



APPLIED OPTOELECTRONICS CENTRE

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# WDM and DWDM Multiplexing





# Multiplexing

- Multiplexing
  - a process where multiple analog message signals or digital data streams are combined into one signal over a shared medium
- Types
  - Time division multiplexing
  - Frequency division multiplexing
- Optically
  - Time division multiplexing
  - Wavelength division multiplexing



# Timeline



Optical Fibre



SDH



DWDM



CWDM



# Problems and Solutions

## Problem:

Demand for massive increases in capacity



## Immediate Solution:

Dense Wavelength Division Multiplexing



## Longer term Solution:

Optical Fibre Networks



# Wavelength Division Multiplexing

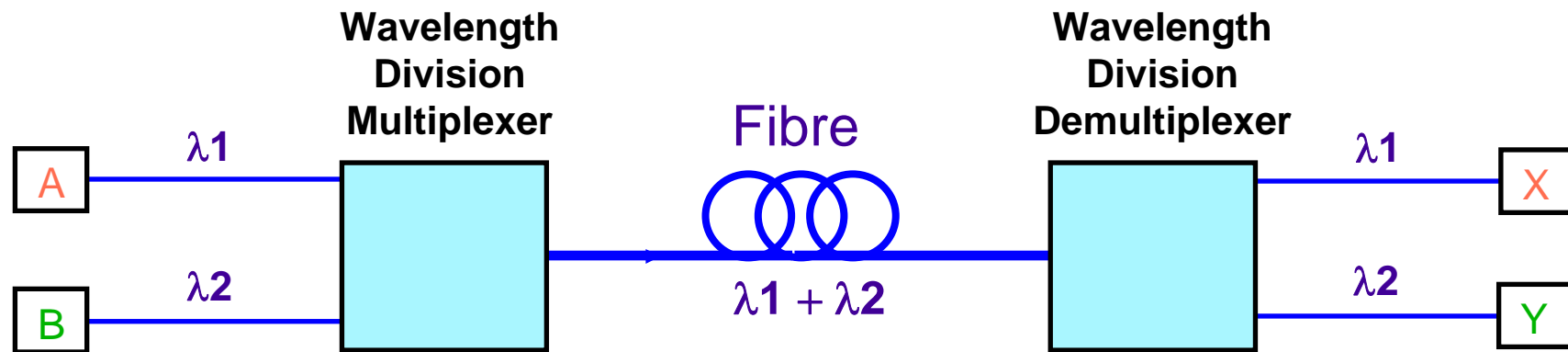


# Dense WDM





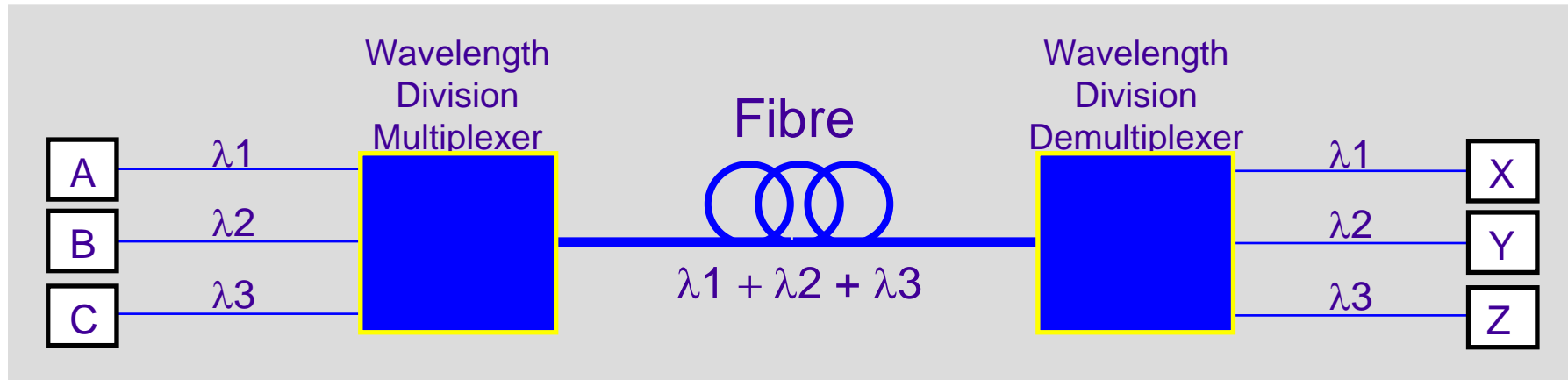
# WDM Overview



- Multiple channels of information carried over the same fibre, each using an individual wavelength
- A communicates with X and B with Y as if a dedicated fibre is used for each signal
- Typically one channel utilises 1320 nm and the other 1550 nm
- Broad channel spacing, several hundred nm
- Recently WDM has become known as Coarse WDM or CWDM to distinguish it from DWDM



# WDM Overview



- Multiple channels of information carried over the same fibre, each using an individual wavelength
- Attractive multiplexing technique
  - High aggregate bit rate without high speed electronics or modulation
  - Low dispersion penalty for aggregate bit rate
  - Very useful for upgrades to installed fibres
  - Realisable using commercial components, unlike OTDM
- Loss, crosstalk and non-linear effects are potential problems





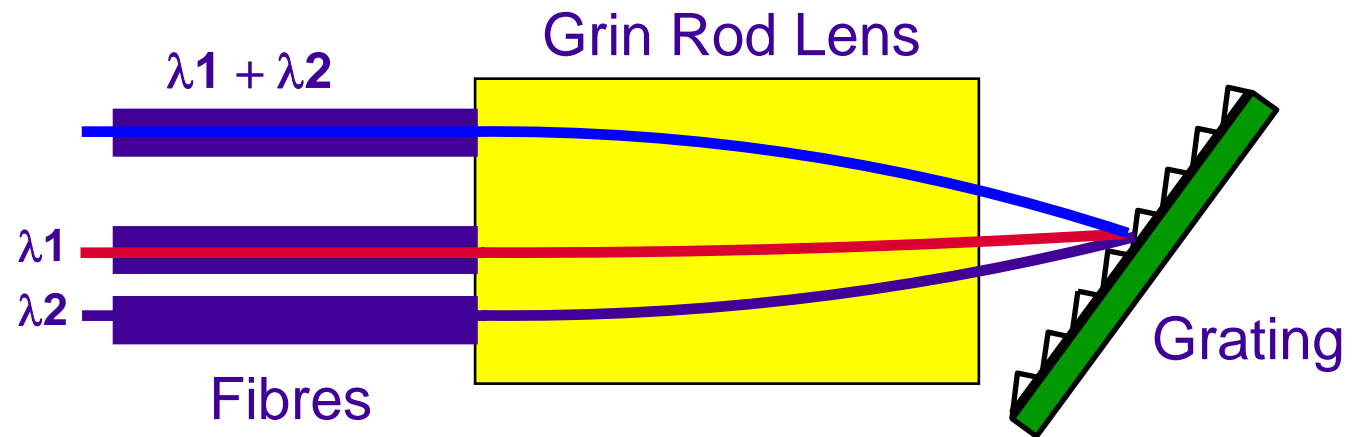
# Types of WDM

	<b>Coarse WDM</b> (includes WWDM)	<b>WDM</b>	<b>DWDM</b> (includes ultra dense WDM)
Channel Spacings	Large, from 1.6 nm (200 GHz) to 25 nm	1310 nm lasers used in conjunction with 1550 nm lasers	Small, 200 GHz and less
Number of bands used	O,E,S,C and L	O and C	C and L
Cost per channel	Low	Low	High
Number of channels delivered	17-18 at most	2	Hundreds of channels possible
Best Application	Short-haul, Metro	PON	Long-haul



# WDM Multiplexers/Demultiplexers

- Wavelength multiplexer types include:
  - Fibre couplers
  - Grating multiplexers
- Wavelength demultiplexer types include:
  - Single mode fused taper couplers
  - Grating demultiplexers
  - Tunable filters





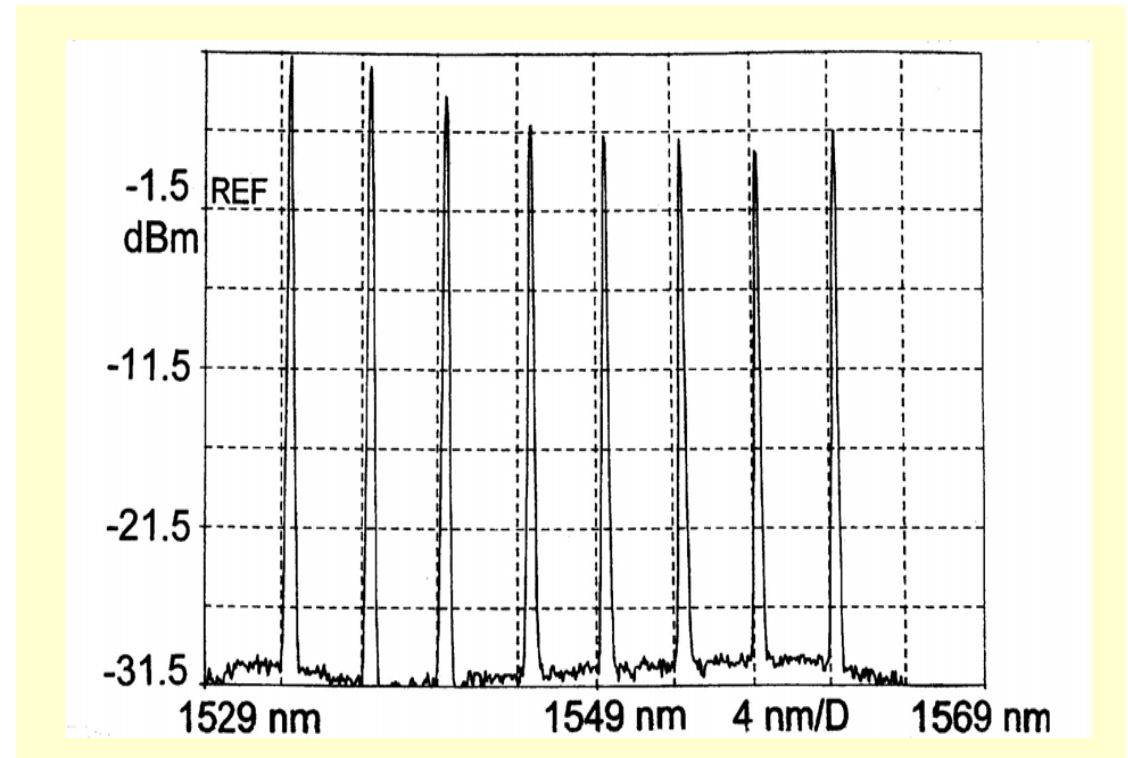
# Tunable Sources

- WDM systems require sources at different wavelengths
- Irish researchers at U.C.D. under the ACTS program are developing precision tunable laser sources
- Objective is to develop a complete module incorporating:
  - Multisection segmented grating Distributed Bragg Reflector Laser diode
  - Thermal and current drivers
  - Control microprocessor
  - Interface to allow remote optical power and wavelength setting



# Early DWDM: CNET 160 Gbits/sec WDM

- 160 Gbits/s
- 8 channels, 20 Gbits/s each
- Grating multiplex/demultiplex
- 4 nm channel spacing
- 1533 to 1561 nm band
- 238 km span
- 3 optical amplifiers used



Multiplexer Optical Output Spectrum

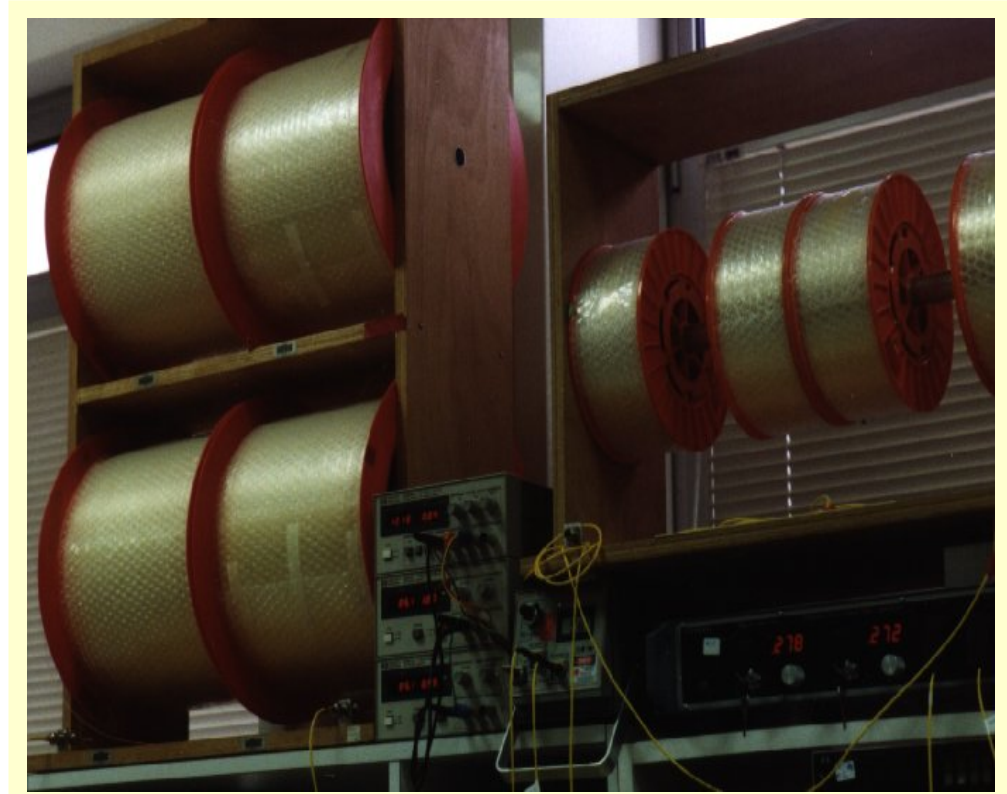


# Early DWDM: CNET WDM Experimental Setup



Optical Transmitters

Buffered Fibre on Reels





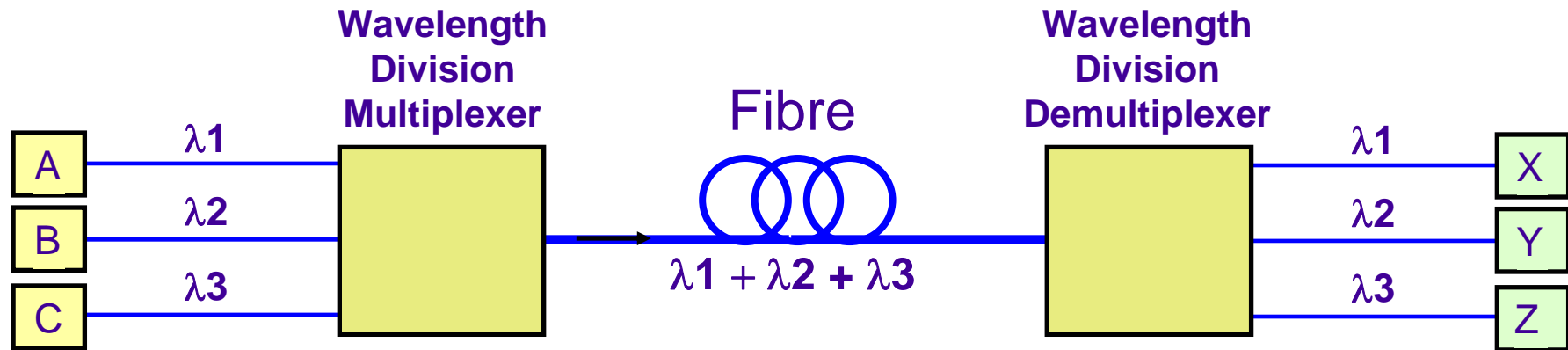
# Dense Wavelength Division Multiplexing





# Dense Wavelength Division Multiplexing

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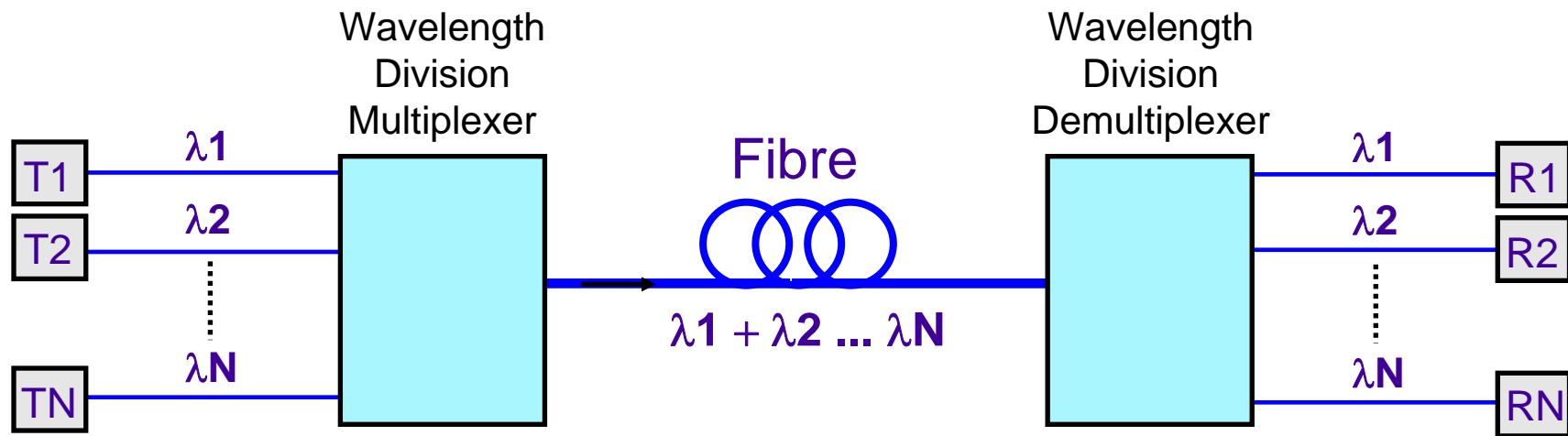


- Multiple channels of information carried over the same fibre, each using an individual wavelength
- *Dense WDM* is WDM utilising closely spaced channels
- Channel spacing reduced to 1.6 nm and less
- Cost effective way of increasing capacity without replacing fibre
- Commercial systems available with capacities of 32 channels and upwards; > 80 Gb/s per fibre





# Simple DWDM System



Multiple channels of information carried over the same fibre, each using an individual wavelength

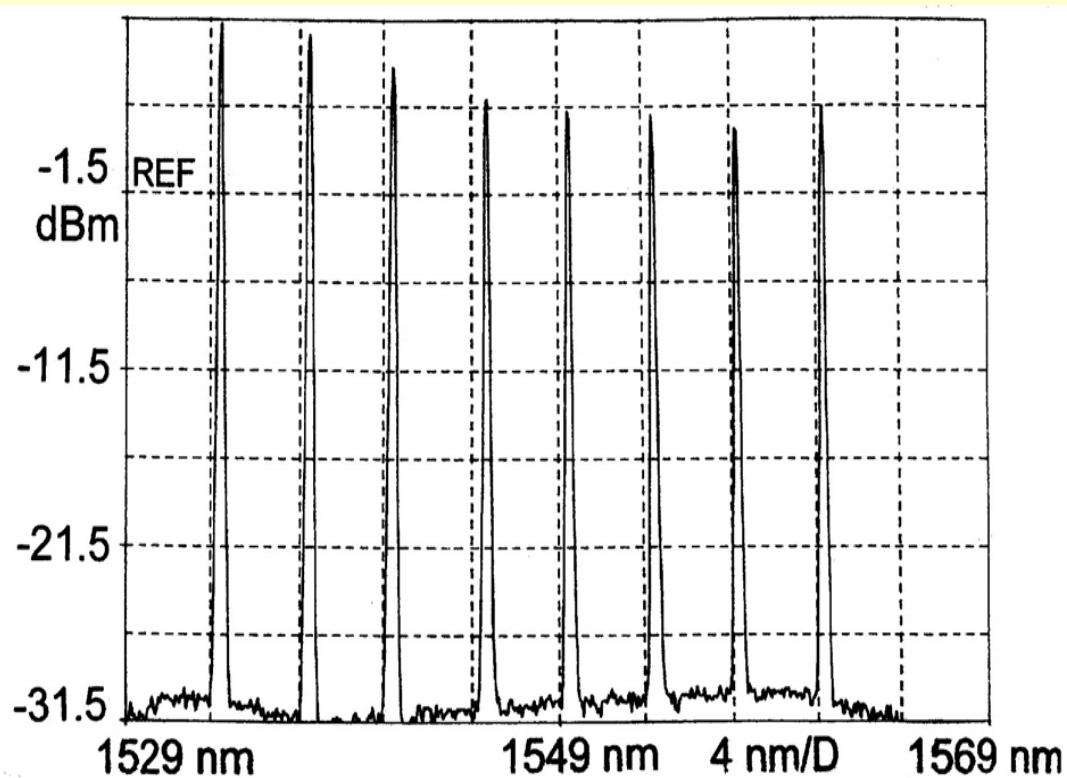
Unlike CWDM channels are much closer together

Transmitter  $T_1$  communicates with Receiver  $R_1$  as if connected by a dedicated fibre as does  $T_2$  and  $R_2$  and so on





# Sample DWDM Signal



**Multiplexer Optical Output Spectrum for an 8 DWDM channel system, showing individual channels**



# DWDM: Key Issues

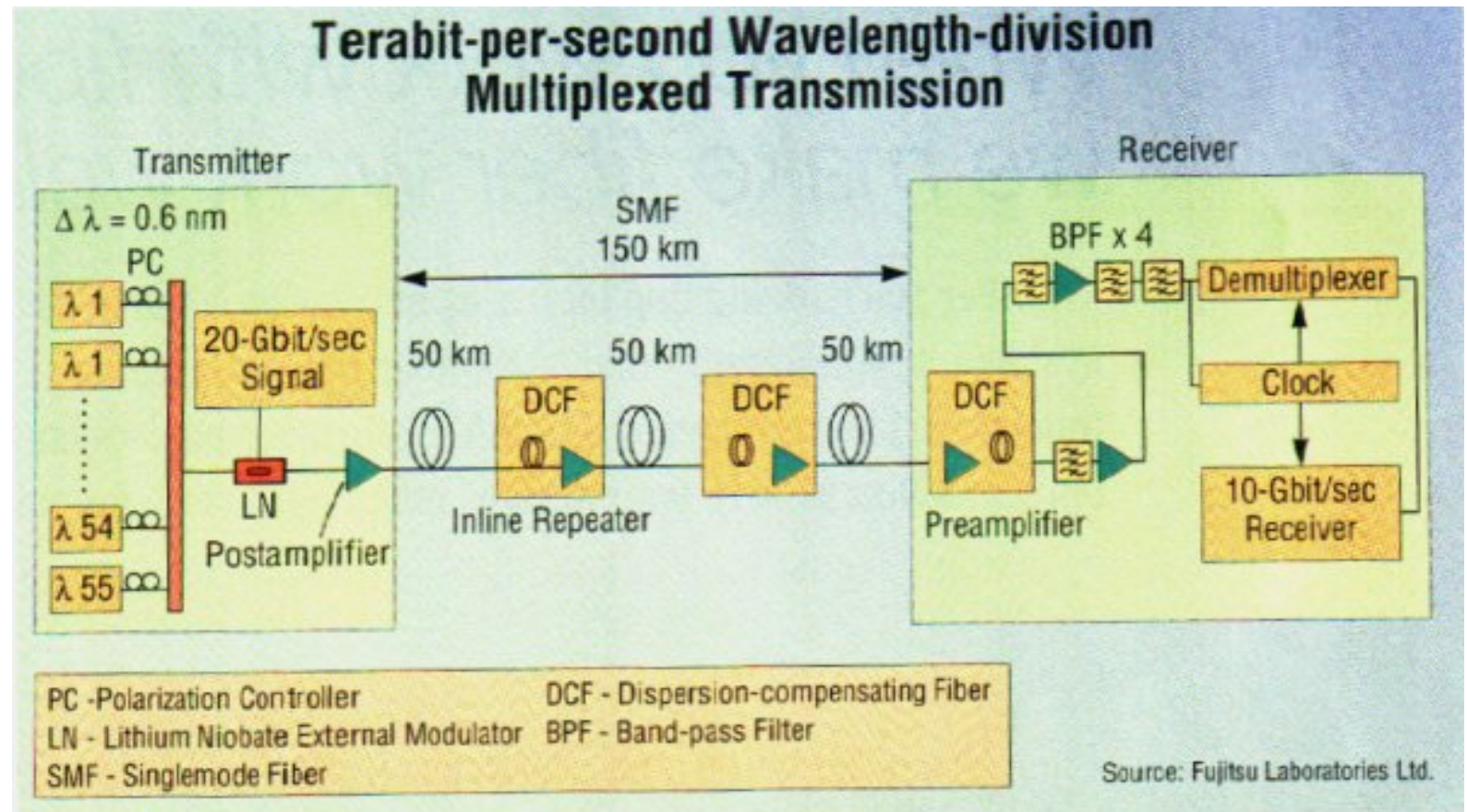
- *Dense WDM* is WDM utilising closely spaced channels
- Channel spacing reduced to 1.6 nm and less
- Cost effective way of increasing capacity without replacing fibre
- Commercial systems available with capacities of 32 channels and upwards; > 80 Gb/s per fibre
- Allows new optical network topologies, for example high speed metropolitan rings
- Optical amplifiers are also a key component



# Terabit Transmission using DWDM

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- 1.1 Tbits/sec total bit rate (more than 13 million telephone channels)
- 55 wavelengths at 20 Gbits/sec each
- 1550 nm operation over 150 km with dispersion compensation
- Bandwidth from 1531.7 nm to 1564.07 nm (0.6 nm spacing)





# Expansion Options



# Capacity Expansion Options (I)

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- Install more fibre
  - New fibre is expensive to install (Euro 100k + per km)
  - Fibre routes require a right-of-way
  - Additional regenerators and/or amplifiers may be required
- Install more SDH network elements over dark fibre
  - Additional regenerators and/or amplifiers may be required
  - More space needed in buildings

# Capacity Expansion Options (II)

- Install higher speed SDH network elements

- Speeds above STM-16 not yet trivial to deploy
- STM-64 price points have not yet fallen sufficiently
- No visible expansion options beyond 10 Gbit/s
- May require network redesign

- Install DWDM

- Incremental capacity expansion to 80 Gbits/s and beyond
- Allows reuse of the installed equipment base



# DWDM Advantages and Disadvantages



# DWDM Advantages

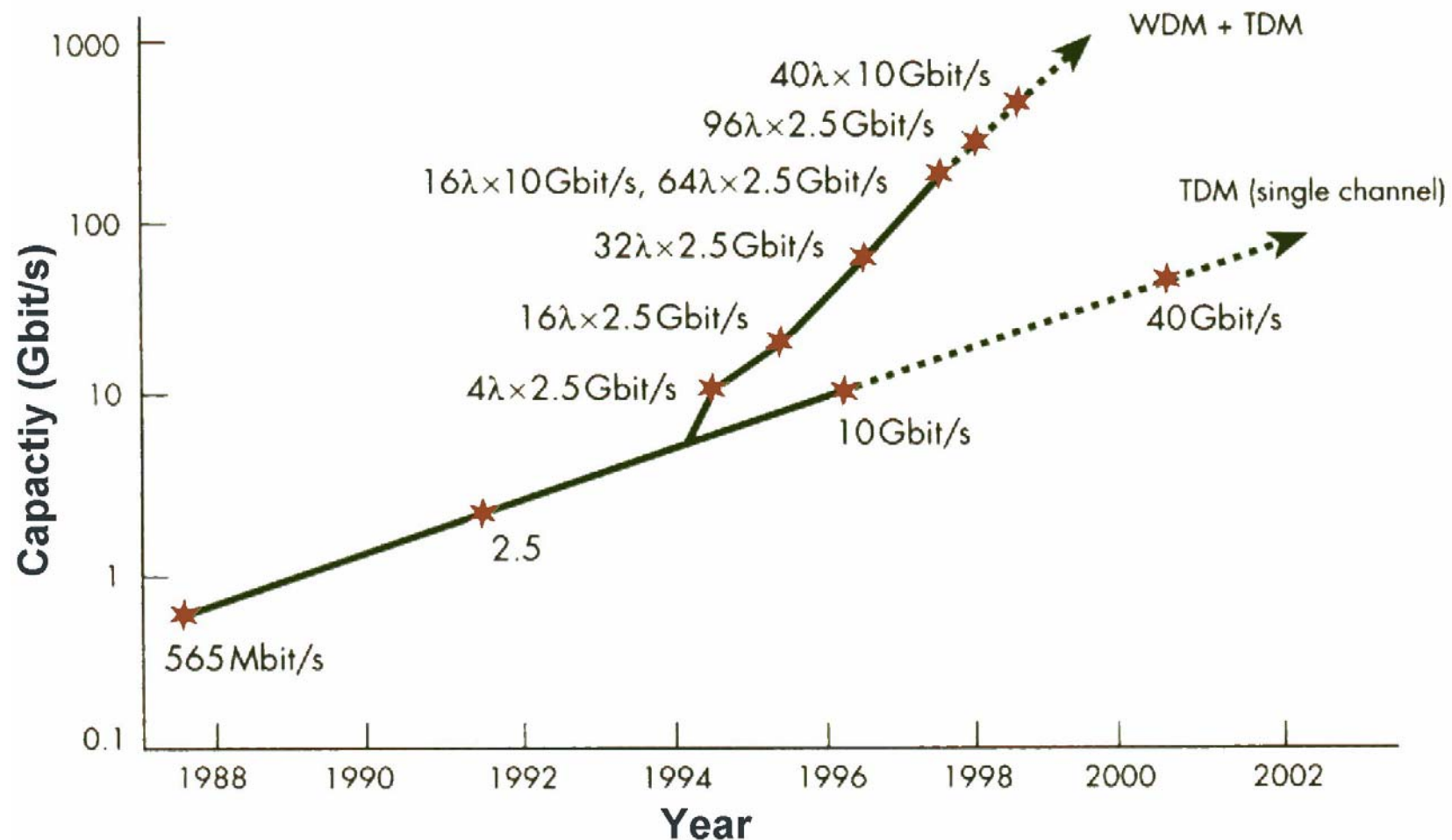
- Greater fibre capacity
- Easier network expansion
  - No new fibre needed
  - Just add a new wavelength
  - Incremental cost for a new channel is low
  - No need to replace many components such as optical amplifiers
- DWDM systems capable of longer span lengths
  - TDM approach using STM-64 is more costly and more susceptible to chromatic and polarization mode dispersion
- Can move to STM-64 when economics improve





# DWDM versus TDM

- DWDM can give increases in capacity which TDM cannot match
- Higher speed TDM systems are very expensive





# DWDM Disadvantages

- Not cost-effective for low channel numbers
  - Fixed cost of mux/demux, transponder, other system components
- Introduces another element, the frequency domain, to network design and management
- SONET/SDH network management systems not well equipped to handle DWDM topologies
- DWDM performance monitoring and protection methodologies developing



# DWDM: Commercial Issues

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- DWDM installed on a large scale first in the USA
  - larger proportion of longer >1000km links
  - Earlier onset of "fibre exhaust" (saturation of capacity) in 1995-96
- Market is gathering momentum in Europe
  - Increase in data traffic has existing operators deploying DWDM
- New entrants particularly keen to use DWDM in Europe
  - Need a scaleable infrastructure to cope with demand as it grows
  - DWDM allows incremental capacity increases
  - DWDM is viewed as an integral part of a market entry strategy



# DWDM Standards





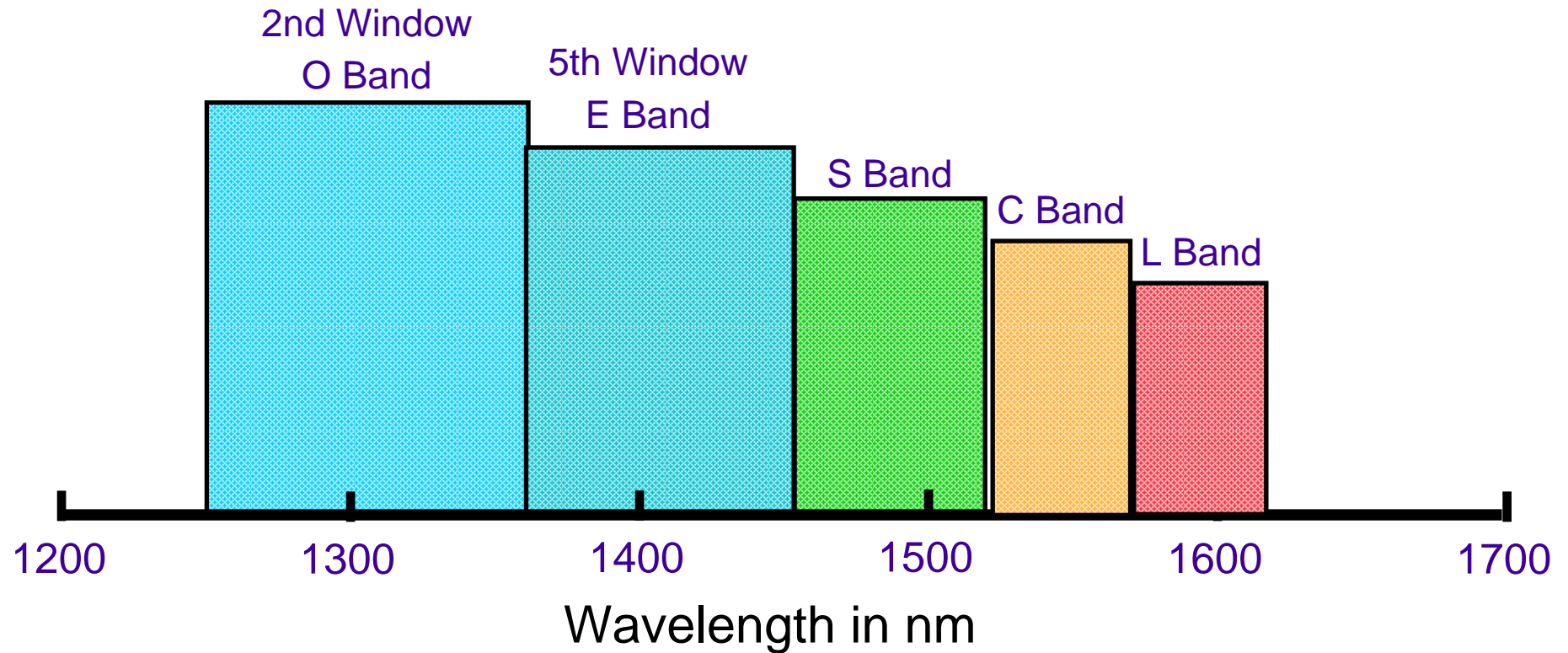
# DWDM Standards

- ITU Recommendation is G.692 "Optical interfaces for multichannel systems with optical amplifiers"
- G.692 includes a number of DWDM channel plans
- Channel separation set at:
  - 50, 100 and 200 GHz
  - equivalent to approximate wavelength spacings of 0.4, 0.8 and 1.6 nm
- Channels lie in the range 1530.3 nm to 1567.1 nm (so-called C-Band)
- Newer "L-Band" exists from about 1570 nm to 1620 nm
- Supervisory channel also specified at 1510 nm to handle alarms and monitoring



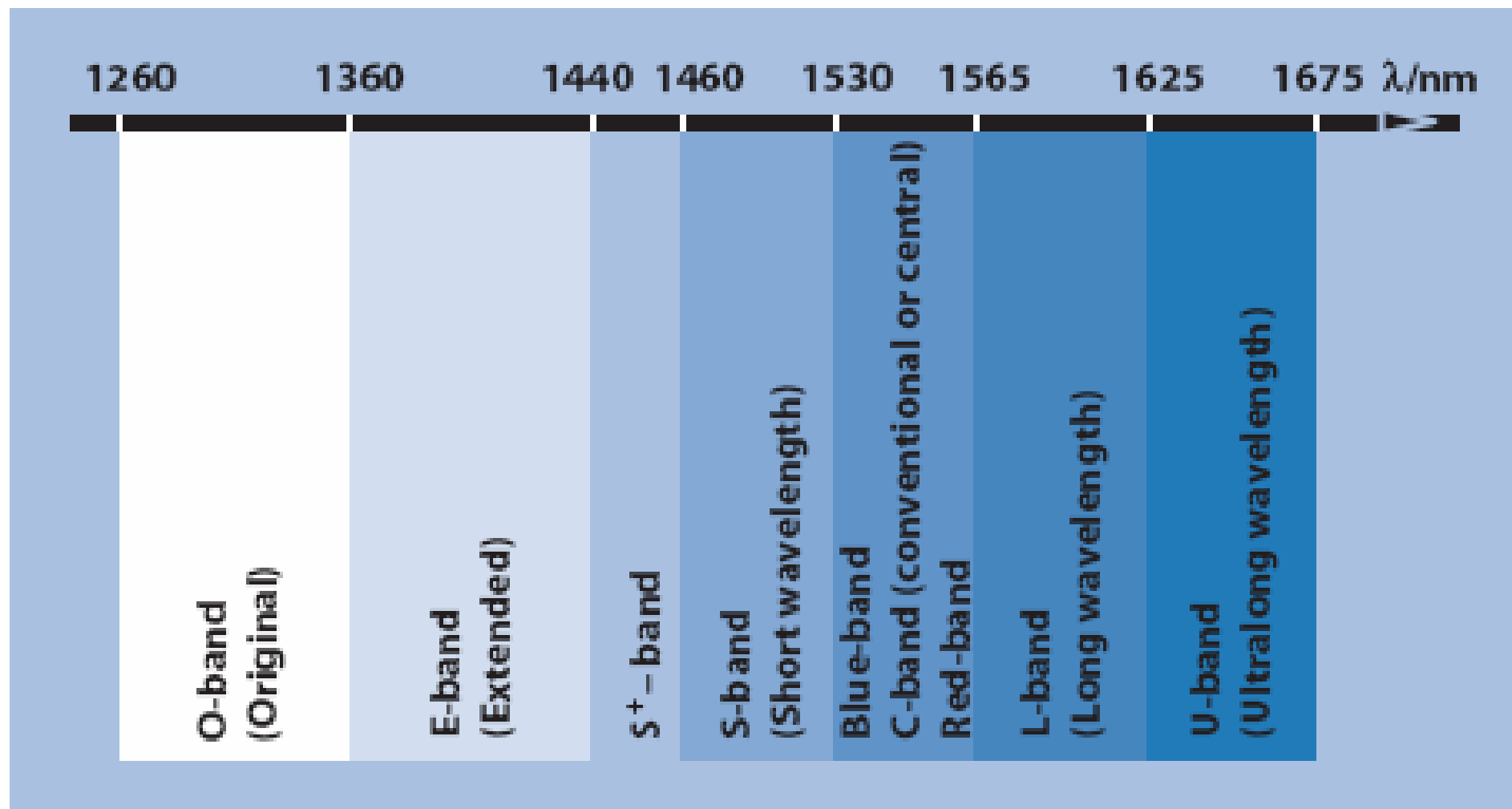


# Optical Spectral Bands





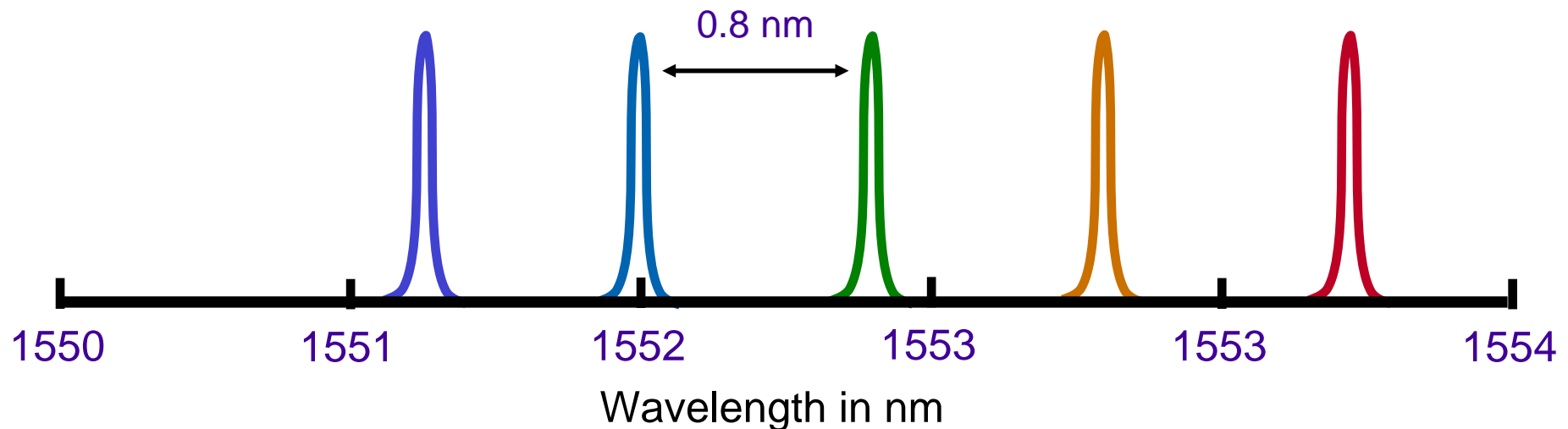
# Optical Spectral Bands





# Channel Spacing

- Trend is toward smaller channel spacings, to increase the channel count
- ITU channel spacings are 0.4 nm, 0.8 nm and 1.6 nm (50, 100 and 200 GHz)
- Proposed spacings of 0.2 nm (25 GHz) and even 0.1 nm (12.5 GHz)
- Requires laser sources with excellent long term wavelength stability, better than 10 pm
- One target is to allow more channels in the C-band without other upgrades







# ITU DWDM Channel Plan

## 0.4 nm Spacing (50 GHz)

### All Wavelengths in nm

1528.77	1534.64	1540.56	1546.52	1552.52	1558.58
1529.16	1535.04	1540.95	1546.92	1552.93	1558.98
1529.55	1535.43	1541.35	1547.32	1553.33	1559.39
1529.94	1535.82	1541.75	1547.72	1553.73	1559.79
1530.33	1536.22	1542.14	1548.11	1554.13	1560.20
1530.72	1536.61	1542.54	1548.51	1554.54	1560.61
1531.12	1537.00	1542.94	1548.91	1554.94	
1531.51	1537.40	1543.33	1549.32	1555.34	
1531.90	1537.79	1543.73	1549.72	1555.75	
1532.29	1538.19	1544.13	1550.12	1556.15	
1532.68	1538.58	1544.53	1550.52	1556.55	
1533.07	1538.98	1544.92	1550.92	1556.96	
1533.47	1539.37	1545.32	1551.32	1557.36	
1533.86	1539.77	1545.72	1551.72	1557.77	
1534.25	1540.16	1546.12	1552.12	1558.17	

So called  
ITU *C-Band*

81 channels defined

Another band called  
the *L-band* exists  
above 1565 nm

# ITU DWDM Channel Plan

## 0.8 nm Spacing (100 GHz)

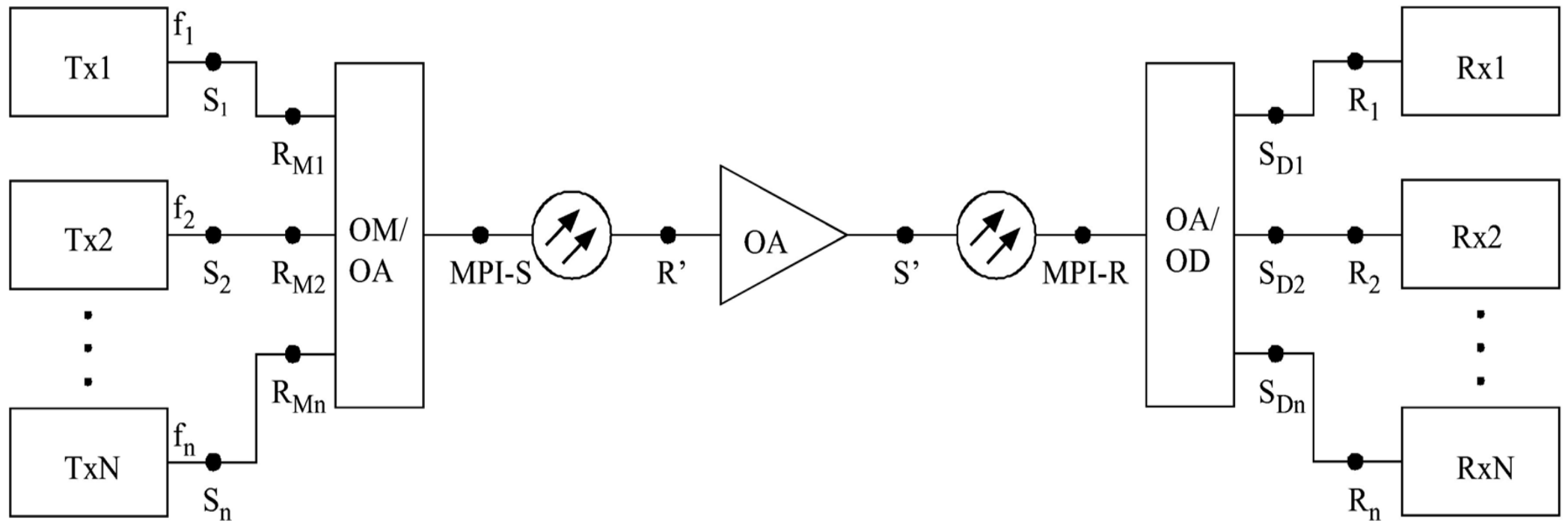
### All Wavelengths in nm

1528.77	1534.64	1540.56	1546.52	1552.52	1558.98
1529.55	1535.43	1541.35	1547.32	1553.33	1559.79
1530.33	1536.22	1542.14	1548.11	1554.13	1560.61
1531.12	1537.00	1542.94	1548.91	1554.94	
1531.90	1537.79	1543.73	1549.72	1555.75	
1532.68	1538.58	1544.53	1550.52	1556.55	
1533.47	1539.37	1545.32	1551.32	1557.36	
1534.25	1540.16	1546.12	1552.12	1558.17	

Speed of Light assumed to be  $2.99792458 \times 10^8$  m/s



# G.692 Representation of a Standard DWDM System



T1527240-97

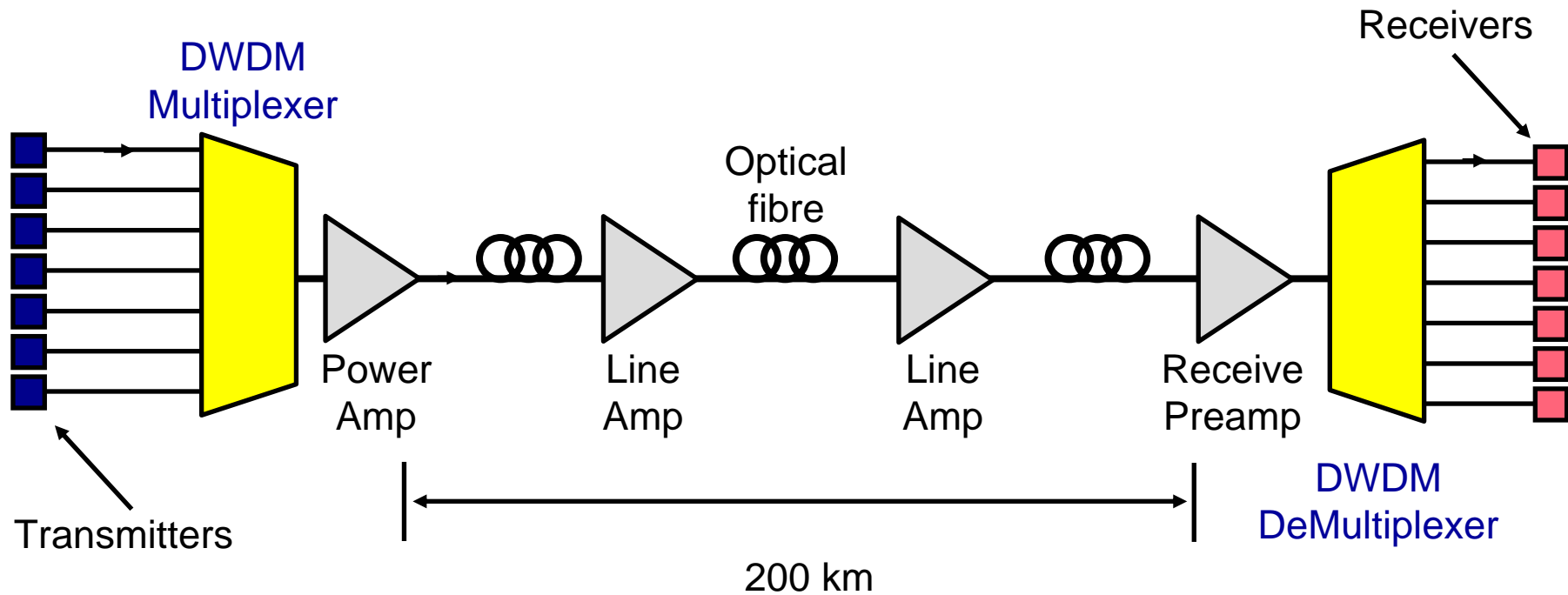
**Figure 1/G.692 – Representation of optical line system interfaces**



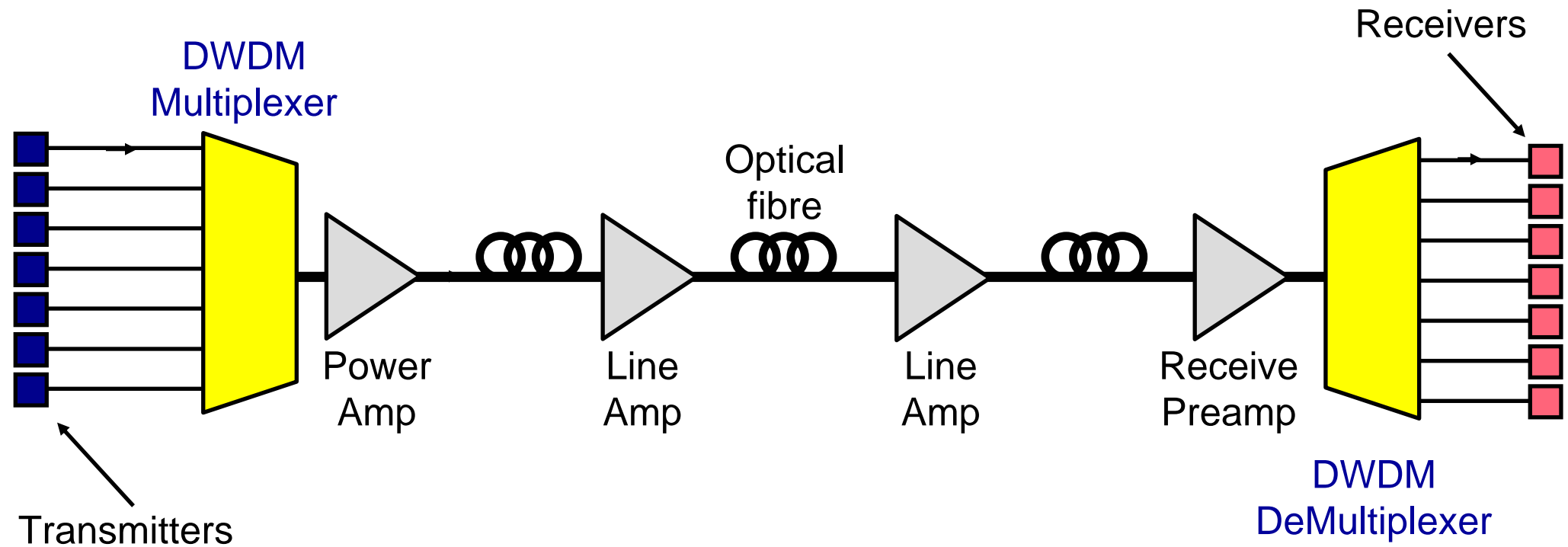
# DWDM Components



# DWDM System



- Each wavelength behaves as if it has its own "virtual fibre"
- Optical amplifiers needed to overcome losses in mux/demux and long fibre spans





# DWDM: Typical Components

- **Passive Components:**

- Gain equalisation filter for fibre amplifiers
- Bragg gratings based demultiplexer
- Array Waveguide multiplexers/demultiplexers
- Add/Drop Coupler

- **Active Components/Subsystems:**

- Transceivers and Transponders
- DFB lasers at ITU specified wavelengths
- DWDM flat Erbium Fibre amplifiers

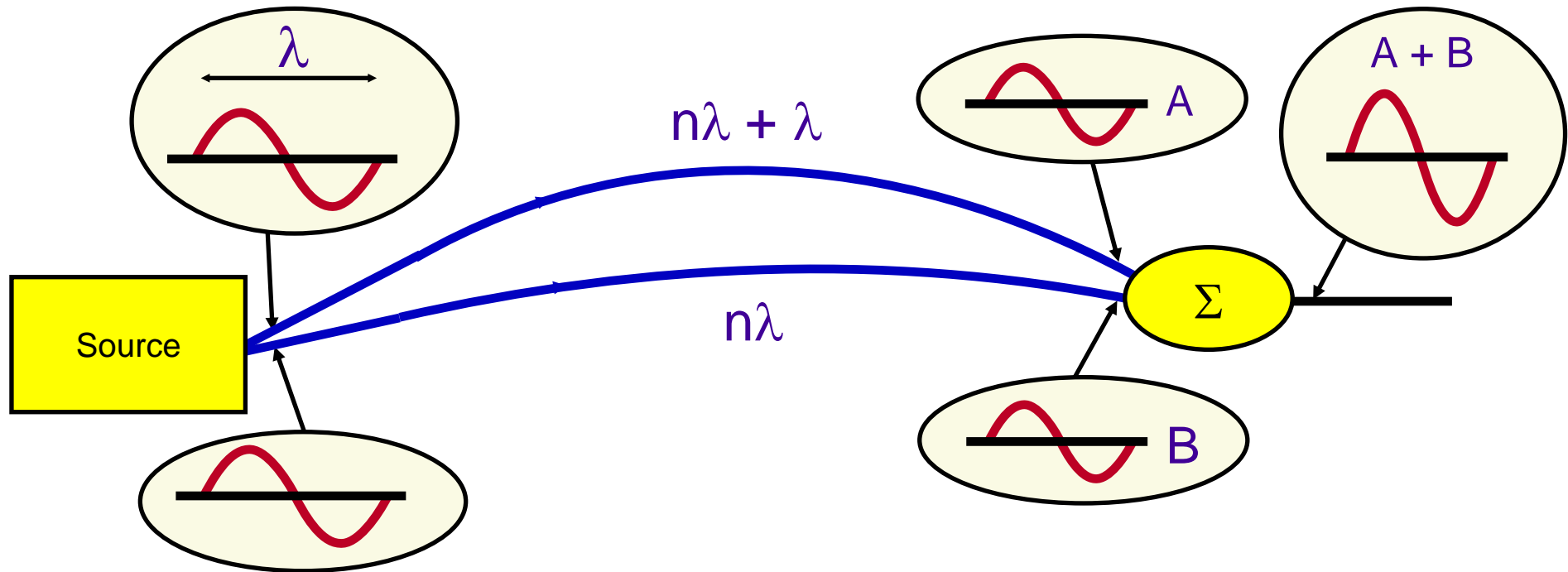


# Mux/Demuxes





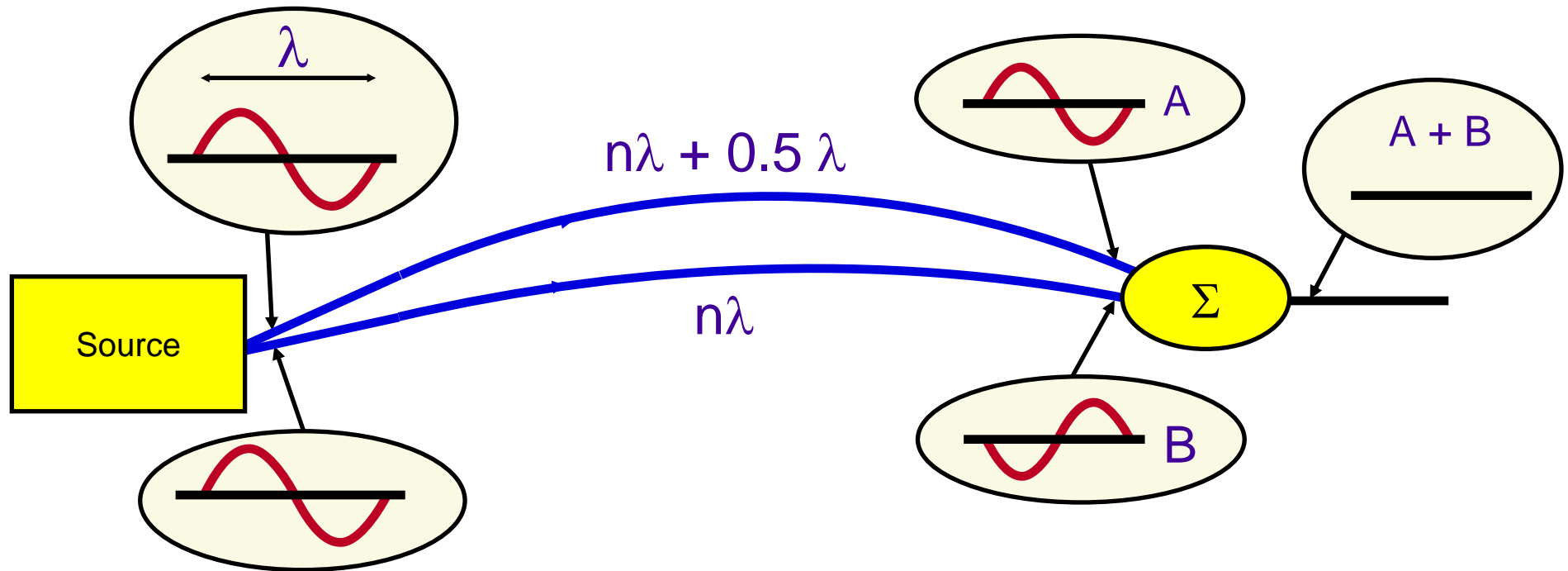
# Constructive Interference



- Travelling on two different paths, both waves recombine (at the summer,  $\Sigma$ )
- Because of the  $\lambda$  path length difference the waves are in-phase
- Complete reinforcement occurs, so-called **constructive interference**



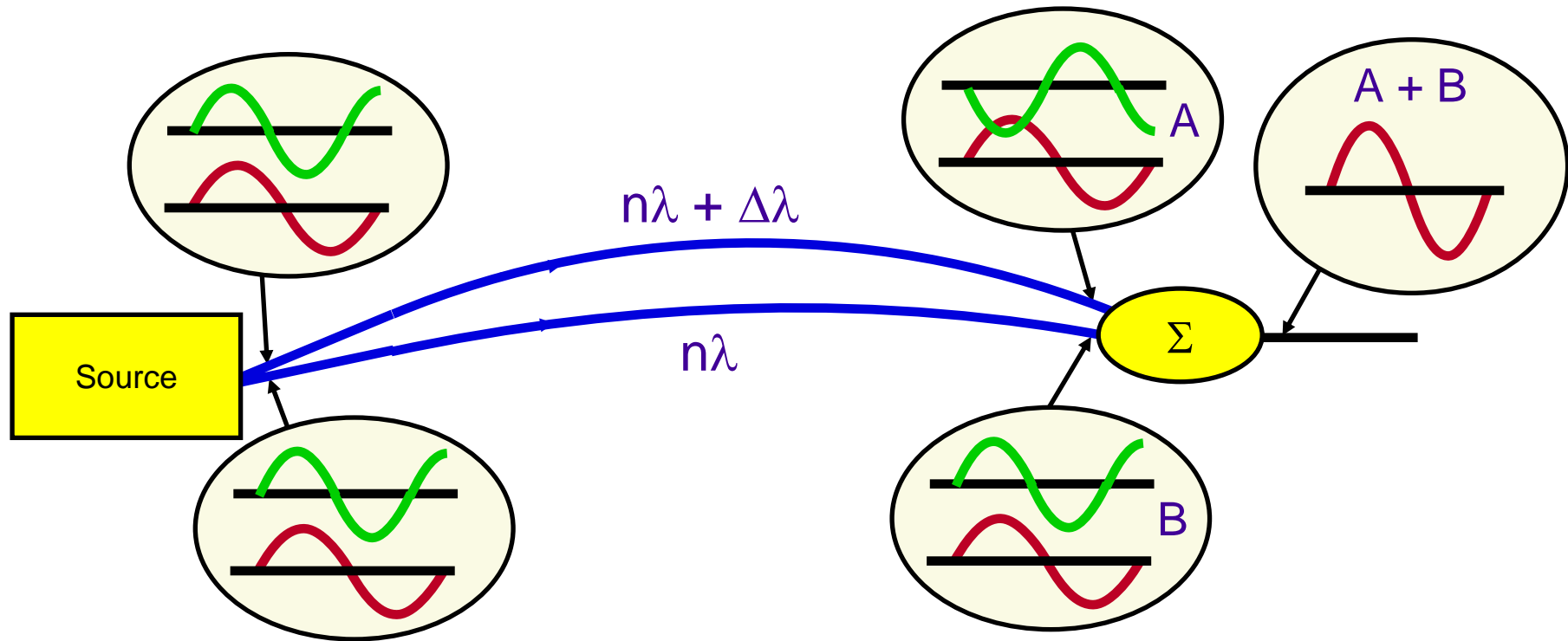
# Destructive Interference



- Travelling on two different paths, both waves recombine (at the summer,  $\Sigma$ )
- Because of the  $0.5\lambda$  path length difference the waves are out of phase
- Complete cancellation occurs, so-called **destructive interference**



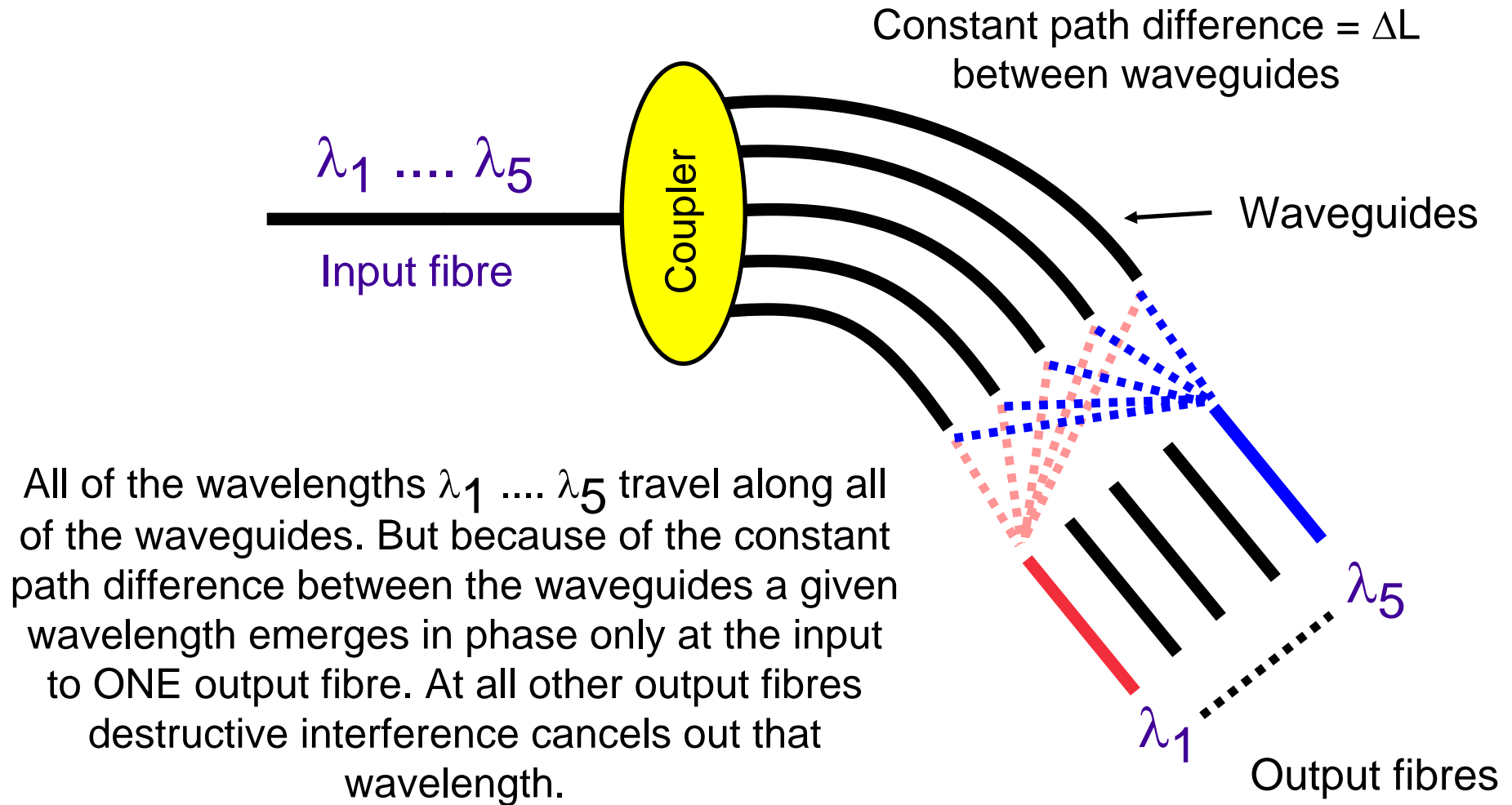
# Using Interference to Select a Wavelength



- Two different wavelengths, both travelling on two different paths
- Because of the path length difference the "Red" wavelength undergoes constructive interference while the "Green" suffers destructive interference
- Only the Red wavelength is selected, Green is rejected

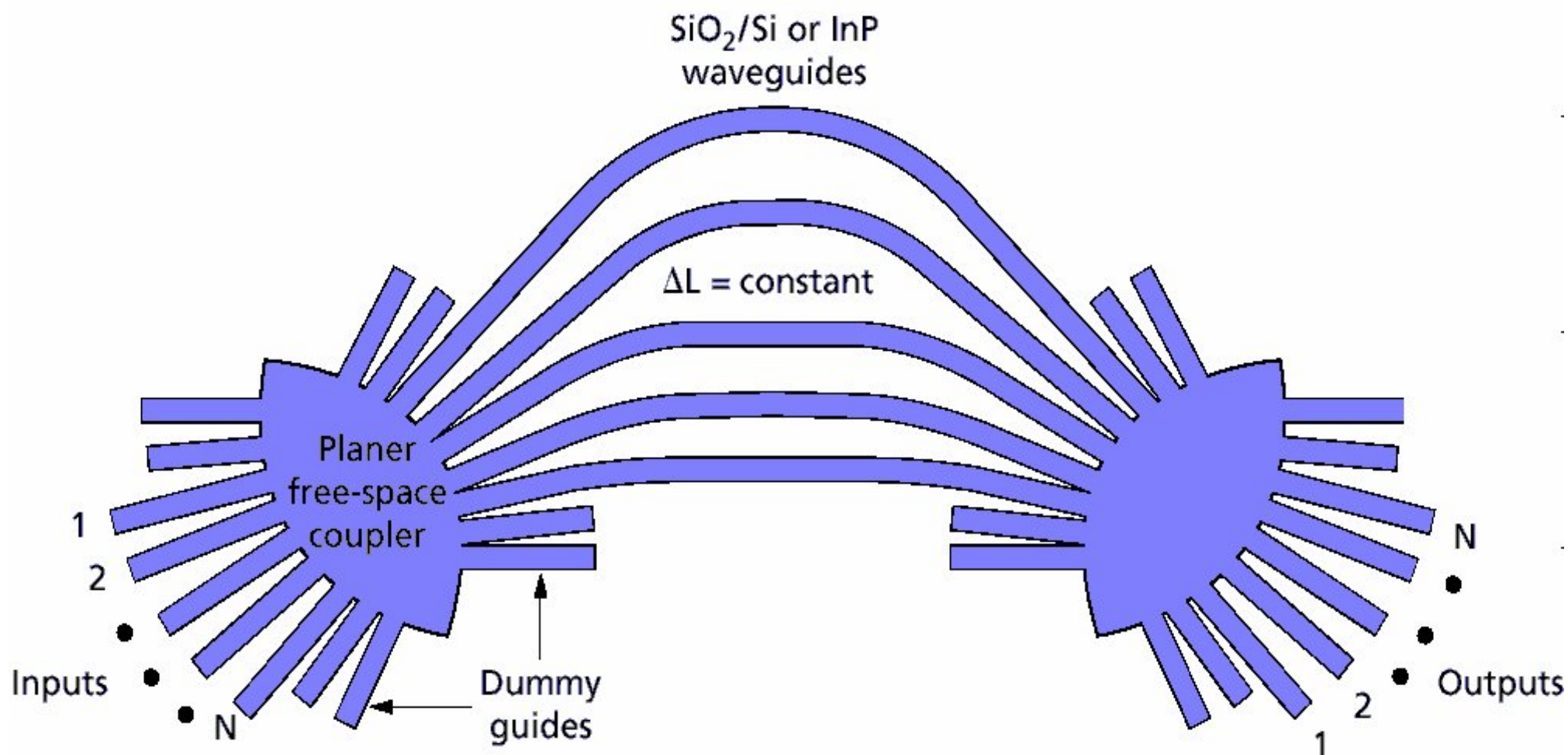


# Array Waveguide Grating Operation: Demultiplexing





# Array Waveguide Grating Mux/Demux



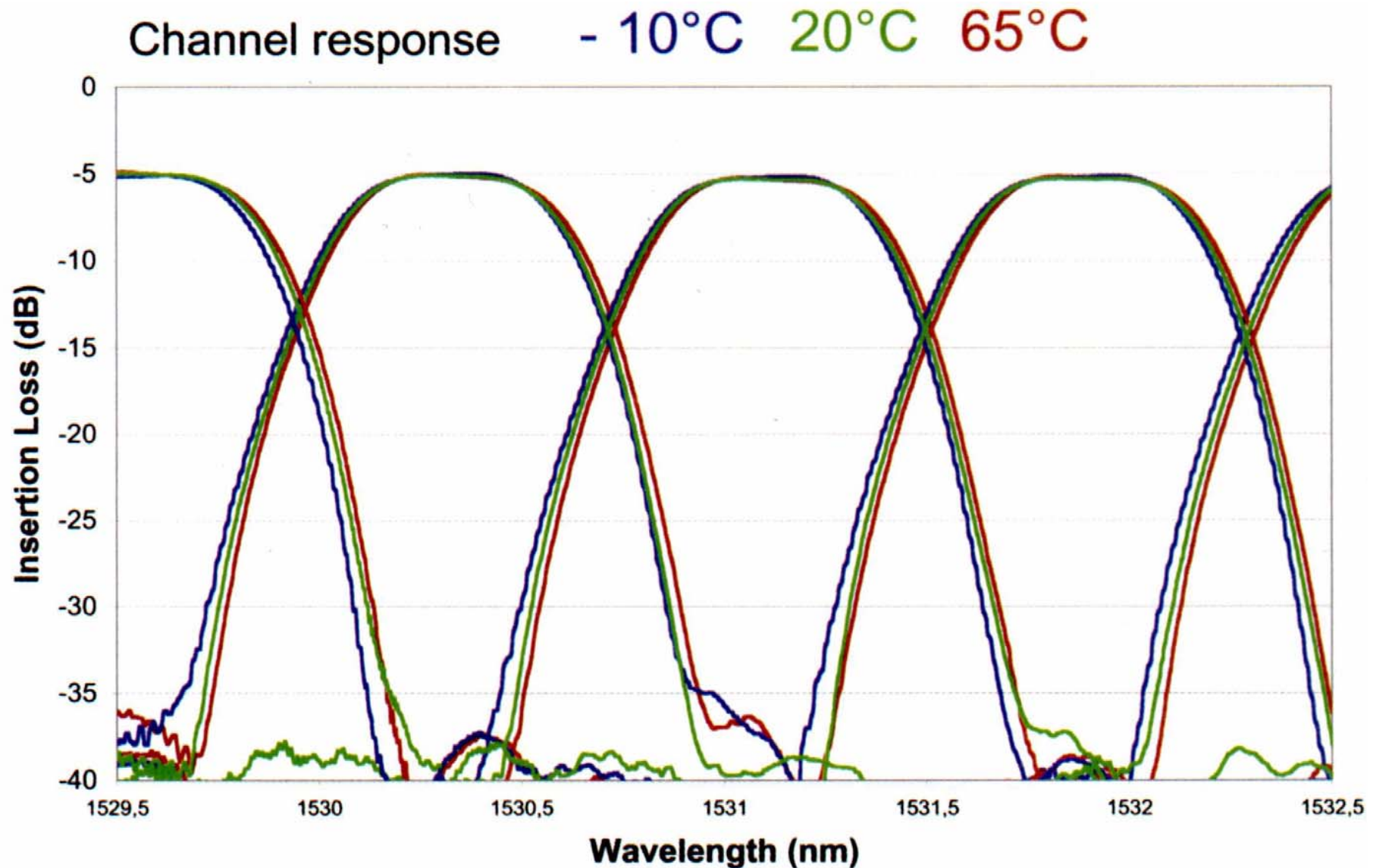


# Array Waveguide Operation

- An Array Waveguide Demux consists of three parts :
  - 1st star coupler,
  - Arrayed waveguide grating with the constant path length difference
  - 2nd star coupler.
- The input light radiates in the 1st star coupler and then propagates through the arrayed waveguides which act as the discrete phase shifter.
- In the 2nd star coupler, light beams converges into various focal positions according to the wavelength.
- Low loss, typically 6 dB



# Typical Demux Response, with Temperature Dependence







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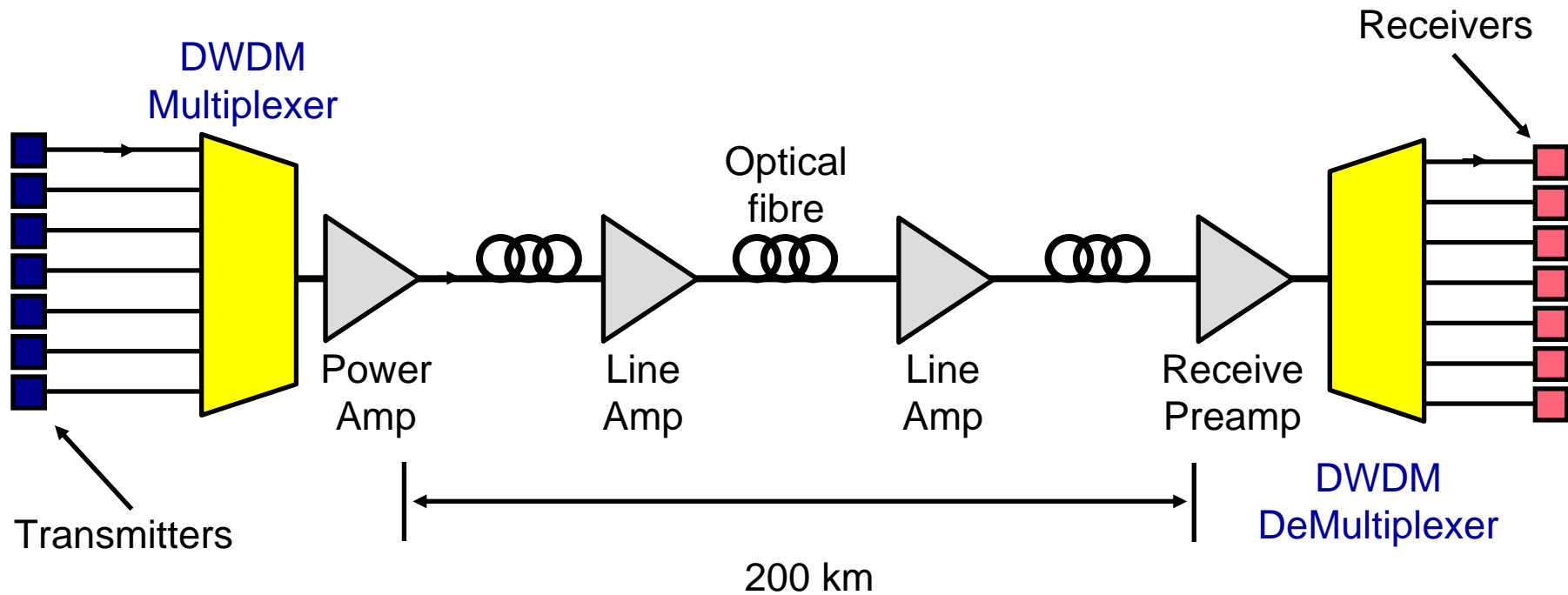
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# DWDM Systems





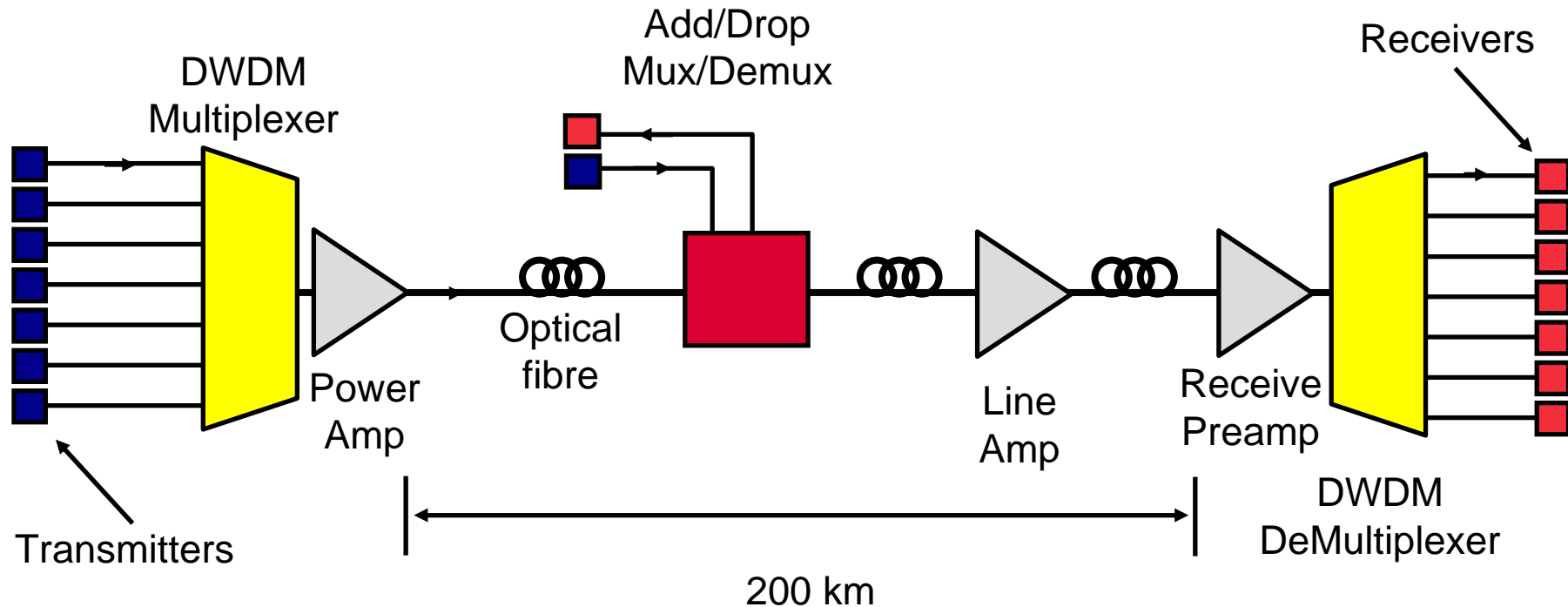
# DWDM System



- Each wavelength behaves as if it has its own "virtual fibre"
- Optical amplifiers needed to overcome losses in mux/demux and long fibre spans



# DWDM System with Add-Drop



- Each wavelength still behaves as if it has its own "virtual fibre"
- Wavelengths can be added and dropped as required at some intermediate location



# Typical DWDM Systems

Manufacturer & System	Number of Channels	Channel Spacing	Channel Speeds	Maximum Bit Rate Tb/s
Nortel OPtera 1600 OLS	160	0.4 nm	2.5 or 10 Gb/s	1.6 Tbs/s
Lucent	40		2.5	
Alcatel				
Marconi PLT40/80/160	40/80/160	0.4, 0.8 nm	2.5 or 10 Gb/s	1.6 Tb/s

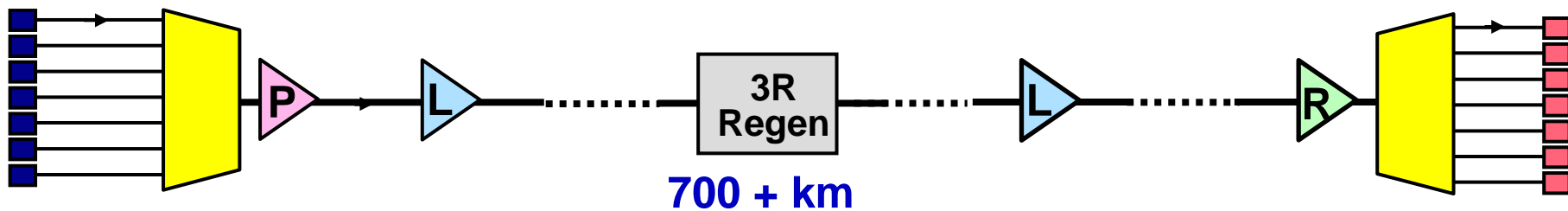
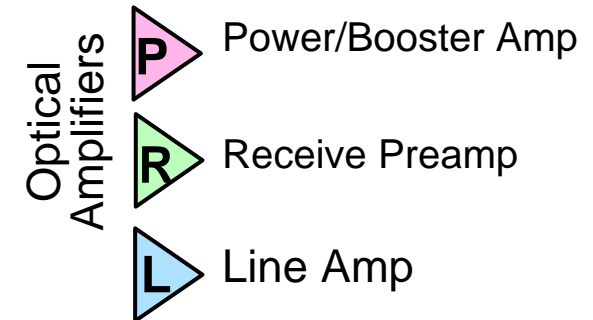
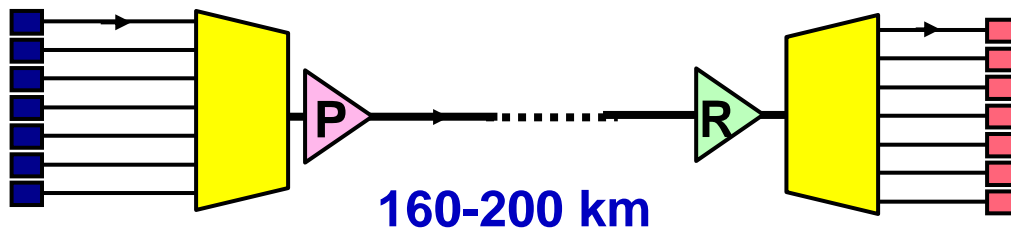


# DWDM Performance as of 2008

- Different systems suit national and metropolitan networks
- Typical high-end systems currently provide:
  - 40/80/160 channels
  - Bit rates to 10 Gb/s with some 40 Gb/s
  - Interfaces for SDH, PDH, ATM etc.
  - Total capacity to 10 Tb/s +
  - C + L and some S band operation
- Systems available from NEC, Lucent, Marconi, Nortel, Alcatel, Siemens etc.



# DWDM System Spans



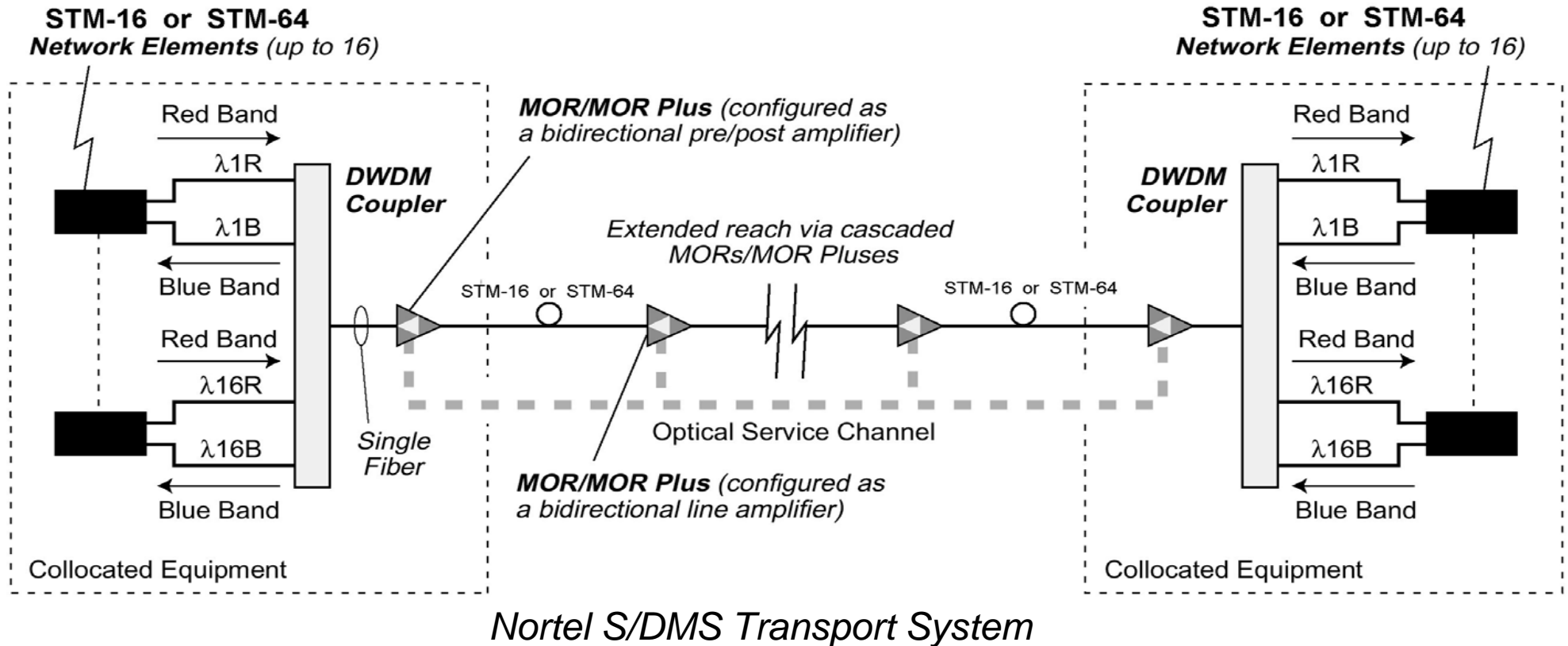


# DWDM Standards

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- G.692 includes a number of DWDM channel plans
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# Nortel DWDM

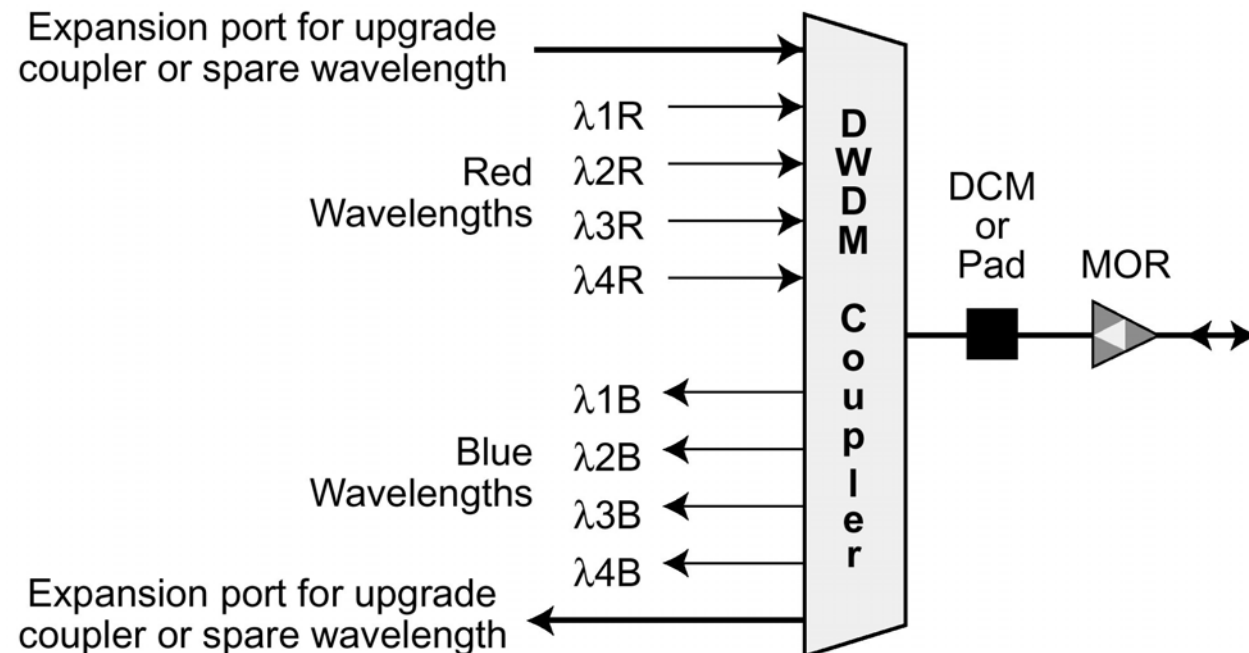


- Aggregate span capacities up to 320 Gbits/sec (160 Gbits/sec per direction) possible
- Red band = 1547.5 to 1561 nm, blue band = 1527.5 to 1542.5 nm



# Nortel DWDM Coupler

- 8 wavelengths used (4 in each direction). 200 GHz frequency spacing
- Incorporates a Dispersion Compensation Module (DCM)
- Expansion ports available to allow denser multiplexing



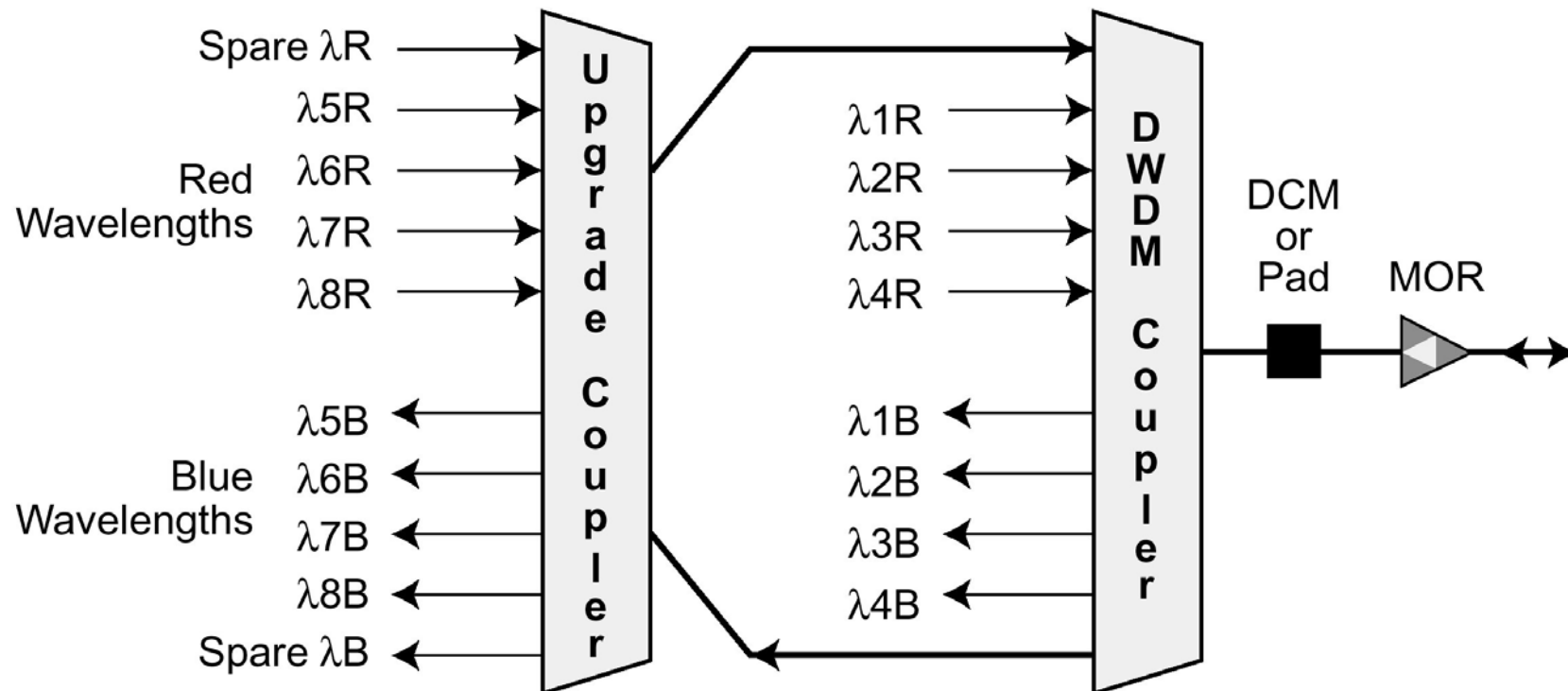
**Red band = 1547.5 to 1561 nm, blue band = 1527.5 to 1542.5 nm**





# Sixteen Channel Multiplexing

- 16 wavelengths used (8 in each direction). Remains 200 GHz frequency spacing
- Further expansion ports available to allow even denser multiplexing

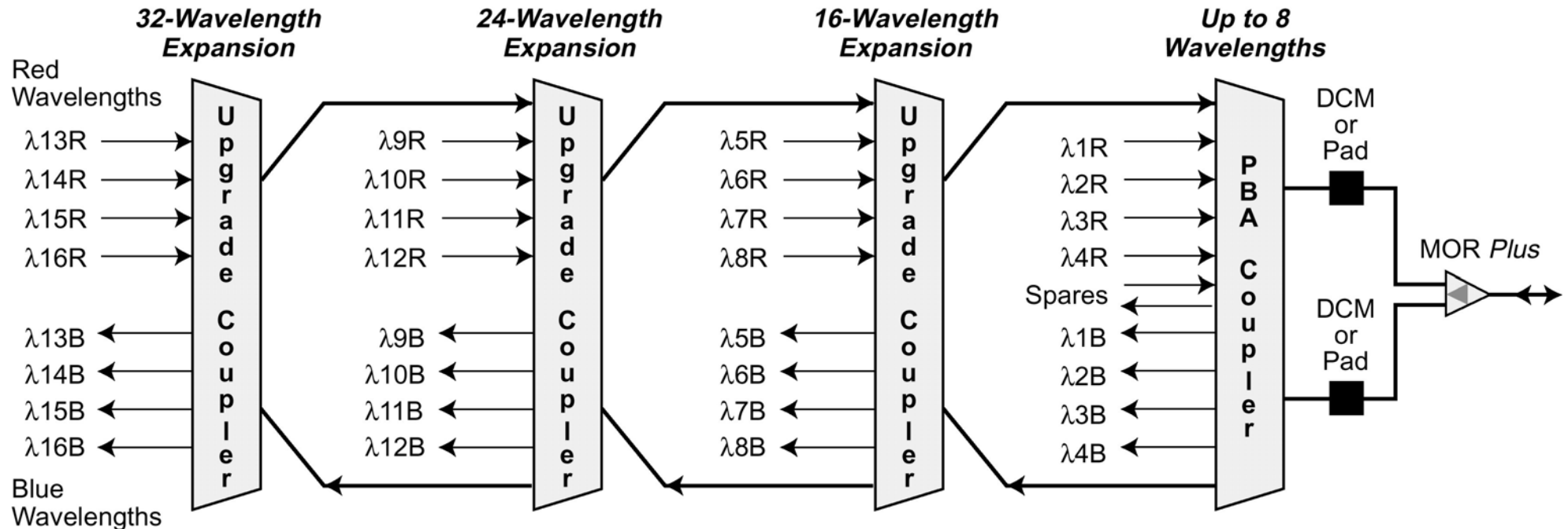


Red band = 1547.5 to 1561 nm, blue band = 1527.5 to 1542.5 nm



# 32 Channel Multiplexing

- 32 wavelengths used (16 in each direction). 100 Ghz ITU frequency spacing
- Per band dispersion compensation



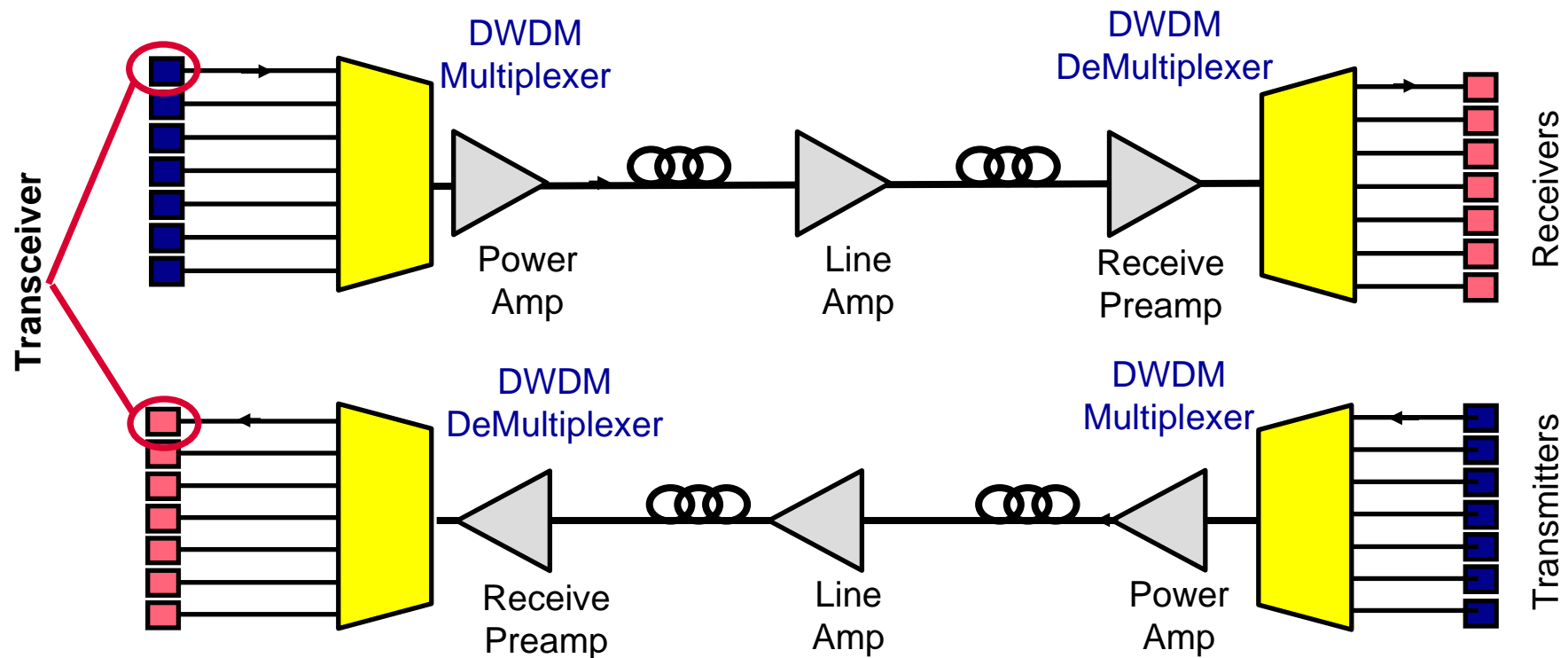
Red band = 1547.5 to 1561 nm, blue band = 1527.5 to 1542.5 nm



# DWDM Transceivers and Transponders



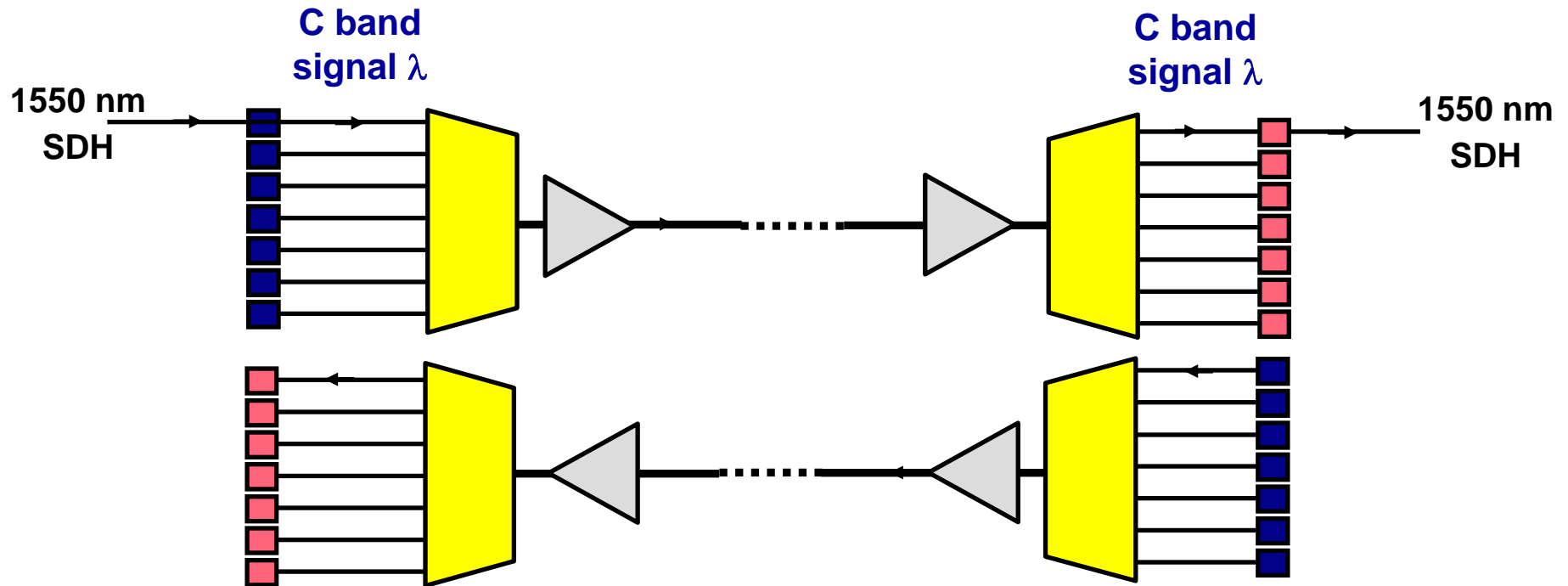
# DWDM Transceivers



- Transmission in both directions needed.
- In practice each end has transmitters and receivers
- Combination of transmitter and receiver for a particular wavelength is a "transceiver"



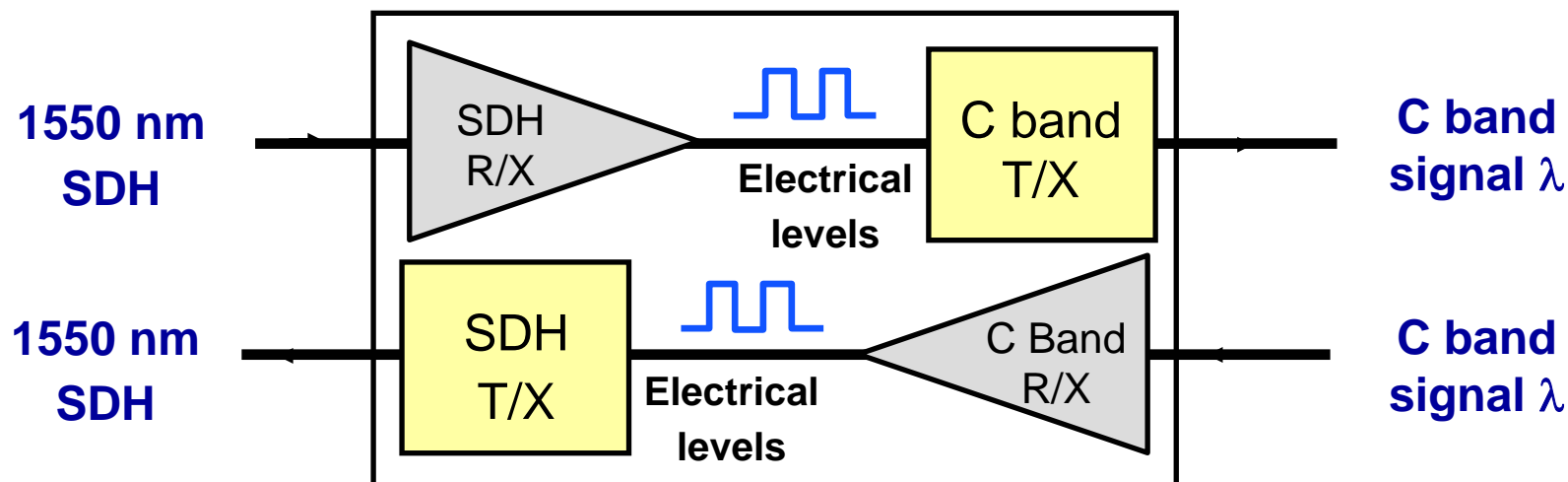
# Transceivers .V. Transponders



- In a "classic" system inputs/outputs to/from transceivers are electrical
- In practice inputs/outputs are SDH, so they are optical, wavelength around 1550 nm
- In effect we need wavelength convertors not transceivers
- Such convertors are called transponders



# DWDM Transponders (I)



- Transponders are frequently formed by two transceivers back-to-back
- So called Optical-Electrical-Optical (OEO) transponders
- Expensive solution at present
- True all-optical transponders without OEO in development



# DWDM Transponders (II)

- Full 3R transponders: (power, shape and time)
  - Regenerate data clock
  - Bit rate specific
  - More sensitive - longer range
- 2R transponders also available: (power, shape)
  - Bit rate flexible
  - Less electronics
  - Less sensitive - shorter range

Input Signal	
Wavelength	1260–1360 nm, 1430–1580 nm
3R transponder bit rate input	STM1 / OC3 STM4 / OC12 STM16 / OC48 Gbit Ethernet
3R transponder input power	G.957 L-4.1 L-4.2 L-16.1 L-16.2
2R transponder min bit rate input	34 Mbit/s
2R transponder max bit rate input	2.5 Gbit/s
2R transponder input power	G.957 S-1.2 S-4.2 S-16.1 S-16.2



**Luminet DWDM  
Transponder**



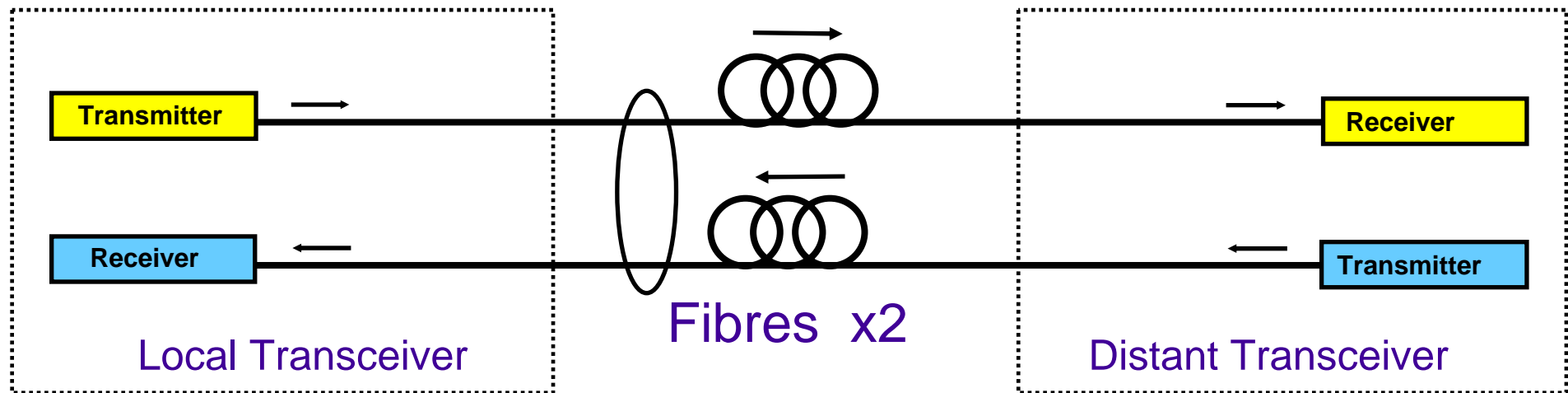
# Bidirectional Transmission using WDM





# Conventional (Simplex) Transmission

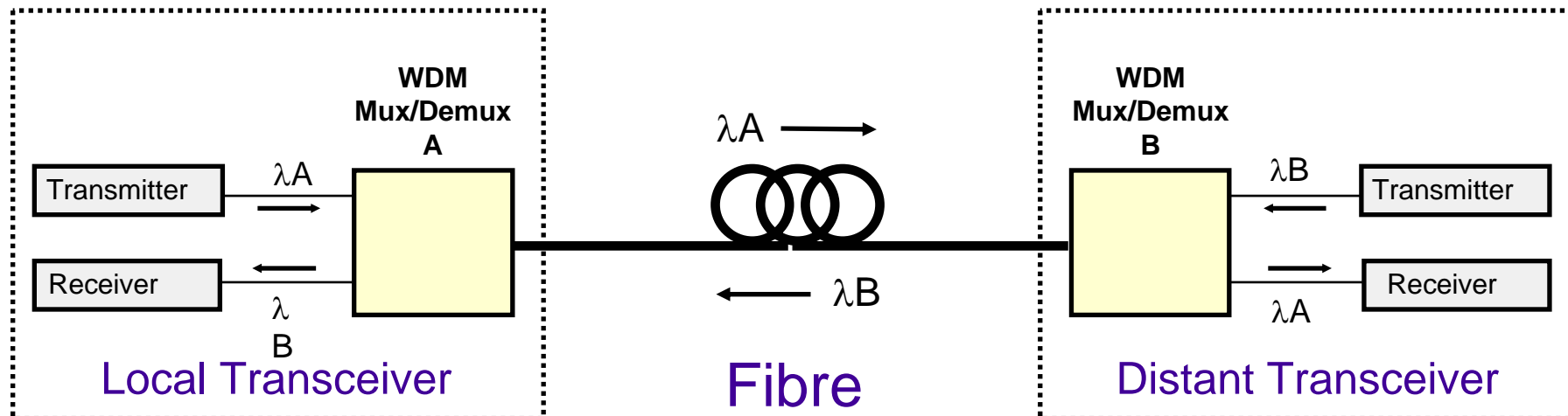
- Most common approach is "one fibre / one direction"
- This is called "simplex" transmission
- Linking two locations will involve two fibres and two transceivers





# Bi-directional using WDM

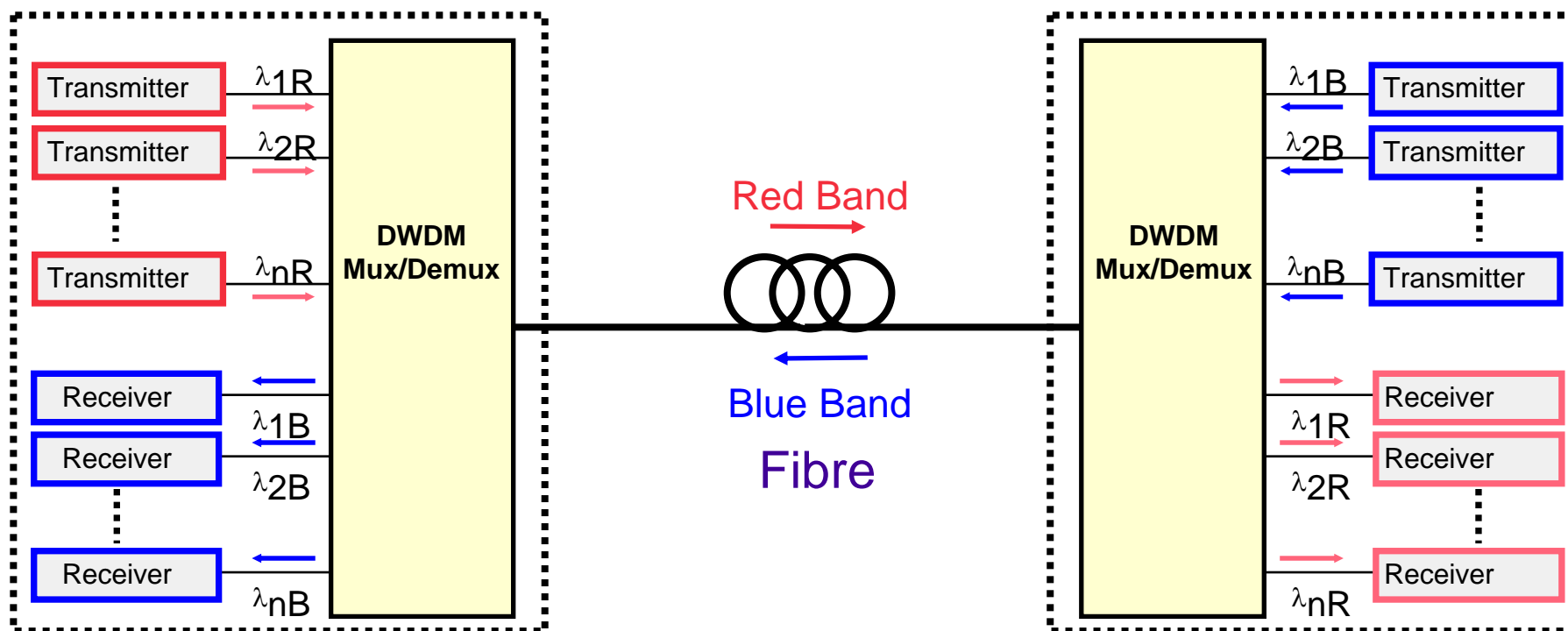
- Significant savings possible with so called bi-directional transmission using WDM
- This is called "full-duplex" transmission
- Individual wavelengths used for each direction
- Linking two locations will involve only one fibre, two WDM mux/demuxs and two transceivers





# Bi-directional DWDM

- Different wavelength bands are used for transmission in each direction
- Typically the bands are called:
  - The "Red Band", upper half of the C-band to 1560 nm
  - The "Blue Band", lower half of the C-band from 1528 nm

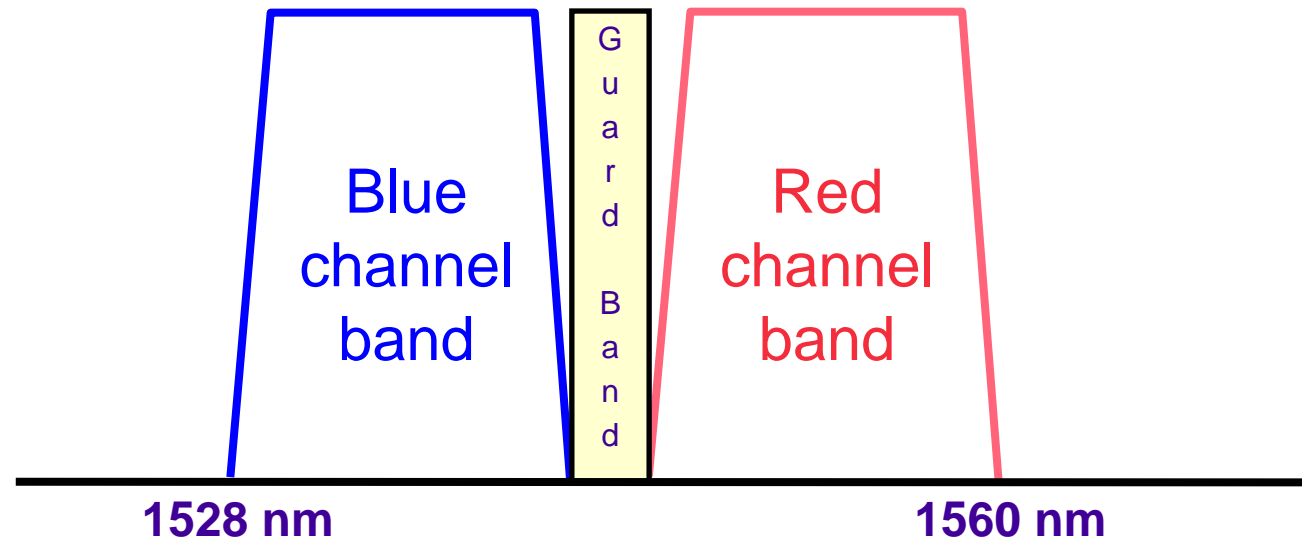




# The need for a Guard Band

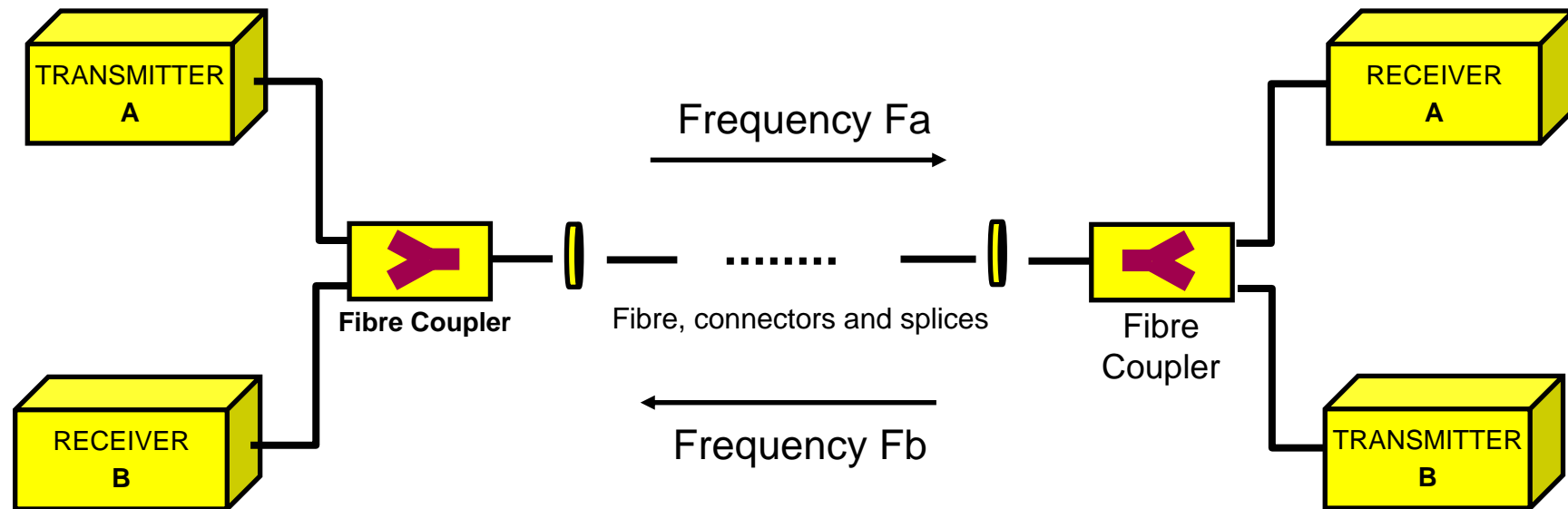
APPLIED OPTOELECTRONICS CENTRE

- To avoid interference red and blue bands must be separated
- This separation is called a "guard band"
- Guard band is typically about 5 nm
- Guard band wastes spectral space, disadvantage of bi-directional DWDM





# Bi-directional Transmission using Frequency Division Multiplexing

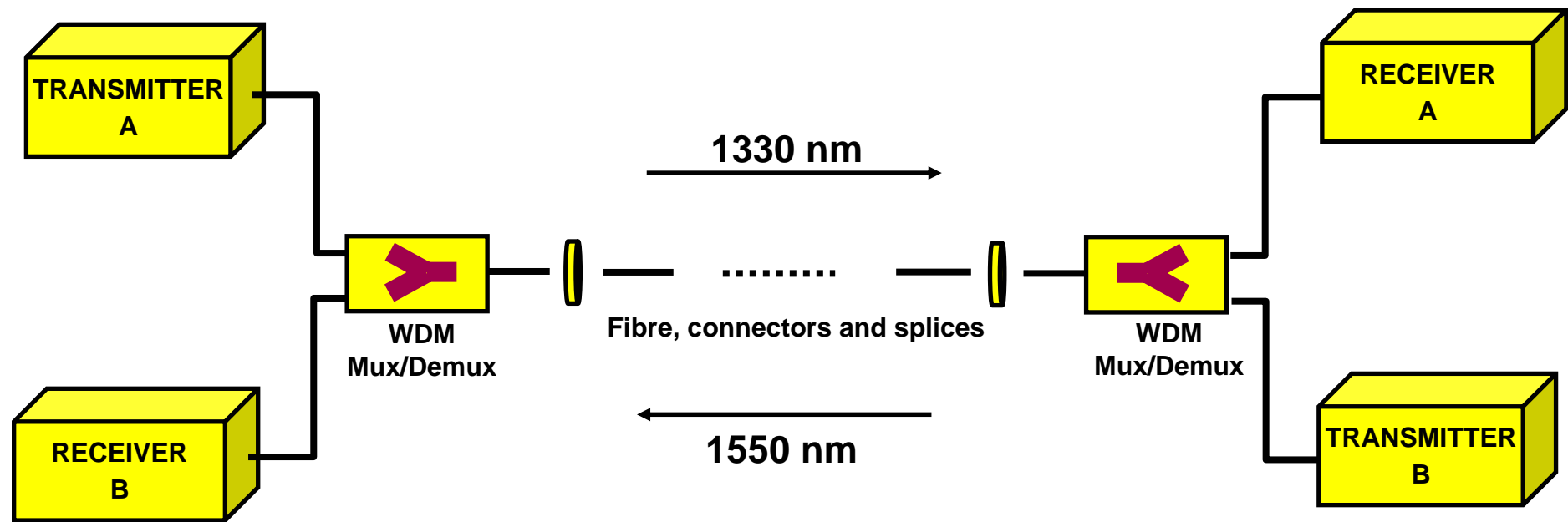


- Transmitter A communicates with Receiver A using a signal on frequency  $F_a$
- Transmitter B communicates with Receiver B using a signal on frequency  $F_b$
- Each receiver ignores signals at other frequencies, so for example Receiver A ignores the signal on frequency  $F_b$



# Bi-directional Transmission using WDM

APPLIED OPTOELECTRONICS CENTRE



- Transmitter A communicates with Receiver A using a signal on 1330 nm
- Transmitter B communicates with Receiver B using a signal on 1550 nm
- WDM Mux/Demux filters out the wanted wavelength so that for example Receiver A only receives a 1330 nm signal



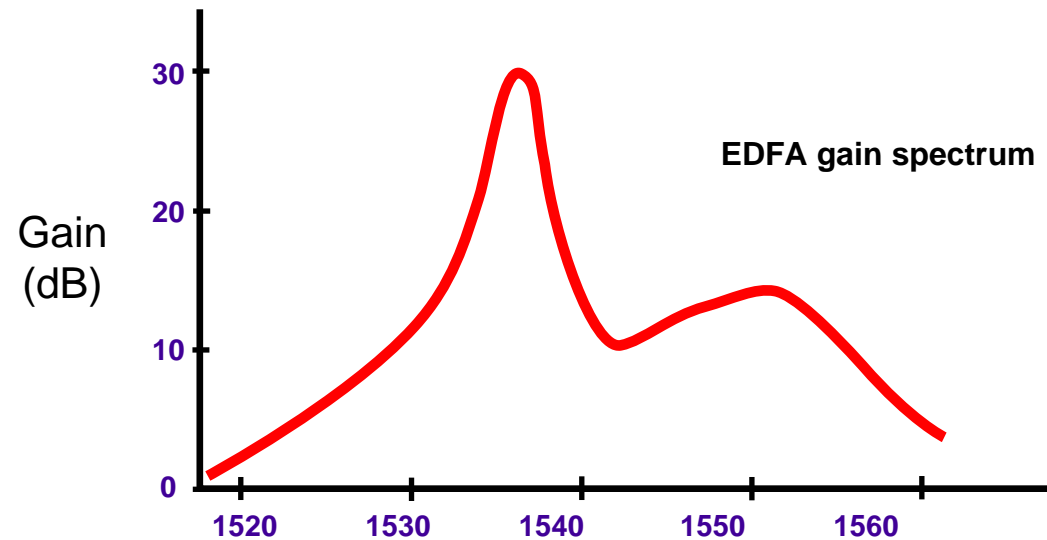
# DWDM Issues

## Spectral Uniformity and Gain Tilt



# DWDM Test: Power Flatness (Gain Tilt)

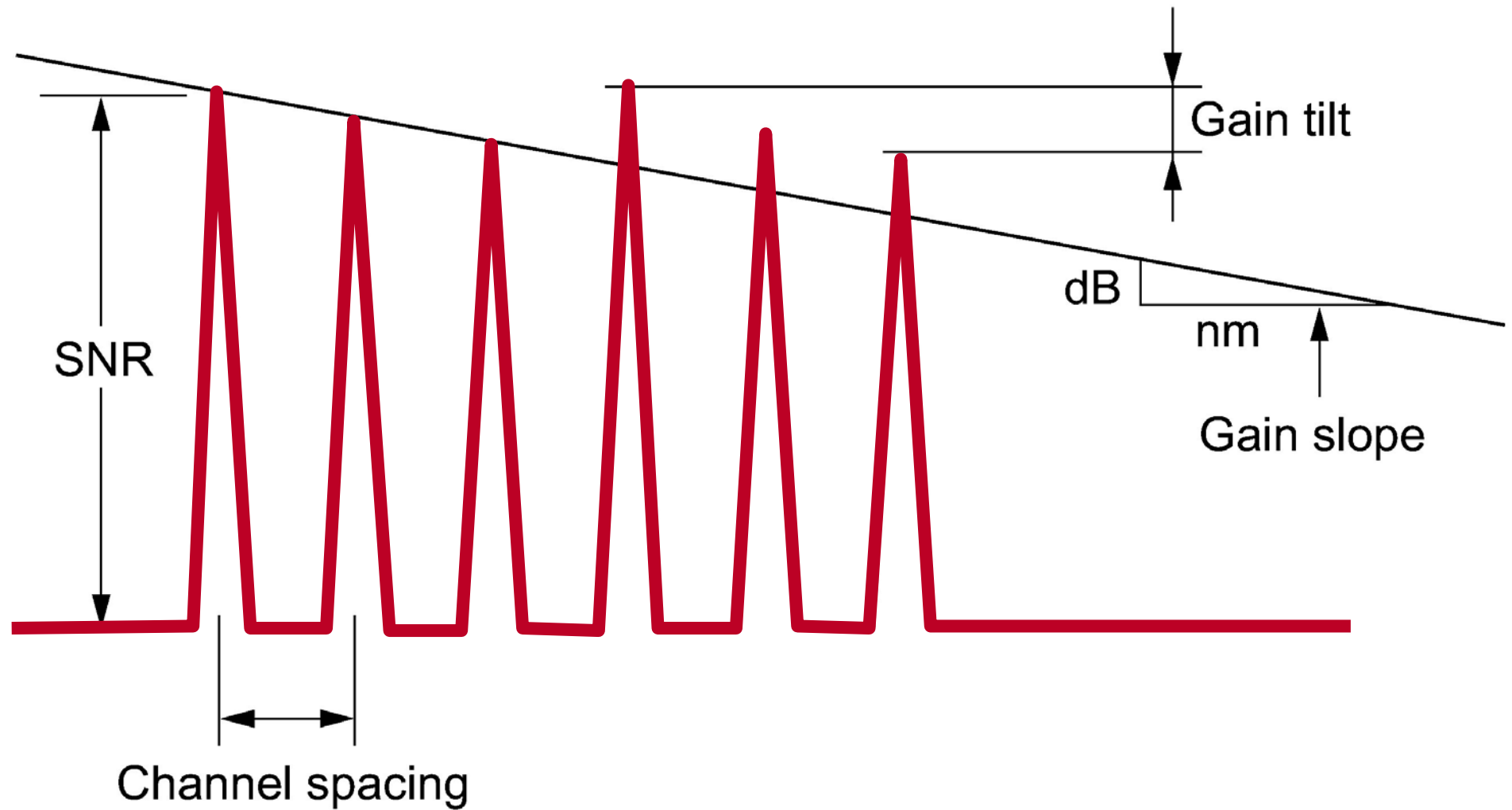
- In an ideal DWDM signal all the channels would have the same power.
- In practice the power varies between channels: so called "gain tilt"
- Sources of gain tilt include:
  - Unequal transmitter output powers
  - Multiplexers
  - Lack of spectral flatness in amplifiers, filters
  - Variations in fibre attenuation







# Gain Tilt and Gain Slope

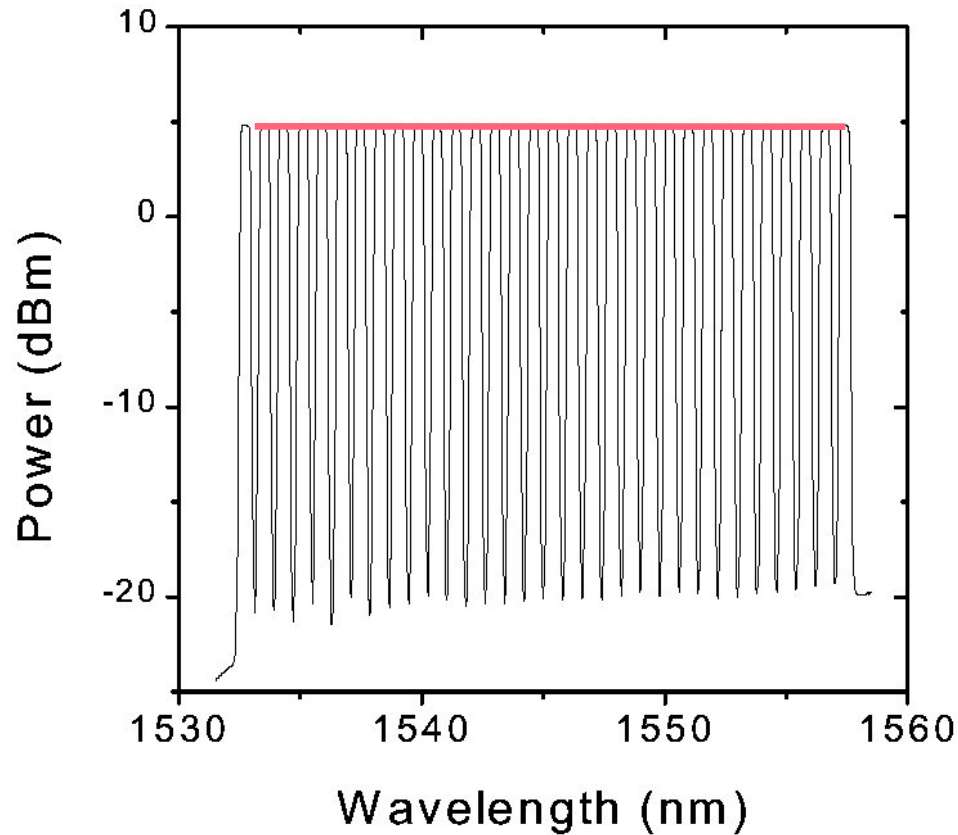




# Gain Tilt Example for a 32 Channel DWDM System

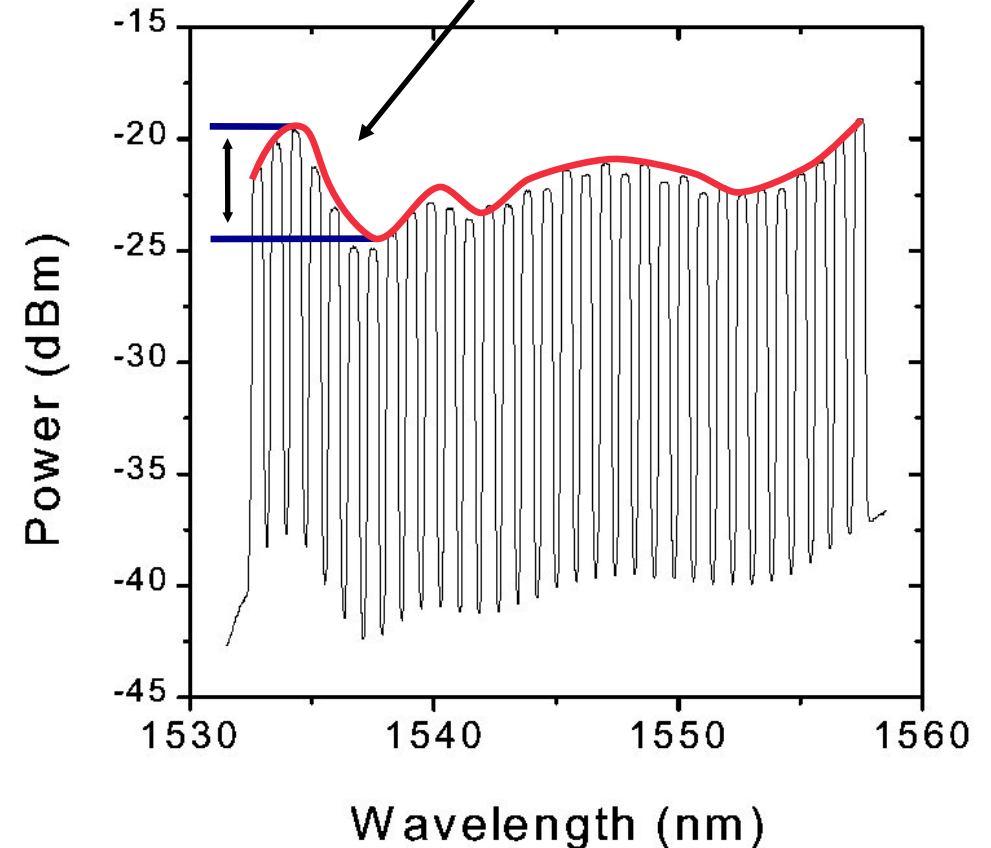
APPLIED OPTOELECTRONICS CENTRE

**Flat: No gain tilt**



**Input spectrum**

**Gain tilt = 5 dB**



**Output spectrum**



# DWDM Issues

## Crosstalk between Channels



# Non-linear Effects and Crosstalk

- With DWDM the aggregate optical power on a single fibre is high because:
  - Simultaneous transmission of multiple optical channels
  - Optical amplification is used
- When the optical power level reaches a point where the fibre is non-linear spurious extra components are generated, causing interference, called "**crosstalk**"
- Common non-linear effects:
  - Four wave mixing (FWM)
  - Stimulated Raman Scattering (SRS)
- Non-linear effects are all dependent on optical power levels, channels spacing etc.



# DWDM Problems

- With DWDM the aggregate optical power on a single fibre is high
- With the use of amplifiers the optical power level can rise to point where non-linear effects occur:
  - Four wave mixing (FWM): spurious components are created interfering with wanted signals
  - Stimulated Raman Scattering (SRS)
- Non-linear effects are dependent on optical power levels, channels spacing etc:

<b>FWM</b>	↑	<b>Channel Spacing</b>	↓
<b>FWM</b>	↑	<b>Dispersion</b>	↓
<b>FWM</b>	↑	<b>Optical Power</b>	↑

<b>SRS</b>	↑	<b>Channel Spacing</b>	↑
<b>SRS</b>	↑	<b>Distance</b>	↓
<b>SRS</b>	↑	<b>Optical Power</b>	↑

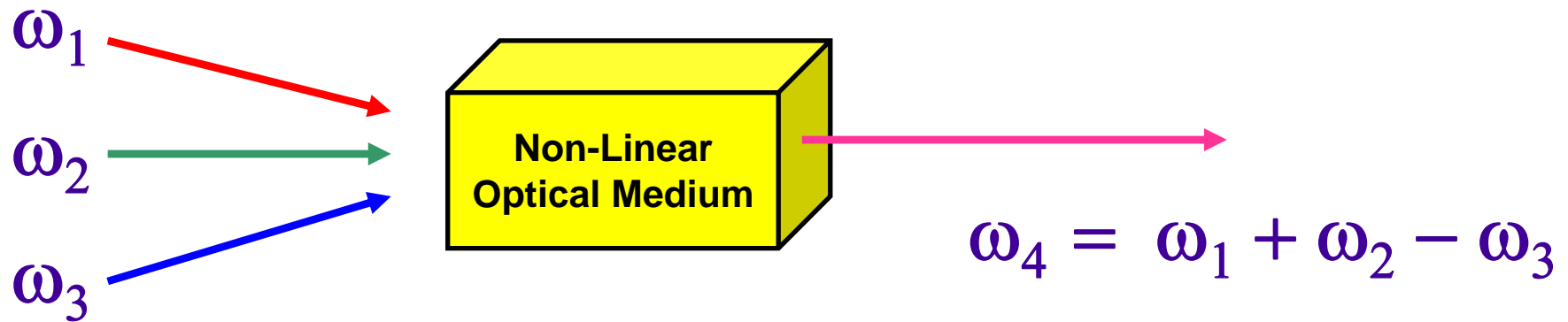


# Four Wave Mixing (FWM)



# Four Wave Mixing

- Four wave mixing (FWM) is one of the most troubling issues
- Three signals combine to form a *fourth* spurious or mixing component, hence the name *four* wave mixing, shown below in terms of frequency  $\omega$ :



- Spurious components cause two problems:
  - Interference between wanted signals
  - Power is lost from wanted signals into unwanted spurious signals
- The total number of mixing components increases dramatically with the number of channels



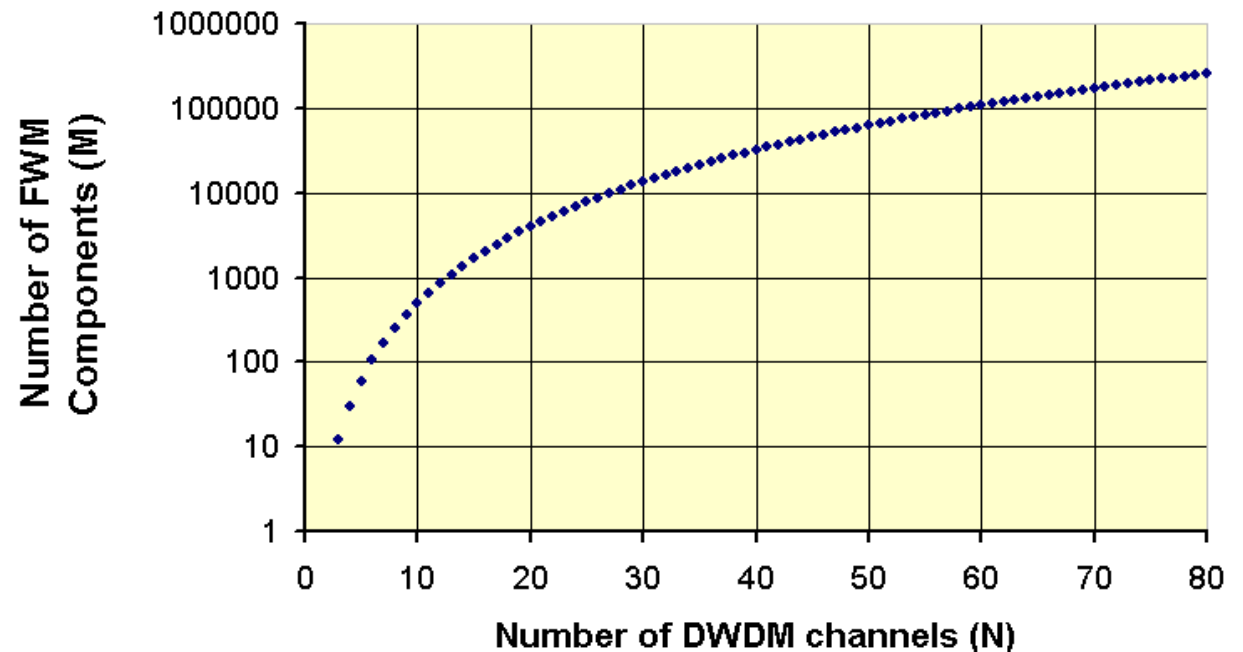
# FWM: How many Spurious Components?

- The total number of mixing components, M is calculated from the formula:

$$M = \frac{1}{2} (N^3 - N)$$

N is the number of DWDM channels

FWM Components and Channel Count

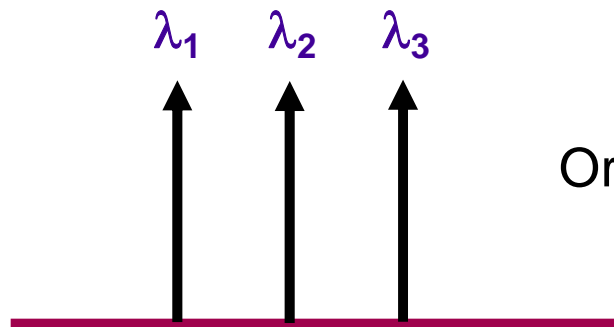


- Thus three channels creates 12 additional signals and so on.
- As N increases, M increases rapidly.....





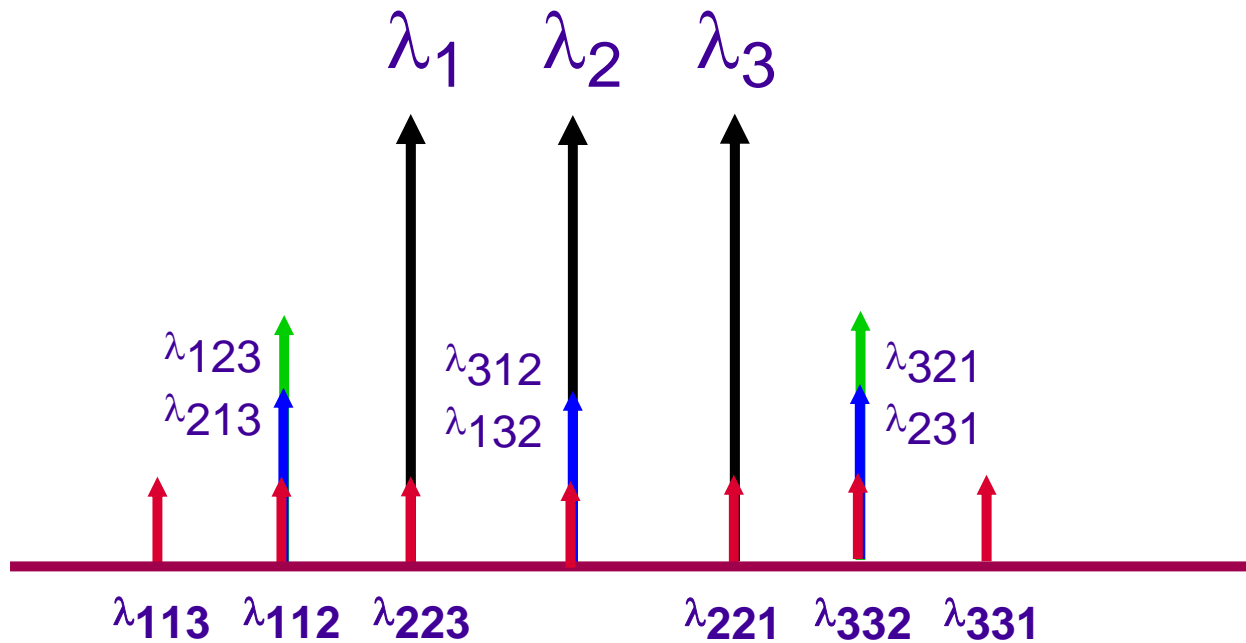
# FWM Components as Wavelengths



Original DWDM channels,  
evenly spaced

Original plus FWM  
components

Because of even  
spacing some FWM  
components overlap  
DWDM channels





# Four Wave Mixing example with 3 equally spaced channels

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3 ITU channels 0.8 nm spacing

Channel	nm
$\lambda_1$	1542.14
$\lambda_2$	1542.94
$\lambda_3$	1543.74

Equal spacing

- For the three channels  $\lambda_1$ ,  $\lambda_2$  and  $\lambda_3$  calculate all the possible combinations produced by adding two channel  $\lambda$ 's together and subtracting one channel  $\lambda$ .
- For example  $\lambda_1 + \lambda_2 - \lambda_3$  is written as  $\lambda_{123}$  and is calculated as  $1542.14 + 1542.94 - 1543.74 = 1541.34$  nm
- Note the interference to wanted channels caused by the FWM components  $\lambda_{312}$ ,  $\lambda_{132}$ ,  $\lambda_{221}$  and  $\lambda_{223}$

FWM mixing components

Channel	nm
$\lambda_{123}$	1541.34
$\lambda_{213}$	1541.34
$\lambda_{321}$	1544.54
$\lambda_{231}$	1544.54
$\lambda_{312}$	1542.94
$\lambda_{132}$	1542.94
$\lambda_{112}$	1541.34
$\lambda_{113}$	1540.54
$\lambda_{221}$	1543.74
$\lambda_{223}$	1542.14
$\lambda_{331}$	1545.34
$\lambda_{332}$	1544.54



# Reducing Four Wave Mixing

- Reducing FWM can be achieved by:
  - Increasing channel spacing (not really an option because of limited spectrum)
  - Employing uneven channel spacing
  - Reducing aggregate power
  - Reducing effective aggregate power within the fibre
- Another more difficult approach is to use fibre with non-zero dispersion:
  - FWM is most efficient at the zero-dispersion wavelength
  - Problem is that the "cure" is in direct conflict with need minimise dispersion to maintain bandwidth
- To be successful the approach used must reduce unwanted component levels to at least 30 dB below a wanted channel.



# Four Wave Mixing example with 3 unequally spaced channels

## 3 DWDM channels

Channel	nm
$\lambda_1$	1542.14
$\lambda_2$	1542.94
$\lambda_3$	1543.84

←  
←  
← unequal spacing

- As before for the three channels  $\lambda_1$ ,  $\lambda_2$  and  $\lambda_3$  calculate all the possible combinations produced by adding two channel  $\lambda$ 's together and subtracting one channel  $\lambda$ .
- **Note that because of the unequal spacing there is now no interference to wanted channels caused by the generated FWM components**

## FWM mixing components

Channel	nm
$\lambda_{123}$	1541.24
$\lambda_{213}$	1541.24
$\lambda_{321}$	1544.64
$\lambda_{231}$	1544.64
$\lambda_{312}$	1543.04
$\lambda_{132}$	1543.04
$\lambda_{112}$	1541.34
$\lambda_{113}$	1540.44
$\lambda_{221}$	1543.74
$\lambda_{223}$	1542.04
$\lambda_{331}$	1545.54
$\lambda_{332}$	1544.74



# Sample FWM problem with 3 DWDM channels

## Problem:

- For the three channels  $\lambda_1$ ,  $\lambda_2$  and  $\lambda_3$  shown calculate all the possible FWM component wavelengths.
- Determine if interference to wanted channels is taking place.
- If interference is taking place show that the use of unequal channel spacing will reduce interference to wanted DWDM channels.

**3 channels 1.6 nm spacing**

Channel	nm
$\lambda_1$	1530.00
$\lambda_2$	1531.60
$\lambda_3$	1533.20



# Solution to FWM problem

## 3 channels 1.6 nm equal spacing

Channel	nm
$\lambda_1$	1530.00
$\lambda_2$	1531.60
$\lambda_3$	1533.20

## FWM mixing components

Channel	nm
$\lambda_{123}$	1528.40
$\lambda_{213}$	1528.40
$\lambda_{321}$	1534.80
$\lambda_{231}$	1534.80
$\lambda_{312}$	1531.60
$\lambda_{132}$	1531.60
$\lambda_{112}$	1528.40
$\lambda_{113}$	1526.80
$\lambda_{221}$	1533.20
$\lambda_{223}$	1530.00
$\lambda_{331}$	1536.40
$\lambda_{332}$	1534.80

## 3 channels unequal spacing

Channel	nm
$\lambda_1$	1530.00
$\lambda_2$	1531.60
$\lambda_3$	1533.40

## FWM mixing components

Channel	nm
$\lambda_{123}$	1528.20
$\lambda_{213}$	1528.20
$\lambda_{321}$	1535.00
$\lambda_{231}$	1535.00
$\lambda_{312}$	1531.80
$\lambda_{132}$	1531.80
$\lambda_{112}$	1528.40
$\lambda_{113}$	1526.60
$\lambda_{221}$	1533.20
$\lambda_{223}$	1529.80
$\lambda_{331}$	1536.80
$\lambda_{332}$	1535.20



# Reducing FWM using NZ-DSF

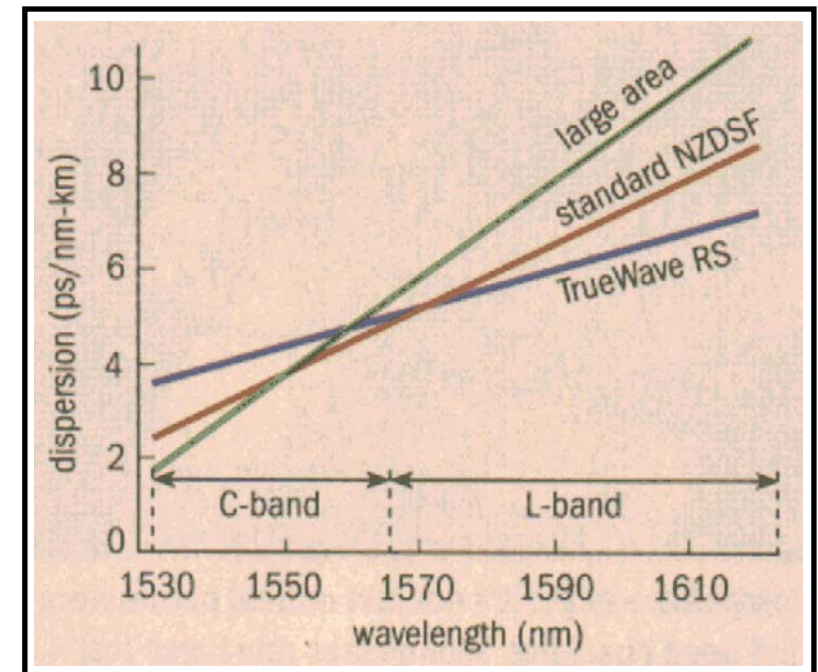
- Traditional non-multiplexed systems have used dispersion shifted fibre at 1550 to reduce chromatic dispersion
- Unfortunately operating at the dispersion minimum increases the level of FWM
- Conventional fibre (dispersion minimum at 1330 nm) suffers less from FWM but chromatic dispersion rises
- Solution is to use "Non-Zero Dispersion Shifted Fibre" (NZ DSF), a compromise between DSF and conventional fibre (NDSF, Non-DSF)
- ITU-T standard is G.655 for non-zero dispersion shifted singlemode fibres



# Lucent TrueWave NZDSF

- Provides small amount of dispersion over EDFA band
- Non-Zero dispersion band is 1530-1565 (ITU C-Band)
- Minimum dispersion is 1.3 ps/nm-km, maximum is 5.8 ps/nm-km
- Very low OH attenuation at 1383 nm ( $< 1\text{dB/km}$ )

## Dispersion Characteristics

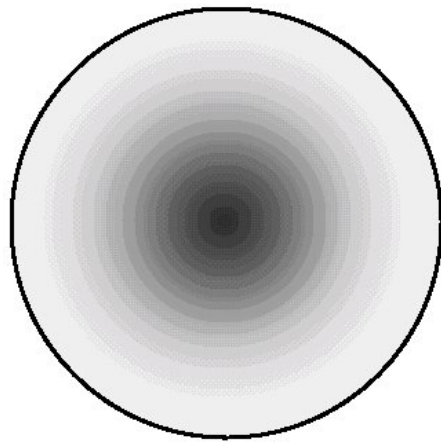




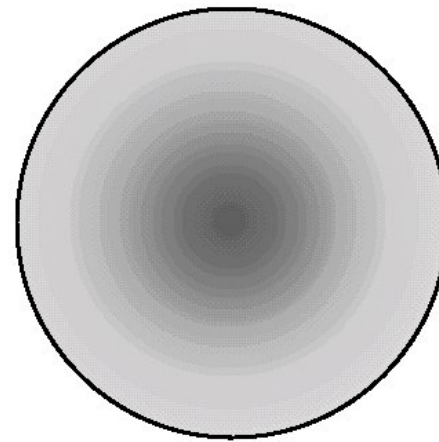


# Reducing FWM using a Large Effective Area Fibre NZ-DSF

- One way to improve on NZ-DSF is to increase the effective area of the fibre
- In a singlemode fibre the optical power density peaks at the centre of the fibre core
- FWM and other effect most likely to take place at locations of high power density
- Large effective Area Fibres spread the power density more evenly across the fibre core
- Result is a reduction in peak power and thus FWM



Traditional NZ-DSF



LEAF<sup>TM</sup> Fiber



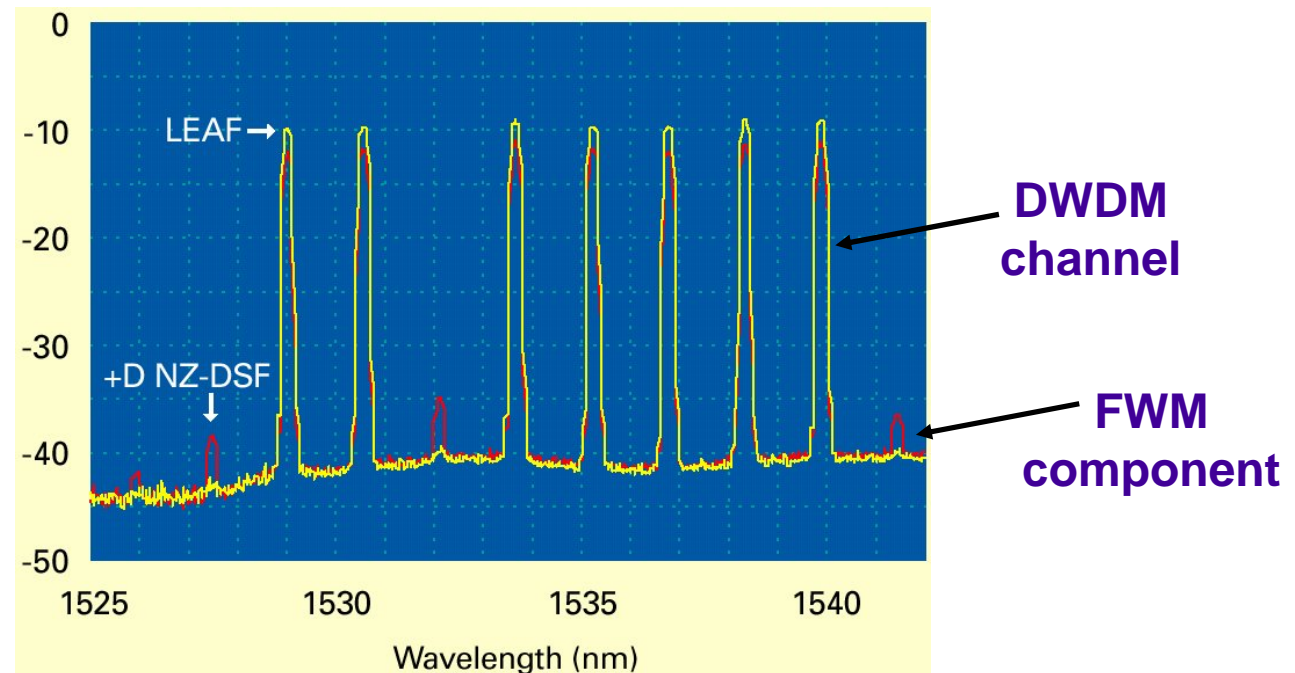
# Corning LEAF

- Corning LEAF has an effective area 32% larger than conventional NZ-DSF
- Claimed result is lower FWM
- Impact on system design is that it allows higher fibre input powers so span increases

## Section of DWDM spectrum

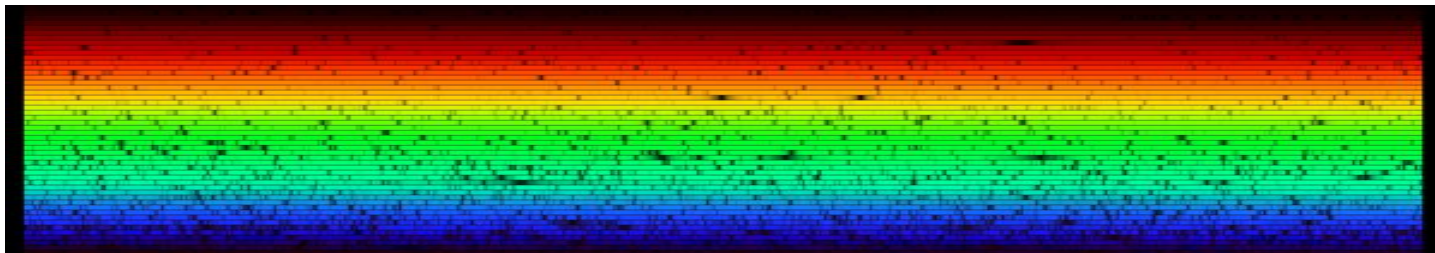
NZ-DSF shows  
higher FWM  
components

LEAF has lower  
FWM and higher per  
channel power





# Wavelength Selection



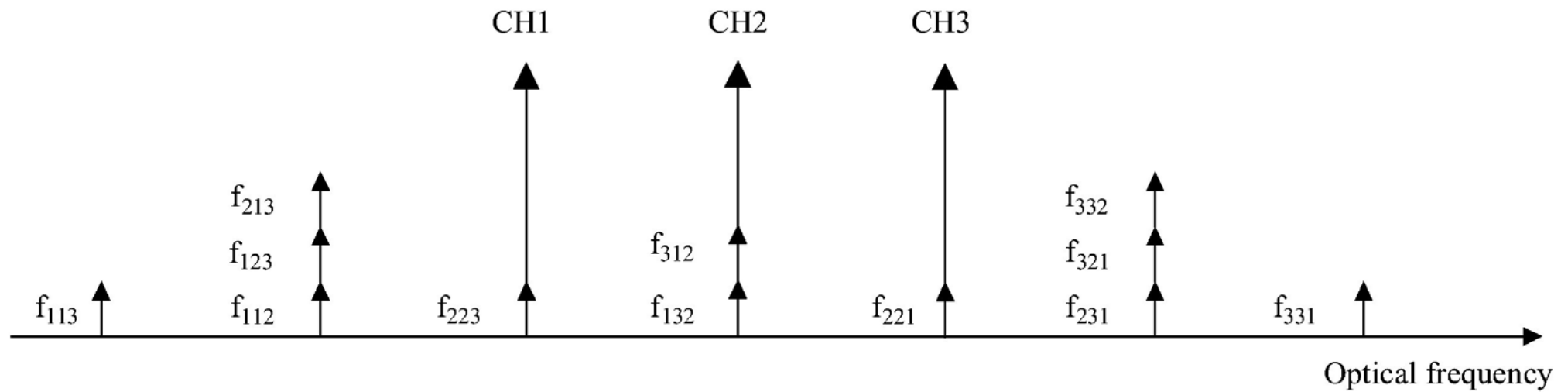


# ITU Channel Allocation Methodology (I)

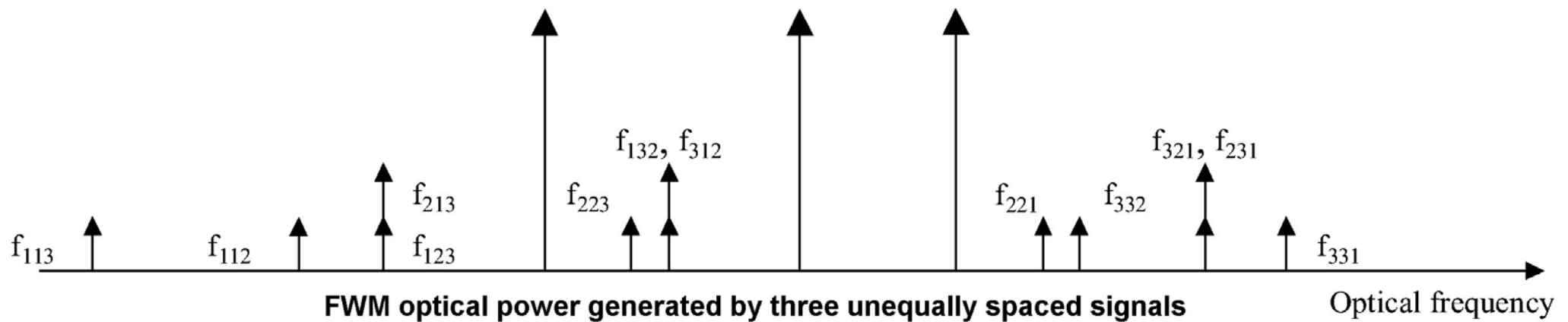
- Conventional DSF (G.653) is most affected by FWM
- Using equal channel spacing aggravates the problem
- ITU-T G.692 suggests a methodology for choosing unequal channel spacings for G.653 fibre
- ITU suggest the use equal spacing for G.652 and G.655 fibre, but according to a given channel plan
- Note that the ITU standards look at DWDM in frequency not wavelength



# ITU Channel Allocation Methodology (II)



**FWM optical power generated by three equally spaced signals**



**FWM optical power generated by three unequally spaced signals**



# ITU Channel Allocation Methodology (III)

- Basic rule is that each frequency (wavelength) is chosen so that no new powers generated by FWM fall on any channel
- Thus channel spacing of any two channels must be different from any other pair
- Complex arrangement based on the concept of a frequency slot " $f_s$ "
- $f_s$  is the minimum acceptable distance between an FWM component and a DWDM channel
- As  $f_s$  gets smaller error rate degrades
- For 10 Gbits/s the " $f_s$ " is 20 GHz.



# Wavelength Introduction Methodologies

- Because of non-linearity problems wavelength selection and introduction is complex
- NOT just a matter of picking the first 8 or 16 wavelengths!
- Order of introduction of new wavelengths is fixed as the system is upgraded
- Table shows order of introduction for Nortel S/DMS system

Order of Introduction	Wavelength Pair
1	1535.04 nm and 1557.36 nm
2	1530.33 nm and 1552.52 nm
3	1528.77 nm and 1550.92 nm
4	1533.47 nm and 1555.75 nm
5	1539.77 nm and 1547.72 nm
6	1538.19 nm and 1558.98 nm
7	1536.61 nm and 1549.32 nm
8	1531.90 nm and 1554.13 nm
9	1529.55 nm and 1551.72 nm
10	1534.25 nm and 1556.55 nm
11	1531.12 nm and 1548.51 nm
12	1532.68 nm and 1550.12 nm
13	1535.82 nm and 1553.33 nm
14	1537.40 nm and 1554.94 nm
15	1538.98 nm and 1558.17 nm
16	1540.56 nm and 1559.79 nm



# High Density DWDM





# Exploiting the Full Capacity of Optical Fibre

## Recent DWDM capacity records

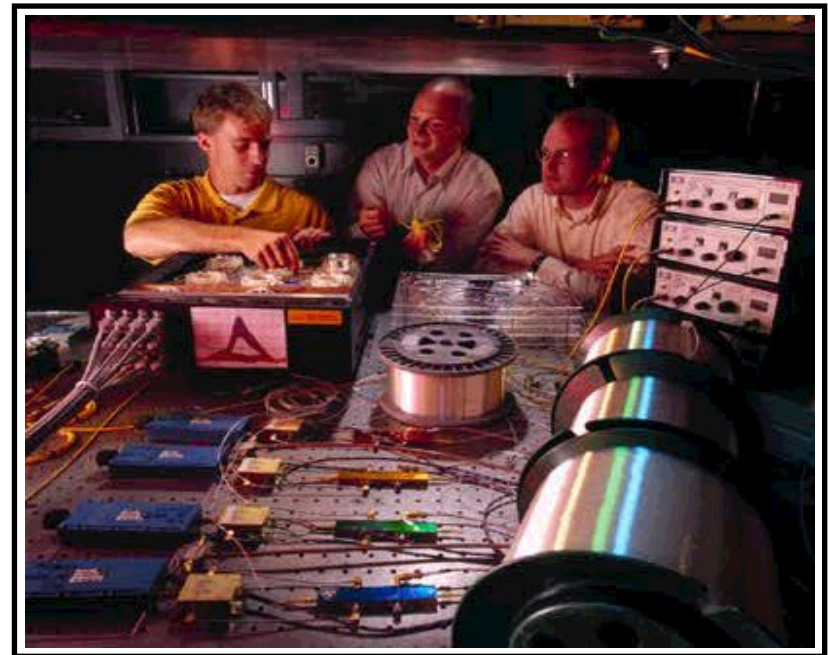
Date	Manufacture	Channel Count	Total Capacity
April 2000	Lucent	82	3.28 Terabits/sec
September 2000	Alcatel	128	5.12 Terabits/sec
October 2000	NEC	160	6.4 Terabits/sec
October 2000	Siemens	176	7.04 Terabits/sec
March 2001	Alcatel	256	10.2 Terabits/sec
March 2001	NEC	273	10.9 Terabits/sec

**Note: Single fibre capacity is  $1000 \times 40 \text{ Gbits/s} = 40 \text{ Tbits/s}$  per fibre**



# Ultra-High Density DWDM

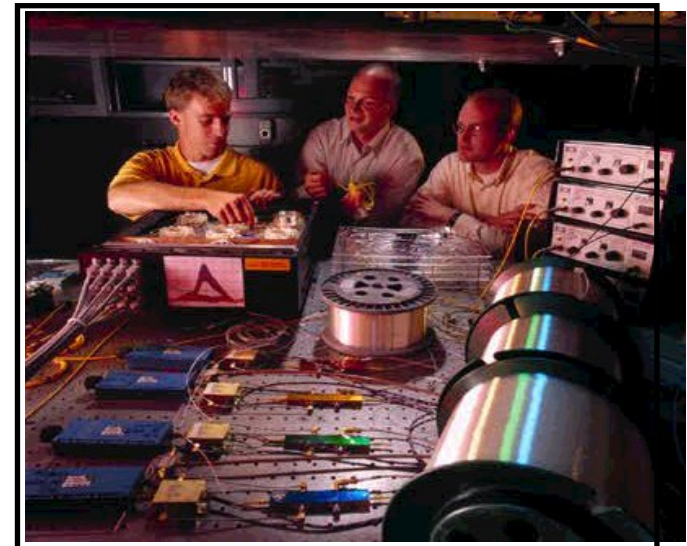
- At present commercial system utilise typically 32 channels
- Commercial 80+ channel systems have been demonstrated
- Lucent have demonstrated a 1,022 channel system
- Only operates at 37 Mbits/s per channel
- 37 Gbits/s total using 10 GHz channel spacing, so called Ultra-DWDM or UDWDM
- Scalable to Tbits/sec?





## 3.28 Terabit/sec DWDM

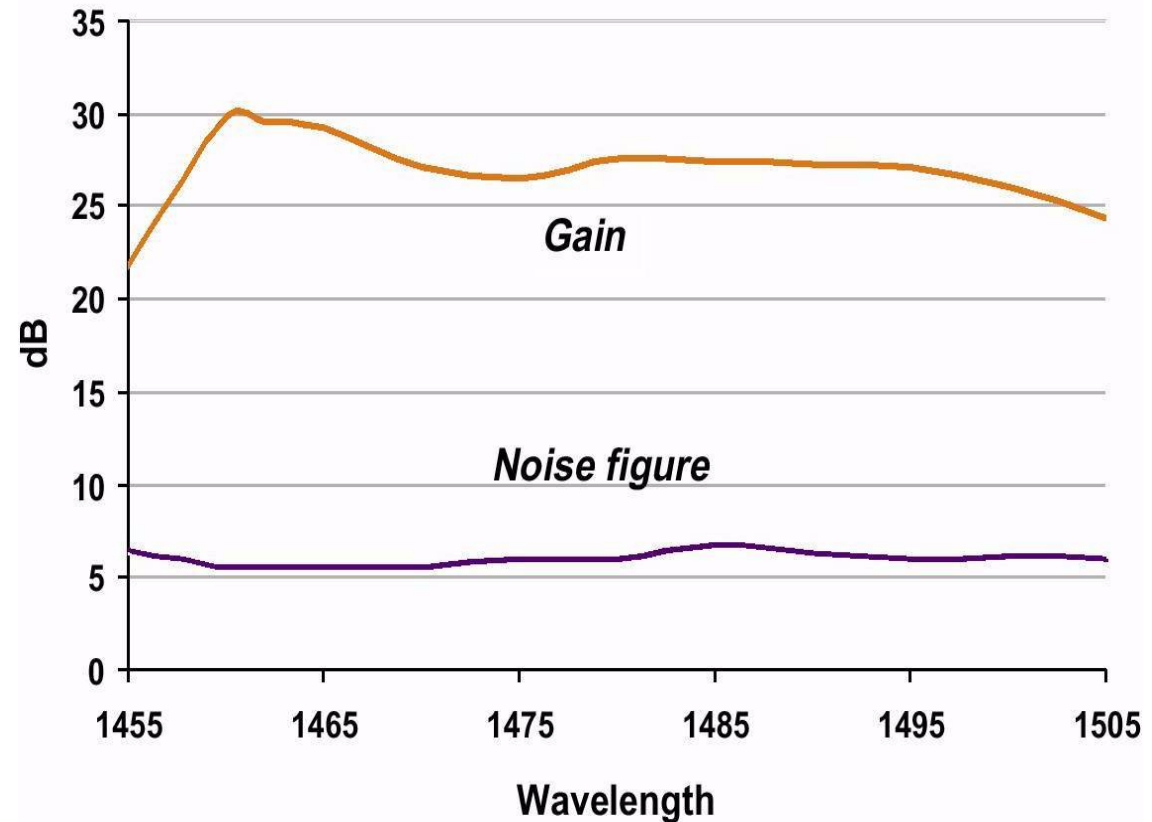
- Lucent demonstration (circa April 2000)
- 3.28 Tbits/s over 300 km of Lucent TrueWave fibre
- Per channel bit rate was 40 Gbits/s
- 40 channels in the C band and 42 channels in the L band
- Utilised distributed Raman amplification





## 10.9 Terabit/sec DWDM

- NEC demonstration in March 2001
- 10.9 Tbits/sec over 117 km of fibre
- 273 channels at 40 Gbits/s per channel
- Utilises transmission in the C, L and S bands
- **Thulium Doped Fibre Amplifiers (TDFAs)** used for the S-band



**Thulium Doped Amplifier  
Spectrum (IPG Photonics)**



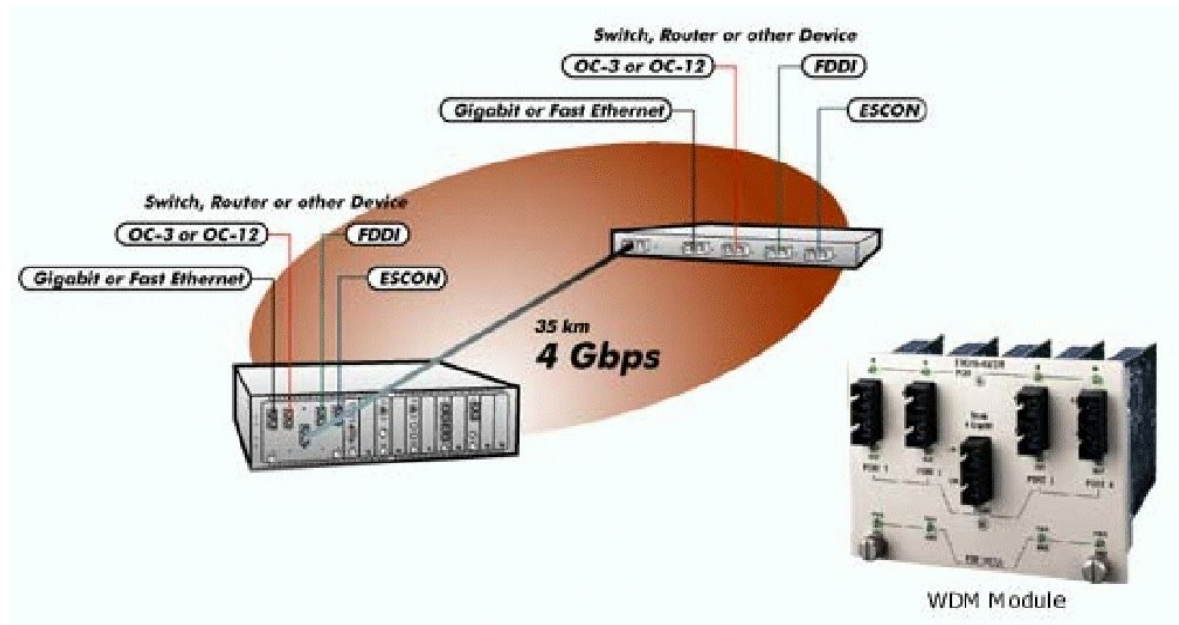
# Wavelength Division Multiplexing in LANs



# WDM in LANs

- Still in its infancy
- Expensive by comparison with single channel 10 Gbits/sec proposals
- Singlemode fibre only
- Typical products from ADVA networking and Nbase-Xyplex
  - Products use a small numbers of channel such as 4 (Telecoms WDM is typically 32 +)
  - Wavelengths around 1320 nm, Telecoms systems use 1530-1570 nm

**Nbase-Xyplex  
System**





# Coarse Wavelength Division Multiplexing



# Coarse Wavelength Division Multiplexing

- WDM with wider channel spacing (typical 20 nm)
- More cost effective than DWDM
- Driven by:
  - **Cost-conscious telecommunications environment**
  - **Need to better utilize existing infrastructure**
- Main deployment is foreseen on:
  - **Single mode fibres meeting ITU Rec. G.652.**
  - **Metro networks**







# CWDM Standards: Recommendation G.695

- First announced in November 2003, as standard for CWDM
- Sets optical interface standards, such as T/X output power etc.
- Target distances of 40 km and 80 km.
- Unidirectional and bidirectional applications included.
- All or part of the wavelength range from 1270 nm to 1610 nm is used.





# CWDM Wavelength Grid: G.694

- ITU-T G.694 defines wavelength grids for CWDM Applications
- G.694 defines a wavelength grid with 20 nm channel spacing:
  - Total source wavelength variation of the order of  $\pm 6-7$  nm is assumed
  - Guard-band equal to one third of the minimum channel spacing is sufficient.
  - Hence 20 nm chosen
- 18 wavelengths between 1270 nm and 1610 nm.



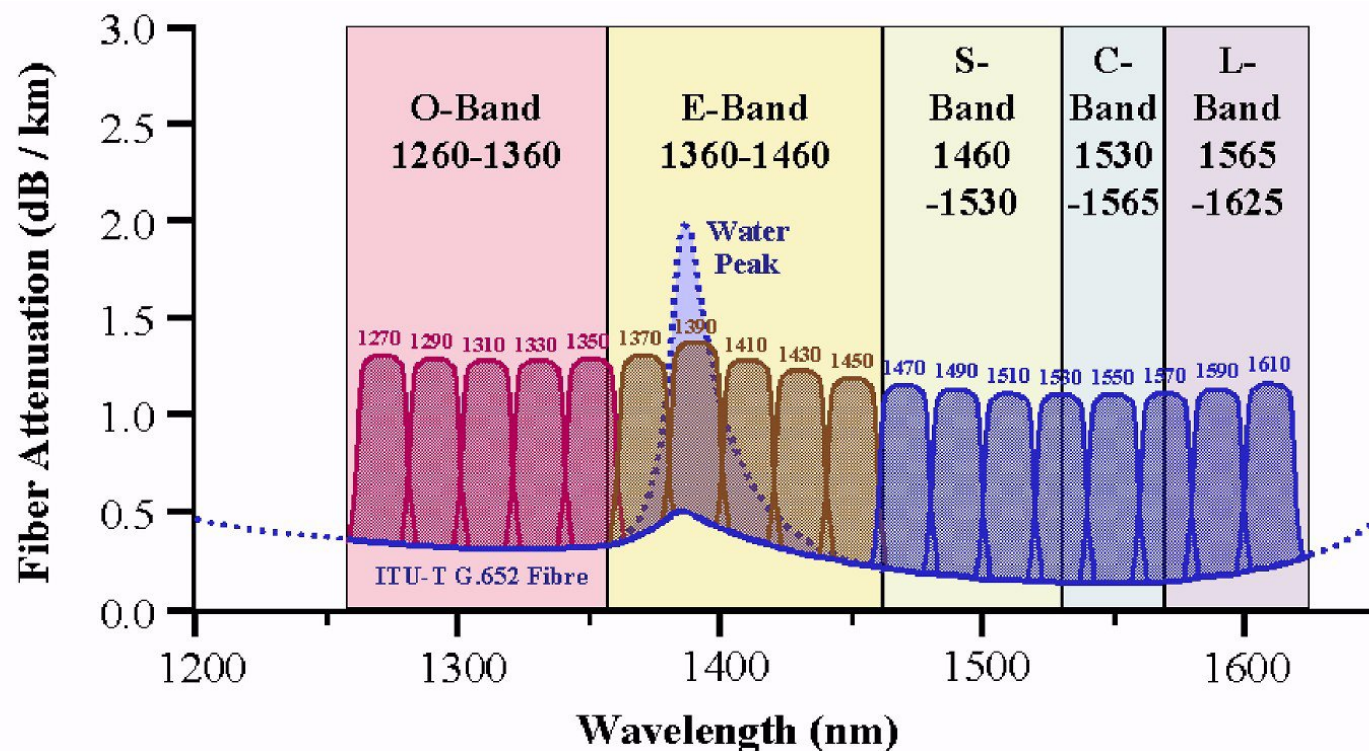
**ITU  
CWDM  
Grid  
(nm)**

1270	1290	1310	1330	1350	1370
1390	1410	1430	1450	1470	1490
1510	1530	1550	1570	1590	1610



# CDWM Issues: Water peak in the E-Band

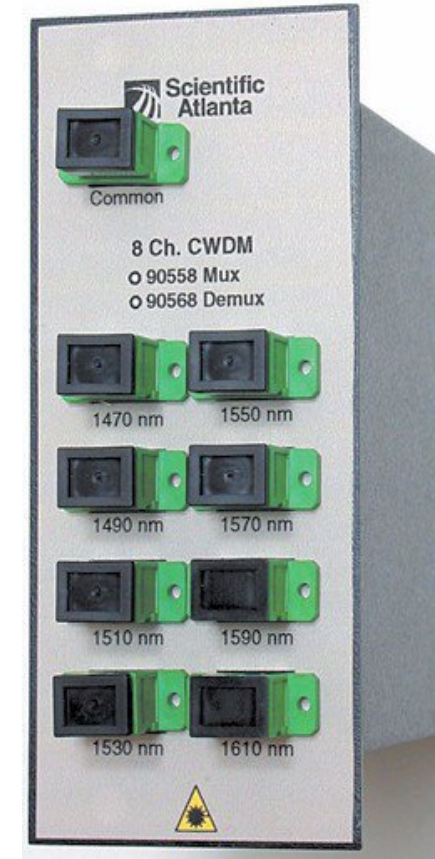
- In principle installation possible on existing single-mode G.652 optical fibres and on the recent 'water peak free' versions of the same fibre.
- Issues remain about viability of full capacity because of water peak issue at 1383 nm





# CDWM Details

- Flexible and scalable solutions moving from 8 to 16 optical channels using two fibres for the two directions of transmission
- Up to 8+8 optical channels using only one fibre for the two directions.
- Support for 2.5 Gbit/s provided but also support for a bit rate of 1.25 Gbit/s has been added, mainly for Gigabit-Ethernet applications. .
- Two indicative link distances are covered in G.695: one for lengths up to around 40 km and a second for distances up to around 80 km

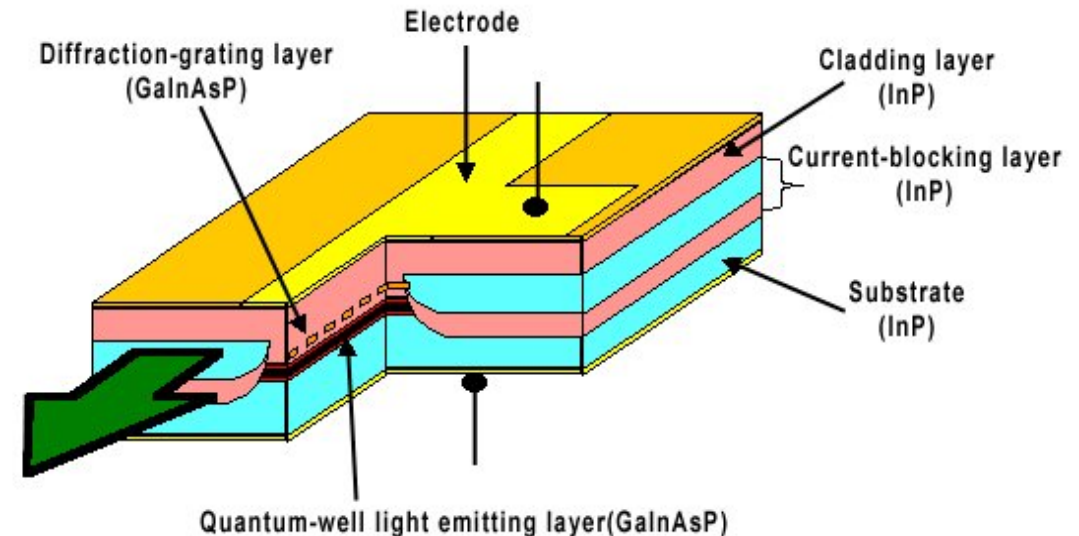


**8 Ch Mux/Demux  
CWDM card**



- CWDM is a cheaper and simpler alternative to DWDM, estimates point to savings up to 30%
- Why is CWDM more cost effective?
  - Less expensive uncooled lasers may be used - wide channel spacing.
  - Lasers used require less precise wavelength control,
  - Passive components, such as multiplexers, are lower-cost
  - CWDM components use less space on PCBs - lower cost

## Why CWDM?



**DFB laser, typical  
temperature drift 0.08 nm  
per deg. C**

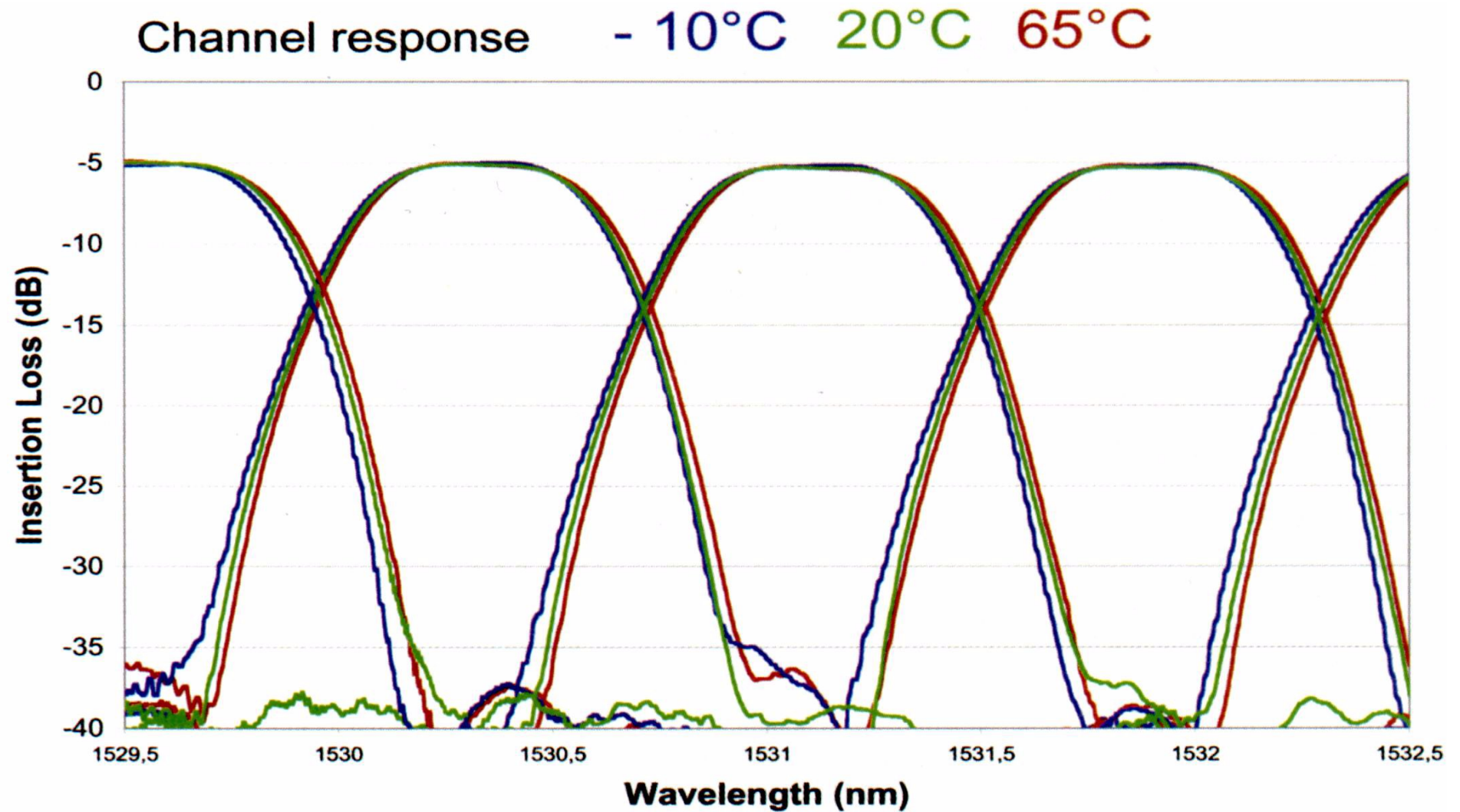
**For a 70 degree  
temperature range drift is  
5.6 nm**





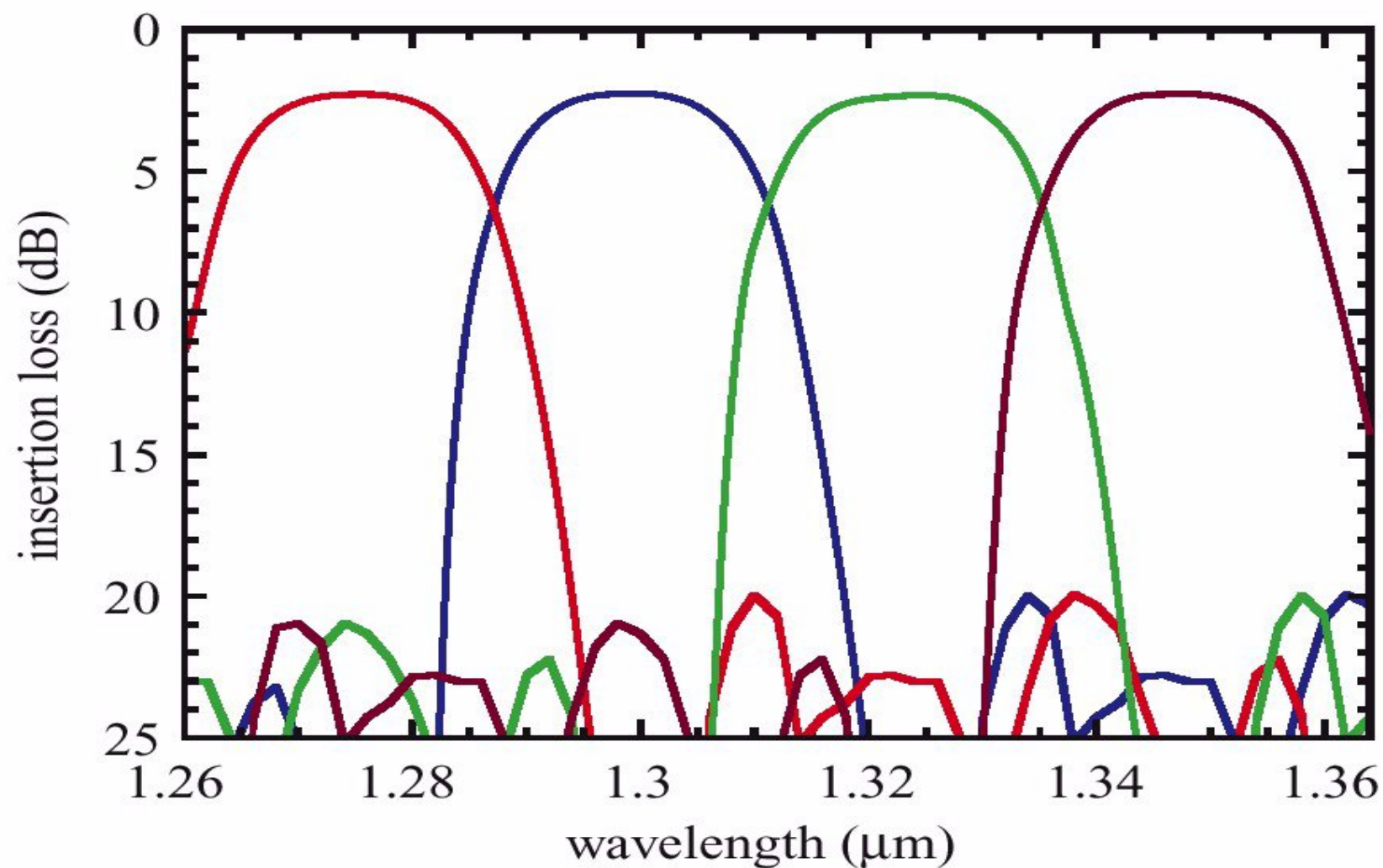
# DWDM Demultiplexer Spectral Response

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# 4 Channel CWDM Demultiplexer Spectral Response





# CWDM Mux/Demux Typical Specifications

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Parameters	Unit	Values
Center Wavelength	nm	1471 1491 1511 1531 1551 1571 1591 1611
0.5dB Pass Bandwidth	nm	$\geq 13$
<b>Insertion Loss</b>	<b>dB</b>	<b><math>\leq 0.8</math></b>
Adjacent Ch. Isolation	dB	$\geq 25$
Optical Return Loss	dB	$\geq 50$
PDL	dB	$\leq 0.1$
Thermal Stability	dB/°C	$\leq 0.005$
Fiber Type Corning		SMF-28
Operation Temperature	°C	-5 to +70

8 Channel Unit: AFW Ltd, Australia





# CWDM Migration to DWDM

- A clear migration route from CWDM to DWDM is essential
- Migration will occur with serious upturn in demand for bandwidth along with a reduction in DWDM costs
- Approach involves replacing CWDM single channel space with DWDM "band"
- May render DWDM band specs such as S, C and L redundant?

