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Tutorial Paper

A Review of WDM Technology and Applications

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The rapid growth in demand for high-capacity telecommunication links, and the speed limitation of single-wavelength links, has resulted in an extraordinary increase in the use of wavelength-division multiplexing (WDM) in advanced lightwave networks. In this work we review the basic concepts of WDM, describe its key features and why network providers are using it, review the enabling technologies, discuss the basic operating characteristics and their associated parameters, and show how WDM is being used worldwide in both terrestrial and undersea installations. Included in this are discussions on management functions that are needed for monitoring the status and health of WDM networks.

1. INTRODUCTION

A powerful aspect of an optical fiber communication link is that many different wavelengths carrying independent signal channels can be sent along a single fiber simultaneously. In particular, telecommunication service providers are using this feature in the low-loss 1300-to-1600-nm spectral region of optical fibers. The technology of combining a number of wavelengths onto the same fiber is known as *wavelength-division multiplexing*, or WDM [1–4]. Conceptually, the WDM scheme is the same as frequency-division multiplexing (FDM) used in microwave radio and satellite systems. Just as in FDM, the various wavelength channels (or optical frequencies) in WDM must be properly spaced to avoid interchannel interference.

The purpose of this paper is to give a comprehensive overview of WDM technology and its applications. We first describe in Section 2 the basic concepts of WDM and discuss what standards are being developed for its implementation. In Section 3 we describe the key features of WDM and why transmission-system

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providers are using it. To understand how it is deployed, in Section 4 we review the enabling technologies that make WDM feasible. Next, Section 5 discusses the basic operating characteristics of WDM links, such as number of wavelengths, channel speed, optical power requirements to achieve a specific bit error rate, and performance limitations due to linear and nonlinear effects.

Using these configurations, we show in Section 6 how WDM is being used worldwide in both terrestrial and undersea installations. Included in this are discussions on management functions that are needed for monitoring the status and health of WDM networks. There is still the potential for substantial growth in both WDM technology and applications. In this context, WDM soliton transmission and the synergy of WDM with very high-speed time-division multiplexing (TDM) are the concluding topics in Section 7.

2. WHAT IS WDM?

Before looking at the benefits of WDM, let us first consider some terminology for transmission rates. With the advent of fiber-optic transmission lines, service providers established a standard signal format called *synchronous optical network* (SONET) in North America and *synchronous digital hierarchy* (SDH) in other parts of the world [5, 6]. The transmission bit rate of the basic SONET signal is 51.84 Mb/s. This is called an STS-1 signal, where STS stands for *synchronous transport signal*. All other SONET signals are integer multiples of this rate, so that an STS-N signal has a bit rate equal to N times 51.84 Mb/s. After undergoing electrical-to-optical conversion and being scrambled for efficient line transmission, the resultant *physical-layer optical signal* is called OC-N, where OC stands for *optical carrier*. In practice, it has become common to refer to SONET links as OC-N links. Algorithms have been developed for values of N ranging from 1 and 255. However, in the range from 1 to 192, the American National Standards Institute (ANSI) T1.105 SONET standard only recognizes the values $N = 1, 3, 12, 24, 48$, and 192.

In SDH the basic rate is equivalent to STS-3, or 155.52 Mb/s. This is called the *synchronous transport module—level 1* (STM-1). Higher rates are designated by STM-M. Values of M supported by the International Telecommunication Union—Telecommunications (ITU-T) recommendations are $M = 1, 4, 16$, and 64. These are equivalent to SONET OC-N signals, where $N = 3M$ (i.e., $N = 3, 12, 48$, and 192). This shows that to maintain compatibility between SONET and SDH, in practice N is a multiple of three. In contrast to SONET, SDH does not distinguish between a logical electrical signal (e.g., STS-N in SONET) and a physical optical signal (e.g., OC-N), so that both signal types are designated by STM-M. Table 1 lists commonly used values of OC-N and STM-M.

In standard simplex point-to-point optical links, a single fiber line has one light source at its transmitting end and one photodetector at the receiving end, as Fig. 1a shows [7]. If we assume that this line has a capacity of 2.5 Gb/s, then by electrically multiplexing together 16 STM-1 SDH or OC-3 SONET data streams operating at 155 Mb/s and using this electrical signal to modulate a laser diode,

TABLE 1
Commonly Used Values of OC-*N* and STM-*M*

SONET level	Electrical level	Line Rate (Mb/s)	SDH equivalent
OC-1	STS-1	51.84	—
OC-3	STS-3	155.52	STM-1
OC-12	STS-12	622.08	STM-4
OC-24	STS-24	1244.16	STM-8
OC-48	STS-48	2488.32	STM-16
OC-96	STS-96	4976.64	STM-32
OC-192	STS-192	9953.28	STM-64

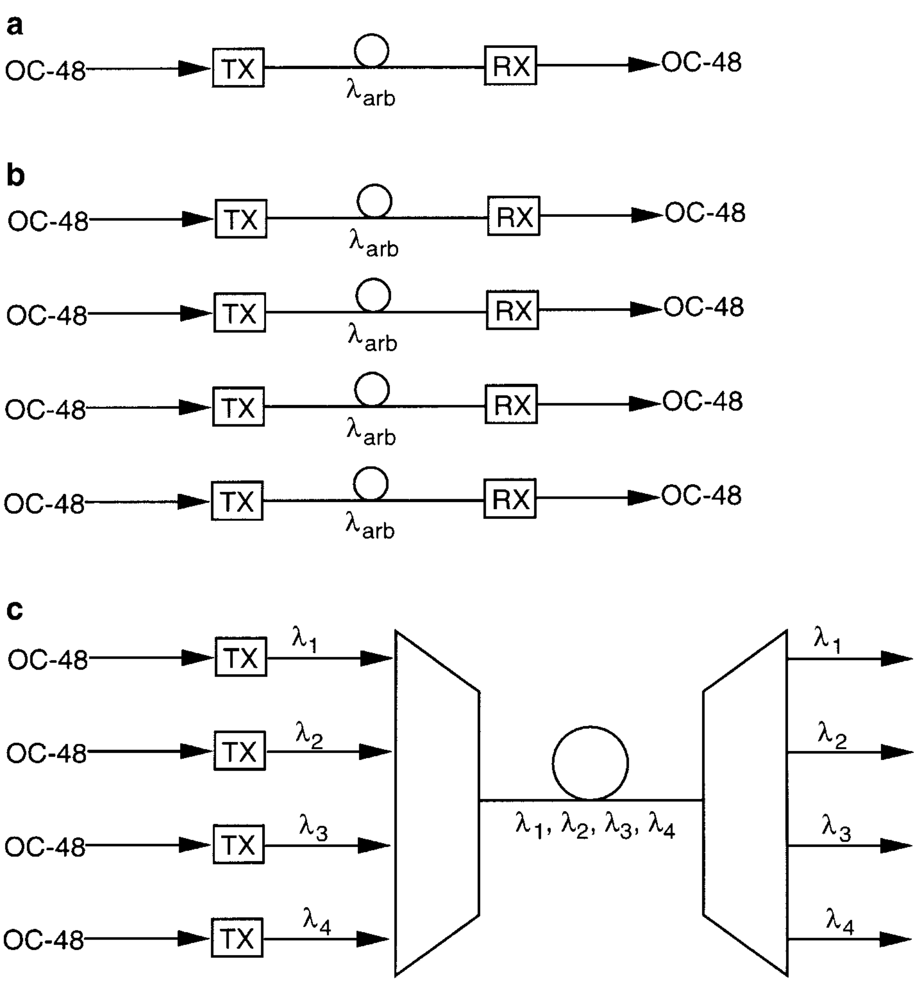

FIG. 1. Progress in increasing link capacity: (1) standard simplex point-to-point optical links; (b) space-division multiplexing of four channels; (c) wavelength-division multiplexing of four channels.

one can send these signals in an optical format over this fiber. With simplex links, signals from different light sources use separate and uniquely assigned optical fibers. To increase the number of OC-3 channels to 64 without going to WDM would require four separate single-wavelength fibers, as illustrated in Fig. 1b. Such a setup is traditionally called *space-division multiplexing*. However, with WDM one can use four independent and appropriately spaced wavelengths to send the 64 OC-3/STM-1 channels over the same fiber, as shown in Fig. 1c.

To see the potential of WDM, let us first examine the characteristics of a high-quality optical source. As an example, a distributed-feedback (DFB) laser has a very narrow frequency spectrum on the order of 1 MHz, which is equivalent to a spectral linewidth of 10^{-5} nm. When using such a source, a guard band of 0.4–1.6 nm is typically employed. This is done to take into account possible drifts of the peak wavelength due to aging or temperature effects, and to give both the manufacturer and the user some leeway in specifying and choosing the precise peak emission wavelength. With these type of spectral-band widths, simplex systems make use of only a very small portion of the transmission bandwidth capability of a fiber. This can be seen from Fig. 2, which depicts the attenuation of light in a silica fiber as a function of wavelength. The curve shows that the two low-loss regions of a single-mode fiber extend over the wavelengths ranging from about 1270 to 1350 nm (the 1310-nm window) and from 1480 to 1600 nm (the 1550-nm window).

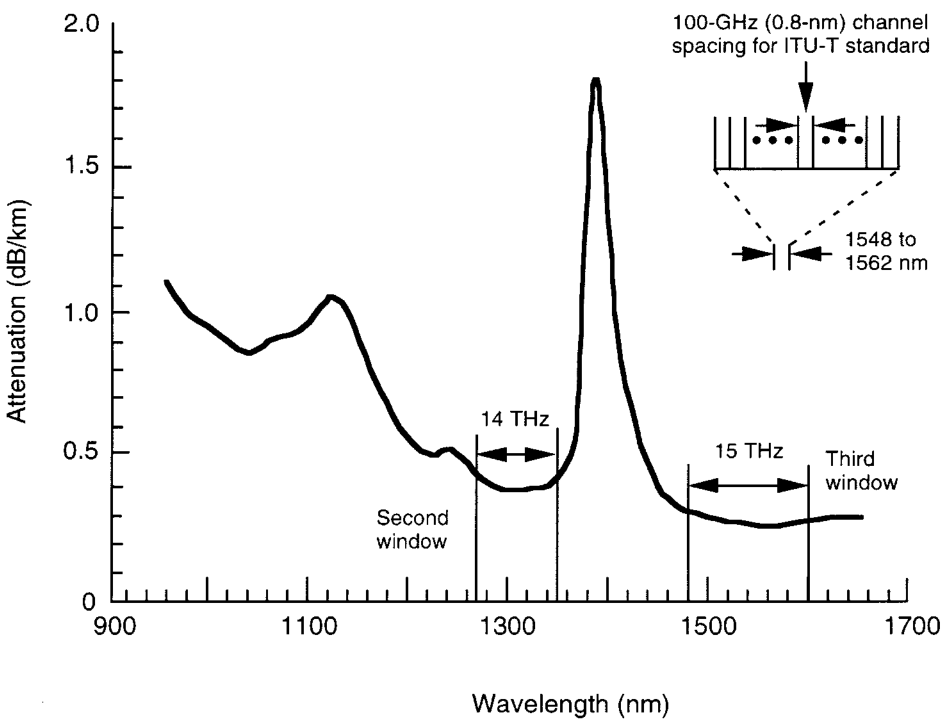

FIG. 2. Attenuation of light in a silica fiber as a function of wavelength.

We can view these regions either in terms of spectral width (the wavelength band occupied by the light signal and its guard band) or by means of optical bandwidth (the frequency band occupied by the light signal). To find the optical bandwidth corresponding to a particular spectral width in these regions, we use the fundamental relationship $c = \lambda\nu$, which relates the wavelength λ to the carrier frequency ν, where c is the speed of light. Differentiating this we have

$$|\Delta\nu| = \left(\frac{c}{\lambda^2}\right)|\Delta\lambda|, \qquad (1)$$

where the deviation in frequency $\Delta\nu$ corresponds to the wavelength deviation $\Delta\lambda$ around λ. From Eq. (1) the optical bandwidth is $\Delta\nu = 14$ THz for a usable spectral band $\Delta\lambda = 80$ nm in the 1310-nm window. Similarly, $\Delta\nu = 15$ THz for a usable spectral band $\Delta\lambda = 120$ nm in the 1550-nm window. This yields a total available fiber bandwidth of about 30 THz in the two low-loss windows.

Since the spectral width of a high-quality source occupies only a narrow optical bandwidth, the two low-loss windows provide many additional operating regions. By using a number of light sources, each emitting at a different peak wavelength that is sufficiently spaced from its neighbor so as not to create interference, the integrities of the independent messages from each source are maintained for subsequent conversion to electrical signals at the receiving end. For example, if one takes a spectral band of 0.8 nm (or, equivalently, a frequency band of 100 GHz) within which a narrow-linewidth laser is transmitting, then one can send 50 independent signals in the 1530-to-1560-nm band on a single fiber. This is the basis of WDM.

The literature and product descriptions often use the term *dense WDM*, in contrast to conventional or regular WDM. This term does not denote a precise operating region or implementation condition, but instead is a historically derived designation. The original use of WDM was to upgrade the capacity of installed point-to-point transmission links. Typically, this was achieved by adding wavelengths separated by several tens, or even hundreds, of nanometers, in order not to impose strict requirements on the different laser sources and the receiving optical wavelength splitters. With the advent of tunable lasers having extremely narrow linewidths in the late 1980s, one then could have very closely spaced signal bands. This was the origin of the term “dense WDM” [8, 9].

A key feature of WDM is that the discrete wavelengths form an orthogonal set of carriers which can be separated, routed, and switched without interfering with one another [10−16]. This holds as long as the total optical power intensity is kept sufficiently low to avoid nonlinear effects such as stimulated Brillouin scattering (SBS) and four-wave mixing (FWM) processes from degrading the link performance [17−20].

Since WDM is essentially frequency-division multiplexing at optical carrier frequencies, the WDM standards developed by the ITU specify channel spacings in terms of frequency [21−23]. The ITU-T Recommendation G.692 specifies selecting the channels from a grid of frequencies referenced to 193.100 THz (1552.524 nm in glass) and spacing them 100 GHz (0.8 nm at 1552 nm) apart. Suggested alternative spacings include 50 GHz (0.4 nm) and 200 GHz (1.6 nm).

Although currently WDM is being deployed mainly for point-to-point applications for relieving link-capacity exhaustion, the potential for using WDM in optical networking has been recognized. Consequently, an extensive standardization effort is underway to merge WDM into optical networks. Emerging ITU-T recommendations aimed at all aspects of optical networking include the following:

1. *Recommendation G.ons* includes definitions of optical-layer overheads for functions such as supervision of the transport wavelengths.

2. *Recommendation G.oeg* describes the types and general characteristics of optical network elements.

3. *Recommendation G.oef* gives the functional characteristics of optical network elements.

4. *Recommendation G.onc* addresses transmission aspects of components and subsystems, such as add/drop multiplexers and optical cross-connects.

5. *Recommendation G.oni* describes information models for optical network elements.

6. *Recommendation G.onp* addresses point-to-point WDM systems optimized for long-haul transport.

7. *Recommendation G.onm* deals with management of optical network elements.

8. *Recommendation G.onf* outlines the links between the various recommendations and the rationale followed in preparing them.

9. *Recommendation G.onr* addresses requirements on the maximum number of cascaded WDM network elements, error performance, and jitter performance for SONET/SDH paths, PDH/SDH paths, and other emerging digital client signals of the optical transport network. PDH is the plesiochronous digital hierarchy, which refers to the three quasi-synchronous signal hierarchies used in North American, European, and Japanese digital networks.

3. WHY USE WDM?

After languishing for many years as an interesting technology without a cost-effective application, wavelength-division multiplexing started playing a major role in telecommunications networks in the early 1990s. This resulted from the surge in demand for high-capacity links and the limitation of the installed fiber plant in handling high-rate optical signals over any substantial distance [24–28]. This limitation led to a rapid capacity exhaustion of long-haul fiber networks.

Since installing an optical fiber cable plant is both expensive and extremely time consuming, expanding the capacity of an installed network is economically attractive. Traditionally, carriers upgraded their link capacity by increasing the transmission rate. This worked well initially, with speeds eventually reaching 2.5 Gb/s (SONET OC-48 or SDH STM-16). Transmission systems operating at these rates have been on the market since 1991 and are now standard SONET/SDH building blocks. However, when going to the next multiplexing level of 10 Gb/s (OC-192), one starts to encounter effects that can seriously degrade WDM network performance. Among these effects are

(1) fiber chromatic dispersion, which limits the bit rate by temporally spreading a transmitted optical pulse;

(2) nonuniform gain across the desired wavelength range in erbium-doped fiber amplifiers (EDFAs);

(3) inelastic scattering processes such as stimulated Raman scattering (SRS) and SBS, which are interactions between optical signals and molecular or acoustic vibrations in a fiber;

(4) nonlinear processes in a fiber that arise from modulation of the refractive index of silica by intensity changes in the signal, thereby producing effects such as FWM, self-phase modulation (SPM), and cross-phase modulation (CPM);

(5) polarization mode dispersion, which arises from orthogonal polarization modes traveling at slightly different speeds owing to fiber birefringence;

(6) Reflections from splices and connectors that can cause instabilities in laser sources.

New fiber designs, special dispersion-compensation techniques, and optical isolators can mitigate these limitations, and newly installed links are operating very well at 10 Gb/s rates per wavelength. However, a large portion of the older installed fiber base is limited to OC-48 rates (2.5 Gb/s) at a given wavelength. Thus, a great interest has been established in using WDM, not only for older links but also to have very high-capacity new links. Section 5.4 gives some details on performance limitations in WDM networks.

4. ENABLING TECHNOLOGIES

Although the concepts for WDM started being explored in the laboratory more than two decades ago, the enabling technology for the cost-effective implementation of WDM was the creation and perfection of various passive and active optical components used to combine, distribute, isolate, and amplify optical powers at different wavelengths. Passive devices require no external control for their operation, so they are somewhat limited in their application in WDM networks. These components are mainly used to split and combine or tap off optical signals. The performance of active devices can be controlled electronically, thereby providing a large degree of network flexibility. Active WDM components include tunable optical filters, tunable sources, and optical amplifiers.

Figure 3 shows the implementation of such components in a typical WDM link. At the transmitting end there are several independently modulated light sources, each emitting signals at a unique wavelength. Here a *multiplexer* is needed to combine these optical outputs into a continuous spectrum of signals and couple them onto a single fiber. At the receiving end a *demultiplexer* is required to separate the optical signals into appropriate detection channels for signal processing. At the transmitter the basic design challenge is to have the multiplexer provide

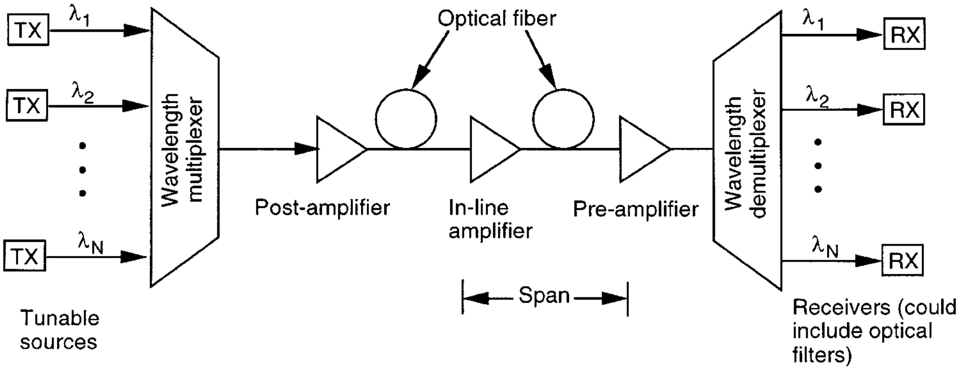

FIG. 3. Implementation of a typical WDM link.

a low-loss path from each optical source to the multiplexer output. Since the optical signals that are combined generally do not emit any significant amount of optical power outside of the designated channel spectral width, interchannel cross-talk factors are relatively unimportant at the transmitting end.

A different requirement exists for the demultiplexer, since photodetectors are usually sensitive over a broad range of wavelengths, which could include all the WDM channels. To prevent spurious signals from entering a receiving channel, that is, to give good channel isolation of the different wavelengths being used, the demultiplexer must exhibit narrow spectral operation or very stable optical filters with sharp wavelength cutoffs must be used. The tolerable interchannel cross-talk levels can vary widely depending on the application. In general, a -10-dB level is not sufficient, whereas a level of -30 dB is acceptable. In principle, any optical demultiplexer can also be used as a multiplexer. For simplicity, the word "multiplexer" is used as a general term to refer to both combining and separating functions, except when it is necessary to distinguish the two devices or functions.

The multiplexers can be either passive or active devices. Since active devices are highly versatile in WDM applications, we shall devote more attention to these components here. This section first looks at basic and advanced passive WDM multiplexers in Sections 4.1 and 4.2, respectively. Active WDM components, such as tunable optical filters, give more versatility in extracting or inserting one or more wavelengths. These devices are discussed in Section 4.3. Tunable optical sources can be used to generate the spectrum of wavelengths needed for WDM, as Section 4.4 shows. Finally, in long transmission distances optical amplifiers are incorporated into the link to boost the power level of a wide band of wavelengths simultaneously. This is the topic of Section 4.5.

4.1. Basic Passive WDM Devices

Passive devices operate completely in the optical domain to split and combine light streams. They include $N \times N$ couplers (with $N \geq 2$), power splitters, power taps, and star couplers. These components can be fabricated either from optical fibers or by means of planar optical waveguides using material such as lithium niobate ($LiNbO_3$) or InP.

Basically most passive WDM devices are variations of a star-coupler concept. Figure 4 shows a generic star coupler, which can perform both power combining and splitting. In the broadest application, star couplers combine the light streams from two or more input fibers and divide them among several output fibers. In the general case, the splitting is done uniformly for all wavelengths, so that each of the N outputs receives $1/N$ of the power entering the device. A common fabrication method for an $N \times N$ splitter is to fuse together the cores of N single-mode fibers over a length of a few millimeters. The optical power inserted through one of the N fiber entrance ports is divided uniformly into the cores of the N output fibers through evanescent power coupling in the fused region.

Any size star coupler can be made in principle, provided that all fibers can be heated uniformly during the coupler-fabrication process. Couplers with 64 inputs and outputs are possible, although more commonly the size tends to be less than 10. One simple device is a power tap. Taps are nonuniform 2×2 couplers which are used to extract a small portion of optical power from a fiber line for monitoring signal quality.

4.2. *Advanced WDM Multiplexers*

Wavelength multiplexers are specialized devices that combine a number of optical streams at distinct wavelengths and launch all their powers in parallel into a single fiber channel. This combination need not be uniform for all wavelengths; that is, one may want to combine 50% of the power from one wavelength, 75% from another source, and 100% from other wavelengths. However, for WDM applications it is usually desirable that the multiplexers combine the optical powers from multiple wavelengths onto a single fiber with little loss. Wavelength demultiplexers divide a composite multichannel (multiwavelength) optical signal into different output fibers according to wavelength without splitting loss. This section describes a phased-array-based WDM multiplexer and a fiber-grating multiplexer as examples of such components.

Phased-Array-Based WDM Multiplexer. A highly versatile passive WDM device is based on using an arrayed waveguide grating [29, 30]. This device can function as a multiplexer, a demultiplexer, an add/drop element, or a wavelength router. A

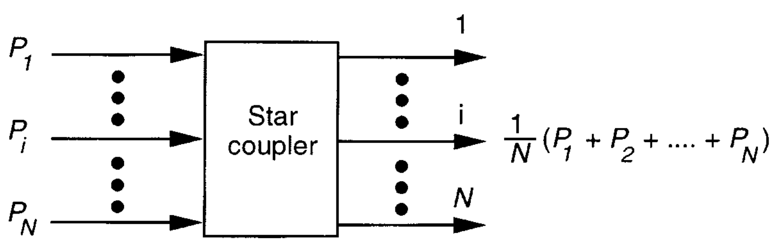

FIG. 4. Basic star-coupler concept.

variety of design concepts have been examined. The arrayed waveguide grating is a generalization of the 2 × 2 Mach–Zehnder interferometer multiplexer. One popular design consists of M_{in} input and M_{out} output slab waveguides and two identical focusing planar star couplers connected by N uncoupled waveguides with a propagation constant β. The lengths of adjacent waveguides in the central region differ by a constant value ΔL, so that they form a Mach–Zehnder–type grating, as Fig. 5 shows. For a pure N-to-1 multiplexer, we can take $M_{\text{in}} = N$ and $M_{\text{out}} = 1$. The reverse holds for a 1-to-N demultiplexer, that is, $M_{\text{in}} = 1$ and $M_{\text{out}} = N$. In the case of a network routing application where any input can be sent to any output, we can have $M_{\text{in}} = M_{\text{out}} = N$.

Fiber-Grating WDM Multiplexer. A fiber grating is another useful device that can be used as a multiplexer, a demultiplexer, or an add/drop element [31–33]. Since this is an all-fiber device, its main advantages are low cost, low loss (around 0.1 dB), ease of coupling with other fibers, polarization insensitivity, low temperature coefficient (< 0.7 pm/°C), and simple packaging. Fabrication of these devices is based on the inherent photosensitivity of conventional germanium-doped silica fibers. By using a pair of ultraviolet beams, a permanent periodic variation in the refractive index is created in the fiber. This is the fiber grating. When a wavelength satisfying the Bragg condition encounters the grating, the energy from this wave is reflected and all others pass through the device with low loss.

Figure 6 shows a simple concept of a demultiplexing function. To extract the desired wavelength, a circulator is used in conjunction with the grating. In a three-port circulator, an input signal on one port exits at the next port. For example, an input signal at port 1 is sent out at port 2. Here the circulator takes the four wavelengths entering port 1 and sends them out port 2. All wavelengths except λ_2 pass through the grating. Since λ_2 satisfies the Bragg condition of the grating, it is reflected, enters port 2 of the circulator, and exits at port 3. More complex multiplexing and demultiplexing structures with several gratings and several circulators can be realized with this scheme.

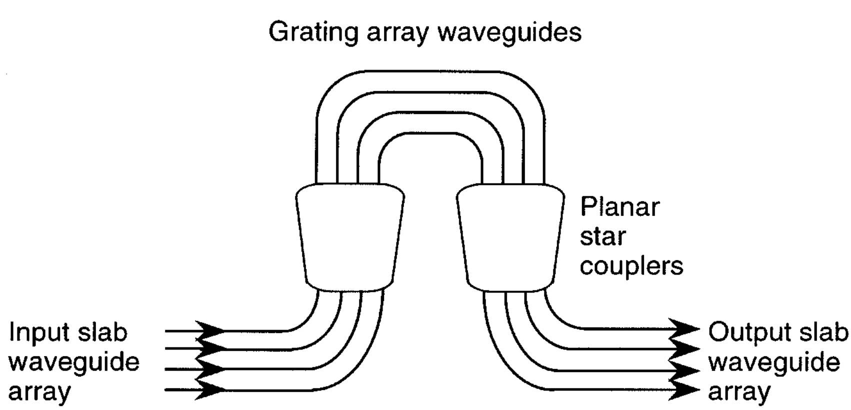

FIG. 5. Arrayed waveguide grating used as a highly versatile passive WDM device.

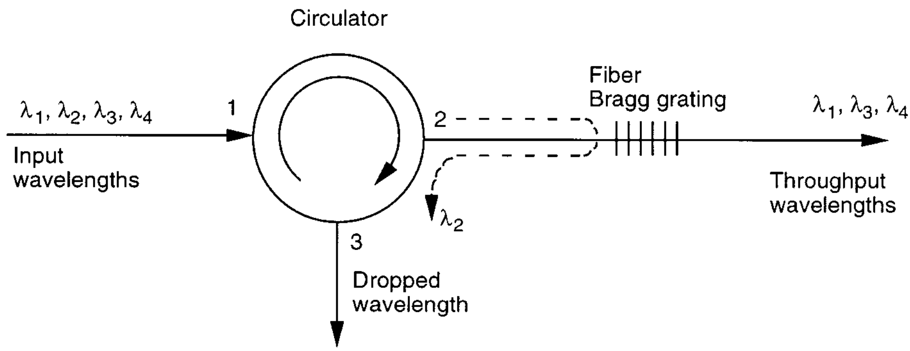

FIG. 6. Simple concept of a demultiplexing function using a fiber grating and a circulator.

4.3. Tunable Optical Filters

Optical filters that are dynamically tunable over a certain optical frequency band can be used to increase the flexibility of a WDM network. Most tunable optical filters operate on the same principles as used in passive devices. The main difference is that in active devices, at least one branch of the coupler can have its length or refractive index slightly altered by means of a control mechanism such as a voltage or temperature change. This allows the network operator to select specific optical frequencies to pass through the filter [34].

Figure 7 shows the basic concept of a tunable optical filter. Here the filter operates over a frequency range Δf and is electrically tuned to allow only one

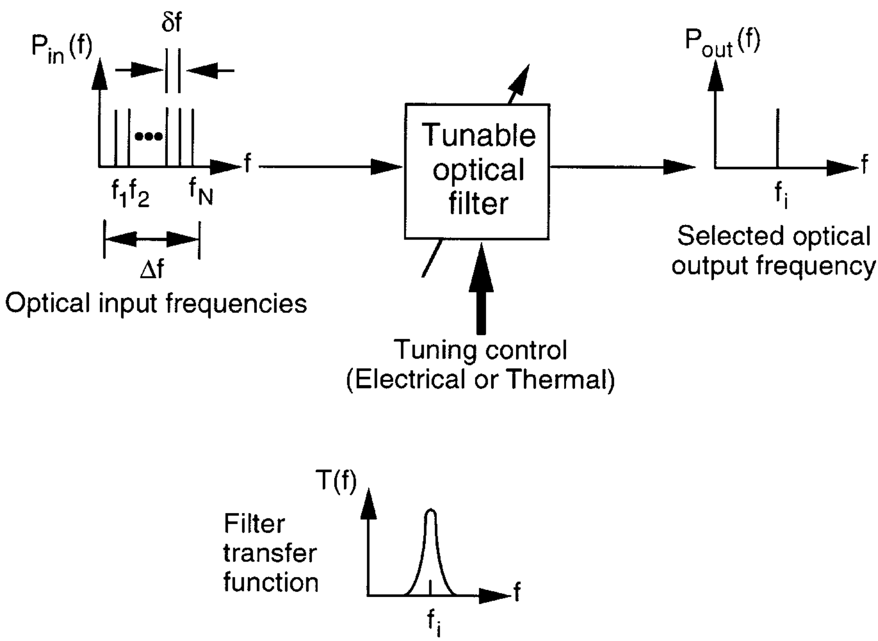

FIG. 7. Basic concept of a tunable optical fiber.

optical frequency band to pass through it. The relevant system parameters include the following:

(1) The *tuning range* Δf over which the filter can be tuned. If the filter needs to be tuned over one of the long-wavelength transmission windows at 1300 or 1550 nm, then 25 THz (or $\Delta\lambda = 200$ nm) is a reasonable tuning range. In networks using fiber-based optical amplifiers, which are addressed in Section 4.5, a maximum range of $\Delta\lambda = 35$ nm centered at 1550 nm (or $\Delta f = 4.4$ THz centered at about 193.1 THz) is adequate.

(2) The *channel spacing* δf, which is the minimum frequency separation between channels that is required to guarantee a minimum crosstalk degradation. The crosstalk signal level from an adjacent channel should generally be about 30 dB below the desired signal in order to have adequate system performance.

(3) The *maximum number of channels* N, which is the maximum number of equally spaced channels that can be packed into the tuning range while maintaining an adequately low level of crosstalk between adjacent channels. This is defined as the ratio of the total tuning range Δf to the channel spacing δf, that is,

$$N = \frac{\Delta f}{\delta f}. \tag{2}$$

(4) The *tuning speed*, which designates how quickly the filter can be reset from one frequency to another. For applications where a channel is left set up for a relatively long time (minutes to hours), a millisecond tuning speed is sufficient. However, if one wants to switch information packets rapidly, then submicrosecond tuning times are required. For example, at a 2.5 Gb/s channel rate, the time to transmit a 500-bit packet is only 0.2 μs.

Many technologies have been examined for creating tunable optical filters. During the evolution of WDM methodologies, interest has moved toward systems having fixed wavelength spacings with channel separations that are multiples of 100 GHz (or 0.8 nm in the 1550-nm transmission window). Tunable optical filters for which $\delta f \leq 100$ GHz include 2×2 directional couplers [35], Mach–Zehnder interferometers [36, 37], fiber-based Fabry–Perot filters [38, 39], waveguide arrays [40, 41], liquid crystal Fabry–Perot filters [42, 43], multigrating filters [44, 45], and acousto-optic tunable filters [46, 48]. Here we describe three common tunable filter types.

Tunable 2×2 *directional couplers* can be constructed by having multiple control electrodes placed on the coupling waveguides. Figure 8 illustrates a multielectrode directional coupler fabricated on a $LiNbO_3$ crystal. For a wavelength-dropping application in this device, M wavelengths enter input port 1. Applying a specific voltage to the electrodes changes the refractive index of the waveguides, thereby selecting one of the wavelengths, say λ_i, to be coupled to the second waveguide, so that it exits from port 4. The remaining $M - 1$ wavelengths pass through the device and leave from port 3.

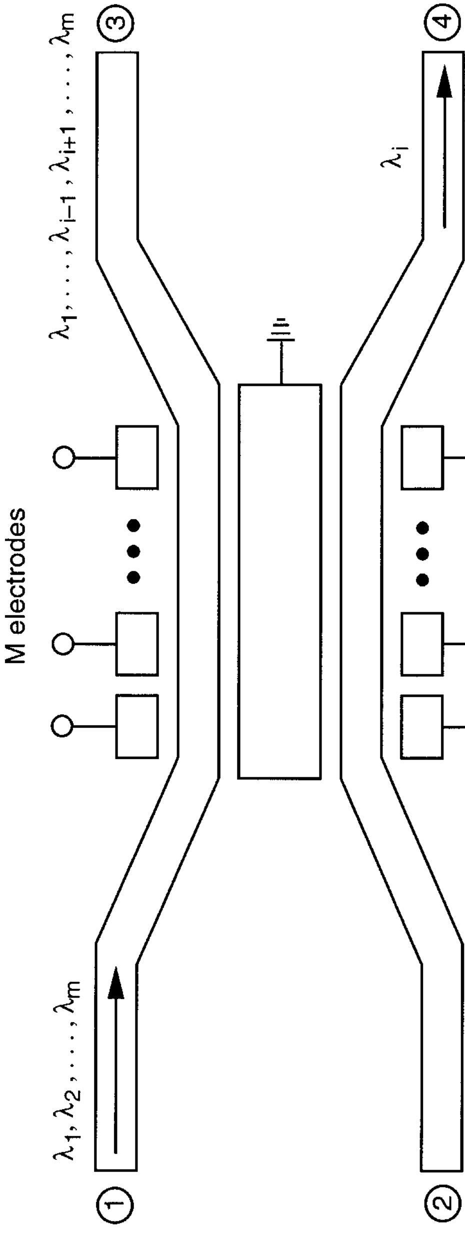

FIG. 8. A multielectrode directional coupler fabricated on a $LiNbO_3$ crystal.

To insert a wavelength and combine it with an input stream entering port 1, one inserts λ_i into port 2, so that it couples across to the top waveguide. Thus it exits port 3 along with the other wavelengths $\lambda_1, \ldots, \lambda_{i-1}, \lambda_{i+1}, \ldots, \lambda_M$ that entered port 1.

Tuning ranges for these type of filters are on the order of 60 nm with channel bandwidths of around 1 nm (125 GHz).

Tunable multigrating filters can be used to add and drop any number of N different wavelengths. Figure 9 illustrates the concept, which uses two 3-port circulators with a series of N electrically tunable fiber-based reflection gratings placed between them. One grating is used for each wavelength in the system. The demultiplexer separates the dropped wavelengths into individual channels and the multiplexer combines wavelengths for transmission over the fiber trunk line.

The device operates as follows: a series of up to N wavelengths enter port 1 of the left-hand circulator and exit at port 2. In the untuned state, each fiber grating is transparent to all wavelengths. However, once a grating is tuned to a specific wavelength, this light will be reflected back, reenter the left-hand circulator through port 2, and exit from port 3 to the demultiplexer. This can be done for any desired number of channels. All remaining wavelengths that are not reflected pass through to the right-hand circulator. Here they enter port 1 and come out of port 2. To add or reinsert wavelengths that were dropped, one injects these into port 3 of the right-hand circulator. They first come out of port 1 and travel toward the series of tuned fiber gratings. The tuned gratings reflect each wavelength so that they head back toward the right-hand circulator and pass through it to combine with the other wavelengths.

Acousto-optic tunable filters (AOTFs) operate through the interaction of photons and acoustic waves in a solid such as lithium niobate. Figure 10 shows the basic operation. Here an acoustic transducer, which is modulated by a nominal 175-MHz radio frequency (RF) signal, produces a surface acoustic wave in the $LiNbO_3$ crystal. This wave sets up an artificial grating in the solid, the grating pitch being

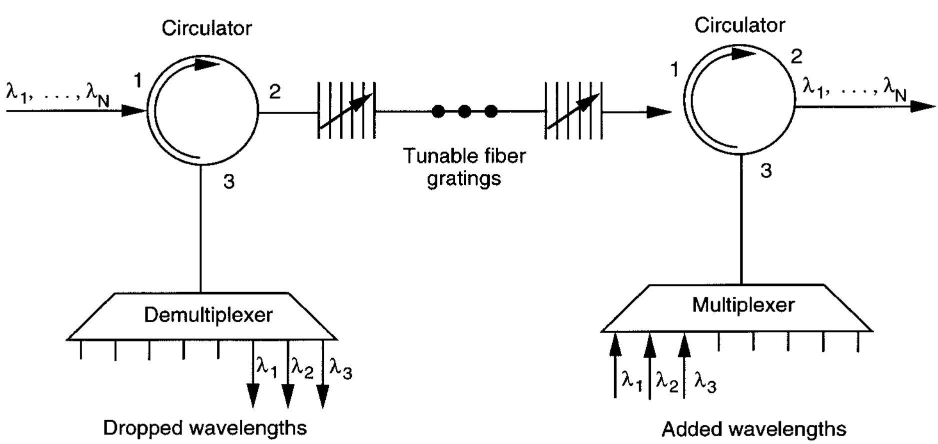

FIG. 9. Tunable multigrating filters used to add and drop any number of N different wavelengths.

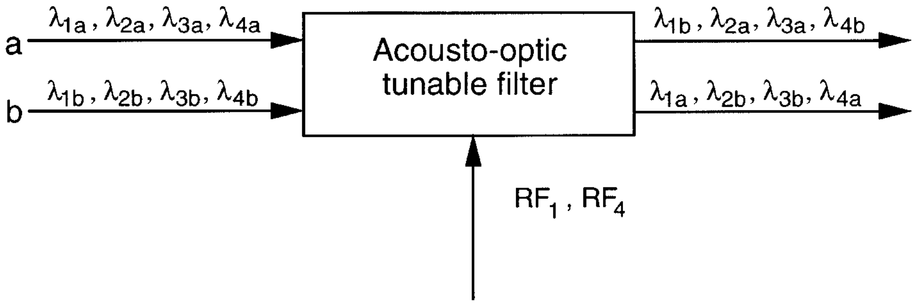

FIG. 10. Operation of an acousto-optic tunable filter.

determined by the frequency of the driving RF signal. More than one grating can be produced simultaneously by using a number of different driving frequencies. Input wavelengths that match the Bragg condition of the gratings are coupled to the second branch of the AOTF, while the other wavelengths continue on through. Analogous to multigrating filters, conventional AOTFs can pass one or more frequencies spaced more than 500 GHz apart, or they can pass one or several 4-nm spectral bands. Switching speeds are on the order of 10 μs with tuning ranges of nominally 145 nm. Recently a new type of tunable AOTF structure featuring triple-stage film-loaded waveguides was demonstrated to operate with a 3-dB optical bandwidth of 0.37 nm, thus showing the possibility of applying AOTFs to ITU-T recommended 0.8-nm-spaced systems [48].

4.4. Tunable Sources

Many different laser designs have been proposed to generate the spectrum of wavelengths needed for WDM. One can choose from three basic options: (a) a series of discrete DFB or distributed Bragg reflector (DBR) lasers, (b) wavelength-tunable (or frequency-tunable) lasers, or (c) a multiwavelength laser array.

The use of discrete single-wavelength lasers is the simplest method. Here one hand-selects individual sources, each of which operates at a different wavelength. Although it is straightforward, this method can be expensive because of the high cost of individual lasers. In addition, the sources must be carefully controlled and monitored to ensure that their wavelengths do not drift with time and temperature into the spectral region of adjacent sources.

With a frequency-tunable laser, one needs only this one source [49–53]. These devices are based on DFB or DBR structures, which have a waveguide-type grating filter in the lasing cavity. Frequency tuning is achieved either by changing the temperature of the device (since the wavelength changes as approximately 0.1 nm/°C), or by altering the injection current into the active (gain) section or the passive section (yielding a wavelength change of 0.8×10^{-2} to 4.0×10^{-2} nm/mA, or, equivalently, 1 to 5 GHz/mA). The latter method is generally used. This results in a change in the effective refractive index, which causes a shift in the peak output wavelength. The maximum tuning range depends on the optical output power, with a larger output level resulting in a narrower tuning range. Figure 11 illustrates the tuning range of an injection-tunable three-section DBR laser.

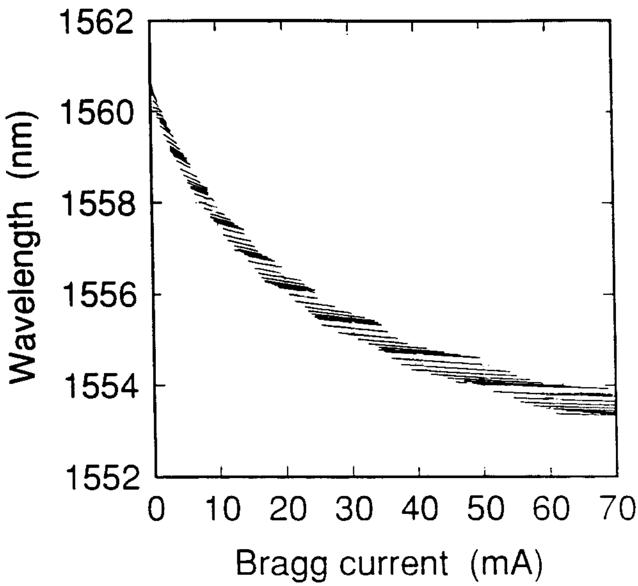

FIG. 11. Tuning range of an injection-tunable three-section DBR laser.

The tuning range $\Delta\lambda_{\text{tune}}$ can be estimated by

$$\frac{\Delta\lambda_{\text{tune}}}{\lambda} = \frac{\Delta n_{\text{eff}}}{n_{\text{eff}}}, \tag{3}$$

where Δn_{eff} is the change in the effective refractive index. Practically, the maximum index change is around 1% resulting in a tuning range of 10 to 15 nm. Figure 12 depicts the relationships between tuning range, channel spacing, and source spectral width. To avoid crosstalk between adjacent channels, a channel spacing of 10 times the source spectral width $\Delta\lambda_{\text{signal}}$ is often specified; that is,

$$\Delta\lambda_{\text{channel}} \approx 10\,\Delta\lambda_{\text{signal}}. \tag{4}$$

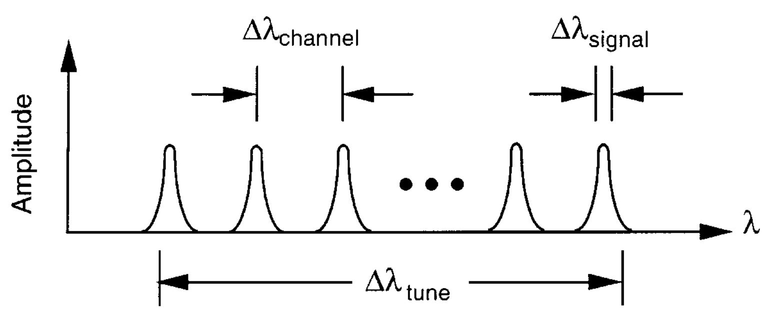

FIG. 12. Relationships between turning range, channel spacing, and source spectral width.

Thus, the maximum number of channels N that can be placed in the tuning range $\Delta\lambda_{\text{tune}}$ is

$$N \approx \frac{\Delta\lambda_{\text{tune}}}{\Delta\lambda_{\text{channel}}}. \tag{5}$$

As an example, suppose that the maximum index change of a particular DBR laser operating at 1550 nm is 0.65%. Then the tuning range is

$$\Delta\lambda_{\text{tune}} = \lambda\frac{\Delta n_{\text{eff}}}{n_{\text{eff}}} = (1500\text{ nm})(0.0065) = 10\text{ nm}. \tag{6}$$

If the source spectral width is 0.2 nm for a 2.5 Gb/s signal, then the number of channels that can operate in this tuning range is

$$N \approx \frac{\Delta\lambda_{\text{tune}}}{\Delta\lambda_{\text{channel}}} = \frac{100\text{ nm}}{10(0.2\text{ nm})} = 50. \tag{7}$$

4.5. EDFAs

An optical fiber amplifier is a key component for enabling efficient transmission of WDM signals over long distances. The active medium in an optical fiber amplifier consists of a nominally 10-to-30-m length of silica or fluoride optical fiber that has been lightly doped (e.g., 1000 parts per million weight) with a rare-earth element, such as erbium (Er), ytterbium (Yb), neodymium (Nd), or praseodymium (Pr). The most popular optical-amplifier design for long-haul telecommunication applications is a silica fiber doped with erbium, which is known as an *erbium-doped fiber amplifier* [54–58]. The operation of an EDFA is limited to the 1530-to-1560-nm region. For simplicity of discussion in this section, we will use the designation "1550-nm signals" to refer to any particular optical channel in the 1530-to-1560-nm spectral band. An advantage of EDFAs is their ability to amplify multiple optical channels, provided the bandwidth of the multichannel signal is smaller than the amplifier bandwidth. For EDFAs this bandwidth ranges from 1 to 5 THz.

One of the most important parameters of an optical amplifier is the *signal gain* or *amplifier gain* G, which is defined as

$$G = \frac{P_{s,\text{out}}}{P_{s,\text{in}}}, \tag{8}$$

where $P_{s,\text{in}}$ and $P_{s,\text{out}}$ are the input and output powers, respectively, of the optical signal being amplified. To achieve this gain, based on energy conservation principles, the power of the pump laser that creates the population inversion in the EDFA must inject a power level P_p into the EDFA of at least

$$P_p = P_s\frac{\lambda_s}{\lambda_p}, \tag{9}$$

where λ_s and λ_p are the signal and pump wavelengths, respectively. Standard pump wavelengths for EDFAs are 980 and 1480 nm. If the pump power is less than this, the signal power drives the optical amplifier into deep saturation and the required signal gain is not met. As an example, consider an EDFA being pumped at 980 nm with a 30-mW pump power. If the gain at 1550 nm is 20 dB (a factor of 100), then from Eqs. (8) and (9) we find that the maximum input signal level that can be fully amplified by 20 dB is $P_{s,\text{in}} = 190\ \mu\text{W}$ (or, equivalently, -14.4 dBm).

The dominant noise generated in an optical amplifier is *amplified spontaneous emission* (ASE). The origin of this is the spontaneous recombination of electrons and holes in the amplifier medium. This recombination gives rise to a broad spectral background of photons that get amplified along with the optical signal.

In a long transmission system, several optical amplifiers are needed to periodically restore the power level, after it has decreased due to attenuation in the fiber. Normally, the gain of each EDFA in this amplifier chain is chosen to exactly compensate for the signal loss incurred in the preceding fiber section. The accumulated ASE noise is the dominant degradation factor in such a cascaded chain of amplifiers. To compensate for this accumulated noise, the signal power must increase at least linearly with the length of the link in order to keep a constant signal-to-noise ratio.

Interchannel crosstalk does not occur in EDFAs, as long as the channel spacing is greater than 10 kHz, which holds in practice. Thus EDFAs are ideally suited for multichannel amplification. For multichannel operation in an EDFA, the signal power for N channels is given by $P_s = \sum_{i=1}^{N} P_{si}$, where P_{si} is the signal power in channel i, that is, at the optical carrier frequency ν_i. Again, to achieve this total signal-power output level, the energy-conservation condition given in Eq. (9) must be satisfied. Otherwise the EDFA runs into deep saturation and the required signal gain per channel is not met and is nonuniform across the channels as well.

Another characteristic of an EDFA is that its gain is wavelength-dependent. Figure 13 shows this behavior. If it is not equalized over the spectral range of operation in a multichannel system, this gain variation will create a large signal-to-noise ratio differential among the channels after passing through a cascade of EDFAs. Numerous techniques have been considered for this equalization, with one successful one being the use of gain-compensating fiber gratings [59–61]. The result is that commercially available EDFAs will have a flat gain behavior, as illustrated by the bottom curve in Fig. 13. The one drawback is that to achieve a flattened gain over the entire 30-nm EDFA spectral band, the gain decreases in most regions to match the lowest gain in the band.

5. WDM SYSTEM OPERATING CHARACTERISTICS

Designing WDM links and networks requires careful consideration of the system operating conditions. Among these are the link bandwidth, optical power requirements for a specific bit error rate, crosstalk between optical channels, and performance limitations due to nonlinear effects.

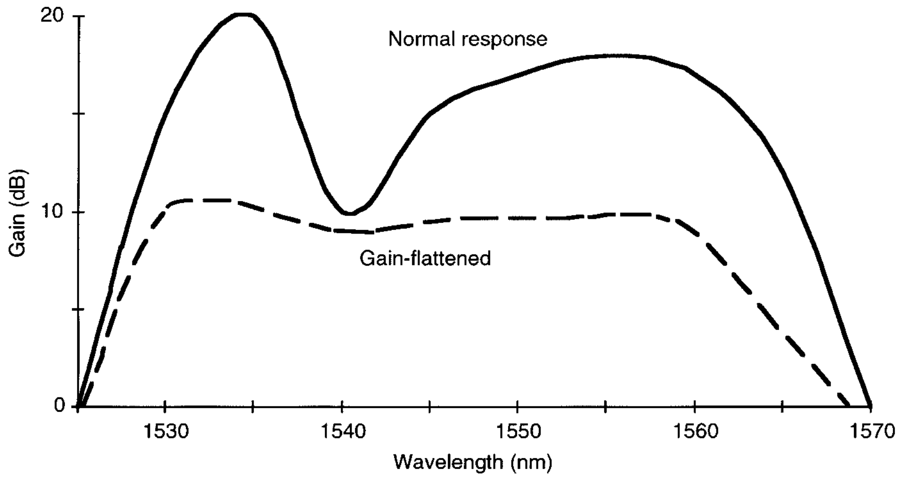

FIG. 13. Wavelength-dependent gain behavior of an EDFA.

5.1. Link Bandwidth

If the N transmitters shown in Fig. 3 operate at bit rates of B_1 through B_N, respectively, then the total bandwidth is $B = \sum_{i=1}^{N} B_i$. When all the bit rates are equal, then the system capacity is enhanced by a factor N compared to a single-channel link. For example, if the bandwidth of each channel is 2.5 Gb/s, then the total bandwidth of the WDM link for eight channels is 20 Gb/s, and for 40 channels it is 100 Gb/s.

The total capacity of a WDM link depends on how closely the channels can be spaced in the available transmission window. The standard wavelength spacing is suggested to be 100 GHz (0.8 nm) by the ITU-T Recommendation G. 692. As noted in that document, the central frequency is 193.100 THz (1552.524 nm), with the wavelength grid ranging from 1537 to 1563 nm. Although DWDM networks with 8, 16, 32, and 40 wavelengths are now commercially available, the industry still needs to define specific wavelength values in order for these networks to truly interoperate transparently from one vendor's equipment to another.

5.2. Optical Power Requirements for a Specific BER

At the outputs of the demultiplexer, system parameters that need to be considered include the signal level, noise level, and crosstalk. The bit error rate (BER) of a WDM channel is determined by the optical signal-to-noise ratio (SNR) delivered to the photodetector. For an acceptably low BER in an ideal link, this should be approximately 14 dB measured in an 0.01-nm optical bandwidth. For commercial systems, taking into account likely variations in realistic components and including reasonable amounts of system margin (usually between 3 and 6 dB), one typically needs SNRs of 18 to 20 dB. These values then determine the amount of optical power that must be launched into each wavelength channel, the number of EDFAs needed over the desired link length, and the fiber attenuation that can be tolerated in the spans between optical amplifiers.

An important factor to keep in mind is the difference in noise effects between an optically amplified WDM link and a conventional link without amplifiers, where the transmission performance is dominated by receiver noise. In an optically amplified link, the main noise factor for a digital "one" arises from the signal mixing with the ASE noise from the EDFA, whereas for a digital "zero" signal the probability of error is determined by the ASE noise alone.

For a given channel transmitted over a link containing several optical amplifiers, the SNR starts out at a high level. It then decreases at each amplifier as the ASE noise accumulates through the length of the link, as shown in Fig. 14. The higher the gain in the amplifier, the faster the ASE noise builds up. However, although the SNR decreases quickly in the first few amplifications, the incremental effect of adding another EDFA diminishes rapidly with an increasing number of amplifiers. As a consequence, although the SNR drops by 3 dB when the number of EDFAs increases from 3 to 6, it also drops by 3 dB when the number of amplifiers is further increased from 6 to 12.

5.3. *Interchannel Crosstalk*

The narrow channel spacings in dense WDM links give rise to crosstalk, which is defined as the feedthrough of one channel's signal into another channel [62, 65]. Crosstalk can be introduced by almost any component in a WDM system, including optical filters, wavelength multiplexers and demultiplexers, optical switches, optical amplifiers, and the fiber itself. Fiber-induced crosstalk, which arises from nonlinear effects on the optical signal as it travels in the dielectric glass medium, is discussed in Section 5.4.

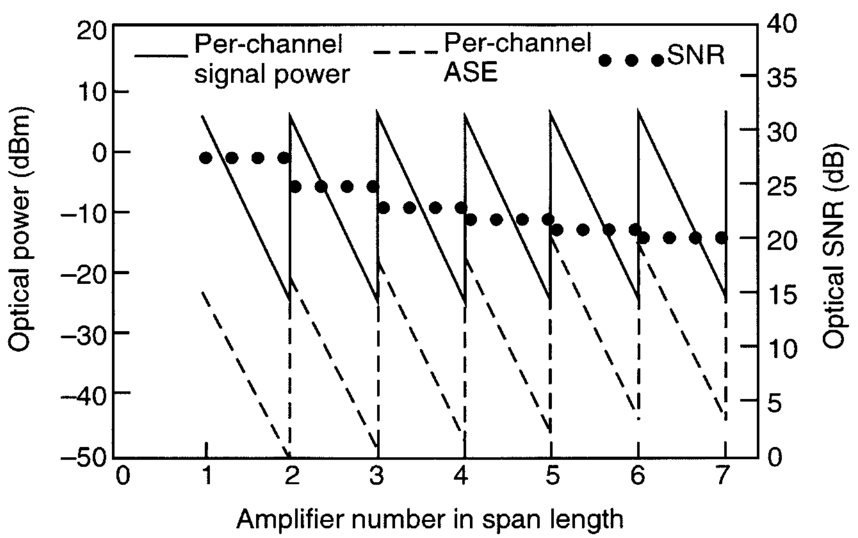

FIG. 14. SNR degradation as a function of link distance over which the ASE noise increases with the number of amplifiers.

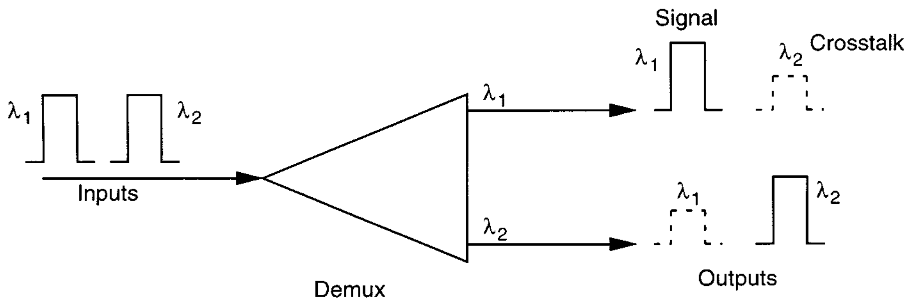

FIG. 15. Example of the origin of interchannel crosstalk.

The two types of crosstalk that can occur in WDM systems are intrachannel and interchannel crosstalk. Both of these cause power penalties in the system performance. As illustrated in Fig. 15 for a demultiplexer function, interchannel crosstalk arises when an interfering signal comes from a neighboring channel. This means that the wavelength of the undesired signal is sufficiently far away from the desired signal wavelength so that the difference is greater than the electrical bandwidth of the receiver.

For intrachannel crosstalk, the interfering signal is at the same wavelength as the desired signal. This effect is more severe than interchannel crosstalk, since the interference falls within the receiver bandwidth. Figure 16 gives an example of the origin of intrachannel crosstalk. Here two independent signals, each at a wavelength λ_1, enter an optical switch. This switch routes the signal entering port 1 to output port 4, and routes the signal entering port 2 to output port 3. Within the switch, a spurious fraction of the optical power entering port 1 gets coupled to port 3, where it interferes with the signal from port 2 that gets switched there.

If the average received intrachannel crosstalk power is a fraction ε of the average received signal power P, then in an amplified system, where the dominant noise component is signal-dependent, the intrachannel power penalty is [16]

$$\text{Penalty}_{\text{intra}} = -5\log\left(1 - 2\sqrt{\varepsilon}\right). \tag{10}$$

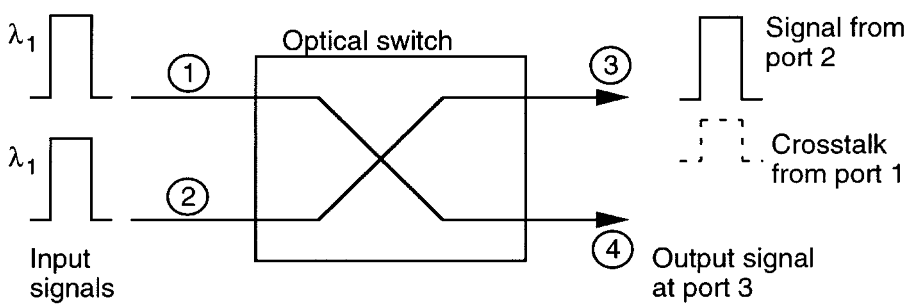

FIG. 16. Example of the origin of intrachannel crosstalk.

If there are N interfering channels in a WDM system, each contributing an average crosstalk power $\varepsilon_i P$, then the factor ε in Eq. (10) is given by

$$\sqrt{\varepsilon} = \sum_{i=1}^{N} \sqrt{\varepsilon_i}\,. \tag{11}$$

For interchannel crosstalk, again let the received crosstalk power be a fraction ε of the average received signal power P. Again considering an amplified system, the power penalty then is [16]

$$\text{Penalty}_{\text{inter}} = -5\log(1 - \varepsilon)\,. \tag{12}$$

In this case for N interfering channels each with an average crosstalk power $\varepsilon_i P$, the factor ε in Eq. (12) is given by

$$\varepsilon = \sum_{i=1}^{N} \varepsilon_i\,. \tag{13}$$

Figure 17 illustrates the power penalties from intrachannel and interchannel crosstalk effects for 10 WDM channels as a function of the individual crosstalk level. Here we assume that each channel contributes an equal amount of crosstalk power. For example, to have the power penalty from intrachannel crosstalk be less than 1 dB, each contributing element must have a crosstalk level that is at least 35 dB below the signal level.

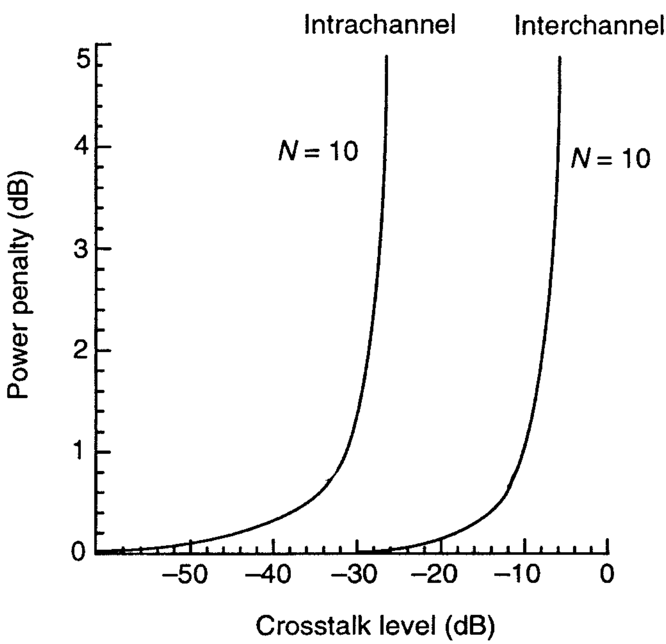

FIG. 17. Power penalties from intrachannel and interchannel crosstalk for 10 WDM channels as a function of the individual crosstalk level.

5.4. Performance Limitations

Several factors exist that limit the transmission capacity and distance in WDM systems. The major limitations are the ASE noise effect on the signal-to-noise ratio, inelastic scattering processes, and various fiber nonlinearities that can create crosstalk between WDM channels [66–74].

At the end of a chain of optical amplifiers, the SNR is determined from the input signal power to the last amplifier and the total amplified ASE noise generated by all the amplifiers in the chain. Since the ASE noise increases with the number of amplifiers, the SNR will gradually decrease along the link. This is illustrated in Fig. 18, which shows the variation in the Q factor (which defines the BER [7]) as a function of the optical power launched in the fiber. As the launched signal power is increased, the Q factor improves since the SNR is larger. However, after a certain power level the Q factor decreases owing to the onset of nonlinear effects in the fiber. Larger effective fiber core areas and amplifier pump wavelengths of 980 nm as opposed to 1480 nm allow higher Q factors to be achieved.

Inelastic scattering processes include SRS and SBS, which are interactions between optical signals and molecular or acoustic vibrations in a fiber. SRS generates scattered light at a wavelength longer than that of the incident light. If another signal is present at this longer wavelength, it will be amplified by the SRS light. Crosstalk levels due to SRS increase with both the number of channels and their spacing. However, if the optical power per channel is not excessively high (e.g., less than 1 mW each), then the effects of SRS do not contribute significantly to the eye-closure penalty as a function of transmission distance.

SBS arises when lightwaves scatter from acoustic waves. The resultant scattered wave propagates principally in the backward direction in single-mode fibers. This

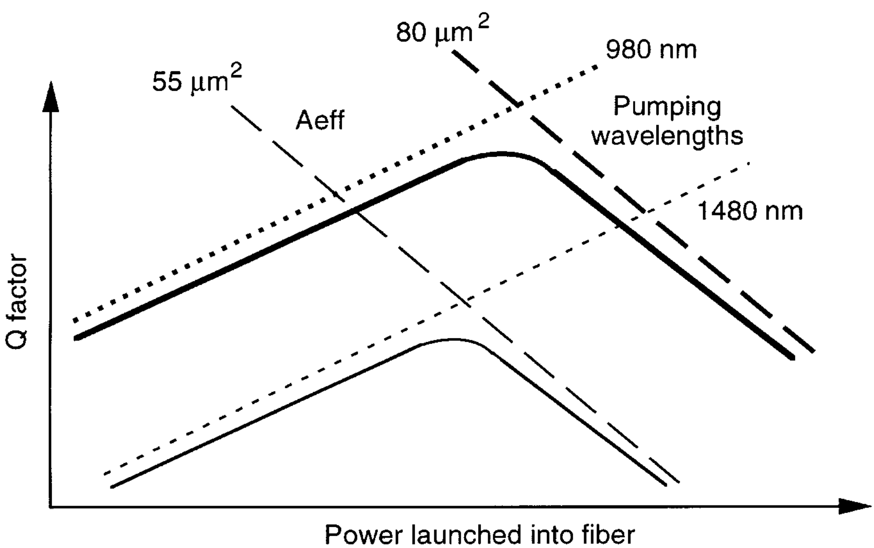

FIG. 18. Variation in the Q factor as a function of the optical power launched into different fibers.

back-scattered light experiences gain from the forward-propagating signals. System impairment starts when its amplitude is comparable to the signal power. For typical fibers the threshold power for this process is around 10 mW for single-fiber spans. In a long fiber chain containing optical amplifiers, there are normally optical isolators to prevent back-scattered signals from entering the amplifier. Consequently, the impairment due to SBS is limited to the degradation occurring in a single amplifier-to-amplifier span. In a WDM system, each wavelength channel interacts with phonons of slightly different frequencies. Thus, the effects of SBS accumulate individually for each channel and consequently occur at the same power level as a single-channel system. Although the SBS threshold is around 1 mW for long signal pulses (pulse widths greater than 1 μs), its effect is negligible for signal pulse widths of less than 10 ns, which holds for the high-speed transmission rates of interest for optically amplified WDM systems.

The refractive index n of many optical materials has a weak dependence on optical intensity I (equal to the optical power per area in the fiber) given by

$$n = n_0 + n_2 I, \tag{14}$$

where n_0 is the ordinary refractive index of the material and n_2 is the intensity-dependent refractive index. Nonlinear processes arise from modulation of the refractive index by intensity changes in the signal, thereby producing effects such as FWM, SPM, and CPM. In single-wavelength links, the SPM effect converts optical power fluctuations in a propagating light wave to phase fluctuations in the same wave. In practice, this effect is quite small and can usually be ignored.

In WDM systems, CPM converts power fluctuations in a particular wavelength channel to phase fluctuations in other copropagating channels. In practical fibers, each wavelength in a WDM system sees a slightly different refractive index, since the dispersion-versus-wavelength curve is not perfectly flat. Consequently, the group velocities of the various WDM channels are not the same, so that pulses from different wavelength channels will pass through each other as they travel along the fiber. This difference in group velocity limits CPM interaction, since in general the pulse collisions virtually eliminate spectral broadening due to CPM by destroying the phase coupling between the copropagating channels.

Four-wave mixing is a third-order nonlinearity in silica fibers, which is analogous to intermodulation distortion in electrical systems. When wavelength channels are located near the zero-dispersion point, three optical frequencies (ν_i, ν_j, ν_k) will mix to produce a fourth intermodulation product ν_{ijk} given by

$$\nu_{ijk} = \nu_i + \nu_j - \nu_k \qquad \text{with } i, j \neq k. \tag{15}$$

When this new frequency falls in the transmission window of the original frequencies, it can cause severe crosstalk. The efficiency of four-wave mixing depends on fiber dispersion and the channel spacings. Since the dispersion varies with wavelength, the signal waves and the generated waves have different group velocities. This destroys the phase matching of the interacting waves and lowers the efficiency at which power is transferred to newly generated frequencies. The higher the group velocity mismatches and the wider the channel spacings, the lower the four-wave mixing.

One approach to reducing the effect of FWM is to use passive dispersion compensation [75–79]. This consists of inserting into the link a loop of fiber having a dispersion characteristic that negates the accumulated dispersion of the transmission fiber. This process is called *dispersion compensation* and the fiber loop is referred to as a *dispersion compensating fiber* (DCF). If the transmission fiber has a low positive dispersion [say, 1 ps/(nm-km)], then the DCF will have a large negative dispersion [say, -16 ps/(nm-km)]. With this technique, the total accumulated dispersion is zero after some distance, but the absolute dispersion per length is nonzero at all points along the fiber. The nonzero absolute value causes a phase mismatch between wavelength channels, thereby destroying the possibility of effective FWM production.

6. INSTALLATIONS

Since 1995, WDM technology has grown rapidly from tens of millions of dollars per year into an annual multibillion dollar business with worldwide installations in both terrestrial and undersea environments. In the USA, every major long-distance service provider was using WDM as an integral part of their networks by the end of 1997. In Europe the information-transport networks are undergoing a rapid migration to WDM owing to the dual requirements of increased capacity and higher resilience. To help meet the rapidly increasing global demand for enormous telecommunications bandwidth, undersea network providers also are turning to WDM.

6.1. *Terrestrial WDM Networks*

As an example of growth rates in terrestrial installations, let us look at the Sprint long-distance network in the USA [80]. Figure 19 shows the basic layout of the Sprint fiber-optic network, which encompasses some 23,000 cable miles. Large-scale deployment of four-channel WDM links began in mid-1995. By the beginning of 1996, 8-channel systems were being put in, and at the end of that same year, 16-channel links were being installed. By the end of 1998, over one billion WDM-channel miles are expected to be in place. All of these Sprint WDM systems operate at OC-48 rates per wavelength and perform at bit error rates of 10^{-11} or better.

As an example of the various European network providers, Hermes Europe Railtel is deploying 40-channel dense WDM technology on its network [81]. Each wavelength path will send information at 2.5 Gb/s, thereby yielding a total capacity of 100 Gb/s. Depending on the demand growth, the same multiplexing equipment can be upgraded to handle 96 wavelengths. Whereas in 1997 there were 1700 route-km of fiber optic cable, the Hermes network will grow tenfold in the following three-year period. As shown in Fig. 20, by the year 2000 the network will connect 33 cities in 16 countries and will encompass 18,000 route-km of fiber optic cable. Connections to the USA and Russia are also planned.

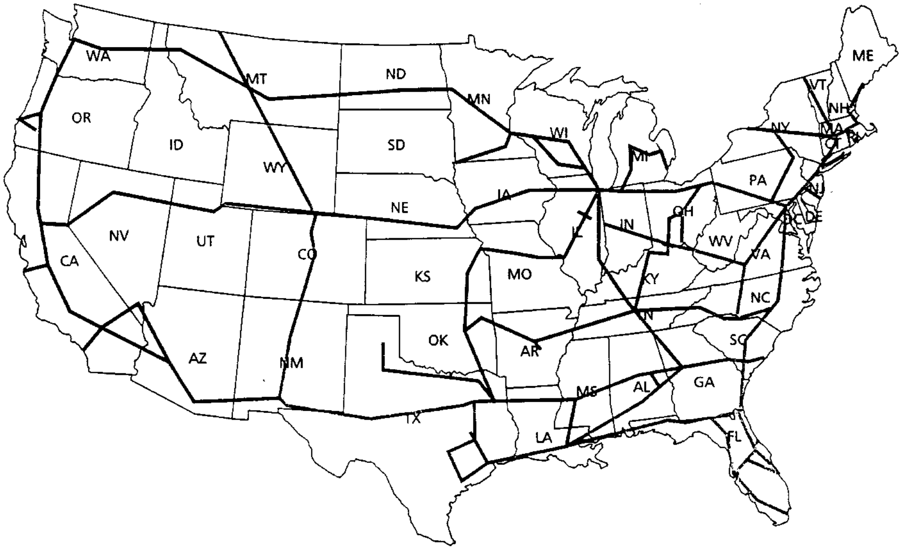

FIG. 19. Basic layout of the Sprint fiber-optic network in the USA.

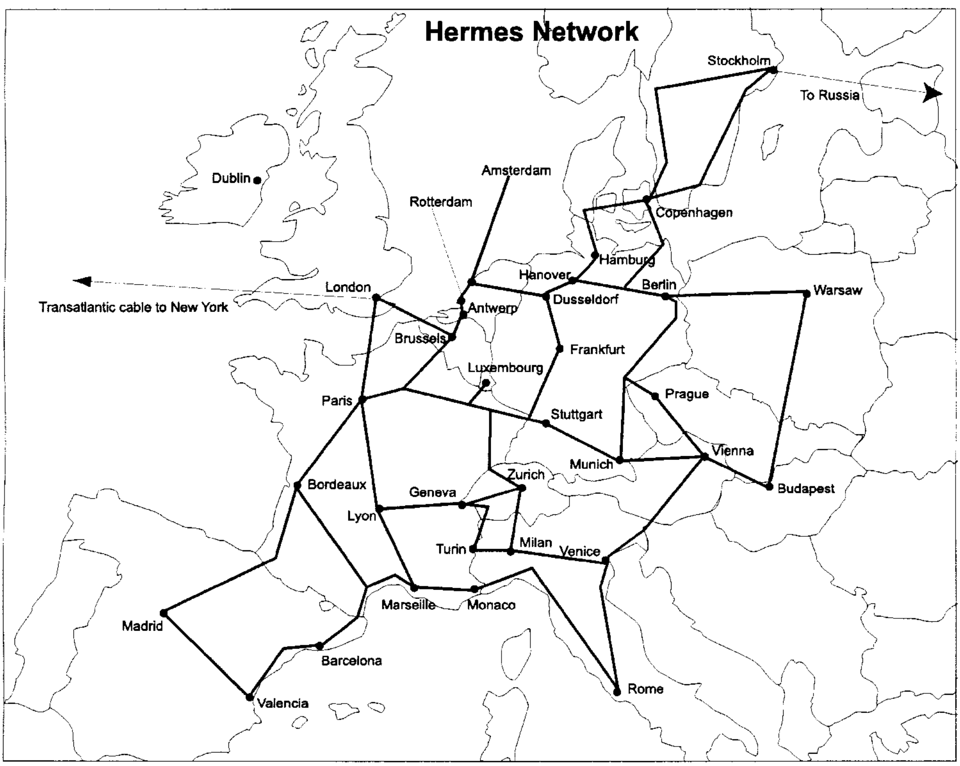

FIG. 20. By the year 2000, the Hermes Europe Railtel network will connect 33 cities in 16 countries using 18,000 route-km of fiber optic cable.

6.2. Undersea WDM Networks

Analogous to terrestrial networks, undersea WDM networks offer higher capacities and greater network configuration flexibility [82–84]. This holds for both already installed fiber links and new undersea cable networks. However, in contrast to terrestrial networks where equipment replacement and upgrades are not too difficult from a logistics point of view, undersea links are expensive to retrofit if in-line submerged equipment needs to be replaced. Thus, for the most part, existing single-wavelength installations are being upgraded by one or two more wavelengths. For example, the TAT-12/13 system between the USA and Europe and the TPC-5 cable network running between Japan and the USA have been in service since 1996. These were originally designed to be single-wavelength links operating at 5 Gb/s. Owing to unanticipated traffic demands, a few years later they were already upgraded, within the limits of the installed systems, to two or three wavelengths per fiber. Each wavelength is carrying traffic at 5 Gb/s.

To handle the ever-increasing capacity demands across the Atlantic and Pacific Oceans, the China–US Cable System and the Atlantic Crossing-1 Network (AC-1) are being constructed as WDM ring networks using four fiber pairs. The Pacific link will carry eight wavelengths at 2.5 Gb/s over a distance of 12,000 km. AC-1 is designed to run at 2.5 Gb/s per wavelength over 7100 km, with landing points in the USA, the United Kingdom, the Netherlands, and Germany.

The SEA-ME-WE-3 Cable System is the first undersea WDM network that uses undersea routing of wavelengths. As shown in Fig. 21, this network runs from Germany to Singapore, connecting more than a dozen countries in between. Hence the name SEA-ME-WE, which refers to Southeast Asia (SEA), the Middle East (ME), and Western Europe (WE). The network has two pairs of undersea fibers with a capacity of eight STM-16 wavelengths per fiber. The undersea branching units (BUs) in the network add and drop specific wavelengths to and from various locations along the route. This configuration allows efficient allocation of bandwidth to separate countries and results in a high degree of traffic sovereignty and security.

To take full advantage of the high-capacity potential offered by WDM, network designers of undersea links now have the challenge to devise systems that can transmit a large number of wavelengths over distances as long as 12,000 km. In carrying out these designs, special care must be taken in choosing the dispersion characteristics of the concatenated fiber sections and in selecting the wavelength spacing. As an example of achievable performance, designs with 0.8-nm spacings have demonstrated that links having 20 channels at 10 Gb/s each can run over 9000 km [85]. Higher capacities are theoretically possible using soliton transmission techniques, as described in Section 7.1.

6.3. Network Management

Every kind of network needs several different disciplines of management in order for it to perform its intended mission. These management disciplines are generally referred to as operation, administration, and maintenance functions.

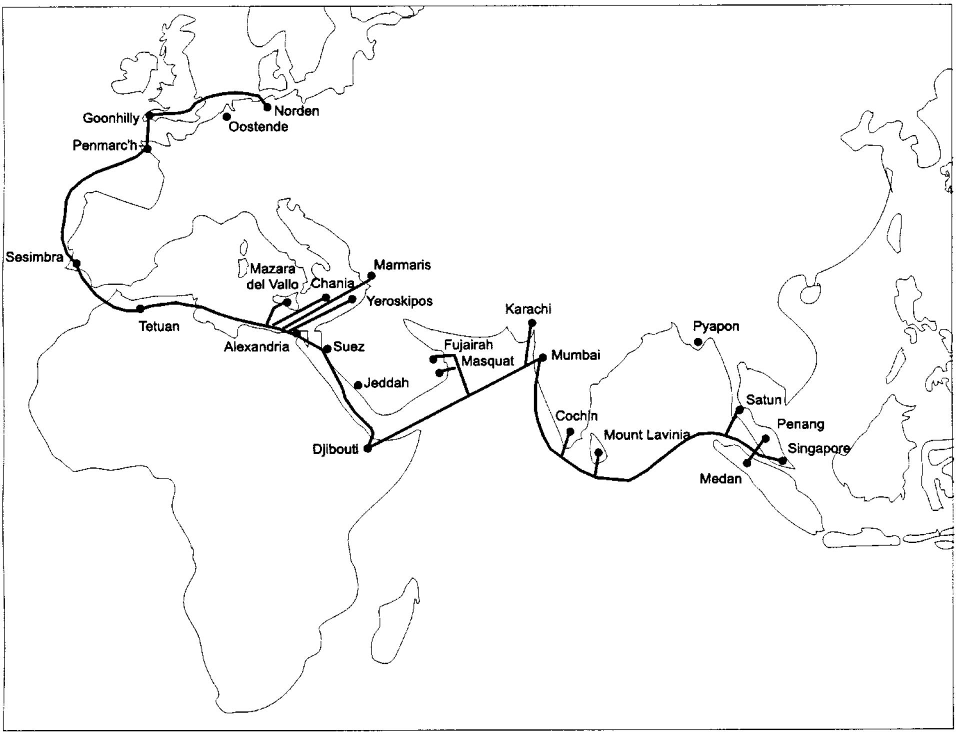

FIG. 21. The SEA-ME-WE-3 cable system.

Classically, they include configuration, performance, fault, security, and accounting management functions [16, 86–90]. The last two are similar to other types of networks, whereas the first three require some special considerations for optical WDM networks.

Configuration management involves managing changes in the network in an orderly fashion. This could involve setting up and taking down lightpath connections, keeping track of the number of wavelengths being used, modularly adding more wavelengths without disrupting the operation of the existing wavelengths, assigning specific wavelengths to each user, and providing a filtering function at the input to the network so that other wavelengths cannot enter the network without permission.

Performance management deals with guaranteeing quality of service to network users. Carrying out this function involves monitoring the performance parameters on all the network connections and taking any actions necessary to ensure that the desired or specified performance goals are met. A major parameter is bit error rate. When multiple wavelengths are involved, it is often not possible to access the overhead bits in the transmitted data to obtain the information necessary to measure the performance. In this case, transmission-related parameters can be monitored to derive an appropriate performance measure to guarantee the BER specified by the user. These parameters include optical power levels, optical signal-to-noise ratios, temperatures of key components, and various operational parameters of the associated electronics. Two methods proposed for monitoring the health of an optical path are (1) the use of a separate supervisory wavelength that is slightly out of the spectral band occupied by the signal wavelengths and gets multiplexed onto the line along with them and (2) the superimposing of a pilot tone on each of the optical signals.

Fault management is concerned with detecting and correcting failures of network links, nodes, and wavelength channels. Failures in a link can occur because of a fiber cut, loss of power, or equipment malfunctions. Within the network, various fault-surveillance modules monitor the operating condition of each component to detect any malfunctions or loss-of-light conditions on the link. Any fault that occurs is then reported to a fault-management unit. This unit analyzes the fault condition to determine its location and how to circumvent or repair the failure.

Figure 22 shows three types of protection schemes that can be used either in point-to-point links or in more expansive networks. In the $1 + 1$ protection method, traffic is sent simultaneously on two separate fibers from the source to the destination. One fiber is usually the *working fiber*, which the destination selects for reception. The other fiber is called the *protection fiber*. Generally these fibers follow different routes to avoid situations where both fibers could be severed at the same time. In 1:1 protection, traffic is transmitted over only the working fiber in normal operation. When there is a failure in this line, the traffic is switched to the protection fiber. A more cost-advantageous arrangement is the $1{:}N$ protection method. Here N working fibers share a common protection fiber. This arrangement will handle only failures on one working fiber at a time, which is sufficient in highly reliable networks.

7. FURTHER DEVELOPMENTS

Researchers and network developers are constantly seeking new techniques for increasing the capacity and flexibility of WDM optical systems. In addition to ongoing technology insertions, two emerging methods are the use of soliton signals and the combination of high-speed TDM with WDM. These topics are addressed in this section.

7.1. Technology Insertion

Future technology insertions in WDM networks will include more wavelength channels and higher TDM transmission rates. Several hardware vendors have already incorporated expansion capabilities to 32 and 96 wavelength channels operating at OC-48/STM-16 in their WDM equipment. As noted earlier, limitations on the number of WDM channels that can be supported are imposed by a combination of light source tolerances and the bandwidth, power, and gain flatness of optical amplifiers. Although these limitations are being mitigated by clever component and system designs, their incorporation into actual networks takes some time. Going to the next TDM multiplexing level of OC-192/STM-64 (9.953 Gb/s) requires that the signal-to-noise level at the receiver be 6 dB higher

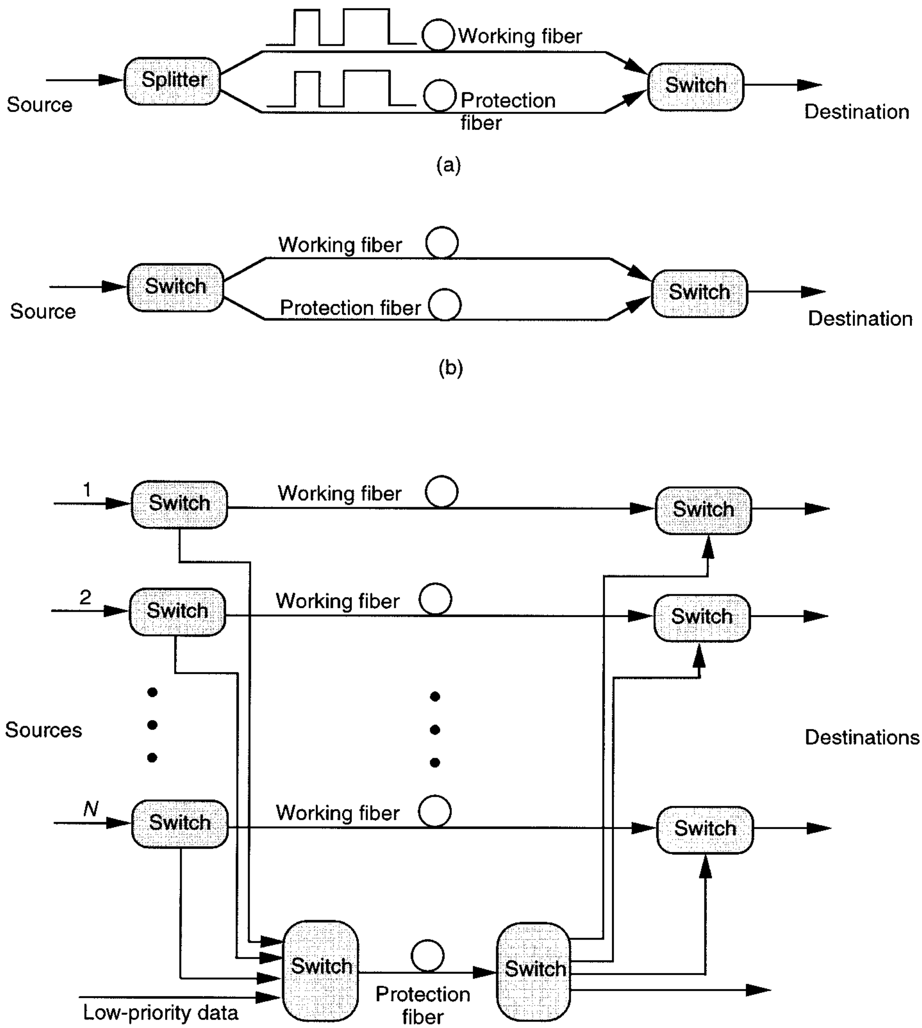

FIG. 22. Three types of protection schemes used either in point-to-point links or in more expansive networks.

than for OC-48/STM-16 rates. In addition, nonlinear effects become more pronounced and need careful compensation designs.

To increase the end-to-end fidelity of an optical transmission line, forward error correction (FEC) can be used if the bit error rate is limited by optical noise and dispersion [91–96]. In FEC techniques, redundant information is transmitted along with the original information. If some of the original data are lost or received in error, the redundant information is used to reconstruct them. Typically the amount of redundant information is small, so the FEC scheme does not use up much additional bandwidth and thus remains efficient. Depending on the application, FEC code properties include the ability to accommodate self-synchronous scramblers (with characteristic polynomial $1 + x^{43}$) used in SONET, the 4B5B line code used in FDDI, or the 8B10B line code used in Fibre Channel.

Investigations of optical cross-connects are underway to provide a very high degree of flexibility in the optical layer of a network [97–99]. Basically, when parts of a network fail or become highly congested, these schemes will allow system restoration or reconfiguration through optical switching. Ideas being considered range from devices that physically switch fibers to another channel, to devices with full nonblocking wavelength-to-wavelength conversion.

7.2. Terrestrial and Undersea WDM Soliton Transmission

During the past several years, researchers have studied and experimented with dispersion-managed soliton transmission to increase the capacity and/or the repeaterless transmission distance of WDM links. As an example, MCI and Pirelli have examined this technique in the 1550-nm window over standard single-mode fiber in a commercial terrestrial-network route running between Chicago and St. Louis [100]. Two different links were examined: one consisted of four wavelengths, each carrying bi-directional OC-192 signals over 450 km; the other was a single-wavelength uni-directional OC-192 link running over 900 km. The measured bit error rate results showed excellent sensitivity for each channel.

As noted in Section 6.2, current undersea WDM installations are running at a maximum speed of 5 Gb/s using non-return-to-zero (NRZ) transmission. Through careful dispersion-management techniques this rate can be increased to 10 Gb/s. The rate can also be increased to 10 or 20 Gb/s through the use of synchronous regeneration of WDM soliton signals [101]. The 10 Gb/s WDM architecture is attractive since it is compatible with the standard terrestrial OC-192/STM-64 rate. Increasing the speed to 20 Gb/s (yielding an optical TDM rate of $2 \times$ 10-Gb/s per wavelength channel) is of interest for minimizing the wavelength granularity. Another advantage of soliton transmission is that transoceanic soliton systems have the potential to extend the optical-amplifier spacing. With solitons this can be between 60 and 200 km (depending on the application) as compared to the 33-to-45-km spacing achievable with standard NRZ. Two issues that still need further investigation in soliton transmission are the precise link-design methodologies and the formulation of schemes for monitoring the fiber transmission link to assure that solitons are propagating properly.

7.3. WDM and Ultrafast TDM

To fully exploit the enormous bandwidth that optical channels can provide, one can combine WDM with high-speed TDM. This is particularly attractive in local area networks (LANs) or metropolitan area networks (MANs), where system performance over the relatively short transmission distances is not as adversely affected by nonlinear dispersion effects as in long-haul links. In these types of applications, ultrafast optical TDM networks combined with WDM have the potential to provide truly flexible bandwidth-on-demand services at burst rates of 100 Gb/s per wavelength.

An advantage of using high-speed TDM instead of WDM is that, depending on the user rates and traffic statistics, TDM potentially can provide improvements in terms of shorter user-access time, lower delay, and higher throughput. For LANs and MANs that service a combination of high-speed and low-speed users operating at rates ranging from 1 to 100 Gb/s, a 100 Gb/s slotted TDM approach has been proposed [102]. The most important features of the network are to provide a backbone to interconnect high-speed networks, to transfer quickly very large data blocks, to switch large aggregations of traffic, and to provide flexible, low-rate access to users.

Combining such TDM schemes with WDM will allow transfer rates in excess of 1 Tb/s to be achieved easily on a single fiber. As an example, a 1 Tb/s rate has been demonstrated in a 50-channel WDM system with each wavelength carrying 20 Gb/s over 600 km [103]. In these systems, the generation of a high-speed signal with uniform pulse separations is important for suppressing crosstalk effects from adjacent pulses and to minimize the jitter during timing extraction [104]. In addition, the design of various high-speed logic elements and optical buffers is an ongoing challenge [105−110].

8. SUMMARY

This paper has reviewed wavelength-division multiplexing from concepts to realization. We first looked at what WDM is and why it is suddenly being used so widely. This discussion explains why, although the concepts for WDM were in place two decades ago, the blending of a dramatic increase in demand for bandwidth and the development of new technologies allowed a cost-effective implementation of WDM. The realization of components that enabled new WDM applications include tunable sources, tunable optical filters and multiplexers, and optical fiber amplifiers. The enthusiasm and faith in success of researchers worldwide, ranging from application of fundamental physical principles to component development to all-optical network designs and their theoretical system analyses, is truly remarkable in this area.

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