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DWDM Technology for High Speed Optical Communications

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***Abstract*- The ever-increasing demand for applications in internet, digital cable TV, e-mail, data transmission etc. has forced the utilization of the available more than two THz transmission bandwidth of single-mode optical fiber at low loss and low dispersion window of 1550 nm. Most of the optical communication systems in use today range from 2.5 Gbit/s, 10 Gbit/s and 40 Gbit/s while 160 Gbit/s and 480 Gb/s systems are in developmental stages. The main stumbling block to achieve this high bit-rate is the limitation of the electronic components used in the receiver and transmitting systems as well as the dispersing in the fibers. In wavelength division multiplexing (WDM) several channels at different wavelengths are multiplexed and transmitted simultaneously over a single fiber. The bit rate in each channel is lower to meet the electronic limitations but overall bit rate is quite high due to large number of channels. As the separation between successive channels becomes very small (1 nm to 0.8 nm) it is customary to use the term Dense Wavelength Division Multiplexing (DWDM) instead of WDM. This paper presents the concept of WDM/DWDM, component requirements, system characterization, current status and future developments.**

***Index Terms* – DWDM, Optical Communication, Dispersion, TDM, Multiplexing, Demultiplexing, Four wave mixing, WDM standards.**

I. INTRODUCTION

The rapid growth of optical fiber technology over the last three decades has surpassed all other communication technologies and has resulted into over 500 million kilometers of fiber networks world-wide. It is expected to grow by several million kilometers by the end of year 2013 [1]. The main reasons for this tremendous growth are several advantages of optical fiber technology like extremely large bandwidth, low loss, immunity from electromagnetic interference, light weight, small size and secure communication. Another important advantage of the fiber technology is that several channels corresponding to different wavelengths can be transmitted simultaneously through a single fiber especially in the low-loss and low dispersion window of 1300-1600 nm wavelength. The most interesting aspect of the fast growth of this new technology is its application in local area networks while in the past main focus was the long distance communication. Now the complete “fiber to the home” (FTTH) systems are very close to realization. The ever-increasing demand for applications in internet, digital cable TV, e-mail, data transmission etc. has forced the utilization of the available more than two THz transmission bandwidth of single-mode optical fiber at low loss and low dispersion window of 1550 nm. Most of the optical communication systems in use today range in 2.5 Gbit/s, 10 Gbit/s and 40 Gbit/s while 160 Gbit/s and 480 Gb/s super channel systems are in developmental stages. The main stumbling block to achieve this high bit-rate is the limitation of the electronic components used in the receiver and transmitting systems. In order to utilize the large bandwidth of optical fibers, the time division multiplexing (TDM) and frequency division multiplexing (FDM) techniques borrowed from microwave communication have been used. In these techniques large number of channels separated in either time or frequency are superimposed on a single carrier to increase the capacity. These techniques have been successful at 2.5 Gbit/s (OC-48) and have been extended to 10 Gbit/s

(OC-192) at a higher cost. However using these techniques beyond this limit is extremely expensive and complex. Most of these limitations have been overcome by using a newer approach called "wavelength division multiplexing (WDM). In wavelength division multiplexing, several channels at different wavelengths are multiplexed and transmitted simultaneously over a single fiber. The bit rate in each channel is lower to meet the electronic limitations but overall bit rate is quite high due to large number of channels. As the separation between successive channels becomes very small (0.8 nm to 0.1 at 1550 nm) it is customary to use the term Dense Wavelength Division Multiplexing (DWDM) instead of WDM. This paper presents the concept of WDM/DWDM, main component requirements, system characterization, current status and future developments.

II. BASIC CONCEPT OF WDM/DWDM AND ANALYSIS

Conceptually, the wavelength division multiplexing (WDM) is same as frequency division multiplexing (FDM) used in microwave communication. One of the most important features of both the multiplexing techniques is proper spacing between channels to avoid interchannel interference. However, the wavelength separation between the channels in WDM is far greater in terms of equivalent frequency separation compared to FDM. Before going into the details of WDM systems it is important to summarize the terminology used for optical transmission rates. All the optical fiber companies in North America have set the standard signal format known as *synchronous optical network* (SONET) while in the other parts of the world the standard are known as *synchronous digital hierarchy* (SDH) [2-3]. The transmission bit rate of the basic SONET signal is 51.84 Mb/s and is generally known as STS-1 i.e. the *synchronous transport signal* level –1. All other SONET signals are integer multiples of this rate. For example, the STS-N signal has a bit rate of N times 51.84 Mb/s. It is also known as OC-N i.e. *optical carrier* level-N with proper electrical-to-optical conversion. Generally the SONET links are referred as OC-N links with N ranging from 1 to 255. However, according to the American National Standards Institute (ANSI) the values of N are: 1,3,12,24,48 and 192. According to SDH the basic rate is equivalent to STS-3 i.e. 155.52 Mb/s and is known as the *synchronous transport module*-level 1 (STM-1). The higher rates are designated as STM-M where M = 1,4,16,64 or M=3N when compared with the OC-N links. These two types of signal levels are shown in Table I.

A. Basic Concept of WDM/DWDM

Most of the performance limitations of TDM are overcome by using WDM. As stated before, a WDM system carries several optical signals each having different wavelength and respecting the data-rate limitations applicable to the transmission system. This is quite different than TDM where the data rate is increased to handle more information. The International Telecommunication Union (ITU-T) has already accepted four to sixteen channel WDM systems and 16-, 40- channel systems are now available in the market. The 40- channel system uses 100 GHz spacing in the 1530 to 1560 nm spectral range. In the beginning the channels were multiplexed in two low-loss and low dispersion windows of 1310 and 1550 nm range i.e. the separation between the channels was several tens or even hundreds of nanometers to avoid strict requirements on laser sources and receiving optical splitters. The main application of these original WDM systems was to upgrade the

Table 1: Commonly Used SONET and SDH Line Rates

SONET Level	Electrical Level	SDH Level	Line Rates (Mb/s)	Commonly used rate names
OC-1	STS-1	-	51.84	-
OC-3	STS-3	STM-1	155.52	155 Mb/s
OC-12	STS-12	STM-4	622.08	622 Mb/s
OC-48	STS-48	STM-16	2488.32	2.5 Gb/s
OC-192	STS-192	STM-64	9953.28	10 Gb/s
OC-768	STS-768	STM-256	39813.12	40 Gb/s

capacity of installed point-to-point transmission links. However, with the advent of very narrow spectral width tunable laser sources and erbium-doped fiber amplifiers (EDFA) it has become possible to multiplex two or more channels within the same spectral window generally at 1550 nm having very narrow separation. Thus the WDM links using two or more channels in 1550 nm spectral range are known as wavelength division multiplexing WDM) systems. The main features of DWDM are the capacity upgrade, transparency, wavelength routing, and wavelength switching. A block diagram of a simple DWDM link is shown in Fig.1.

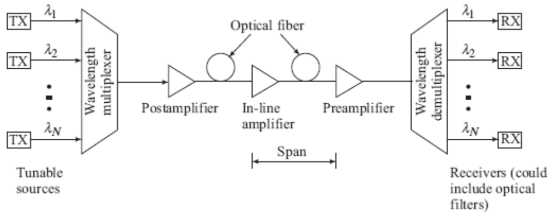

Fig.1. A DWDM link with several channels

The separation in frequency between two wavelengths in the 1310 and 1550 nm window can be obtained from the relationship $c = \lambda\nu$ with c as the speed of light, λ as the wavelength and ν as the carrier frequency. Differentiating both sides with respect to λ for $\Delta\lambda << \lambda^2$, results in

$$|\Delta\nu| = (c/\lambda^2)|\Delta\lambda| \qquad (1)$$

where the deviation in frequency $\Delta\nu$ corresponds to the wavelength deviation $\Delta\lambda$ around λ. Thus a narrow spectral width of 0.8 nm is equivalent to 100 GHz separation in frequency. Thus one can send can 50 independent signals in the 1520 to 1560 nm band on a single fiber. The channel separation of 100 GHz is not possible in simple FDM system for carrying large number of channels. This is the fundamental difference between WDM and FDM even though conceptually both are same. The main feature of DWDM is that the discrete wavelength carriers being orthogonal, can be separated, routed and switched without any interference with one another [6]. A optical transmission bandwidth in O- and C- band are shown in Fig. 2 where several 100 GHz spaced channels are obtained. The bidirectional DWDM systems also known as BWDM are being developed where optical signals travel in both the directions simultaneously thus reducing the number of fibers and amplifiers required compared to unidirectional systems. In order to avoid interference between channels, it is necessary that each optical source produces very narrow spectral components and highly stable. This requires extremely high temperature stability of optical sources. Due to this reason cooling of laser sources may become a must.

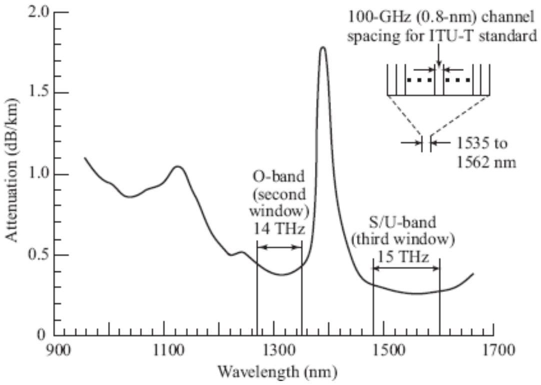

Fig.2. O- and C- band transmission windows

III. COMPONENTS AND DEVICES USED IN DWDM

The WDM/DWDM technology has already reached to a fairly matured level by now. It took over three decades for the development and perfection of various passive and active optical components used for combining, distribution, isolation and amplification of optical signals at different wavelengths. The passive components do not have much flexibility in their application for DWDM networks as they have no external control except few recent developments. On the other hand the active components have large degree of flexibility due to external electronic control. A DWDM link as shown in Fig. 1, consists of mainly the following components:

A. Optical Sources

The success of DWDM system depends on the use of multiple channels at different wavelengths and the characteristics of the laser source for each channel. It is important that the wavelengths of these sources do not change with temperature or time to avoid interference with neighboring sources. At the same time all the channels must fit into the operating band of the EDFAs used in the link. In the beginning single wavelength DFB laser sources were more common until the arrival of tunable lasers [7-10]. The tuning of these sources is done in different ways like: by varying temperature or current, wavelength tunable laser, frequency locking method, spectral slicing by optical filter etc. Fig. 3 shows the relationship between tuning range, channel spacing and spectral width. In order to avoid cross-talk between adjacent channels, the channel spacing should be 10 times the source spectral width given as,

$$\Delta\lambda_{channel} \approx 10\Delta\lambda_{signal} \tag{2}$$

and the number of channels N in the tuning range is obtained from

$$N = \frac{\Delta\lambda_{tune}}{\Delta\lambda_{channel}} \tag{3}$$

The MEMS based tuning mirrors are also being investigated for tuning cavities.

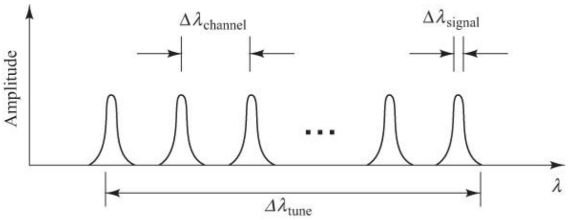

Fig.3 Relationship between various tunable wavelength parameters

B. Multiplexers and Demultiplexers

Optical tunable filters and OADM are being used for this application. The optical add/drop multiplexer (OADM) or filter combines signals from various channels at the transmitter and feeds the composite signal to the fiber link. On the other hand, a demultiplexer separates signal into various channels and feeds them to the respective receivers. The MUX/DEMUX, as generally known, has great impact on the capacity and flexibility of DWDM system and is a very critical element of the optical link. A simple OADM using MEMS mirrors is shown in Fig. 4.

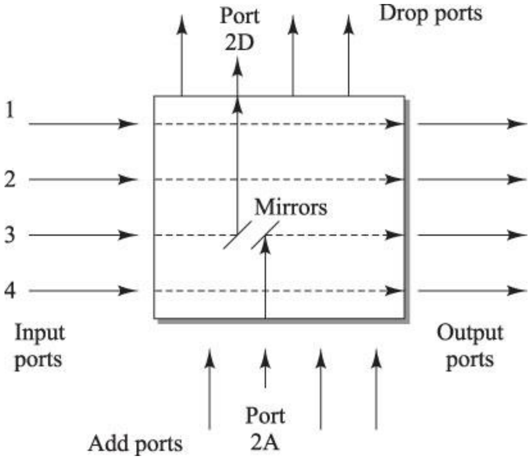

Fig. 4. A 4-Channel OADM with switching mirrors

Lately two and three-dimensional acousto-optic cell array (AOCA) based MUX/DEMUX or OADMs have been proposed [11-12]. In these systems the acoustic signals are used to create refractive index variation in anisotropic materials like $LiNbO_3$ or InP, thus diffracting incident light wavelengths in different directions. The acoustic signals are generated from an RF source using a transducer. The main advantage of this system is the variation in diffraction directions due to variation in RF signal frequency and power both.

The other devices which have been used for MUX/DEUX applications are phased array arrayed-waveguide grating devices, tunable optical filters, diffraction grating devices, fiber

Bragg gratings (FBG) and MOEMS mirror based devices [13- 19]. The multiplexing of 4 wavelengths using FBG and circulators is shown in Fig. 5

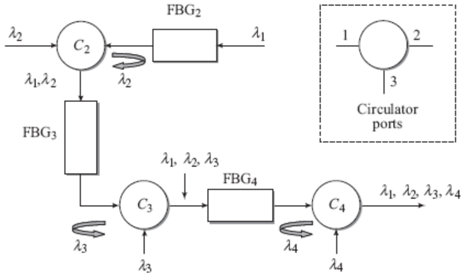

Fig.5. Four wavelength FBG multiplexer with circulators

C. Erbium-Doped Fiber Amplifiers (EDFA)

The erbium-doped fiber amplifiers have become quite popular in a short span of time due to their ability to amplify light signals directly [20-21]. They can provide low-noise amplification over a range of wavelengths and have become an integral part of today's DWDM links. The amplifier consists of a 10-to-30 m long silica fiber with light doping of erbium (Er) so that it can convert energy from separately provided pump radiation to the incoming optical signal through population inversion like in laser sources. The operating range of an EDFA is limited to 1530 to 1560 nm region, which is close to 1550 nm low-loss region and is enough for many distinct DWDM channels. The main advantage of EDFA is that they can amplify multiple optical channels so far as the bandwidth of the multichannel signal is less than the amplifier bandwidth, which is 1 to 5 THz. A pump laser provides energy for amplification at erbium absorption peaks at 980 or 1480 nm through DWDM coupler as shown in Fig. 11. This coupler combines the signal and the pump power. Isolators are provided at the input and output of the coupler to avoid any instability due to reflected signals. The *amplifier gain* or signal gain G is an important parameter and is achieved through population inversion in EDFA by injecting a minimum pump power level. If the pump power is less than this value, the large signal power drives the amplifier into saturation and the required signal gain is not achieved. On the other hand the *noise gain* is the gain due to a small signal having no impact on the amplifier operating point. A simple EDFA for DWDM application is shown in Fig.5.

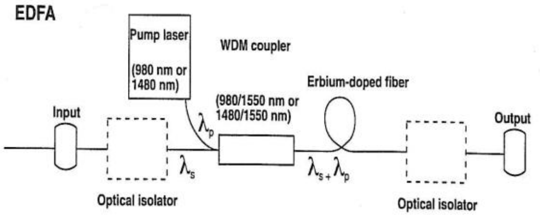

Fig.6. EDFA with pump laser source and DWDM coupler

The main noise in the amplifier is the *amplified spontaneous emission* (ASE) noise due to spontaneous recombination of electrons and holes in the amplifier medium. This noise gets amplified along with the signal. In a long optical fiber link a chain of EDFAs are used to restore the power level as it decreases due to fiber attenuation. The gain of each EDFA must be able to compensate for the losses in the preceding fiber section. In this case the accumulated ASE noise is the main degradation factor requiring linear increase in the signal power to maintain constant signal-to-noise ratio. Other important parameters of an EDFA are: *profile, channel gain, gain tilt* and *gain flatness.* The term *profile* refers to the wavelength dependence of a particular property like gain is a wavelength dependent parameter. Another important property of the EDFAs is the absence of interchannel crosstalk if the channel spacing is greater than 10 kHz, which is the practical situation in DWDM. This property make them very suitable for multichannel amplification provided the pump power in the coupler is maintained above the minimum required value as discussed before**.**

D. Optical Fiber

Optical fiber is one of the most important components of the entire DWDM link. It is supposed to carry optical signals in all the channels from one point to another with minimum possible loss and dispersion. From this perspective it is necessary to investigate some non-linear phenomena like *stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS)* and *four-wave mixing* occurring in the fiber. The SBS is the strongest nonlinear phenomenon in optical fiber. The interaction between strong electric field of laser beam and fiber material results into backscattering of optical signal. This backscattered light is not only the loss of the main signal but may interfere with the source output thus causing phase shift or wavelength variation of the main signal. This is dominant in the case of high power (> 5 dBm) and narrow bandwidth channels (BW< 20 MHz). The SRS is also the result of the interaction between transmitted light signal and fiber material causing a shift of power from shorter (higher energy) to longer (lower energy) wavelengths. This results in an amplitude tilt in the spectrum. However, it is not so severe in DWDM systems due to high threshold value. In four-wave mixing when the power level is high, two or more optical signals in a fiber mix in a nonlinear fashion and produce new optical frequency components, which extract energy from the main signal. At the same time these new components may interfere with a channel signal. This effect can be reduced by increasing channel spacing, by using unequal channel spacing or using a fiber with proper chromatic dispersion. Non-zero dispersion fibers have been developed to eliminate four-wave mixing effects at 1550 nm. In non-zero dispersion fibers, a small controlled amount of chromatic dispersion is introduced over the 1530-1565 nm band just enough to suppress the four-wave mixing effects and still allowing proper transmission over 1000 km distance. This is preferred fiber DWDM application.

Other optical components like attenuators, filters, switches, isolators, circulators, dispersion compensation devices, star couplers, wavelength dependent couplers are equally important but cannot be discussed in detail due to page limitations. These components are being discussed during the presentation.

IV. SYSTEM CHARACTERIZATION AND STANDARDS

For proper design of DWDM links and networks, several factors like bandwidth, power requirements according to specific BER, crosstalk between channels and performance limitations due to nonlinear effects, are to be considered.

A. Link Bandwidth

As we have seen that by using DWDM, large number of channels can be transmitted which in turn increases the total bit rate by a factor of N for N-channel system compared to a single-channel link. For an 8-channel system DWDM link having 2.5 Gb/s as each channel bandwidth, the total bandwidth is 20 Gb/s and for 40 channels system the overall bandwidth is 100 Gb/s. Total capacity of a DWDM link is decided by the channel spacing within the transmission window. According to ITU-T standards the spacing between two adjacent channels has been suggested as 100 GHz or 0.8 nm with central frequency as 193.100 THz or 1552.524 nm with entire wavelength range from 1537 to 1563 nm. Other suggested spacings between channels are 50 GHz (1.6 nm) and 200 GHz (0.4 nm) with wavelength drift tolerance of ± 0.02.

B. Power Requirements for Specific BER

The stringent requirements on DEMUX compared to a MUX, the parameters of prime importance at the DEMUX output are: signal level, noise level and crosstalk. The bit error rate (BER) of a DWDM system is determined from optical signal-to-noise ratio (SNR) at the photodetector. Accurate determination of BER would be helpful in determining the required optical power from the source, number of EDFAs needed over the entire link and tolerable fiber attenuation between two optical amplifiers. For practical systems, with 3 to 6 dB system margin, SNR in the range of 18 to 20 dB is necessary.

C. Interchannel Cross Talk

In DWDM the channel spacing is very small resulting into crosstalk i.e. filtering of the signal from one channel to another channel [22]. Fiber, optical filters, MUX/DEMUX, optical switches and optical amplifiers can introduce the crosstalk in a DWDM system. The nonlinear effects in the fiber contribute to the fiber crosstalk. In a DWDM link both the interchannel and intrachannel crosstalks may occur which degrade the system performance.

D. New Standards for DWDM Systems

The emergence of standards for any new technology is a sign of significant growth of that technology. Just a few years back the DWDM systems were growing without any international standards. The standards provide guidance to the manufacturers on the most promising areas for future product development. At the same time, adherence to standards permits systems from different service-providers, using equipment from different suppliers and serving different base needs with relative ease. The international standards in the telecommunication field are defined mainly by two organizations. The International Telecommunication Union (ITU) based in Geneva with a focus on application standards and the International Electrotechnical Commission (IEC), are mainly concerned with the definition of product standards. These agencies work closely with regional or major national standardization bodies like TIA/EIA (USA), ETSI (Europe) and TTC (Japan).

V. FUTURE TECHNOLOGIES UNDER INVESTIGATION

The main focus of continuous development and advancement in DWDM technology is the flexibility, increasing capacity and lately its modification for LAN and MAN applications. The development of existing technology and search for newer technologies involving soliton signals and combination of high-speed TDM with DWDM are currently underway. At the same time the development 100 Gb/s single fiber DWDM systems in underway. The main modulation technique being investigated for such a high speed systems is coherent polarization multiplexed quadrature phase shift keying (C-PM-QPSK) [23]. Also, the effect of nonlinearities has to be reduced to the minimum to achieve higher channel rates. For improving end-to-end fidelity of optical signals, forward error correction (FEC) technique of transmitting redundant information, is being investigated. This requires proper coding/decoding of the signals. In order to provide a higher degree of flexibility to DWDM systems, high quality optical cross-connects are being developed. In case of failure or congestion in one part of the network, the cross-connects would divert the transmission to other parts or wavelengths. In order to increase the capacity or to have repeaterless transmission in DWDM links, the dispersion-controlled soliton transmission is being experimented. This would require precise link-design and monitoring of soliton performance.

VI. CONCLUSION

This paper summarizes the basic concept of DWDM, optical components used and present and future technologies with the help of some very useful and up-to-date references. The key to the future success of DWDM technology is the flexibility, the ability to reconfigure network services and to increase bandwidth without recabling or redesigning existing networks. It is unlikely that the quest for higher network capacity will stop at 2 Tb/s, thus forcing the development of more impressive system performance, better components and faster networks.

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