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TECH pedia

OPTICAL SYSTEMS AND NETWORKS

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Explanatory Notes

Definition

Interesting

Note

Example

Summary

Advantage

Disadvantage

ANNOTATION

This teaching material describes optical networks, such as Optical Access Networks, FTTx technology, Active/Passive Optical Networks, optical systems using Wavelength Division Multiplexing: DWDM, CWDM. It introduces parameters and working regimes of optical networks, including system maintenance issues (OTDR, splicing) and signal recovery (EDFA, SOA, Raman amplifiers, dispersion compensation).

OBJECTIVES

A student will learn how to distinguish between different implementations of optical networks with and evaluate whether the network meets basic standard criteria. The student will gain knowledge on optical system planning, all-optical signal recovery and network maintenance.

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1 Current ITU-T recommendations for optical transmission systems

1.1 Recommendations for PON by ITU and IEEE

ITU (*International Telecommunication Union*) published recommendation for *Passive Optical Networks* (**PON**), including Reach Extended PON. There are a number of options in terms of attenuation classes, reach, wavelengths and bit rates.

PON - *Passive Optical Networks* (one of the main topics addressed in this teaching module) is a multipoint network that can be classified according to the functionality of components splitting optical signals. It uses passive components (of course besides lasers as sources of optical symbols), where power level decreases gradually with the distance from the laser sources.

Basic recommendation for current Passive Optical Networks - comparison of IEEE and ITU-T standards.

Recommendation	**10GEPON by IEEE 802.3av (2009)**	**EPON by IEEE 802.3ah (2004)**	**GPON by ITU-T G.984 (2003)**	**XG-PON by ITU-T G.987 (2010)**
Transmission rate options	10G/10G symmetric or asymmetric	1G/1G symmetric	1.25G/1.25G symmetric, 2.5G/1.25G asymmetric, 2.5G/2.5G symmetric	10G/2.5G asymmetric
Transmission rate at the physical layer	10.3125 Gbps, 1.25 Gbps	1.25 Gbps	1.24416 Gbps, 2.48832 Gbps	9.95328 Gbps, 2.48832 Gbps
Attenuation classes	PR10, PRX10, PR20, PRX20, PR30, PRX30	PX10, PX20	Class A, B, B+,C	Class Nominal 1, 2, Class Extended 1, 2
Wavelengths [nm]	Downstream 1575-1580 Upstream 1260-1280 or 1260-1360	Downstream 1480-1500 Upstream 1260-1360	Downstream 1480-1500 Upstream originally 1260-1360, newly 1290-1330	Downstream 1575-1580 Upstream 1260-1260
Physical reach [km]	≤10, ≤20	≤10, ≤20	≤20	≤20 (future ≤40)
Max. splitting ratio	1:16, 1:32 (future 1:64, 1:128)	1:16, 1:32	1:64 (proprietary 1:128)	1:256

1.2 Recommendation for Reach Extended PON

Passive Optical Network can however use optical amplifiers in certain cases to increase the reach, without the necessity to build up vast active-components infrastructure.

Recommendations for Reach Extended GPON with permitted amplifiers

GPON class	**Optical Distribution Network range [dB]**	**Attenuation range from the provider to an end user[dB]**	**Max. physical reach (physical layer) [km]**
Class B+	13-28	13-28	40
Class C	15-30	15-30	40
Class C+	17-32	17-32	60

2 Systems with Wavelength Division Multiplexing - CWDM and DWDM grid

2.1 General idea of multiplexing

The general idea how to increase the bit rate and information capacity of a system is to transmit information at many channels (wavelengths) concurrently. Long distance networks with the capacity of tens of Tbps must operate at hundreds channels, each running at the rate of tens of Gbps.

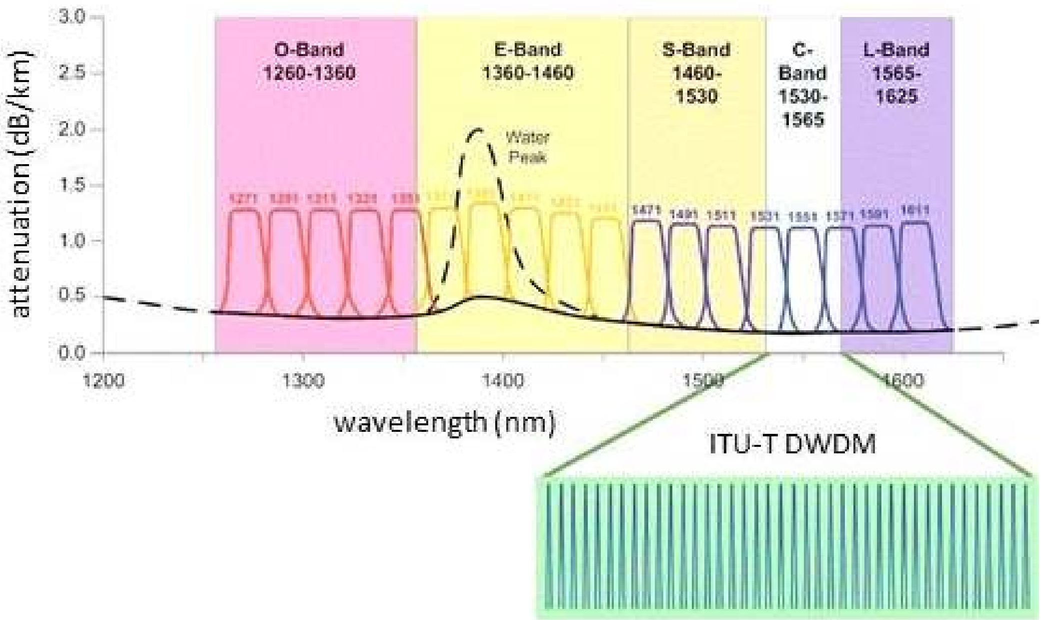
DWDM - *Dense Wavelength Division Multiplexing* requires using narrow-spectrum source of radiations, which are *Distributed Feedback Lasers* (**DFB**). In addition, the central wavelength must be stable (it is generally known that laser wavelength is temperature tunable); for this purpose it is recommended to use cooled DFB where operating temperature is fixed between 20 and 30°C.

Metropolitan networks can operate at much lower bit rates. **CWDM** - *Coarse Wavelength Division Multiplexing* uses 4 to 16 channels, with huge spacing of 20 nm, which allows using lasers with broader spectrum of emitted wavelengths, such as Fabry-Perot lasers, or non-cooled DFB. Such arrangement is less expensive.

2.2 CWDM and DWDM grid

Grid spacing in CWDM and DWDM systems

Technology	**CWDM**	**DWDM – regional networks**	**DWDM – long-distance networks**
Number of channels (wavelengths)	4-16	32-80	80-160
Bands	O, E, S, C, L	C, L	C, L, S
Channel spacing	20 nm or more (2500 GHz or more)	0.8 nm, 100 GHz	0.4 nm or less – 0.2 nm or 0.1 nm, (50 GHz or less)
Transmission capacity per channel	1.5 Gbps	10 Gbps	10-40 Gbps
Fibre capacity	20-40 Gbps	100-1000 Gbps	Tens of Tbps
Laser type	Non-cooled DFB or FP	Cooled DFB	Cooled DFB
Reach	50-80 km	100 km	1000 km
Price	Low	High	Highest



CWDM and DWDM operating wavelengths (exemplary).

3 Types of optical networks, their architectures and basic parameters (OTH, FFTx)

3.1 FTTx architecture

FTTx (*Fibre to the …cabinet, curb, building, office, home*) – access network based on optical fibres. All-optical network FTTO and FTTH or hybrid solutions FTTEx, FTTCab, FTTC, FTTB.

Hybrid solutions

In general:

- Optical fibres are combined with symmetric metallic lines for ADSL2+ VDSL2.
- Optical fibres are combined with coaxial cables for *Cable TV* (**CATV**).
- Combination with wireless network.

- **FTTEx** (*Fibre to the Exchange*) – optical fibres are terminated at the local telephone exchange, DSLAM multiplexor splits signal to existing metallic lines to provide **xDSL** (*Digital Subscriber Line*). FTTEx is the most common solution nowadays, but it is not an all-optical access network.
- **FTTCab** (*Fibre to the Cabinet*) – optical fibres are terminated in an outdoor splitter.
- **FTTC** (*Fibre to the Curb*) – optical fibre reaches the group of buildings.
- **FTTB** (*Fibre to the Building*) – optical fibres reach particular buildings, they can be terminated inside them at the particular telephone boxes or they may be followed by wireless connection.

All optical solutions

- **FTTO** (*Fibre to the Office*) – optical fibres terminate at the office of important customers with huge demands on the transmission rate.
- **FTTH** (*Fibre to the Home*) – optical fibres are terminated at the end user's socket.

3.2 Access Networks

OAN - *Optical Access Networks*

- Simplex transmission with **SDM** (Space Division *Multiplexing*), for each direction of transmission there is one fibre.
- Duplex transmission with **WDM** (*Wavelength Division Multiplexing*), signals are transmitted in one fibre, one direction of transmission is in the area of 1310 nm, the opposite direction is in the area of 1550 nm.
- Duplex transmission with **FDM** (*Frequency Division Multiplexing*), signals is transmitted in one fibre, directions of transmission are around one wavelength and they are separated by frequency spacing.
    - Short Haul – max. attenuation 16.5 dB in CWDM, min. attenuation 5 dB, reach 30 – 50 km for P2P.
    - Long Haul – max. attenuation 25.5 dB in CWDM, min. attenuation 14 dB, reach 50 – 80 km for P2P.
    - Typical attenuation of CWDM network elements is 3.5 – 7.5 dB. EDFA can extend the reach.

Active Optical Networks

AON - *Active Optical Networks*. It employs active network components to interconnect network elements, such as amplifiers.

However, there are *Reach Extended PON* (**REPON**), where using an *Erbium Doped Fibre Amplifier* (**EDFA**) is permitted.

Passive Optical Networks

E=m·c²

PON - *Passive Optical Networks*: multipoint networks that can be classified according to the functionality of components splitting optical signals. They can be splitters or *Array Waveguide Gratings* (**AWG**). In WDM, signals can be split by optical filtering by using so-called add-drop multiplexors.

- **BPON** - *Broadband PON* - 622.04 Mbps was added, two fibres are used for both directions of transmission or there is one fibre combined with WDM: 1260 - 1360 nm – uplink, 1480 - 1500 nm – downlink. Optionally 1539 - 1565 nm – is for 16 + 16 DWDM channels with the 0.8 nm channel spacing, 1550 - 1560 nm – is for distribution of video.
- **GPON** - *Gigabit PON* - ITU-T G.984 –with nominal rate of 1.244 and 2.488 Gbps (max. 128 users).

- **EPON** - *Ethernet PON*. Optical connection: P2MP. 1.25 Gbps in accordance with 1000BASE-PX. For upstream (from user to provider), the wavelength of 1310 nm is used, for downstream, it is 1490 nm. Type 1 – max. reach is 10 km. Type 2 – max. reach 20 km.

3.3 Optical Transport Hierarchy

OTH – *Optical Transport Hierarchy*. Signals of optical hierarchy are known as **OTM** (*Optical Transport Module*). The simplest option (zero level) assumes no wavelength multiplex. Optical transport modules are denoted as OTM-n.m, where n is the number of channels (operating wavelengths) and m expresses the type of signal. Different basic rates can be multiplied; potential combinations refer to OTM-n.123 (2.5; 10; 40 Gbps).

Optical Transport Hierarchy OTH –transport modules without multiplexing

Hierarchic level	Transmission rate [Mbps]	It can transmit STM-N
OTM-0.1	2488.32	STM-16
OTM-0.2	9953.28	STM-64
OTM-0.3	39813.12	STM-256

An **STM** is *Synchronous Transport Module*, a basic transport unit in **SDH** (*Synchronous Digital Hierarchy*). N stands for multiplication of the basic unit's capacity.

Optical transport modules with wavelength multiplexing

Hierarchic level	Transmission rate [Mbps]	It can transmit
OTM-n.1	n x 2488.32	n x STM-16
OTM-n.2	n x 9953.28	n x STM-64
OTM-n.3	n x 39813.12	n x STM-256

4 Splicing of optical fibres and installation of fibre optic links

4.1 Goal

Splicing of optical fibres is necessary to create permanent connections between separate lengths.

While more flexible solutions are available in the form of connectors, splices offer lower losses in comparison and are therefore useful in cases where the fibres need not be separated after joining. For example, they can be used to repair damaged fibres.

This is a reason why an extra of fibre margin of fibre is generally used when installing fibres – if a section is damaged, the extra length can bridge the gap and a splice can be made.

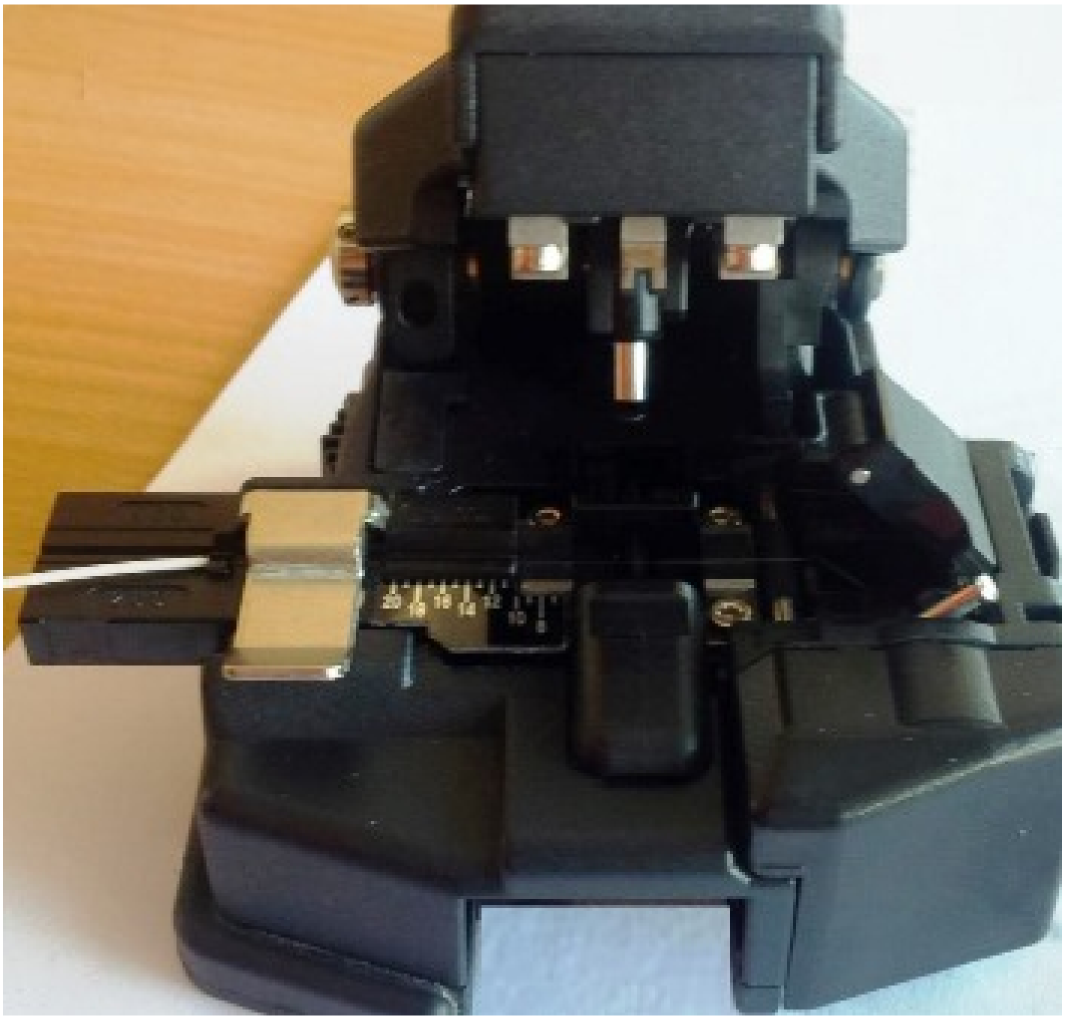
Optical splicer – Fujikura 18s.

Equipment needed to splice two fibres is, as follows:

- the fibres themselves;
- strippers to remove the coating layer(s);
- a cleaver to cut the fibre ends cleanly; and
- a splicer to align the fibres correctly and join them.
- isopropyl alcohol for cleaning the de-coated fibres, and tissue for removing excess alcohol.

4.2 Procedure

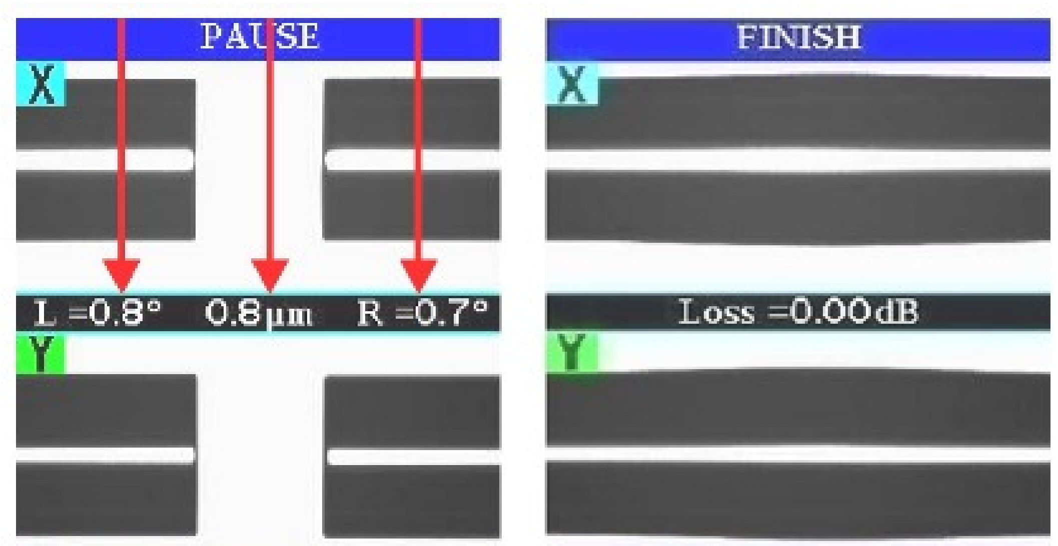
- Two lengths of around 100 mm should be roughly cut from a spool of fibre to be joined again.
- Firstly, using the strippers, the primary and secondary coating layers of the fibre were removed up to approximately 50mm from each end, leaving only the cladding and the core intact.
  - Isopropyl alcohol on a tissue should be used to clean any remaining coating from the exposed cladding.
- The exposed fibre core and cladding should be cut cleanly using the cleaver, to ensure a flat and non-angled surface.
- The fibre should be placed in the v-groove of the cleaver such that the end of the fibre should be extended sufficiently to reach the opposite side of the cutter so that the fibre would be cut rather than bent.
- The fibre is then clamped in position using a spring-loaded clip (silver, left of frame).
  - The mechanism at the bottom of the cleaver should be depressed and the upper part lowered to cleave the fibre. It is essential not to use excessive force for this, as the cut quality may be compromised.



Cleaver with fibre clamped and ready to be cut.

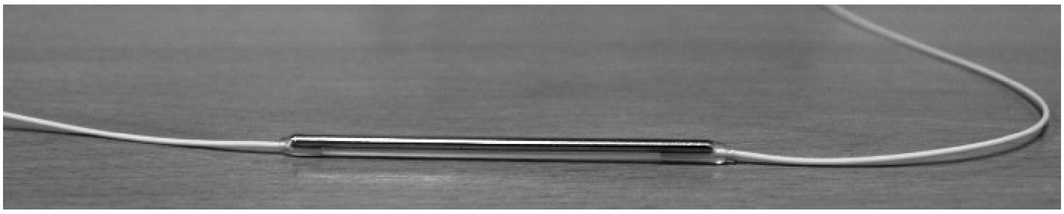
- After both have been successfully cut, we can move onto the actual splicing of the fibres.
- The two fibre ends are placed in the v-grooves of the splicer.
    - It is important that no coating remains on the fibre at the parts where the height is levelled – if it is, the angle of the end of the fibre may be increased and the splice quality decreased. The fibre ends should be as close as possible to the electrodes, but should not overlap the central line between them. When the fibres are correctly positioned, they should be clamped in place and the cover of the splicer can be closed.
- The splicer should then be switched on if it isn't already, and the 'Set' button pressed – the splicer will then fine-tune the positioning of the fibres to try to align their axes and bring them as close as possible together.

Splicer with fibres positioned close to the electrodes in the centre, held in place by spring-loaded clamps.



Automatic gap setting by the splicer and the spliced fibres.

If the positioning and / or the cut quality is particularly bad, the splicer will display a warning on-screen and the fibres can be removed and repositioned or recut. If the conditions are satisfactory, however, the 'Set' button can be pressed again and the splicing process will be initiated. A voltage is applied across the electrodes and the ends of the fibres are spliced.



Final appearance of a splice with protection coating.

5 Testing optical paths by using Optical Time Domain Reflectometer

5.1 Optical Time-Domain Reflectometer

An *Optical Time-Domain Reflectometer* (**OTDR**) is a measurement device that can be used to characterise optical communication systems. By recording the intensity of Rayleigh back-scattered light from a source (typically a pulsed laser) in the time domain, the OTDR can approximate the distance travelled by the light, given that the refractive index of the fibre is known.

+

Thereby it is able to identify the attenuation of different lengths of the fibre, and the position of network components, for example splices or connectors. The identification and location of defects within the optical communication system is the primary motivation for using OTDRs.

Optical Time Domain Reflectometer.

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The OTDR should be connected to the end of an optical fibre in the order of tens of kilometres in length and with a number of splices and connectors along that length.

- The OTDR can be configured to produce pulses of either 1550nm or 1310nm central wavelength, and pulse durations of 10ns to 10us.

- There is a trade-off between penetration depth and resolution of the measurement, which is determined by pulse duration.
- Shorter pulses have both a better spatial resolution and a worse penetration depth.
- There is preferred pulse duration for each application, ideally the greatest resolution while maintaining depth data.
- There may exist fibres for which adequate clarity is not achieved at great depths.

A simple solution to this problem is to connect the OTDR at the opposite end of the fibre.

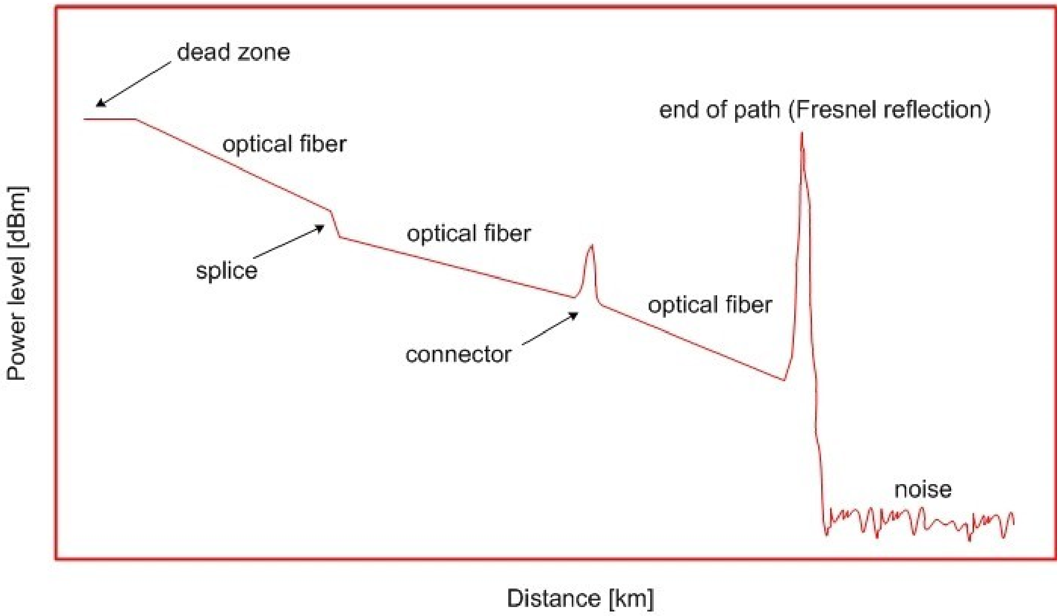
Interpretation of measured data

The on-screen results obtained with the OTDR are given in a figure.

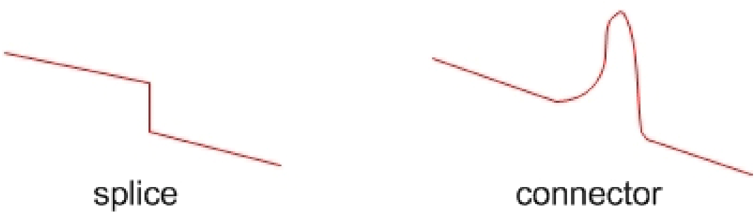
- OTDR manages to identify network components: connectors and splices due to the shape of the attenuation profile.
- A short, sharp drop indicates a splice.
- A local peak is observed at connectors, with a greater drop-off on the right-hand side of the peak.

This is due to the better optical coupling of splices; the local maxima observed at connectors are a consequence of increased back reflection due to poor quality of the joint.

The peak is an artefact of the assumptions made in the system (specifically, the assumption that back reflection intensity can be used as an analogue of attenuation) and therefore the attenuation of the connector is not related to the height of the peak, but rather the power loss from the start to the end of the peak.



On-screen attenuation diagram measured by OTDR.



Connectors and splices on an OTDR diagram.

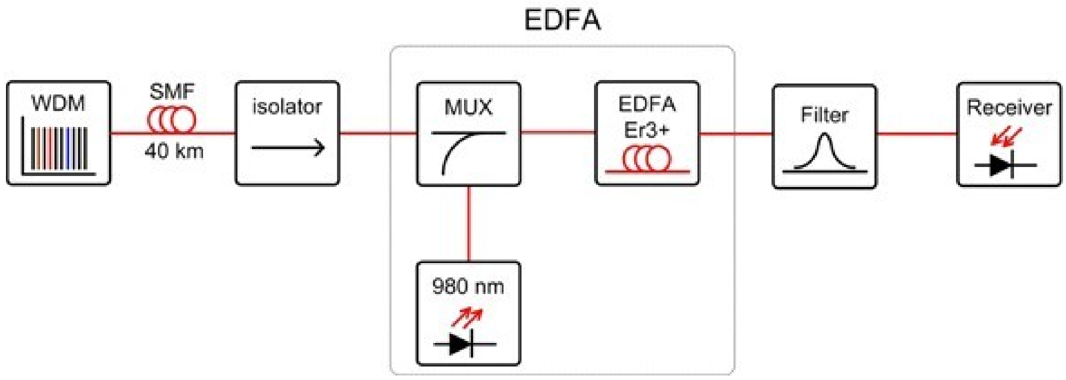
6 Regeneration of signals in optical networks by using link EDFAs

6.1 Erbium Doped Fibre Amplifiers

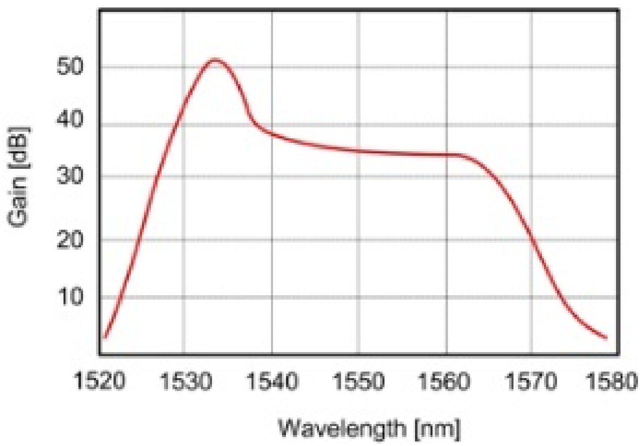
Doped fibres are often used as optical amplifiers within optical networks. Erbium is the most common dopant - it follows that *Erbium Doped Fibre Amplifiers* (**EDFAs**) are the most common optical amplifiers of this type. EDFAs are pumped with a diode laser with a central wavelength of 980 nm that is multiplexed with the signal-carrying fibre. The pump radiation excites the dopant ions along the fibre amplifier.

E=m·c²

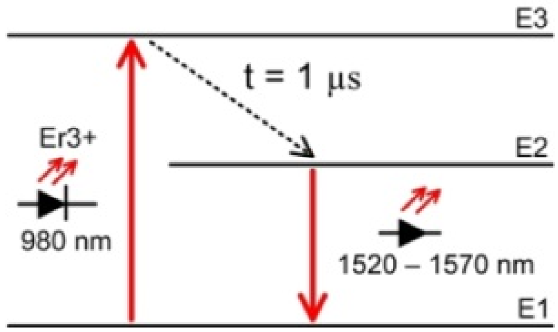
The excited erbium ions then undergo a rapid, non-radiative relaxation to a lower energy band, after which they experience a slow, radiative relaxation to their ground state. The relative decay times of these states are critical to the achievement of population inversion – a prerequisite for high stimulated to spontaneous emission ratio, which, in more practical considerations, manifests itself as a high signal-to-noise ratio and greater amplification efficiency.



EDFA operating as in-line amplifier.



Operating wavelengths and gain of EDFA.



Energy model of EDFA.

The solution comprises of a *distributed feedback* (**DFB**) laser source, a 980 nm pump module, a multiplexer, an EDFA and spectral analyser. The DFB laser source and the pump module's outputs were combined using the multiplexer and then transmitted through the EDFA.

Advantages:

- Broad operating range (C+L band – 1530 nm to about 1680 nm).
- Huge gain 20 to 50 dB (nowadays gain larger than 20 dB is no longer required for the reasons of exciting undesired nonlinear phenomena, such as *Four Wave Mixing* (**FWM**) in very high-speed networks).
- Construction – a fibre using optical pump.
- Relatively flat gain for transparent optical networks using **WDM** (*Wavelength Division Multiplexing*).
- Low price.
- Application as in-line amplifier.

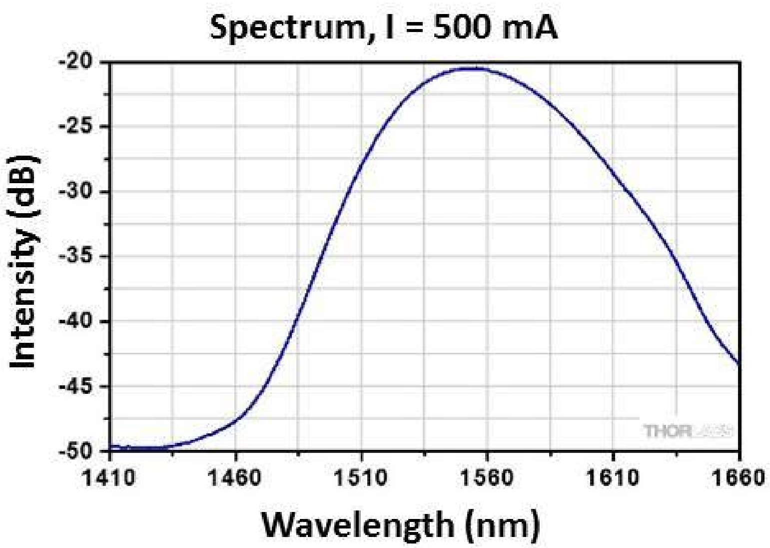
Disadvantages:

- Significant **ASE** noise (*Amplified Spontaneous Emission*).
- Cannot be used as a booster because of gain suppression (saturation).
- Cannot be used as a preamplifier without special filters.

7 Semiconductor amplifiers (SOA) and Raman amplifiers

7.1 Semiconductor optical amplifiers

A *Semiconductor optical amplifier* (**SOA**) make use of a semiconductor as a gain medium and as such, are electrically pumped. They can be compared to laser diodes, with the caveat that the end mirrors are replaced with anti-reflection layers. The signal is amplified by stimulated emission in the electrically excited active layer.



Spectral characteristic of SOA.

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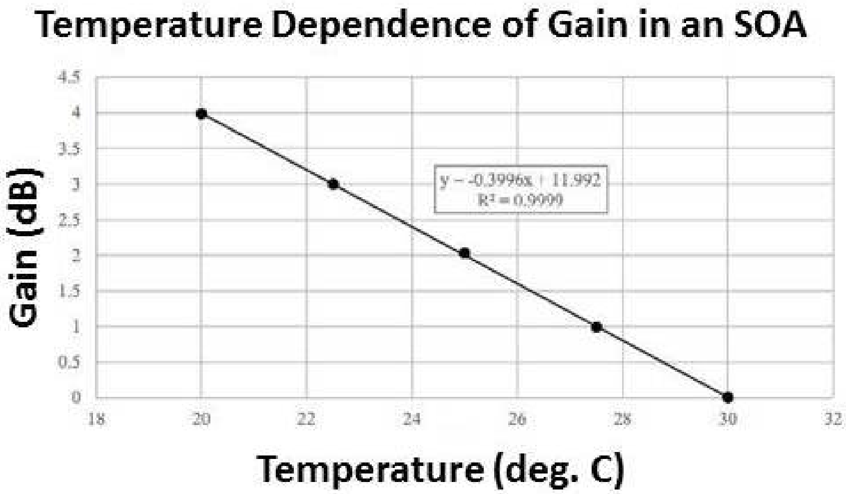
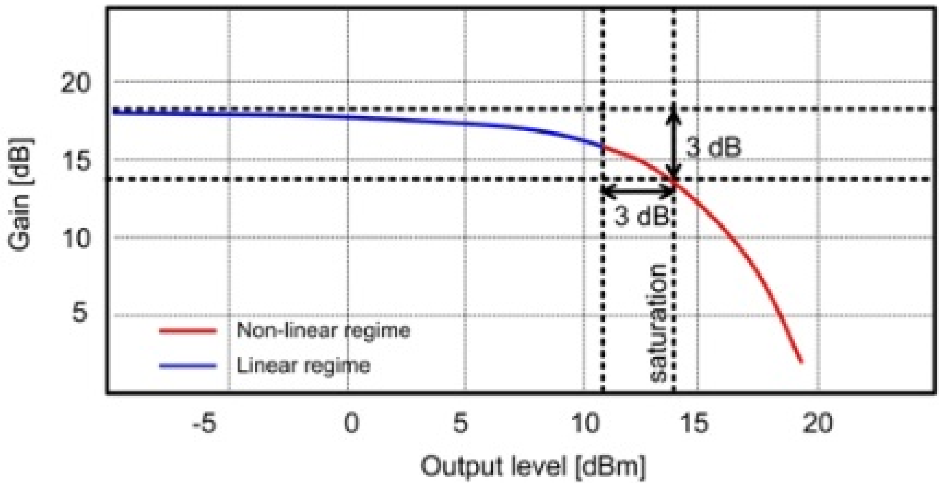
The temperature displays a very strong linear effect on gain. Practical applications resulting from this are unclear due to the slow nature of temperature control. However, it can be seen at least that the temperature must be held steady in order to provide consistent amplification, and that minimal temperature results in maximal amplification.



Temperature dependence of gain in an SOA.

The classification of the linear and nonlinear regimes of the SOA is useful as it is generally undesirable to operate the amplifier in the nonlinear regime.



Linear and nonlinear regimes of an SOA.

7.2 Raman amplifier

Raman amplification uses the *Stimulated Raman Scattering* (**SRS**).

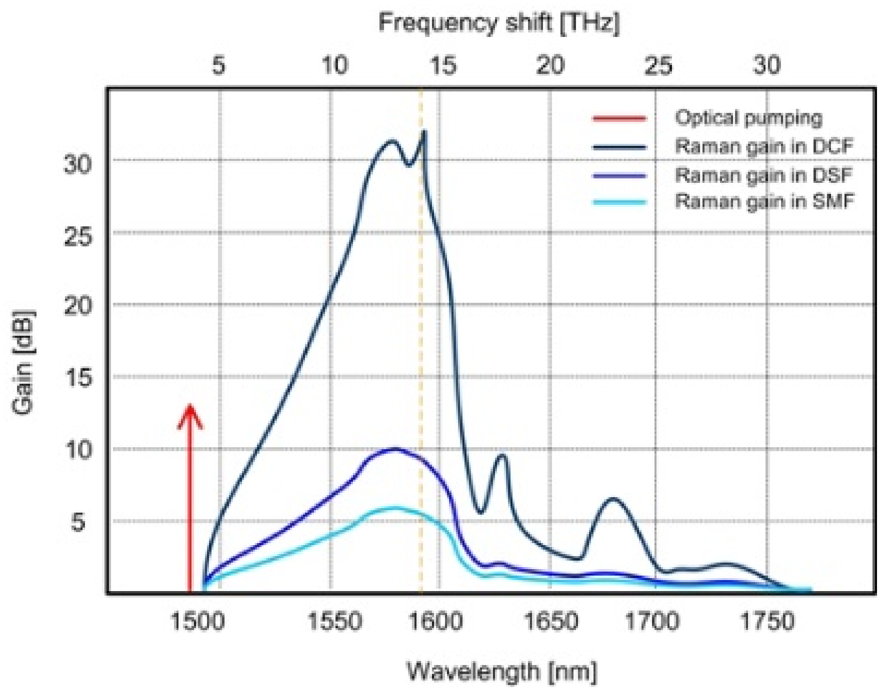
A longer wavelength photon induces the inelastic scattering of a shorter wavelength pump photon (mother wavelength) in an optical fibre. Another photon is produced at the wavelength shifted by about 100 nm (valid for standard telecom fibres).

This phenomenon is successfully used for the construction of an optical amplifier. If the Raman pump is located locally, where gain is to be achieved, we call such amplifier:

- **LRA** – *Lumped Raman Amplifier*.

However, since the SRS accumulates along the entire fibre, it is more optimal to place Raman pump at the opposite end of a fibre:

- **DRA** – *Distributed Raman Amplifier*.



Raman gain in different types of optical fibres: Single Mode Fibre (SMF), Dispersion Shifted Fibre (DSF) and Dispersion Compensating Fibre (DCF) .

Commercially available EDFA, SOA and Raman amplifier.

Raman effect is not always desired. In DWDM systems, SRS can produce crosstalk between transmission channels. Raman crosstalk is a generally undesirable, non-linear optical effect in networks that occurs due to minute imperfections in the fibre. It is an inelastic photon scattering effect (i.e. there is a change in photonic energy). In practical terms this results in crosstalk between channels and a migration of channel power from shorter to longer wavelengths (or from faster to slower frequencies).

8 Dispersion compensators for fibre optic paths

8.1 Dispersion in optical fibres

Dispersion causes pulse extension or pulse compression (if dispersion is negative) in time domain. It can lead to Inter Symbol Interference. If neighbour pulses stand for logical 1, the space between pulses stands for logical 0, if the two pulses cover each other partially, the decoder will not be able to recognize the "0" symbol.

The unit of dispersion is [ps/nm] (picoseconds/nanometre), but in fibre optics, where the length of optical structures is a key parameter, dispersion is referred to the unit length and is expressed as [ps/nm/km]. The dispersion of 1 ps/nm/km means that the delay between the slowest and the fastest frequency component of an optical pulse, its bandwidth is 1 nm, will be 1 ps after the distance of 1 km.

Chromatic dispersion

Chromatic dispersion consists of two components: material dispersion and waveguide dispersion.

Material dispersion (**DMat**) is due to the bandwidth of a laser source, which is not endlessly narrow. In practice, there is no ideal monochromatic light (with endlessly narrow bandwidth). Emitted light, transmitted pulse contains couple of frequency components (they correspond to many similar colours). Each frequency component is characterized by specific phase constant of propagation – there is different index of refraction for specific colours. Each frequency component (each colour) is then propagated at different phase velocity and reaches the end of a fibre at different time instant.

- Material dispersion is present in both: single mode and multimode fibres.
- Material dispersion can be negative or positive.

Waveguide dispersion (**WD**) is caused by the change of mode shape at certain distance and is strictly associated with the waveguide geometry, which causes the change of group velocity (the shape of the whole pulse "envelope") as a function of wavelength. It is a suitable tool to adjust the dispersion property of a fibre, because by the suitable design of geometrical parameters describing your waveguide, one can specify the value of waveguide dispersion, which is then responsible for the total dispersion.

- Waveguide dispersion is always negative, thus, it can be used for the compensation of material dispersion.

Solution: the use of *Dispersion Compensating Fibres* (**DCF**) or special fibre gratings.

Modal dispersion

In *modal dispersion* (**MD**) each of beams passes through the fibre to its output along different trajectory. The shortest trajectory is for the beam propagating along the fibre axis of symmetry, the longest path refers to the beam, which exhibits the maximum number of reflections at the core/cladding interface. With increasing the input angle of NA, there is greater number of reflections during propagation and the overall path of a beam is getting longer. Particular beams (modes) reach the fibre end at different time instants. They are detected as superposition; the result is an extended current pulse at the output of a photo detector.

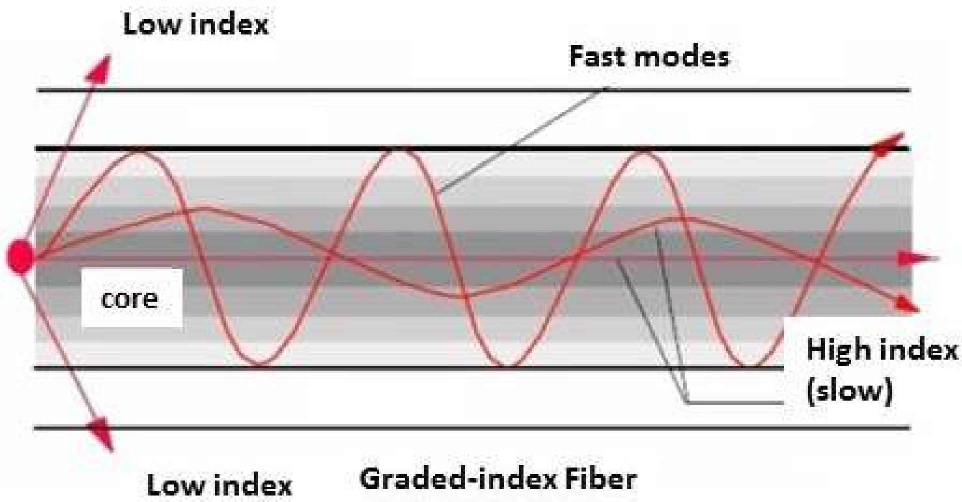
- Modal dispersion is present only in multimode fibres (there is only one mode in single mode fibres, so we cannot consider the difference between two modes), it is usually few ns/nm/km.

It is NOT caused by different speed of particular components (beams, modes) – they are all guided at the same phase and group velocity = modal dispersion is not the function of a wavelength.

Multimode graded-index fibres

Solution: to decrease the speed for short trajectories, to increase the speed for long trajectories.

In *Multi-mode Graded Index* (**MM-GI**) fibres, the index of refraction of a core is not constant; it decreases gradually as a function of distance from the core centre. The densest material is in the centre of a core, layer around it is less dense. The greater the distance from the core is, the lower refractive index of a material is used. There is refraction on couple of layers and finally the beam is reflected at specific layer or at the boundary between the last core layer and the cladding. The beam propagating along axis of symmetry has the shortest trajectory, but its speed is slow, because the centre of a core is a high-index material. On the other hand, beams propagating along longer trajectories are gradually getting to the low-index, “fast” material.

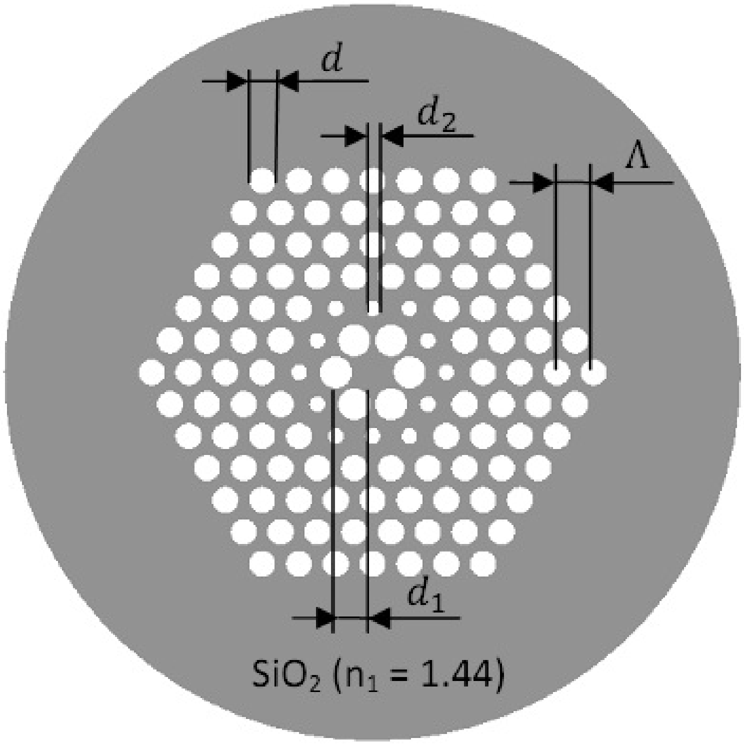


Modal dispersion in multimode graded-index fibre.

8.2 Dispersion Compensation

Dispersion Compensating Fibres

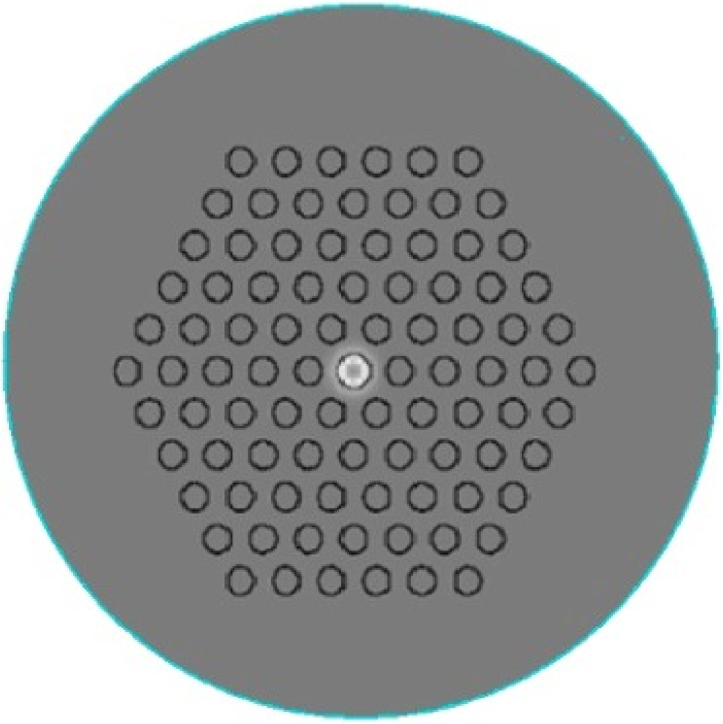
DCFs (*Dispersion Compensating Fibres*) are specific for low negative dispersion parameter ~ -100 ps/nm/km, even to ~ -10000 ps/nm/km (there are many papers reporting even wider range of theoretical values), which is to compensate accumulating dispersion. DCFs differ from standard SMFs, as far as we talk about its geometry and material composition. The most mature DCFs are those based on *Photonic Crystal Fibres* (**PCF**).



Sample design (cross-section) of mature DCFs.

Some DCFs are designed to operate at a specific wavelength, their wavelength evolution of dispersion is parabolic with one dispersion minimum and two *zero dispersion wavelengths* (**ZDW**).

DCFs for DWDM systems have to be able to compensate dispersion in all channels a once. Broadband DCF has strong negative dispersion parameter available at all telecommunication windows, at which fibres are transparent. Dispersion upon wavelength of such DCF copies the reverse slope of a standard fibre to be compensated over broad spectrum of operating wavelengths.



Dispersion in broadband DCFs.

Fibre Bragg gratings

Another possibility is the use of *fibre Bragg grating* – **FBG** in the fibre along its core (attention: we do NOT deal with microstructured Bragg Fibre).

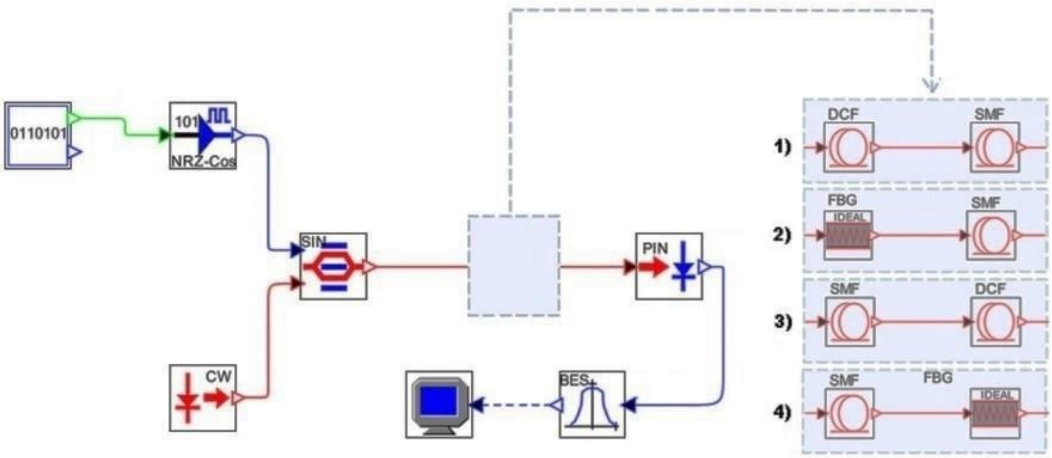
Disadvantage

–

- It operates at specific wavelength. One can tune the grating (its period), but for many DWDM channels, one grating is not enough. Many channels = many gratings.
- The grating can be tuned, but wavelength division multiplex DWDM contains many channels, one grating is not enough
- Many wavelengths = many gratings

Compensation schemes

Different compensation options are possible: pre or post compensation. To decide, which option is suitable for a given network, it is recommended to perform numerical simulation of a specific network, providing the answer to this question.



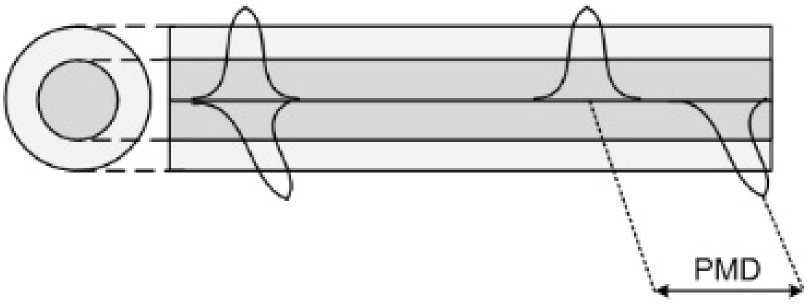
Dispersion compensation schemes for optical networks.

While performing dispersion compensation, one should pay attention not to achieve exactly zero dispersion. On one hand zero dispersion means no pulse spreading, but on the other hand it leads to a nonlinear phenomenon known as **FWM** – *Four Wave Mixing*. Zero dispersion is one of a few conditions to originate it.

8.3 PMD – Polarization Mode Dispersion

PMD – *Polarization Mode Dispersion* originates because of different refractive index for different polarization (polarization practically means oscillations of E or H vector in specific direction), or in other words, because of different refractive index for "x" axis and "y" axis. There is so-called fast axis and slow axis. Such material is called an anisotropic environment. PMD is usually small – couple of picoseconds, however, it can be a problem for high-speed transmission systems.

Finding optimal solutions is problematic, because PMD is a random process. Specialty electronic polarization correctors are used to receive data properly. To avoid PMD, specialty birefringent fibres with strong asymmetry are used.



PMD in an optical fibre.

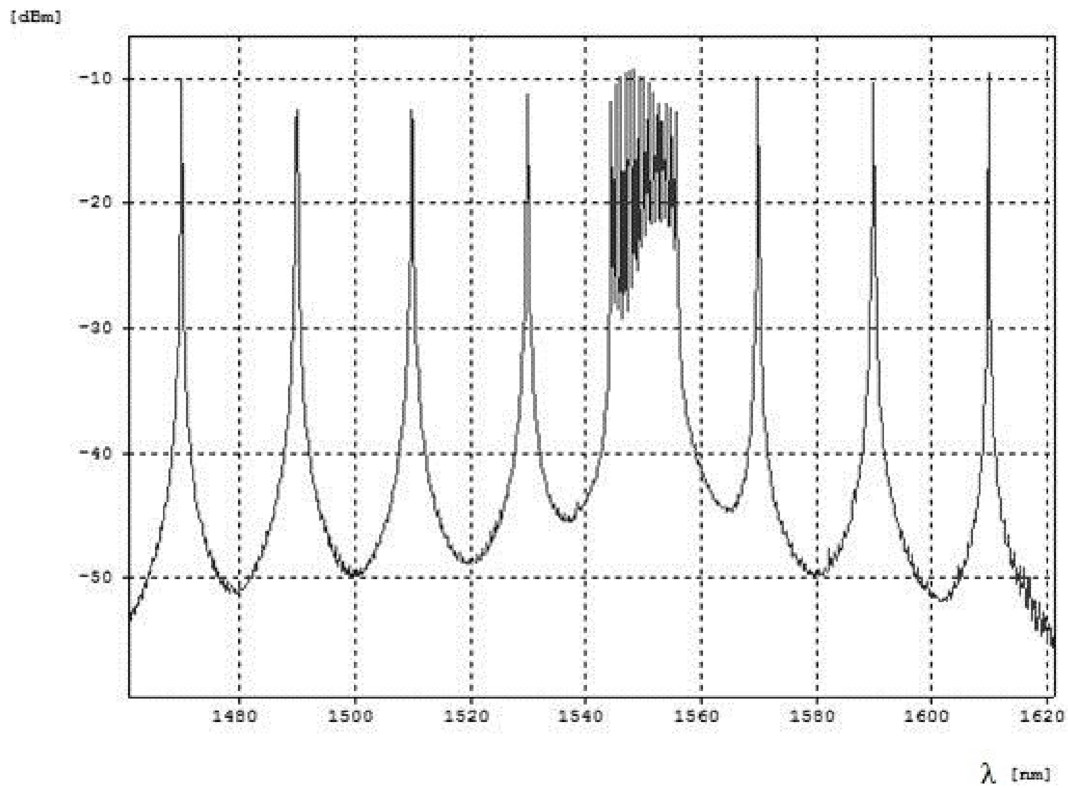
9 Convergence and upgrade of optical networks

9.1 Convergence and upgrade of optical networks

Demand for higher information capacity and bit rates require upgrading existing optical systems or running more systems on one fibre. Coexistence of optical systems refers to CWDM and DWDM networks sharing the passive optical infrastructure.

DWDM over CWDM

- CWDM
  - 8x10 Gbps channels - 1470 nm - 1610 nm.
- CWDM/DWDM
  - Replacement of the 5th channel in CWDM (1550 nm).
  - DWDM with 15x10 Gbps channels with 100 GHz spacing.
  - ΔQuality factor is changed by less than 0.1 dB.

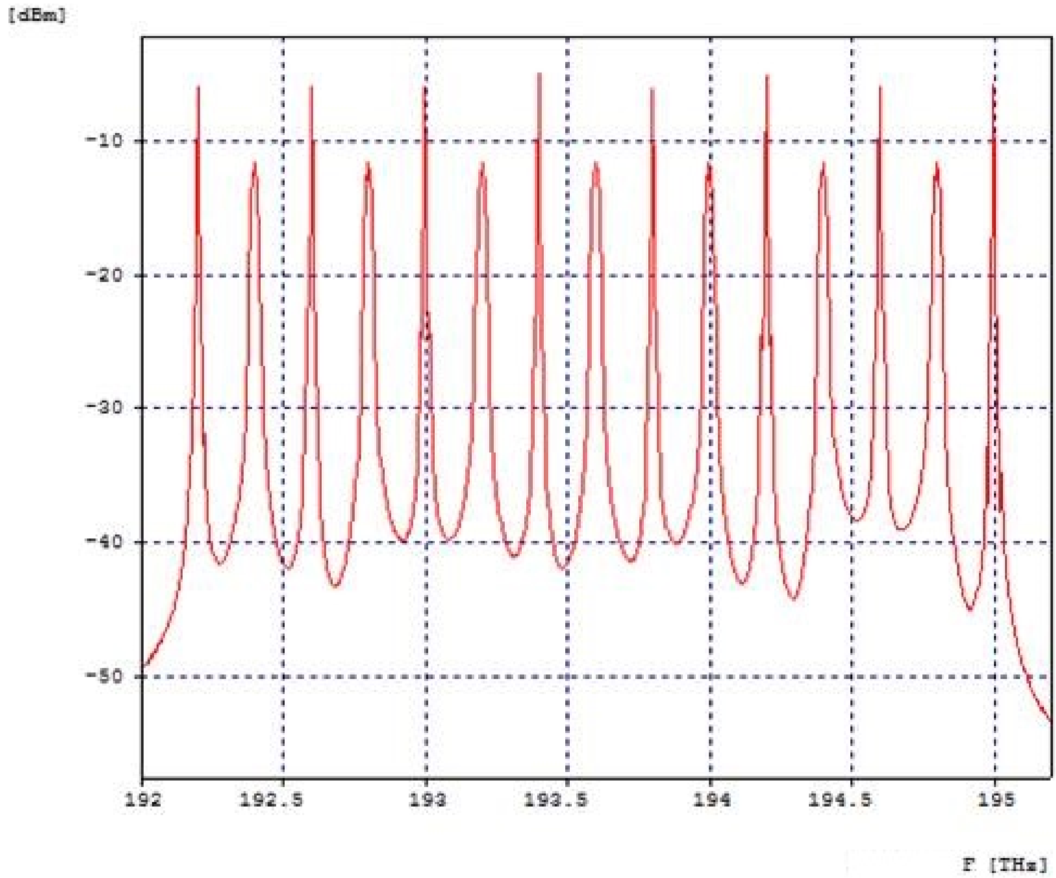


Sample solution for DWDM over CWDM system – optical channels.

Hybrid solutions

Hybrid DWDM 10G/40G

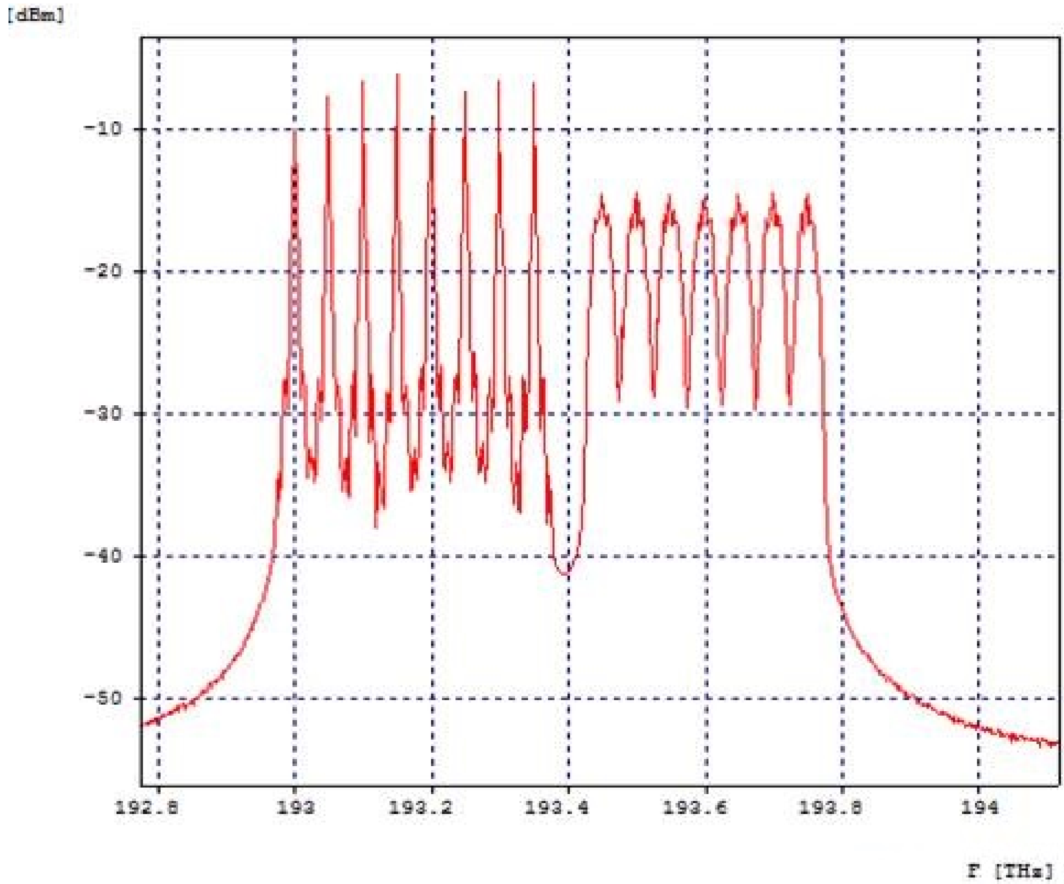
- Initially 10G DWDM system
  - 15x10 Gbps, NRZ-OOK, 50 GHz spacing.
  - 6x80km SSMF (dual phase amplifiers, post-compensation).
- Hybrid DWDM 10G/40G with channel interleaving
  - Combining with 7x40 Gbps system.
  - Duobinary modulation, P-DPSK, RZ-DQPSK modulation formats.
  - Influence of 10 Gbps channels on 40 Gbps channels.
  - *Cross Phase Modulation* (**XPM**) problem.



Optical spectrum of DWDM with channel interleaving.

Hybrid DWDM 10G/40G with safety band

Spectral split of 10G and 40G by safety band can help reducing the cross phase modulation from the 10G system.



Safety band (100 GHz) splitting two systems (RZ-DQPSK and P-DPSK 40G channels).

10 Conclusion

FTTx involve optical networks, depending on network capacity and reach it covers:

- *Passive Optical Networks* (**PON**) - cheap, but bit rates are about 10 Gbps and the reach of a fibre span can be tens of kilometres.
- *Active Optical Networks* (**AON**) - allows achieving high bit rates over 1 Tbps by employing DWDM systems:
  - Solve topology, attenuation, dispersion and nonlinear issues – network planning.
  - Channel rate at least 100 Gbps.
  - Run at least 40 G DWDM over 10 G DWDM.
  - Potential coexistence or convergence of different systems with different specifications.