Chapter

Optically Multiplexed Systems: Wavelength Division Multiplexing

Meena Dasan, Fredy Francis, Kundil T. Sarath, Elambilayi Dipin and Talabattula Srinivas

Abstract

Optical multiplexing is the art of combining multiple optical signals into one to make full use of the immense bandwidth potential of an optical channel. It can perform additional roles like providing redundancy, supporting advanced topologies, reducing hardware and cost, etc. The idea is to divide the huge bandwidth of optical fiber into individual channels of lower bandwidth, so that multiple access with lower-speed electronics is achieved. This chapter focuses on one of the most common and important optical multiplexing techniques, wavelength division multiplexing (WDM). The chapter begins with a quick historical account of the origin of optical communication and its exponential growth following the invention of erbium-doped fiber amplifier (EDFA) leading to the widespread adoption of WDM. Alternate multiplexing schemes are also briefly discussed, including time-division multiplexing (TDM), space-division multiplexing (SDM), etc. A typical WDM link and its components are then discussed with special focus on WDM Mux/demultiplexer (DeMux). Further, certain challenges in this field are addressed along with some potential solutions. The chapter concludes by highlighting some features and limitations of optically multiplexed WDM systems.

Keywords: WDM, Mux, DeMux, EDFA transients, optical components

1. Introduction

Since its advent in the mid-1960s, optical technologies and components have been changing the landscape of communication as such. The constant push for higher data rates ensured that optical components matured fast, enabling the terabits of data rates we are enjoying today. It all started with extremely lossy optical fibers coupled with a broadband source, which could transmit only a few mbps over a few meters. The scenario drastically changed over half a century, reaching data rates of even terabit/sec possible over a single fiber. Now we have the luxury of external cavity lasers (ECL) which can easily give linewidths below 1 MHz, Mach-Zehnder modulators (MZM) which can easily operate at 40 Gbps and above, low attenuation dispersion managed fibers, dispersion compensation fibers, low-noise high-gain optical amplification systems, very high-speed detectors, and extremely fast digital signal processing (DSP) capabilities which make many compensation hardware redundant.

A commonly overlooked component of this lot is the multiplexer, without which the entire system is only fast enough as any of its electronic counterpart. Multiplexer is the one which helps in combining (and splitting) the data from different sources so that the tremendous bandwidth of the system could be utilized. As with other components, Mux/DeMux came a long way into maturing and providing the kind of precise work it does today. So, this chapter is dedicated for giving the readers a quick understanding of the different types and techniques for the implementation of wavelength division multiplexing (WDM) schemes.

Multiplexing is the process of combining multiple signals into a shared channel used for tapping the full potential of the optical links. It facilitates networking with advanced topologies supported with redundancy features. Historically, multiplexing had been used to share the limited bandwidth of the medium between different transmitters, but with optical systems it is more about making full use of the huge available bandwidth. This is where wavelength division multiplexing comes in where different channels are multiplexed into a single fiber. It divides the huge bandwidth of optical fiber into various logical channels of lower bandwidth that can be filled with electronically achievable data rates. The advent of coherent optical links and advanced multiplexing techniques used in wireless communication raised the achievable bandwidth limit of fiber links. But the proposed chapter focuses on one of the most common and important multiplexing techniques, wavelength division multiplexing.

The advent of erbium-doped fiber amplifiers (EDFAs) in the late 1980s proved to be a great impetus for multichannel system implementation. EDFA, with its capability to amplify the C-band, proved to be a vital component that could facilitate WDM in long-haul links. As the different WDM channels could traverse the fiber without cross talk, and EDFA can amplify these signals simultaneously, it increased the transmission rates exponentially. This ushered in the need of multiplexers, specifically wavelength division multiplexers. A few popular optical multiplexing techniques are discussed later in this chapter. Also, it should be noted that being bidirectional, most of these devices in these schemes can be used as Mux or DeMux.

1.1 Other optical multiplexing techniques

With the optical components maturing and becoming very reliable and accurate, almost all multiplexing techniques possible in the wireless communications are viable in optics now. Though a few are truly developed, the others are expected to mature in the near future. A few of these techniques are discussed here.

1.1.1 Time-division multiplexing

Probably the most used scheme in electrical and wireless systems, optical time-division multiplexing (OTDM) does not have that much widespread use, probably because of the large bandwidth already available with optical fibers and the widespread use of WDM but is still used in different applications. Pulse interleaving is used to allow different optical data streams to use the full capacity of the fiber, albeit for a limited time. Different optical data pulses thus share the same optical channel with its full capacity for a limited time and passes on to the next pulse and so on so forth. Thus, the overall data rate in the fiber is improved despite the fact that the individual data streams are still operating at the same speed. But the optical pulses have to be compressed, to fit in the time slot per bit. A train of ultrashort pulses can be helpful in this regard, along with an optical delay line for combining all the pulses. So, for a good OTDM link, we need pulses with high extinction, short duration, and low timing jitter.

1.1.2 Space-division multiplexing

The basic idea is to have different channels separated spatially. This spatial separation can be brought out in different ways; the simplest is with the use of multiple fibers. But this requires most of the channel infrastructure to be duplicated for each fiber, hence not most economical. But still there could be some cost improvements as one may choose to use a high-power laser along with splitters to pump different optical amplifiers corresponding to each fiber. Or multiple fibers can be integrated to form one fiber cable or use a fiber ribbon. Another possible way of cost reduction is by using a vertical-cavity surface-emitting laser (VCSEL) array at the source along with the integration of different receivers into the same chip. Also, some electronics can also be shared between different channels too.

A better implementation of SDM will be using multicore fibers. These are single optical fibers having multiple cores, each core carrying one communication channel. The cores are usually separated enough that there is no coupling and cross talk. But this limits the number of cores, as increasing the cladding diameter tends to make the fiber more brittle. Additionally, this makes fiber splicing more difficult.

A work around of this is to keep the core together allowing the different modes to couple to form a supermode (coupled SDM fiber) and then later electronically process the detected data using multiple input/multiple output (MIMO) techniques in detection process. MIMO techniques have already matured in wireless communication. Photonic crystal fibers are a very good candidate for these kinds of coupled SDM fibers. But there are a lot of challenges that are to be dealt with before this becomes commercial; this includes difficulties in splicing multicore fibers, maintaining the correct rotation orientation, developing spatial multiplexers and fiber amplifiers, providing sufficient gain uniformity over different modes, etc.

Another potential method for the MIMO setup is the use of few-mode fibers, using a technique called mode division multiplexing (MDM). This has some advantages like easier fiber connections and splices. But as the cross talk with different fiber modes are high and there is a significant difference in the group velocity of the different modes, MIMO receivers are much more complex than the above techniques [1].

1.1.3 Polarization-division multiplexing

Generally used together with phase modulation or QAM, the idea is to modulate different information on orthogonal polarizations of the same frequency effectively doubling the data rate. PDM signal can be transmitted over normal WDM infrastructure expanding its capacity. But here the challenges are the drifts in the polarization state of the fiber-optic system over time. Also polarization mode dispersion, polarization-dependent losses, and cross-polarization modulation create additional challenges. But the DSP techniques at the receiver are becoming faster and more efficient in compensating these impediments.

1.1.4 Orbital angular momentum multiplexing

The orbital angular momentum (OAM) of the light waves is used to carry orthogonal information. OAM can in theory have huge number of parallel channels, bound only by practical limitations. OAM states of light is not supported on conventional single-mode fiber, instead few-mode or multimode fibers are to be used. Additionally, conventional fiber suffers from mode coupling which changes the orbital angular momentum when the fiber is bent or stressed causing mode instability. But coherent detection along with signal processing techniques can be used to correct mode mixing in fiber. These coherent systems are normally complex in nature.

2. WDM link and components

A WDM link typically used in communication system is as shown in the block schematic (**Figure 1**). There are multiple transmitters each working on its own dedicated wavelength. These individual data streams on independent wavelengths are all multiplexed together using a WDM Mux and transmitted through an optical fiber. The transmitted power is kept low enough in the link, so as not to trigger any nonlinearities in the fiber. In the absence of nonlinearities, the wavelengths do not talk to each other or induce cross talks. The C-band can be divided coarsely every 20 nm (called coarse WDM) if the link is low cost or have to support only limited number of parallel light paths. Dense WDM uses a much more tighter wavelength division scheme and needs costlier components and better lasers with lower linewidths and external modulators. It supports a greater number of channels resulting in a much higher throughput, e.g., 40 channels within 1530–1565 nm, C-band with 100 nm spacing, or 80 channels at 50 GHz spacing or even 12.5 GHz—all at the cost of significant overhead costs.

These multiplexed data will become weaker over the distance, and that's where the EDFA comes in. It's EDFA's broad bandwidth, which helps in amplifying all the channels with nearly the same gain, that paved the path for the bandwidth explosion within the fiber. After the amplification the wavelengths are demultiplexed at the DeMux and forwarded to the corresponding receivers which completes the link.

Typical WDM link consists of components like transmitters, add/drop multiplexers, and necessary detectors for the communication link. Based on the requirements, it also includes preamplifier, line amplifiers, and post amplifiers in the link. Specific WDM components like WDM/demultiplexer (Mux/DeMux) matured fast to make the systems relatively common and affordable. It also made possible to have fiber links to their maximum possible bandwidth capability.

2.1 Optical source

Laser is the most widely used optical source, owing to its inherent advantages like single-frequency operation, coherence, high intensity, and directionality [2]. Laser is essentially an oscillator, having a gain medium and feedback mechanism. The gain medium is kept at an excited state by external pumping mechanisms (optical or electrical). This produces population inversion which is a necessary condition for lasing. Initial photons can be introduced into the medium by spontaneous emission, and those modes that are supported by cavity and gain spectrum are lasered out. The basic assembly of a laser is as shown in **Figure 2**.

The development of semiconductor lasers operating at room temperature (1970) provided a compact, highly efficient, and reliable optical source, which is put to great use by the communication industry [3]. Semiconductor laser needs

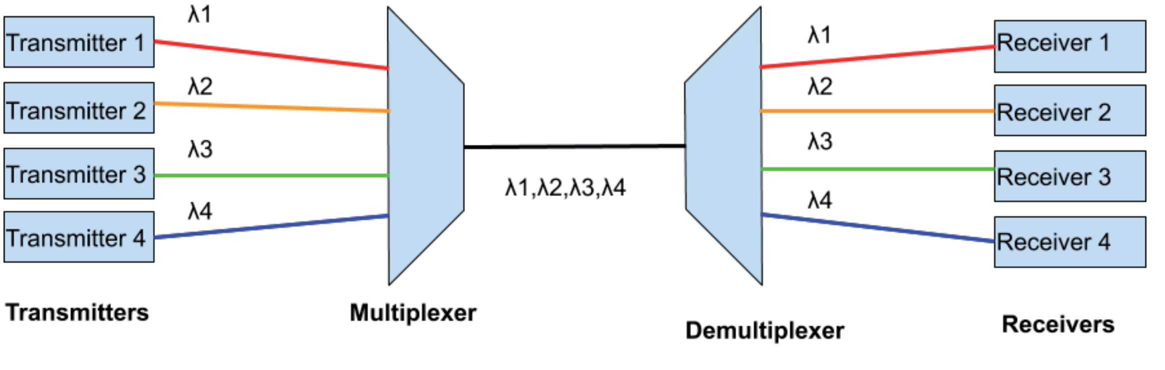

Figure 1.
Block schematic of a basic WDM link.

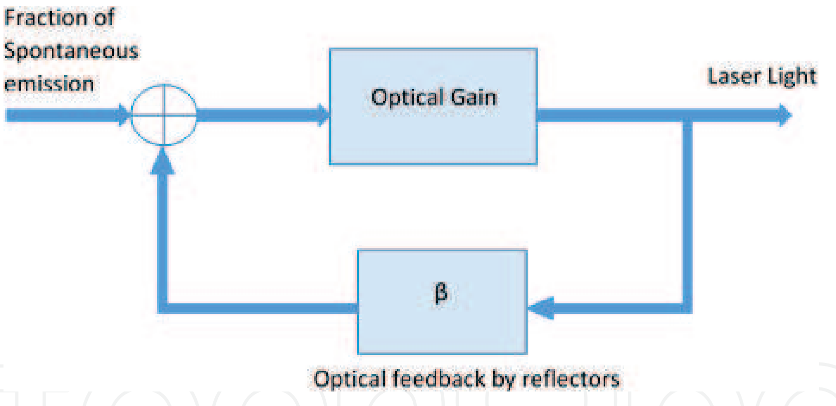

Figure 2.
Laser assembly block schematic.

an optical feedback mechanism for converting it from an amplifier to oscillator. Oscillations begin when the loop gain exceeds unity. Gain is obtained due to stimulated emission in optical gain medium, and the cavity formed by cleaved laser facets provides the required feedback for sustained oscillations. This configuration forms a Fabry-Perot (FP) cavity. FP laser can lase at multiple longitudinal modes that are spaced apart according to $\Delta \nu_L = c/2L$ where n is the refractive index (RI) and L is the cavity length. If the spacing between neighboring modes are small enough, then the laser cavity can provide almost the same gain for each of those longitudinal modes causing them to coexist. Such longitudinal modes travel with a different velocity inside the optical fiber causing group velocity dispersion and hence limits the maximum data rate through the optical fiber. So, lasers operating within a single longitudinal mode are preferred for many applications. To overcome this, distributed feedback (DFB) lasers, which achieve single longitudinal mode operation by distributing the reflection throughout cavity length, are introduced [3].

DFB laser developed during the 1980s is the most commonly used single-mode laser. The idea is to introduce a wavelength selective element within the laser cavity. This is achieved by introducing an etched diffraction grating within the laser waveguide structure. This can be done in two ways. If the grating layer extends through the whole of the active layer, it is called DFB, and if the gain region is in a separate planar section, the device is known as distributed Bragg reflector (DBR). **Figure 3** shows the structure of a DFB laser.

In DBR lasers, the fiber Bragg gratings are used like mirrors in FP cavity with the difference that these gratings reflect only one longitudinal mode. The active layer provides cumulative gain only for the feedback wavelength, hence resulting

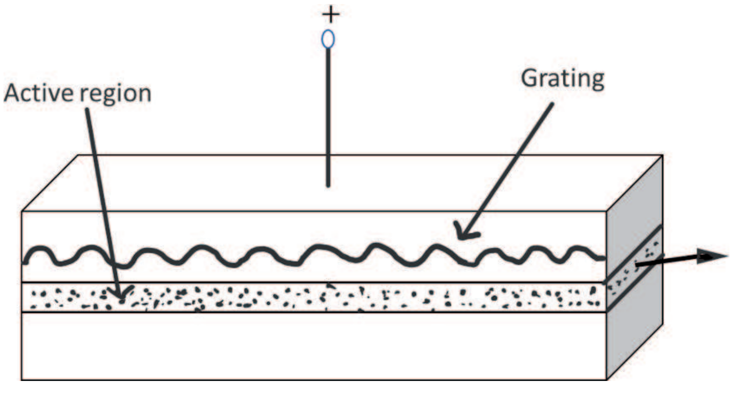

Figure 3.
DFB laser structure [3].

in single-wavelength operation of laser. A Bragg grating is realized by periodically varying refractive index along the length of the optical transmission. Condition for reflection of Bragg wavelength λ_B from a grating with period Λ is given by

$$\Lambda = m\ (\lambda_B/2n) \tag{1}$$

where m is an integer and n is the refractive index. Due to frequency selective nature of the feedback mechanism, the output of the laser becomes highly monochromatic. Later improvements in DFB lasers include phase-shifted DFB laser [4] and gain-coupled DFB lasers [5].

In a semiconductor laser under forward bias, population inversion occurs, and optical gain is realized only when the injected current into the active region is greater than a minimum value known as the transparency value [3]. The input signal propagating inside the gain medium is amplified by a factor of e^{gz}, where g is the gain coefficient and z is the length within the cavity. A certain portion of the generated photons is lost due to cavity losses and needs to be replenished. The optical gain must be high enough to compensate for this loss, else the photon population does not build up. This puts a minimum value of gain with which the laser should be operated to achieve lasing. This is the laser threshold, which is achieved only if the laser works above a threshold pumping level which corresponds to the threshold current.

2.2 Modulators

The process of imposing data on the light stream is called modulation. At bit rates more than 10 Gb/sec, chirp effect induced by direct modulators is predominant and puts a limit on modulation bandwidth. Chirp is a phenomenon wherein the carrier frequency of transmitted pulse varies with time, causing broadening of the transmitted spectrum. Laser output acts as a carrier signal over which the input signal gets modulated with the help of modulators. These modulators are classified into electro-absorption (EA) and electro-optic modulators. The performance of an external modulator is measured based on extinction ratio and the modulation bandwidth.

In direct modulation the laser output intensity is controlled by directly modulating the injection current of laser diode in accordance with the input signal. But this can lead to chirping effect at higher frequencies. So, it is preferred to keep the laser source as itself and modulate the light output from it by keeping an external modulator in front. **Figure 4** shows the schematics of direct and external modulation schemes.

2.2.1 Direct modulation

Direct modulation of laser drive current is simpler, cost effective, and gives satisfactory performance for lower-frequency-modulating signals. But as the drive current to laser is varied directly, turn on delay and oscillation can result out of the fast-changing pumping current causing frequency chirping and linewidth broadening [6]. ON and OFF operations of laser cause the gain to change rapidly in the lasing medium. The change in gain causes a change in carrier concentration which in turn changes the refractive index, and this periodic change in the refractive index results in frequency chirping (the spectrum changes with time). When a chirped pulse propagates through a dispersive medium like optical fiber, the spread in frequency causes certain portion of the wave to travel faster/slower with respect to other portions leading to intersymbol interference (ISI).

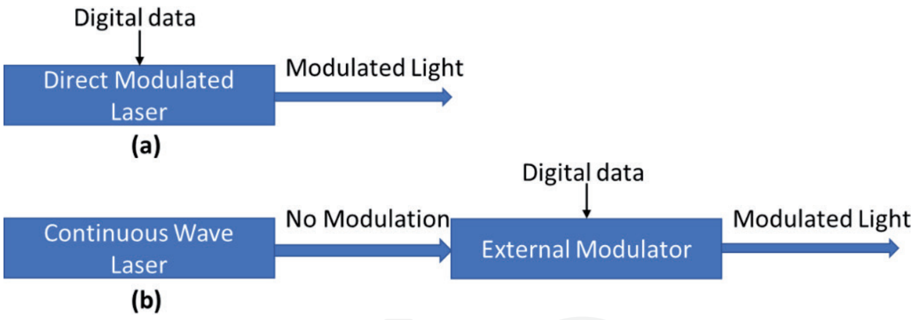

Figure 4.
Modulation schemes (a) direct modulation and (b) external modulator.

2.2.2 External modulation

A direct modulation is not suited for very high data rate transmission due to reasons such as chirp in DFB laser and mode partition noise in FP laser. So external modulation schemes are used for high-frequency modulation as it does not affect the laser characteristics and is implemented as an additional component in front of a CW laser. But this leads to an additional insertion loss for external modulators. Large modulation bandwidth and depth, small insertion loss, lower electrical drive power, etc. far outweigh its cons for bit rates above some 10 Gb/s. Some desirable characteristics of external modulators are polarization independence, good linearity (between drive current and modulated output), lower cost, and smaller size.

External modulators make use of techniques like electro-optic effect, acousto-optic effect (AOF), and electro-absorption effect to modulate the information signal over the incident CW optical beam. Acousto-optic modulators are slower and hence are commonly not used for communication purposes. *Electro-absorption* modulators are usually II–V materials, which alter its absorption coefficients according to an external voltage to obtain intensity modulation directly. These modulators are generally capable of attaining an extinction ratio of 15 dB or more at bit rates up to 40 Gb/s [7]. They have further advantages of being efficient and compact in size and can also be easily integrated into the same chip along with laser, as these modulators are also made of the same material.

Another class of external modulators are the *electro-optic modulators*, which works by altering its optical properties (mostly the refractive index (RI)) with the application of electrical field. This refractive index change may be due to Pockels effect, where the RI changes linearly with the applied electric field, or due to Kerr effect wherein the RI change is proportional to square of the electric field amplitude. When an optical signal passed through the altered RI region, it induces a phase change (or polarization rotation) in the signal, which can be converted to amplitude modulation by using Mach-Zehnder interferometer (MZI) configuration. LiNbO3 is the most widely used medium for this purpose, as it is optically birefringent and hence can be externally controlled by an applied electric field. A Mach-Zehnder-type external modulator uses phase modulation along with an integrated Mach-Zehnder interferometer to achieve intensity modulation. These modulators are capable of modulating up to 60 GHz [7]. The modulating frequency can be further extended up to 100 GHz or higher with traveling wave electrode configuration [8].

2.3 WDM multiplexer and demultiplexer

The inherent immense bandwidth of optical fiber systems can be tapped by the use of multiplexing techniques, which facilitates the electronics to work in much lower rate than the optical transmission rate. It is known that transmitting data over a single fiber with higher rates is more economical than carrying lower data rates over several fibers [9]. This makes multiplexing a must, so that huge transmission capacity of the optical fibers can be supported using moderate electronic component rates.

Different varieties of Mux/DeMux are available. Mostly these are reciprocal devices, hence can be used as both Mux and DeMux. They can be classified under two broad categories, diffraction-based and interference-based. Diffraction-based devices rely on angular dispersive element like diffraction gratings to decompose the incident light into its spectral components.

Interference-based DeMux are based on optical filter and directional couplers. Filter-based Mux uses optical interference for wavelength selectivity. MZI-based filters are the most used. One arm of MZI can be made longer to induce phase difference with respect to the other arm. This phase difference is frequency dependent. The path length is adjusted such that power from two different input ports adds up at only one output port (Mux operation).

The idea is to spatially separate the different wavelength that were traversing together in the optical fiber. Each of these wavelengths can be collected in those points into individual optical fibers. Optical Mux/DeMux can be broadly classified into passive and active. Popular passive Mux/demultiplexers are based on Prims, diffraction gratings, and spectral filters. Active Mux/DeMux is usually implemented as some passive components along with tunable detector, each tuned to separate wavelength. We will see each of them in a bit more details now.

2.3.1 Prism-based devices

These devices work based on the principle of dispersion, where different wavelengths see a different refractive index in the medium. This difference in refractive index results in some wavelengths to bend more (or less) than others which helps in separating them out. As can be seen in **Figure 5**, the incoming wavelengths are collimated and incident on the prism. Each wavelength seems a slightly different refractive index and bends differently according to Snell's law. At the output another lens focuses the different wavelengths to different output fibers.

2.3.2 Superprism-based devices

Superprisms employ photonic bandgap that make certain wavelength forbidden within the structure. This is achieved using special structures called photonic crystal. A photonic crystal is a periodic dielectric structure fabricated usually on Si using nanofabrication. This three-dimensional periodicity in refractive index causes periodic distribution in bands and gaps, and these can be tuned by varying the periodicity so as to make certain wavelength to propagate or not. It can act both

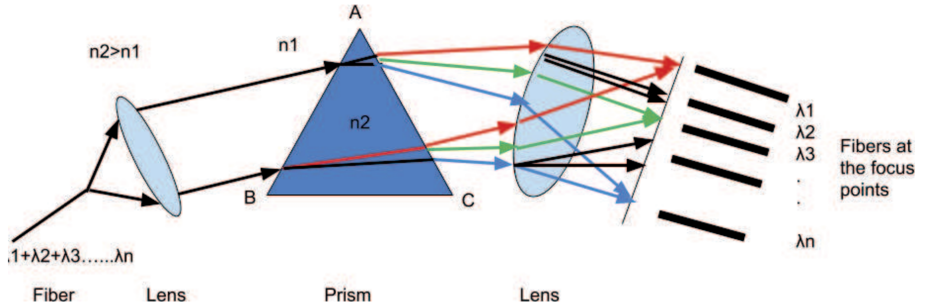

Figure 5.
Prism-based DeMuX configuration [10].

as energy bandgap filters as described above and as highly dispersive media. This high-dispersion property can be used to make prism called superprisms as they have almost 500 times more dispersion than normal prisms.

2.3.3 Diffraction grating-based devices

Diffraction elements as the name suggests use diffraction of light to separate different wavelengths. When a polychromatic light wave is incident on a diffraction grating, each wavelength is diffracted at a different angle from where they can be collected to achieve demuxing (**Figure 6**).

2.3.4 Arrayed waveguide grating (AWG)-based devices

AWG works on the principle of interference on a specially designed structure as shown in **Figure 7**. It has two free space propagation regions (S1 and S2), an array of waveguides (Wn) in the middle and fibers for input and output. A WDM signal incident on S1 through F traverses the free space and enters the arrayed waveguide region. The length of each waveguide in the arrayed waveguide section is varied such that it introduces a wavelength-dependent phase delay in S2. This phase delay causes the interference points of each wavelength to be spatially separated, where a fiber is connected to collect each wavelength, hence attaining DeMux.

AWG has some interesting features as follows which makes it very attractive.

- AWG has a flat spectral response.

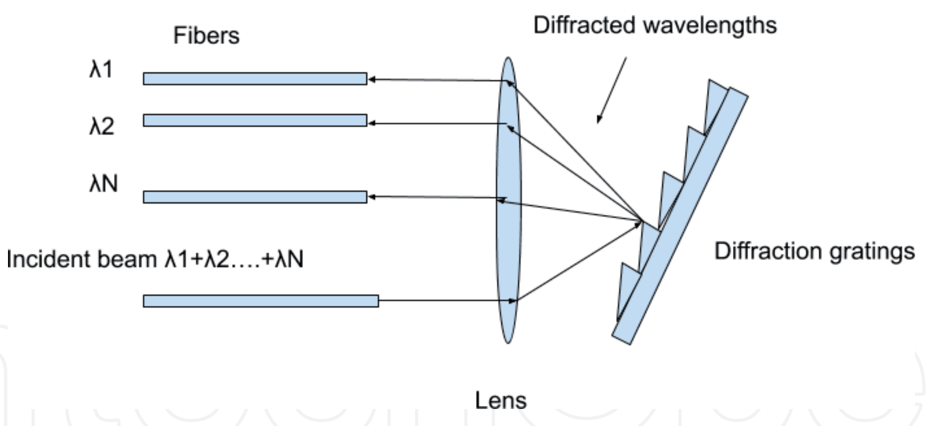

Figure 6.
Diffraction grating-based Mux configuration [10].

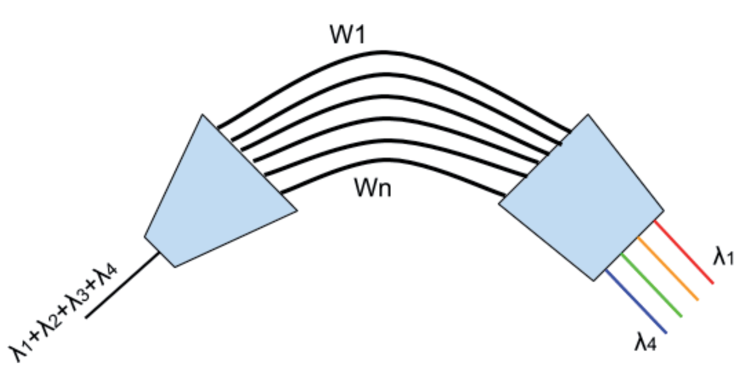

Figure 7.
AWG-based Mux/DeMux configuration [10].

- It has low losses and cross talk (insertion loss <−3 dB and cross talk <−35 dB).
- It can be fabricated on Si as photonic-integrated circuit (PIC) and can be easily integrated with photodetectors as well.

AWG suffers from drawbacks like polarization dependency and temperature sensitivity. A lot of works have been done in addressing these issues.

2.3.5 Mach-Zehnder interferometer-based devices

MZI-based Mux/DeMux works in the same principle of interference, where interfering coherent light of different wavelengths forms maxima at different spatial points and hence can be demuxed out. MZI-based Mux/DeMux devices can be integrated on silica.

2.3.6 Spectral filter-based devices

A spectral filter inserted in the optical path can be used to sort out wavelengths and hence can be used as DeMux. These devices can be implemented in different configurations, a couple of which are shown in **Figure 8**.

The first one is a fiber sandwiched at the cleaved surface of a fiber. The incident ray with two wavelengths is incident on the filter, which passes one and reflects the other. The reflected one is collected through another fiber achieving DeMux operation. Another form of filter can be implemented in a graded-index (GRIN) rod.

2.3.7 Acousto-optic filter-based devices

An interesting method for realizing a DeMux is shown in **Figure 9**. The device consists of an all-pass polarizer which linearly polarized the input signal. For demultiplexing these linearly polarized wavelengths, a combination of AOF and polarizing beam splitter (PBS) is used. The AOF can be controlled with electrical signal to rotate the polarization of a desired wavelength from transverse electric (TE) to transverse magnetic (TM). The PBS then reflects one of the wavelengths based on its polarization, resulting in DeMux operation.

2.4 Amplifier

Optical signals produced by laser, modulated with information at the multiplexer and segregated and propagated through optical fiber, are prone to attenuation and losses arising from all these components. Optical fiber technology is so advanced now that the transmission loss is practically negligible for short-haul communications. It is the component insertion loss that causes more serious signal attenuation. Eventually signal amplitude may get small enough to fall below the receiver sensitivity, which can be prevented with the use of

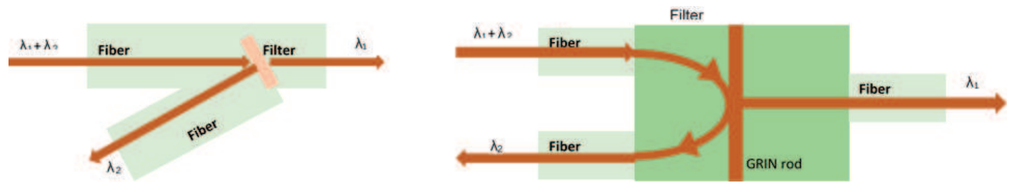

Figure 8.
Spectral filter-based devices [10].

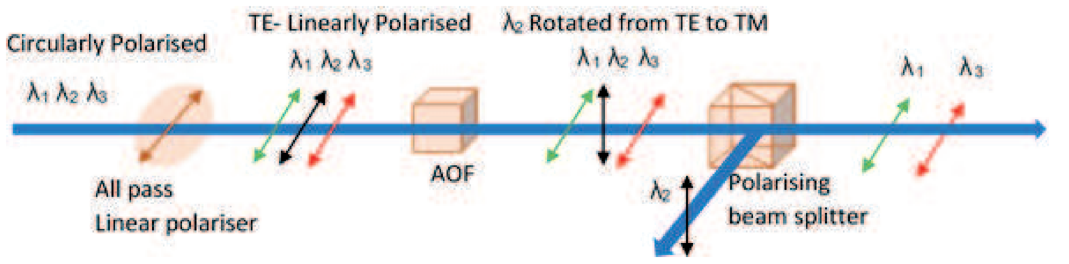

Figure 9.
Acousto-optic filter configuration [10].

amplifiers in the optical link. Before the invention of optical amplifiers, amplification could only be done in electrical domain. But this needed conversion from optical to electrical and then back to optical conversion (O-E-O). Additionally, electrical regenerators are generally sensitive to bit rate and modulation formats, which make it less flexible for additional capacity. But optical amplifiers work in optical domain and amplify the signals without O-E-O conversion. Further, they are transparent to bit rate and modulation format changes. Now, there are amplifiers that have a wide gain-bandwidth like EDFA, Raman amplifiers that can amplify signals over a large wavelength range. These facilitate the widespread use of WDM systems, which need simultaneous amplification of a wide range of wavelengths.

2.4.1 Erbium-doped fiber amplifier

EDFAs are the most commonly used optical amplifiers owing to their larger spectrum and high gain and simplicity. EDFA came into being by the early 1990s and has completely changed the landscape of optical communication industry. The most significant advantages of EDFA is its ability to amplify a wider bandwidth of signals, which is a big boost to WDM technique, as multiple channels can be amplified simultaneously. Other important aspects that make EDFA so mainstream is the availability of compact and high-power pump laser source, polarization insensitivity, easiness in coupling, absence of cross talk, and its inherent simplicity [3].

EDFA is an optical fiber with its core doped with rare earth mineral, which acts as the amplifying medium. Doping can also be done using holmium, neodymium, samarium, thulium, and ytterbium to provide gain in ranges from 500 to 3500 nm. EDFA has the capability to amplify signals in 1550-nm band, the standard telecommunication regime [11].

One main problem with EDFA is its nonuniform spectra. Different channels are amplified differently, and the difference builds up over a long-haul system with multiple EDFAs. Energy levels and gain spectrum of EDFA are shown in **Figure 10**. Several solutions have emerged in addressing this issue efficiently.

2.5 Detector

Optical detectors are devices that convert the optical signals into electrical signals. Usually a photodetector is followed by a front-end amplifier to amplify the electrical signal, which is followed by a decision circuit that estimates the data content of the electrical signal. Decision circuit needs to know the modulation scheme used for transmission. An optional optical preamplifier section can be used in front of the photodetector.

Photodetector works based on photoelectric effect. It is desirable for a photodetector to have "high sensitivity, fast response, low noise, low cost, and high

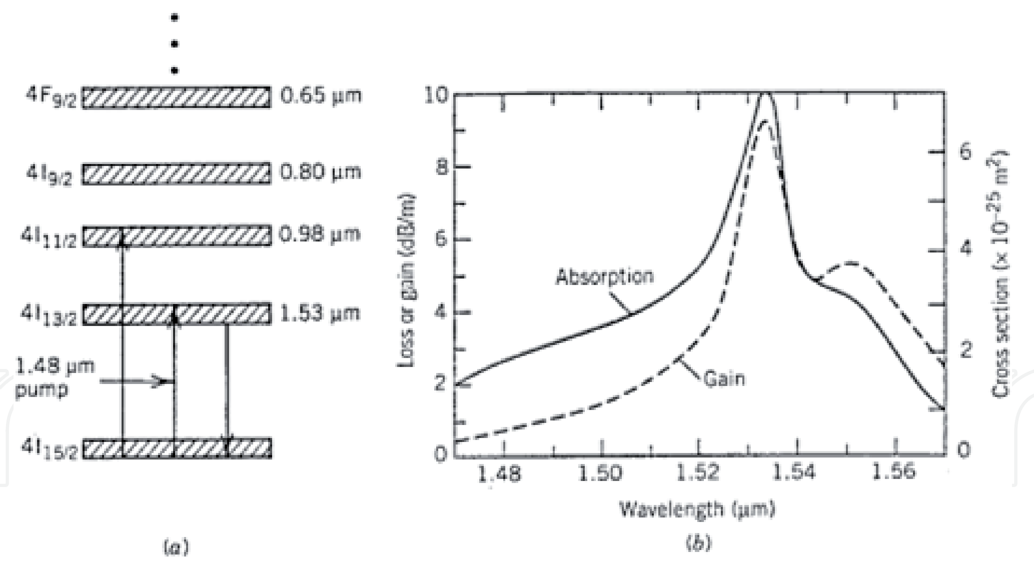

Figure 10.
(a) EDFA energy level diagram (b) absorption and gain spectra (codoped with Germania) [11].

reliability" for being more effective in communication engineering. When a photon of energy, hν, which exceeds the photodetector band gap, is incident on a photodetector, the photon is absorbed, and an electron-hole pair is generated (**Figure 11**). The electric field across the junction sweeps off this excess charge, hence producing a current flow in the external circuit.

Normally a reverse bias is applied to the junction. A reverse bias adds to the junction electric field, and the photocurrent generated by the absorption of photon is proportional to the incident optical power. It should be noted that the optical power is exponentially attenuated while it passes through the semiconductor material. The energy of the incident photon should be larger than the bandgap, e.g., of the detector. The lowest such wavelength is the cutoff wavelength above which the detector cannot operate. As Si and Ge have cutoff wavelength lower than 1550 nm, they are not used for communication application. Generally, indium gallium arsenide (InGaAs) and indium gallium arsenide phosphide (InGaAsP) are used in 1550 and 1310 nm wavelength ranges.

An important characteristic of photodetector is its responsivity, R. It is defined as

$$R = I_p / P_{in} \tag{2}$$

where I_p is the average photocurrent and P_{in} is the incident optical power. As $P_{in}/h\,\nu_e$ electrons are generated by a photon of Energy P_{in} and assuming only η fraction of incident photons is actually absorbed, then R can be written as [9]

$$R = \frac{\eta\,\lambda}{h\,\nu_e} \tag{3}$$

which can be written in terms of λ as $R = \frac{\eta\lambda}{1.24}$ where λ is expressed in μm.

2.5.1 PIN photodiode

As light is incident on the end of PN junction, the electron-hole pairs generated have to diffuse to the depletion region before getting swept away (drift) to the corresponding electrode, hence creating current in the external circuit. Diffusion velocity is slow and is in the range of 1 ns per µm. This causes the input signal to be distorted at the electrical output. Increasing the depletion region length can decrease the diffusion time. This is the idea behind PIN photodiode [3].

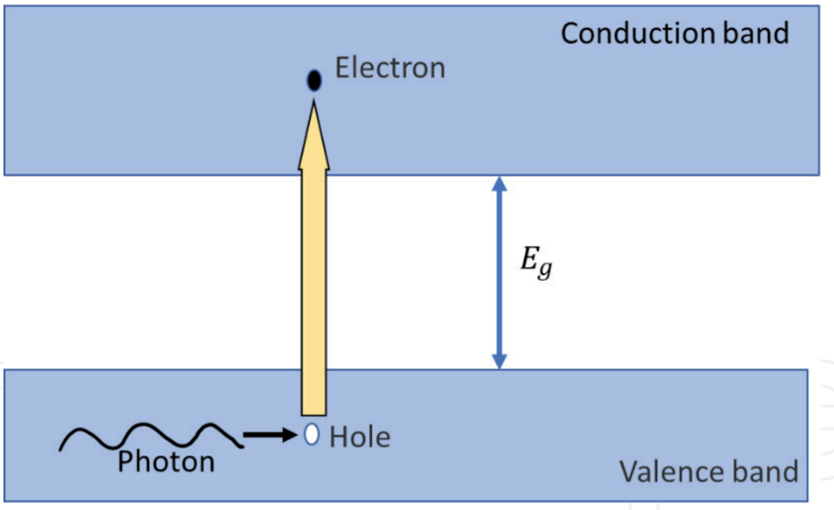

Figure 11.
Photodiode basic principle.

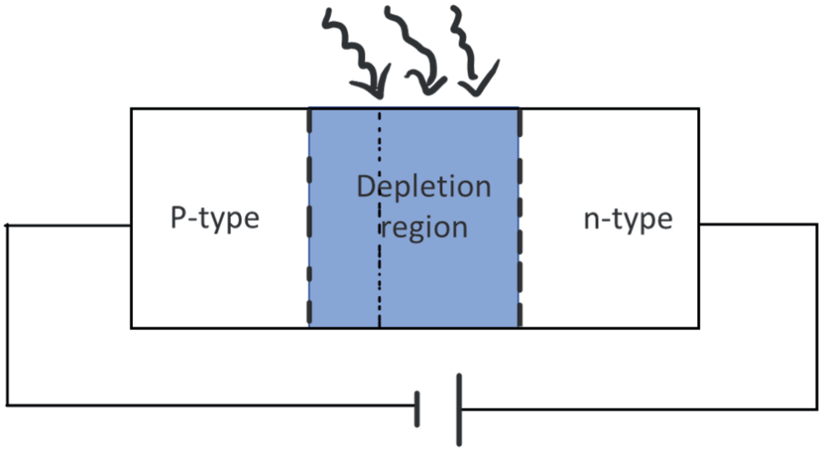

Figure 12.
PIN photodiode structure.

In PIN photodiode, the depletion region width is increased by the introduction of layer of very lightly doped intrinsic semiconductor material between p and n sides, hence the name PIN. **Figure 12** shows the structure of PN junction.

Due to the light doping, this layer provides high resistance and most of the voltage drops across it. In effect, most of the recombination happen in the depletion region; hence, the drift current far overweighs the diffusion current. So a longer W will increase the photodiode sensitivity, but a longer depletion width also implies larger transit time for the charge carries, hence increasing the response time. So there needs to be a trade-off between sensitivity and response time.

Similar to PN photodetectors, double-heterostructure design can further improve the performance of PIN photodiodes. By choosing material of sufficiently larger bandgap as p and n regions, the absorption can be limited only to the i regions. One such example is to use InP as the p and n region while using InGaP as the intrinsic layer [12]. Such a design helps to avoid the diffusion part of photocurrent, hence increasing the efficiency to nearly 100%. Reflections from the front facets can be reduced by coating with suitable dielectric layers.

Responsivity of PN diode is limited by Eq. (3). This is due to the fact that one incident photon can generate maximum of only one e-h pair. Avalanche photodiodes have internal mechanism which overcomes this and can provide larger photocurrent. They are especially preferred when the incident intensity on the photodetector is expected to be low.

3. Challenges to be addressed in WDM systems

As with any maturing technology, WDM too had a lot of challenges to be tackled as it progresses. For example, [13] discusses a hybrid multiplexer which can be used for WDM and MDM. Also WDM have found applications beyond communication, which also brings about additional challenges. Like in [14], WDM is used for optical beam steering, which is archived using photonic crystal waveguide and an integrated version of WDM in coupled micro-ring Muxs. Another field where WDM has found application is inter-chip links, as in [15] where micro-ring wavelength demultiplexers are used.

This section discusses about some of the realization challenges like EDFA transients and unequal link output power, which are not desirable in WDM-based systems. In this section, these effects are analyzed under different test cases and validated experimentally. Transient analysis is based on variations with input power, pump power, duty cycle, cascading stages, and multiplexed configurations.

3.1 Unequal channel power and its equalization

As seen before, EDFA is a major component in a WDM link for providing amplification in wavelength range around 1550-nm optical communication band. The non-flat gain spectrum of EDFA leads to uneven amplification levels for various WDM channels. This becomes more serious as more and more amplifiers are added in the link. Another serious problem for WDM networks is the wavelength-dependent gain saturation of EDFAs. Because of this effect, the loss or removal of one or more channels at the input of an EDFA can cause large changes in the output powers of the remaining channels. This effect is more predominant in CWDM systems than DWDM systems with a smaller number of wavelengths because of wider wavelength spacings when a single "C"-band EDFA is used for amplification.

To overcome this problem, an L-band EDFA in combination with a C-band EDFA can be used to flatten the EDFA gain spectrum. By using EDFA with longer fiber length or heavy doping concentration, EDFA gain characteristics can be altered [9]. So an L-band EDFA with a longer fiber length was considered. In the proposed configuration, multiplexed signal is split and passed through C- and L-band EDFAs. **Figure 13** shows the variation of gain spectra for L-band EDFA. It is suggested that if wavelengths are beyond 1565 nm, L-band EDFAs are better for practical applications [9]. CWDM configuration where the signals are splitted first and then amplified using two separate EDFAs is shown in **Figure 14**. These signals are recombined later.

3.2 EDFA transients

Due to slow gain recovery of EDFA gain, the low bit rate signals passing through EDFA undergo saturation and recovery effects during level transitions. The characteristic saturation and recovery times are, for typical operating conditions, in the range of 100 μs to 1 ms. As a result, EDFAs are intrinsically immune to the effects of cross talks at high data rates [16, 17]. The recovery time is of few hundred microseconds, hence do not affect the high bit rate signal amplification, as the erbium concentration is not significantly altered by the high bit rate signal during its short ON time period. But this is not the case with low bit rate signals, which is ON for enough time for reducing the population inversion, hence reducing the gain. The effect can be seen in **Figure 15**, when EDFA is input (1550 nm) with square optical pulse of 2 KHz and varying duty cycle, pumped with a 980-nm laser at 70 mW. The transient effects are sensitive to input signal duty cycle, signal power, and pump power of EDFA configuration. The following section focuses on EDFA transients applicable to multiplexed fiber links.

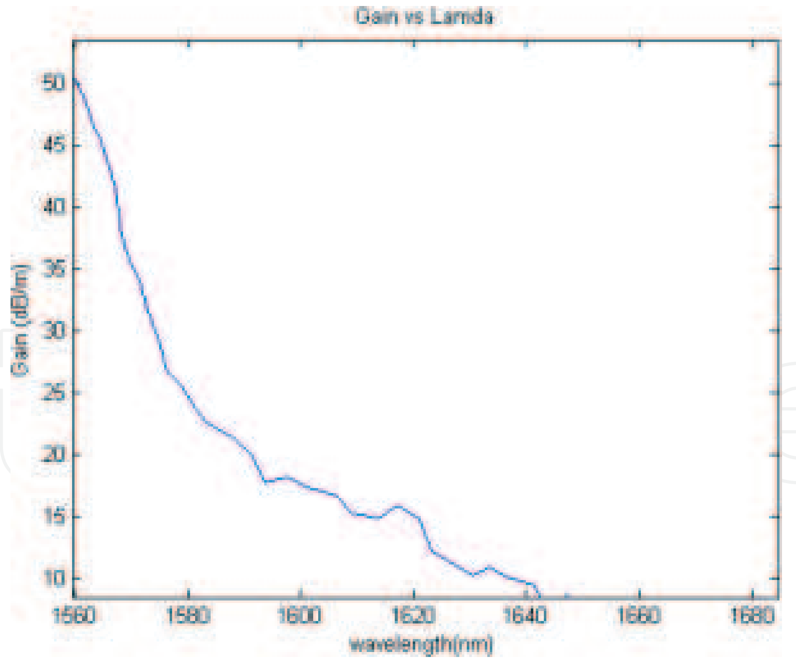

Figure 13.
L-band EDFA gain spectrum (30 m).

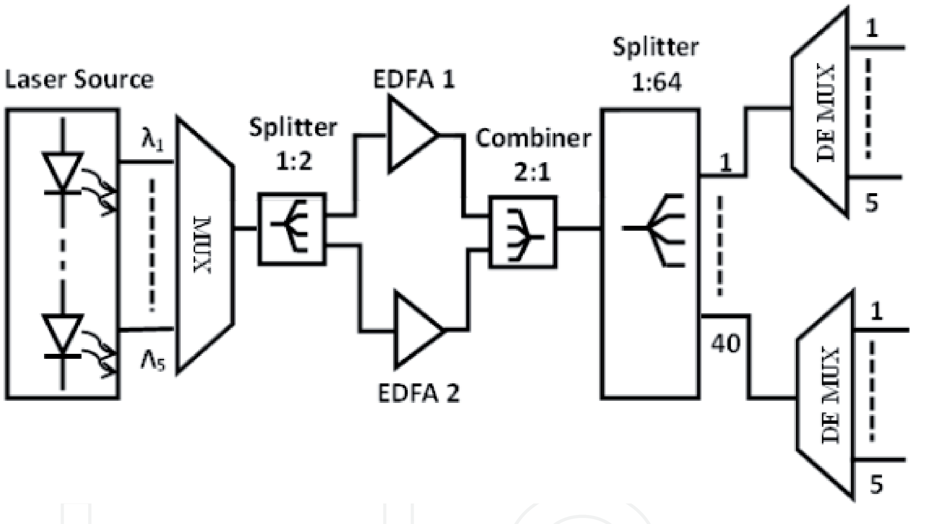

Figure 14.
Block schematic diagram with C- and L-band EDFAs for power equalization.

EDFA transients disappear with increasing bit rate as shown in **Figure 16** (bit rate 10 KHz and 1 MHz). It also decreases with lower signal and pump power (**Figure 17**).

Transient effects can produce a negative impact as the pulse shape at the output of the link is heavily distorted, it can lead to misinterpretation of data at the receiver side. Also, in cascaded EDFA applications, the transients can accumulate over length and can cause problems at detector stage. A few compensation techniques are described below.

3.2.1 Compensation using complementary pulse

To accomplish this, another complementary signal is multiplexed into the link at a different wavelength which ensures the EDFA input power remains constant. The block schematic and results are as shown in **Figure 18**. As the wavelength of compensation signal approaches the original wavelength of the signal pulse, the distortion is reduced, i.e., the closer the compensation wavelength, the better the compensation.

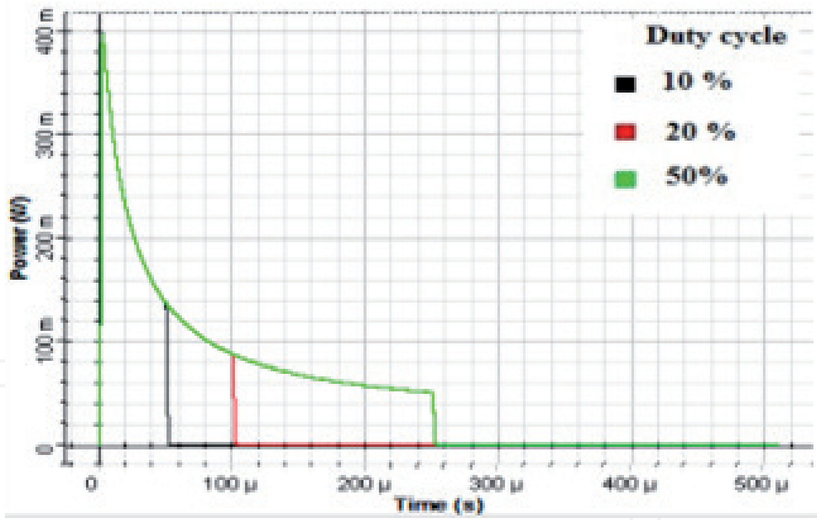

Figure 15.
EDFA response to duty cycle variation (single input pulse).

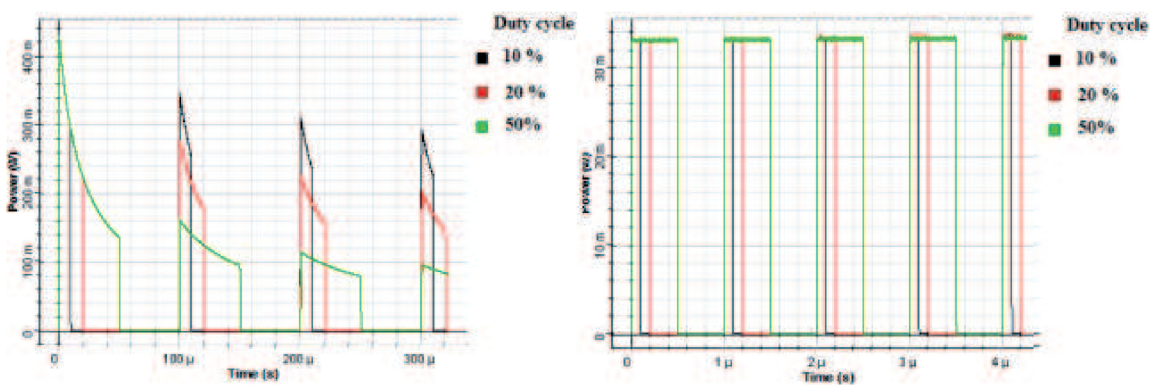

Figure 16.
EDFA response to 10 KHz (left) and 1 MHz (right) with different duty cycles.

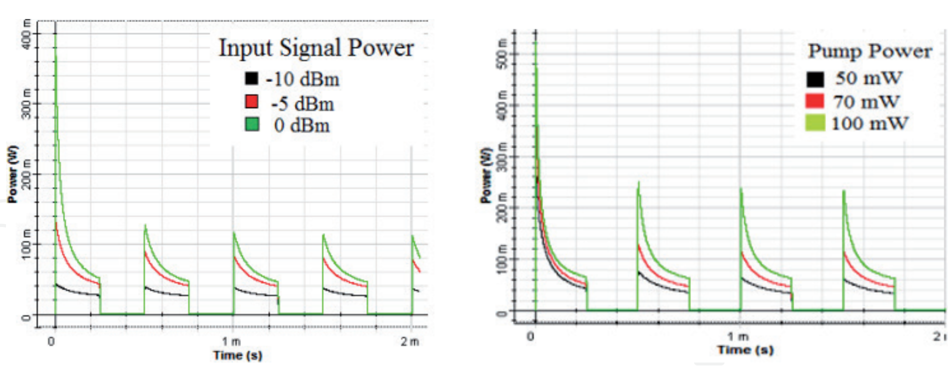

Figure 17.
EDFA transient response to signal (left) and pump variations (right).

3.2.2 Compensation using delayed pulse

In the case of 50% duty cycle pulse, two more additional suppression techniques are proposed. One uses electrical delay and the other uses optical delay. **Figure 19** shows the block schematic used for transient suppression of 50% duty cycle signal using optical delay line. **Figure 19** shows the experimental result of the transient suppressed output. The delay introduced should be equivalent to the ON/OFF time of transmitted signal. In this case, only one laser source is required. Optical delay can be introduced by using fiber spools of longer length. The delay can be applied electrically too; schematic and results are shown in **Figure 20**.

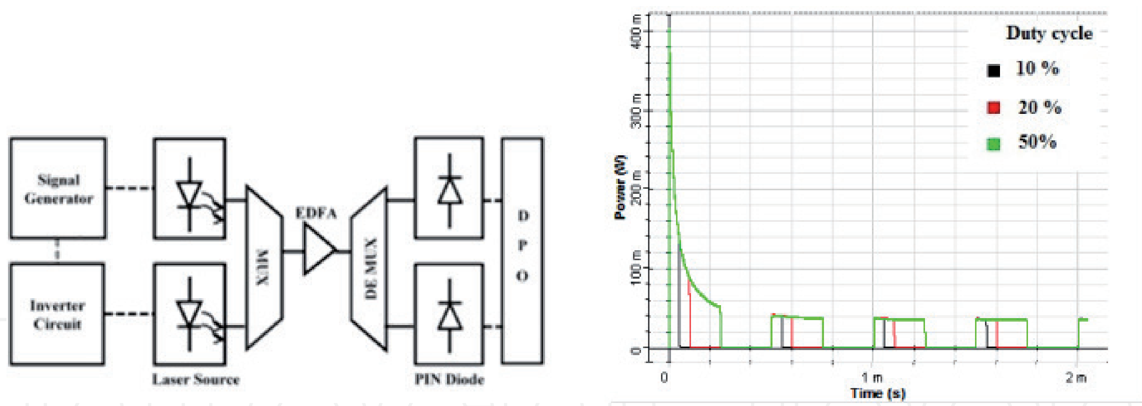

Figure 18.
Compensation using complementary pulse. Block schematic (left) and results (right).

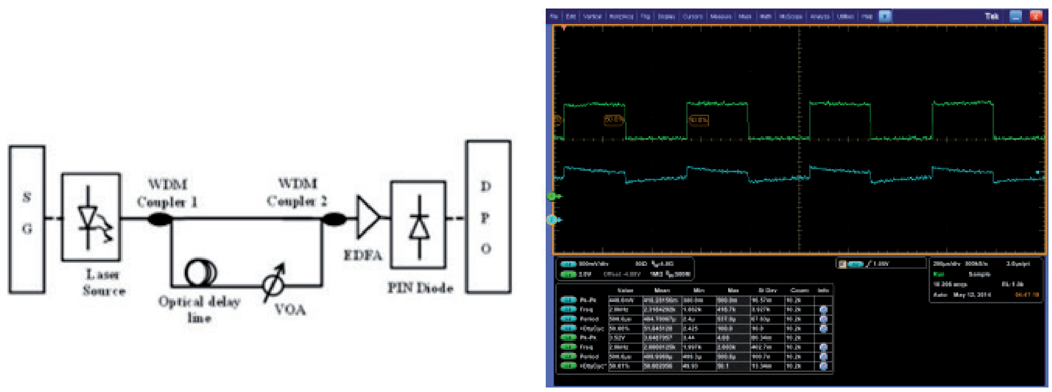

Figure 19.
Compensation using delayed pulse. Schematic (left) and experimental result (right).

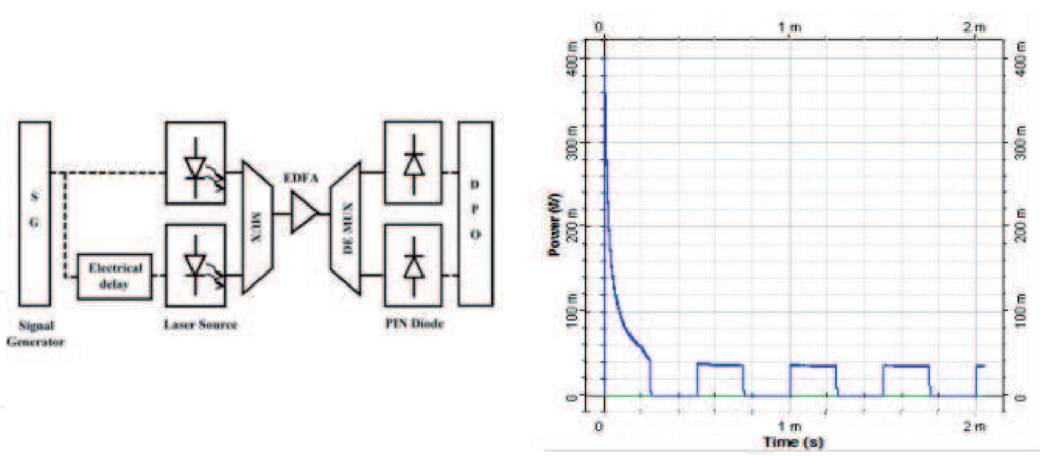

Figure 20.
Compensation using electrical delayed pulse. Schematic (left) and result (right).

EDFA transients affect WDM systems too in a similar manner by distorting the transmitted signal [17]. The description of the same is not included within the scope of this chapter.

4. Conclusion

The chapter introduces the concept of optical multiplexing with special focus on wavelength division multiplexing. Other multiplexing methods are also briefly described highlighting the operation and potential applications. A WDM link is explained by going into detail of the different components making up the link. The chapter also includes a few challenges which degrade the performance of the link and potential methods to overcome those effects.

With the WDM Mux/DeMux described above, adding or dropping an unplanned channel may require the traffic in the entire link be suspended. But with a reconfigurable optical add-drop multiplexer (ROADM), an operator can remotely reconfigure the multiplexing so that data in the other channels are not interrupted. Several technologies are developed for achieving this.

Another interesting development is the emerging of super-channels, which reduces the channel gap close to the Nyquist bandwidth. The idea is to combine multiple coherent carriers to create a unified channel, called a super-channel, which will operate at the maximum data rate supported by the analog-to-digital convertor (ADC) at the receiver. The absence of guard channels and coherent detection ensures high spectral efficiency. Some techniques include orthogonal frequency division multiplexing (OFDM), orthogonal band multiplexed (OBM), no-guard-interval (NGI)-OFDM, multichannel equalization (MCE)-WDM, Nyquist WDM, etc.

These WDM links are widely used in various regimes of communication. At present, majority of the links are made with discrete components. When a greater number of channels are required to be transmitted, a small form factor solution is preferable. Currently many researches are being carried out to bring these components to a photonic-integrated circuit form which can reduce the size to a greater extent. It is quite sure that with the latest advancements in nanotechnology, more components can be integrated resulting in a very-small-factor WDM chips.

Author details

Meena Dasan[1]*, Fredy Francis[2], Kundil T. Sarath[3], Elambilayi Dipin[3] and Talabattula Srinivas[4]

1 Electronics and Radar Development Establishment (LRDE), DRDO, Bangalore, India

2 Indian Institute of Technology Madras, Chennai, India

3 Nanatom Technologies, Bangalore, India

4 Electrical Communication Engineering, Indian Institute of Science, Bangalore, India

*Address all correspondence to: dmeenasatish@gmail.com

References

[1] Space Division Multiplexing. Available from: https://www.rp-photonics.com/space_division_multiplexing.html [Accessed: June 14, 2019]

[2] Xu K, Wang R, Dai Y, Yin F, Li J, Ji Y, et al. Microwave photonics: Radio-over-fiber links, systems, and applications. Photonics Research. 2014;**2**(4):B54-B63

[3] Agrawal GP. Fiber-Optic Communication Systems. John Wiley & Sons; 2012

[4] Akiba SH, Usami MA, Utaka KA. 1.5-μm λ/4-shifted InGaAsP/InP DFB lasers. Journal of Lightwave Technology. 1987;**5**(11):1564-1573

[5] Li GP, Makino T, Moore R, Puetz N, Leong KW, Lu H. Partly gain-coupled 1.55 mu m strained-layer multiquantum-well DFB lasers. IEEE Journal of Quantum Electronics. 1993;**29**(6):1736-1742

[6] What When How. Optical-Time-Division-Multiplexed-Communication-Networks- Part-4. Available from: http://what-when-how.com/fiber-optics/Optical-time-division-multiplexed-communication-networks-part-4 [Accessed: June 14, 2019]

[7] Phillips ID, Ellis D, Thiele J, Manning RJ, Kelly AE. 40 Gbit/s all-optical data regeneration and demultiplexing with long pattern lengths using a semiconductor nonlinear interferometer. Electronics Letters. 1998;**34**(24):2340-2342

[8] Nishihara H, Haruna M, Suhara T. Optical Integrated Circuits. New York; 1989. pp. 7-8

[9] Ramaswami R, Sivarajan K, Sasaki G. Optical Networks: A Practical Perspective. Morgan Kaufmann; 2009

[10] Optical Demultiplexers. Available from: https://ftp.utcluj.ro/pub/users/cemil/dwdm/dwdm_Intro/5_5311736.pdf [Accessed: June 14, 2019]

[11] Desurvire E, Bayart D, Desthieux B, Bigo S. Erbium-Doped Fiber Amplifiers: Device and System Developments. New York, NY: Wiley-Interscience; 2002

[12] Tucker RS, Taylor AJ, Burrus CA, Eisenstein G, Wiesenfeld JM. Coaxially mounted 67 GHz bandwidth InGaAs PIN photodiode. Electronics Letters. 1986;**22**(17):917-918

[13] Tan Y, Wu H, Wang S, Li C, Dai D. Silicon-based hybrid demultiplexer for wavelength-and mode-division multiplexing. Optics Letters. 2018;**43**(9):1962-1965

[14] Ito H, Tatebe T, Abe H, Baba T. Wavelength-division multiplexing Si photonic crystal beam steering device for high-throughput parallel sensing. Optics Express. 2018;**26**(20):26145-26155

[15] Jia H, Yang S, Zhou T, Shao S, Fu X, Zhang L, et al. WDM-compatible multimode optical switching system-on-chip. Nano. 2019;**8**(5):889-898

[16] Desurvire E. Analysis of transient gain saturation and recovery in erbium-doped fiber amplifiers. IEEE Photonics Technology Letters. 1989;**1**(8):196-199

[17] Dasan M, Thodiyil S, Francis F, Elambilayi D, Talabattula S. An investigation on transient effects in EDFA with variable duty cycle and wavelength multiplexed signals. Microwave and Optical Technology Letters. 2015;**57**(2):352-356