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Invited Paper

Technology Trends in Dense WDM Demultiplexers

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Demultiplexers are a key component in dense WDM systems. The performance of these devices helps determine the overall system capacity. A variety of technologies have been developed to implement WDMs. This article reviews the various device technologies and their key characteristics.

1. INTRODUCTION

The past 10 years have seen a dramatic increase in the deployment of WDM systems. Two and four channel systems without amplifiers have evolved into 40 channel systems that utilize the latest in amplifier technology. While today's 40 channel systems operate in the wavelength range 1528 to 1562 nm with 100 GHz channel spacing, many suppliers are moving toward using 50 GHz channels spacing to increase the channel count to 80. In addition, other wavelength ranges such as 1570 to 1610 nm[1] are being developed. In the near future, the development of Raman amplifiers[2] or thulium doped amplifiers[3] will make additional regions of the spectrum such as 1440 to 1520 nm available.

The dense demultiplexer technology began with two channel systems that divided the EDFA bandwidth into two bands centered on 1532 and 1555 nm. As the number of channels increased they were placed in the 1549 to 1560 nm region where the EDFA has small wavelength variation. When the number of channels increased the entire EDFA bandwidth was utilized. In the initial systems dielectric filter technology was the preferred method. However, as the channel spacing decreased and channel count increased other technologies such as fiber Bragg gratings and arrayed waveguide grating routers became applicable. Today, these and other technologies are competing for advanced applications. In this paper the advantages and limitations of the various technologies are examined.

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2. DEVICE CHARACTERISTICS

While each technology has its unique characteristics there are common metrics that can be used for comparison. While most of these parameters appear to be obvious they are not always well defined. Some definitions can be found in Telcordia GR-2883. In this section we define these parameters such as bandwidth, crosstalk, and isolation. Figure 1 show schematically a set of passbands and the resulting obvious parameter definitions. The difference between isolation and crosstalk is discussed in section 2.6. However, in reality the passbands are seldom that well defined.

2.1. Number of Channels

The channel spacing is a straightforward parameter, how many channels can the unit separate. A related issue is can the number of channels be increased to include adjacent spectral regions. For example, in some fiber Bragg grating and dielectric filter designs the additional spectrum that is not demultiplexed is available at the output. Connecting this output to additional devices provides a way to increase the number of channels gracefully. This would not be the case with technologies such as waveguide routers and bulk gratings. The difference is that first types operate on individual channels while the latter operate on all channels simultaneously.

2.2. Channel Spacing

This is initially a straightforward parameter, we just measure the distance between the center of adjacent passbands. Of course we must include the effects of temperature and polarization on the location of the passband. The International Telecommunications Union (ITU) has defined standard channel spacings of 200 GHz and 100 GHz[4]. Now channel spacing on a 50 GHz grid is being developed and channel spacing on a 25 GHz grid is expected in future systems.

2.3. Bandwidth and Channel Shape

The bandwidth and channel shape are intimately related as the definition of the bandwidth will depend on the shape of the passband. This is a key parameter for the system designer. The actual shape will determine the requirements on the laser stability. That is, the more pointed or rounded the shape the more variation in the

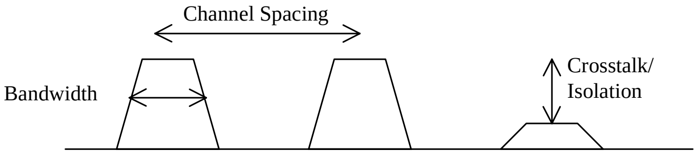

FIG. 1. Definition of measurement parameters.

laser wavelength will affect system performance. Typical laser requirements for 50 GHz systems are ±100 pm. The ideal shape is a flat top with very steep sides.

The bandwidth is determined by measurements of the width of the channel at typical values such as 0.5 dB, 3 dB, and 20 dB, from a reference point. The question then is what is the correct reference point. Two options are the exact ITU standard vacuum wavelength or the minimum insertion loss in the passband. A commonly accepted approach is to measure the bandwidth as between the outside 0.5 dB points and measure the center frequency as the mid point between the 3dB points. The net or clear channel bandwidth is then defined as:

$$\begin{aligned}\text{net.bw} = \text{measured.bw} &- |\text{ITU.wavelength} - \text{center.wavelength}| \\ &- \text{temperature.drifts}\end{aligned}$$

Many DWDM devices that have promised wide bandwidths have failed to be deployed in telecommunication systems because the wavelength centering error and environmental drifts have shrunk the net bandwidth below a usable width.

One interesting aspect is how to handle ripple or peaks in the passband. For example, a sharp peak in the passband may make the device appear to have a very narrow bandwidth. A key issue in measuring the bandwidth is correctly measuring the slope of the edges. The band shape can be characterized by a figure of merit defined as:

$$\text{FOM} = \frac{\text{bandwidth@0.5dB}}{\text{bandwidth@25dB}}$$

In the ideal case the FOM = 1, but in most practical cases the FOM is < 0.5.

2.4. Insertion Loss

The insertion loss is related to the bandwidth as both parameters should be referenced to the same point. The insertion loss should be specified with regard to the polarization state. This implies knowledge of the polarization properties of the source. An unpolarized source will give the average insertion loss, while a polarized source will provide an arbitrary value. A complete characterization of the insertion loss would include both the polarization and temperature dependence. Another parameter related to the insertion loss is uniformity or flatness, how does the insertion loss change across channels.

2.5. Polarization Dependence

Many of the parameters such as bandwidth, center wavelength, and insertion loss are dependent on the state of polarization. As the polarization varies the shape of the demultiplexer function will change. It is important to map the changes in the spectrum for all the polarization states across the entire band. As the channel shape changes the center wavelength can shift and the insertion loss will vary. This can cause increased crosstalk or a reduction in the link margin. For example in Figure 2 the polarization dependence of a fiber Bragg grating filter is shown. The

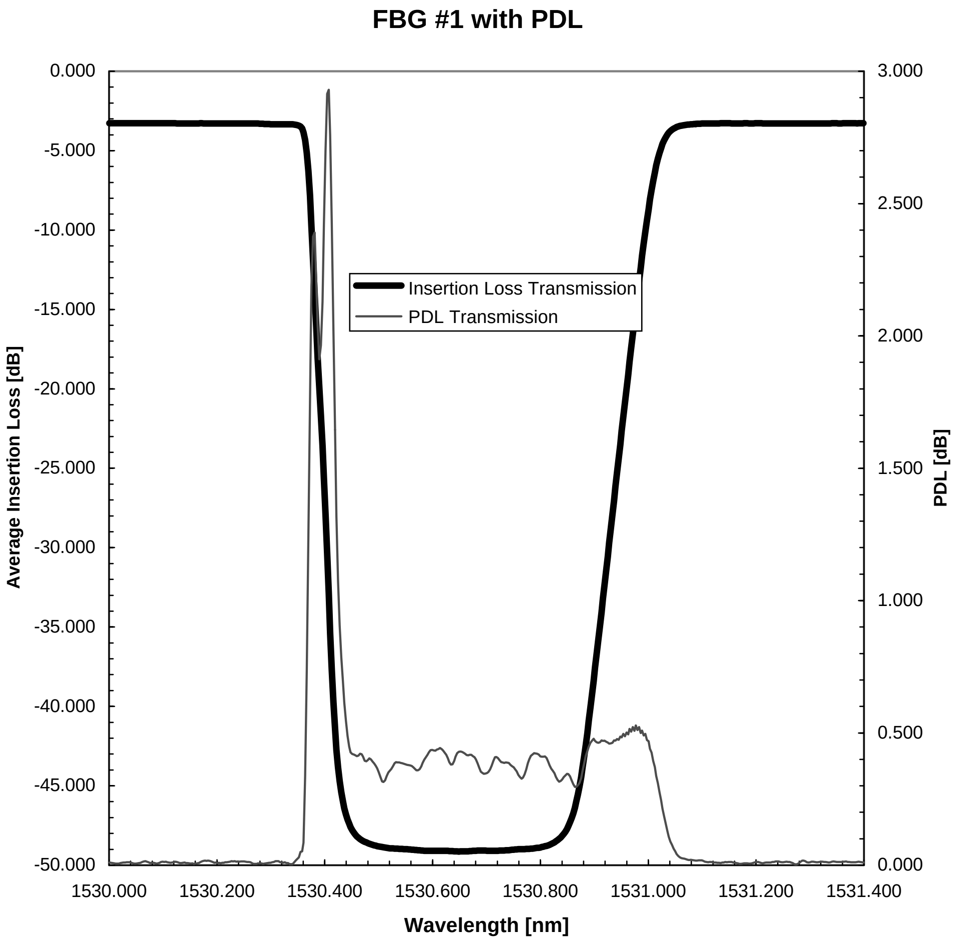

FIG. 2. Example of PDL in a Fiber Bragg Grating.

PDL of this device is almost 3 dB at the edge. This could lead to an increase in the crosstalk for this channel for some polarization states.

2.6. Crosstalk / Isolation

Crosstalk and isolation are complementary parameters. Isolation typically refers to the amount of loss outside of the passband. There are two cases adjacent channel isolation and integrated isolation. Crosstalk refers to how much power is present due to an adjacent channel. Crosstalk is the more appropriate term in a systems context. System designers are concerned because the system penalty is 1 dB for a crosstalk of 11 dB.[5] The adjacent channel isolation is the loss due to the nearest channel. An interesting measurement problem is how is this measured. A simple way is to measure the loss between the exact passband wavelength and the next exact wavelength. This approach assumes that the channel bandwidth is not large enough to interact with any drift of the adjacent channel laser's wavelength and that there is no structure.

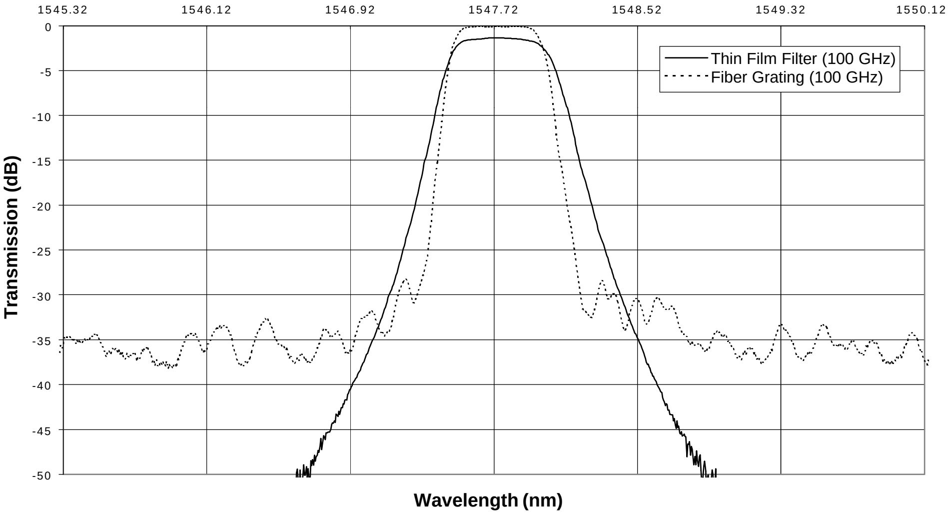

FIG. 3. 100 GHz filter shape for dielectric filter and Bragg grating.

The integrated crosstalk is that due from all other channels. This can become significant for devices that have a periodic response function such as a waveguide router. Here the response is like that of a Fabry-Perot and thus there are multiple wavelengths that will pass through the device. Another case is a fiber Bragg grating that has cladding modes > 10 nm away from the center wavelength. As the number of channels in a system increases the integrated crosstalk becomes larger. The integrated crosstalk results in a system penalty. As an example, the channel shape of a dielectric filter and a fiber Bragg grating are shown in Figure 3. The integrated crosstalk for the Bragg grating will be greater than the dielectric filter.

2.7. *Temperature Stability*

A simple measurement is usually required. How does the insertion loss, bandwidth and center wavelength change over a specified temperature range? While the standard central office specification[6] is -5 to 50°C higher temperatures may be required. The best way to measure this parameter would be to either use unpolarized light or to measure all the polarization states.

A related issue is does the device need to be temperature stabilized. Typically devices are stabilized at a temperature higher than will be experienced during use. The addition of temperature stabilization reduces the reliability and increases the cost and power consumption. Technologies that do not require stabilization are usually preferred.

2.8. *Dispersion*

There are two types of dispersion that are of concern in WDM systems, polarization mode dispersion (PMD), and chromatic dispersion. PMD is the variation in delay as a function of polarization state. This is typically not a concern for

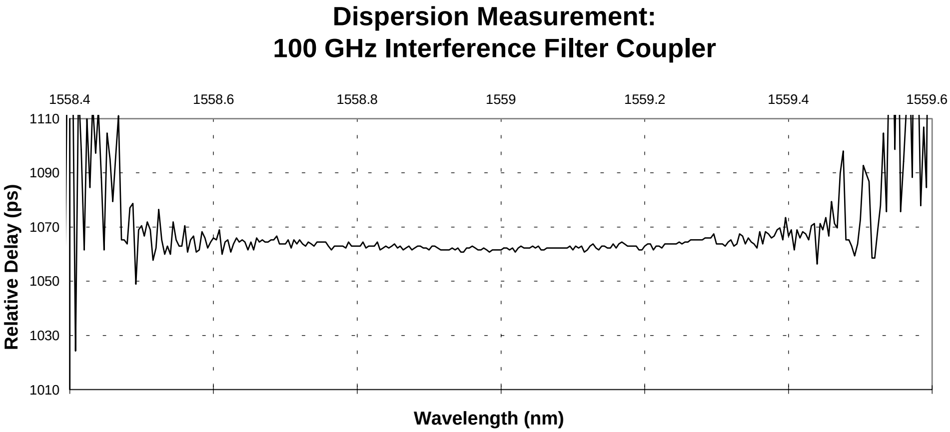

FIG. 4. Delay for 100 GHz filter

the technologies discussed here. The chromatic dispersion is the difference in delay times as a function of wavelength. In demultiplexers, the total amount of delay in the passband is not important but the variation is. For many of the technologies the delay in the passband is constant but varies significantly at the edges[7], Figure 4. However, fiber Bragg gratings can have some ripple in the passband, Figure 5.

As the transmission rate increases the effect of chromatic dispersion becomes more important. The chromatic dispersion in the filters may be the same but the bit time has decreased. For systems with multiple add drop nodes the total chromatic dispersion can be the sum of all the filter stages.

2.9. Cost

The previous sections discussed optical performance. In the next few sections we examine issues related to cost. The first one is the cost of the device. There are

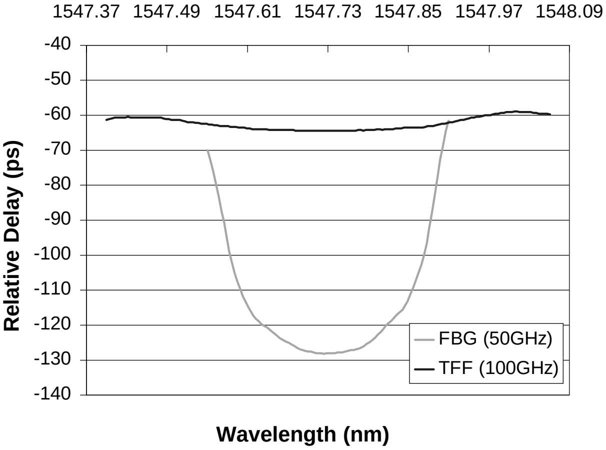

FIG. 5. Dispersion for a fiber Bragg grating (FBG) and a thin film dielectric filter (TFF).

three elements in the total cost. First, is the device cost, a figure of merit is the cost per channel. Second is the operational cost, for example some devices require temperature control. This increases the design complexity due to the extra circuitry required and uses up some of the thermal budget. Third is the cost of any additional components required. For example some technologies might require a circulator or an additional isolator.

2.10. Complexity

This parameter relates to the number of devices required to implement the demultiplexer. For example, the bulk grating technology results in a single device. For fiber Bragg gratings or dielectric filters individual devices are needed for each channel. Thus, a 40 channel demultiplexer might require 40 devices and take up significant board space.

2.11. Scalability

Scalability refers to two concepts. The first is can the number of channels being demultiplexed be increased without completely replacing the demultiplexer. For example, some devices have a port where the remaining wavelength regions are available. This port can then be connected to additional demux devices. Dielectric filter devices can be engineered so that any spectral region that is not demultiplexed is provided as an output. This is in contrast to a waveguide grating router that does not. The second concept is can the device be used to implement and drop an individual channel. In principle all the technologies can do this but the loss and cost is higher for those devices that always operate on all the channels. For example fiber Bragg gratings and dielectric filter based devices are made up of individual channel filters. These filters can then be used to implement add/drop functionality.

2.12. Device Repeatability

System designers require that the devices be repeatable. Variations in channel shape and isolation can use up system design margins. So it is imperative that the manufacturing variations be kept to a minimum. As an example dielectric filters are typically very repeatable from device to device for a particular filter growth. When that substrate is used up the next filter may have some differences. A corollary to this however is that systematic variations are a detriment to long systems. If there is a feature in the filter response it can add up and create unacceptable variations in the passband.

2.13. Tunability

In some optical network designs a tunable demultiplexer offers additional system features. Tunable add/drops can be used to implement optical routing and switching. When speed is not a factor temperature tuning can be utilized. Here, fiber Bragg gratings are applicable. They can be temperature tuned at a rate of

10 pm/°C, if they have not been packaged in a temperature compensating package.

2.14. *Reliability*

A key issue for system designers is meeting the Telcordia specifications for device reliability. GR-1209 and GR-1221 outline a detailed set of environmental tests. The testing required involves up to 5000 hours and requires multiple devices. The length of time and required capital equipment makes this an expensive undertaking.

2.15. *Volume Manufacturing*

While we all like to see the latest and most advanced devices the real question is can they by manufactured in sufficient volumes. This issue is directly related to cost and availability. The required capital equipment and number of employees varies significantly with each technology. For example, waveguide grating routers require semiconductor manufacturing equipment.

3. TECHNOLOGIES

The last few years have seen the deployment of a variety of technologies for demultiplexers. In this section the various technologies are described and their performance examined with respect to the metrics listed above. Table 1 summarizes the data of a number of commercial devices.

3.1. *Dielectric Filters*

Dielectric filter technology has been widely applied to different aspects in WDM systems and is one of the mature technologies. The dielectric filter, or thin-film resonant cavity filter, is an etalon where the mirrors surrounding the cavity are realized by using multiple reflective dielectric thin-film layers. This device behaves as a bandpass filter, passing a particular wavelength band and reflecting all other wavelengths. In DWDM applications, a multi-cavity design is normally used to achieve flat top transmission characteristics and high FOM in spectral shape. Figure 6 illustrates a five-cavity 200 GHz filter spectral plot.

Dielectric filters are a single channel device designed into a micro-optic component arrangement. To obtain multi-channel multiplexing or demultiplexing, a number of these filters have to be cascaded together to form a multi-channel device. To optimize the design requires the choice of a proper architecture, Figure 7. The first architecture is a cascade approach where each filter transmits one wavelength and the rest is reflected. One issue with this approach is that the losses for each channel may not be the same. As the number of channels increases the loss at the last channel will be higher. One advantage of this approach is that the remaining spectrum is available for future use. The broadcast architecture may have more uniform but higher losses. It also does not allow for the use of any additional spectrum.

TABLE 1

Parameter	Dielectric filters	Fiber Bragg gratings	Bulk grating	AWG	Mach-Zehnder
Number of channels	40	32	40	40	16
Channel spacing (GHz)	100	50	100	100	100
Channel shape	Flat top	Flat top	Gaussian	3 dB Bandwidth 40%	Sinusoidal
Adjacent channel isolation (dB)	25	25	22	22	40
Group delay variation	< 1 ps	20 ps	< 1 ps	< 1 ps	
Complexity for N channel device	N filters	N filters and circulators?	1 device	1 device	N-1 devices
Insertion loss (dB)	8 (40 ch)	0.2/fbg	8 (40 ch)	7	5.0
Optical bandwidth at − 0.5 dB (nm)	0.22	0.25	0.2		0.25
PDL (dB)	0.25	< 0.1	0.5	0.5	0.1
Repeatability (processing method)	Deposition	UV writing	Opto mechanica 1	Wafer	Fused fiber devices
Scalability	Yes	Limited	Yes	No	Yes
Temperature stability pm/°C	1.2	0.5	1	Requires stabilization	1
Tunability	No	Yes	No	Yes	Yes
Uniformity (dB)	1	1	2		0.8

Dielectric filter technology has advantages over technologies that use parallel processing, such as waveguide grating routers. First dielectric filters are passive devices, with a temperature drift coefficient of about < 1.2pm/°C. Second, dielectric filters have a flat-top spectral response that is highly desirable in system applications. Third, there is no accumulative cross-talk issue for demultiplexing applications in large channel count systems due to a large free spectral range. Finally, dielectric filter WDM can meet today's network requirements and deployment strategies, both in scalability and in modularity.

An example of the scalability and modularity required is shown in Figure 8. Here a modular design provides a way to reduce the initial deployment cost, and implements a pay as you grow architecture. This approach does not limit the potential capability of the network. The 100 GHz demultiplexers used in Figure 8 are commercially available with less than 8 dB of insertion loss. An alternative to the modular architecture would be a banded approach. This would allow the network operator to do per band upgrade and per band add/drop between nodes to minimize system power penalty.

Currently, dielectric filter technology is the most commercially deployed WDM demultiplexing technology in high speed fiber-optic systems. 200 GHz dielectric filters are gradually becoming commodity products while 100 GHz products have

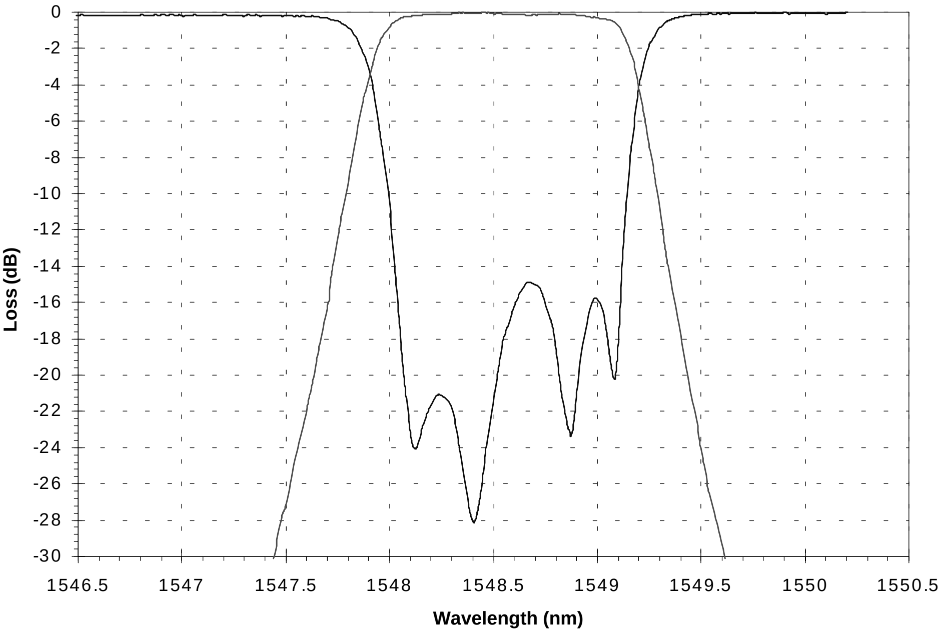

FIG. 6. 200 GHz dielectric filter response. The center passband is the reflection response while the other curve is the transmission response.

been widely deployed in live networks in the past year. Both 75 GHz and 50 GHz 2-port bandpass filters are now available. The latest results on fully functional 50 GHz dielectric filters show $\ll$ 1pm/°C thermal drift. The low thermal drift is due to the improved density of the films obtained with plasma assisted deposition.

3.2. *Fiber Bragg Gratings*

Fiber Bragg gratings are one of the new technologies that has emerged since optical communications began to expand rapidly. The initial discovery was by accident when it was discovered that an intense periodic pattern of ultra violet or blue light could create a matching refractive index pattern.[8] Further work by Meltz

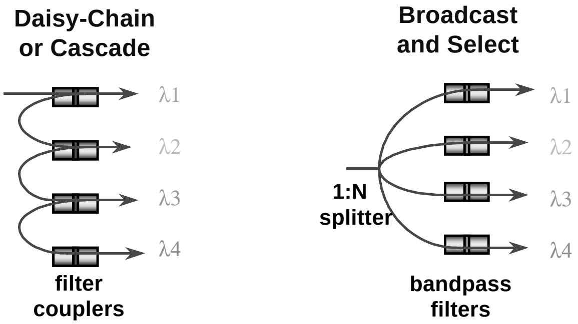

FIG. 7. Thin film filter WDM demultiplexer architectures.

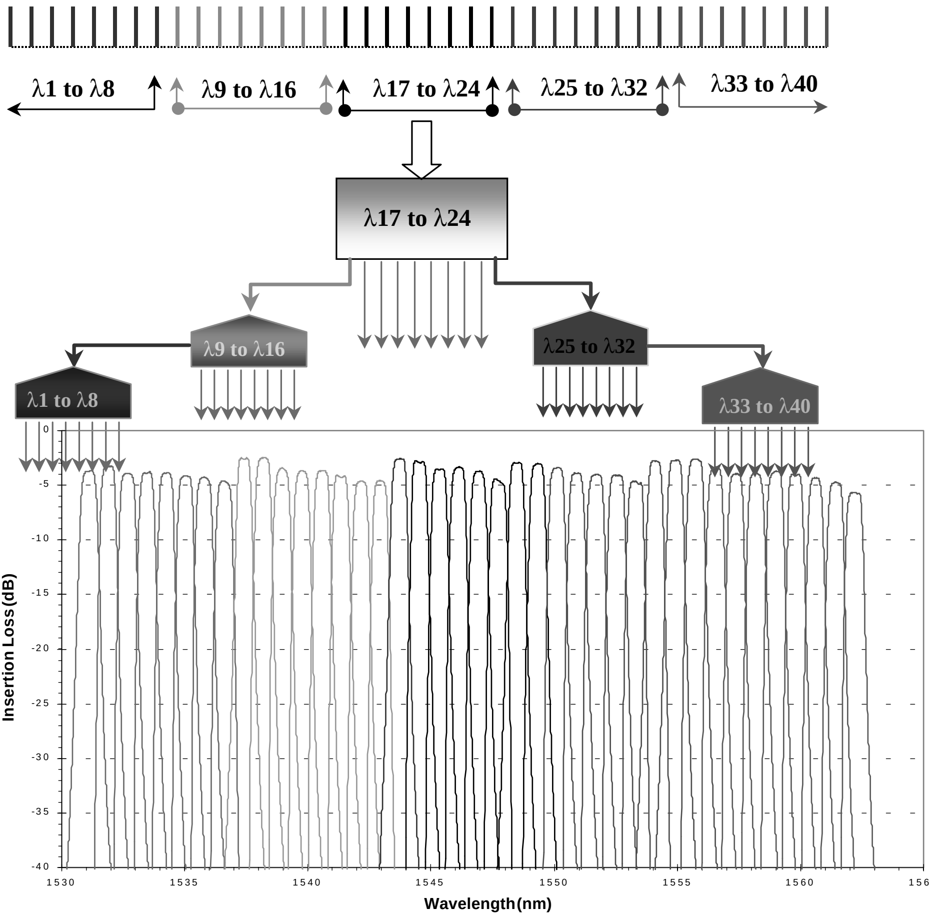

FIG. 8. Modular 40-channel 100 GHz dielectric filter WDM a) Architecture b) Spectral response

et. al. developed a side writing process so that a pattern of any period could be written in the fiber and the fiber Bragg grating could be used as a filter at telecommunication wavelengths.[9] Fiber Bragg gratings have the potential to be extremely low cost high quality optical filters. The basic material is a piece of optical fiber. The production process used by most manufacturers is to place a piece of fiber behind a mask and shine a uv laser through the mask so that a periodic pattern is written into the fiber. This process is only suitable for a small number of gratings to be written simultaneously and so a short alignment and exposure time are essential for a high volume production operation.

The fiber Bragg grating is a periodic structure which reflects light at a wavelength corresponding to twice the grating period.[10] The bandwidth of the reflected light reduces as a function of the length of the grating if the period is uniform and the grating strength is weak. The typical length of a grating for 50 GHz demultiplexing is 20 mm, and the spectral shape is shown in Figure 9. DWDM gratings have high reflectivities, the demux grating shown blocks light to -25 dB over a 0.25 nm window. The stronger the grating the larger the out of band reflections

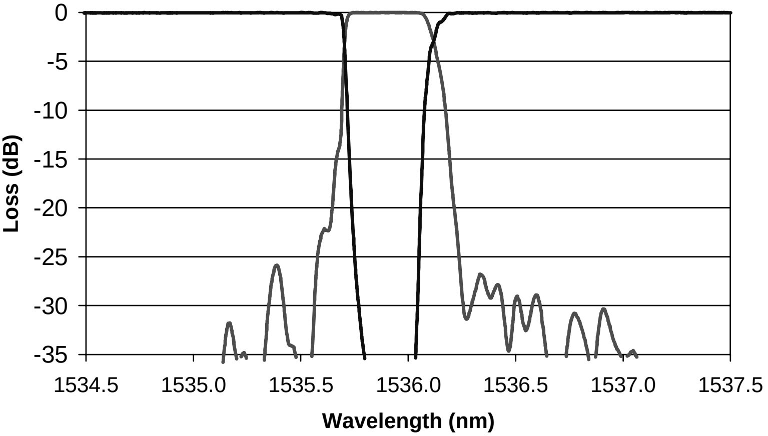

FIG. 9. Typical reflection and transmission spectra of a fiber Bragg grating for 50 GHz add drop applications.

that are caused by side-modes and irregularities in the periodic structure. The side-modes are minimized to below 25 dB by apodizing the grating refractive index profile and the other out of band reflections are minimized by the use of high quality phase masks and high quality optics. A major limitation of fiber Bragg gratings for DWDM applications is the cladding modes which are produced when the Bragg structure couples light at wavelengths below the reflection peak into modes guided by the fiber cladding. The wavelength at which the cladding modes start is a function of the fiber numerical aperture, Figure 10 shows a comparison between standard telecom fiber and high numerical aperture fiber. The high numerical aperture fiber enables fiber Bragg gratings to be used in parts of the network with sixteen 100 GHz spaced channels or thirty-two 50 GHz spaced channels.

One of the big advantages of fiber Bragg gratings over other DWDM technology is the availability of precise temperature compensation by using a packaging process which increases the tension on the fiber Bragg grating as the temperature

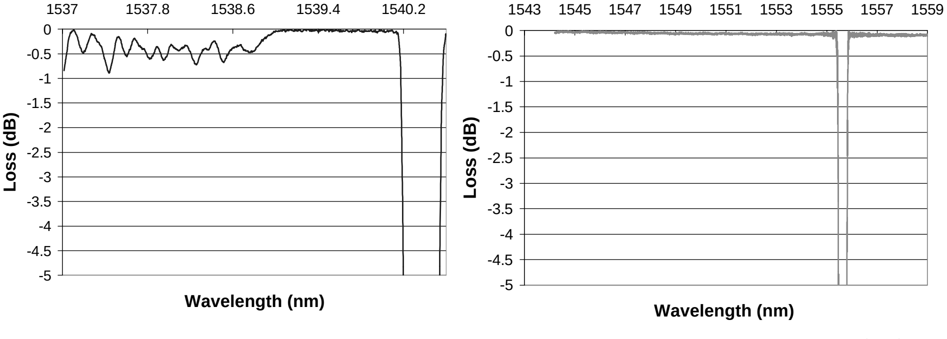

FIG. 10. Comparison of cladding modes in fiber Bragg grating written in SMF28 fiber (left) and high NA fiber (right).

decreases. It is possible to balance out the temperature coefficient to below 0.5 pm/°C. Without compensation the temperature dependent wavelength change is 10pm/°C which is too large for DWDM systems. The fiber Bragg grating offers the best bandwidth and cross-talk performance of all the passive filtering techniques for 50 GHz channel spacing. Fiber Bragg gratings are infinite response filters and they typically have a parabolic group delay, as shown in figure 4, which gives a high group velocity dispersion at the edges. It is possible to bias this group delay response so that the dispersion has one sign over the channel passband and can provide dispersion compensation.

3.3. Free Space Diffraction Gratings

The free space diffraction multiplexers and demultiplexers utilize the same technology as found in monochromators. Simple devices using GRIN rod lenses and a grating were demonstrated as early as 1977.[11] The basic concept is that each wavelength is diffracted by the grating at a different angle. With the proper lens arrangements the angular distribution is converted into a spatial distribution. By placing the fibers at the correct locations the light from each wavelength can be collected. In principle the wavelength range can be very large, but the lens design gets very difficult. One of the key advantages of this type is that only a single grating is required, all the channels are operated on in parallel. The main drawback is the packaging of the optical system and all the fibers for large channel counts.

One approach to implementing a large channel count device is shown in, Figure 11. Light incident on the grating is diffracted at different angles depending on the incident wavelength. The lens converts the angular wavelength dependence into spatial wavelength dependence. The position verses wavelength is given by:

$$x = \frac{f \times \delta\lambda \times p}{\cos\left(\sin^{-1}\left(p\frac{\lambda}{2}\right)\right)}$$

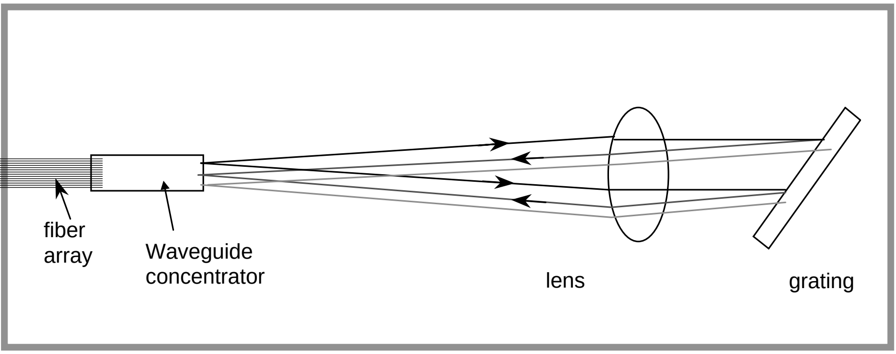

FIG. 11. Schematic of free space diffraction grating demultiplexer.

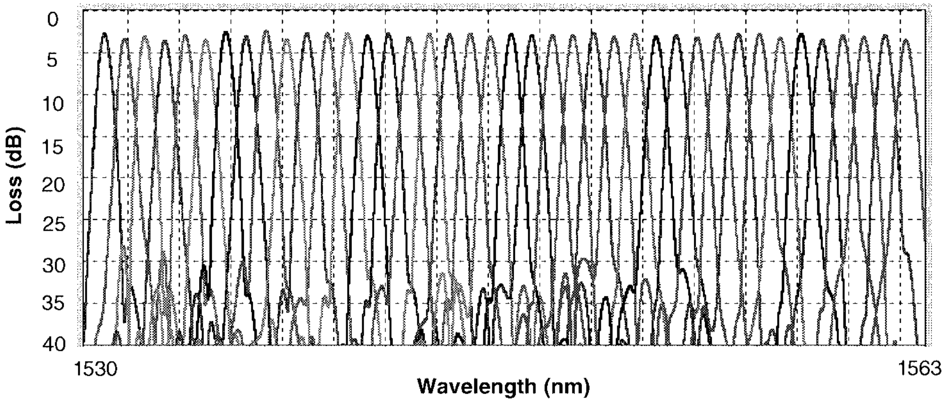

FIG. 12. Spectrum of 42 channel diffraction grating with 100 GHz channel spacing.

where $\delta\lambda$ is the channel spacing, p is the period of the grating and f is the focal length of the lens. The channels are not evenly spaced with frequency as would be required to match the ITU channel grid so a waveguide concentrator chip is used with non uniform pitch to provide an even channel spacing. The waveguide concentrator chip brings the inputs closer together than the 125 μm minimum fiber spacing so that a smaller focal length lens can be used and a compact device can be constructed. The use of the waveguides also allows for wider channel bandwidths. The typical spectral output of such a device is shown in Figure 12. The channels are Gaussian shaped with low levels of cross talk.

If the number of channels is not large then the waveguide concentrator is not required. An alternative approach utilizes a micro-lens array and a linearizing prism.[12] This design also includes a birefringent crystal and a half wave plate to compensate for the polarization dependence of the grating. A 32 channel device with a 3.5 dB loss has been demonstrated. Another approach is to put the grating in a solid block of glass. By choosing the correct glasses the device can be passively thermally compensated.[13]

The advantages of the free space diffraction grating demultiplexer are the low insertion loss that comes from the parallel paths for each channel; the low cross-talk that results from the low scatter level at the grating and the accurate channel centering that is achieved by fine tuning the optical alignment. Typical device parameters for a 42 channel device are shown in Table 1.

A major advantage of the diffraction grating over an AWG device is the potential for stable operation over a wide temperature range. This is achieved by constructing the device with very low expansion materials and using optics with small temperature dependent refractive index changes. The main limitation of the diffraction grating based demultiplexer is that the open optics are vulnerable to contamination and humidity.

3.4. *Mach-Zehnder Based Devices*

Demultiplexers can also be fabricated by using cascaded Mach-Zehnder interferometers. A Mach-Zehnder interferometer is constructed from two 2 × 2 3 dB couplers with the outputs of one device connected to the inputs of the second device. A small path difference is fabricated between the two arms, Figure 13. The resulting interferometer has a response given by[14]

$$I_0(\nu) = I_i(\nu)\cos^2\left(\nu\frac{n\Delta l\pi}{c}\right)$$

where ν is the optical frequency, n is the refractive index of the propagating mode, Δl is path length difference, and c is the speed of light. Thus the channel shape has a $\cos^2$ shape with each output of the interferometer having every other channel. These devices can be fabricated in waveguides[15] or with fused fiber devices. Since the path length and coupling ratio can be controlled precisely the channel spacing is very precise. To obtain individual channels multiple devices with different spacings are cascaded. For example, a 0.8 nm demultiplexer uses 4 stages, 0.8 nm, 1.6 nm, 3.2 nm, and 6.4 nm channel spacing to obtain a 16 channel device, Figure 14.

Some advantages of this device include expandability and low loss. Additional channels at half the channel spacing can be obtained by adding another interferometer at the input of the existing device. For example, a 16 channel 100 GHz device can be upgraded to a 32 channel 50 GHz device[16]. Also, these devices can also be used for multiplexers as the insertion loss for a 16 channel device is only 3.2 dB. However, the passband shape is not a flat top.

Some of the disadvantages of the device include a need for additional filtering or at the output of each channel or doubling of the number of interferometers. The cascaded devices do not provide sufficient isolation by themselves. The filters can be either a dielectric or fiber Bragg grating filter. Another disadvantage for some manufacturers is that they need active temperature stabilization. Device performance is summarized in Table 1 for a 16 channel device.

3.5. *Interleavers*

Another application of the sinusoidal response is a class of devices called interleavers. A de-interleaver is a device that separates a stream of channels into

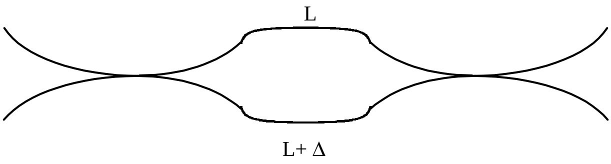

FIG. 13. Mach-Zehnder structure.

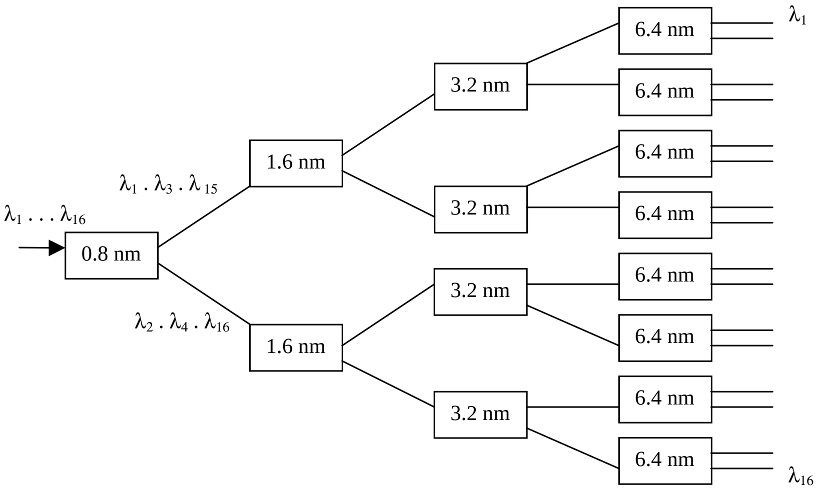

FIG. 14. Mach-Zehnder Based Demux.

two steams of channels each with twice the channel spacing as shown in Figure 15. An interleaver is the same device used to combine two streams of channels into one. The interleaver is a powerful device for future systems in which closer channel spacing will be required. Most DWDM technologies do not have the accuracy or the stability to operate usefully at a channel spacing of 50 GHz or less because of the combined effects of the wavelength temperature coefficient, the channel centering accuracy, and aging. The interleaver converts the 50 GHz spaced channels into more manageable 100 GHz spaced channels. A further pair of interleavers can convert the 100 GHz spaced channels into 200 GHz channels that can be demultiplexed by a various technologies.

In order to offer a benefit over a demultiplexer the interleaver must provide a wider a net pass-band and hence must have low temperature dependence or have active temperature control. The advantage of active temperature control is that not only can the temperature dependence be removed, but also the interleaver can be precisely tuned to the ITU grid.

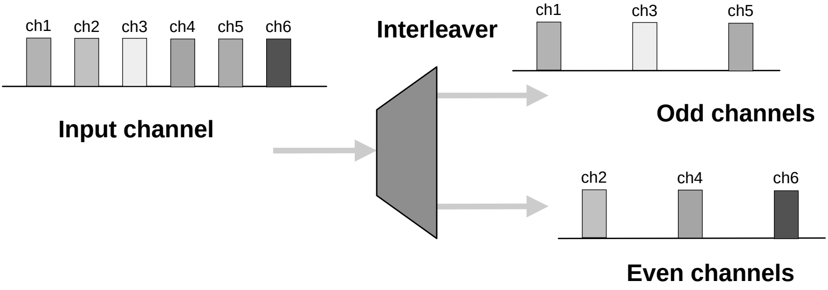

FIG. 15. Operation of a de-interleaver/interleaver.

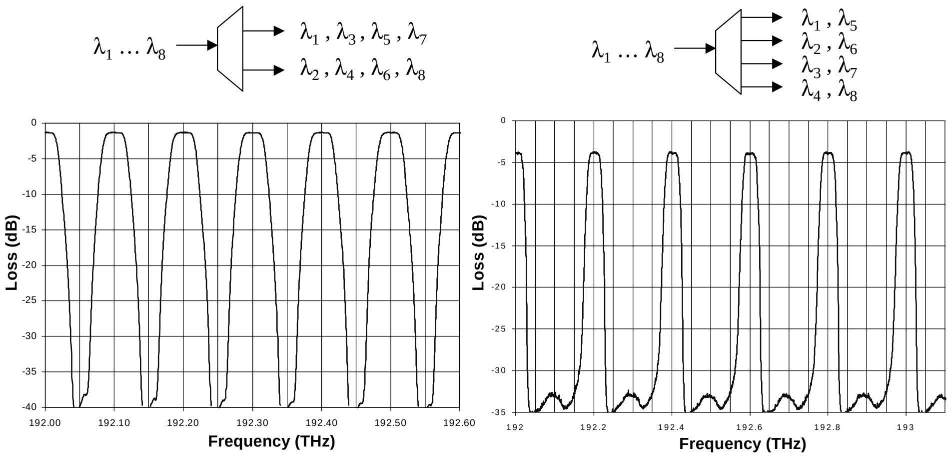

FIG. 16. Output spectra of single and double stage interleavers.

There are many methods for making interleavers. The most common are Mach-Zehnder interferometers, etalons, and polarization based devices. The properties of the Mach-Zehnder interferometer based device were discussed in the previous section, the sinusoidal response does not provide a wide enough bandwidth and low enough cross-talk for most DWDM applications. An etalon requires the correct design of the cavity to obtain the desired spacing. Most likely, temperature stabilization is required. The polarization based device works on the principle of using wavelength dependent birefringent plates to convert wavelength dependent polarization rotation to a wavelength dependent spatial dependence.

Typical parameters for a 50 GHz to 100 GHz de-interleaver would be insertion loss < 1.5 dB, isolation greater than 25 dB, with a net channel 1 dB bandwidth of 0.22 nm. Figure 16 shows the spectral characteristics of a square top single stage and double stage interleaver. Current DWDM systems have 80×50 GHz channels over the 1530 to 1560 nm band and an interleaver would be expected to operate over the entire range. It is therefore essential that the interleaver has a free spectral range very close to 100 GHz and that it maintains this over all operating conditions. For example an interleaver with a 99.5 GHz free spectral range would be off the ITU grid by 0.16 nm and this would result in a net channel bandwidth too small for proper system performance.

3.6. Waveguide Grating Routers

The arrayed waveguide grating router is perhaps the most successful passive integrated optical component. Devices for 8 and 16 channel systems are currently in the field, while 32 channel devices are commercially available. The waveguide router consists of four sections,[15] Figure 17. The input waveguide couples the light from the fibers to the slab waveguide. In the slab waveguide the light diverges and couples into the arrayed waveguides. The length of the array waveguides is chosen such that the optical path difference between adjacent waveguides equals an

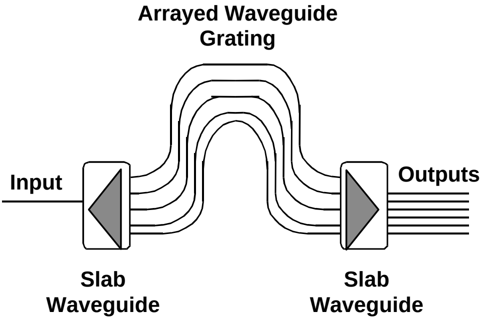

FIG. 17. Waveguide Grating Router.

integer multiple of the central wavelength of the device. For this wavelength the fields in the waveguides will arrive at the output slab waveguide with equal phase. The field distribution at the input is reproduced at the output. Since the length of the waveguides varies, the phase will change with wavelength. This will cause the focal point to shift at the output of the waveguides. The output waveguides are placed at the correct position corresponding to each different wavelength.[17]

There are a number of issues in using these devices. First the device must be temperature stabilized, typically at about 70°C. One interesting approach to eliminating the temperature dependence is to vary the location of the input waveguide slightly.[18] In this design the fiber is coupled directly to the slab waveguide section. For a 16 channel 100 GHz device the insertion loss is less than 7 dB. This value is higher than the filter based devices. The insertion loss can be improved through careful design and fabrication.[19] Also, these devices have a free spectral range similar to Fabry-Perot devices. Thus, they may need additional interference filters to eliminate these additional passbands. A key advantage of this technology is that it can be extended to devices with greater than 32 channels. However, careful attention must be paid to device uniformity. Any variation in the waveguides leads to increased crosstalk.

The majority of these devices have been fabricated in silica on silicon devices. An alternative material system is based on InP materials,[20] which allows the integration of amplifiers. Another material choice is polymer based waveguides.[21]

3.7. Polarization Based Devices

Another technology for implementing demultiplexers and interleavers is based on manipulating the polarization of the individual wavelengths.[22] In this design the input light is split into two polarizations by a birefringent element. The light is then passed through a number of birefringent plates. The amount of polarization rotation depends on the wavelength of the light. By using a number of elements a desired filter shape can be obtained. After passing through each of the birefringent plates the initial horizontal and vertical polarization components of each wavelength are spatially separated. At the output the polarization states of each wavelength are combined back into a single output. Some of the issues for this device are PMD and temperature stability. The device can be made tunable if a polarization rotator is placed after the first birefringent element.

4. FUTURE DIRECTIONS

The demand for bandwidth is insatiable and since installing more cables is both expensive and a lengthy process there is a constant demand to maximize the capacity of installed cables. WDM has provided a way of filling up the bandwidth of installed fibers. While today's systems use 2.5 Gb/s in the 1528-1562 nm band systems with 10 Gbit/s and 50 GHz channel spacing are being planned and will provide 0.8 Tbit/s capacity on the C band and 1.6 Tbit/s capacity if the longer wavelength L band is used. To go beyond this capacity 40 Gbit/s bit rates will be used, but it will be very difficult to operate at channel spacing below 100 GHz so the capacity limit for the near future will be 3.2 Tbit/s per fiber direction.

High channel count demultiplexers will probably use interleavers to increase the channel capacity and to reduce the insertion loss. The quality of the transmitted signal at 40 Gbit/s is very sensitive to fiber dispersion, polarization mode dispersion, self and cross phase modulation. It is probable that the passive network will require active compensation schemes that will keep the network parameters such as dispersion, PMD and channel power in the range for low error 40 Gbit/s communication. The network will no longer be a static entity, but will be dynamic so that it can respond to the changes produced by reconfiguration, the environment, and aging. To get further capacity will mean using additional bandwidth and there will be increased interest in the 1280 to 1480 nm transmission wavelengths, particularly with the coming availability of Raman and semiconductor amplifiers in this spectral region.

Adding extensive switching will further increase network capacity so more of the available bandwidth can be used. Future architectures will need switchable wavelength routing so that optical signals can be sent long distances without optical to electrical conversion. The signal could pass through many filters and therefore flat pass-bands are essential to prevent signal degradation.

There will be a spreading of DWDM to the local network and to the home as demand for bandwidth increases. This will result in a requirement for very low cost demultiplexing components since subscribers are not willing to pay for more bandwidth. The technologies that win in the local network will be the highly integrated devices that can be mass-produced in a similar method to integrated circuits.

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