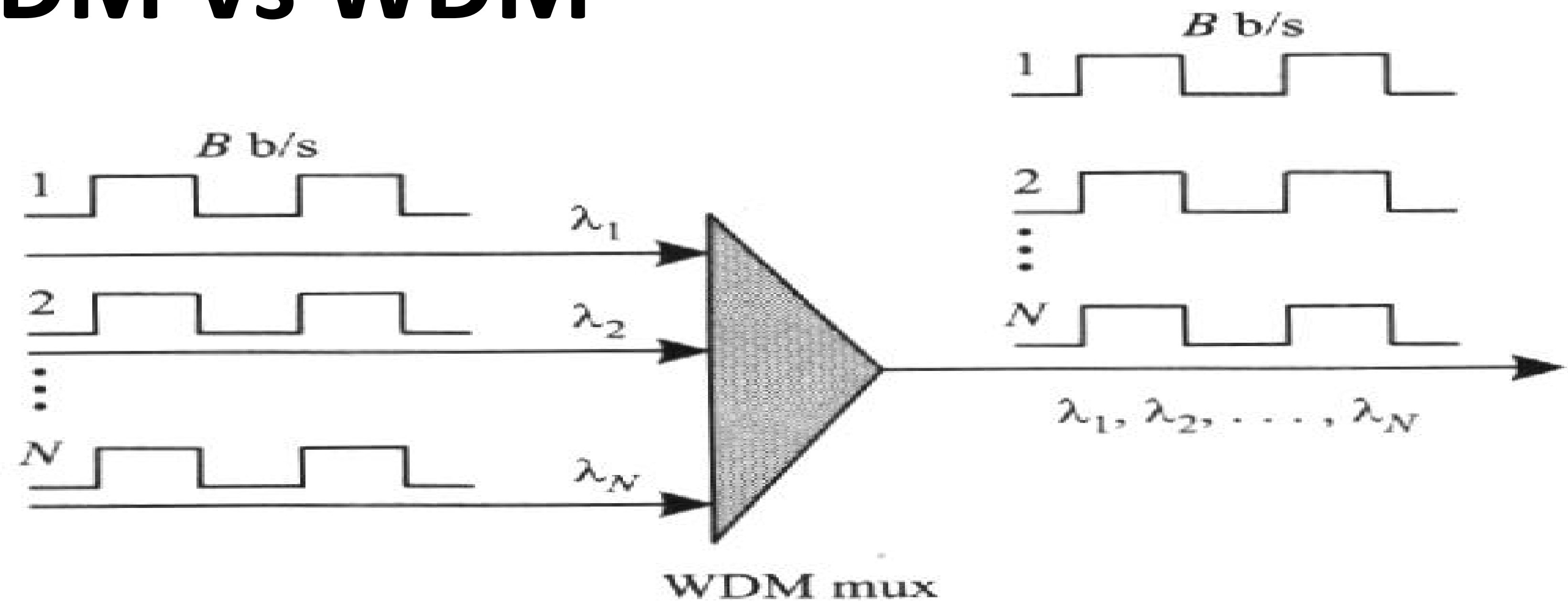
Wavelength Division Multiplexing



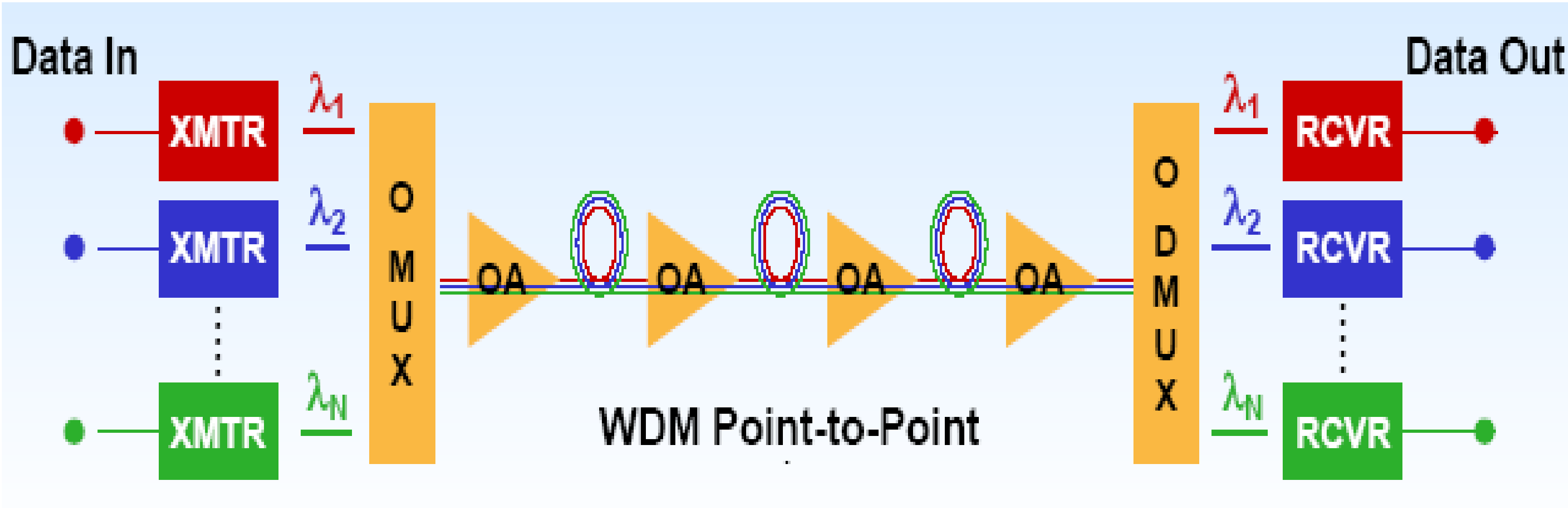
Each wavelength is like a separate channel (fiber)


B b/s
1
2
N
NB b/s
Ex: SONET
TDM or OTDM mux

TDM Vs WDM


B b/s
1
2
N
λ_1
λ_2
λ_N
B b/s
1
2
N
$\lambda_1, \lambda_2, \ldots, \lambda_N$
WDM mux

Wavelength Division Multiplexing



- Passive/active devices are needed to combine, distribute, isolate and amplify optical power at different wavelengths

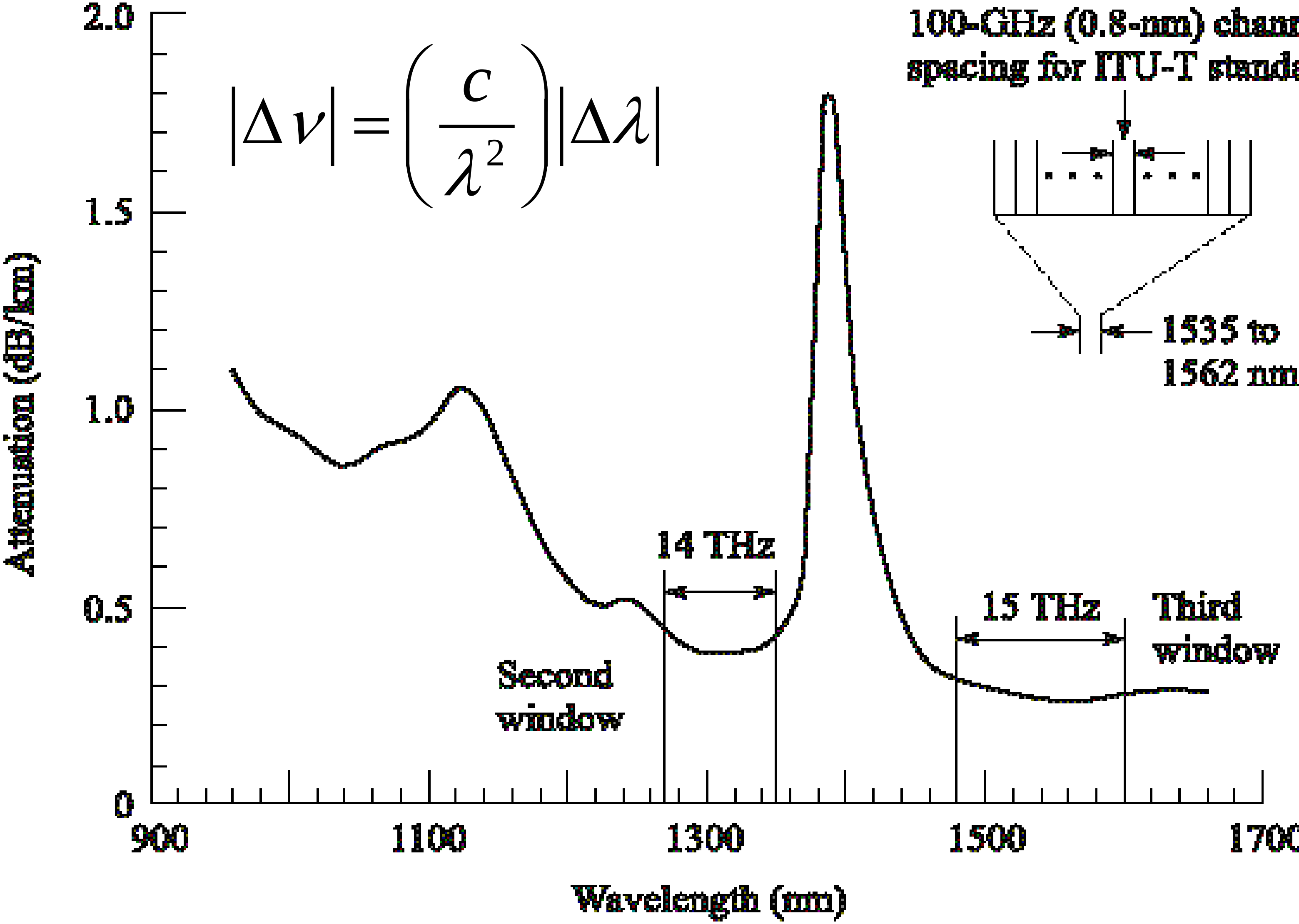
WDM, CWDM and DWDM

- WDM technology uses multiple wavelengths to transmit information over a single fiber
- Coarse WDM (CWDM) has wider channel spacing (20 nm) – low cost
- Dense WDM (DWDM) has dense channel spacing (0.8 nm) which allows simultaneous transmission of 16+ wavelengths – high capacity

WDM and DWDM

- First WDM networks used just two wavelengths, 1310 nm and 1550 nm
- Today's DWDM systems utilize 16, 32,64,128 or more wavelengths in the 1550 nm window
- Each of these wavelength provide an independent channel (Ex: each may transmit 10 Gb/s digital or SCMA analog)
- The range of standardized channel grids includes 50, 100, 200 and 1000 GHz spacing
- Wavelength spacing practically depends on:
  - laser linewidth
  - optical filter bandwidth

ITU-T Standard Transmission DWDM windows



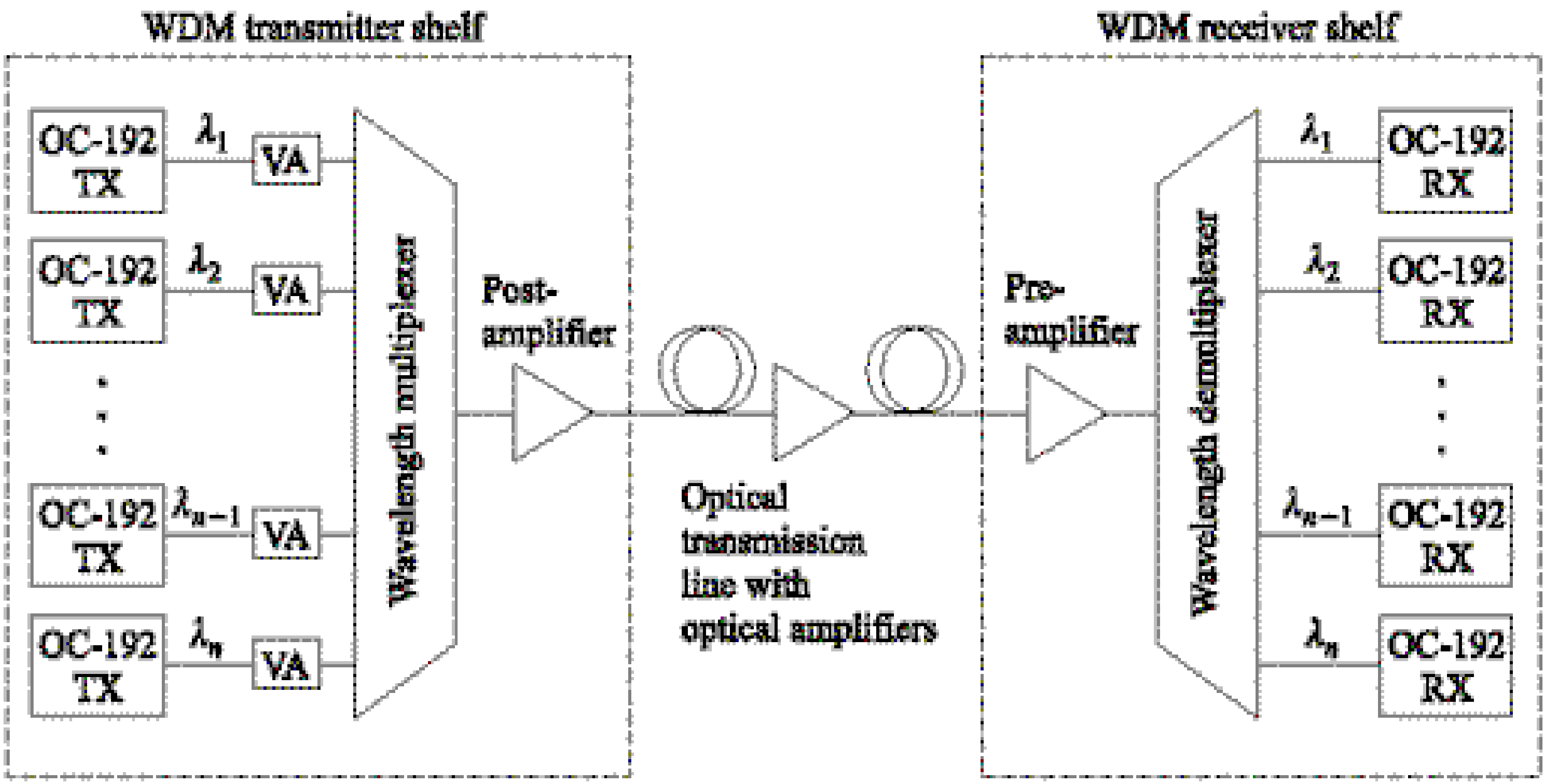
Principles of DWDM

- BW of a modulated laser: 10-50 MHz → 0.001 nm
- Typical Guard band: 0.4 – 1.6 nm
- 80 nm or 14 THz @1300 nm band
- 120 nm or 15 THz @ 1550 nm
- Discrete wavelengths form individual channels that can be modulated, routed and switched individually
- These operations require variety of passive and active devices

$$|\Delta \nu| = \left(\frac{c}{\lambda^2}\right)|\Delta \lambda|$$

Ex. 10.1

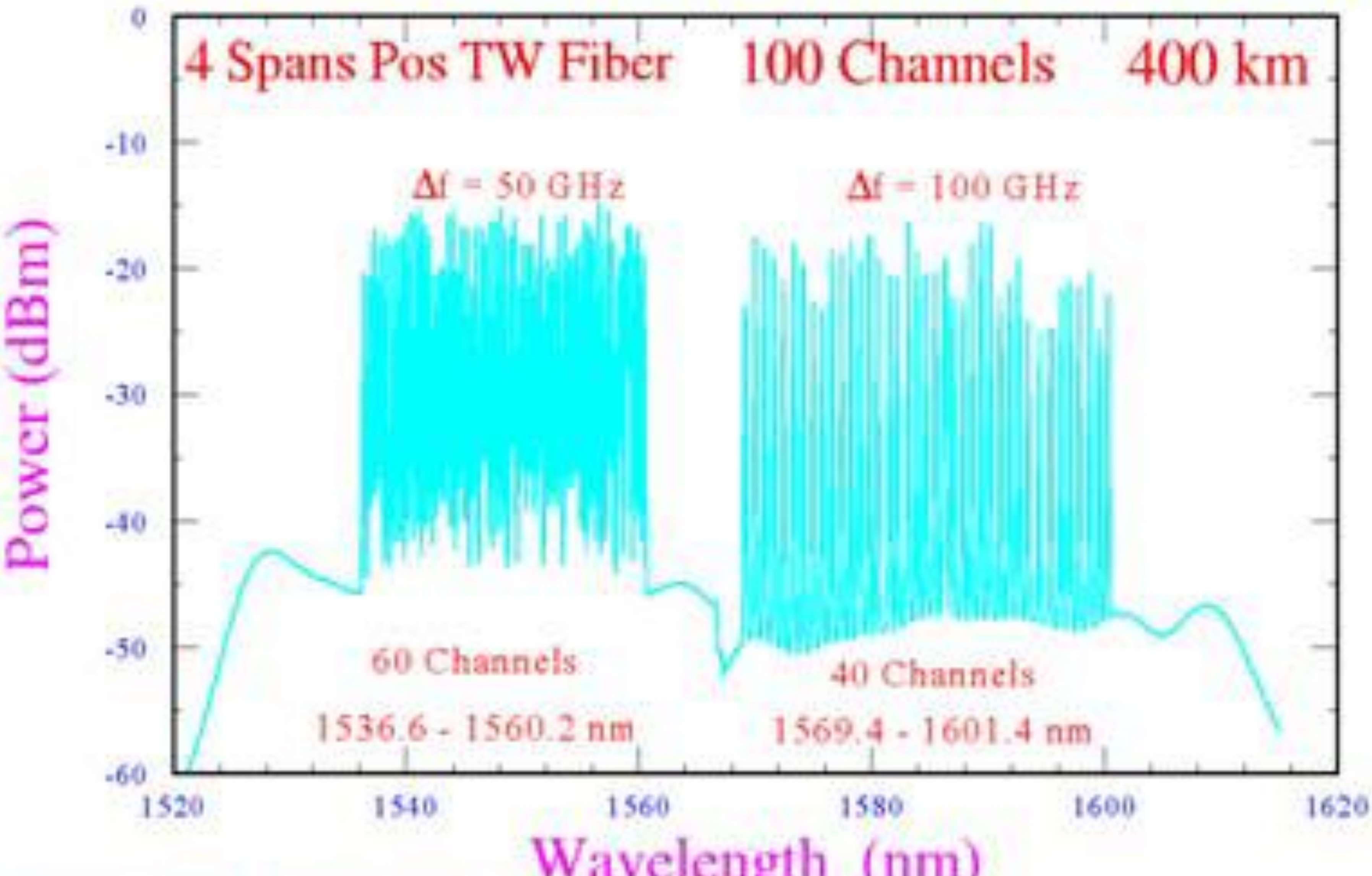
Nortel OPTERA 640 System



TX: Optical transmitter
RX: Optical receiver
VA: Variable attenuator

64 wavelengths each carrying 10 Gb/s

1Tb/s Experiment: Channel Spectrum



Srivastava and Sun 02.14.98

DWDM Limitations

Theoretically large number of channels can be packed in a fiber

For physical realization of DWDM networks we need precise wavelength selective devices

Optical amplifiers are imperative to provide long transmission distances without repeaters

Part II: WDM Devices

Key Components for WDM

Passive Optical Components

- Wavelength Selective Splitters
- Wavelength Selective Couplers

Active Optical Components

- Tunable Optical Filter
- Tunable Source
- Optical amplifier
- Add-drop Multiplexer and De-multiplexer

Photo detector Responsivity

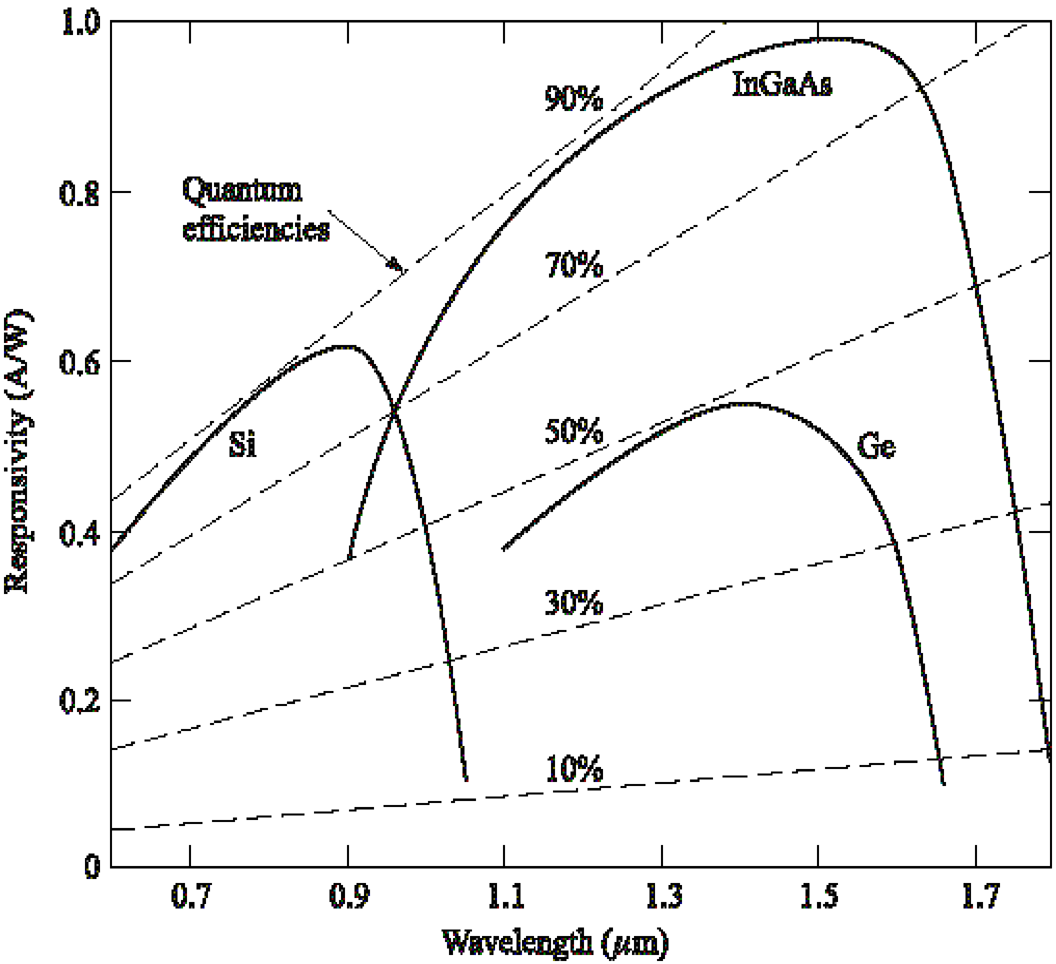


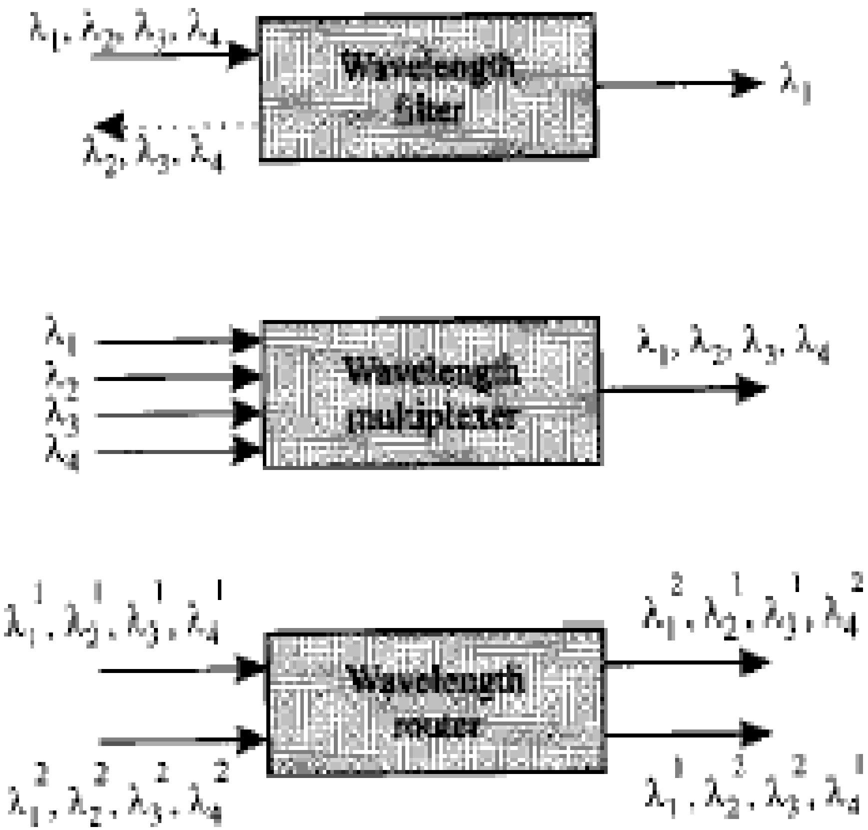
Photo detectors are sensitive over wide spectrum (600 nm).

Hence, narrow optical filters needed to separate channels before the detection in DWDM systems

Passive Devices

- These operate completely in the optical domain (no O/E conversion) and does not need electrical power
- Split/combine light stream Ex: *N X N* couplers, power splitters, power taps and star couplers
- Technologies: - Fiber based or
  - Optical waveguides based
  - Micro (Nano) optics based
- Fabricated using optical fiber or waveguide (with special material like InP, $LiNbO_3$)

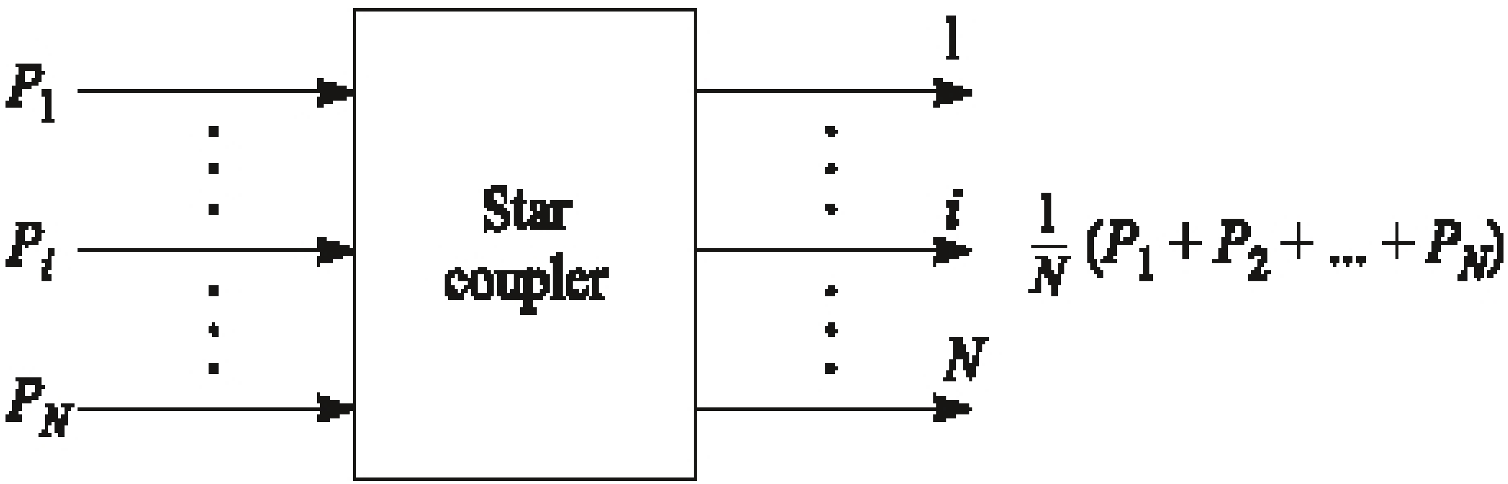
Filter, Multiplexer and Router



- Applications
  - — wavelength selection, channel add/drop
  - — reduction of amplifier noise
  - — basic building block of more advance components such as multiplexers and demultiplexers
- Requirements
  - — low insertion loss
  - — low polarization dependent loss
  - — robust (temperature insensitive)
  - — flat passbands, steep slopes
  - — tunable (for dynamic operation)

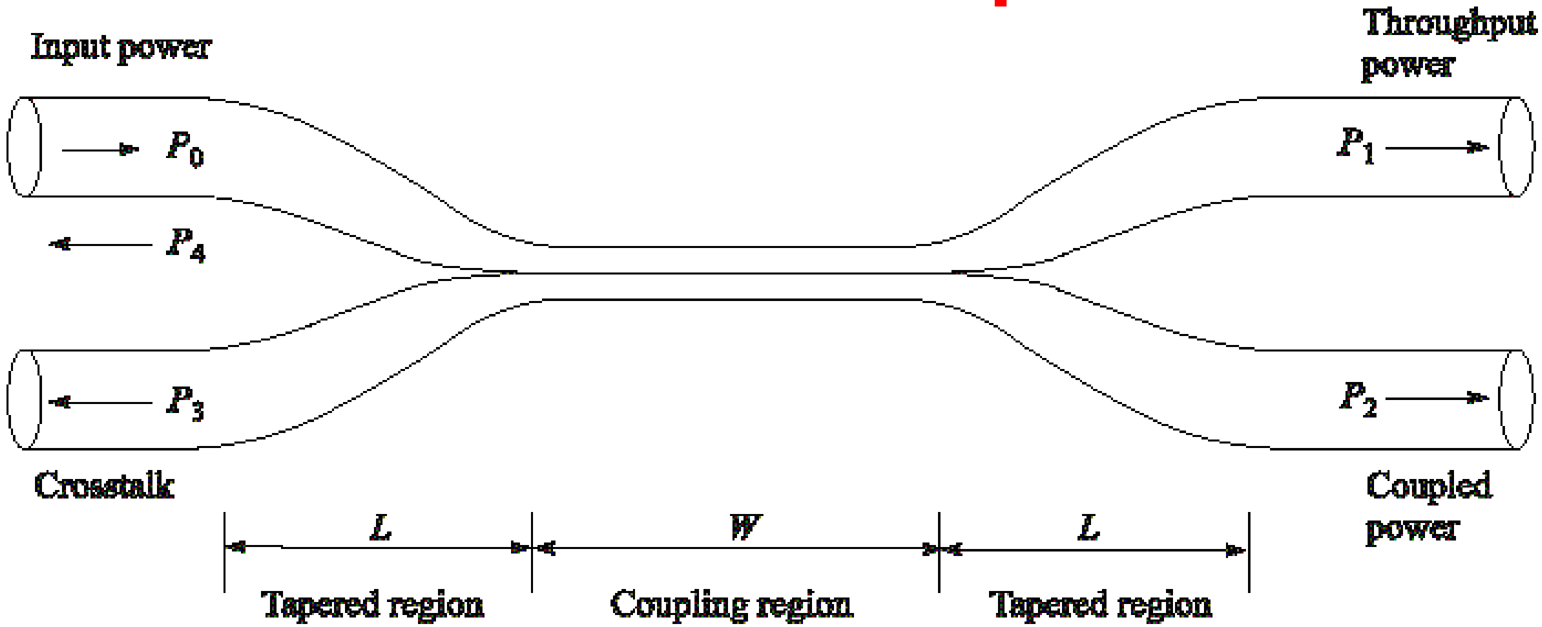
Basic Star Coupler

May have *N* inputs and *M* outputs



- Can be **wavelength selective/nonselective**
- **Up to N =M = 64, typically N, M < 10**

Fused-Biconical coupler OR Directional coupler



- *P3, P4* extremely low (-70 dB below Po)
- Coupling / Splitting Ratio = *P2/(P1+P2)*
- If $P_1=P_2$ → It is called 3-dB coupler

Fused Biconical Tapered Coupler

- Fabricated by twisting together, melting and pulling together two single mode fibers
- They get fused together over length *W;* tapered section of length *L;* total draw length *= L+W*
- Significant decrease in *V*-number in the coupling region; energy in the core leak out and gradually couples into the second fibre

Definitions

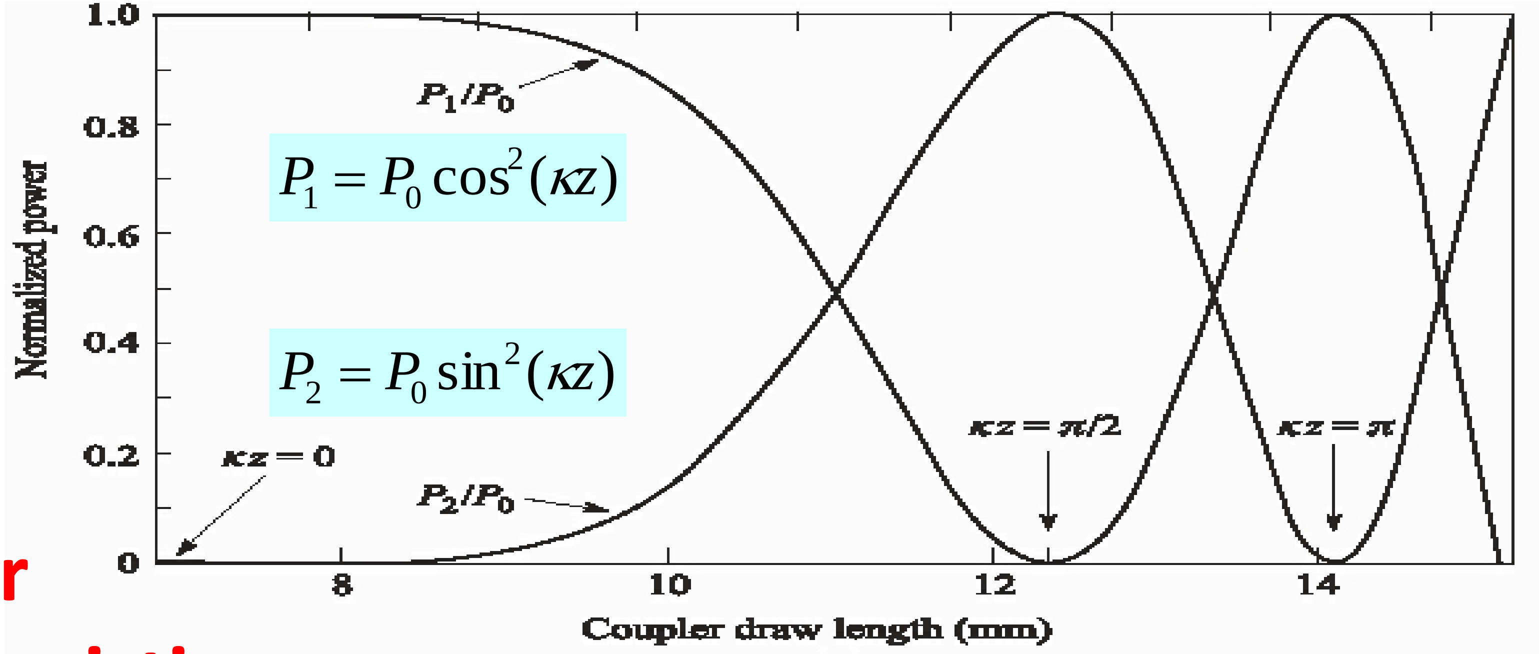
Splitting (Coupling) Ratio = $P_2/(P_1+P_2)$

Excess Loss $=10\ \mathrm{Log}[P_0/(P_1+P_2)]$

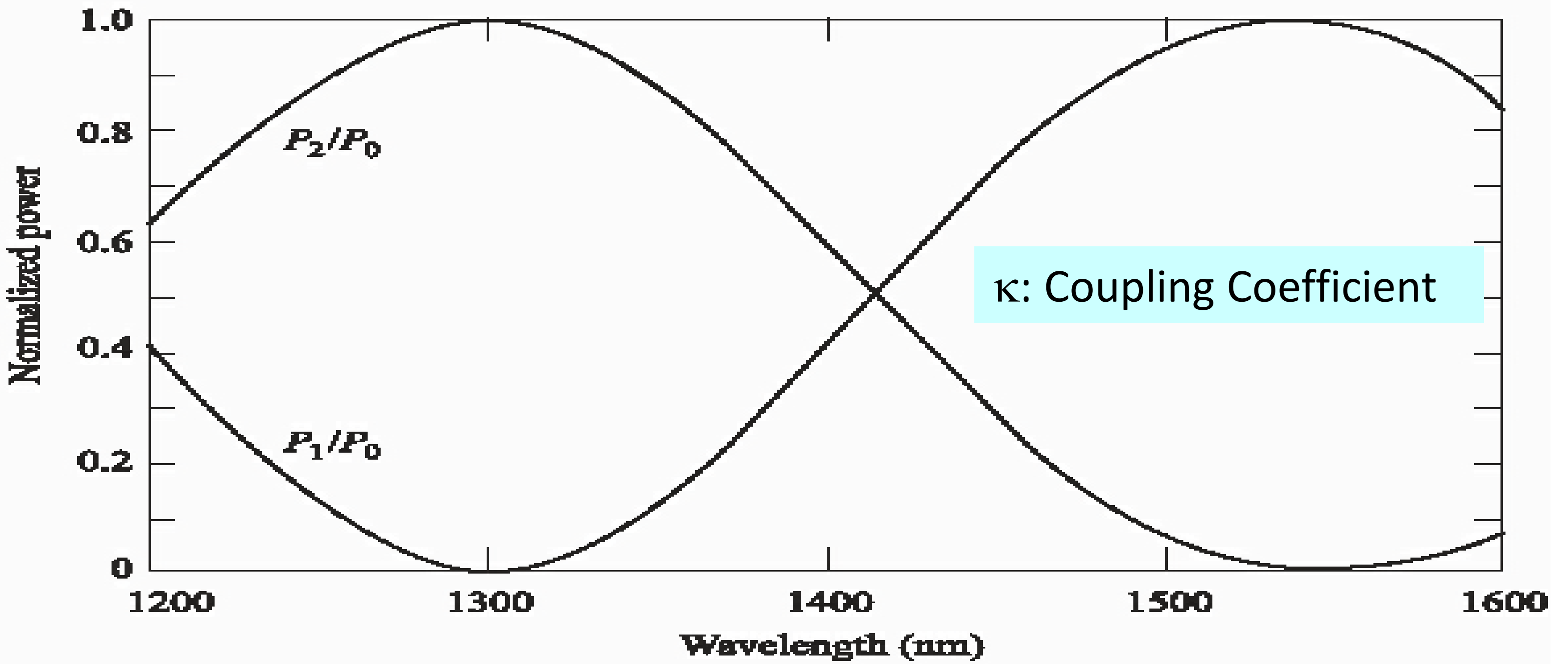
Insertion Loss $=10\ \mathrm{Log}[P_{in}/P_{out}]$

Crosstalk $= 10\ \mathrm{Log}(\mathrm{P}_3/\mathrm{P}_0)$

Coupler characteristics



(a)



(b)

Coupler Characteristics

- power ratio between both output can be changed by adjusting the draw length of a simple fused fiber coupler

- It can be made a WDM de-multiplexer:
  - Example, 1300 nm will appear output 2 (p2) and 1550 nm will appear at output 1 (P1)
  - However, suitable only for few wavelengths that are far apart, not good for DWDM

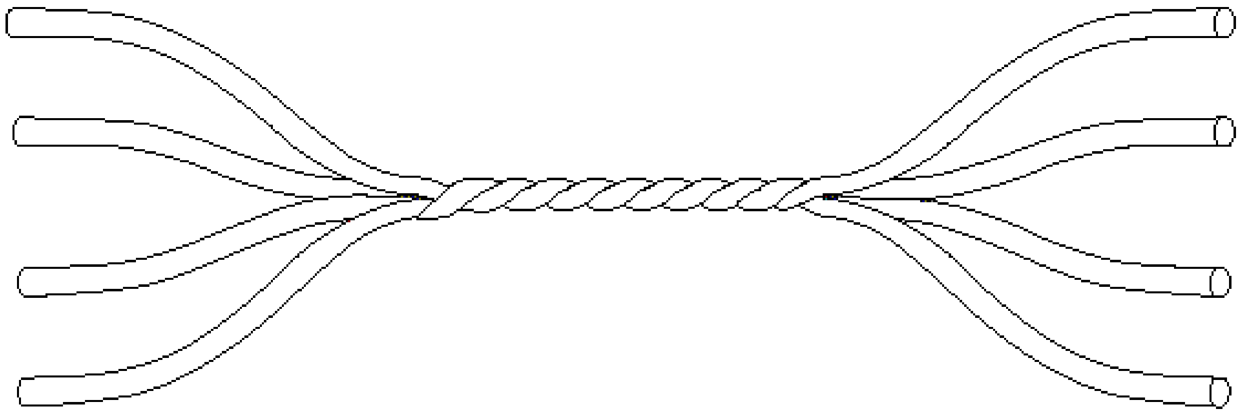
Wavelength Selective Devices

These perform their operation on the incoming optical signal as a function of the wavelength

Examples:

- Wavelength add/drop multiplexers
- Wavelength selective optical combiners/splitters
- Wavelength selective switches and routers

Fused-Fiber Star Coupler

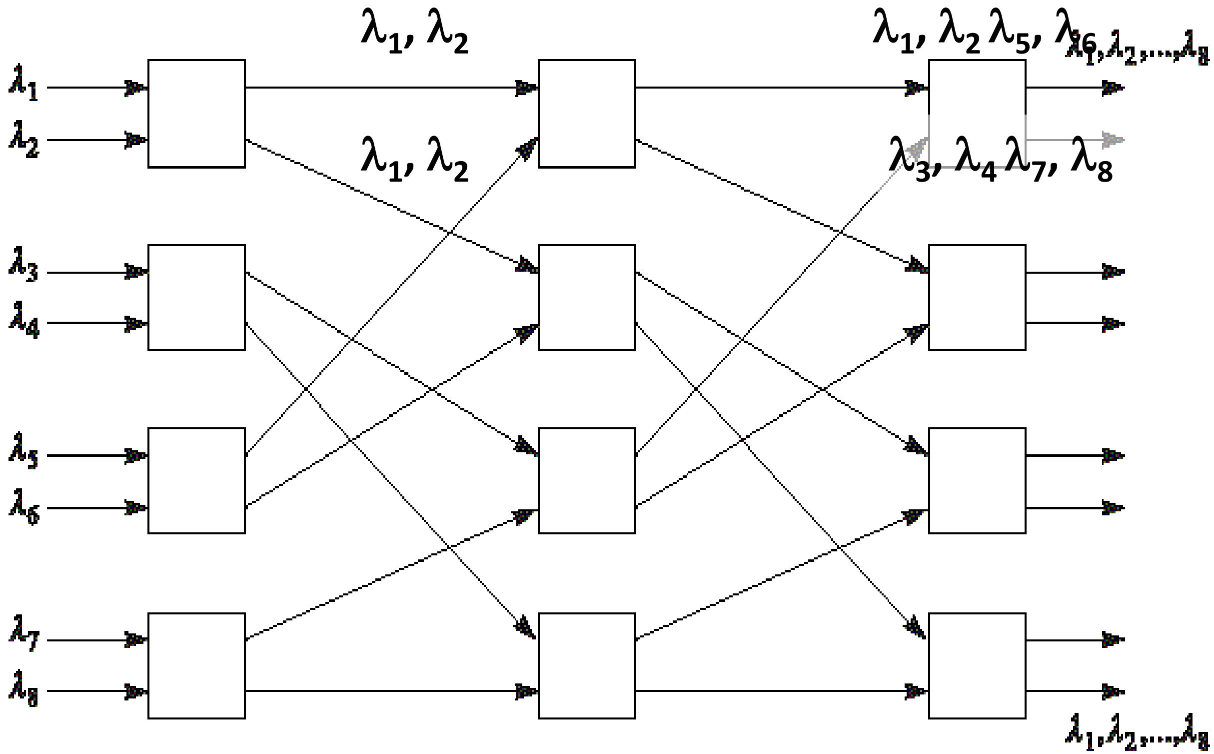


Splitting Loss = -10 Log(1/N) dB = 10 Log (N) dB

Excess Loss = 10 Log (Total P_{in}/Total P_{out})

Fused couplers have high excess loss

8x8 bi-directional star coupler by cascading 3 stages of 3-dB Couplers



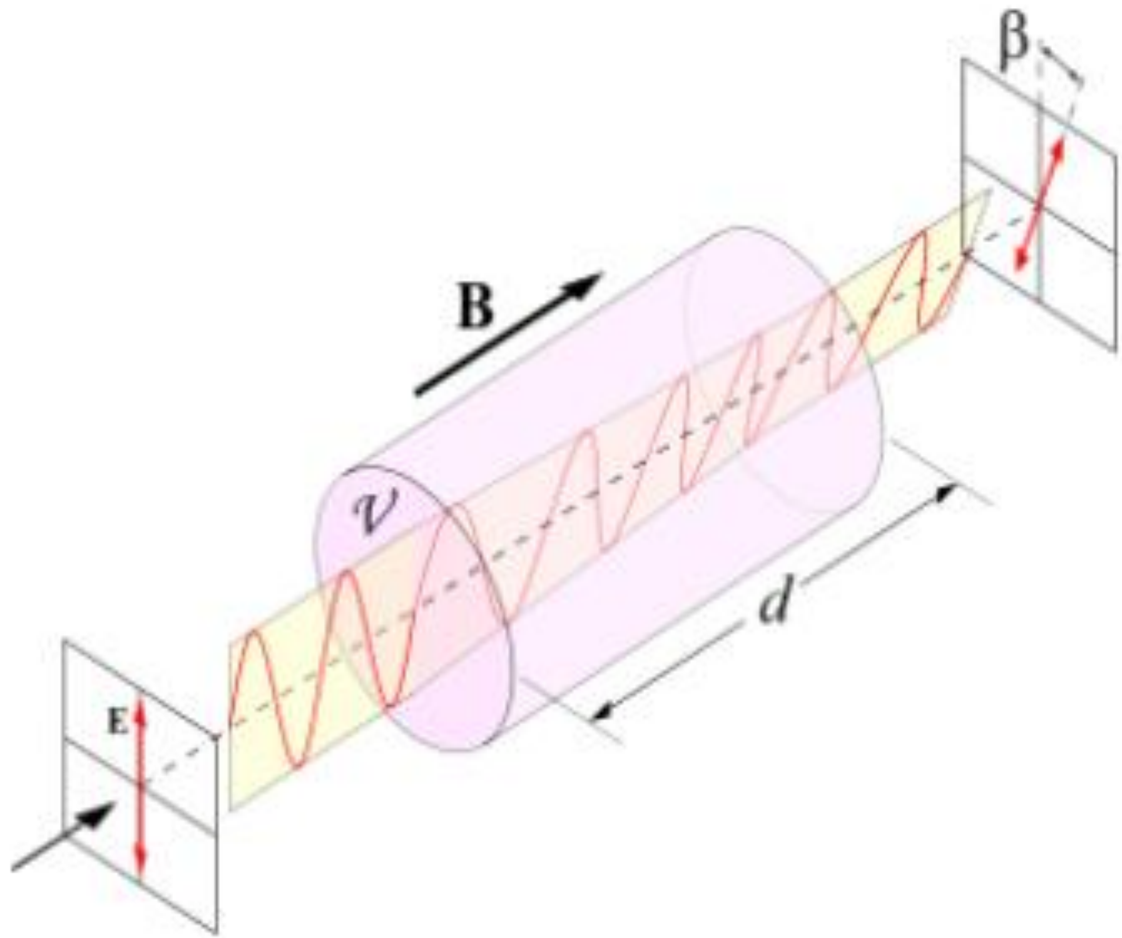
Number of 3-dB Couplers $N_c = \frac{N}{2} \log_2 N$

There are N/2 elements in the vertical direction and log2 N = log N/log 2 elements horizontally.

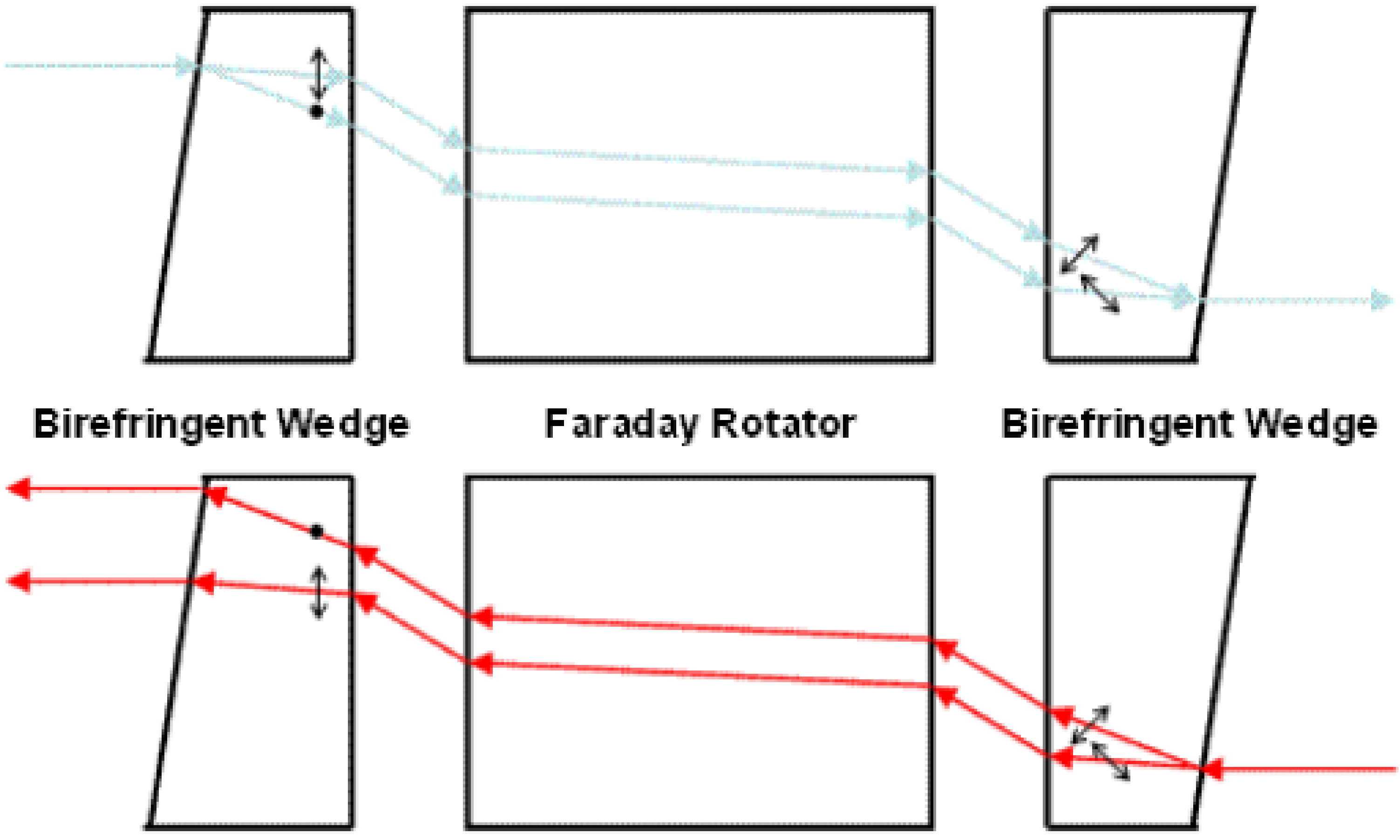
Contd

- Any higher order coupler can be constructed with 2x2couplers
- 32x32, 64X64 can be constructed with 2x2couplers

Polarization dependent Isolator

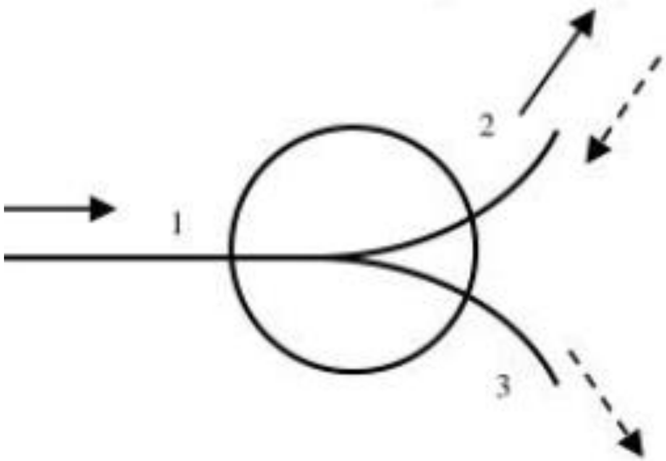


Polarization independent Isolator

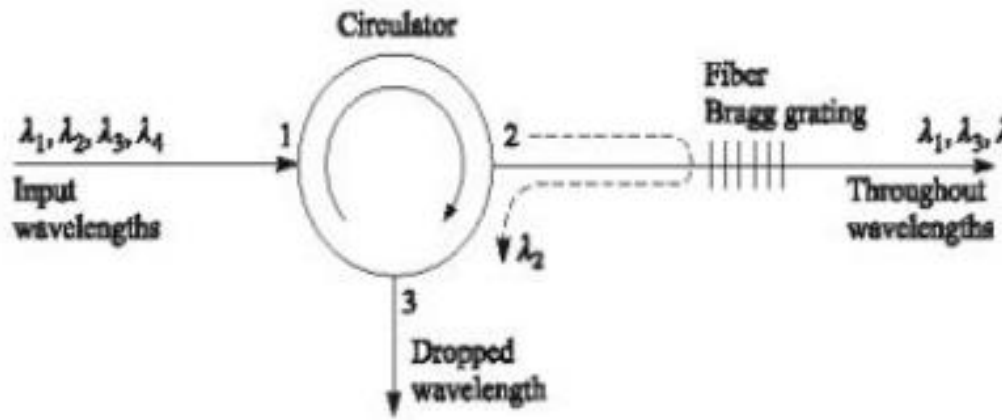


CIRCULATORS

Optical circulators redirects light sequentially from port-to-port in a unidirectional path



Same characteristics as isolator: by looking port 1-2 @ port 2-3



To extract the desired wavelength, a circulator is used in conjunction with the rating

Fiber Bragg Grating

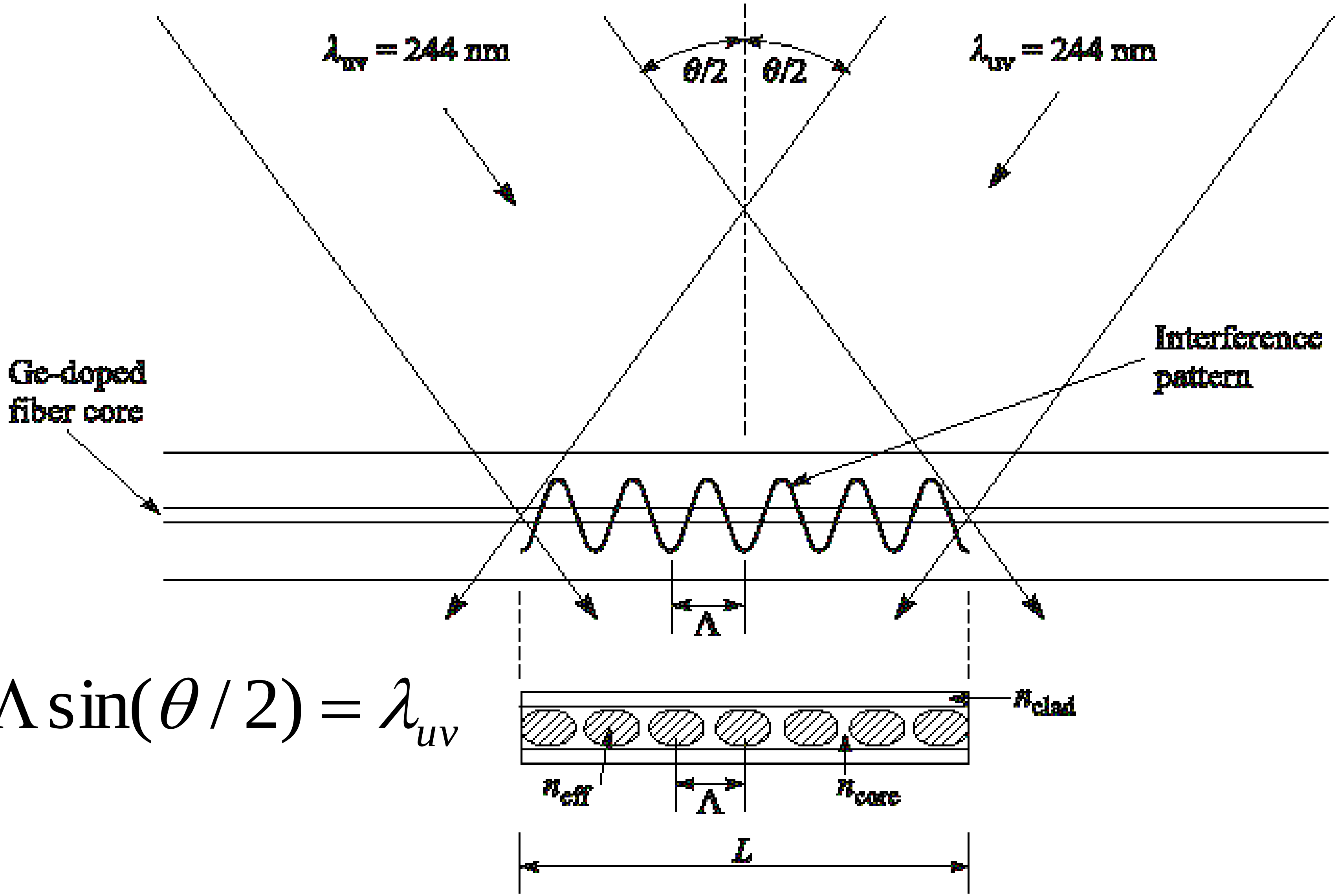
Fiber Bragg Grating

- This is invented at Communication Research Center, Ottawa, Canada
- The FBG has changed the way optical filtering is done
- The FBG has so many applications
- The FBG changes a single mode fiber (all pass filter) into a wavelength selective filter

Fiber Brag Grating (FBG)

- Basic FBG is an in-fiber passive optical band reject filter
- FBG is created by imprinting a periodic perturbation in the fiber core
- The spacing between two adjacent slits is called the pitch
- Grating play an important role in:
  - Wavelength filtering
  - Dispersion compensation
  - Optical sensing
  - EDFA Gain flattening
  - Single mode lasers and many more areas

Bragg Grating formation



$$2\Lambda \sin(\theta / 2) = \lambda_{uv}$$

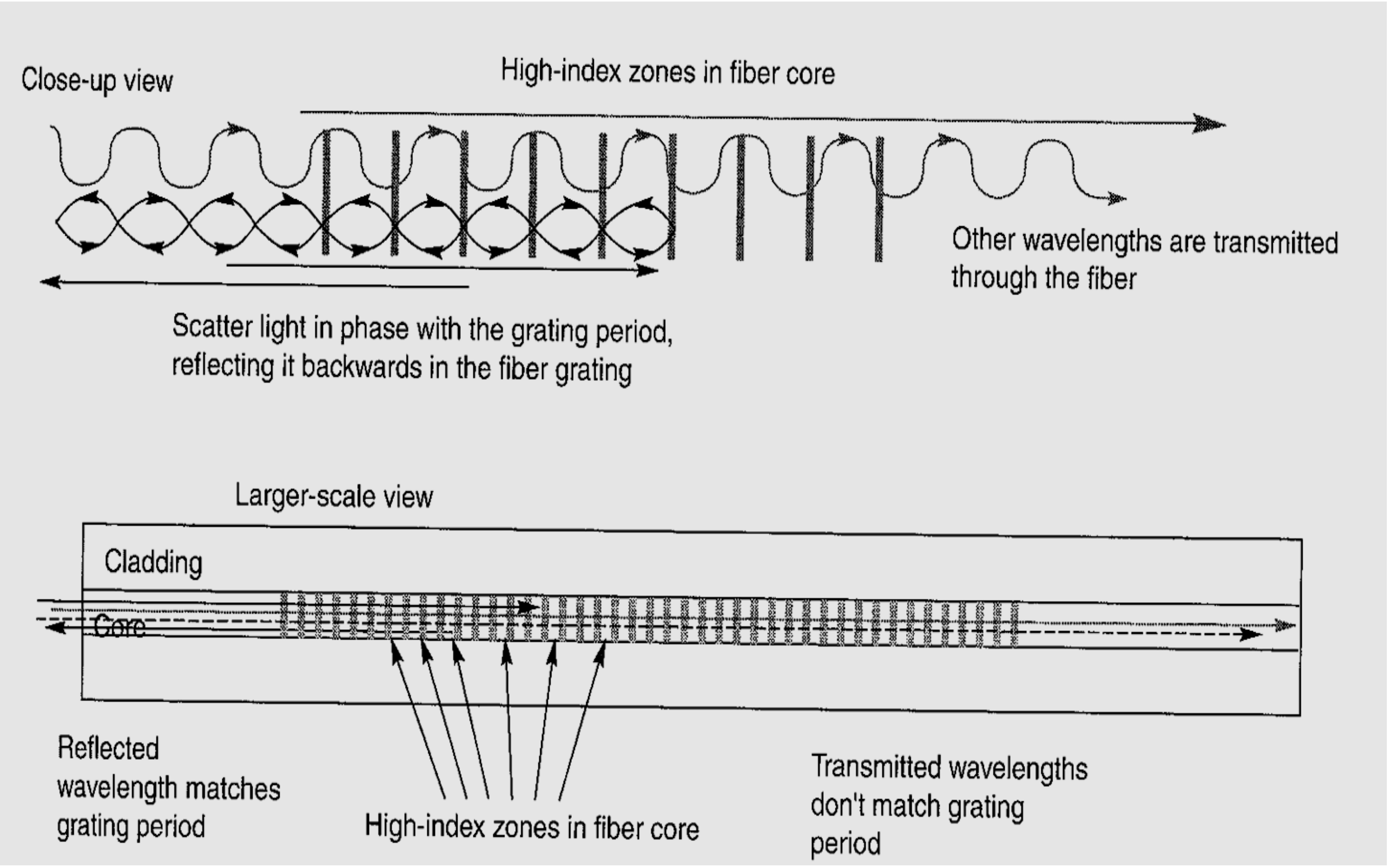
FBG Theory

Exposure to the high intensity UV radiation changes the fiber core *n(z)* permanently as a periodic function of *z*

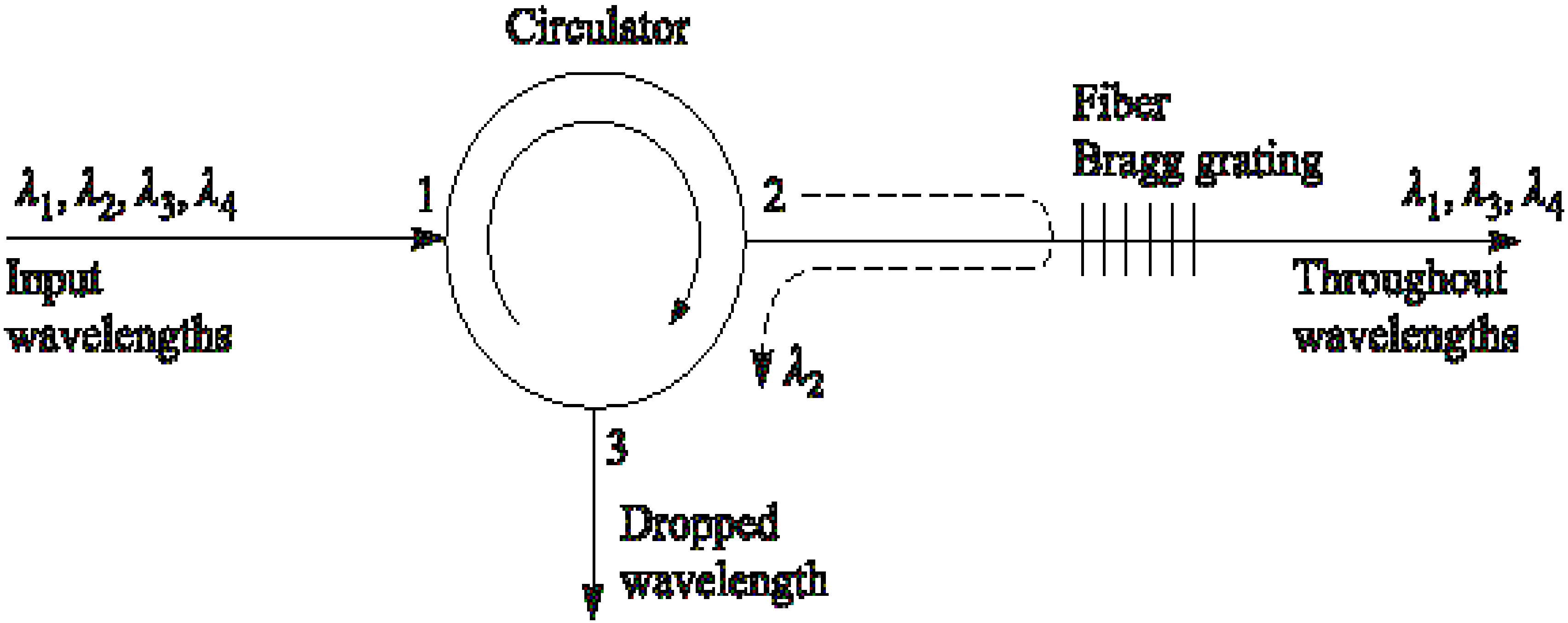
$$n(z) = n_{core} + \delta n[1 + \cos(2\pi z / \Lambda)]$$

z:	Distance measured along fiber core axis
Λ:	Pitch of the grating
n_{core}:	Core refractive index
δn:	Peak refractive index

Reflection at FBG



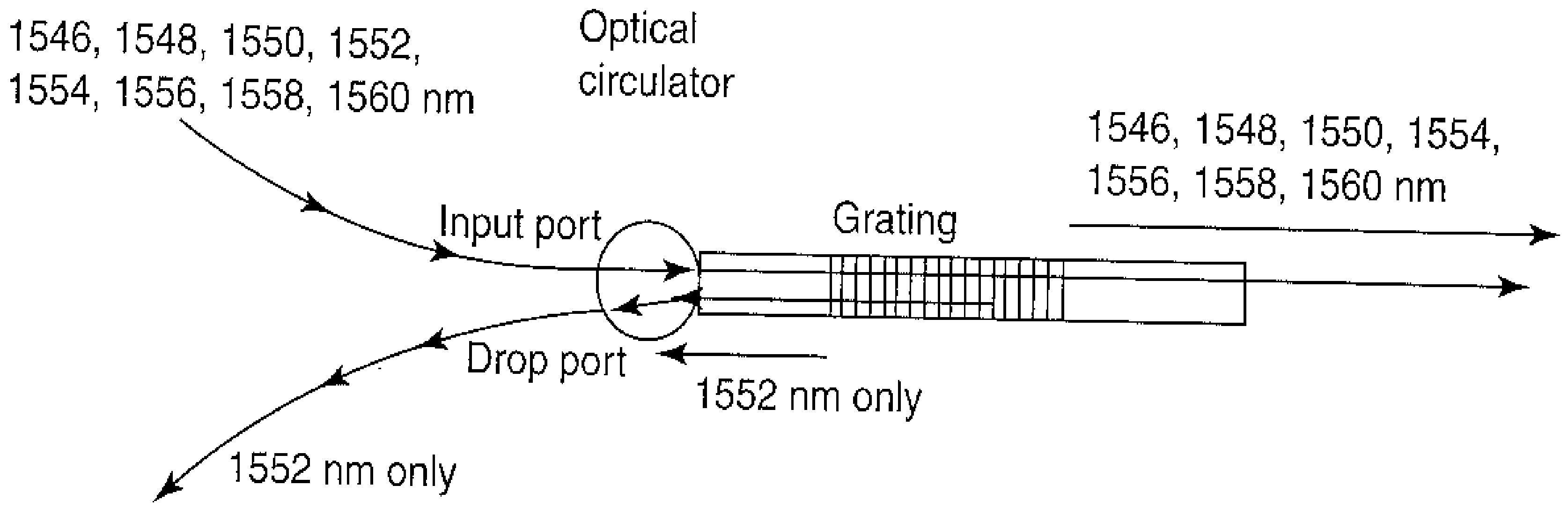
Simple De-multiplexing Function



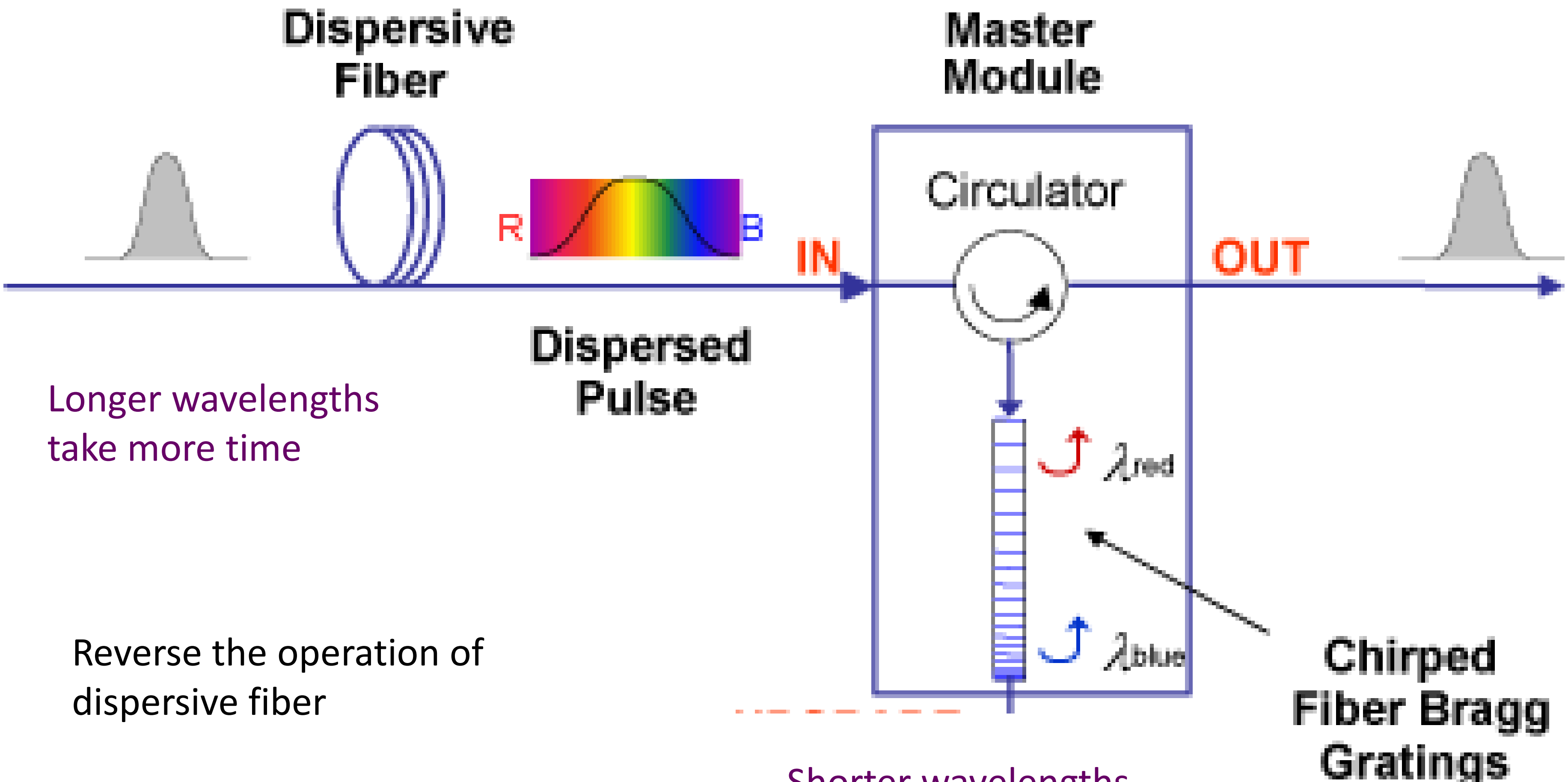
Reflected Wavelength $\lambda_B = 2\Lambda n_{eff}$

Peak Reflectivity $R_{max} = tanh^2(kL)$

Wavelength Selective DEMUX



Dispersion Compensation



Longer wavelengths take more time

Reverse the operation of dispersive fiber

Shorter wavelengths take more time