CHAPTER 5

ACTIVE AND PASSIVE COMPONENTS / SUBSYSTEMS

Introduction

This Chapter describes the characteristics of the most relevant components of the optical fibre systems such as optical transmitters, sources and modulators (Clause 1), optical receivers (Clause 2), optical amplifiers and their different applications (Clause 3), adaptive chromatic dispersion compensators (Clause 4), PMD compensators (Clause 5), OADMs / ROADMs (Clause 6), Photonic Cross-Connects (Clause 7). Optical wavelength MUX/DMUX, regenerators and transponders, optical attenuators and optical branching devices are dealt with in Clauses 8, 9, 10 and 11.

1 Optical Transmitters

The objective of the optical transmitters is to convert an electrical input signal into a corresponding optical signal and then launch it into the optical fibre serving as a communication channel. The major components of optical transmitters are the optical sources and the modulators.

Optical transmitters use semiconductor optical sources such as light-emitting diodes (LEDs) and semiconductor lasers because of several advantages offered by them, such as compact size, high efficiency, good reliability, correct range of wavelengths, small emissive area compatible with fibre-core dimensions, and possibility of direct modulation at relatively high frequencies.

In some cases, a direct modulation is not suitable and an external modulator is necessary. The two most used types of optical modulators developed for optical systems are the electro-absorption modulator and the $LiNbO_3$ modulator with a Mach-Zehnder (MZ) interferometer.

The parameters which characterize the optical transmitters are dealt with in Chapter 6.

1.1 Light-emitting diodes

A light-emitting diode (LED) is a device that emits light (optical signal) when voltage (electrical signal) is applied across its two terminals. In this way an LED converts an electrical data signal into a corresponding optical signal. An example LED is shown in Figure 5-1.

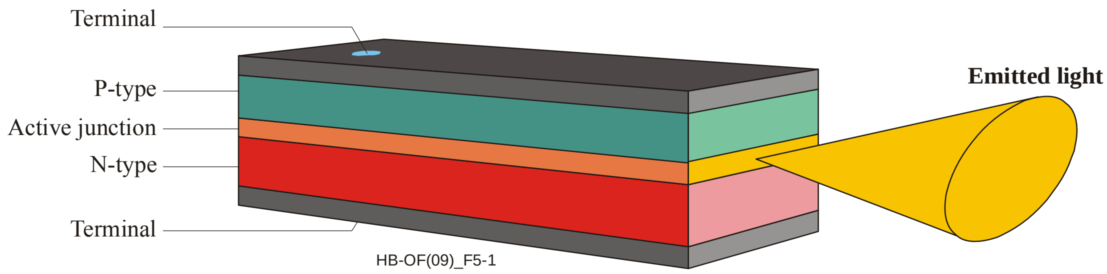


Figure 5-1 – Example LED

The main characteristics of LEDs are the following:

i) LEDs transmit light within a relatively wide cone. The power coupled into the fibre depends on many parameters, such as the numerical aperture of the fibre and the distance between fibre and LED. With a proper design, LEDs can couple up to 1% of the internally generated power into an optical fibre;

ii) LEDs emit a limited optical power (≈ a few mW);

iii) LEDs exhibit a relatively wide spectral width ($\Delta\lambda$ = 50-70 nm). Because of this large spectral width, the bit rate – distance product (BL) is limited considerably by fibre dispersion;

iv) Modulation bandwidth of LEDs is in the range 50-140 MHz;

v) LEDs are inexpensive relative to laser diodes.

In spite of a relatively low optical power and low modulation bandwidth compared with those of lasers, LEDs are useful for low-cost applications requiring data transmission at bit rates of 100 Mbit/s or less over a few kilometres.

1.2 Semiconductor Lasers

Semiconductor lasers (Light Amplification by Stimulated Emission of Radiation) are also devices which convert an electrical input signal into a corresponding optical signal and launch it into the optical fibre (Figure 5-2). The difference from LEDs is that lasers emit light trough stimulated emission.

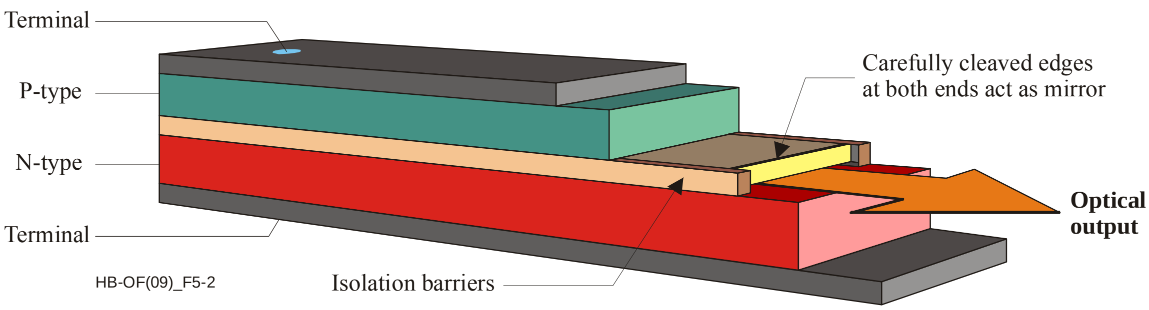


Figure 5-2 – Laser structure based on the Fabry-Perot principle

As a result of the stimulated emission, they have the following characteristics:

i) a relatively narrow angular spread of the output beam compared with LEDs which permits high power coupling efficiency (≈ 50%) into single-mode fibres;

ii) emission of high powers (≈ 100 mW for transmitter lasers);

iii) a relatively narrow spectral width of emitted light which allows operation at high bit rates (>40 Gbit/s), since fibre dispersion becomes less critical for such an optical source;

iv) possibility to be directly modulated at high frequencies (up to 25 GHz).

In spite of their higher cost and technological complexity, most optical communication systems use semiconductor lasers as an optical source because of their superior performance compared with LEDs.

1.2.1 Types of lasers

A *Fabry-Perot (FP) laser* generally emits light in several longitudinal modes. Some of neighbouring modes on each side of the main mode carry a significant portion of the laser power together with that of the main mode. Such lasers are called *Multi Longitudinal Mode* (MLM) *semiconductor lasers*. Since each mode propagates inside the fibre at a slightly different speed because of group-velocity dispersion, the multimode nature of these semiconductor lasers limits the bit-rate-distance product BL to values below 10 (Gbit/s)-km for systems operating near 1.55 μm.

Distributed Feedback (DFB) semiconductor lasers are designed such that the power carried by the side modes is usually a small fraction (< 1 %) of the power of the main mode. Such lasers are called Single Longitudinal Mode (SLM) semiconductor lasers. Despite their technological complexity, DFB lasers are routinely produced commercially and are used in nearly all 1.55 μm optical communication systems operating at bit rates of 2.5 Gbit/s and more.

Multi-section DFB lasers. Modern WDM lightwave systems require, as said above, single-mode, narrow-linewidth lasers whose wavelength remains fixed over time. DFB lasers satisfy this requirement, but their wavelength stability comes at the expense of tunability. The large number of DFB lasers used inside a WDM transmitter make the design and maintenance of such a lightwave system expensive and impractical. The availability of semiconductor lasers whose wavelength can be tuned over a wide range would solve this problem. Multi-section DFB lasers meet the somewhat conflicting requirements of stability and tunability. In this type of laser, the laser wavelength can be tuned almost continuously over a large range of wavelengths (35-40 nm).

Vertical-Cavity Surface-Emitting Lasers (VCSELs) also operate in a single longitudinal mode. Their specific properties result in a number of advantages (wavelengths can be tuned over wide range, low-cost packaging, etc.). However, their main disadvantage is that they cannot emit more than a few milliwatts of power. For this reason they are mostly used only in local area networks where they have virtually replaced LEDs.

1.3 Optical sources reliability

An optical transmitter should operate reliably over a relatively long period of time (10 years or more) in order to be useful as a major component of optical systems. By far the major reason for failure of optical transmitters is the optical source itself. It is common to quantify the lifetime by a parameter known as "mean time to failure" (MTTF). Its use is based on the assumption of an exponential failure probability. Typically the MTTF of the optical sources should exceed 10^5 hours (about 11 years).

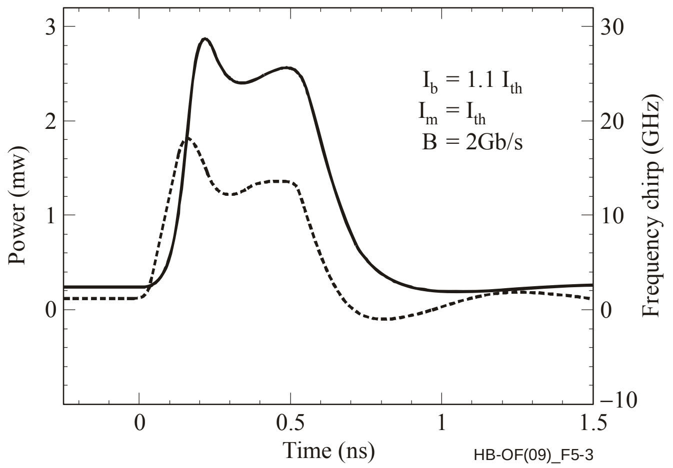
Both LEDs and semiconductors lasers can stop operating suddenly (catastrophic degradation), or they may exhibit a gradual mode of degradation in which the device efficiency degrades with aging. Attempts are made to identify devices that are likely to degrade catastrophically. A common method is to operate the device at high temperatures and high current levels. This technique is referred as accelerated aging.

Extensive tests have shown that LEDs are normally more reliable than semiconductor lasers under the same operating conditions. Nevertheless the reliability of semiconductor lasers is large enough to allow their use also in submarine optical systems designed to operate reliably for a period of 25 years.

It is important to say that, because of the adverse effect of high temperature on device reliability, most transmitters use a thermoelectric cooler to maintain the source temperature near 25°, even when the ambient temperature may be high as 80°.

1.4 Optical modulators

In optical systems the laser can be directly modulated by large signal, but the optical pulses do not have sharp leading and trailing edges and exhibit a rise time (≈ 100 ps) and a fall time (≈ 300 ps). As a consequence the optical pulse from the direct modulation is not an exact replica of the applied electrical pulse (Figure 5-3), even if deviations are small enough that semiconductor lasers can be used in practice.



Note – The solid curve shows the pulse shape and the dashed curve shows the frequency chip imposed on the pulse.

Figure 5-3 – Modulation response of a semiconductor laser

The problem is that amplitude modulation (from the direct modulation) in semiconductor lasers is accompanied by phase modulation. A time-varying phase is equivalent to transient changes in the mode frequency. Such a pulse is called "chirped". The dashed line in Figure 5-3 shows the frequency chirp across the optical pulse. Such a frequency shift implies that the pulse spectrum is considerably broader than that expected in the absence of frequency chirp. This means that the frequency chirp can limit the performance of optical systems due to the increase of the dispersion impairments. It turns out that 1.55 μm optical systems with direct modulation can be limited to distances below 100 km, even at a bit rate of 2.5 Gbit/s, because of the frequency chirp.

Higher bit rates and longer distances can only be realized with a laser continuously operated and with an external modulator placed next to the laser. In this way the frequency chirp due to direct modulation can be avoided. In practice, optical systems operating at 10 Gbit/s, or more, use external modulators.

There are two most used types of external optical modulators used in optical systems. The first type is the *electro-absorption modulator*, which has the advantage that it is made using the same semiconductor material that is used for the laser, and thus it can be easily integrated on the same chip. The second type is the *$LiNbO_3$ modulator with a Mach-Zehnder (MZ) interferometer* for intensity modulation.

The performance of an external modulator is quantified through the on-off ratio (called also "extinction ratio") and the modulation bandwidth. Modern $LiNbO_3$ modulators provide an extinction ratio in excess of 20 dB (measured at low frequency) and can be modulated at speeds up to 75 GHz, suitable for system bit rates of 10 Gbit/s and of 40 Gbit/s.

One can even design a modulator to reverse the sign of the chirp resulting in improved system performance (see Chapter 7).

2 Optical receivers

The role of an optical receiver is to convert the optical signal back into electrical form and recover the data transmitted through the optical system. Its main component is a *photodetector* that converts light into electricity through the photoelectric effect. The requirements for a photodetector are similar to those of an optical source (compact size, high efficiency, good reliability, right wavelength range, small emissive area compatible with fibre-core dimensions). These requirements are best met by photodetectors made from semiconductor materials.

The most widely used photodetectors are PIN photodiodes and avalanche photodiodes.

The optical parameters which characterize the optical receivers are described in Chapter 6.

PIN photodiodes. PIN (pronounced “pee-eye-en”) photodiodes have a layer of undoped (or lightly doped) semiconductor material between the p- and n-doped regions. Since the middle layer consists of nearly intrinsic material, such a structure is referred as a p-i-n photodiode. Most of the incoming photons are absorbed in the intrinsic region, and carriers generated therein can efficiently contribute to the photocurrent.

The responsivity (output current / input optical power) is one of the most important parameters that characterize a PIN.

Avalanche photodiodes (APD). Avalanche photodiodes differ in their design from that of PIN photodiodes mainly in one respect: an additional layer is added in which secondary electron-hole pairs are generated through impact ionization.

The responsivity (output current / input optical power) of an APD is about two orders of magnitude higher than that of a PIN photodiode.

3 Optical amplifiers

(For further information, see Recommendations ITU-T G.661, ITU-T G.662 and ITU-T G.663.)

The transmission distance of optical fibre systems is generally limited by fibre losses. For long-haul systems, the loss limitation has traditionally been overcome using regenerators (see § 8), in which the optical signal is first converted into an electric current and then regenerated using a transmitter. Such regenerators become quite complex and expensive for wavelength division multiplexed (WDM) systems. An alternative approach to compensate this loss makes use of optical amplifiers, which amplify the optical signal directly without requiring its conversion to the electrical domain. Several types of optical amplifiers were developed during the 1980s and the use of optical amplifiers for long-haul optical systems became widespread during the 1990s.

3.1 Application of optical amplifiers

Optical amplifiers (OAs) are devices based on conventional laser principles. They receive one or more optical signals, each within a window of optical frequencies and simultaneously amplify all wavelengths. That is, they coherently release more photons at each wavelength.

Application of OAs in optical transmission systems offers a number of advantages. Chief among these advantages is the ability to realize very long unregenerated system lengths. Deployment of OAs is likely to permit the retirement of many existing conventional regenerator sites and, in the case of new routes, to render unnecessary the construction of many new sites. OAs also enable consideration of new optical system architectures for application in terrestrial and submarine long haul and access networks. Two examples of this are wavelength division multiplexing and point-to-multipoint applications, approaches heretofore generally considered prohibitively complex and expensive. OAs also offer potential advantages with respect to network upgrade options, due to their independence from modulation format and bit rate.

However, the application of OAs also brings to light some new and potentially serious system impairments, which result from the high power levels produced by the OAs and the long distances between regeneration. These transmission effects include optical fibre nonlinearities, polarization effects and effects due to the amplification characteristics of the OA itself. Chromatic dispersion also becomes increasingly significant for the long unregenerated systems enabled by the OA. In addition the dispersion characteristics of the fibre influence the severity of the impairment produced by several of the dominant nonlinear effects. In the following the OA applications are described.

OAs find application in single-channel and in multichannel systems. In addition to the transmission impairments found in single-channel systems, multichannel systems may also suffer degraded performance due to certain non-linear effects. These include four-wave mixing (FWM), cross phase modulation (XPM) and, potentially, stimulated Raman scattering (SRS). As a result, special precautions must be taken when designing multichannel systems to avoid or alleviate these impairments (see Chapter 7).

3.1.1 Booster amplifier

The booster (power) amplifier (BA) is a high saturation-power OA device to be used directly after the optical transmitter to increase its signal power level. The BA does not need stringent requirements for noise and optical filtering.

The application of BAs (often in conjunction with pre-amplifiers) is very attractive, especially in those cases where intermediate locations with active equipment are either undesirable or inaccessible, as in submarine systems. In any case, fewer intermediate locations imply easier maintenance for the network operator.

Because of the relatively high level of input power, the undesirable amplified spontaneous emission (ASE) noise, inherently present due to the statistical process of photon generation inside the OA, is usually negligible. However, application of BAs may result in fibre nonlinearity induced system penalties, due to the high optical power levels produced by BAs and the long interactive lengths provided by the optical path.

3.1.2 Pre-amplifier

The pre-amplifier (PA) is a very low noise OA device to be used directly before an optical receiver to improve its sensitivity. The requisite low level of ASE noise may be achieved through the use of narrow-band optical filters. In this case, automatic tuning of the centre wavelength of the pre-amplifier filter to the transmitter wavelength would be advantageous, since it would permit the relaxation of requirements on both the initial transmitter wavelength tolerance and its long-term stability. As noted previously, the use of PAs (usually in conjunction with BAs) is a straightforward means to realize significant increases in available power budget.

3.1.3 Line amplifier

The line amplifier (LA) is a low-noise OA device to be used between passive fibre sections to increase the regeneration lengths or, in correspondence with a multipoint connection, to compensate for branching losses in the optical access network.

As noted previously, line amplifiers might replace some or all conventional regenerators in long-haul fibre sections. It can be envisioned that more than one conventional regenerator can be replaced by a single LA, with the evident advantage of reduced equipment in transmission links. Furthermore, a situation can be envisaged where both line amplifiers for compensation of signal attenuation and conventional regenerators for compensation of signal distortion appear in long-distance networks.

A typical configuration of an OA (as LA) in a multichannel application is shown in Figure 5-4.

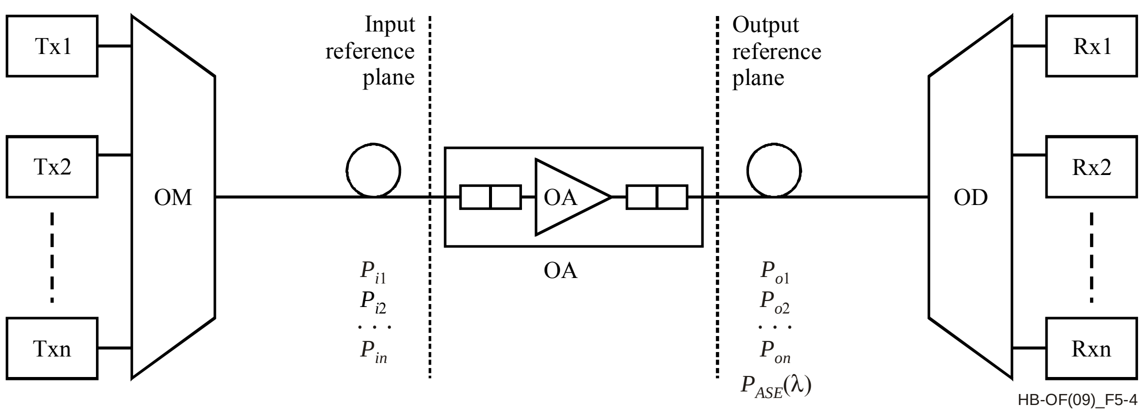
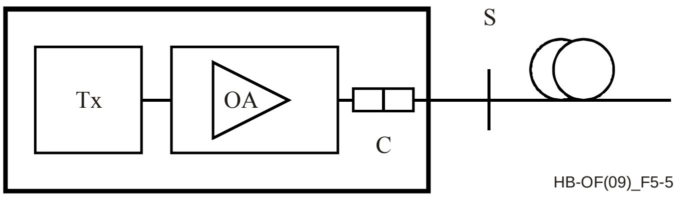


Figure 5-4 – Line amplifier in a multichannel application

At the transmitting side *n* signals, coming from *n* optical transmitters, Tx1, Tx2, . . . Txn, each with a unique wavelength, λ_1, λ_2, . . . λ_n, respectively, are combined by an optical multiplexer (OM). At the receiving side, the *n* signals at λ_1, λ_2, . . . λ_n, are separated with an optical demultiplexer (OD) and routed to separate optical receivers, Rx1, Rx2, . . . Rxn, respectively.

3.1.4 Optically amplified transmitter

The optically amplified transmitter (OAT) is an OA sub-system in which a power amplifier is integrated with the laser transmitter, resulting in a high-power transmitter (Figure 5-5).



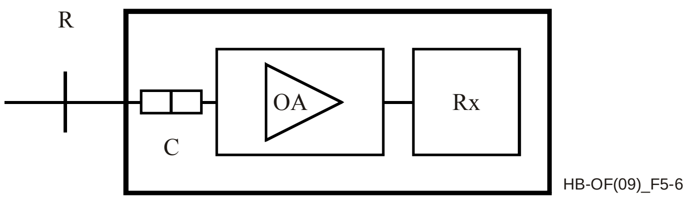
S Reference point in the optical fibre just after the optical connection (C) of the OAT

Figure 5-5 – OAT reference diagram

The connection between the transmitter and the OA is proprietary and it is not specified. The application considerations of OATs are generally the same as those for BAs.

3.1.5 Optically amplified receiver

The optically amplified receiver (OAR) is an OA sub-system in which a pre-amplifier is integrated with the optical receiver, resulting in a high sensitivity receiver (Figure 5-6).



R Reference point in the optical fibre just before the optical connection (C) of the OAR

Figure 5-6 – OAR reference diagram

The connection between the receiver and the OA is proprietary and it is not specified. The application considerations of OARs are generally the same as those for PAs.

3.2 Types of optical amplifiers

There are several types of OAs. Among them: erbium-doped fibre amplifier (EDFA), semiconductor optical amplifiers (SOA), and Raman amplifiers. OAs require electrical or optical energy to excite the state of electron-hole pairs. Energy is typically provided by injecting electrical current (in SOA), or optical light in EDFA and Raman amplifiers.

3.2.1 EDFA-type amplifiers

An EDFA is a fibre segment, a few metres long, that is doped with the rare earth element erbium. The erbium ions may be excited by being pumped at a number of optical frequencies. The two more convenient excitation wavelengths are 980 nm and 1 480 nm.

When these wavelengths propagate through the active fibre, erbium ions are excited and an incoming optical signal can be amplified by stimulated emission, releasing photon energy in the wavelength range 1 530-1 565 nm (the C-band). By modifying the design of the amplifier, this range can also be shifted to longer wavelengths (the L-band) (see Chapter 6).

The basic structure of an EDFA consists of a coupling device, an erbium-doped fibre and two isolators (one at each end) (Figure 5-7).

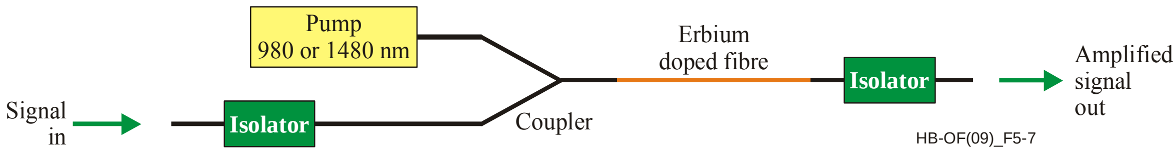


Figure 5-7 – An example of EDFA amplifier

The fibre carrying the signal is connected via the isolator that suppresses optical reflections. The EDFA is stimulated by a laser source, known as the pump laser. The pump power (980 nm or 1 480 nm) is coupled into the EDFA together with the incoming data signal. The pump excites the fibre dopant ions, resulting in amplification of the data signal passing through at a wavelength in the 1 550 nm region.

3.2.2 SOA type amplifiers

The physical mechanism providing gain in semiconductor optical amplifiers (SOAs) differs in various aspects from that of the above EDFA amplifiers. Basically, SOAs are semiconductor lasers without the optical cavity feedback (the facets of the chip have an anti-reflection coating), and so the population inversion is generated in the active region by an electrical current. The stimulated emission of photons occurs via electron-hole recombination processes induced by the signal photons (at wavelengths included in the amplification band of the semiconductor material).

3.2.3 Raman amplifiers

(For further information, see Recommendation ITU-T G.665.)

Stimulated Raman Scattering (SRS) amplifiers are non-doped fibre amplifiers that employ high-power pumps to take advantage of the non-linear properties of the fibre. Figure 5-8 shows how a fibre can be used as a Raman amplifier.

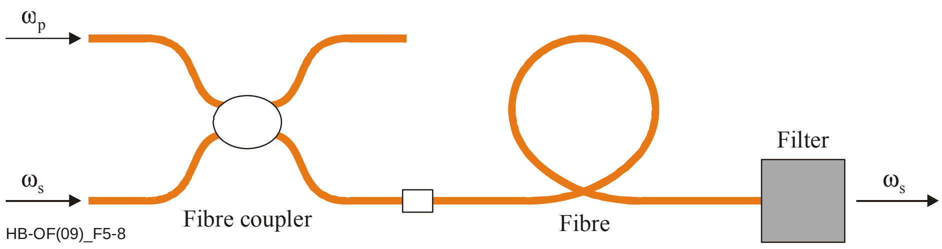


Figure 5-8 – Schematic of a Raman amplifier

The pump and the signal are injected into the fibre through a fibre coupler. The energy is transferred from the pump beam to the signal beam through SRS as the two beams co-propagate inside the fibre. The pump and the signal beams counter-propagate in the backward-pumping configuration commonly used in practice.

Raman amplifiers are called distribute or discrete, depending on their design. In the discrete case, a discrete device is made by spooling 1-2 km of an especially prepared fibre. The fibre is pumped at a wavelength near 1.45 µm for amplification of 1.55 µm signals. In the case of distributed Raman amplification, the same fibre that is used for signal transmission is also used for signal amplification. The pump light is often injected in the backward direction and provide gain over relatively long lengths (>20 km).

The most important feature of the Raman amplifiers is a large bandwidth range which can extend over the complete useful spectrum from 1 300 nm to 1 600 nm with no restriction to gain over bandwidth, thus enabling a multi-terabit transmission. On the negative side, Raman amplification require pump lasers with high optical power (>1 W), with the related thermal management issues as well as safety issues.

3.2.3.1 Distributed Raman amplifiers

Distributed Raman amplifiers are amplifiers where the amplification effect is achieved via a portion of the optical fibre used for transmission. Such amplifiers are deemed to be distributed, since part or all of the transmission fibre is used for amplification purposes. Distributed Raman amplifiers can be further classified into three sub-categories.

Reverse-pumped Raman amplifier: The pump energy and signal propagate in opposite directions in the transmission fibre. These Raman amplifiers can have their pump near the receiver and the pump light travels in opposite direction towards the source (Figure 5-9, where RP_i is the reverse-pumped signal input reference point, RP_o is the reverse-pumped signal output reference point and GMP is the gain measurement point).

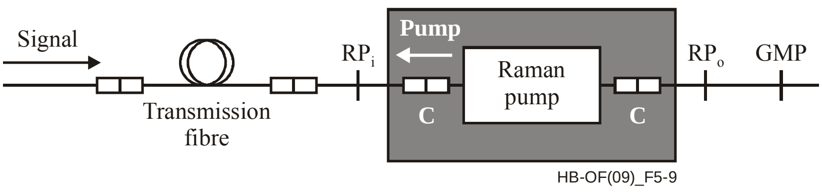


Figure 5-9 – Reverse-pumped Raman amplifier

Thus the pump is strongest at the receiver and weakest at the source. This arrangement has an important advantage: the pump power is where it is most needed (at remote distance from the source) and less needed (in the vicinity of the source). Consequently the signal is amplified where it is weakest and less where it is strongest.

Forward-pumped Raman amplifier: The pump energy and signal co-propagate along the transmission fibre (Figure 5-10, where FP_i is the forward-pumped signal input reference point, FP_o is the forward-pumped signal output reference point and GMP is the gain measurement point).

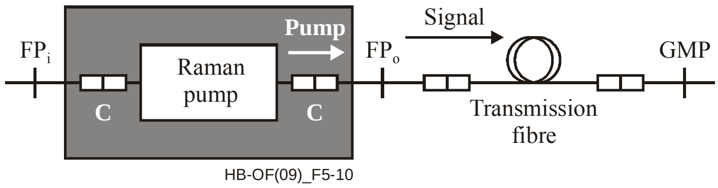


Figure 5-10 – Forward-pumped Raman amplifier

Bidirectionally-pumped Raman amplifier: The pump energy is applied in both ends of the transmission fibre. This configuration features two pumps, one at the transmitting side and one at the receiving side, with each pump at different wavelengths, e.g. to meet a simultaneous C- and L-band amplification or to realize a specific power versus wavelength shape of the used channels. In this case, part of the pump energy co-propagates with the signal and part of the pump energy counter-propagates with the signal inside the transmission media (Figure 5-11).

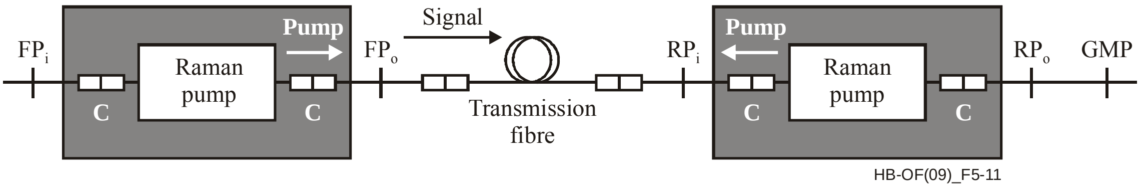


Figure 5-11 – Bidirectionally-pumped Raman amplifier

3.2.3.2 Discrete Raman amplifiers

A discrete Raman amplifier is an amplifier for optical signals whose amplification effect is achieved via the fibre stimulated Raman scattering effect, where all of the physical components of the amplifier are completely contained inside the device (Figure 5-12, where A_i and A_o mark the input and output reference points). In many cases a specific optical fibre (other then the transmission fibre) is used, in order to reduce the needed pump power for achieving a specific gain.

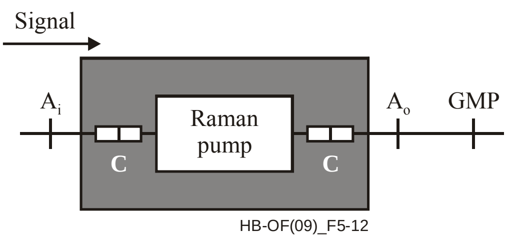


Figure 5-12 – Discrete Raman amplifier

3.2.3.3 Applications of EDFAs, SOAs and Raman amplifiers

EDFAs represent the most mature OFA technology and have been distributed on the market for several years and are produced by various manufacturers worldwide. The EDFA OA is particularly attractive for WDM optical systems and it is widely used for these applications.

On the other hand, SOAs are still at the R&D stage. Today, very few manufacturers produce them and the yield is very low. Even though the technology of SOAs is based on the very well assessed semiconductor laser technology, several important problems related to packaging, pig tailing, anti-reflection coating and polarization sensitivity have not found yet satisfactory mass-scale production solutions.

Moreover, field trials with SOAs have started recently and there is today only a limited experience in using SOAs in the field.

At the present stage of the SOA technology, the most suitable applications of SOAs, as gain blocks in optical point-to-point systems, seem to be as booster amplifiers, integrated with the emitter laser, even though there are some limitations in terms of output power.

Problems related to line and pre-amplifier applications (such as polarization sensitivity and relatively high noise figure) are going to be solved. SOAs have a great potential as functional devices in optical switches, to simultaneously provide gain and fast gating functions, and in other signal processing devices (wavelength converters, optical multiplexers and demultiplexers), due to the strong non-linear response they have in the saturation regime. They can also be integrated in optical switch matrices to compensate for the losses internal to the matrix itself.

Raman amplifiers are mainly used in long haul or ultra long haul transmission systems with very high capacity where the signal degradation coming from the noise of the EDFAs is not tolerable or the required optical bandwidth is larger then what an EDFA can support. Especially distributed Raman amplifiers can help to improve the optical signal-to-noise ratio (OSNR) by using the transmission fibre as active media. Due to the higher component cost, especially caused by the high pump power, this type of amplifier is not widely installed in today’s network but furthermore dedicated for specific applications.

4 Adaptive chromatic dispersion compensators

(For further information, see Recommendation ITU-T G.667.)

Chromatic dispersion in a single-mode fibre is a combination of material dispersion and waveguide dispersion and it contributes to pulse broadening and distortion in a digital signal (see Chapter 1). It does this by inducing a frequency dependent phase shift of the signal travelling in the fibre, which causes pulse broadening of the optical waveform at the receiver.

For links where the chromatic dispersion would otherwise be too large, a dispersion compensation device is used to compensate the chromatic dispersion of the optical path. Presently, various different types of dispersion accommodation (DA) technology are used. For example: passive dispersion compensation (PDC), self phase modulation (SPM), prechirp (PCH) and dispersion supported transmission (DST).

Moreover in some applications, the chromatic dispersion of the optical path varies with time or optical network re-configuration to such an extent that, to avoid signal degradations at the receiver, an adaptive dispersion compensator (ADC) is used to dynamically compensate the chromatic dispersion change of the optical link.

4.1 ADC applications

Adaptive dispersion compensators are expected to be used in at least two applications: compensation of slow changes in link dispersion and compensation of step changes in link dispersion.

i) Slow change link dispersion application

In this application, the ADCs are used to compensate for slow changes of link dispersion over time due to environmental effects.

One example application is an ultra-long haul 10 Gbit/s optical transmission system. Since the chromatic dispersion in a fibre varies with time/temperature, the residual dispersion of each channel varies accordingly. If the variation of channel residual dispersion exceeds the dispersion tolerance of the transmitter – receiver pair, a single or multichannel adaptive dispersion compensator is needed to dynamically compensate for the chromatic dispersion change of the optical link.

Similarly, for a long distance 40 Gbit/s optical transmission system, since the dispersion tolerance of a transmitter – receiver pair is typically much lower than that of 10 Gbit/s systems, dynamically adjusted dispersion compensation may also be needed to compensate for the optical link fibre dispersion variation with time/temperature.

Since the variation of fibre chromatic dispersion with time/temperature is slow, the minimum rate of change of dispersion compensation parameter is used to specify the tuning performance of the ADCs.

ii) Step change link dispersion application

In this application, the ADCs are used to compensate for sudden step changes of link dispersion due to switching or other transmission link re-configuration process.

One example application is illustrated in Figure 5-13.

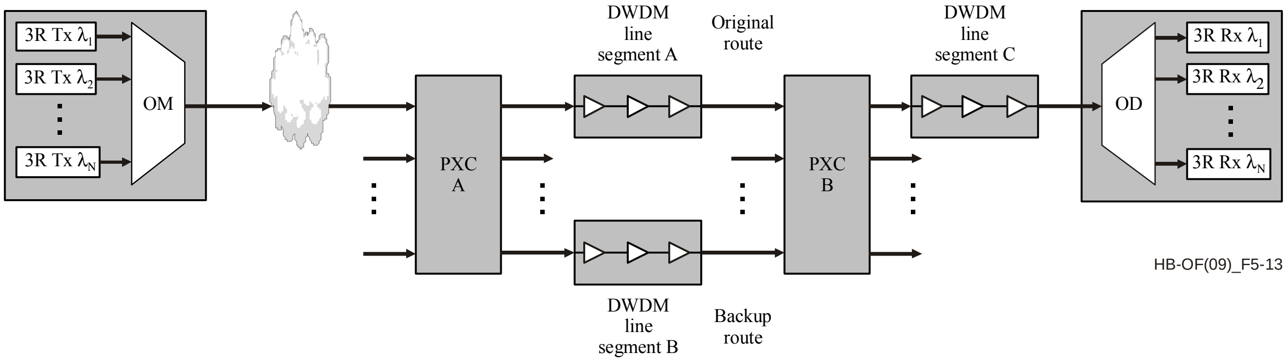


Figure 5-13 – Example step change link dispersion application

A dense wavelength division multiplexing (DWDM) optical signal is originally routed through DWDM line segment A.

After re-configuration, the route is changed from segment A to segment B. Since the link dispersion of DWDM line segment A is different from DWDM line segment B, a step change of channel residual dispersion occurs. If the step change of channel residual dispersion exceeds the dispersion tolerance of the transmitter – receiver pair, a single or multichannel adaptive dispersion compensator is needed to dynamically compensate the chromatic dispersion change of the optical link.

Since the change of dispersion in this case occurs as a step, the maximum dispersion compensation tuning time parameter is used to specify the tuning performance of the ADCs.

4.2 ADCs reference configurations

A generic configuration of a transmission system with ADC(s) is shown in Figure 5-14 (where MPI-S is the single channel source main path interface reference point and MPI-R is the single channel receive main path interface reference point). It consists of a transmitter terminal, a receiver terminal and a transmission link, with optional Line ADC(s), in between.

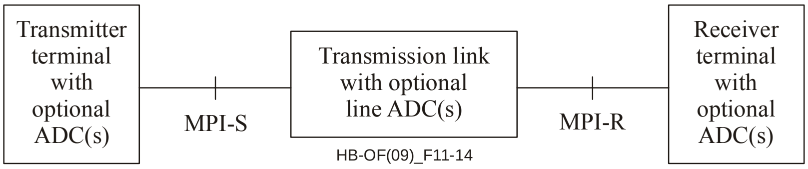


Figure 5-14 – Generic configuration of a transmission system with ADCs

Line ADCs, ADC transmitters, and receivers are all described in Recommendation ITU-T G.667.

Figure 5-15 shows, as an example, an ADC receiver (ADC-Rx) in which the ADC functionality is embedded in the receiver black-box.

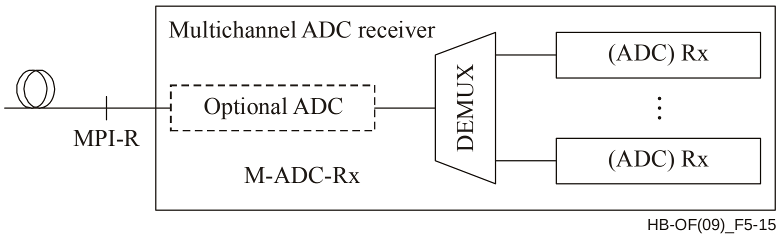


Figure 5-15 – Reference configuration of a multichannel ADC receiver

There are several different types of receiver-based electronic dispersion compensation (EDC) techniques. In all cases, however, an adaptive data processor is used to reduce the inter-symbol interference of the optical to electrical converted signal that was introduced by chromatic dispersion and other non-linear effects. The different adaptive data processor technologies that are currently being used are: feed forward equalization (FFE), decision feedback equalization (DFE), and maximum likelihood sequence estimation (MLSE). They are all described in Recommendation ITU-T G.667.

5 PMD compensators

(For further information, see Recommendation ITU-T G.666.)

Polarization mode dispersion is the differential group delay (DGD) time between two orthogonal polarized modes, which causes pulse spreading in digital systems and distortions in analogue systems.

Polarization mode dispersion compensators (PMDCs) are intended to be used in optical transmission systems in order to reduce PMD-induced signal degradations. Therefore, characteristics of PMDCs must be considered – at least in part – in conjunction with a whole transmission system.

The requirements and key parameters for first- and higher-order PMD compensators, including dynamic PMD characteristics are in Recommendation ITU-T G.666.

A transmission system with PMDC(s) consists of a transmitter terminal, a receiver terminal and a transmission link, with optional line PMDC(s), in between. The receiver terminal, which contains PMDC functionalities, is called in this case a “PMDC receiver”.

An example of the various possible PMDC configurations of a multichannel PMDC receiver is presented schematically in Figure 5-16. A multichannel optical signal enters the receiver terminal at the reference point MPI-R. There it either passes a PMDC before entering a demultiplexer (DEMUX) and the receivers Rx for the individual optical channels, or it passes directly through the demultiplexer where all of the receivers are PMDC Rx.

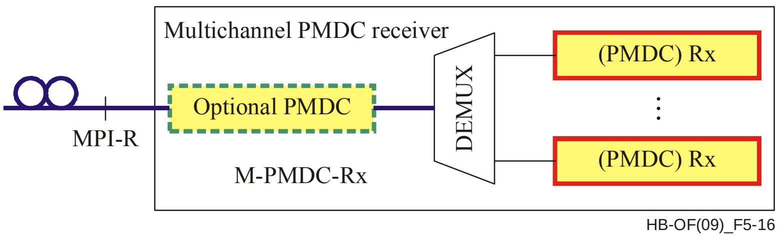


Figure 5-16 – Reference configuration of a multichannel PMDC receiver

6 OADMs and ROADMs

(For further information, see Recommendations ITU-T G.671 and ITU-T G.680.)

An optical add/drop multiplexer (OADM) subsystem is a wavelength selective branching device (used in WDM transmission systems) having a wavelength “drop” function in which one or more optical signals can be transferred from an input port to either an output port or drop port(s) depending on the wavelength of the signal. An OADM also has a wavelength “add” function in which optical signals presented to the add port(s) are also transferred to the output port as shown in Figure 5-17.

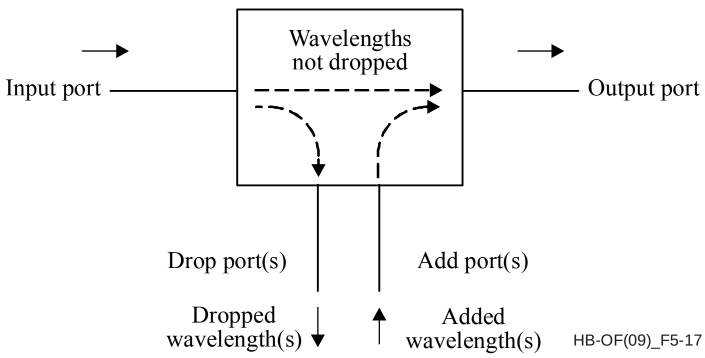


Figure 5-17 – Optical add/drop multiplexer (OADM) subsystem

The add/drop functionality can be of two types:

i) *OADM with fixed wavelengths*. The wavelength(s) to be dropped / inserted are selected and remain(s) the same until human intervention changes them;

ii) *ROADM (Reconfigurable OADM) with dynamically wavelengths selectable*. The wavelengths between the optical demultiplexer and multiplexer to be added / dropped may be dynamically changed, usually, by a remote management system. An example of ROADM is in Figure 5-18, where OLAs are Optical Line Amplifiers.

OADMs and ROADMs are needed for the backbone and for the metropolitan area networks, in which one or more channels need to be dropped or added while preserving the integrity of the other channels.

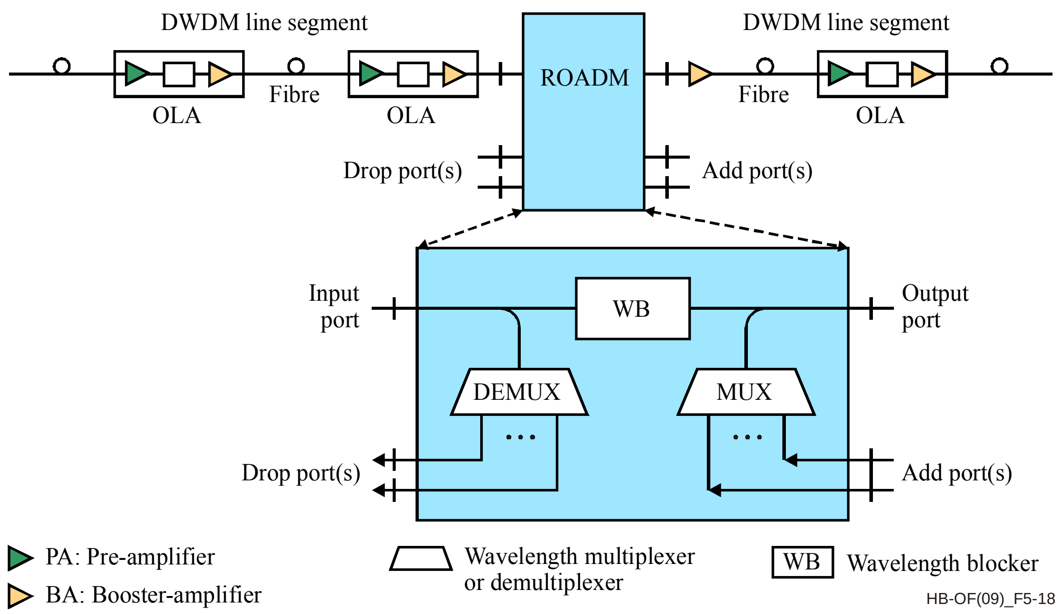


Figure 5-18 – Example of ROADM

7 Photonic Cross-Connects

(For further information, see Recommendation ITU-T G.680.)

The development of wide-area WDM networks requires a dynamic wavelength routing scheme, which can reconfigure the network. This functionality is provided by photonic cross-connect (PXC) which performs the same functions as that provided by electronic digital switches in telephone networks.

The PXC is a cross-connect device, used in WDM transmission systems, in which one or more signals can be cross-connected from one of a number of input ports to one of a number of output port(s). An example of reference diagram for a PXC is shown in Figure 5-19.

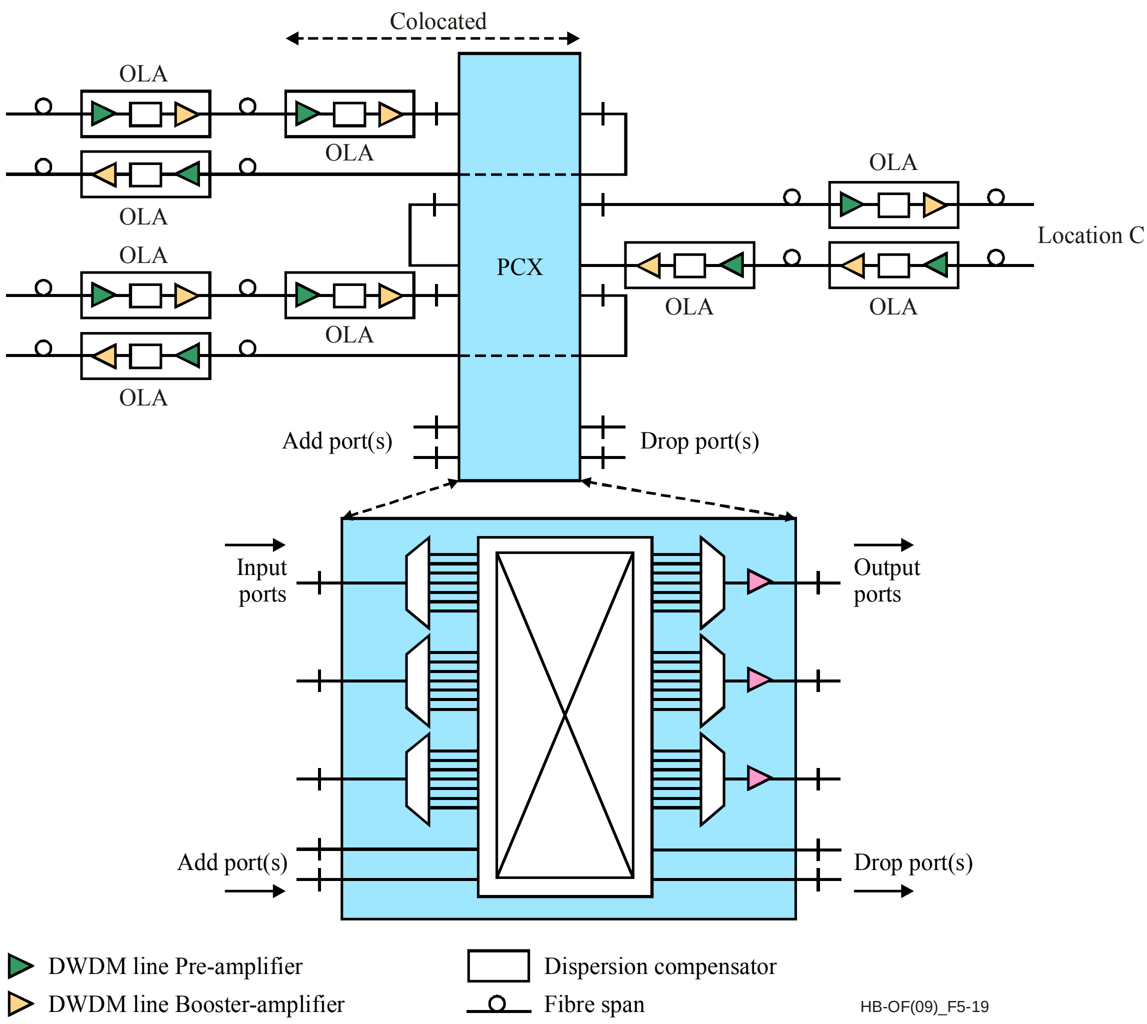


Figure 5-19 – Example of PXC

In this example the PXC has the additional feature that one or more single channel ports are directly available at the input or output side of the switch, thereby enabling to additionally perform the function of adding or dropping individual channels.

A variety of PXC types are included within this definition such as devices which switch from any input port to any output port:

i) any wavelength;

ii) groups of wavelengths;

iii) all wavelengths;

iv) a combination of the above.

These PXCs may also include additional optical functions such as chromatic dispersion compensation, PMD compensation, etc.

8 Optical wavelength MUX/DMUX

A wavelength multiplexer (MUX) (or optical multiplexer (OM)) is a branching device with two or more input ports and one output port, where the light in each input port is restricted to a preselected wavelength range and the output is the combination of the light from the input ports.

A wavelength demultiplexer (DMUX) (or optical demultiplexer (OD)) is a device which performs the inverse operation of a wavelength multiplexer, where the input is an optical signal comprising two or more wavelength ranges and the output of each port is a different preselected wavelength range.

Both wavelength multiplexers (MUX) and wavelength demultiplexers (DMUX) are generally called "WDM Devices" since often the same device can be used to multiplex and demultiplex channels.

An application of MUX and DMUX is shown in Figure 5-4 where they are used in two terminal stations for transmitting on an optical fibre several signals at different wavelengths. Another application is in Figure 5-19 where they are used for cross-connecting optical channels among different traffic directions.

9 Regenerators and transponders

9.1 3R regenerators

(For further information, see Recommendations ITU-T G.680 and ITU-T G.959-1.)

A 3R regenerator is a device or sub-system that performs simultaneously the "re-amplification", "re-shaping" and "re-timing" functions on an optical signal. Thus, this device or sub-system restores the amplitude of the signal to a level suitable for onward transmission, removes any amplitude noise or distortion present on the waveform and also re-times the signal to remove any timing jitter that may be present.

From the transmission viewpoint, an optical connection shows a behaviour like an analogue connection (e.g. the optical transmission impairments due to attenuation, dispersion, fibre nonlinearity, amplified spontaneous emission, etc., accumulate in a manner similar to the accumulation of noise and other impairments in analogue networks). Within digital networks, mitigation of such impairments is achieved at 3R regeneration points, located in the transmission path according to engineering guidelines designed to achieve the required link error performance objective. As a consequence 3R regeneration is used at certain locations to maintain the error performance objectives. Currently, the 3R process typically relies on electro-optic conversion. The technology of all-optical 3R regeneration is not still mature for deployment in the telecommunication networks.

A regenerator is nothing but a receiver-transmitter pair that detects the incoming optical signal, recovers the electrical bit stream and converts it back into optical form by modulating an optical source (Figure 5-20).

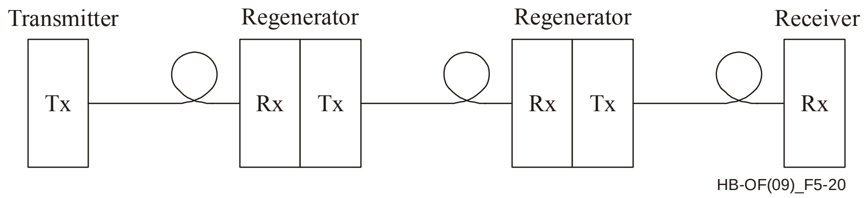


Figure 5-20 – 3R Regenerators

Fibre attenuation can also be compensated by using optical amplifiers (see § 3), which amplify the optical bit stream directly without requiring conversion of the signal in the electrical domain. However, even with the use of optical amplifiers, periodically it is necessary to regenerate the optical bit stream with regenerators, which compensate for all sources of signal degradation.

9.2 Transponders

The transport network of most operators is based on the use of equipment from a variety of different vendors. In order to allow coexistence of equipment from different vendors at the border of DWDM optical transmission, optical transponders are used, as shown in Figure 5-21.

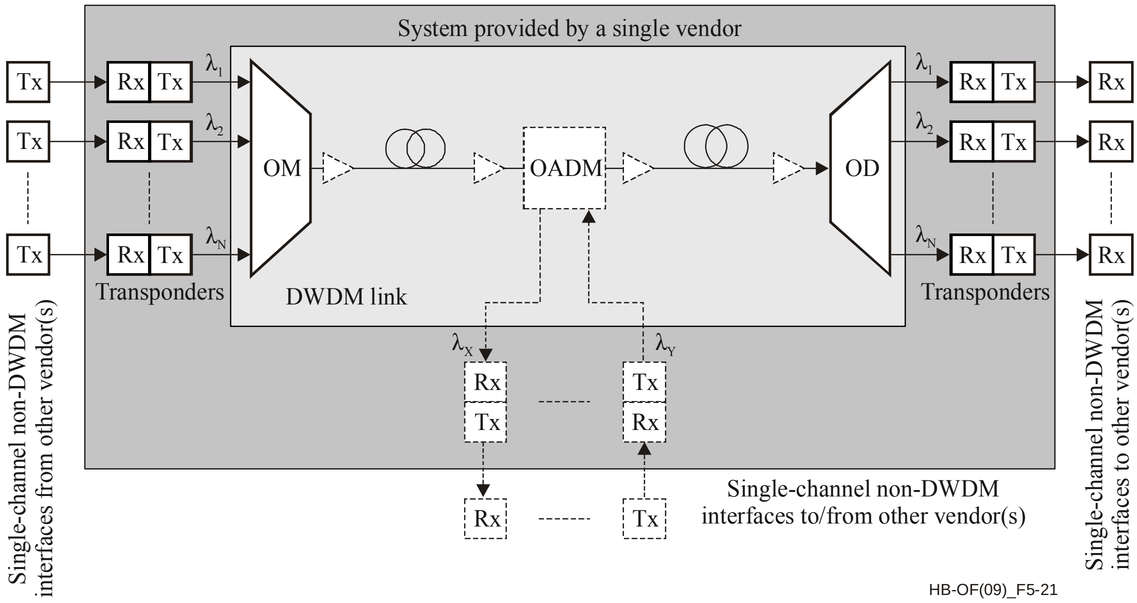


Figure 5-21 – Transponders

The optical interfaces labelled in the figure, "Single-channel non-DWDM interfaces from other vendor(s)", can then be any short–reach, standardized optical interface that both vendors support, such as those found in Recommendations ITU-T G.957, ITU-T G.691, ITU-T G.693, ITU-T G.959.1, etc. This arrangement allows the direct connection of a wide variety of equipment to the DWDM line system such as:

i) a digital cross-connect with multiple optical interfaces supplied by a different vendor from the line system;

ii) multiple optical client devices, each from a different vendor supplying one channel each;

iii) a combination of the above.

Through the use of the single channel DWDM interfaces specified in some ITU-T Recommendations (e.g. ITU-T G.698.1, and ITU-T G.698.2), however, this interconnection can also be achieved while removing the need for one short-reach transmitter and receiver pair per channel (eliminating the transponders), with obvious associated cost savings, as shown in Recommendation ITU-T G.698.2.

10 Optical attenuators

(For further information, see Recommendation ITU-T L.31.)

Optical fibre attenuators are passive optical components that are often required in an optical fibre transmission link to reduce the optical power incident on the photodetector.

They can introduce a fixed level of attenuation (fixed attenuators) or they may have a tuning control to set the level of attenuation into a range of selectable values (variable attenuators).

Typical applications for optical fibre attenuators are:

i) to assure the linear behaviour of optical fibre receivers avoiding optical power overloading;

ii) to balance the optical power into passive optical network (PON) branches or DWDM links;

iii) to make measurements on an optical telecommunication system.

Regarding the first application, the optical power emitted by the source in a transmission system usually exceeds the needed power budget: the aim is to guarantee the operating condition of the system, even if some degradation phenomena occur in the link. The direct control of the optical emission of the sources can be made only for a limited dynamic range and may produce undesired modification of the characteristics of the emitted optical beam, like modal distribution or change of central wavelength. Therefore, attenuators are used in optical telecommunication systems to limit the optical power level at the receiver.

The second application of these components is justified by the non-uniformity of the link losses in a real point-to-multipoint network. In fact, due to the topology of the network, different optical paths may suffer different losses so that specific optical attenuators may be needed in some branches of the network to assure the same linear operating range at each optical receiver.

Finally, the third application mainly concerns variable optical attenuators. In fact, these kinds of components can be very important for making several measurements in an optical telecommunication system, for example, each time the performance (bit error ratio) as a function of the received optical power has to be characterized.

Every type of optical attenuator is normally inserted at the receiving end of the link: in fact, light intensity regulation at the transmitting end would require remote power monitoring of the received level of the optical signal.

In particular, the ideal attenuator should have a stable attenuation over a wide temperature range and under mechanical stresses; it should be independent of wavelength and state of polarization and should not cause reflection or interference of the optical signal. In addition, other desired characteristics for an ideal variable attenuator are low insertion loss, wide attenuation range and accurate mechanical or non-mechanical control of attenuation.

Until recently the most common types of attenuator that are permanently installed in optical fibre plant were fixed. However, with the increase of capacity, bit rate and transmission distances in modern DWDM systems, more and more tuneable attenuators are used to optimize transmission performance and to allow for more flexible re-configuration of optical routes through a network. Therefore, technological efforts are aimed at optimizing the reliability and minimizing the dimensions of, not only fixed, but also tuneable attenuators by meeting the specifications to allow for the usage in wide bandwidth DWDM systems.

11 Optical branching devices including PON splitters

(For further information, see Recommendations ITU-T L.37 and ITU-T G.671.)

An optical branching component (wavelength non-selective) is a passive component possessing three or more ports, which shares optical power among its ports in a predetermined fashion, without any amplification, switching, or other active modulation.

Optical branching components provide a method for splitting optical signals between M input and N output ports (Figure 5-22). Optical branching components are required when an optical signal has to be split into two or more fibre lines or when several signals coming from different fibre lines have to be mixed in a single fibre line; in general, optical branching components are dividers/combiners of transit signals.

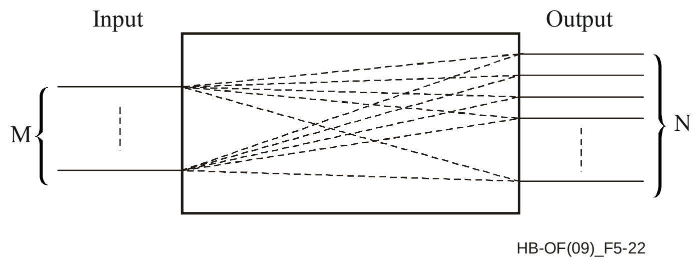


Figure 5-22 – Schematic of an MXN branching component

In passive optical networks (PON) with a point-to-multipoint distribution architecture (see Chapter 9), optical branching components are used to connect an OLT located at a central office to several ONUs located in outside plant or on subscriber premises. The specified values for PONs are 1 input port and X output ports, where X = 4, 8, 16, 32.

Optical branching components can be designed to operate at a single wavelength (e.g. 1 310 or 1 550 nm), to be wavelength flat (e.g. insensitive to wavelength variations within a single window) or to be wavelength independent (e.g. insensitive to wavelength variations within both the second and third windows, 1 260-1 360 nm and 1 450-1 600 nm.

Optical branching components for PONs are characterized by several parameters, the most important of which are: insertion loss, reflectance, optical wavelength range, polarization-dependent loss, directivity and uniformity.

All these parameters are defined and specified in Recommendation ITU-T G.671.

For the application of the PON splitters in the optical access networks, see Chapter 9.