UNIVERSITY OF TARTU
FACULTY OF SCIENCE AND TECHNOLOGY

Computer science profession

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OPTICAL WAVELENGHT-DIVISION MULTIPLEXING

Bachelor’s work

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Introduction

This research is compiled as the Bachelor’s thesis of the Institute of Computer Science of the University of Tartu. It discusses the present situation in the sphere of optical wavelength-division multiplexing. This graduation thesis is compiled taking into account the principles of information technology and is primarily a basis for research in this field and for developing the existing broadband networks. The thesis is a good base material for scientists, administrators of broadband networks, students and for everybody interested in the field and in the subject.

The subject was chosen because of the author’s great interest in broadband networks. It appeared that optical wavelength-division multiplexing is scientifically intriguing and that there is no clear overview of this field in the University of Tartu. The aim of this thesis is to fill that gap. The author worked through a large amount of scientific publications, articles and specialized reference books in order to find mistakes and on the basis of these to compile a checked and a thorough Bachelor’s thesis on the subject of optical wavelength-division multiplexing. On the basis of much of the used literature, the author has compiled a sufficiently short and clear informing material about the WDM technology. This thesis is capacious enough to give a reader who is not familiar with the WDM technology a sufficient overview of the subject, so that this information could be used for improving broadband networks. Knowledge of the WDM technology is important to understand the directions of development of broadband and optical wavelength-division multiplexing and to create new technology.

According to Google head Eric Schmidt about ten hours of video materials are uploaded to Youtube every second and he predicts that soon Youtube might crash due to the increasing demand. The larger communication providers have pointed out that the data traffic increases 300% per year [1]. Optical networks installed 10 years ago are not able to cover present high-speed demands anymore. As there is constant demand for increased data transmission, much is invested into technology that would enable to increase connection rates per Gbps as cheaply as possible. It is believed, that an all-optical network remains illusive and a future goal. The WDM technology is one of the many means to enhance the speed of data transmission. It can successfully be used on the optical light cables already installed. With the use of the WDM technology, also other components of the optical network need development. Every component has its purpose and requirements. While developing all the components of the WDM technology we might face many physical limitations that hinder taking the development to a desired degree. There are different technological approaches that would be the possible leaders in the future of the WDM technology. The more different wavelengths the system is able to take into use, the more the link’s data transmission speed increases. Unfortunately, with the development of every specific device the development of other optical data communication devices must follow as the maximum speed of data transmission between these two points is as fast as is the slowest device between these two points. If there is a component in the optical network that cannot keep up with the development of the WDM, it can turn out to be the “bottleneck” of the entire connection speed.

This thesis shortly explains the main components of the WDM connection. It tries to explain to the reader the principles of the WDM and its usefulness in the future. Under the reader administrators of broadband networks, lecturers of data communication, students and other people interested in the subject are meant. As information technology is a field developing especially fast, the thesis will benefit many readers who try to follow the optical data communication technology and to understand the future directions of development in optical data communication.

The purpose of this thesis is to cover the following questions: can using WDM develop in systems that are already implemented in past? How can service providers and enterprises offer higher-speed services at a low cost? How can service providers and enterprises respond quicker to the changing demand by allocating bandwidth on demand? In the case of a more complex optical network, development in routers, switches and amplifiers are needed as the demand grows. How much of the network will remain electronic and how much can be implemented optically? Based on WDM technology, how can it be used on network apparatuses and modified as easily as possible? Because of the growth of bandwidths and demand, it is necessary to develop the WDM system and the optical network routing. Many engineers who are experts in the physical layer field must still study the optical system, networks and the corresponding engineering problems in order to design new state-of-the-art optical networking products.

A short overview of the structure of the thesis

The thesis is divided into chapters and subsections to make it easier for the reader to find the topic of interest. It uses an index that enables to look up the new notion in the text by the page number, where the notion is explained. The overview of the chapters:

Bandwidth demand and WDM. This introductory chapter presents the need of increasing the speed of data transmission in data communication. An overview of the forerunners and new standards of WDM technology is given.

Components. An overview of the components of the WDM technology, the more important devices and their parts in creating data communication are mentioned.

Attenuation. The processing of each device, optical fiber and signal results in the fading out of the signal are analyzed. This chapter discusses the signal's fading out and the means to avoid it.

Constructing the WDM network. Discusses, which aspects of the existing network of data communication should be noticed when assembling or renewing it.

Optical layer management. Gives an overview of managing and detecting faults in the WDM data communications network.

1. Optical wavelength-division multiplexing

The sudden increase in demand for network bandwidth is largely caused by the growth in data traffic, specifically *Internet Protocol* (IP). The leading service providers report bandwidths doubling on their backbones about every six to nine months. This happens largely in response to the 300 percent growth per year in Internet traffic, while traditional voice traffic grows only about 13 percent (see Figure 1.1).

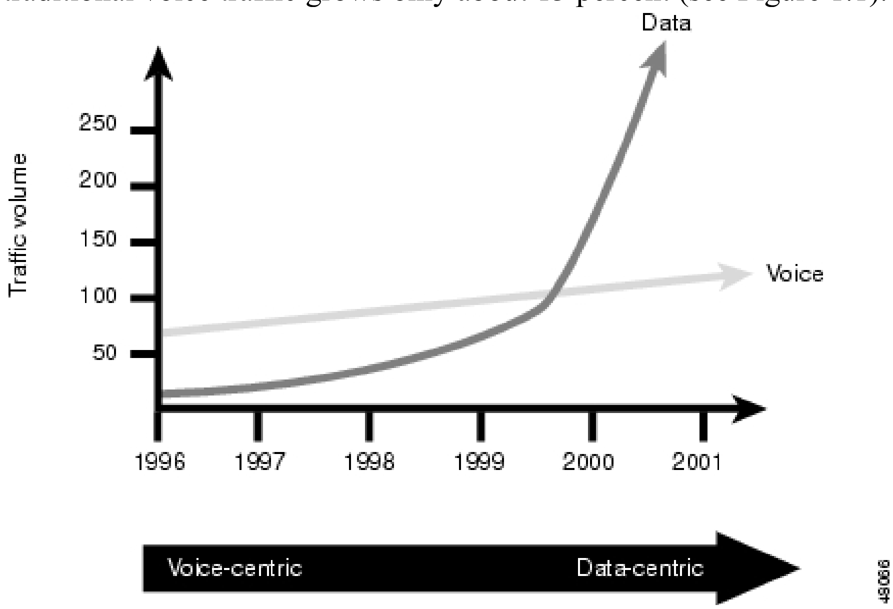


Figure 1.1. Data traffic overtakes voice traffic [1].

There is an increasing proportion of delay in the case of sensitive data, such as voice over IP and streaming videos and while the network traffic volume is increasing, the nature of the traffic itself is becoming more complex. Google head Eric Schmidt said in March 2008, that about ten hours of video materials are uploaded to Youtube every second [2]. The traffic carried on a backbone can be circuit based (*Time-division Multiplexing* TDM voice and fax), packet based (IP) or cell based (*Asynchronous Transport Mode* ATM and Frame Relay). Long-haul service providers are now moving away from TDM based systems, which were optimized for voice but now prove to be costly and inefficient. [1]

While the demand for bandwidth is driven largely by new data applications, Internet usage and the growth in wireless communication, two additional factors have to be considered: competition and network availability. Competition affects the industry in mainly two ways:

- Enhanced services are created by newcomers trying to compete with incumbents. In the metropolitan market, for example, there are broadband wireless and *Digital Subscriber Loop/Line* (DSL) services for homes and small and medium-sized business, high-speed private line and *Virtual Private network* (VPN) services for corporations, and transparent LAN services for enterprise network customers.

* New operators entering the scene create new infrastructure so that they do not have to lease it from existing operators. Using this strategy, they have more control over provisioning and reliability.

As telecommunications and data services have become more important to business operations, service providers have been required to ensure that their networks are fault tolerant. In order to meet these requirements, providers have had to build backup routes, often using simple 1:1 redundancy in ring or point-to-point configurations. Achieving the required level of reliability, however, means reserving capacity for failover. These can double the need for bandwidth in an already strained infrastructure (see Figure 1.2.).

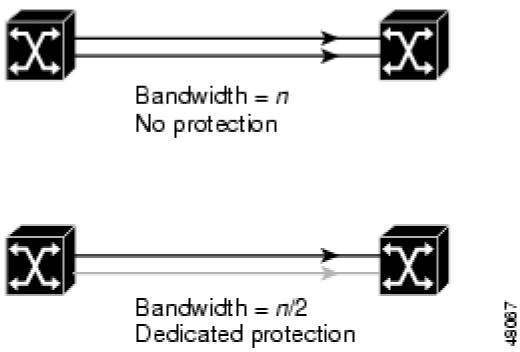


Figure 1.2. Reserving bandwidth reduces overall capacity [1].

In case of link failure, service restoration maximum time is 60 ms according to the SDH standard. Therefore quite often is used in ring topology a back-up fiber lines against fiber or component failure. Wavelength division multiplexing (WDM) can carry multiple protocols without a common signal format, while SONET/SDH cannot.

Faced with the challenge of drastically increasing capacity while constraining costs, the carriers have two options: to install new fibers or to increase the bandwidth efficiency of existing fibers. Deploying new fibers is costly, the price is about 25 000 € per kilometer, most of which is the cost of permits and construction expense rather than the price of fiber itself [1]. Laying new fibers may be reasonable only when it is desirable to expand the embedded base. Increasing the effective capacity of existing fibers can be accomplished in two ways:

* Increasing the bit rate of existing systems. Using Time-Division Multiplexing (TDM), data is now routinely transmitted at 2.5 Gbps (OC-48) and, increasingly, at 10 Gbps (OC-192); recent advances have enabled even the rate of 40 Gbps (OC-768). The electronic circuitry that makes this possible, however, is complex and costly to purchase and to maintain.
* Increasing the number of wavelengths on a fiber. In this approach, many wavelengths are combined onto a single fiber. Using Wavelength Division Multiplexing (WDM) technology, several wavelengths can simultaneously multiplex signals of 2.5 to 40 Gbps each over a strand of fiber. Systems with

wavelengths of 128 and 160 are operating today, with higher density on the horizon. [1]

1. 1. WDM standards

Developments in fiber optics are closely tied with the use of specific regions on the optical spectrum where optical attenuation is low. These regions, called *windows*, lie between high absorption areas. The earliest systems were developed to operate around 850 nm, the first window placed in silica-based optical fiber. The second window (S band), at 1310 nm, soon proved to be superior to it because of its lower attenuation. The third window (C band) followed at 1550 nm with an even lower optical loss. Today, the fourth window (L band) close to 1625 nm is under development and early deployment. [1].

WDM is essentially a frequency division multiplexing at optical carrier frequencies that uses the WDM standards developed by the International Telecommunication Union (ITU) to specify channel spacing in terms of frequencies. The main reason for selecting fixed-frequency spacing rather than constant-wavelength spacing, is that when a laser is locked to a particular operating mode, it is the frequency of the laser that is fixed. The first ITU-T specification for WDM in 2000 was Recommendation G.692, *Optical Interfaces for Multichannel Systems with Optical Amplifiers* [3]. This document specifies selecting the channels from a laser grid for point-to-point of frequencies referenced to 193.100THz (1552.524 nm) and spacing them 100 GHz (about 0.8 nm at 1550 nm) apart. (see Table 1.1)

Table 1.1. ITU-T grid, recommendation G.692 [1, 3].

Frequency (THz[*])	Wavelength (nm[**])	Frequency (THz)	Wavelength (nm)	Frequency (THz)	Wavelength (nm)
196.1	1528.77	164.6	1540.56	193.1	1552.52
196.0	1529.55	194.5	1541.35	193.0	1553.33
195.9	1530.33	194.4	1542.14	192.9	1554.13
195.8	1531.12	194.3	1542.94	195.8	1554.94
195.7	1531.9	194.2	1543.73	192.7	1555.75
195.6	1532.68	194.1	1544.53	192.6	1556.56
195.5	1533.47	194.0	1545.32	195.5	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	192.4	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

[*] THz = terahertz

[**] nm = nanometer

Suggested alternative spacing in G.692 include 50 and 200 GHz, which correspond to spectral widths of 0.4 and 1.6 nm respectively at 1550 nm. [4]. In 2002 the ITU-T released Recommendation G.694.1, which is titled *Spectral grids for WDM applications: DWDM frequency grid* [5]. Suggested alternative spacing in G.694.1 includes 12.5 GHz spacing. In 2003 ITU-T released Recommendation G.694.2, which is titled *Spectral grids for WDM applications: CWDM wavelength grid* [6]. More closer tis he spacing, more it is affected by a channel crosstalk. Spacing at 50 GHz also limits the maximum data rate per wavelength to 10 Gbps. There is no guarantee for compatibility between two end systems from different vendors, and there is a design trade-off in the spacing of wavelengths between the number of channels and the maximum bit rate.

Dense WDM (DWDM) combines more and more closely spaced wavelengths into a narrow spectral band. The wavelengths must be properly spaced to avoid having adjacent channels, which would distort the signal. Laser temperature and timing can cause signal pulses to drift or to spread out. When the guard band between wavelength channels is too small, the signal being produced at one wavelength will trespass into the spectral territory of another signal band and create interference. In 2002 the ITU-T released an updated standard aimed specifically at DWDM. This is Recommendation G.694.1, which is titled *Dense Wavelength Division Multiplexing (DWDM)*. It specifies WDM operation in the S-, C-, and L-bands for high-rate high-quality *Metro-Area Network* (MAN) and *Wide-Area Network* (WAN) services. It requires narrow frequency spacing of 100 to 12.5 GHz (0.8 to 0.1 nm at 1550 nm). This implementation requires the use of stable high-quality temperature- and wavelength-controlled (frequency-locked) laser diode light sources. For example, the wavelength drift tolerances for 25GHz channels are $\pm$ 0.02 nm. [4, 5]

Increases in channel density resulting from DWDM technology have had a significant impact on the fiber's carrying capacity. In 1995, when the first 10 Gbps systems were demonstrated, the bandwidth capacity rapidly increased after every year (see Figure 1.5). [1]

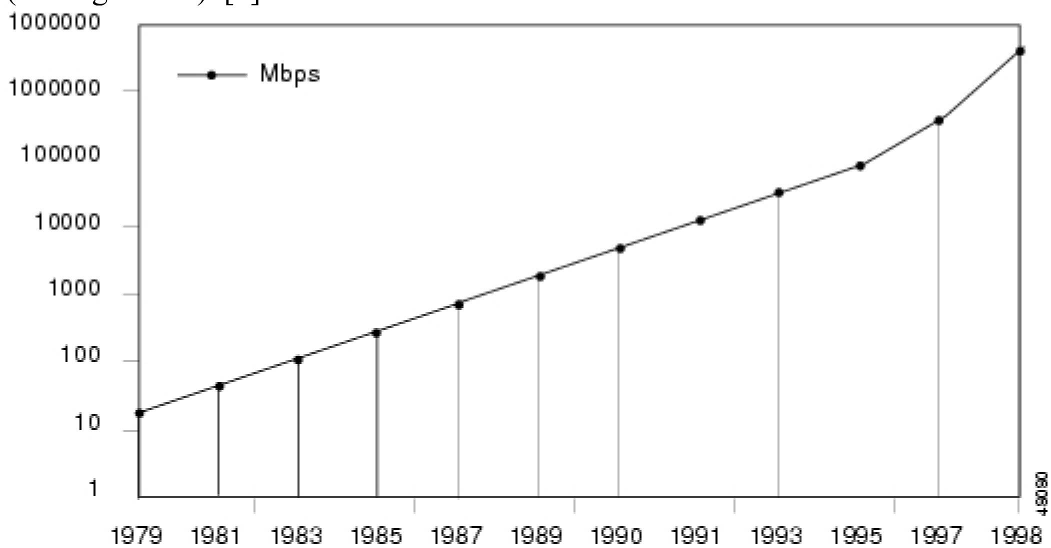


Figure 1.3. Growth in fiber capacity [1].

With the production of full-spectrum (low-water-content) fibers, the development of relatively inexpensive *Vertical Cavity Surface-Emitting Laser* (VCSEL) optical sources and the desire to have low-cost optical links operating in metro- and local-area networks, the concept of *Coarse WDM* (CWDM) was created. In 2002 the ITU-T released standards specifically aimed at CWDM. This is ITU-T Recommendation G.694.2, which is titled *Coarse Wavelength Division Multiplexing* (CWDM*)*. The CWDM grid is made up of 18 wavelengths defined within the range of 1270 to 1610 nm (O-through L-bands) spaced by 20 nm with wavelength drift tolerances of $\pm$ 2 nm. This can be achieved with inexpensive vertical cavity surface-emitting laser (VSCEL) light sources that are not temperature-controlled. The target transmission distance for CWDM is 50 km in *single-mode* fibers (see chapter 4), such as those specified in ITU-T Recommendation G.652, ITU-T Recommendation G.653 and ITU-T Recommendation G.655. [4]

2. Components

Optical communication link components are transmitters, optical fibers, receivers, passive devices, optical amplifiers and active components. The transmitter consists of a light source and of an associated electronic circuitry. As source can be a light-emitting diode or a laser diode. The optical fiber is placed inside a cable that offers mechanical and environmental protection. Inside the receiver is a photodiode that detects the weakened and distorted optical signal and converts it to an electrical signal. The receiver also contains amplification devices and circuitry to restore signal fidelity. Passive devices are optical components that require no electronic control for their operations. After the optical signal has traveled a certain distance along a fiber, it becomes weakened due to power loss along the fiber. At a certain point the optical signal needs to get a power boost. Traditionally, the optical signal has been converted to an electrical signal, electrically amplified, and then converted back to an optical signal (O*ptical-Electrical-Optical*, OEO). Lasers and optical amplifiers fall into the category of active devices, which require electrical control for their operation. Also, under that category belong light signal modulators, tunable (wavelength-selectable) optical filters, optical attenuators and optical switches. [4].

Transponders are currently a key determinant of the openness of D*ense WDM* (DWDM) systems. Within the DWDM system a transponder converts the client's optical signal back to an electrical signal and performs the 3R functions (*Re-time, re-transmit, re-shape*). The 3R Transponders were fully digital and usually able to view SONET/SDH section layer overhead bytes such as A1 and A2 to determine the signal quality's health. Many systems will offer 2.5 Gbps transponders, which usually means that the transponder is able to perform 3R regeneration on OC-3/12/48 signals, and possibly Gigabit Ethernet, and reporting on signal health by monitoring SONET/SDH section layer overhead bytes. Many transponders will be able to perform full multi-rate 3R in both directions. Some vendors offer 10 Gig transponders, which will perform Section layer overhead monitoring to all rates up to and including OC-192. [7]

This electrical signal is then used to drive the WDM laser. Each transponder within the system converts its client's signal to a slightly different wavelength. The wavelengths from all of the transponders in the system are then optically multiplexed. In the receiver direction of the DWDM system, the reverse process takes place. [1] Transponders in some systems supporting 40 GHz nominal operation may also perform *forward error correction* (FEC) via 'digital wrapper' technology, as described in the ITU-T G.709 standard [7].

The implementation of WDM networks requires a variety of passive and/or active devices to combine, distribute, isolate, add, drop, attenuate and amplify optical power at different wavelengths. Passive devices require no external control for their operation, thus they have a fixed application in WDM networks. These passive components are used to split and combine or to tap off optical signals. The performance of active devices can be controlled electronically, thereby providing great network flexibility. Active WDM components include tunable optical filters, tunable sources, *Optical Add/Drop Multiplexers* (OADM), *Variable Optical Attenuators* (VOA), *Dynamic Channel Equalizers* (DCE), optical switches and optical amplifiers. [4]

Future designs include passive interfaces, which accept the ITU-compliant's light directly from an attached switch or router with an optical interface. [1]

2. 1. Optical fibers

An optical fiber is nominally a cylindrical dielectric waveguide that combines and guides light waves along its axis and transmit light at about two-third the speed of light in vacuum. Standard optical fiber consists of a cylindrical glass core surrounded by a glass cladding. The core has a refractive index n_1 and cladding have smaller refractive index n_2 ($n_2 < n_1$), which is the condition required for light traveling in the core to be totally internally reflected at the boundary with the cladding. A light ray entering the fiber core from a medium of refractive index n, which has to be less than the index n_1 of the core. Light can be reflected or refracted depending upon the angle of incidence (the angle at which light strikes the interface between an optically denser and optically thinner material).

There are two general categories of optical fiber in use today, multimode fiber and single-mode fiber. Multimode, the first type of fiber to be commercialized, has a larger core than the single-mode fiber. It gets its name from the fact that numerous *modes* or light rays can be carried simultaneously through the waveguide. Figure 2.1 shows an example of light transmitted in the first type of multimode fiber, called a *step-index*.

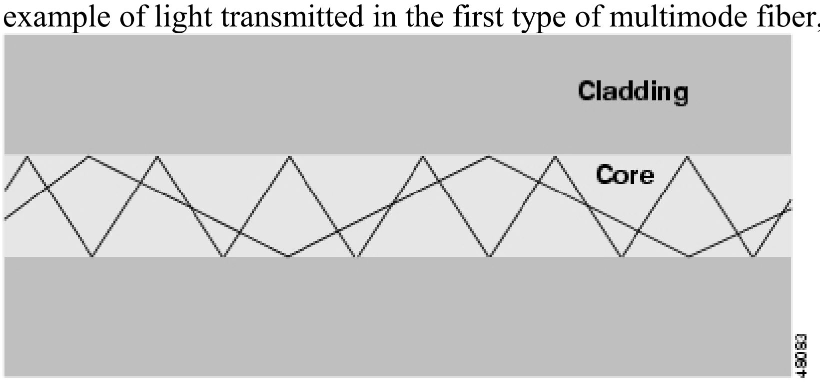


Figure 2.1. Reflected light in a step-index multimode fiber [1].

The step-index refers to the fact that there is a unified index of refraction throughout the core; thus there is a step in the refractive index where the core and cladding interface. Notice that the two modes must travel different distances to arrive at their destinations. This disparity between the times that the light rays arrive is called *modal dispersion*. This phenomenon results in poor signal quality at the receiving end and ultimately limits the transmission distance. This is why multimode fiber is not used in wide-area applications.

In order to compensate for the dispersion drawback of the step-index multimode fiber, the graded-index fiber was invented. *Graded-index* refers to the fact that the refractive index of the core is graded – it gradually decreases from the center of the core outwards. The higher refraction at the center of the core slows the speed of some light rays, allowing all the rays to reach their destination at about the same time reducing modal dispersion.

The second general type of fiber, single-mode, has a much smaller core that allows only one mode of light at a time through the core (see Figure 2.2). As a result, the fidelity of the signal is better retained over longer distances, and modal dispersion is greatly reduced. These factors attribute to a higher bandwidth capacity than multimode fibers are capable of. For its large information-carrying capacity and low intrinsic loss, single-mode fibers are preferred in the case of longer distance and higher bandwidth applications, including DWDM.

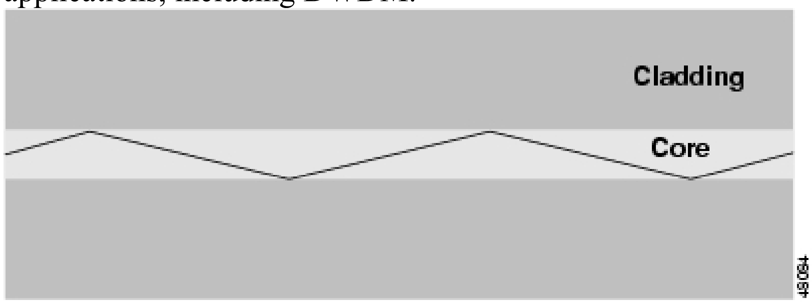


Figure 2.2. Reflected light in single-mode fiber [1].

Designs of single-mode fiber have evolved over several decades. The three principle types and their ITU-T specifications are:

- *Non-dispersion-shifted fiber* (NDSF), G.652 (support DWDM in Metropolitan Area [1])
- *Dispersion-shifted fiber* (DSF), G.653
- *Non-zero dispersion-shifted fiber* (NZ-DSF), G.655 (designed for the C-band) [1]
- *Advanced non-zero dispersion-shifted fiber* (A-NZ-DSF), G.655b (designed for the S-band and C-band) [4]

Some types of older fiber are not suitable for DWDM use, while newer types, such as NZ-DSF, are optimized for DWDM [1]. [1, 4, 8]

2. 2. Attenuation

Light traveling in a fiber loses power over distance, mainly because of absorption and scattering mechanisms in the fiber. Attenuation determines the maximum transmission distance between the transmitter and the receiver before the signal power needs to amplify. The degree of the attenuation depends on the wavelength of the light and on the fiber material. In addition, light power can be lost as a result of two types of fiber bending. One is macroscopic bending, that have radii which large compared with the fiber diameter, for example when a fiber cable turns a corner. The second is microscopic bending, when the fiber axis arises as fibers are incorporated into cables. In general, cable fabrication processes keep microscopic bending at a very low value, which is included in the published cable loss specification. The most common form of scattering, *Rayleigh scattering*, is caused by small variations in the density of glass as it cools. These variations are smaller than the used wavelengths and therefore act as scattering objects (see Figure 2.3). Scattering affects short wavelengths more than long wavelengths and limits the use of wavelengths below 800 nm. [1, 9]

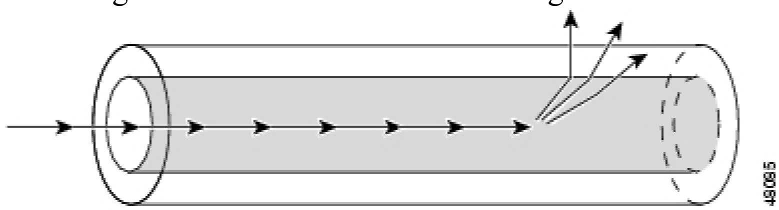


Figure 2.3. Rayleght scattering [1].

Attenuation due to absorption is caused by the intrinsic properties of the material itself, the impurities in the glass and by any atomic defects in the glass. These impurities absorb the optical energy, causing the light to become dimmer (see Figure 2.4). Intrinsic absorption is an issue at longer wavelengths and increases dramatically above 1700 nm. However, absorption due to water peaks introduced in the fiber manufacturing process are being eliminated in some new fiber types.

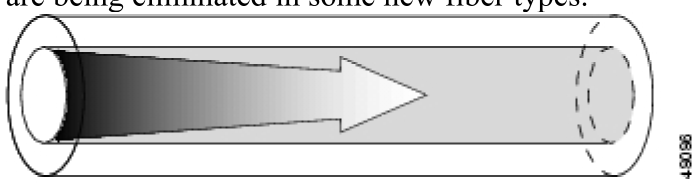


Figure 2.4. Absorption [1].

Figure 2.5. shows the loss in decibels per kilometer (dB/km) by wavelength from Rayleigh scattering, intrinsic absorption, and total attenuation from all causes.

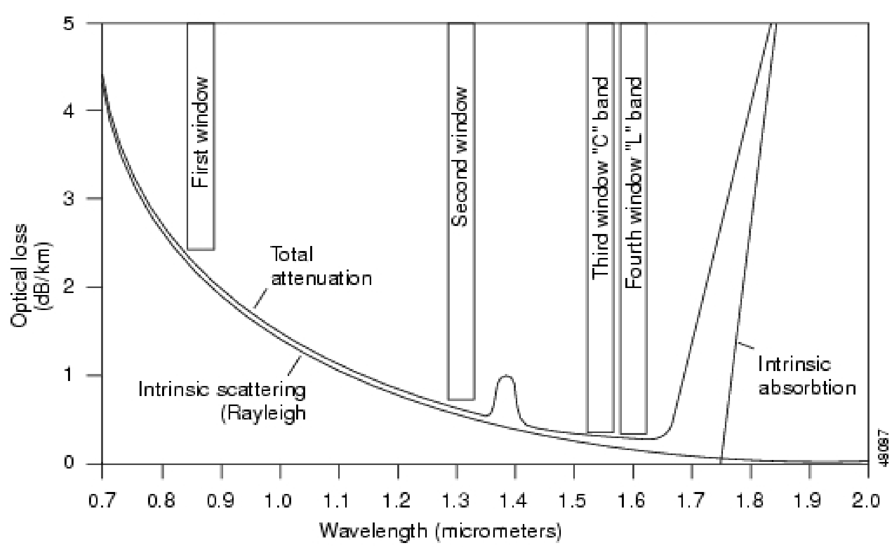


Figure 2.5. Total attenuation curve [1].

2. 3. Dispersion

The information-carrying capacity of the fiber is limited by signal dispersion factors and nonlinear effects. The three main dispersion categories are modal, chromatic and polarization mode dispersions. *Modal dispersion* arises from the different path lengths associated with various modes, light rays travel at different angles, as shown in figure 2.6. It appears only in multimode fibers, not in single-mode fibers, because there is only one mode. If all the rays are launched into a fiber at the same time in a given light pulse, then they will arrive at the fiber end at slightly different times. This causes the pulse to spread out and is the basis of modal dispersion. [4].

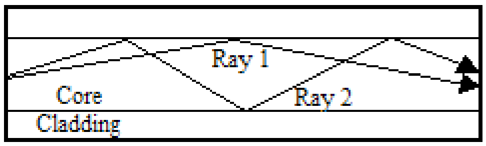


Figure 2.6. Rays that have steeper angles have longer path lengths.

Different wavelengths within an optical pulse travel at slightly different speed through the fiber. Therefore each wavelength will arrive at the fiber end at slightly different times, which leads to pulse spreading. This factor is called *chromatic dispersion*. It is a fixed quantity at a specific wavelength and it is measured in units of picoseconds per kilometer of fiber per nanometer of optical source spectral width, abbreviated as D_{CD} = ps/(km· nm). Total chromatic dispersion, along with its components, is plotted by the wavelength in Figure 2.7. for dispersion-shifted fiber. Transmission at OC-192 over single-mode (SM) fiber, for example, is 16 times more affected by chromatic dispersion than the next lower aggregate speed, OC-48. [1, 4, 10].

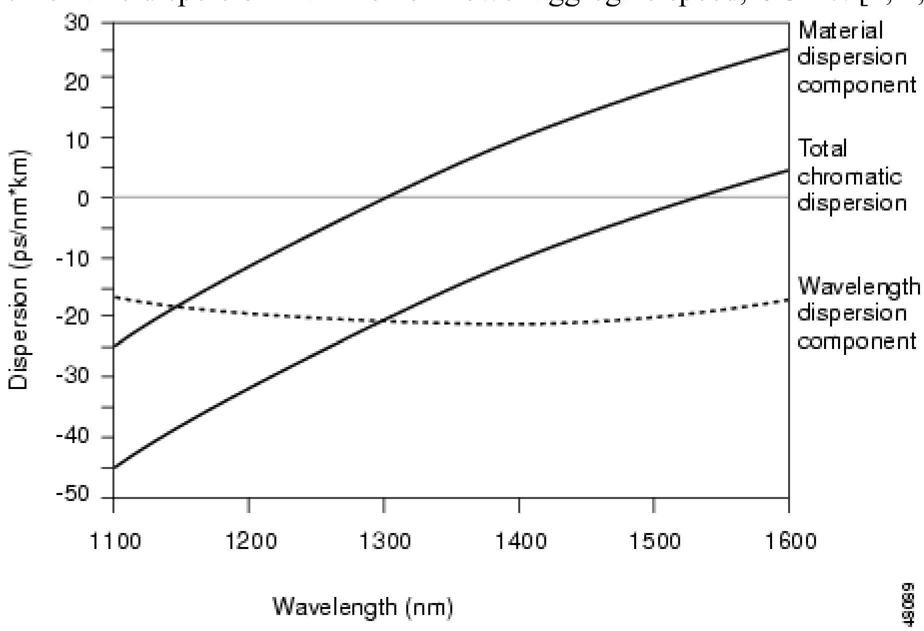
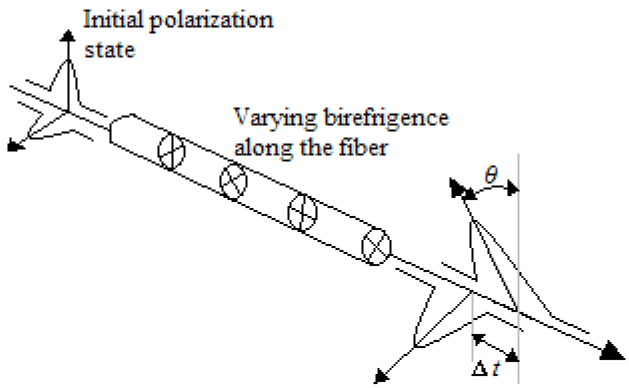


Figure 2.7. Chromatic dispersion [1].

At the start of the fiber the two polarization states are aligned. However, the fiber material is not unified throughout its length. In particular, the refractive index is not perfectly unified across any given cross-sectional area. Consequently, each polarization mode will encounter a slightly different refractive index, so that each will travel at a slightly different velocity and the polarization orientation will rotate with distance. This condition is known as the *birefringence* of the material and it is a basis for polarization mode dispersion and will result in pulse spreading. [4].



Picture 2.8. Variation in polarization states of an optical pulse as it passes through a fiber that has varying birefringence along its length [4].

It varies by the square root of distance and thus is specified as a mean value of units of ps/√km. A typical value is D_{PMD} = 0,05ps/√km. The total dispersion is given by formula

$$t_T = \sqrt{t_{mod}^2 + t_{CD}^2 + t_{PMD}^2} \tag{2.1}$$

where t_{mod}, t_{CD}, and t_{PMD} are the modal, chromatic and polarization mode dispersion times then the total dispersion t_T can be calculated by formula 2.1. Note that $t_{mod} = 0$ for single-mode fibers. [4]

By rule of thumb, the information-carrying capacity over a certain length of fiber is determined by specifying that the pulse spreading would not be more than 10 percent of the pulse width at a designated data rate.

In addition to polarization mode dispersion, there are other nonlinear effects. Because nonlinear effects tend to manifest themselves when the optical power is very high, they become important in DWDM. Linear effects such as attenuation and dispersion can be compensated, but nonlinear effects *accumulate*. The most important types of nonlinear effects are stimulated Brillouin scattering, stimulated Raman scattering, self-phase modulation, and four-wave mixing (FWM). In the case of DWDM, the four-wave mixing is the most critical of these types. Nonlinear interactions among different DWDM channels create sidebands that can cause interchannel interference. In figure 2.9 three frequencies interact to produce a fourth frequency, resulting in cross-talk and signal-to-noise degradation.

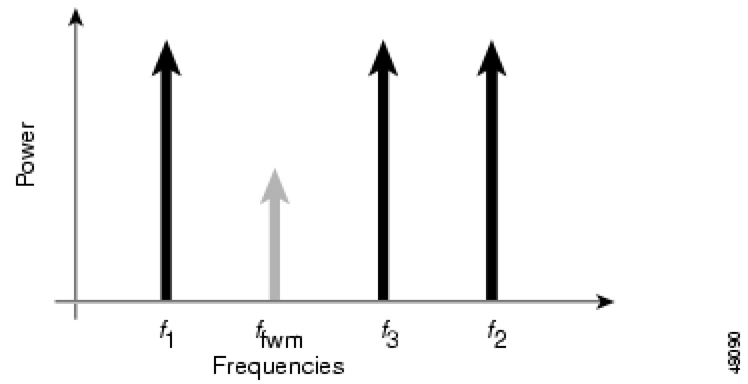


Figure 2.9. Four-wave mixing [1].

FWM is nonlinearity in silica fibers, which causes three optical waves of frequencies f_i , f_j, and f_k ($k \neq i, j$) to interact in a multichannel WDM system [11] to generate a fourth wave of frequency given by,

$$f_{ijk} = f_i + f_j - f_k \qquad (2.2)[10]$$

The four-wave mixing cannot be filtered out either optically or electrically and it increases with the length of the fiber, so the four-wave mixing limits the channel capacity of a DWDM system. This prompted the invention of NZ-DSF, which takes advantage of the fact that a small amount of chromatic dispersion can be used to mitigate four-wave mixing. [1, 4, 10]

2. 4. Dispersion compensation

As chromatic dispersion is a fully deterministic effect, it is in principle possible to fully compensate for it [12]. This is achieved by a signal having gone through a fiber that has a known total dispersion by putting the signal through an additional element having dispersion with equal magnitude and an opposite sign. The total cumulative dispersion will be equal to zero. [10]

A *dispersion-compensating fiber* (DCF) has a dispersion characteristic that is opposite that of the transmission fiber. Dispersion compensation is achieved by inserting a loop of DCF into the transmission path. If the transmission fiber has a low positive dispersion [say 2.3 ps/(nm · km)], then the DCF will have a large negative dispersion [say -90ps/(nm · km)]. With this technique, the total accumulated dispersion is zero after some distance, but the absolute dispersion per length is nonzero at all points along the fiber. The nonzero absolute dispersion value causes a phase mismatch between wavelength channels, thereby destroying the possibility of effective FWM production.

To compensate for the difference in arrival times of the various frequency components resulting from anomalous dispersion, one can use a chirped fiber Bragg grating that provides normal dispersion. As shown in figure 2.10 in such a dispersion compensator the grating spacing varies linearly over the length of the grating.

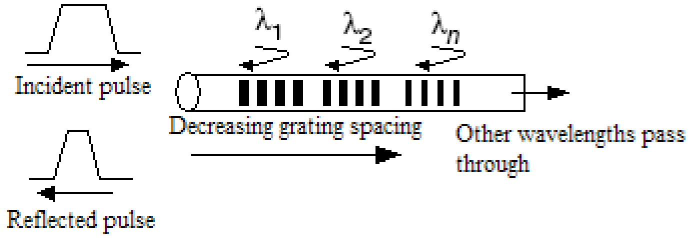


Figure 2.10. Chromatic dispersion compensation can be accomplished through the use of a chirped fiber Bragg grating.

This results in a range of wavelengths that satisfy the Bragg condition for reflection. In the configuration shown, the spacing decreases along the fiber which means that the fiber Bragg wavelength decreases with distance along the gating length. Consequently the shorter-wavelength components of a pulse travel farther into the fiber before being reflected. Thus, they experience greater delay in going through grating than the longer-wavelength components. The relative delays induced by the grating on the different frequency components of the pulse are the opposite of the delays caused by the fiber. This results in dispersion compensation, since it compresses the pulse. [4]

2. 5. Wavelength-Division Multiplexing (WDM)

When optical fiber systems were first deployed, they consisted of simple point-to-point links in which a single fiber line had one light source at its transmitting end and one photo-detector at the receiving end. The initial use of wavelength division multiplexing (WDM) was to upgrade the capacity of installed point-to-point transmission links. The use of WDM offers a further boost in fiber transmission capacity. The idea of WDM is to use multiple light sources operating at different wavelengths to simultaneously transmit several independent information streams over the same fiber. Figure 2.11 illustrate the WDM's basic concept, a TDM in figure 2.11 is included for comparison. Due to the fact that each channel is transmitted at a different frequency, we can use a tuner to select from them. [1]. With the appearing of tunable lasers that have extremely narrow spectral emission widths, one could then space wavelengths by less than a few nanometers. Each wavelength carries an independent signal, so that the link capacity is greatly increased. The key is to ensure that the peak wavelength of a source is spaced sufficiently far from its neighbor to avoid creating interference between their spectral extents. To maintaining strict control over the wavelength, system designers usually include an empty guard band between the channels. Different separate optical fibers are connected into the optical multiplexer, each of which carries its own data streams and wavelength, the received signals are multiplexed and transmitted into one single optical fiber. [4, 7]

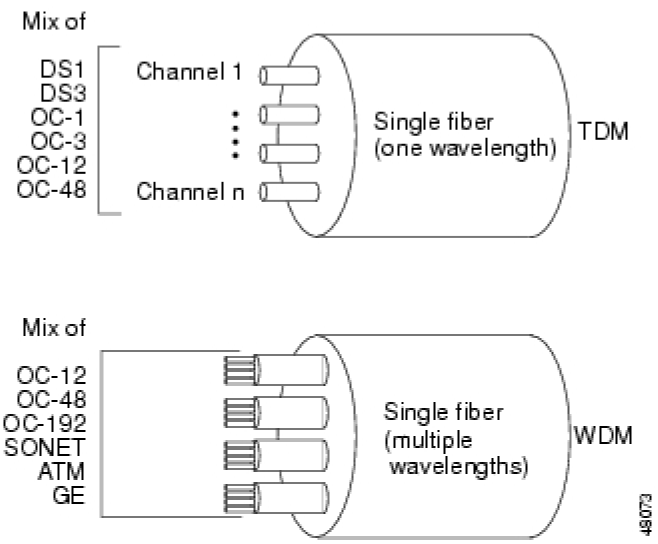


Figure 2.11. TDM and WDM interfaces [1].

2. 5. 1. Multiplexers and demultiplexers (MUX/DEMUX) for WDM

A key component is the wavelength *multiplexer*. The function of this device is to combine independent signal streams operating at different wavelengths onto the same fiber and a *demultiplexer* at the receiver end is used to split them apart [7]. There are many different techniques that have certain advantages and various limitations. These include thin-film filters, arrayed waveguide gratings, Bragg fiber gratings, diffraction gratings and interleavers. The performance demands on these components are increasing constantly with the desire to support higher channel counts and longer distance between terminals. [4] At the receiving end the system must be able to single out the light components so that they can be detected discreetly. Demultiplexers perform this function by separating the received beam into its wavelength components and by coupling them to individual fibers. Demultiplexing must be done before the light is detected, because photo-detectors are inherently broadband devices that cannot detect a single wavelength selectively. [1]

While prior to ITU-T Recommendation G.692 wavelength spacing was 100 GHz for 2.5 Gbps DWDM links, the current move is toward 10 Gbps ultra dense systems operating with channels that are spaced 25 or 12,5 GHz apart. A more extensive compressing of the channels is evident in the hyperfine WDM products that have separations down to 3.125 GHz. For 40 Gbps systems the channels are nominally spaced 50 or 100 GHz apart because of the greater impact from nonlinear dispersion effects at these higher data rates. The expansion of WDM channels beyond the C-band into the S- and L-bands has allowed sending 320 wavelengths spaced 25 GHz apart in the combined C- and L-band with 10 Gbps transmission rates per channel.

Multiplexers for CWDM applications have less stringent performance demands for certain parameters, such as center wavelength tolerance, its change with temperature and the passband sharpness. They still need to have a good reflection isolation, a small polarization-dependent loss and low insertion losses. These CWDM devices can be produced by thin-film filter technology. [4]

Multiplexers and demultiplexers can be either passive or active in design. Passive designs are based on prisms, diffraction gratings, or filters, while active designs combine passive devices with tunable filters. The primary challenges for these devices are to minimize cross-talk and to maximize channel separation. [1]

2. 5. 1. 1. Prism

A simple form of multiplexing or demultiplexing of light can be done by using a prism. Figure 2.12 demonstrates a case of demultiplexing. A parallel beam of polychromatic light impinges on a prism's surface; each wavelength component is refracted differently. This is the "rainbow" effect. In the output light, each wavelength is separated from the next at a certain angle. A lens then focuses each wavelength to the point where it needs to enter a fiber. The same components can be used reversely to multiplex different wavelengths onto one fiber.

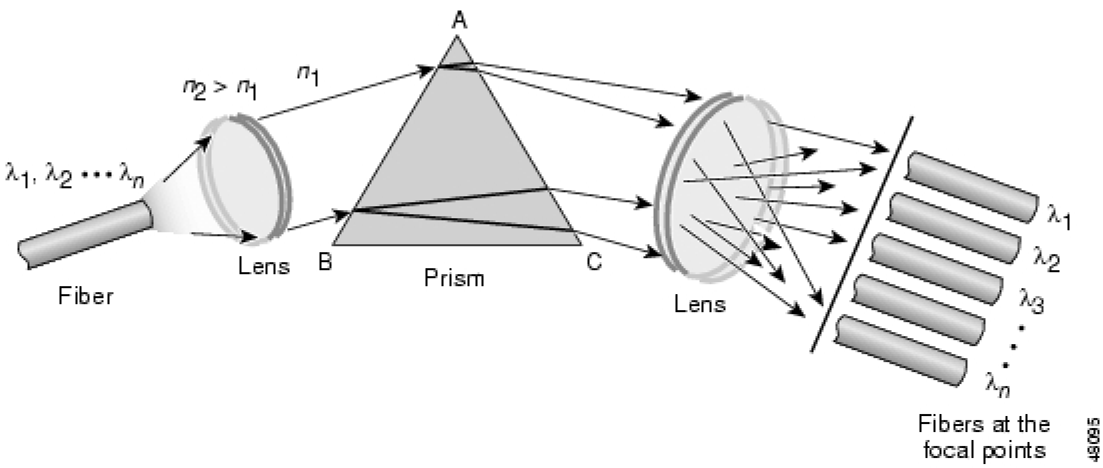


Figure 2.12. Prism refraction demultiplexing [1].

2. 5. 1. 2. Thin-film filters

A thin-film filter allows only a very small spectral width to pass through it and it reflects all other light outside this band. In order to create a wavelength multiplexing device for combining or separating N wavelength channels, cascade N – 1 thin-film filters are needed. Figure 2.13. illustrates a multiplexing function for the four wavelengths λ_1, λ_2, λ_3 and λ_4. Here the filters labeled TFF_2, TFF_3 and TFF_4 pass wavelengths λ_2, λ_3 and λ_4, and respectively, and reflect all others. The first filter TFF_2 reflects the wavelength λ_1 and allows the wavelength λ_2 to pass through. These two signals are then reflected from the filter TFF_3 where they are joined by the wavelength λ_3. After a similar process at the filter TFF_4, the four wavelengths can be coupled into a fiber through a lens mechanism. To separate the four wavelengths, the directions of the arrows in figure 2.13. are reversed. The light beam loses some of its power at each TFF because the filters are not perfect; this multiplexing architecture only works for a limited number of channels. This is specified to 16 channels or less.

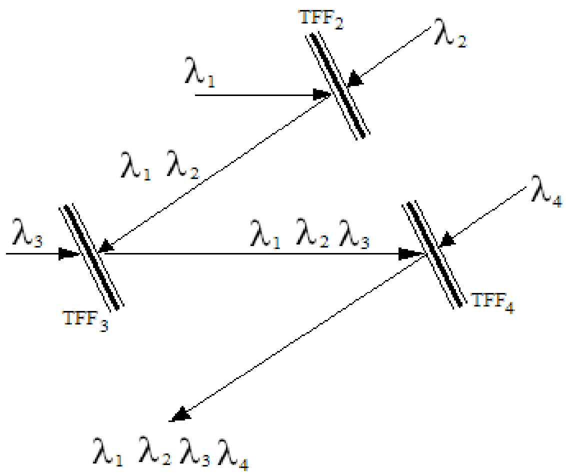


Figure 2.13. Thin film filters.

This method has the potential for providing the lowest insertion loss because light is coupled into fiber for each channel only once. However, this method requires the highest control on filters and on the manufacturing process because of the cascading configuration. [13] Thin-film filters have emerged as the chosen technology for OADM´s in current metropolitan DWDM systems because of their low cost and stability. For the emerging second generation of OADM´s, other technologies, such as tunable fiber gratings and circulators, will become prominent. [1] With the continued design innovation, improving the deposition process and enhancing optical processing technology in device design, thin-film filter based MUX/DEMUX will continue to be one of the key technologies in dense WDM systems [4, 13].

2. 5. 1. 3. Fiber Bragg gratings (FBG)

A *fiber Bragg grating* (FBG) allows optical channel spacing as narrow as 25 GHz. By using special packaging techniques, Bragg gratings can be made to have a very low thermal drift of less than one-half of a picometer (pm) per degree Celsius and they exhibit a very low interchannel crosstalk. The fiber Bragg grating-based devices are relatively simple devices and can be formed by simply modulating the refractive index of the optical fiber core by using an ultraviolet (UV) light source. [13] When a light with a broad spectrum is launched into one end of a fiber containing a fiber Bragg grating, the part of the light with wavelength matching the Bragg grating wavelength will be reflected back to the input end, with the rest of the light passing through to the other end. From the momentum conservation requirement of the Bragg grating condition, the following equation can be obtained:

$$2\left(\frac{2\pi n_{eff}}{\lambda_B}\right)=\frac{2\pi}{\Lambda} \qquad (2.3)$$

Where n_{eff} is the effective refractive index of the fiber core and λ_B the wavelength of the light reflected by the Bragg grating and Λ is modulation period. Therefore, the Bragg grating wavelength can be expressed as:

$$\lambda_B = 2\, n_{eff}\Lambda \qquad (2.4)[13]$$

Several methods have been developed to fabricate the FBG. Among them, interferometric [14], phase mask [15] and point-by-point techniques [16] using UV light are the most common ways of making FBG for optical communication applications. The FBG grating consists of a periodic refractive index variation in the core of an optical fiber, as shown in figure 2.14., where the refractive index of the fiber core is modulated with a period of Λ.

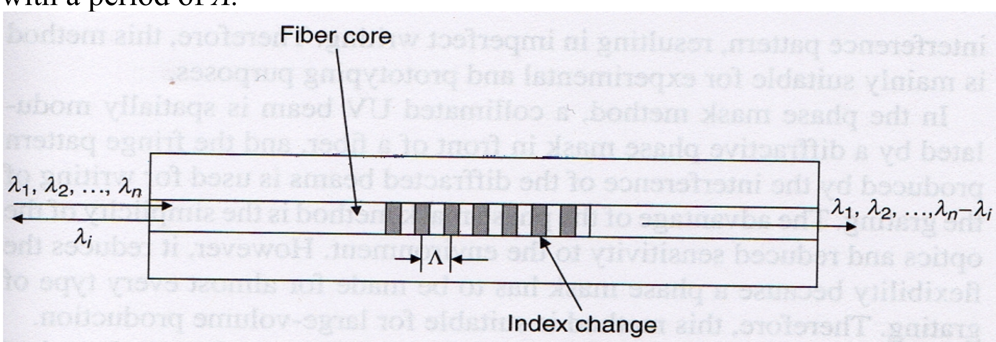


Figure 2.14. Schematic diagram of a fiber Bragg grating [13]

In contrast to a thin-film filter, an FBG reflects a narrow spectral slice and allows all other wavelengths to pass through it. To create a device for combining or separating N wavelengths, one needs to cascade N – 1 fiber Bragg gratings and N – 1 circulators (see figure 2.15).

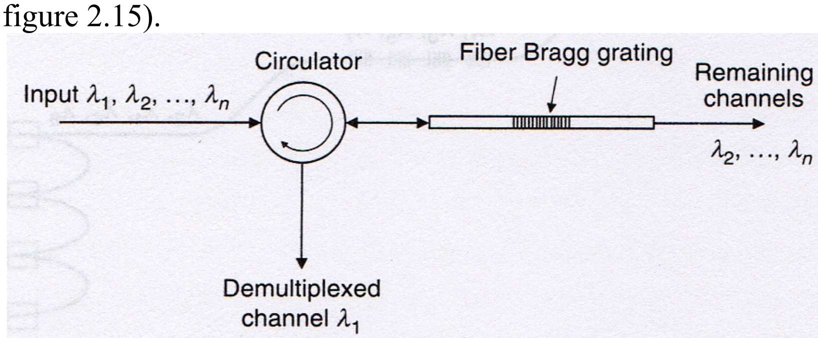


Figure 2.15 Schematic diagram of a fiber Bragg grating-based single channel DEMUX device [13]

Similar with the use of thin-film filters to form multiplexers, the size limitation while using the fiber Bragg gratings is that one filter is needed for each wavelength and normally the operation is sequential with wavelengths being transmitted by one filter after another. Therefore, the losses are not the same from channel to channel, since each wavelength goes through a different number of circulators and fiber gratings, each of which adds loss to that channel. This may be acceptable for a small number of channels, but the loss differential between the first and the last inserted wavelength is a restriction for large channel counts. Therefore, it is suitable to add a *Dynamic Channel Equalizer* (DCE) after the FBG multiplexer. Unfortunately, the DCE supports the maximum of 80 channels spaced 50 GHz in C- and L-band.

In WDM systems, a *grating* is an important element, which is for combining and separating individual wavelengths. A grating is a periodic structure or perturbation in a material. This variation in the material has the property of reflecting or transmitting light in a certain direction depending on the wavelength. [4]

2. 5. 1. 4. Arrayed Waveguide gratings (AWG)

An *arrayed waveguide grating* (AWG) is the fourth DWDM device category. Arrayed waveguide gratings (AWG's) are also based on diffraction principles. An AWG device, sometimes called an optical waveguide router or waveguide grating router, consists of an array of curved-channel waveguides with a fixed difference in the path length between adjacent channels (see Figure 2.16). The waveguides are connected to the input and output cavities. When light enters the input cavity, the waveguide is diffracted in the coupling region and exits all the arrayed channel waveguides. After traveling through the channel waveguides, light beams from the channel waveguides are diffracted again and constructively interfere with each other at different focal points in the second coupling region, then couple into the output waveguides. [13] There the optical length difference of each waveguide introduces relative phase delays in the output cavity, where an array of fibers is coupled. The process results in different wavelengths having maximal interference at different locations, which correspond to the output ports.

Similar to the diffraction grating equation, the grating equation for the AWG can be expressed as

$$n_s d(\sin\theta_i + \sin\theta_o) + n_0 \Delta L = m\lambda \qquad (2.5)$$

where θ_i and θ_o are the input and output beam angles, n_0 and n_s the effective refractive indexes of the channel waveguides at the center wavelength and the coupling region, respectively, d is the pitch of the channel waveguides, m is the grating diffraction order, λ is the wavelength and ΔL is the path length difference between adjacent waveguides. [1, 4, 13]

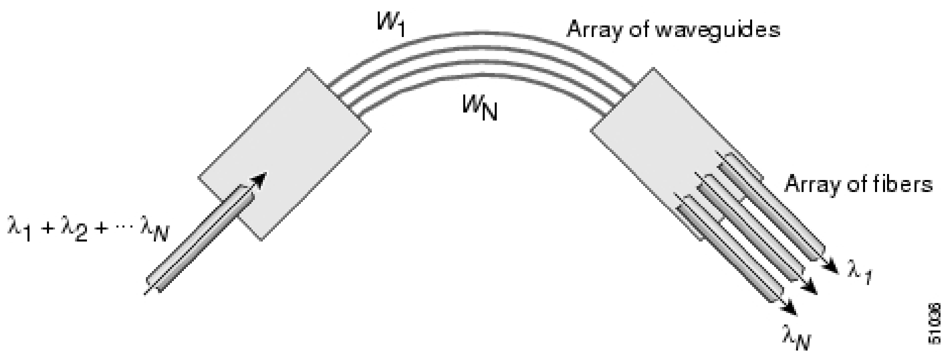


Figure 2.16. Arrayed waveguide grating. [1]

2. 5. 1. 5. Diffraction gratings

The fifth DWDM technology is based on diffraction gratings. A diffraction grating is a conventional optical device that spatially separates the different wavelengths contained in a beam of light. The device consists of a set of diffracting elements, such as narrow parallel slits or grooves, separated by a distance comparable to the wavelength of light. These diffracting elements can be either reflective or transmitting, thereby forming a reflection grating or a transmission grating.

The adjacent-channel crosstalk in a diffraction grating is very low, usually less than 30 dB. The insertion loss is also low (less than 3 dB) and it is unified within 1 dB over a large number of channels, because all channels are multiplexed/demultiplexed at the same time. Therefore, the diffraction grating is more suitable for making MUX/DEMUX devices where a large number of channels are involved. [13] A passband 30 GHz at 1 dB ripple is standard. Packaging designs can make the device a-thermal, so that no active temperature control is needed.

Reflection gratings are fine ruled or etched parallel lines on some type of reflective surfaces. With these gratings, light will bounce off the grating at an angle. The angle at which the light leaves the grating depends on its wavelength, so the reflected light fans out on a spectrum. For DWDM applications, the lines are spaced equally and each individual wavelength will be reflected at a slightly different angle, as shown in figure2.17.

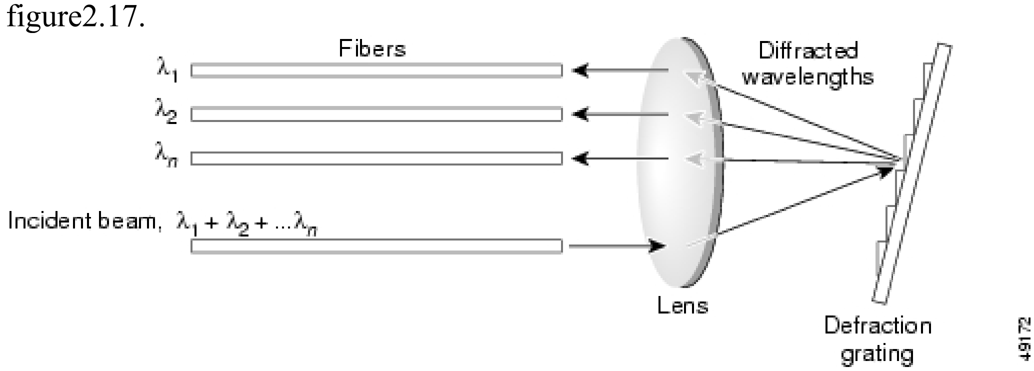


Figure 2.17. Waveguide grating diffraction [1].

The reflective diffraction grating works reciprocally: if different wavelengths come into the device on the individual input fibers, all wavelengths will be focused back into one fiber after traveling through the device.

One type of *transmission grating*, which is known as a *phase grating*, consists of a periodic variation of the refractive index of a grating. These may be characterized by a Q parameter which is defined as

$$Q=\frac{2\pi\lambda d}{n g \Lambda^2 \cos(\alpha)} \tag{2.6}$$

where λ is the wavelength, d is the thickness of the grating, n_g is the refractive index of the material, Λ is the grating period and α is the incident angle as shown in figure 2.17. After a spectrum of wavelength channels passes through the grating, each wavelength emerges at a slightly different angle and can be focused into a receiving fiber.[1, 4]

2. 5. 1. 6. Interleavers

Another wavelength multiplexing component is an *interleaver*, which is a passive low-dispersion device that can increase the channel density in a WDM system. This device can combine or separate very high-density channels with a spacing as low as 3.125 GHz. A unique feature is that it can be custom-designed to route or drop a group of channels while allowing all other wavelengths to pass straight through (which commonly are referred to as the *express channels*).

Interleavers are bidirectional, so that they can be used either as a multiplexer or a demultiplexer. For simplicity of discussion we will consider here the demultiplexing function. Interleavers are characterized by the designation 1 × N, which indicates one input and N output ports, as shown in figure 2.18. For example, consider a series of wavelengths separated by 25 GHz entering a 1 × 4 interleaver. The interleaver splits the incoming channels into four sets of 100 GHz spaced channels. This greatly simplifies further demultiplexing by allowing optical filtering at 100 GHz instead of at the initial 25 GHz. Note that for a 1 × N demultiplexer, each *N*th wavelength is selected to exit a particular port. For example, in the 1 × N interleaver, wavelengths λ_1, λ_5, λ_9 … exit port 1 and even channels exit port 2. [4]

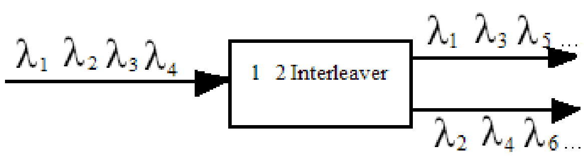


Figure 2.18. Example of wavelength separations by a interleaver.

2. 5. 1. 7. Optical add/drop multiplexers (OADM)

A wavelength selective branching device (used in WDM transmission systems) has 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 and also having a wavelength "add" function in which optical signals presented to the add port(s) are also transferred to the output port. [17]

Between multiplexing and demultiplexing points in a DWDM system, as shown in Figure 2.19 there is an area in which multiple wavelengths exist. It is often desirable to be able to remove or insert one or more wavelengths at some point along this span. An optical add/drop multiplexer (OADM) performs this function. Rather than combining or separating all wavelengths, the OADM can remove some while passing others on. The OADMs have a key role in moving toward the goal of all-optical networks, no conversion of the signal from optical to electrical takes place. [1] A traditional OADM consists of three parts: an optical demultiplexer, an optical multiplexer and between them a method of reconfiguring the paths between the optical demultiplexer, the optical multiplexer and a set of ports for adding and dropping signals [18].

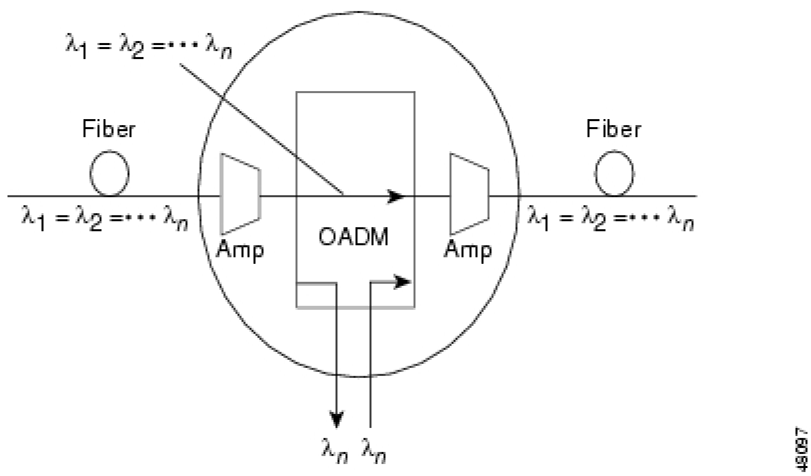


Figure 2.19. Selectively removing and adding wavelengths [1].

Add and drop functions can be controlled by MEMS-based miniature mirrors that are activated selectively to connect the desired fiber paths (more information about MEMS is under section 2.7). When no mirrors are activated, each incoming channel passes through the switch to the output port. Incoming signals can be dropped from the traffic flow by activating the appropriate mirror pair (see figure 1.20). With a *reconfigurable optical add-drop multiplexer* (ROADM), network operators can remotely reconfigure the multiplexer by sending soft commands. The architecture of the ROADM is such that dropping or adding wavelengths does not interrupt the 'pass-through' channels.

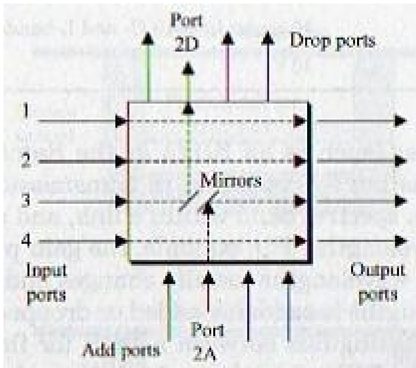


Figure1.20. An example of adding and dropping wavelengths with a 4 x 4 OADM devices that uses miniature switching mirrors [4].

There are two general types of OADM´s. The first generation is a fixed device that is physically configured to drop specific predetermined wavelengths while adding others. The second generation is reconfigurable and capable of dynamically selecting, which wavelengths are added and which dropped.

In regular OADM, adding or dropping wavelengths requires manually inserting or replacing wavelength-selective cards. This is costly, and in some systems requires that all active traffic be removed from the DWDM system, because inserting or removing the wavelength-specific cards interrupts the multi-wavelength optical signal. With a *Reconfigurable Optical Add/Drop Multiplexer* (ROADM), network operators can remotely reconfigure the multiplexer by sending soft commands. [7] In 2005, ROADM began to appear in metro-optical systems because of the need to build out major metropolitan networks in order to deal with the traffic driven by the increasing demand for packet-based services. [19]

2. 8. Light sources and transmitters

Light sources, or light emitters, are transmit-side devices that convert electrical signals to light pulses. The light source used in the design of a system is an important consideration because it can be one of the most costly elements. Light emitting devices used in optical transmission must be compact, monochromatic, stable, and long-lasting. [1]. *A light emitting diode* (LED) is an inexpensive and highly reliable light source. LEDs are cheaper and easier to use in transmitter designs. However, because of their relatively low power output, broad emission pattern and slow turn-on time, their use is limited to low-speed (less than 200Mbits) short-distance applications using multimode fibers. LEDs exhibit a relatively wide spectrum width and they transmit light in a relatively wide cone. [1] The term *modulation speed* refers to the speed how fast a device can be turned on and off by an electric signal to produce a corresponding optical output pattern. [4]

Semiconductor-based *laser diodes* are the most widely used optical sources in fiber communication systems, because of their properties. Figure 1.21 shows the general principles of launching laser light into fibers. The laser diode chip emits light in one direction to be focused by the lens onto the fiber and in the other direction onto a photodiode. The photodiode, which is angled to reduce reflections back into the laser cavity, provides a way of monitoring the output of the lasers and providing feedback so that adjustments can be made

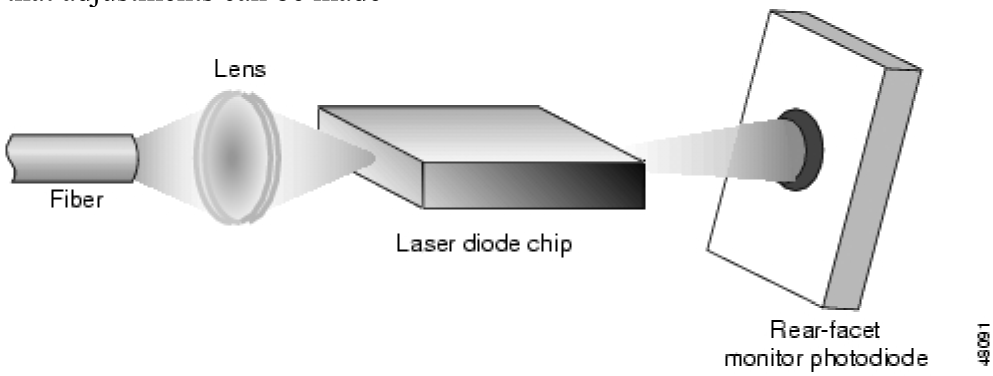


Figure 1.21 Typical laser design [1].

The requirements for lasers include a precise wavelength, a narrow spectrum width, sufficient power, and control of *chirp* (the change in frequency of a signal over time). Semiconductor lasers satisfy the first three requirements nicely. Chirp, however, can be affected by the means that are used to modulate the signal. The four main laser types are the *Fabry-Perot* (FP) laser, the D*istributed Feedback laser* (DFB), the *tunable laser* and the V*ertical cavity surface-emitting laser* (VCSEL). The DFB type is particularly well suited for DWDM applications, as it emits a nearly monochromatic light, is capable of high speed, has a favorable signal-to-noise ratio, and has superior linearity. DFB lasers also have center frequencies in the region around 1310 nm, and from 1520 to 1565 nm. The latter wavelength range is compatible with an *Erbium-Doped Fiber Amplifier* (EDFA). [1] The DFB lasers have a temperature dependence of the wavelength of about 0.1 nm/ºC. Thus they need thermoelectric coolers to maintain specified wavelengths. The fine adjustment of wavelength is achieved wit the set temperature for operation. [10]

The greatest laser advances against LEDs are high optical output powers (greater than 1mW), narrow line widths and high directional output beams for efficient coupling of light info fiber core. In many networks there is a need to tune the wavelength of a laser transmitter. This is especially important in a multiwavelength network. In high-speed systems the laser needs to emit at a precise wavelength, thus the ability to tune the laser is essential. A number of different technologies have been developed to make tunable lasers, each having certain advantages and limitations with respect to tuning range, tuning speed, power output and tuning complexity. Lasers with wider spectrum tunability are being developed, which will be important in dynamically switched optical networks. [1] Tuning is achieved by changing the temperature of the device (the wavelength changes 0,1nm/°C), by altering the injection current into the gain region (the wavelength changes 0,01 to 0,04nm/mA), or by using a voltage change to vary the orientation of a *Microelectromechanical System* (MEMS) mirror to change the length of a lasing cavity. [4].

Table 2.1. Tunable laser technologies and typical parameters (T = temperature, C = current, V = voltage).

Technology	Tuning	Tuning range, nm	Tuning time, ms	Output power, mW	Advantages	Limits
DFB	*T*	3 - 9	10 000	2	Proven reliability	Slow, small range
DBR	*C*	8 - 10	10	5	Simple device, high power output	Intermediate tuning range
GCSR	*C*	40	10	2	Wide tuning range	Complex control
SG+DBR	*C*	40	10	2	Wide tuning range	Complex control
VMPS	*V*	32	10	10 - 20	Wide tuning, high output	Complex hybrid packaging

The transmitter controller is maintaining laser stability and operating an external modulator. The external modulator can be in a separate package or it can be integrated within the laser package. The transmitter control functions are:

- temperature control (laser diode stability is 0.02ºC)
- wavelength control
- laser bias control
- transmitter output power control
- alarm processor
- transmission control signal processor [4]

2. 8. 1. Wavelength lockers

Moving towards spacing wavelengths very closely together in a DWDM system calls for strict wavelength control of lasers since spacing 25 GHz requires a wavelength accuracy of ± 0.02 nm. Fabry-Perot etalon-based wavelength lockers can offer such accuracy with one device providing multiple wavelengths locking across the S-, C-, and L-bands. Since they are very small solid-state devices, they can be integrated into the laser diode package.

Figure 2.22 shows a top-level function of a wavelength locker assembly. Usually, a small percentage of the light is tapped off after the modulator and it is fed into a beam splitter. One part of the beam goes to a reference photodiode and the other part goes through an etalon. The microprocessor-based transmitter controller then compares the two signals and adjusts the laser wavelength and the optical power accordingly. [4]

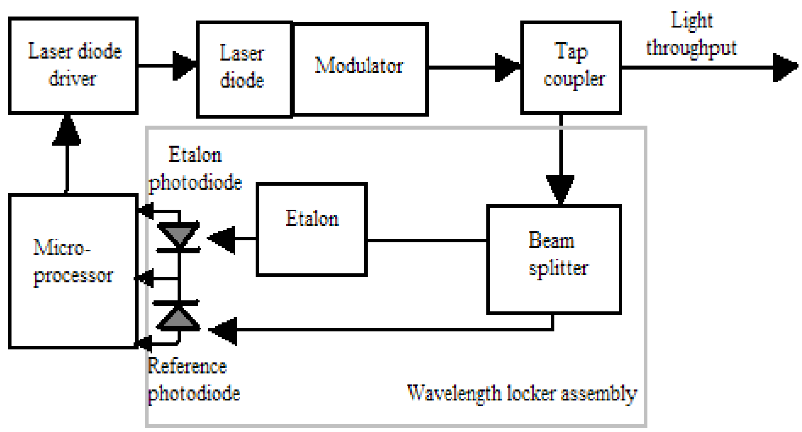


Figure 2.22. Top-level function of a wavelength locker assembly.

2. 9. Receivers

Light detectors perform the opposite function of light emitters. They are the receive-side opto-electronic devices that convert light pulses into electrical signals. [1] On the receiver end, it is necessary to recover the signals transmitted at different wavelengths on the fiber. Because photodetector are by nature wideband devices, the optical signals are demultiplexed before reaching the detector.

Two types of photodetector are widely deployed: the positive-intrinsic-negative (PIN) photodiode and the avalanche photodiode (APD). The PIN photodiodes work on principles similar to, but in the reverse of, LEDs. That is, light is absorbed rather than emitted, and photons are converted to electrons in a 1:1 relationship. The APDs are similar devices to PIN photodiodes, but provide gain through an amplification process: one photon acting on the device releases many electrons. The PIN photodiodes have many advantages, including low cost and reliability, but the APDs have higher receiver sensitivity and accuracy. However, the APDs are more expensive than the PIN photodiodes, they can have very high current requirements, and they are temperature sensitive.

2. 10. Passive optical components

Although optical fibers and connectors are passive elements, one usually considers them separately from other passive optical components. Some basic passive functions and the devices which enable them as follows:

1. Transfer energy: optical fibers
2. Attenuate light signals: optical attenuators, isolators
3. influence the spatial distribution of light wave: directional coupler, star coupler, beam expander
4. Modify the state of polarization: polarizer, half-wave plates, Faraday rotator
5. Reflect light: fiber Bragg gratings, mirror

6. Redirect light: circulator, mirror, grating
7. Select a narrow spectrum of light: optical filter, grating
8. Convert light wave modes: fiber grating, Mach-Zehnder interferometer
9. Combine or separate independent signals at different wavelengths: WDM device

Some of these passive devices also can be configured as active devices.

2. 10. 1. Optical couplers

The concept of a *coupler* encompasses a variety of functions, including splitting a light signal into two or more streams, combining two or more light streams, tapping off a small portion of optical power for monitoring purposes or transferring a selective range of optical power from one fiber to another.

The 2 × 2 coupler is a simple fundamental device, these are known as *directional couplers*. Common construction is the fused-fiber coupler illustrated in figure 2.23. This is fabricated by twisting together, melting and pulling two single-mode fibers so they get fused together over a uniform section of length *W*. Each input and output fiber has a long tapered section of length *L*, since the transverse dimensions are reduced gradually down to that of of the coupling region when the fiber are pulled during the fusion process. P_0 is the input power, P_1 is the throughput power, P_2 is the power coupled into the second fiber, P_3 and P_4 are extremely low optical signal levels from backward reflections and scattering due to packaging effects and bending the device.

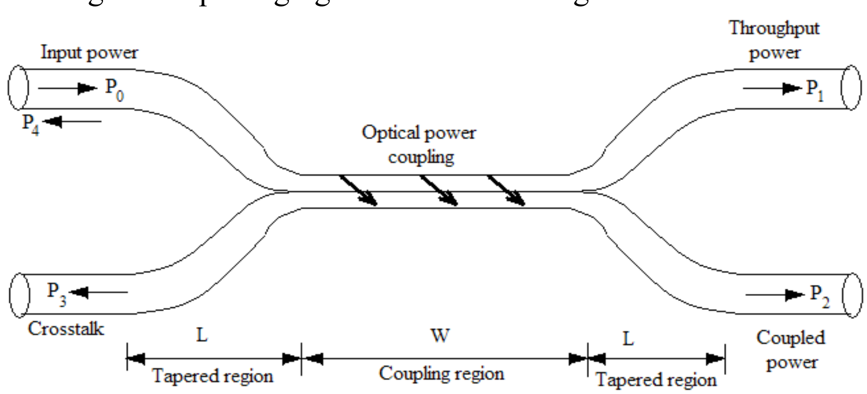


Figure 2.23. Cross-sectional view of fused fiber coupler having coupling region W and two tapered regions of length L. The total span 2L + W is the coupler draw length.

N × *N* coupler is called a *star coupler* and small coupling of around 1 to 5 percent is called *tap coupler*.

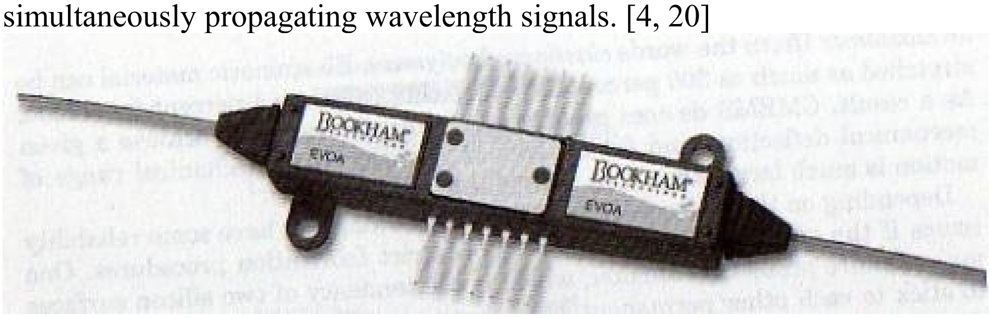
2. 10. 2. Optical circulators

An *optical circulator* is a nonreciprocal multiport passive device that directs light sequentially from port to port in only one direction. The operation of a circulator is similar to that of an isolator except that its construction is more complex. Typically is consists of a number of walk-off polarizers, half-wave plates and Faraday rotators and has three or four ports, as shown in figure 2.15 in section 2. 5. 1. 3. Optical circulators are often used in conjuction with the fiber Bragg gratings, MUX/DEMUX devices, tunable optical Add/Drop Multiplexers and other applications. [4, 13]

2. 11. Optical attenuators

The precise active signal-level control is essential for proper operation of DWDM networks. For example, all wavelength channels exiting an optical amplifier need to have the same gain level, certain channels may be needed to be planked out to perform network monitoring, span balancing may be needed to ensure that all signal strengths at a user location are the same and signal attenuation may be needed at the receiver to prevent photodetector saturation. A *variable optical attenuator* (VOA) offers such dynamic signal-level control. This device attenuates optical power by various means to control signal levels precisely without disturbing the other properties of a light signal. This means that the VOA should be independent from polarization, attenuate light independently of the wavelength and have a low insertion loss. Typical VOA package is shown in picture 2.24.

The most popular control methods are MEMS-based and electro-optic-based techniques. For MEMS techniques the electrostatic actuation method is the most common and well developed, since the integrated-circuit process offers a wide selection of conductive and insulating materials. By this method a voltage change across a pair of electrodes provides an electrostatic actuation force. This requires lower power levels than other methods do, and it is the fastest. When wavelengths are added, dropped or routed in the WDM system a VOA can manage the optical power fluctuations of this and other simultaneously propagating wavelength signals. [4, 20]



Picture 2.24. A typical VOA package for moderate optical power [4].

2. 12. Tunable optical filters

Tunable optical filters are key components for dense WDM optical networks. There are two key technologies to make tunable filters: the MEMS-based and Bragg-grating-based devices.

The fiber Bragg gratings are wavelength-selective reflective filters with steep spectral profiles and flat tops.

A 100-GHz filter has a reflection bandwidth of less than 0,8nm and 25dB below the peak, as shown in figure 2.25. The standard uniform spaced fiber gratings have large sidelobes, which lie only about 9dB below the central peak. These sidelobes can be reduced to be at least 30dB below the peak using a special apodization mask to precisely control the UV beam's shape in the Bragg grating fabrication process. *Apodization* is a mathematical technique used to reduce ringing in an interference pattern, thus giving a large central waveform peak with low sidelobes. Such optical filter can be made for the S-, C-, and L-bands for operation in the 1310-nm region. [4]

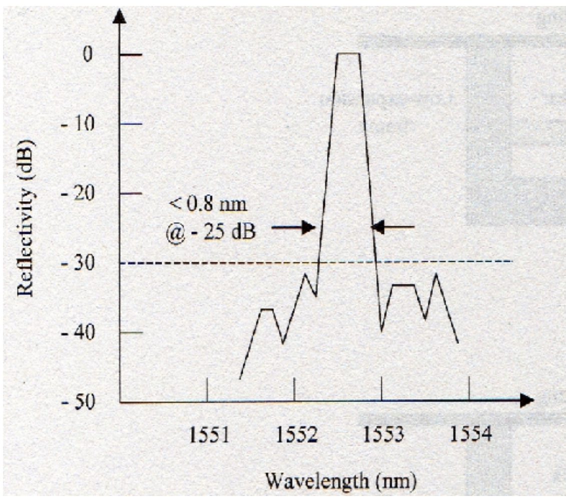


Figure 2.25. Fiber Bragg gratings are wavelengths selective of reflective filters with steep spectral profiles [4].

2. 13. Dynamic channel equalizer (DCE)

A device that is capable of transforming, by internal or external automatic control, a multichannel input signal with time-varying averaged powers into an output signal in which all working channel powers are nominally equal or are set for a required level of pre-emphasis [17].

A *dynamic channel equalizer* (DCE) is used to reduce the attenuation of the individual wavelengths within a spectral band. The function of the DCE is equivalent to filtering out individual wavelengths and equalizing them on a channel-by-channel basis.

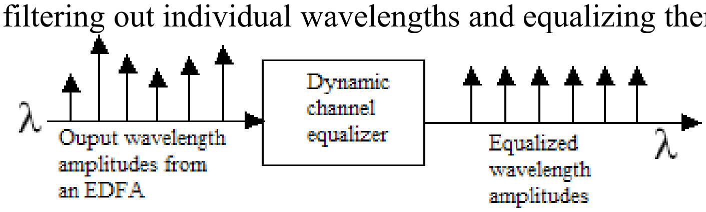


Figure 2.26. Example of how a DCE equalizes gain profile of an erbium-doped fiber amplifier.

Their application includes flattering the nonlinear gain profile of an optical amplifier, compensating for variation in transmission losses on individual channels across a given spectral band within a link and attenuating, adding or dropping selective wavelengths. For example, the gain profile across a spectral band containing many wavelengths usually changes and needs to be equalized when one of the wavelengths is suddenly added or dropped on a WDM link. [4]

These devices operate by having individual tunable attenuators, such as a series of VOAs, and control the gain of a small spectral segment across a wide spectral band, such as the C- or L-band. For example, within a 4-THz spectral range a DCE can individually attenuate the optical power of 40 channels spaced at 100 GHz or 80 channels spaced at 50 GHz. The operation of these devices can be controlled electronically and configured by software residing in a microprocessor. This control is based on feedback information received from a performance monitoring card that provides the parameter values needed to adjust and adapt to required link specification. This allows a high degree of agility in responding to optical fluctuations that may result from changing network conditions. [4]

2. 16. Erbium-doped fiber amplifier (EDFA)

The active medium in an optical fiber amplifier consists of a nominally 10- to 30-m length of optical fiber that has been lightly doped (1000 parts per million weights) with rare earth elements, such as erbium (Er), ytterbium (Yb), neodymium (Nd) or praseodymium (Pr). The host fiber can be standard silica, fluoride-based glass or multicomponent glass. The operating regions of these devices depend on the host material and the doping elements.

The most common material for long-haul telecommunication applications is a silica fiber doped with erbium, which is known as an *erbium-doped fiber amplifier* (EDFA). Originally the operation of an EDFA by itself was limited to the C-band (1530 – 1560-nm region), since the gain coefficient for erbium atoms is high in this region. This fact actually originates from the designation *conventional band* or C-band. In addition, a combined operation of an EDFA together with Raman amplification techniques for the L-band has resulted in a hybrid amplifier that can boost the gain over the 1531- to 1616-nm region with a 3-dB gain bandwidth of 75-nm [4, 7]. The EDFA amplifies all the channels in a WDM signal simultaneously, whereas regenerators require optical to electrical conversion for each channel. [7, 21]

Whereas semiconductor optical amplifiers use external current injection to excite electrons to higher energy levels, optical fiber amplifiers use *optical pumping*. In this process, one uses photons to directly raise electrons into excited states. [4]. The semiconductor pump laser introduces a powerful beam at a shorter wavelength into a section of erbium-doped fiber several meters long. The pump light excites the erbium atoms to higher orbits, and the input signal simulates them to release excess energy as photons in a phase and at the same wavelength. The pump light is typically 1480-nm or 980-nm. The figure 2.27 is illustrative of the working concepts of the EDFA optical amplifier. [21]

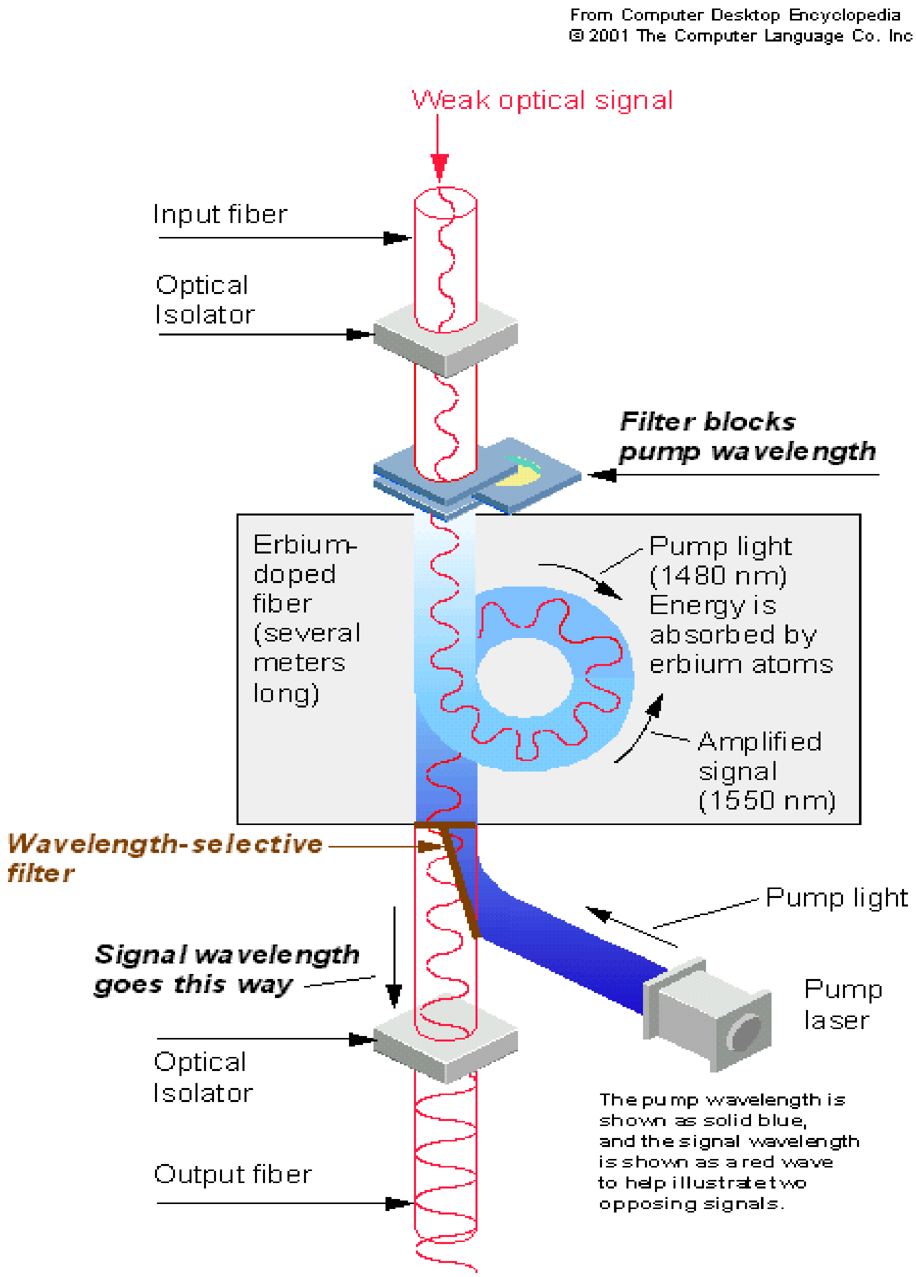


Figure 2.27. Simplified energy-level diagrams and various transitions processes of Er^{3+} ions in silica [21].

2. 16. 1. EDFA noise

The dominant noise generated in an optical amplifier results from *amplified spontaneous emission* (ASE). The origin of this is the spontaneous recombination of electrons and holes in the amplifier medium. This recombination gives rise to a broad spectral background of photons that get amplified along with the optical signal. This is shown in Picture 2.28. for a 1480-nm pump and an EDFA amplifying a signal at 1540-nm.

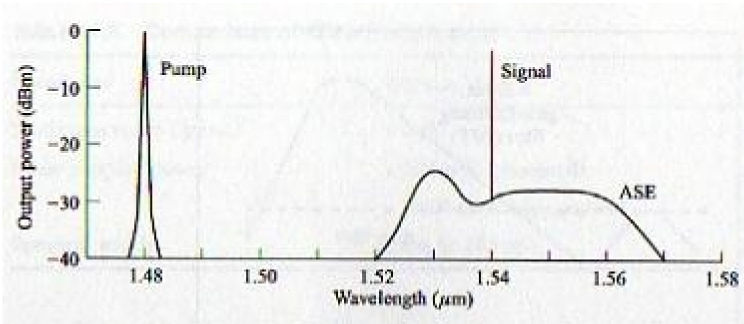


Figure 2.28. Representative 1480-nm pump spectrum and typical output signal at 1540-nm with a associated ASE noise [4].

2. 6. Optical Cross-connect (OXC)

An optical *cross-connect* (OXC) is a device used by telecommunications carriers to switch high-speed optical signals in a fiber optic network. These types of elements are usually considered to be wavelength insensitive.

A basic cross-connect element is the 2 × 2 crosspoint element. A 2 × 2 crosspoint element routes routes optical signals from two input ports to two output ports and has two states: cross state and bar state. In the cross state, the signal from the input port is crossed and routed to the output port. In the bar state, the signal from the input port is routed straight to the output port (see figure 1.21). The features that an OXC should ideally support are similar to these of an OADM, but OXC need to additionally provide:

- Strictly nonblocking connectivity between input and output ports.
- Span and ring protection as well as mesh restoration capabilities.[8]

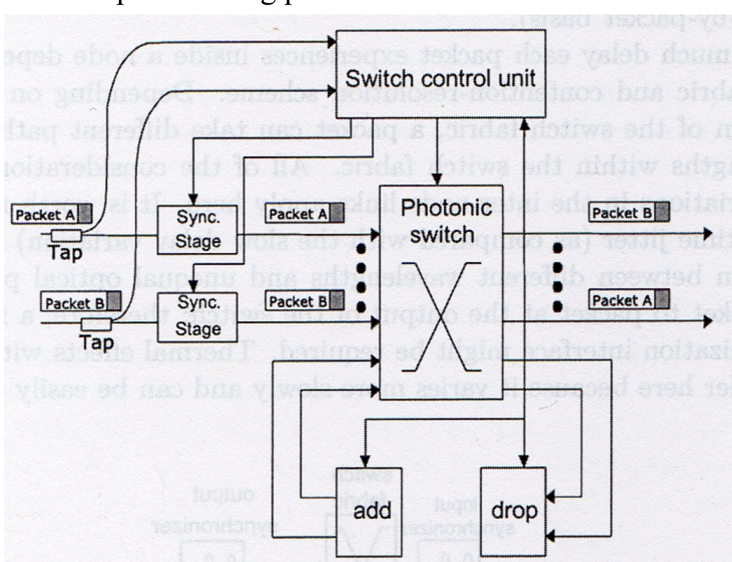


Figure 1.21. A generic node architecture of the slotted network [8]

There are several ways to realize an OXC. One can implement an OXC in the electronic domain: all the input optical signals are converted into electronic signals after they are demultiplexed by demultiplexers. After the electronic switching signals are converted back into optical signals by using them to modulate lasers and then the resulting optical signals are multiplexed by optical multiplexers onto outlet optical fibers. This is known as an *Optical-Electrical-Optical* (OEO) design. Such architecture prevents an OXC from performing with the same speed as an all-optical cross-connect, and it is not transparent to the used network protocols. The advantage is that the optical signals are regenerated, so that they leave the node free of dispersion and attenuation, thus it is easy to monitor signal quality in an OEO device, since everything is converted back to the electronic format at the switch node. An electronic OXC is also called an *opaque OXC*.

Switching optical signals in an all-optical device is the second approach to realize an OXC. Such a switch is often called a *transparent OXC* or *photonic cross-connect* (PXC). Optical signals are demultiplexed, then the demultiplexed wavelengths are switched by optical switch modules. After switching, the optical signals are multiplexed onto output fibers by optical multiplexers. Such switch architecture keeps the features of data rate and protocol transparent, but it is not easy to perform an optical signal quality monitoring.

Translucent OXC is a compromise between opaque and transparent OXCs, which consists of an optical switch module and an electronic switch module. When the optical switch module's switching interfaces are all busy or an optical signal needs signal regeneration through an OEO conversion process, the electronic module is used. Translucent OXC nodes provide a compromise between the full optical signal transparency and the comprehensive optical signal monitoring. It also provides the possibility of signal regeneration at each node. [8, 20]

In OXC architectures, optical crosspoint elements have been demonstrated using two types of technologies:

- The generic directive switch, in which light is physically directed to one of two different outputs. [22]
- The gate switch, in which optical amplifier gates are used to select and filter input signals to specific output ports.[8]

2. 7. MEMS technology

MEMS is *microelectromechanical systems*, which are miniature devices that combine mechanical, electrical and optical components to provide sensing and actuation functions. The control or actuation of a MEMS device is done through electrical, thermal, or magnetic beams such as microgears or movable levers, shutters or mirrors.

Initially, MEMS devices were based on a standard silicon technology, which is a very stiff material. Because stiffer materials require higher voltages to achieve a given mechanical deflection, polymeric materials have recently been taken into use. These are very compliant and 6 orders of magnitude less stiff than silicon. This class of components is referred to as *compliant MEMS*, or CMEMS. This technology employs a soft, rubberlike material called an *elastomer* (from the words *elastic* and *polymer*). The elastomeric can be stretched as much as 300 percent, as opposed to less than 1 percent for silicon. As a result, CMEMS devices require much lower voltages to achieve the given mechanical deflection and for equivalent voltages their mechanical range of motion is much larger than that with silicon MEMS.

MEMS devices may have some reliability issues, if the manufacturer does not follow strict fabrication procedures. One major failure problem is silicon surfaces sticking to each other, with a tendency to do so permanently. The second concern is how to keep contaminants such as dust and saw-generated particles away from MEMS structures during intersection, which is the process of cutting up a large fabricated wafer into individual MEMS devices. The third issue involves packaging the devices so that no liquid, vapor, particles or other contaminants are present to cause malfunction in the moving parts of the MEMS device. [4]

Figure 1.22 shows the basic configuration of the 3D MEMS optical switch. In the switch, any connection between input and output fibers can can be accomplished by controlling the tilt angle of each mirror. The 3D MEMS-based all-optical switch has been built in sizes ranging from 256 × 256 to 1000 × 1000 bi-directional port machines. A truly all-optical switch is bit-rate and protocol independent. The combination of thousands of ports and bit-rate independence results in a theoretically future-proof switch with unlimited scalability. [8]

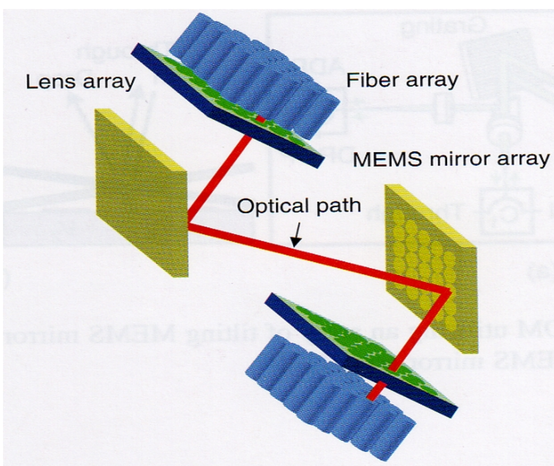


Figure 1.22. Schematic diagram of a 3D MEMS optical switch [13]

3. Constructing the WDM network

If the 160 channels are separated by 50 GHz, then the frequency span is 8 THz. This shows that operation is required over both the C- and L-bands simultaneously. As a result various active and passive components must meet high performance requirements, a long-haul DWDM link needs to include the following components:

- Wide spectral optical amplifiers.
- A high-power pump laser for the optical amplifiers to amplify a large number of channels.
- An optical amplifier that must emerge each wavelength with the same power level to prevent an increasing skew in power levels from one wavelength to another as the signals pass through successive amplifiers.
- A laser transmitter with strict device temperature and light frequency control to prevent crosstalk between channels.
- Fast modulators and receivers, forward-error-correction (FEC) schemes, chromatic and polarization-mode dispersion compensations.

Although these performance requirements result in expensive components, the cost is distributed over many information channels. [1, 4]

3. 1. Wideband long-haul WDM network

Wideband long-haul networks are essentially a collection of point-to-point trunk lines with one or more optical add/drop multiplexers (OADM) for inserting and extracting traffic at intermediate points. Standard transmission distance in long-haul terrestrial WDM links are 600 km with 80 km between optical amplifiers. Modern systems can carry 160 channels running at 2.5 or 10 Gbps (OC-48/STM-16 or OC-192/STM-64, respectively). By boosting the transmission capacity, long-haul DWDM networks lower the cost per pit for high rate traffic.

The rapid advancement and evolution of optical technologies makes it possible to move beyond point-to-point WDM transmission systems to an all-optical backbone network that can take full advantage of the bandwidth available by eliminating the need for per-hop packer forwarding. Such a network consists of a number of optical cross connects (OXC) arranged in some arbitrary topology and its main function is to provide interconnection to a number of *Internet Protocol/Multiprotocol Label Switching* (IP/MPLS) subnetworks. Each OXC can switch the optical signal coming in on a wavelength of an input fiber link to the same wavelength in an output fiber link. The OXC may also be equipped with converters that permit to switch the optical signal on an incoming wavelength of an input fiber to some other wavelength on an output fiber link. [10]

3. 2. Narrowband metro WDM network

Metro topologies can be viewed as consisting of core networks and access networks, as illustrated in figure 3.1. Nominally a *metro core network* consists of point-to-point connections between central offices of carriers that are spaced 10 to 20 km apart. These connections typically are configured as SONET/SDH rings. The core ring usually contains six to eight nodes and is nominally from 80 to 150 km in circumference. The *metro access network* consists of links between the end user and the central office. The ring configurations in this case range from 10 to 40 km in circumference and typically contain three or four nodes. Optical add/drop multiplexers provide the capability to add or drop multiple wavelengths to other locations or networks. A router or another switching equipment allows interconnections to a long-haul network.

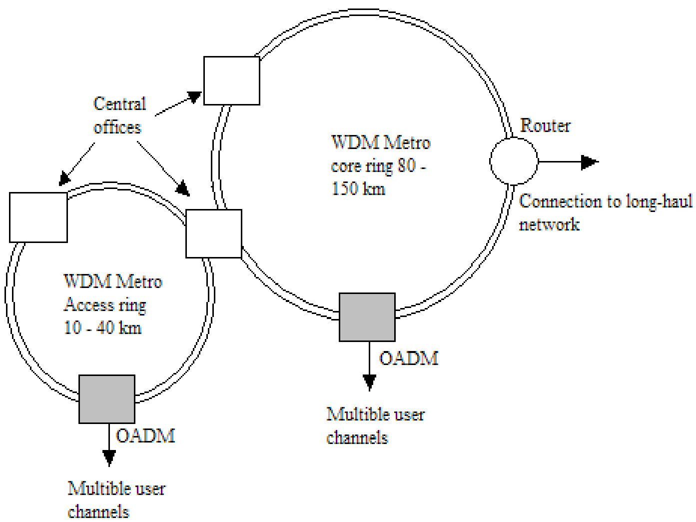


Figure 3.1. Metro topologies can be viewed as consisting of core networks and access networks.

Shorter transmission spans in metro- and LAN applications are not that stringent as wideband long-haul WDM systems. In particular, if a coarse WDM is employed, the broad frequency tolerances allow the use of devices that are not temperature-controlled. However, other requirements unique to metro-applications arise, for example the following points: [4]

- A high degree of connectivity is required to support the meshed traffic in which various wavelengths are put on and taken off the fiber at different points along the path.
- A modular and flexible transmission platform is needed since the wavelength add/ drop patterns and link capacities vary dynamically with traffic demands from different nodes.
- Variable optical attenuators (VOA) are needed to equalize the power of newly added wavelengths with those that already are on the fiber.
- Metro-optimized optical amplifiers are essential. The transmission loss in metro-applications is fairly high because of interconnection losses and cascade optical passthrough in successive nodes.

- Metro WDM networks must support a wide variety of transmission formats, protocols and bit rates. These include SONET/SDH traffic ranging form OC-3/STM-1 to OC-192/STM-64, ESCON (Enterprise System Connection from IBM), FICON (Fibre Channel connection from IBM), Fast Ethernet, Gigabit Ethernet, 10GigE, Fibre Channel and digital video. [4]

3. 3. DWDM networks

A dense WDM enables large channel counts within a limited spectral band, such as the C-band, but they can be expensive to implement. However, the DWDM is cost-effective in long-haul transport networks and large metro-rings. WDM systems are popular with telecommunications companies because they allow them to expand the capacity of the network without laying more fibers [7]. In these cases the cost is justified, since it is distributed over many high-capacity long-distance channels.

Figure 3.2 shows a generic long-haul DWDM network. Such networks are typically configured as large rings in order to offer reliability and survivability features. For example, if there is a cable cut somewhere, the traffic that was supposed to pass through that area can be routed in the opposite direction on the ring and still to its intended destination. As shown in figure 3.2 there are three 10-Gbps DWDM rings and the major switching centers where wavelengths can be regenerated, routed, added or dropped.

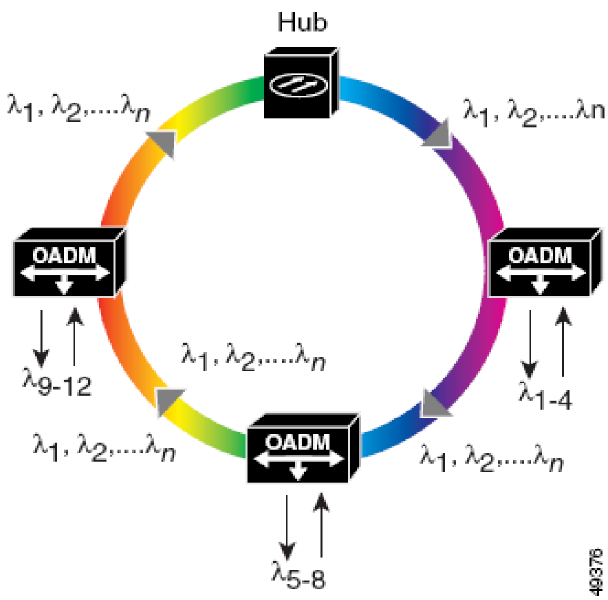


Figure 3.2. DWDM hub and ring architecture [1].

The links between DWDM nodes have optical amplifiers every 80 km to boost the optical signal amplitude and regenerators every 600 km to overcome degradation in the quality of the optical signals. Extended-reach long-haul networks allow path lengths without regenerators of several thousand kilometers. [4]. The new 10 Gigabit Ethernet standard is supported by using a *very short reach* (VSR) OC-192 interface over MM fiber between 10 Gigabit Ethernet and DWDM equipment [1].

As a more complex example, consider the WDM link shown in figure 3.3. Assume that this is a four-channel link with each channel running at 10 Gbps. The system operates in the C-band and contains optical add/drop multiplexer (OADM), and EDFA with gain of 20 dB, a gain flattering filter (GFF) following the EDFA and optical filters at the receivers. The fiber has an attenuation of 0.25 dB/km. The individual laser diode transmitters have fiber-coupled outputs of P_S = 2 dBm and the individual InGaAs APD receiver needs a power level of at least P_R = -24 dBm to maintain 10^{-11} bit error rate (BER).

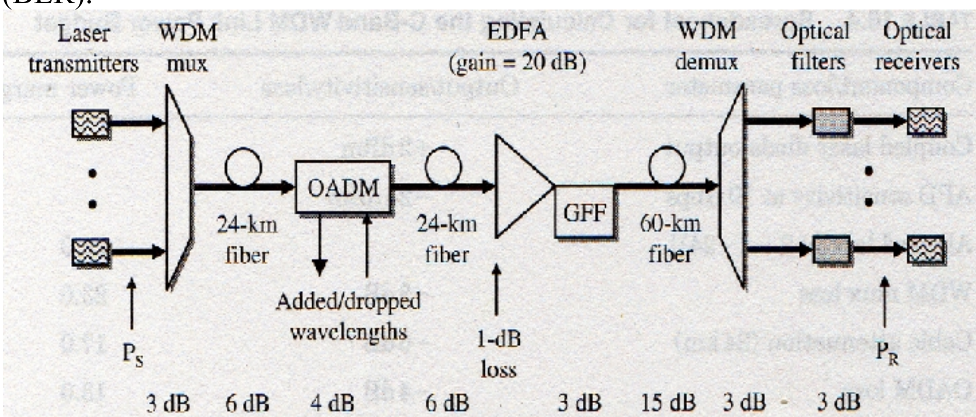


Figure 3.3. Example of optical power losses of various components in a WDM link [4].

The task is to make sure there is sufficient power margin in the link. The various power losses are shown at the bottom in figure 3.3 and calculation gives final margin only 2.0 dB. This is not sufficient, particularly since no allowance was made for any possible power penalties yet. Thus an optical amplifier is needed, for example, just ahead of the wavelength demultiplexer.

Mesh architectures are the future of optical networks. As networks evolve, rings and point-to-point architectures will still have a place, but mesh promises to be the most robust topology. Mesh and ring topologies can be joined by point-to-point links (see Figure 3.4). [1]

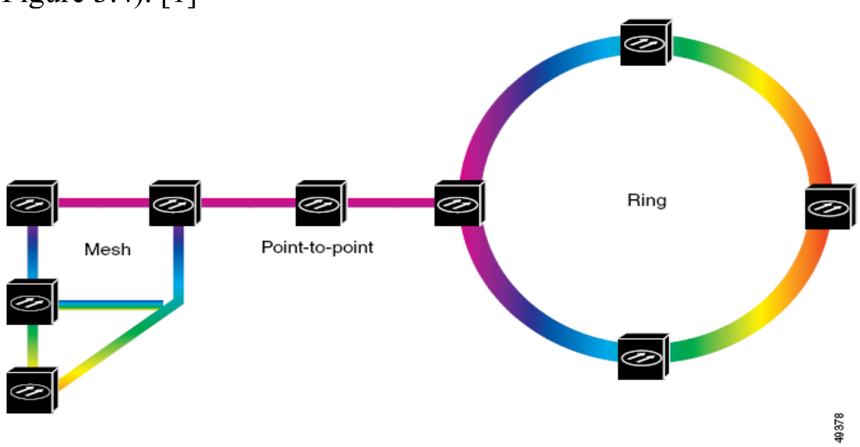


Figure 3.4. Mesh, ring and point-to-point architectures [1].

The DWDM is also moving beyond transport to become the basis of an all-optic networking with wavelength provisioning and mesh-based protection. Switching at the photonic layer will enable this evolution, as will the routing protocols that allow light paths to traverse the network in much the same way as virtual circuits do today. Figure 3.5 shows an example of an all-optical infrastructure, using mesh, ring, and point-to-point topologies at the optical layer to support the needs of enterprise, metropolitan access, and metropolitan core networks. [1]

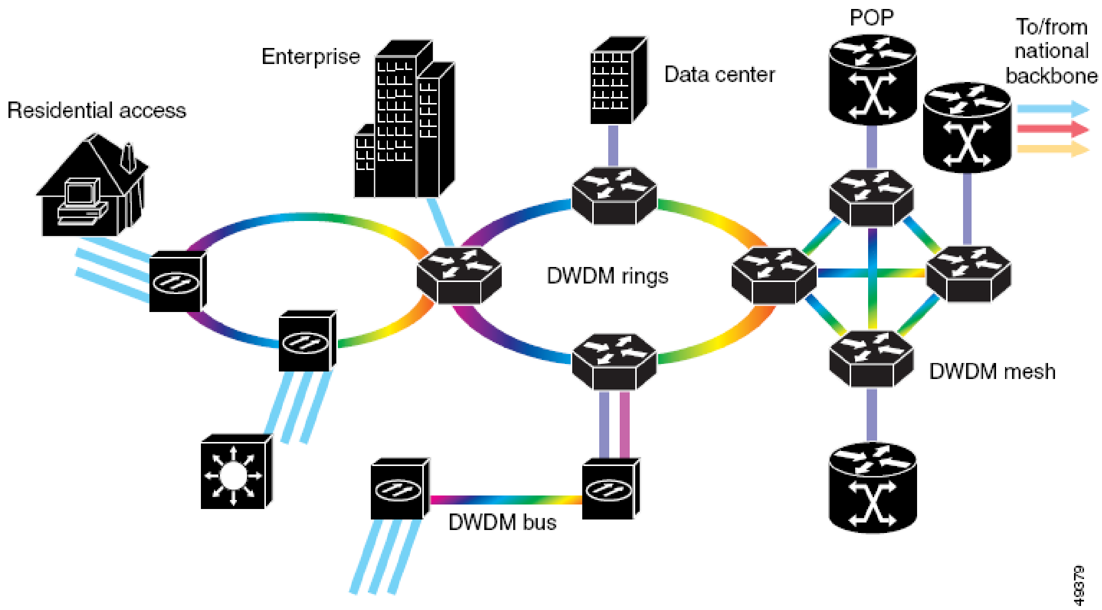


Figure 3.5 Next generation metropolitan optical network [1].

3. 4. CWDM networks

Coarse WDM applications include enterprise networks, metropolitan area networks (MAN), storage area networks (SAN) and access rings. For example, within the facilities of a business organization, the CWDM can easily increase the bandwidth of an existing Gigabit Ethernet optical infrastructure without adding new fiber standards. ITU-T has published G.655.C Recommendation that describes fibers for CWDM applications. In general, these things shared the fact that the choice of channel spacing and frequency stability was such that *erbium*-doped fiber amplifiers (EDFA) could not be utilized. Therefore, this limits the total CWDM optical span to somewhere near 60 km for a 2.5 Gbps signal, which is suitable for use in metropolitan applications. [7] The CWDM enables enterprises to add or drop up to eight channels into a pair of single-mode fibers, therefore minimizing or even negating the need for additional fibers. The bit rate is in the range of 622 Mbps to 10 Gbps per channel. Since the CWDM is protocol-independent, such an upgrade allows the transport of various traffic such as SDH, Gigabit Ethernet, multiplexed voice, video or Fibre Channel on any of the wavelengths. With the appearance of client/server environments, information that was previously centralized became distributed across the network. Composed of servers, storage devices (tapes, disk arrays) and network devices (multiplexers, hubs, routers, switches and so on), a SAN constitutes an entirely separate network from the LAN (see Figure 3.6). [1]

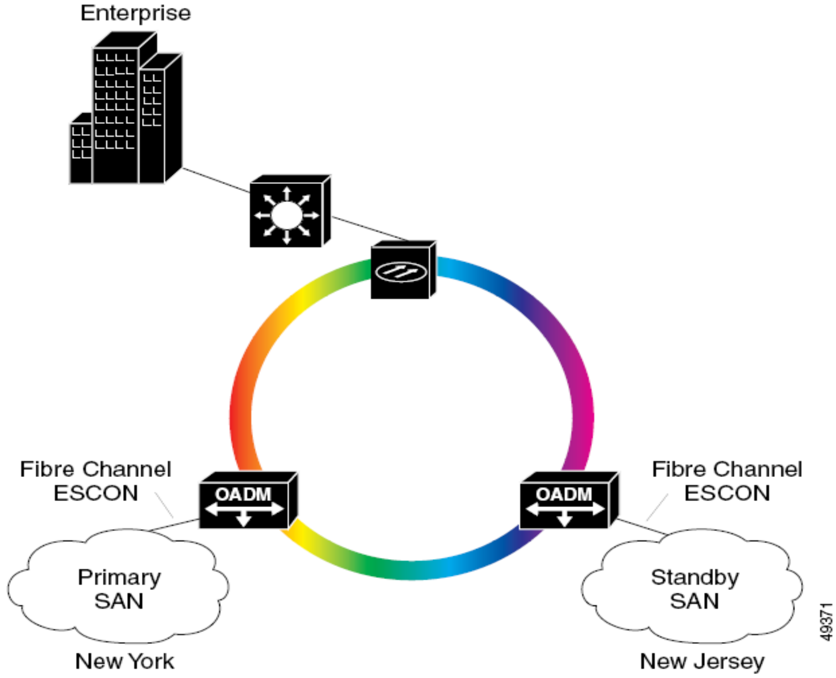


Figure 3.6. SAN access over the optical layer [1].

A more complex network is the hub-and-spoke configuration, as shown in fig. … Here multiple nodes (or spokes) are connected by means of a ring of single-mode fiber. Each hub-node connection can consist of one or several wavelengths, each carrying a full gigabit Ethernet channel or other protocol. Protection from fiber cuts in the ring is achieved by connecting the hubs and nodes through bidirectional links in the optical ring. [4]. Other interfaces important in metropolitan area and access networks are commonly supported: Ethernet (including Fast Ethernet and Gigabit Ethernet), ESCON, Sysplex Timer and Sysplex Coupling Facility Links, and Fibre Channel. [1]

3. 5. SONET/SDH

With the appearance of fiber optic transmission lines, the next step in the evolution of the digital time division multiplexing (TDM) scheme was a standard signal format called *synchronous optical network* (SONET) in North America and *synchronous digital hierarchy* (SDH) in other parts of the world.

In the middle of the 1980s, several service providers in the United States started making efforts on developing a standard that would allow network engineers to interconnect fiber optic transmission equipment from various vendors through multiple trunk networks. This soon grew into an international activity, which after many different opinions of implementation philosophy was resolved, resulted in a series of ANSI T1.105 standard for a SONET and a series of ITU-T G.957 recommendations for a SDH.

Although there are some implementation differences between the SONET and the SDH, all SONET specifications conform to the SDH recommendations. [4]

For the SDH systems the fundamental building block is the 155.52 Mbps *synchronous transport signal – level 1* (STM-1). Higher-rate information streams are generated by synchronously multiplexing *N* different STM-1 signals to form the STM-N signal. Figure 3.7 shows an example of increase in the bit rate by a factor of four in time slot *T*.

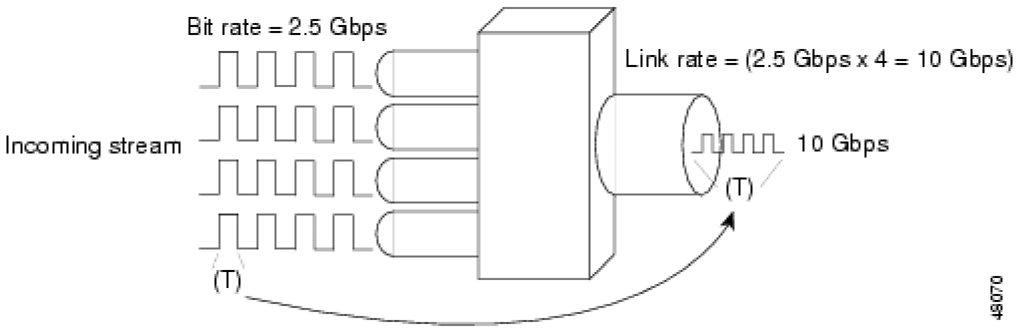


Figure 3.7. SONET/SDH TDM [1].

With TDM, the input sources are serviced in a round-robin fashion. This method is inefficient, because each time a slot is reserved even when there is no data to send. This problem is mitigated by the statistical multiplexing used in Asynchronous Transfer Mode (ATM). Although the ATM offers better bandwidth utilization, there are practical limits to the speed that can be achieved due to the electronics required for segmentation and reassembly (SAR) of ATM cells that carry packet data.

Table 1.1 shows commonly used SDH and SONET signal levels and the associated OC rates.

Table 1.1 SONET/SDH multiplexing hierarchy. [1, 4]

Optical Carrier	**SONET/SDH Signal**	**Bit Rate**	**Capacity**
OC-1	STS-1/STM-0	51.84 Mbps	28 DS1s or 1 DS3
OC-3	STS-3/STM-1	155.52 Mbps	84 DS1s or 3 DS3s
OC-12	STS-12/STM-4	622.08 Mbps	336 DS1s or 12 DS3s
OC-48	STS-48/STM-16	2488.32 Mbps	1344 DS1s or 48 DS3s
OC-192	STS-192/STM-64	9953.28 Mbps	5379 DS1s or 192 DS3s

Most DWDM systems support standard SONET/SDH short-reach optical interfaces to which any SONET/SDH compliant client device can be attached. In today's long-haul WDM systems, this is most often an OC-48c/STM-16c interface operating at the 1310-nm wavelength. [1]

While SONET/SDH has evolved into a very resilient technology, it remains fairly expensive to implement. More importantly, capacity scaling limitations - OC-768 may be the practical limit of SONET/SDH - and unresponsiveness to increasing IP traffic, makes any TDM-based technology a poor choice for the future. Two of the most important applications for DWDM technology in the MAN are in the areas of SANs and SDH migration. [1] Migration from SONET to DWDM may in fact be the single most important application in the near future. In general, this migration begins by replacing backbones with the DWDM, and then moves toward the edges of the network. By using the DWDM to increase the capacity of the existing SDH ring, one fiber can essentially act as many (see figure 3.8) [1, 23].

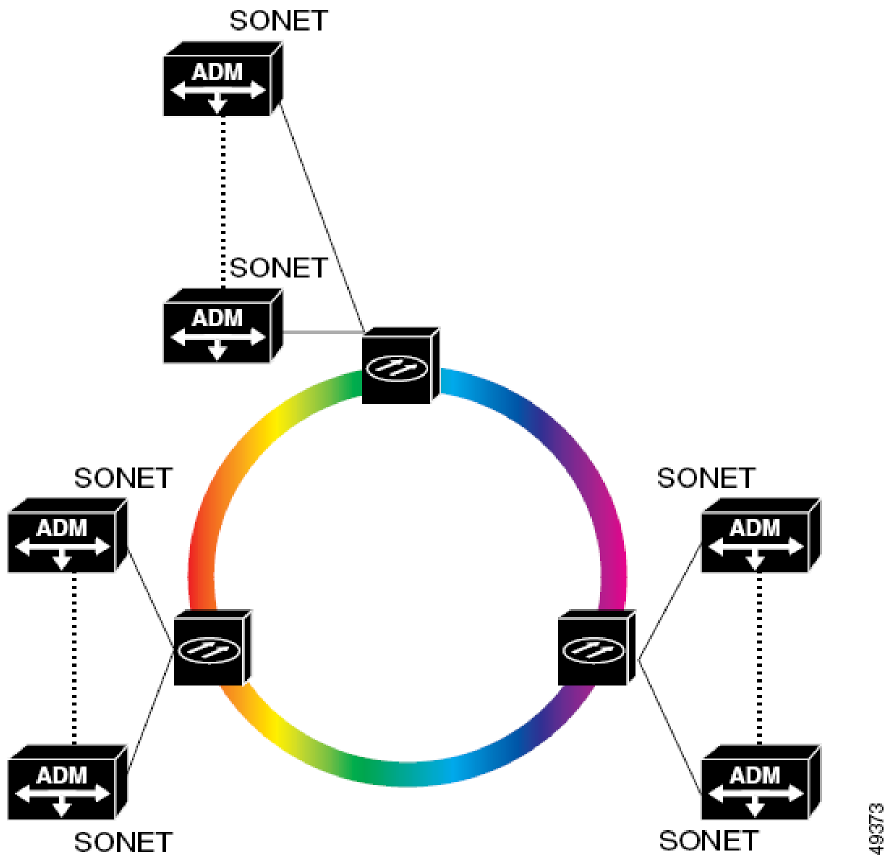


Figure 3.8. Migrating the SDH ring to DWDM [1].

3. 6. Optical Gigabit Ethernet

Ethernet is widely deployed in local-area networks, since it is known for its robustness and low cost. Standard-compliant interfaces are available on numerous devices running at line rates ranging from 10 Mbps to 10 Gbps. Therefore, Ethernet has matured to become the Local-Area Network (LAN) technology of choice with the best price and performance characteristics. It is relatively inexpensive compared to other technologies that offer the same transmission rate, but does not provide quality of service (QoS) or fault tolerance on its own. [1]

Ethernet is also being used in metropolitan-area networks and is extending into wide-area networks. In these environments, Ethernet can increase network capacity cost-effectively and has the ability to offer a wide range of services in a simple, scalable and flexible manner. When used in a MAN, Ethernet is referred to as *Metro Ethernet*. In enterprise applications, Metro Ethernet is used for interfacing to the public Internet and for connectivity between geographically separate corporate sites. The latter application extends the functionality and reach of corporate networks. [4]

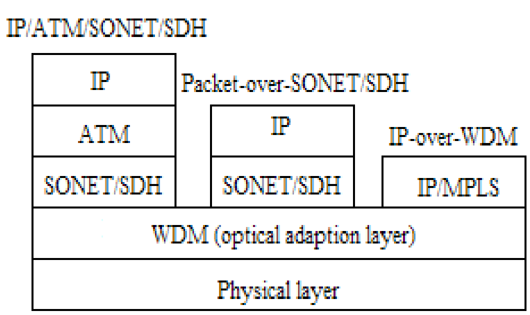
Because the optical physical layer can support much longer distances than traditional Category 5 cable, Gigabit Ethernet over fiber (1000BASE-LX, for example) can be extended into the wide-area realm using the DWDM. [1] By using optical fiber transmission lines in MAN and WAN environments, Ethernet provides a low-cost, high-performance networking solution that can span distances up to at least 70 km. Ethernet over fiber is deployed mainly in a point-to-point or mesh network topology. A high degree of scalability is possible through the use of CWDM or DWDM, since capacity can be increased either by raising the bit rate and/or by adding more wavelengths. In addition, with WDM users can lease wavelengths with varying bandwidth and protocol characteristics on a temporary or time-of-day basis. Architecturally, Ethernet's advantage is its emerging potential to serve as a scalable, end-to-end solution. Network management can also be improved by using Ethernet across the MAN and WAN. [1]

3. 7. IP over WDM

The movement in the telecommunication industry toward a grater use of IP is resulting in a dramatic complexity reduction of multiprotocol routing in networks. The popularity of IP is that it has widespread use in enterprise networks and the Internet, it is understood more than any other protocol, gateways for non-IP applications exist and protocol stacks are available at both the IP and higher levels (e.g., TCP).

As shown in figure 3.9 the network layering of a typical wide-area network carries IP on top of ATM, ATM top of SONET/SDH and SONET/SDH on top of WDM.
Figure 3.9. Progression of network layering methodologies moving from IP/ATM/SONET/SDH to packet-over-SONET/SDH to IP-over-MPLS.

Recently the trend is to format all voice, video and data as IP packets instead of first encapsulating them in ATM cells. With this "IP-over-SDH" structure, the SDH network



protection mechanisms are still in place but the high ATM overhead (at least 5 B in a 53-B cell) is eliminated, thereby reducing the number of management levels from four to three. Both ATM and IP are candidates for transport directly over the DWDM. In either case, the result is a simplified network infrastructure, lower cost due to fewer network elements and less fiber, open interfaces, increased flexibility, and stability. The question is, in which format IP will travel over an optical network: IP over ATM over SONET, IP over SONET (as POS), or IP over Gigabit Ethernet or 10 Gigabit Ethernet (see figure 3.10)? [1]

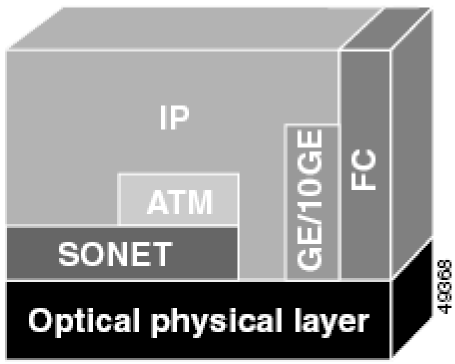


Figure 3.10. Data link and network protocols over the optical layer [1].

A further trend is aimed at bypassing the SONET/SDH layer, thereby combining the IP and SDH layers into one network layer based on *multiprotocol label switching* (MPLS). A protocol based on MPLS is under development to support routed paths through an all-optical network [1]. This "packet-over-WDM" scheme would provide faster provisioning of services and eliminate one electronic bottleneck, so that then there would be only two levels of management. However, there are major framing and fault recovery concerns with this approach. Since an IP packet contains only source and destination IP addresses, to map IP onto a wavelength requires an intermediate step of encapsulating the IP packet into a transport protocol in order to attach a header that contains source and destination physical addresses. This could be a protocol such as Ethernet, ATM or SDH. One possible protocol for *Storage Area Networks* (SAN) is Fibre Channel, like other protocols, can be carried directly over the optical layer using DWDM at speeds 400 MBps (megabytes per second) interfaces are in testing. [1] After the packet is encapsulated, it is inserted into the modulation format of the wavelength being used. [4]

For ISPs, all of their traffic is using IP. ISPs need rapid build-out of networks and favor packet-over-light wave or Gigabit Ethernet, rather than ATM or SONET. Other requirements of this market include load sharing strategies for resilience, leverage of dark fiber and simpler datacom-like management. [1]

3. 8. Optical Transport Networks (OTN)

Emerging next-generation transport networks are referred to as *optical transport networks* (OTNs). The key to understanding OTN can be summed up in one word: transparency [24]. In these networks it is envisioned that DWDM-based dynamic optical elements such as optical cross-connect switches and optical add/drop multiplexers (OADM) will have full control over all wavelengths. In addition, they are expected to have full knowledge of traffic-carrying capacity and the status of each wavelength. With such intelligence these networks are envisioned as being self-connecting and self-regulating. However, there are still many challenges to overcome before such completely intelligent optical networks are feasible.

Many people are working on OTN concepts and the ITU-T is establishing recommendations. In November 2001 the ITU-T agreed on the following nine new and revised OTN documents (see also G.984.1 and G.984.2).

- G.872, *The architecture of Optical Transport Networks*
- G.709, *Interface for the OTN*
- G.798, *Characteristics of OTN Hierarchy Equipment*
- G.8251, *The Control of Jitter and Wander within the OTN*
- G.7041, *Generic Framing Procedure (GFP)*
- G.7710, *Common Equipment Management Function Requirements*
- G.874, *Management Aspects of the OTN Element*
- G.874.1, *OTN Protocol-Neutral Management Information Model for the Network Element View*
- G.7712, *Architecture and Specification of Data Communications Networks*

[4, 24]

3. 8. 1. Wavelength routing

Recently, systems that use optical wavelength switches or optical cross-connects to enable data to be routed entirely in the optical domain have been devised. Wavelength-routed networks need a control mechanism to set up and take down all-optical connections. The functions of the control mechanisms are to assign a communication wavelength when a connection request arrives and to configure the appropriate optical switches in the network and to provide information on usage and status of the wavelengths so that the nodes can make routing decisions. The wavelength routing can be static or dynamic. In static routing a group of light paths is set up together and kept in place in the network for long periods of time. In dynamic routing a light path is set up for each connection request as it arrives and is released after the requested call is over. [4]

4. Optical layer management

To deal with standardized management functions in the optical layer, in February 2001 the ITU-T defined a three layer model. The document is ITU-T Recommendation G. 709, *Network Node Interface for the Optical transport Network (OTN)*, which is also referred to as the *Digital Wrapper standard*. The structure and layers of the OTN closely parallel the path, line and section sublayers of SDH.

The model is based on a client/server concept. The exchange of information between processes running in two different devices connected through a network may be characterized by a client/server interaction. The process or element that requests or receives information is called client and the process or element that supplies the information is called the server.

Figure 4.1 illustrates the three-layer model for a simple link. Client signals such as IP, Ethernet or OC-*N*/STM-*M* are mapped from an electrical digital format into an optical format in an optical channel (OCh) layer. The OCh deals with single wavelength channels as end-to-end paths or as subnetwork connections between routing nodes. The OCh is divided further into three sublayers as shown in figure 4.1: the *optical channels transport unit* (OTU), the *optical channel data unit* (ODU) and the *optical channel payload unit* (OPU).

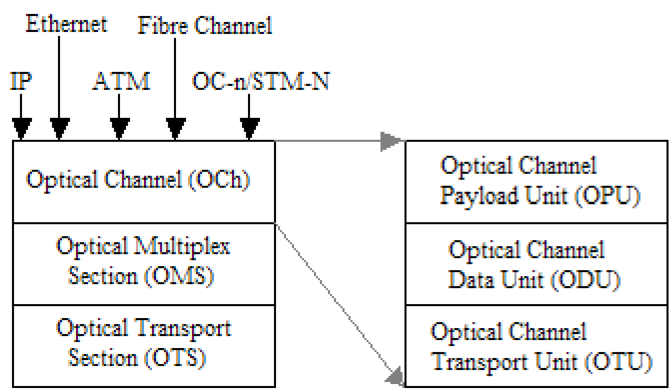


Figure 4.1. Three-layer model for a simple link in an OTN. The OCh is divided further into three sublayers.

Each of these sublayers has its own functions and associated overhead, which are as follows:

- The OPU frame structure contains the client signal payload and the overhead necessary for mapping any client signal into the OPU. Mapping of client signals may include rate adaptation of the client signal to a constant-bit-rate signal. Examples of common signals are IP, various forms of Ethernet, ATM, Fibre Channel and SONET/SDH. The three payload rates associated with the OPU sublayer are 2.5, 10 and 40 Gbps.
- The ODU is the structure used to transport the OPU. The ODU consists of the OPU and the associated ODU overhead and provides path-layer-connection monitoring functions. The ODU overhead contains information that enables

maintenance and operation of optical channels. Among these are maintenance signals, path monitoring, tandem connection monitoring, automatic protection switching and designation of fault type and location.

- The optical channel transport unit (OTU) contains ODU frame structure, the OUT overhead and appended forward error correction (FEC). The OUT changes the digital format of the ODU into a light signal for transport over an optical channel. It also provides error detection, correction and section layer connection monitoring functions.

The *optical multiplex section* (OMS) layer represents a link carrying groups of wavelengths between multiplexers or OADM. The *optical transmission section* (OTS) layer relates to a link between two optical amplifiers. [4] A comprehensive network management tool will be needed for provisioning, performance monitoring, fault identification and isolation, and remedial action. Such a tool should be standards-based (SNMP, for example) and be able to interoperate with the existing operating system [1].

4. 2. Element monitoring

In general, there are many factors that can result in optical signal loss. The most obvious of these is the distance of the fiber itself; this tends to be the most important factor in long-haul transport. In MANs, the number of access nodes, such as OADMs, is generally the most significant contributor to optical loss. [1]

Since the signal quality of an optical network depends critically on the proper operation of all its constituent elements, monitoring techniques that can be performed directly in the optical domain are a key requirement. The three main parameters for any element are wavelength, optical power and optical signal-to-noise ratio (OSNR). The measurement instruments are based on spectrum analysis techniques and are known by a variety of names. For example, see the names *optical channel monitor* (OCM), *optical performance monitor* (OPM) or *optical channel analyzer* (OCA). For simplicity we will refer to them as *optical performance monitors*. ITU-T Recommendation G.697 (06/04) *Optical monitoring for DWDM systems* defines *Optical Monitoring* (OM) that can help in DWDM systems to perform the following activities:

- Configuration management for system and channel activation, addition of new channels, etc.
- Fault management to detect and to isolate faults.
- Degradation management in order to keep the system running and to detect degradations before a fault occurs. [25]

An OPM taps off a small portion of the light signal in a fiber and separates the wavelengths or scans them onto a detector or detector array. This enables the measurement of individual channel powers, wavelength and OSNR. These devices have an important role in controlling DWDM networks. Most long-haul DWDM networks incorporate automated end-to-end power-balancing algorithms that use a high-performance OPM to measure the optical power level of each wavelength at optical amplifiers and at the receiver end to adjust the individual laser outputs at the transmitter end. This information is exchanged by means of a separate supervisory channel, which is described in the next section. Manufactures may embed an OPM function into dynamic elements such as an EDFA, an OADM or an OXC to provide feedback for active control of total output power and to balance the power levels between channels. Other functions of an OPM include determining whether a particular channel is active, verifying whether wavelengths match the specific channel plan and checking whether optical power and OSNR levels are sufficient to meet the *quality of service* (QoS) requirements. [4]

The key to a precise optical power budget calculation is to get an accurate reading on the fiber using an optical time domain reflectometer (OTDR). Using an OTDR, you can obtain the following information about a span:

- Length of the fiber
- Attenuation in dB of the whole link, as well as attenuation of separate sections of the fiber
- Attenuation characteristics of the fiber itself
- Locations of connectors, joints and faults in fiber. [1]

4. 3. Optical service channel

A channel that is accessed at each optical line amplifier site that is used for maintenance purposes including (but not limited to) remote site alarm reporting, communication necessary for fault location, and orderwire. The *Optical Supervisory Channel* (OSC) is not used to carry payload traffic [3]. ITU-T Recommendation G.692 describes the use of a separate optical supervisory channel (OSC) in links that contain optical amplifiers. This channel shall be capable of being accessed at each amplifier. For optical line amplifiers implemented using Erbium-Doped Fibre Amplifier (EDFA) technology, the optical supervisory channel can be located outside the usable gain bandwidth of the EDFA ("out-of-band OSC") or alternatively, within the usable gain bandwidth ("in-band OSC"). There are design trade-offs associated with each of these possible choices. For example, in a C-band DWDM link (1530 to 1565 nm) the OSC might operate at 1310, 1480, 1510 nm. From these, the ITU–T has adopted 1510 nm as the preferred wavelength. In a 32-channel system this would be referred to as using the *33rd wavelength* (or channel 0), which allows the OSC to control and manage traffic without deploying a separate Ethernet control connection to each active device in the network. This is an additional wavelength usually outside the EDFA amplification band (at 1510nm, 1620nm, 1310nm or another proprietary wavelength) [3, 7].

As sown in figure … the OSC bypasses the device being monitored and always terminates the neighboring node. This is in contrast to data channels which do not necessarily terminate a given node (such as an optical amplifier or an OADM).

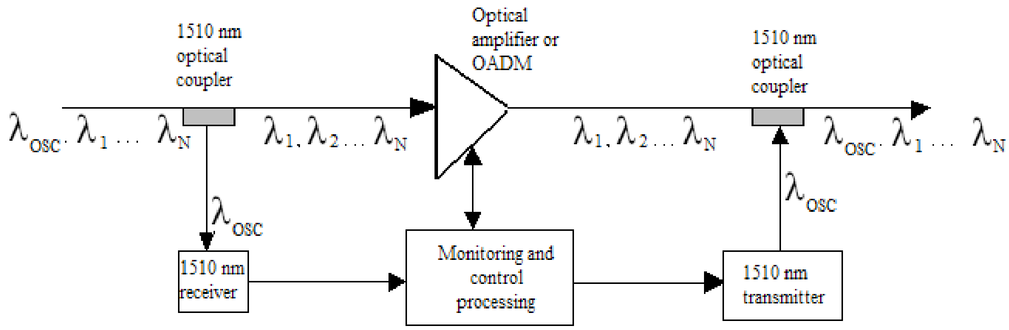


Figure 4.2. The OSC bypasses the device being monitored.

An OSC carries out the following types of functions:

- *Discovery*. This function sends packets over the OSC to discover the logical topology of the network
- *Monitoring*. With this keep-alive function, nodes exchange packets that allow them to determine the operational status of their neighbor
- *Management*. IP packets are carried over the OSC to support *Simple Network Management Protocol* (SNMP) and Telnet sessions.

A variety of vendors offer 1510 nm channel couplers and lasers that operate from the 2- to 155-Mbps data rates on the OSC. [4]

Summary

As a further step toward realizing the full potential of optical fiber transmission capacity, researchers are considering the concept of an intelligent WDM network. The major activity in this area is the development of an optical cross-connect (OXC) that will switch optical signals at line rates (e.g., at 10-Gbps OC-192 or 40-Gbps OC-768 rates) without optical-to-electric conversion. The eventual creation of such a component will provide lower switching costs and higher capacity than the currently used electrical cross-connections.

The information-carrying capacity of the fiber is limited by various distortion mechanisms in fibers, such as signal distortion factors and nonlinear effects. The ITU-T has published recommendations for single-mode fibers to use the DWDM (ITU-T G.655 and ITU-T G.655b) and CWDM (ITU-T G.655.C)

The transmitters for optical communications come in a wide range of complexity. DWDM applications require a highly sophisticated laser transmitter that includes a temperature controller to maintain a 0.02ºC stability, a wavelength-locking controller to stabilize the wavelength to a few picometers, optical power level with sensing and control functions, an alarm processor and optionally a built-in light modulator.

The passive components include optical couplers, isolators, circulators, filters, gratings and wavelength multiplexers. Optical couplers perform functions such as splitting a light signal, combining light streams and tapping off small portion of optical power. Isolators allow light to pass through in only one direction to prevent scattered or reflected light from traveling in the reverse direction. An optical circulator is a nonreciprocal multiport passive device that directs light sequentially from port to port in only one direction. A dielectric thin-film filter (TFF) is used as an optical bandpass filter. A grating is an important element for combining and separating individual wavelengths.

Dynamically tunable devices are essential for high-performance WDM networks. Their functional parts include tunable optical sources, variable optical attenuators, optical switches, optical filters, dynamic gain equalizers, add/drop multiplexers, dispersion-compensating modules, polarization controllers and optical performance monitors.

The most common optical fiber amplifier for long-haul telecommunication applications is an EDFA. Improvements in EDFA design and the use of pump lasers at different wavelengths have allowed an EDFA amplifier extension from C- to L-band.

Wavelength-division multiplexing allows many different wavelengths ranging from the O-band through the L-band to be sent along a single fiber simultaneously. WDM technologies include thin-film filters, arrayed waveguide gratings, Bragg fiber gratings, diffraction gratings, interleavers, wavelength lockers etc. The first ITU-T specification for WDM was Recommendation G.692, *Optical Interfaces for Multichannel Systems with Optical Amplifiers*. This document specifies selecting the channels from a grid of frequencies referenced to 193.100 THz and spacing them 100 GHz apart. Suggested alternative spacing in G.692 includes 50 and 200 GHz. The CWDM grid is made up of 18 wavelengths defined within the range of 1270 to 1610 nm spaced by 20 nm with wavelength drift tolerances of ± 2 nm.

The design of a high-quality transmission link involves a series of tradeoffs among the many interrelated performance variables of each component based on the system operating requirements. The link analysis may require several iterations before they are completed satisfactorily and the designer must choose the components carefully to ensure that the link meets the operational specifications over the expected system lifetime without overstating the components' requirements. Emerging next-generation transport networks are referred to as optical transport networks (OTN). In these networks it is envisioned that DWDM-based dynamic optical network elements such as optical cross-connect switches and optical add/drop multiplexers will have full control over all wavelengths and being self-connecting and self-regulating.

Once the hardware and software elements of an optical network have been installed properly and integrated successfully, they need to be managed to ensure that they are configured correctly and operating properly. The gathering of status information from network devices is done via a type of network management protocol, for example the *Simple Network management Protocol* (SNMP). ITU-T Recommendation G.692 describes the use of a separate *optical service channel* (OSC) in links that contain optical amplifiers. The OSC operates on a wavelength that is outside the standard WDM transmission grid being used.

Resümee

Optical wavelength-division multiplexing

Bakalaureusetöö
Andres Anderson

Nõudlus andmete edastuskiirustele lairiba võrgus on jätkuvalt olnud suur ja on ka edaspidi. Andmeside teenus pakkujad peavad nõudlusega kaasas käima, et säilitada oma funktsiooni. Cisco väidab, et juhtivad teenuse pakkujad on teatanud, et iga kuue kuni üheksa kuuga kasvab neil andmeedastuse maht kahe kordselt. Üheks mooduseks on paigaldada lisa kaableid ja seadmeid. Teine võimalus oleks kasutada optilise andmeside jagatud lainepikkuse multipleksimise (WDM) tehnoloogiat, mis kasutaks olemasolevaid *single-mode* fiiberoptilist kaableid.

Transponderi sisendisse antakse optiline signaal, mis võib olla SONET/SDH, Gigabit Ethernet, ATM, IP jne. ja väljundisse antatakse teatud lainepikkusega signaal, mille lainepikkus on vahemikus 1270 kuni 1625 nm. Igale kanalile antakse oma lainepikkus ja signaal suunatakse edasi multiplekserini. Multiplekseri ülesanne on kõik sisenevad optilised signaalid (kõigil erinev lainepikkus) juhtida ühte kiudoptilisse fiibrisse. ITU-T G.692 standardi põhjal soovitatav kanalitele jagatud lainepikkused oleksid jagatud 100 Ghz (0.8 nm) vahedega, nii et baas lainepikkus oleks 1552.524 nm. Lubatud on ka 200 Ghz ja 50 Ghz vahedega lainepikkuste omandamine erinevatele optilistele kanalitele. Uuemad tehnoloogiad on näidanud lainepikkuse jagamist 25 Ghz ja 12.5 Ghz kaupa, vastavalt 0.2 ja 0.1 nm vahedega jagatud signaali lainepikkused. Andmeside võrkudes, kus ei vajata palju eri kanaleid ja fiiberoptiliste kaablite vahemaad pole pikad, ITU-T G.694.2 standardi kohaselt on sobiv kasutada hõredalt jagatud lainepikkuse multipleksimist (CWDM), mille kohaselt kasutatakse maksimaalselt 18 kanalit vahemiskus 1270 kuni 1610 nm. Soovitatav fiiber on ITU-T G.655 standardi järgi n*on-zero dispersion-shifted fiber*, mis on sobivaim tihedalt jagatud lainepikkuse multipleksimisel (DWDM). Kuna lairiba andmeside korral vahemaad on pikad, siis signaal kogu teekonna jooksul nõrgeneb ja venib pikemaks. Selle tõkestamiseks on signaali võimendid, signaali hajumise tõkestajad ja signaali taas-genereerijad. Nõrgenenud signaali võimendina kasutatakse DWDM andmesides erbium-rikastatud fiiber-võimendit (EDFA), mis võimendab kõiki DWDM erinevate lainepikkustega kanaleid üheaegselt.

Kuna WDM andmeside peab olema paindlik ja suure ribalaiusega, siis signaali suunamine optiliste kommutaatorite abil on vältimatu. Kommutaatoriteks on optiline rist-ühendus (OXC) ja optiline lisamis/eemaldamis multipleksija, millede arhitektuurilised ehitused on erinevad. Hetkel on käimas suur töö OXC ja märgendiga kommuteerimine multiprotokoll (MPLS) arendamisel ja täiustamisel, et WDM side oleks optiliselt intelligentne. Järgmise põlvkonna andmeside võrgud on Optilise Andmeside Võrgud (OTN), mida saab iseloomustada ühe sõnaga – läbipaistvus. ITU-T G.697 on standard WDM andmeside seadmete jälgimiseks ja ITU-T G.692 standard kirjeldab seadmete haldamist läbi WDM andmeside.

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