Basic Note
DWDM Systems

BN 8000
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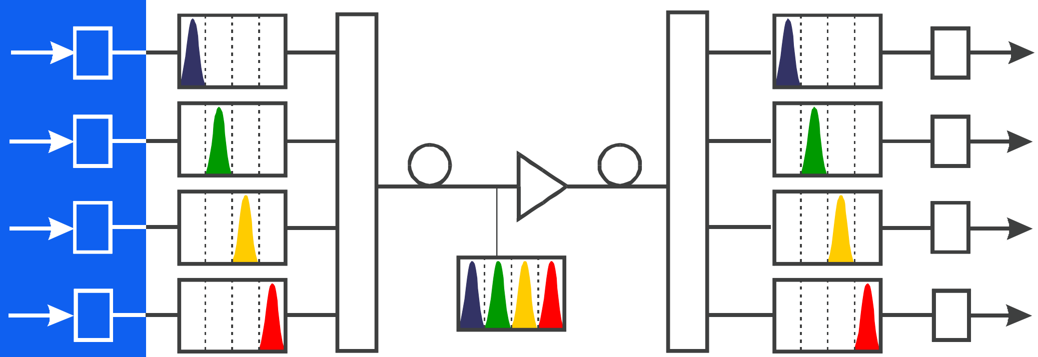

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Basics on DWDM systems

Summary

Due to the internet boom the demand for transmission capacity is growing rapidly. Optical data transmission is the key to meet this requirement.

Principally, there are three possibilities to increase the transmission capacity: space division multiplex (deployment of further transmission cables), time domain multiplex (increasing the data rate) and dense wavelength division multiplex (transmitting several channels via one singlemode fiber).

As in the wavelength range of 1280nm to 1650nm the technically useable bandwidth of the singlemode fiber is 53THz, it is only consequent to take advantage of this large frequency range by using transmitters of different wavelengths.

This note describes the basic structure of a dense wavelength division multiplex system and the requirements to the components of the system. Finally we talk about the most important measurements and have a look at the prospects of future developments.

Contents

1 Two ways to high-bit rate systems

By deploying additional fibers increasing data quantities can be transmitted (SDM: **S**pace **D**ivision **M**ultiplex). This way to increase the transmission capacity is very expensive and does not take any advantage of the high transmission capacity of the singlemode fiber.

space division multiplex

By time domain multiplex (**TDM**) the data rate transmitted via a singlemode fiber can be increased continuously corresponding to the known hierarchies. The costs related to the data rate decrease with the increase in the level of hierarchy.

time domain multiplex

But there are certain limits to TDM: For transmission systems of 10Gbit/s and more, the requirements to the electronics are extremely demanding and the required measurement technique is quite expensive. These systems are still under development. At the moment there seems to be no way to realize a 40 Gbit/s system with TDM only.

A number of physical effects do not allow a mere extrapolation of the previous trends. Especially the requirements to the dispersion properties at these data rates can hardly be fulfilled with already installed fibers.

Therefore starting from 2,5Gbit/s, **combinations** of time domain multiplex (TDM) and wavelength division multiplex (**WDM**) are used (fig. 1). The development has gone into the direction of DWDM systems (**D**ense **W**avelength **D**ivision **M**ultiplex).

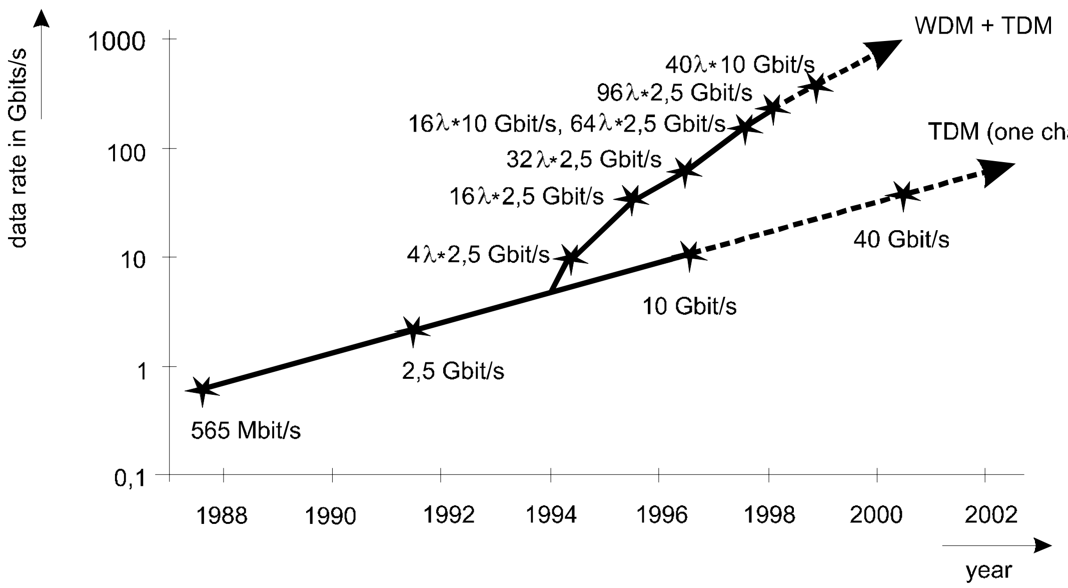


Figure 1: Two ways to high-bit data rate systems [1]

DWDM systems are an advancement of the classical WDM systems. With classical WDM systems a few wavelengths (mostly two) are transmitted via a singlemode fiber.

dense wavelength division multiplex

These wavelengths show a wide spectral distance from each other. They can be coupled into or decoupled from a singlemode fiber by means of conventional wavelength selective couplers (multiplexers / demultiplexers).

Thus, for example, a bi-directional or an unidirectional transmission via a singlemode fiber is realized at wavelengths of 1,31µm and 1,55µm.

Whereas in classical WDM systems the transmission capacity mostly only doubles, in DWDM systems it increases for a factor n=4, 16, 32, 64 or 128 depending on the configuration.

The specification $n\lambda*$data rate in fig. 1 indicates, that **n channels** with differing wavelengths are transmitted via **a singlemode fiber** with the specified data rate.

By multiplexing many wavelengths in one fiber the transmission capacity is increased. The logarithmic subdivision of the ordinate in fig. 1 shows the enormous increase in transmission capacity.

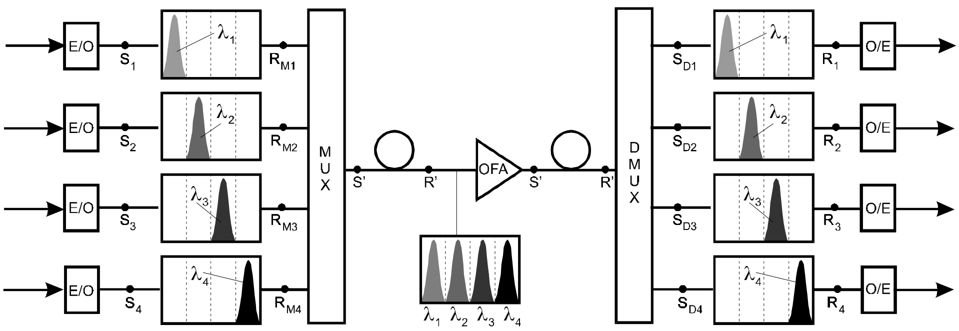
increase in transmission capacity

Besides the **multiplication of the data rate** in a single fiber, DWDM systems have the advantage that the number of channels can be adapted **according to the actual demand**. The provider of the transmission system does not have to invest today in transmission capacity that may only be required some years later. Thus DWDM even gets attractive for the providers of smaller nets, for example, city nets.

In a DWDM system the light of **laser diodes** with wavelengths recommended by the ITU is launched into the inputs of a **wavelength multiplexer** (MUX). At the output of the wavelength multiplexer all wavelengths are then combined and coupled into a singlemode fiber (fig. 2).

At the end of the transmission link the optical channels are separated again by means of a **wavelength demultiplexer** (DMUX) and thus get to the different outputs.

In long transmission links it is necessary that the DWDM signals are optically amplified by an optical fiber amplifier (OFA).



MUX: wavelength multiplexer **DMUX:** wavelength demultiplexer **OFA:** optical fiber amplifier

E/O: transmitter **O/E:** receiver

Figure 2: Set-up of a DWDM system (4 channels) with recommended points for reference measurements

2 Bandwidth and wavelength

2.1 The transmission capacity of singlemode fibers

There is a correlation between the frequency f, the propagation velocity v („phase velocity") and the wavelength λ^*:

$$v = \lambda^* \cdot f \qquad (1)$$

In this the frequency f is determined by **the processes during the generation of radiation**. The **medium**, in which the wave is propagating, **determines** the **phase velocity** v. Consequently, the wavelength λ^* **is no independent quantity.** It results from the frequency and the phase velocity according to the equation (1).

Thus the light has the same frequency but different wavelengths in different substrates. For the propagation in a vacuum it is:

$$c = \lambda \cdot f \qquad (2)$$

In this, c is the **vacuum velocity of light** and λ the wavelength in the vacuum. All correlations stated in the following between frequency and wavelength refer to the wavelengths in the vacuum.

In principle, with the standard singlemode fiber for telecommunication a wavelength range of approx. λ_1=1280nm to λ_2=1650nm can be utilized. In this, the **lower wavelength limit** results from the core diameter of the singlemode fiber.

The **upper wavelength limit** results from the fact that above this limit the attenuation coefficient rapidly increases and the fiber gets very sensitive regarding macro bending.

Corresponding to the equation (2) the resulting **usable wavelength range** is from f_1=235THz to f_2=182THz. In this, THz=Terahertz=10^{12} oscillations per second. Thus the intrinsic transmission capacity of the singlemode fiber is:

intrinsic transmission capacity

$$B = f_1 - f_2 = 53\text{THz} \qquad (3)$$

This transmission capacity is often called „bandwidth of the fiber". From the equation (3) it is obvious that the **transmission capacity** of the singlemode fiber is only used at a **very small scale** at present. A 2,5Gbit/s signal, for example, only uses this bandwidth capacity with 0,005% and a 10Gbit/s signal with 0,02%!

It is obvious that the transmission capacity of a singlemode fiber can be exploited much better by a simultaneous transmission of several wavelengths.

2.2 DWDM wavelengths

For several reasons it is currently not possible to make an unlimited use of the total wavelength range from 1280nm to 1650nm. For a reasonable application of DWDM certain **conditions have to be fulfilled**.

Since DWDM systems are also used to built up long transmission links, **optical amplifiers** have to be employed. These, however, are only working well for the 3. and 4. optical window (about 1550nm to 1610nm) today (see chapter 3.4).

The attenuation and the dispersion properties of a singlemode fiber are wavelength dependent, too. Thus the fibers cannot be used for all wavelengths.

Resulting from these restrictions, the frequencies given in table 1 were recommended by the ITU [2] for DWDM transmission. The **krypton line** at 193,10THz was considered to be the **reference line, 100 GHz** was determined as **channel spacing.**

reference frequency: 193.10THz
channel spacing: 100GHz

These standardized frequencies will be maintained and only be supplemented by **additional frequencies**, for example, for the wavelength range from 1565nm to 1610nm that becomes usable in connection with new optical fiber amplifiers.

Table 1 shows the standardized frequencies and the resulting wavelengths in the vacuum according to the equation (2). For the vacuum velocity of light 299792,458km/s were determined.

Frequency/ THz	Center wavelength/nm		Frequency/ THz	Center wavelength/nm		Frequency/ THz	Center wavelength/nm
195,9	1530,33		194,4	1542,14		192,9	1554,13
195,8	1531,12		194,3	1542,94		192,8	1554,94
195,7	1531,90		194,2	1543,73		192,7	1555,75
195,6	1532,68		194,1	1544,53		192,6	1556,55
195,5	1533,47		194,0	1545,32		192,5	1557,36
195,4	1534,25		193,9	1546,12		192,4	1558,17
195,3	1535,04		193,8	1546,92		192,3	1558,98
195,2	1535,82		193,7	1547,72		192,2	1559,79
195,1	1536,61		193,6	1548,51		192,1	1560,61
195,0	1537,40		193,5	1549,32		192,0	1561,42
194,9	1538,19		193,4	1550,12		191,9	1562,23
194,8	1538,98		193,3	1550,92		191,8	1563,05
194,7	1539,77		193,2	1551,72		191,7	1563,86
194,6	1540,56		193,1	1552,52			
194,5	1541,35		193,0	1553,33			

Table 1: DWDM wavelength according to the ITU recommendation

The channel spacing of 100 GHz in the 3. optical window results – according to the equation (2) – in an average wavelength spacing of 0,8nm.

Fig. 3 shows the multi-channel DWDM laser source PRO 8000 by Profile. Each PRO 8000 mainframe can be equipped with 8 laser source modules with wavelengths according to the ITU recommendation (see table 1) and output powers from 10 to 40mW. Each laser source can be tuned in wavelength via temperature for ± 0.85nm. The desired operating wavelength can be entered directly and is displayed.

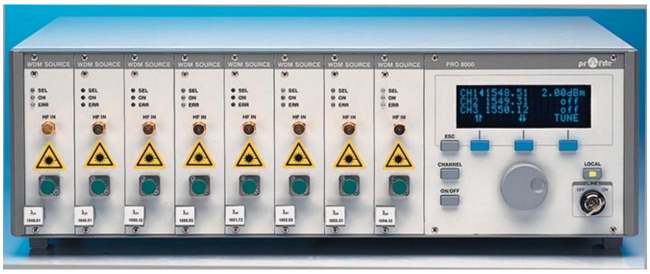


Figure 3: Multi-channel DWDM laser source PRO 8000 by Profile

The PRO 8000 excels in its very high stability in output power (< 0,01dB) and wavelength stability (< 0,01nm) (see chapter 3.1).

3 Components of DWDM systems

3.1 Laser sources

stabilized wavelength

DWDM transmission puts high demands to the components of the system and their parameters. This especially concerns the output wavelengths of the laser sources. The laser diodes must emit exactly at the center wavelengths given in table 1.

Therefore the laser diode for the respective channel is selected individually. The preselected laser can then be fine-tuned to the exact center wavelength, for example, by changing the chip temperature.

To avoid interferences from adjacent transmission channels, the deviations from the center frequencies are not allowed to be more than $\pm 0{,}2 \cdot \Delta f$. At a frequency grid of Δf=100GHz this corresponds to a tolerance of ±20GHz or ±0,16nm. That is why DWDM lasers have to be extremely stable in wavelength and must provide a small linewidth.

The wavelength of the laser diode changes by **aging** (approx. 0,001nm to 0,01nm per year), by **changes in temperature** (approx. 0,02nm/K to 0,1nm/K if the chip temperature changes and approx. 0,002nm/K if the package temperature changes) and by **power back-reflections** into the laser (also refer to BN 1000: Basic Note Laser Diodes).

Therefore, the laser temperature must be stabilized and power back-reflections into the light source must be minimized. Power back into the light source is mainly due to back scattering within the fiber and also due to backreflections at fiber splices and optical connectors. Backreflections at connectors can be reduced drastically by using **high-return-loss connectors,** that provide angled end faces (8°) and a physical contact at the fiber end face.

Additionally an **optical isolator** can be installed directly behind the laser chip. This isolator has a low insertion loss from the laser diode to the fiber and a high insertion loss from the fiber to the laser diode.

DFB lasers (**D**istributed **F**eed**b**ack, refer to BN 1000) are well suited as laser sources for DWDM applications. A DFB laser **emits** highly stable in **singlemode** with an **extremely small linewidth** (approx. 0,0001nm) and can be tuned to the exact ITU center wavelength. DFB laser

If a laser is direct modulated via the laser current, a disturbing effect occurs:
When the laser is switched on it will not immediately oscillate on its center wavelength (= carrier frequency) but it will take a finite time to reach it. This temporary effect, occurring at each fast enough change in current, is called chirping. Chirping may result in a broadening of the spectral linewidth of up to 0,2nm. chirping

This **broadening of the spectral linewidth** has two big disadvantages (fig. 4):

- At dense DWDM systems with low channel spacing the broa-dened spectrum may reach into the adjacent channel and result in **interferences**.
- The broadened signal is increasingly subjected to the chromatic dispersion. The chromatic dispersion results from the fact that light of different wavelengths is propagating at different velocity in a fiber. Signal shares with higher frequency and signal shares with lower frequency do not arrive at the receiver at the same time. Signal distortions are the result. chromatic dispersion

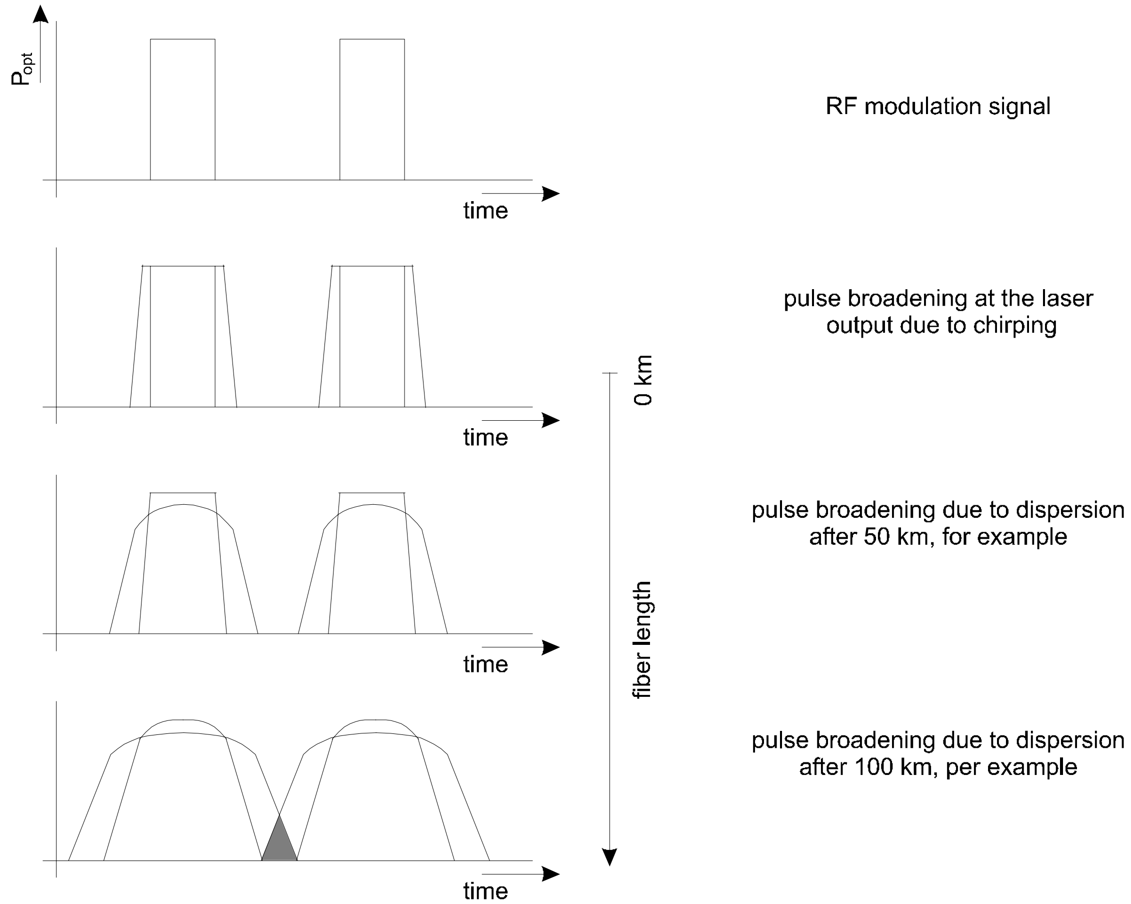


Figure 4: Principle on how the signal is influenced by chirping and dispersion

With optical transmission the carrier of the information (= light) is influenced by the signal (= information) to be transmitted. The allocation of a signal to a carrier is achieved by modulation. The easiest way of modulation in DWDM systems is the direct modulation. The laser is switched on and off (fig. 5).

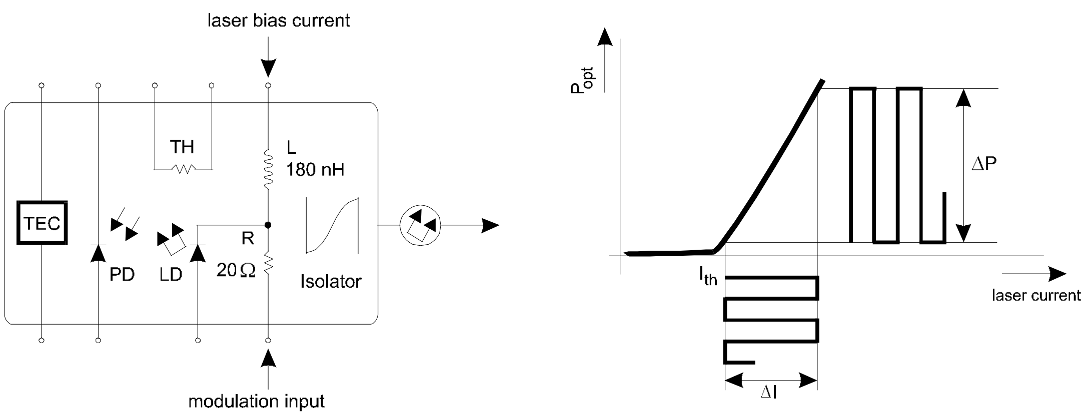


Figure 5: Principle of direct modulation of a laser diode

EA-modulation

A better chirping behavior can be achieved by using for example electro-absorption modulators.
If an additional pn-junction is integrated in a DFB laser chip, the absorption of the wave and thus the laser power can be controlled by an external electrical field applied to this pn-junction. This principle is called electro-absorption modulation (EA modulation) (fig. 6).

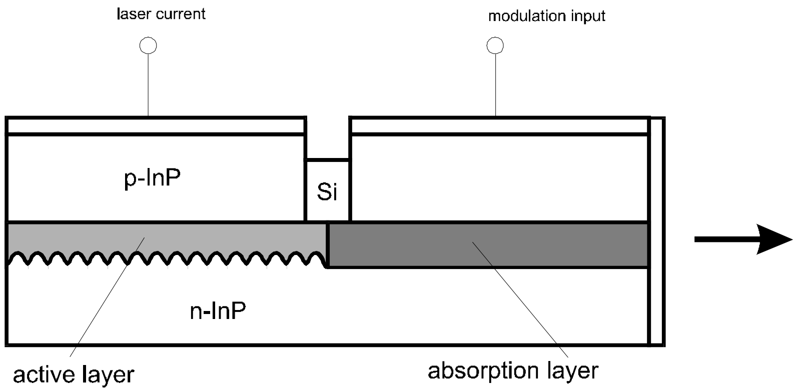


Figure 6: DFB laser with integrated EA modulator

Without this field being applied the light propagates in the fiber almost unattenuated. With the electrical field being applied the attenuation strongly increases due to the **Franz-Keldysh effect**. The optical power is attenuated to only a few percent by amplitude modulation. EA modulation excels in a clearly lower chirping compared to direct modulation.

The DWDM laser sources by Profile are available with either direct or EA modulation.

For higher modulation rates starting at 10 Gbit/s, there are further external electro-optical modulators available. Their inner structure is based on a Mach-Zehnder interferometer structure. Fig. 7 shows a waveguide structure embedded between electrodes.

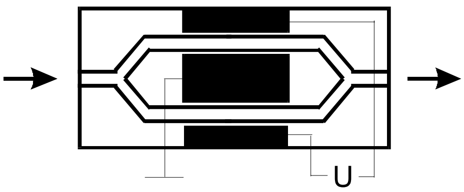


Figure 7: Principle structure of an external electro-optical modulator

The launched light is divided into two identical light paths by a 3-dB coupler. At the end of the modulator the light paths are combined again. An external electrical field changes the propagation time of the light in one path. If the resulting difference in path lengths is λ/2, the two beams will superpose destructively. An extinction of the light is the consequence.

For reasons of completeness, **two further modulation methods** will be given in the following. They are, however, only of subordinate meaning for the DWDM technique.

Pockels effect

The intensity of the light can also be influenced by using the Pockels effect. Here the linearly polarized light of the laser source propagates in an optically active medium. Depending on an applied electrical field the **polarization plane is rotated**.

A polarizer located behind the active medium allows only that part of the light to continue which have the same state of polarization as of the polarizer.

AO modulator

With an acousto - optical modulator (AO modulator), a standing wave wave is generated in a quartz glass bloc by an intensity modulated sound wave. This results in differences in density and the quartz bloc will react as a diffraction grating with a controllable efficiency.

Independent of the modulation method **side frequencies** will occur above and below the carrier frequency (= light). The width of the frequency range covered by the side frequencies is defined as **modulation bandwidth**. It depends on the signal frequency and on the modulation method.

The correlation between signal frequency and carrier frequency represented in fig. 8 can be converted into a wavelength range via the equation (2).

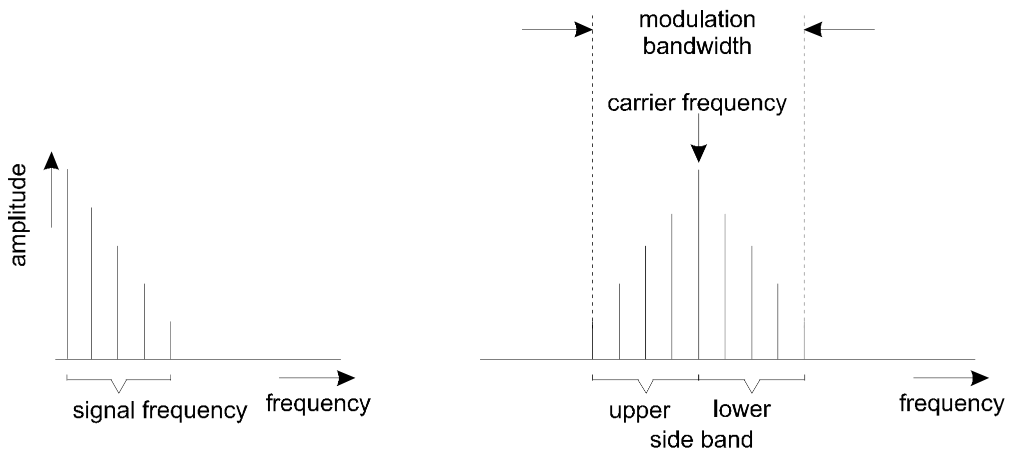


Figure 8: Modulation bandwidth

Using **all technical possibilities,** for the transmission of a 2,5Gbit/s signal a spectral bandwidth of **at least** 0,02nm is required. At a data rate of 10Gbit/s 0,08nm are required proportionally.

Fig. 9 shows the 0,8nm wavelength grid in DWDM systems, considering the allowed tolerances of the center wavelengths and the modulation bandwidth required for a 10 Gbit/s modulation.

Up to a 10Gbit/s modulation in observing the allowed wavelength tolerances there is an adequate **"safety-distance"** between the allowed wavelength ranges (50% of the channel distance).

The situation gets more critical if the channel spacing is reduced to its half (0,4nm). Then the allowed wavelength tolerance will also decrease to its half.

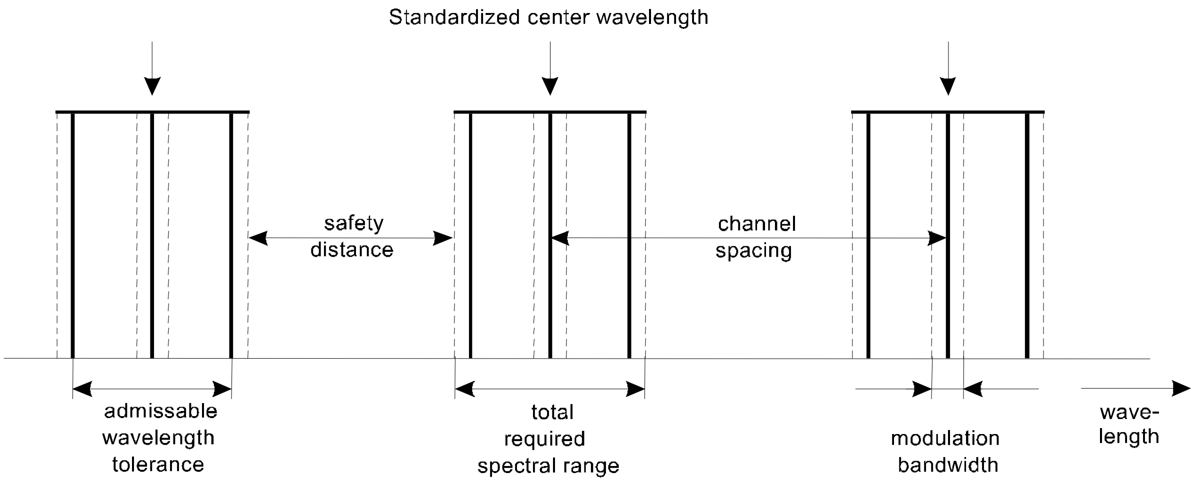


Figure 9: Wavelength grid in a DWDM system

The stability demands to the laser sources have to be increased accordingly. The safety-distance at a 10Gbit/s modulation is then reduced to only 40 %.

Should a wavelength drift away, caused, for example, by a change in temperature or a broadening of the spectral linewidth due to chirping, the safety-distance may decrease rapidly so that the channels will influence each other.

As the safety-distances are rather small, a continuous monitoring of all transmission channels (WDM monitoring) is imperative (see chapter 4.2).

3.2 Multiplexer and demultiplexer

multiplexer ⇔ demultiplexer

Multiplexes and demultiplexers are key components in each DWDM system. Multiplexers (MUX) provide n optical inputs. Each input is equipped with a selective filter for a certain wavelength.

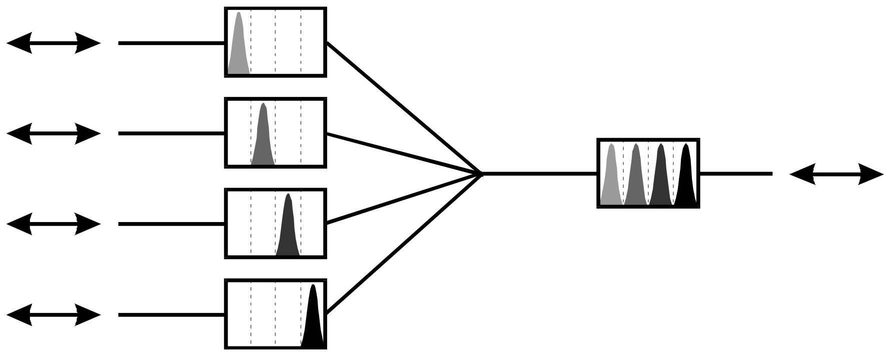


Figure 10: Multiplexer

The outputs of these filters are coupled to one singlemode fiber. At the receiver the wavelengths are separated again by a demultiplexer (DMUX or DEMUX). Multiplexers and demultiplexers are identical components. The only difference is that they are driven in opposite direction (fig. 10).

A special type is the **add/drop-multiplexer**. With an add/drop-multiplexer new channels can be added to and other channels can be dropped off the transmission link (fig. 11).

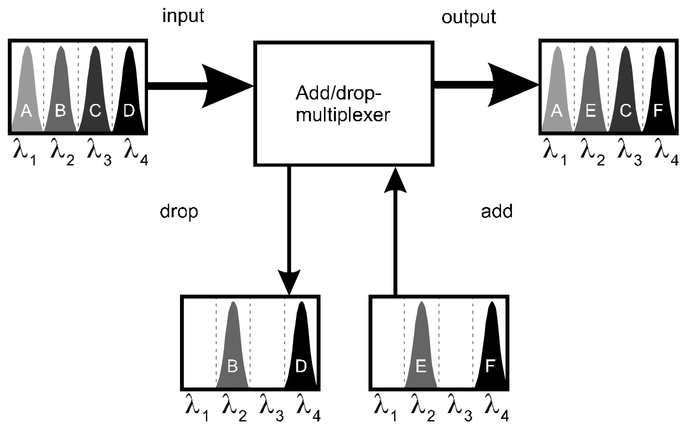


Figure 11: Add/drop-multiplexer

These components are required because, in general, not all transmission channels have the same start and destination. In future transparent optical nets the add/drop-multiplexer will be a key component, too.

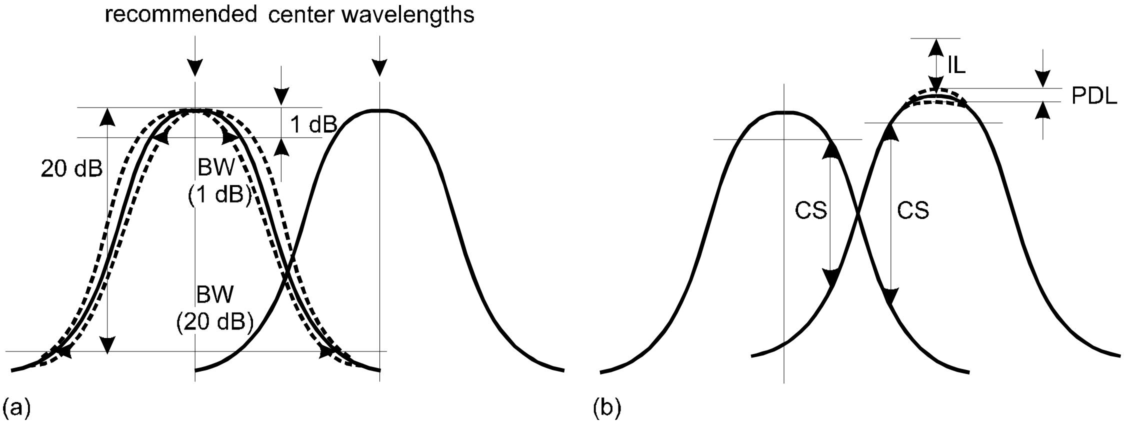


Figure 12: Spectral behavior of two neighboring channels of a multiplexer (a) and definition of the most important parameters (b): IL: insertion loss, PDL: polarization dependent loss, CS: cross talk

The center wavelengths of the multiplexer/demultiplexer have to be **adapted** exactly to the **standardized center wavelengths**. Within the tolerance range of the transmission channel the optical multiplexer / demultiplexer must have a low insertion loss, outside a high insertion loss is required.

Fig. 12 (a) shows the spectral behavior of two neighboring channels of the multiplexer. Typical parameters are the **spectral width** of the transmission band, indicated by a 1dB-drop (BW(1dB)), and the **filter slope**, characterized by a 20dB-drop (BW(20dB)).

Due to the non-ideal filter slope a defined spacing between the single channels is necessary.

The spectral width in the transmission band of the multiplexer / demultiplexer must be wider than the total spectral range required by the laser diode according to fig. 9. Then an insertion loss of <1dB per channel is guaranteed.

For the examples given above, the range required by each channel was 50 % or 60 % of the channel spacing. The ideal case for the transmission band of a multiplexer would even be 80 %. However, this cannot be realized yet.

In multiplexing as well as in demultiplexing the **cross talk** (CS) plays an important role. CS indicates that part of the power that couples over from an adjacent channel. It should be as low as possible.

Since the optical receivers are broad-banded, they cannot distinguish between the information signal and the cross talk. This may cause interferences and lead to a higher bit BER error rate. Demultiplexers have cross talk values of 25dB. More complex networks may require up to 45dB.

Figure 13: Typical spectral behavior of a demultiplexer for 20 channels with 0,8nm channel spacing

Fig. 13 shows the spectral behavior of a real demultiplexer. The **non-uniformity** of the insertion losses of the single channels and the **overlapping areas** are clearly visible.

This figure illustrates the extremely high demands to multiplexers and demultiplexers, especially, if the channel spacing is very small.

Furthermore, the **polarization dependency** of the attenuation of the multiplexer / demultiplexer should be as low as possible to avoid **polarization dependent losses** (PDL).

Multiplexers / demultiplexers are based on **optical gratings** (Bragg gratings or bulk gratings) **or on integrated optical components** (Phasar).

fiber Bragg gratings

3.3 Singlemode fibers

Singlemode fibers that are used for DWDM must have an **insertion loss** as **low** as possible. The hydrogen ions inevitably present in standard singlemode fibers effect an absorption peak at 1385nm (fig. 14) which may cause an attenuation up to 1 dB/km.

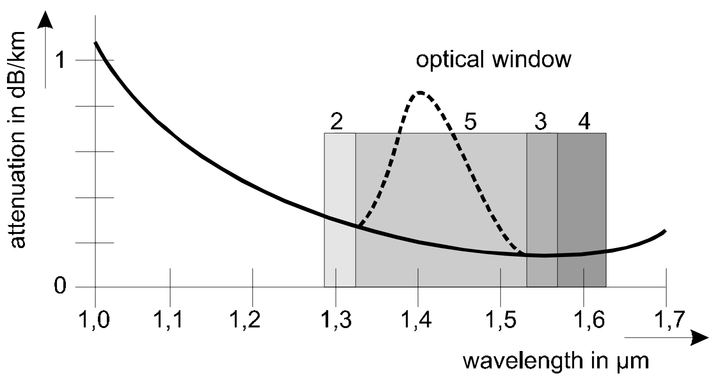


Figure 14: Optical windows in a singlemode fiber

all-wave-fiber

If the so-called 5. optical window is to be used, a special fiber, the all-wave-fiber, is to be used. In this fiber the absorption peak is suppressed by a special technology.

As already mentioned in chapter 3.1, most singlemode fibers show a chromatic dispersion. Since chromatic dispersion leads to increasing signal distortions with increasing transmission distance, a fiber with a very low, or even better, none dispersion must be used.

At real fibers it can be recognized that the dispersion can fluctuate extremely and may also show **zero crossings**.

Therefore, for certain wavelength ranges of a singlemode fiber the transmission is hardly influenced by chromatic dispersion. Other ranges cannot be used with the present methods of data transmission.

However, research has recently found methods that enable to use also these wavelength ranges. Due to the **Soliton management**, signal transmissions with high data rates have been enabled for wavelength ranges that could not be used before.

Despite this fact, with already installed fibers, the transmission of high data rates can only be realized in wavelength ranges where the dispersion is almost zero.

dispersion-shifted fiber

In the 2. optical window standard singlemode fibers have a zero-crossing of the chromatic dispersion. The 3. optical window, which is presently used for the DWDM transmission, therefore requires special fibers where, during manufacturing a refractive index profile has been created at which the zero-crossing of the dispersion is close to 1550nm (fig. 15).

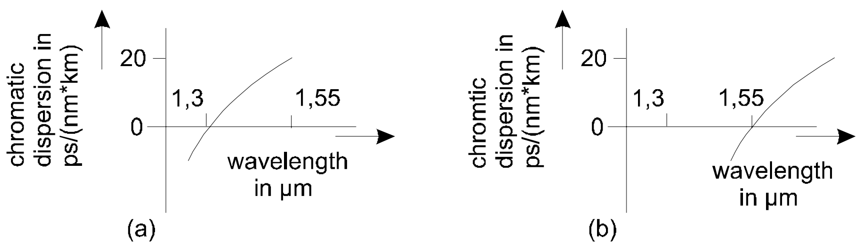


Figure 15: Chromatic dispersion of a standard singlemode fiber (a) and a dispersion-shifted singlemode fiber (b)

polarization mode dispersion

Besides the chromatic dispersion, singlemode fibers also show dependencies of the refractive index on the polarization plane of the propagating radiation. This polarization mode dispersion (PMD) impacts the signals similar to the chromatic dispersion.

Different polarization modes propagate at different speeds in the fiber. In this, the propagation time is subjected to strong statistical fluctuations. The error rate at data transmission increases.

Really disagreeable with the PMD is the fact that it strongly depends on external influences and that it fluctuates statistically (also refer to BN 9000 “Basic Note PMD and Polarization”). The influence of the PMD on the transmission safety gets serious at data rates of more than 2,5Gbit/s. High-bit rate transmission systems should therefore have a PMD compensation for all transmission channels.

Basically, all components used in DWDM systems should be polarization independent.

Besides the linear effects, for example the dispersion, also **non-linear effects** occur in singlemode fibers. Certain properties of the fiber will change, dependent on the field intensity caused by the propagating light.

One of these effects is the four wave mixing. It occurs if several channels are transmitted simultaneously via a singlemode fiber and must therefore be considered in DWDM systems.

four wave mixing

In singlemode fibers the laser light is concentrated in the very small core. This causes high electric field intensities and leads to interactions between light and the substrate which can only be explained with the laws of the **non-linear optics.**

The impact of the non-linearity is low. But it can sum up over long transmission distances if the waves are synchronous in phase.

This synchronism of phases can be disturbed and thus the effect of the four wave mixing be suppressed if the transmission is outside the zero-crossing of the chromatic dispersion. Therefore the chromatic dispersion should be outside the range from **+0,8ps/(nm km) to -0,8ps/(nm km).**

For this reason the **non-zero dispersion fiber** has been developed for high-bit rate DWDM. With this non-zero dispersion fiber it is possible to use an extended wavelength range up to 1620nm (4. optical window, see fig. 14) by suppressing the four wave mixing.

3.4 Optical amplifiers

Since DWDM systems are used for long transmission links, the signal must be amplified after a certain fiber length.

The amplification can be done with an electrical repeater. A repeater converts the optical signal by means of a photodiode into an electrical signal, amplifies the electrical signal and converts it back to an optical signal.

electrical repeater

Fig. 16 (a) shows a 1-channel system above and a DWDM system below with electrical amplification.

You will recognize that within the multi-channel system **each single channel** requires a separate opto-electrical transformation, amplification and electro-optical transformation back. Thus, for an n channel system n repeaters are required.

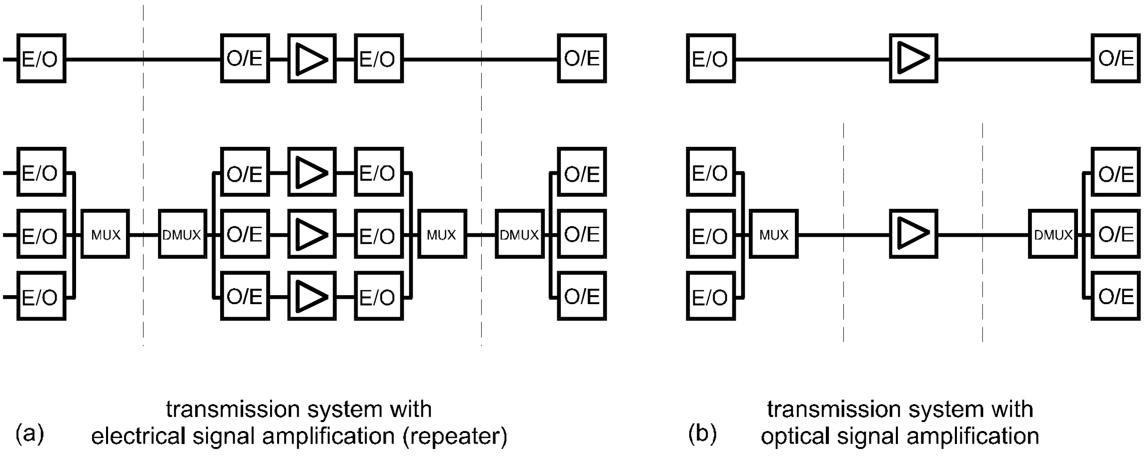


Figure 16: 1-channel system (above) and DWDM system (below) with electrical (a) or optical (b) signal amplification

A further disadvantage is that with a given repeater only a given protocol at a fixed data rate can be transmitted. Therefore it is more reasonable to use optical amplifiers in DWDM systems.

Fig. 16 (b) shows a 1-channel system above and a DWDM system below with optical amplification. In comparing the two multi-channel DWDM systems the **superiority of using an optical amplifier becomes obvious.**

fiber optic amplifier

The optical amplification is **independent** of the bit rate as well as of the transmission capacity. Thus, optical amplifiers are of special interest for DWDM systems. Furthermore, the optical amplifier is independent of the data protocol. It operates without converting the signal into the electrical range.

Until now **optical amplifiers** with appropriate features have been available for the **3. optical window** only. Suitable optical amplifiers for the **4. optical window** are being developed now. Therefore, DWDM systems can soon be realized in the 3. and the 4. optical window up to 1610nm (L-band, long wavelength).

L-band

The usable wavelength range for DWDM systems thus strongly depends on the availability of appropriate optical amplifiers.

Analyses found out that DWDM systems show a clear advantage in price in comparison to TDM systems if larger transmission distances have to be covered where an amplification is necessary.

Up till now, mainly fiber optic amplifiers for the 3. optical window around 1550nm have been on the market, the so-called EDFAs (**Er**bium **D**oped **F**iber **A**mplifier). Nowadays also amplifiers for the **wavelength range from 1565nm to 1610nm** are being developed. Different principles of amplification are here being discussed.

Fiber amplifiers for the 2. optical window around 1310nm are still in the stage of research, for example by using praseodymium doped fluoride fibers (PDFA: **P**raseodymium **D**oped **F**iber **A**mplifier).

4 Measurements at DWDM systems

4.1 Measuring the dispersion

In singlemode fibers the chromatic dispersion is the **dominating kind of dispersion** at low data rates. The measurement set-up to characterize the chromatic dispersion is sophisticated and expensive. A suitable field measurement method is not available. Usually the chromatic dispersion is not measured at installed fibers.

The chromatic dispersion is normally specified by the manufacturer of the transmission cable. Due to improper deployment of the cable the attenuation of the single fibers may increase, the dispersion, however, will rather decrease.

The chromatic dispersion of singlemode fibers D_{CHROM} together with the spectral width $\delta\lambda$ of the laser source determine the usable channel width B_K, that can be used for transmission over a distance L. For the pulse broadening t_H due to chromatic dispersion it is:

$$t_H = \delta\lambda \cdot L \cdot D_{CHROM} \qquad (4)$$

pulse broadening

This results for the channel width in:

$$B_K \sim \frac{0{,}4\ldots0{,}5}{t_H} \qquad (5)$$

channel width

It is important that already when designing a DWDM system the chromatic dispersion is kept as low as possible by using suitable fibers.

A 2,5Gbit/s transmission can be realized over more than 400 km by using an externally modulated DFB laser and a standard singlemode fiber in the 3. optical window.

Since with externally modulated DFB lasers the bandwidth increases proportional to the data rate (see chapter 3.1), the **transmission distance decreases with the square of the data rate.**

Consequently, in a 10 Gbit/s transmission via a standard singlemode fiber the chromatic dispersion will already have a limiting effect after approx. 25 km.

Then, for a transmission in the 3. optical window a **dispersion-shifted fiber** or a **non-zero dispersion fiber** is required.

Besides the chromatic dispersion the polarization mode dispersion (also refer to BN 9000) may cause signal distortions. With the PAT 9000 B Profile offers a sophisticated measurement system for reliable evaluation of the PMD.

polarization mode dispersion

The PMD of common singlemode fibers normally enables a transmission of up to 2,5Gbit/s over 100 km without problems.

During the production of modern fibers an **oscillating, stress-free twist** is introduced into the fiber. This forces a strong coupling of all modes. It results in a decrease in the absolute values and in a decrease in the fluctuations of the PMD. These fibers enable a 10Gbit/s transmission over more than 400km.

However, the PMD is subjected to strong statistical fluctuations that can influence the transmission quality considerably. Therefore, a PMD compensation at the receiving end is imperative if already installed fibers are to be used to transmit data rates of more than 2,5Gbit/s. Profile will be offering a suitable PMD compensator soon.

4.2 Spectral measurements

During installation and operation of a DWDM system continuous **spectral measurements are required**. This is called spectral management.

spectral management

For this purpose defined **measurement points** are recommended in the DWDM system (see fig. 2). These measurement points should be recommended by the supplier of the DWDM system and must be low in backreflections.

DWDM systems are very complex. Although the manufacturers specify their components, the installation in the field may deteriorate their properties. Tolerances in the parameters as well as interactions between the components may influence the transmission quality negatively.

By using **an optical spectrum analyzer** (OSA) various measurements can be done. It is possible to determine the single wavelengths and their drifts. The optical power of each channel and the total power can be measured. And it is also possible to measure the differences in power between the single channels. Finally with an OSA the signal-to-noise ratio and the cross talk can be determined (fig. 17).

optical spectrum analyzer

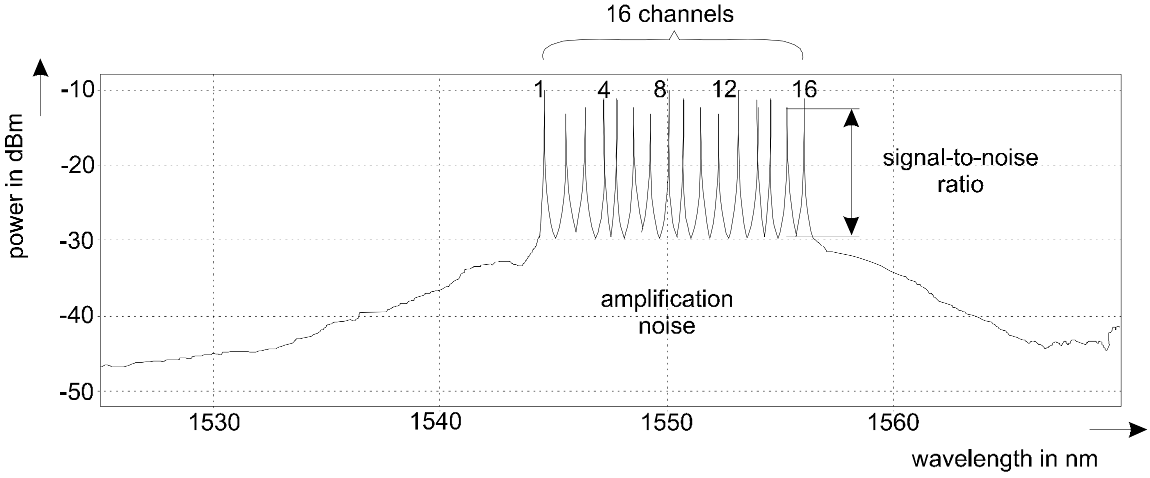


Figure 17: Typical DWDM spectrum

WDM monitor

Also during operating a DWDM system all these parameters have to be monitored continuously. The reason is rather simple: if an error occurs on one transmission channel, for example the complete failure of a laser source, the provider of the transmission link must be able to switch this channel to a standby channel quickly (< 50ms).

4.3 Measuring the bit error rate

In addition to the signal-to-noise ratio it is necessary to measure the dispersion depending differential group delay at high-bit data rates.

Each single channel is characterized by its **own bit error rate**. Therefore, for a bit error rate measurement the single channels have to be selected.

This may be done by means of a spectrometer if it disposes of an optical output. The spectrometer will then have the effect of a **tunable demultiplexer** (fig. 18).

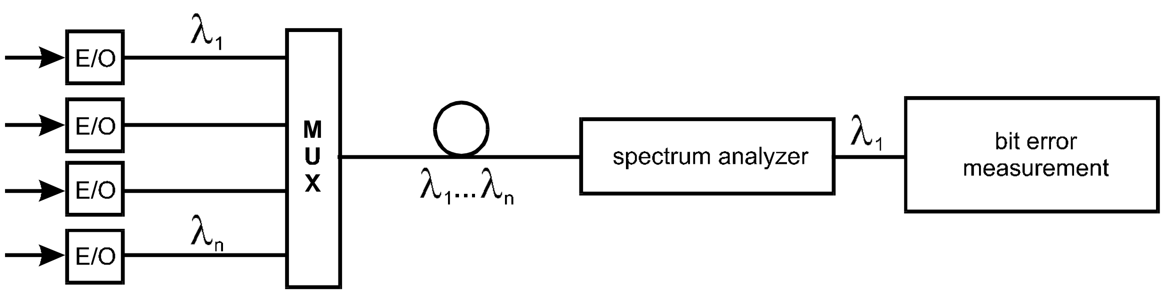


Figure 18: Bit error rate measurement in a DWDM system

The growing demands to the bit error rates and the increasing number of channels result in very time consuming measurements.

5 Future developments

5.1 Extension of the wavelength range

Current trends aim at a better utilization of the **intrinsic bandwidth** of the singlemode fiber. This can be achieved in two ways:

One way is to decrease the channel spacing. Presently standardized and mainly applied are DWDM systems with a channel spacing of 100GHz (see table 1).

decreasing the channel spacing

Recent experiments try to reduce the channel spacing to 50GHz. However, this drastically increases the demands to all components of the system.

The other way is to open up to a larger wavelength range for transmission. The corresponding possibilities have already been described in chapter 3.

extending the wavelength range

If DWDM systems are operated together with optical amplifiers, the so-called **C-band** is available for the wavelength range from 1530nm to 1560 nm and the so-called **L-band** for the range from 1565nm to 1610nm. The multi-channel laser source PRO 8000 by Profile is already available with laser sources in the L-band.

C-band

L-band

If the DWDM system is operated without optical amplifiers, the total singlemode wavelength range from 1280nm to 1650nm could be used. However, suitable laser sources are not available yet for the total range. Furthermore, a fiber with minimized attenuation and dispersion properties that avoids non-linear effects must be used for the respective wavelength range (see chapter 3.3).

5.2 Photonic nets

At present, DWDM systems are mainly used for point-to-point transmissions. In future, photonic nets will be installed. Data will then be transmitted optically only.

If both, transmission and routing are effected optically, the net will be optically transparent. There will be no opto-electronic interface between transmitter and receiver anymore.

optically transparent

The installation of photonic nets requires the development of special, highly sophisticated techniques and components. The following components will be a must for future photonic nets:

- **Add/drop-multiplexers**
- **Routing modules**: enable signal distribution
- **Optical cross connectors**: switch optical signals of any input lines to any output lines by means of mechanical, optical or thermo-optical methods
- **Dispersion compensating components**

6. Literature

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[2] ITU -T-Recommendation G.692: Optical Interfaces for Multichannel
Systems with Optical Amplifiers.