WAVELENGTH DIVISION MULTIPLEXING FOR HIGH-CAPACITY NETWORK APPLICATIONS

Sibel GÜLER
Uludağ University
Department of Electronics Engineering
BURSA/TURKEY

Güneş YILMAZ
Türk Prelli Kablo ve Sistemleri A. Ş.
R&D Department
MUDANYA/TURKEY

Key Words: WDM, optical systems, high speed systems

Abstract: The transmission capacity of present networks has to be increased in order to satisfy the current rapid growth in demand for more bandwidth per user. Nowaday strong efforts are made to develop components which enable frequency multiplexing in optical networks. This method is called Wavelength Division Multiplexing (WDM). It is evident that both wavelength division multiplexing (WDM) and optical time division multiplexing (OTDM) techniques can be used for high-capacity data networks. With a combination of OTDM and WDM the maximum possible bitrate transmitted through a fiber may rise from a few Gbit/s to the Tbit /s range. For each channel, a separate laser operates at the corresponding wavelength.

WDM technology was born from the idea of simultaneously injecting several trains of optical signals into same fiber at the same speed of modulation, but each one with a distinct wavelength. Today the WDM system comprises 4, 8, 16, 32 and even 80 optical channels with capacities of 10, 20, 40, 80 and even 200Gbit/s respectively taking a nominal flow of 2.5 Gbit/s per channel. Such a system with 8 channels 2.5 Gbit/s makes it possible to transmit 250 000 simultaneous telephone conversations on a single fiber. Recent experiments with WDM technology in long haul submarine systems have very impressive results. Transmission of high speed signals suffers from limiting effects of the fiber such as dispersion, nonlinear effects and polarization mode dispersion.

1. INTRODUCTION

The multiplexing technique has a long past and a widespread usage in communications. Multiplexing is the transmission of the information over the same transmission medium from more than one source to more than one destination. There are two basic ways of implementing the multiplexing. Frequency division multiplexing (FDM) is an analog multiplexing technique. Each of the communication channels uses a different frequency. Time division multiplexing (TDM) is a standard technique for digital transmission distances. Information transmission and long haul telecommunication systems use TDM in order to combine low speed channels into special time intervals of a high speed channel. WDM is the simultaneous transmission of several optical signals with wavelengths divided by appropriate intervals from different light sources over the same fiber. WDM uses the same principles with FDM and TDM except the usage of distinct wavelength instead of time or frequency. WDM increases the fiber bandwidth with several high speed communication applications sharing the same fiber simultaneously [1],[2].

2. WDM DEVİCE

A single fiber path has an optical source at the end of the transmitter and a photo-detector at the receiver port in point to point systems. Since the optical sources have narrow spectral widths, a single optical source uses a small part of the available spectral transmission band of a fiber as shown in Fig.1. There are lots of processing regions as shown in here. An effective increase in the information capacity of the fiber can be achieved by simultaneous transmission of the optical source signals divided by appropriate intervals over the same fiber. Simultaneous using of many spectral channels is the basic principleof WDM [3].

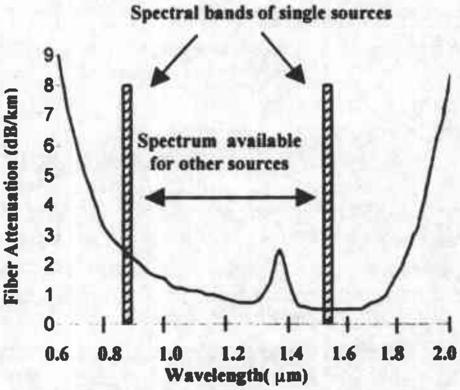

Figure 1. Available spectral transmission band of single fiber and bandwidth of two separate optical sources .

There are two different WDM setups shown in Fig. 2 and Fig. 3. A unidirectional WDM device is used to combine the optical carrier signals on the same fiber at one end and separate them to photo-detectors at the other end in Fig 2.

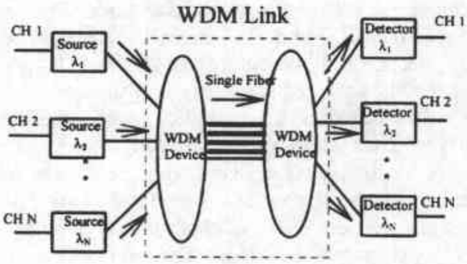

Figure 2. A unidirectional WDM system

A bidirectional WDM system, in which two or more wavelengths are transmitted simultaneously in opposite directions over the same fiber, is shown schematically in Fig 3. The optical signals are sent in one direction at a wavelength λ_1 and simultaneously in the opposite direction at a wavelength λ_2 [3].

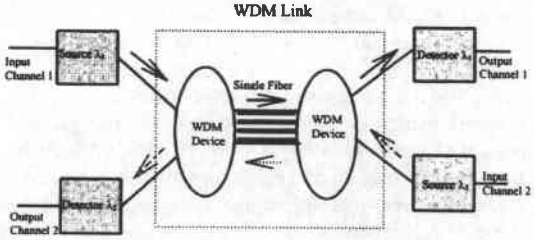

Figure 3. A bidirectional WDM system

Widely used wavelength division multiplexers are classified into two categories. Angularly dispersed devices like prisms or grills and filter based devices like multi-layer thin film interference filter and single mode integrated optical devices.

The basics of angular dispersive multiplexer is shown in Fig. 4 for two wavelength system where $d\theta/d\lambda$ is the angular dispersion of the device.

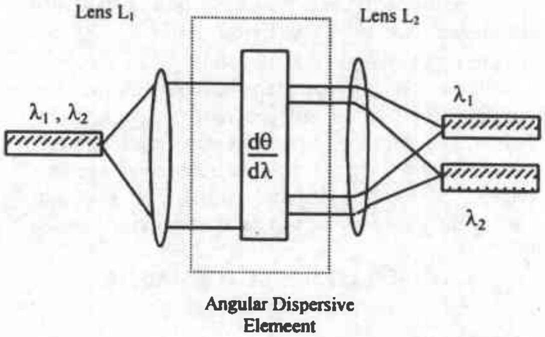

Figure 4. An angularly dispersive WDM element shown for two wavelengths.

Many wavelengths can be combined or separated with this type of device. When the device is used as a demultiplexer the light coming from fiber at the left, including λ_1 and λ_2 wavelengths is separated out with the lens L_1 and passed through the $d\theta/d\lambda$ dispersive element which separates the light and routes channels with different wavelengths to different places. Then the focusing lens L_2 focuses output lights to appropriate receiver fibers or detectors.

The linear dispersion $dx/d\lambda$ at output fibers shown on the right side of Fig. 4 is

$$\frac{dx}{d\lambda} = f\frac{d\theta}{d\lambda} \tag{1}$$

where f is the focal length of lens L_2. In the ideal case of aberrationless optics and zero source spectral width, the intrinsic insertion loss and cross talk will be zero if the output signals are separated by more than their diameter d, that is,

$$\frac{dx}{d\lambda}\Delta\lambda \geq d \tag{2}$$

where $\Delta\lambda$ is the spectral separation between channels. Here we shall assume that all fibers(input and output) have the same diameter d and numerical aperture NA.

To collect all the light from the input fiber, the collimating lens L_1 must have a diameter b satisfying the condition

$$b\rangle 2f\frac{NA}{n'} \tag{3}$$

where n' is the refractive index of the medium between the dispersive device and the lens L_1. Combining Eqs .(1)through (3) yields

$$b \geq \frac{2(NA/n')d}{\Delta\lambda.(d\theta/d\lambda.)} \tag{4}$$

In any real system the output beam spreads out because of the finite size of the light source and the angular dispersion resulting from the wavelength spread of the source spectral width.

The fractional increase S in the beam diameter is approximately given by

$$S = \frac{b'-b}{b} \approx (1+m)\frac{Wd(NA)}{b^2 n'} \tag{5}$$

where m is the number of wavelength channels, b' is the diameter of lens L_2, and W is the total path length from the output of lens L_2 to the input of lens L_1. To avoid overfilling the numerical aperture of the output fiber , the total beam spread must be a small fraction of the collimating lens diameter ,that is, S<<1 [3].

Most of the channels can be combined or separated by angular dispersive multiplexing method with the module in Fig. 4. Most of these devices use grill plus lens combination. A prism sometimes can be used as an angular dispersive multiplexing element. The losses are typically between 1 and 3 dB and the cross-talk levels are between -20 and -30 dB.

The function of filter type multiplexing element is shown in Fig . 5 for wavelengths λ_1 and λ_2. The filters are designed in order to transmit the light in a specific wavelength and either to absorb or to reflect all other wavelengths. In general, using reflection type filters gives more positive results. Reflection filter is formed by a glass layer at the lower side and one or more different dielectric films having selectivity property at different wavelengths at the upper side.

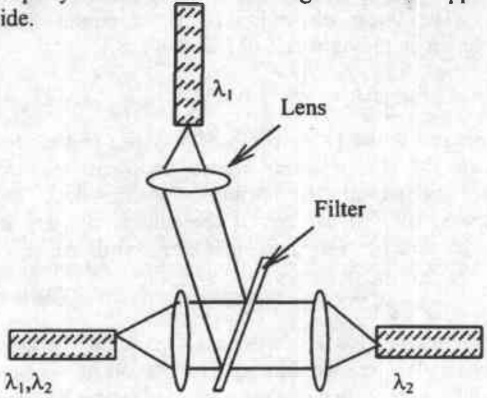

Figure 5. Multi-layer thin film filter reflector used for WDM.

When multi-layer reflection type thin film filter is used as WDM, it reflects at wavelength λ_1 and transmits at wavelength λ_2. In order to separate additional wavelength channels this filters are used in series. The complexity caused by placing filters in series and increases in the signal loss limits the process with two or three filters [3].

3. DESIGN CONSIDERATION FOR WDM SYSTEMS

Various segments in WDM system design must be examined. Wavelengths in WDM systems must be determined by considering fiber losses (including spectral losses), device losses and existing laser diode and photodiodes. These factors limit the possible transmitting range and bit rate.

Wavelengths that can be detected by photodetector and radiate with the laser diodes must be determined, considering wavelengths in WDM systems. When choosing the WDM device the cost and performance are the most significiant components. The input and reflection losses , channel width and cross-talk affect the performance [1],[4].

The input loss is defined as the amount of the power that occurs at joint segment of WDM coupler device and in the fiber optic path. This includes losses which occur in connectivity point of WDM element to fiber link and internal losses inside the multiplexer element. Practically designers can tolerate 1 or 2 dB of input losses.

The channel width is the wavelength region allocated to a special optical source . If laser diodes used in order to eliminate internal channel interferences caused by the source bistability, a 10 nm channel width is required. Because of their wider spectral outputs 10 or 20 times bigger channel widths are required for LED sources.

Cross talk points the amount of signal coupling from one channel to the other and reduces the transmit quality by increasing the error rate in digital systems. It provides waveform distortion in analog systems . Furthermore it provides security and safety problems. The communication of person or information can be received by another person [1].

Therefore the cross talk under the optical level which can be detected at bit rate must be eliminated. Beside the laser oscillation and photodetection optical amplification wavelength must be considered for some applications. For example, it is better to use 1,5 μm wavelength region for video distribution may require an optical amplification and 1,5 μm band is available for today's EDFA amplification. The signal bit rate is also an important factor for WDM system design. WDM systems use the same optical transmit link. Therefore optical transmitting loss is similar in each channel except the spectral loss coupling of optical fibers and optical devices. High bitrated transmitting systems require the highest optical receiver power. The following equation is used for the loss budget holds:

$$\Delta L = 10\log\left({}^{B_1}\!/_{B_2} \right)(\mathrm{dB}) \quad (6)$$

Where ΔL , B_1 and B_2 are loss differences and bit rates for first and second WDM systems. For example, B_1=500MB/s and B_2 =50MB/s and ΔL=10dB.

If we allocate first system 1 to 1,5 μm region and second system to 1,3 μm region the transmit loss for 1,5 μm region can be decreased. In order to design the transmit loss differences let's assume the optical transmit losses 1 and 0,5 dB/km for wavelengths of 1,3 and 1,5 μm . The transmit loss difference for a 5 km transmission is 2,5 dB which is not enough for ΔL=10dB [4].

When all services are predetermined the solutions thought for this problem is designing the loss budget with the highest bit rate. Although this is a possible solution optical subscriber systems depend on service demand, which are unknown during the system design of each subscriber.

4. WDM BASED MULTI-CHANNEL SYSTEMS

WDM based multi-channel systems are applications of WDM and designed to be used in the initialize case of WDM. Each of the wavelengths allocates to each of the subscriber in Figure 6(a).

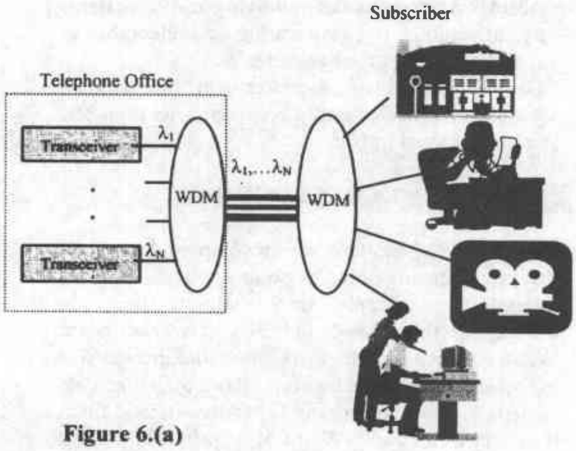

Figure 6.(a)

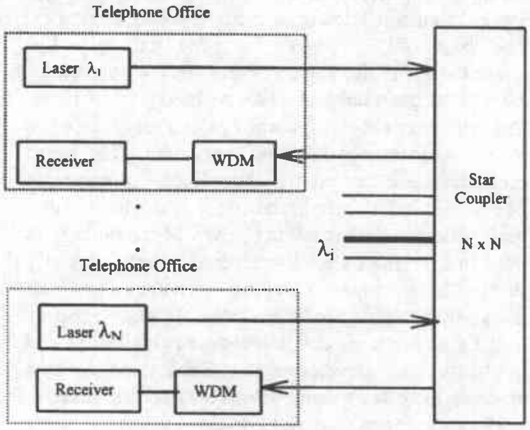

Figure 6.(b) WDM based multi-channel systems

This system requires several wavelengths which suit the number of subscribers connected in WDM. (This number is 16:8 in the example) The advantage of this system is the independence of the channels because of the practically low cross-talk level.Since this system uses WDM device, there is no additional loss. Although the WDM device has a little input loss, here the transmission loss is smaller compared with a system that has a star coupler. The disadvantage of this system is the requirement of wavelength transparency which hasn't considered during the design case and difficulty in using new wavelengths. An other disadvantage is using several laser types at different wavelengths which increases the system cost.

Another example of WDM based systems is shown in Fig. 6(b). This system is designed for video distribution applications. The NxN star coupler is used to mix the information and also as a radiation of the mixed information. This NxN star coupler must have a wavelength dependence. The loss is given by the following equation when the power is divided equally in NxN star coupler.

$$L_B = -10\log_{10}(1/N)\,(\mathrm{dB}) \qquad (7)$$

where N is the branching number.Each telephone office has a transmitter with a single wavelength.The other telephone offices get this wavelength from a WDM device and a star coupler. When a fixed WDM device is used, the predetermined wavelength can be received.An example of a tunable WDM device is shown in Fig7. The grill is used for the WDM device and a desirable wavelength can be found with the grating rotation [4].

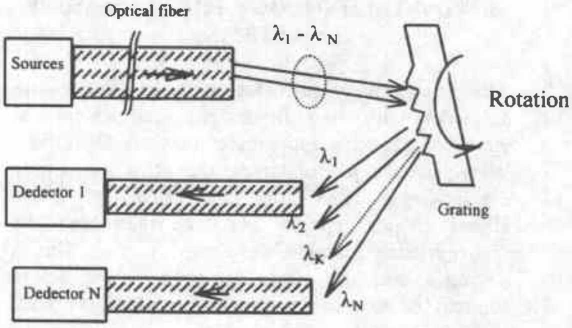

Figure 7. Example of a Tunable WDM Device

5. KEY ADVANTAGES IN WDM TECHNOLOGY

The key advantages in WDM technology are

- Carrying force of existing fiber capacity
- Low cost
- Elimination of long range single mode converters
- Fast access to new channels
- Protocol independence

Carrying force: WDM can use the existing fiber capacity in order to provide full processing new channels. For example a four channel WDM system can create three new application path for each of the fiber pair.

Low cost: WDM provides a more economic solution for high speed information transmission applications. The cost advantages occur from two main points:

-The WDM device is cheaper than a private cable and a leased-line for ranges more than 2 km.

-The WDM device creates several growth solutions for new applications.

Elimination of long range single mode converters: WDM technology uses single mode remote lasers for WDM systems in order to create separate wavelengths. This property makes a translation process from multi mode to single mode which is required to form interface between the local input (generally with multi modes) and the long range fiber communication systems. This causes a saving in the space and cost of converters or long range laser cards.

Fast access to new channels: Since the base of installed fibers becomes inadequate and most of the servers go through specialization, it becomes harder to get fibers allocated in most of the metropolitan areas. When the fiber is suitable it takes 4 or 12 months to provide a point to point service.

Protocol independence: WDM systems create completely transparent and independent paths over each of the fiber. This allows the multi application protocols to get combined without any issues of latency software setup rate proprietorship and etc. over the same fiber. A multi channel WDM link will act as multiple virtual fiber pairs.

6. WDM TECHNOLOGY FOR SUBMARINE SYSTEMS

WDM technology provides undersea fiber optics networks with two fundamental enhancements: increased capacity and greater network flexibility. When used with undersea repeaters containing erbium-doped fiber amplifiers (EDFAs), WDM allows greater capacity per fiber than could be realized using a single wavelength carrier. This is having a dramatic effect not only on the design capacity of new cable systems but also an optical amplifier based undersea systems installed since 1994. Transoceanic systems with up to sixteen wavelengths per fiber are possible over distances of 8000km. These systems transport an STM-16 (2.5Gb/s) on each wavelength, supporting a maximum capacity of 40 Gb/s per fiber. Wavelengths within the fiber paths can be routed and reconfigured independently. The second fundamental enhancement that WDM technology provides is in networking capabilities. This enhancement creates an opportunity to design more complex undersea networks with more landing points and more flexibility in traffic routing with fewer fiber pairs and the corresponding undersea equipment. WDM allows undersea networks to use the wavelength layer to add and drop, more traffic capacity at more landing points, while keeping the number of fiber pairs in the system to a minimum. The advancement of WDM technology will undoubtedly continue to have a major impact on the design of international undersea cable networks. As the technology develops to allow for more wavelengths to be carried longer distances and at higher bit rates, new undersea cable networks will be built connecting more countries with more capacity than ever before [2],[5].

The primary advantages for submarine applications are:

- Uses existing transmission technologies
- One or more wavelengths can be added or dropped at intermediate nodes
- Network capacity upgrades may be progressive
- Offers carriers "sovereignty" by allowing them to use dedicated, discrete, secure wavelengths, which they manage and control throughout the network.
- Ability to accommodate evolving traffic patterns by allocating or reallocating wavelengths to specific routes in the networks.

Eases integration of domestic and international networks, by dedicating wavelengths to domestic and international traffic.

7. CONCLUSION

WDM systems are developing fastly and they are used in point to point applications. This technology became the interest point in developing the new optical networks. Since WDM decreases the installation and growth cost of optical networks allowing more than one data sequence to be carried on the same optical fiber, it is very attractive. WDM also provides great carrying capacities so that it is possible to get higher transmit rates in optical carrying networks. The cross-talk increase caused by the nonlinearity of fiber parameters in the case when a multi access demand like placing too many channels over the long ranges exists, decreases the WDM performance in some networks. The other problems are caused by nonlinear components like optical amplificators, switches and multiplexers / demultiplexers . WDM technology is used in carrying data between two points specially in the long range carrying networks which transmit the data in high rates. It also offers quick responses for cost advantage , flexibility and application development. Submarine WDM systems have been demonstrated in recent years in both laboratories and field trials. Submarine fiber optic WDM networks can be as large as transoceanic systems or as small as a coastal festoon system that acts as an extension of a terrestrial national network. Within the network, wavelength can be dedicated to domestic traffic and international traffic, or voice-band services and data services, depending on the carrier needs. As demand for international capacity increases, wavelengths can be added. The fast growth trend in Internet and other communication services will increase the use and development of WDM technology during the next few years.

References:

1-TOMASI Wayne, Elektronik leti im Sistemleri, pp. 697-741

2-O'Mahony Mike J,Optical Multiplexing in Fiber Networks:Progress in WDM and OTDM,IEEE Com. Magazine, December 1995, pp 85-88

3-KAISER Gerd, Optical Fiber Communication, pp.401-403

4-KASHIMA Norio, Optical Transmission For The Subscriber Loop, pp.233-240

5-Patrick Trishitta and William C. Marra, Applying WDM technology to undersea cable networks, IEEE Com. Magazine, February 1998, pp 62-66