5.9 Wavelength Stabilization

Luckily for us, it turns out that the wavelength drift due to temperature variations of some of the key components used in WDM systems is quite small. Typical multiplexers and demultiplexers made of silica/silicon have temperature coefficients of 0.01 nm/°C, whereas DFB lasers have a temperature coefficient of 0.1 nm/°C. Some of the other devices that we studied in Chapter 3 have even lower temperature coefficients.

The DFB laser source used in most systems is a key element that must be kept wavelength stabilized. In practice, it may be sufficient to maintain the temperature of the laser fairly constant to within ±0.1°C, which would stabilize the laser to within ±0.01 nm/°C. The laser comes packaged with a thermistor and a thermoelectric (TE) cooler. The temperature can be sensed by monitoring the resistance of the thermistor and can be kept constant by adjusting the drive current of the TE cooler. However, the laser wavelength can also change because of aging effects over a long period. Laser manufacturers usually specify this parameter, typically around ±0.1 nm. If this presents a problem, an external feedback loop may be required to stabilize the laser. A small portion of the laser output can be tapped off and sent to a wavelength discriminating element, such as an optical filter, called a *wavelength locker*. The output of the wavelength locker can be monitored to establish the laser wavelength, which can then be controlled by adjusting the laser temperature.

Depending on the temperature range needed (typically −10 to 60°C for equipment in telco central offices), it may be necessary to temperature-control the multiplexer/demultiplexer as well. For example, even if the multiplexer and demultiplexer are exactly aligned at, say, 25°C, the ambient temperature at the two ends of the link could be different by 70°C, assuming the given numbers. Assuming a temperature coefficient of 0.01 nm/°C, we would get a 0.7 nm difference between the center wavelengths of the multiplexer and demultiplexer, which is clearly intolerable if the interchannel spacing is only 0.8 nm (100 GHz). One problem with temperature control is that it reduces the reliability of the overall component because the TE cooler is often the least reliable component.

An additional factor to be considered is the dependence of laser wavelength on its drive current, typically between 100 MHz/mA and 1 GHz/mA. A laser is typically operated in one of two modes, constant output power or constant drive current, and the drive circuitry incorporates feedback to maintain these parameters at constant values. Keeping the drive current constant ensures that the laser wavelength does not shift because of current changes. However, as the laser ages, it will require more drive current to produce the same output power, so the output power may decrease with time. On the other hand, keeping the power constant may require the drive current to be increased as the laser ages, inducing a small wavelength shift. With typical channel spacings of 100 GHz or thereabouts, this is not a problem, but with tighter channel spacings, it may be desirable to operate the laser in constant current mode and tolerate the penalty (if any) due to the reduced output power.

5.10 Design of Soliton Systems

Although much of our discussion in this chapter applies to the design of soliton systems as well, there are a few special considerations in the design of these systems, which we now briefly discuss.

We discussed the fundamentals of soliton propagation in Section 2.6. Soliton pulses balance the effects of chromatic dispersion and the nonlinear refractive index of the fiber, to preserve their shapes during propagation. In order for this balance to occur, the soliton pulses must have not only a specific shape but also a specific energy. Due to the inevitable fiber attenuation, the pulse energies are reduced, and thus the ideal soliton energy cannot be preserved. A theoretical solution to this problem is the use of dispersion-tapered fibers, where the chromatic dispersion of the fiber is varied suitably so that the balance between chromatic dispersion and nonlinearity is preserved in the face of fiber loss.

In practice, soliton propagation occurs reasonably well even in the case of systems with periodic amplification. However, the ASE added by these amplifiers causes a few detrimental effects. The first effect is that the ASE changes the energies of the pulses and causes bit errors. This effect is similar to the effect in NRZ systems, although the quantitative details are somewhat different.

Although solitons have a specific shape, they are resilient to changes in shape. For example, if a pulse with a slightly different energy is launched, it reshapes itself into a soliton component with the right shape and a nonsoliton component. When ASE is added, the effect is to change the pulse shape, but the solitons reshape themselves to the right shape.

A second effect of the ASE noise that is specific to soliton systems is that the ASE noise causes random changes to the center frequencies of the soliton pulses. For soliton propagation, per se, this would not be a problem because solitons can alter their frequency without affecting their shape and energy. (This is the key to their ability to propagate long distances without pulse spreading.) To see why this is the case, consider the soliton pulse shape given by

$$U(\xi, \tau) = e^{i\xi/2}\operatorname{sech}\tau. \tag{5.28}$$

Here, the distance ξ and time τ are measured in terms of the chromatic dispersion length of the fiber and the pulse width, respectively. The pulse

$$U(\xi, \tau + \Omega\xi)e^{i(\Omega t + \Omega^2 \xi/2} \quad (5.29)$$

is also a soliton for any frequency shift Ω, and thus solitons can alter their frequency without affecting their shape and energy.

Because of the chromatic dispersion of the fiber, however, changes in pulse frequencies are converted into changes in the pulse arrival times, that is, timing jitter. This jitter is called Gordon-Haus jitter, in honor of its discoverers, and is a significant problem for soliton communication systems.

A potential solution to this timing jitter problem is the addition of a bandpass filter whose center frequency is close to that of the launched soliton pulse. In the presence of these filters, the solitons change their center frequencies to match the passband of the filters. For this reason, these filters are called *guiding filters*. This has the effect of keeping the soliton pulse frequencies stable, and hence minimizing the timing jitter. This phenomenon is similar to the solitons reshaping themselves when their shape is perturbed by the added ASE.

The problem with the above solution is that the ASE noise accumulates within the passband of the chain of filters. As a result, the transmission length of the system, before the timing jitter becomes unacceptable, is only moderately improved compared to a system that does not use these filters. The solution to this problem is to change the center frequencies of the filters progressively along the link length. For example, if the filters are used every 20 km, each filter can be designed to have a center frequency that is 0.2 GHz higher than the previous one. Over a distance of 1000 km, this corresponds to a change of 10 GHz. The soliton pulses track the center frequencies of the filters, but the accumulation of ASE noise is lessened. This technique of using *sliding-frequency* guiding filters significantly minimizes timing jitter and makes transoceanic soliton transmission practical.

5.11 Design of Dispersion-Managed Soliton Systems

There are a few drawbacks associated with conventional soliton systems. First, soliton systems require fiber with a very low value of anomalous chromatic dispersion, typically, $D < 0.2$ ps/nm-km. This rules out the possibility of using solitons over the existing fiber infrastructure, which primarily uses SMF or NZ-DSF, since these fibers have much higher values of dispersion. Second, solitons require amplifier spacings on the order of 20–25 km—much closer than what is typically used in practical

WDM systems. Finally, cross-phase modulation (CPM) in WDM systems using conventional solitons causes soliton-soliton collisions, resulting in timing jitter. For these reasons, soliton systems have not been widely deployed.

The use of chirped RZ pulses (see Section 2.6.1), also called dispersion-managed (DM) solitons, overcomes all three problems associated with soliton transmission. First, these pulses can be used over a dispersion-managed fiber plant consisting of fiber spans with large local chromatic dispersion, but with opposite signs such that the total, or average, chromatic dispersion is small. This is typical of most fiber plants used today for 10 Gb/s transmission since they consist of SMF or NZ-DSF spans with dispersion compensation. Thus, no special fiber is required. Second, DM solitons require amplification only every 60–80 km, which is compatible with the amplifier spacings in today's WDM systems. Finally, the effect of CPM is vastly reduced because of the large local chromatic dispersion and thus there is no timing jitter problem. For the same reason, the Gordon-Haus jitter is also reduced, and the sliding-frequency guiding filters used in conventional soliton systems are not required.

In a dispersion-managed system, the spans between amplifiers consist of fibers with alternating chromatic dispersions, as shown in Figure 5.32. Each fiber could have a fairly high chromatic dispersion, but the total chromatic dispersion is small. For example, each span in a dispersion-managed system could consist of a 50 km anomalous chromatic dispersion segment with a chromatic dispersion of 17 ps/nm-km, followed by a 30 km normal chromatic dispersion segment with a chromatic dispersion of −25 ps/nm-km. The total chromatic dispersion over the span is $50 \times 17 - 30 \times 25 = 100$ ps/km. The average chromatic dispersion is $100/80 = 1.25$ ps/nm-km, which is anomalous. A dispersion-managed system could have an average span dispersion that is normal or anomalous. In the same example, if the normal fiber had a chromatic dispersion of −30 ps/nm-km, the average span dispersion would have been $-50/80 = -0.625$ ps/nm-km, which is normal.

When NRZ pulses are used, the average chromatic dispersion can be anomalous or normal, without having a significant impact on system performance. However, in a DM soliton system, the average chromatic dispersion must be designed to be anomalous in order to maintain the shape of the DM solitons. This is similar to the case of conventional solitons, but with the crucial difference that the chromatic dispersion need not be uniformly low and anomalous.

An important aspect of the design of DM soliton systems is the choice of the peak transmit power and the average chromatic dispersion. Both should lie within a certain range in order to achieve low BER operation. This range can be plotted as a contour in a plot of peak transmit power versus average chromatic dispersion, as shown in Figure 5.33. In this figure, we show a typical contour for achieving a BER of 10^{-12} (or $\gamma = 7$) in a 5160 km system with 80 km spans. For values of the transmit power and average chromatic dispersion lying within this contour, the desired BER is achieved or exceeded. In the same plot, the contour for a 2580 km NRZ system

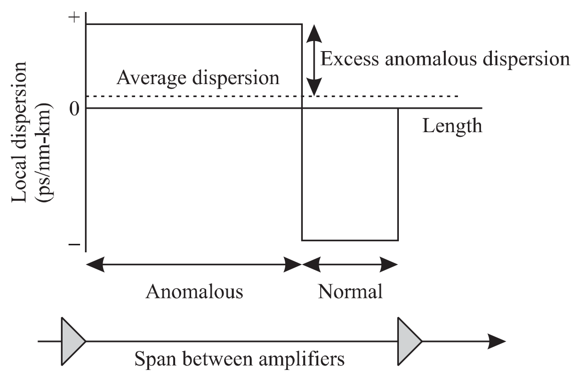

Figure 5.32 A typical dispersion-managed span consisting of a segment of fiber with anomalous chromatic dispersion followed by a segment with normal chromatic dispersion.

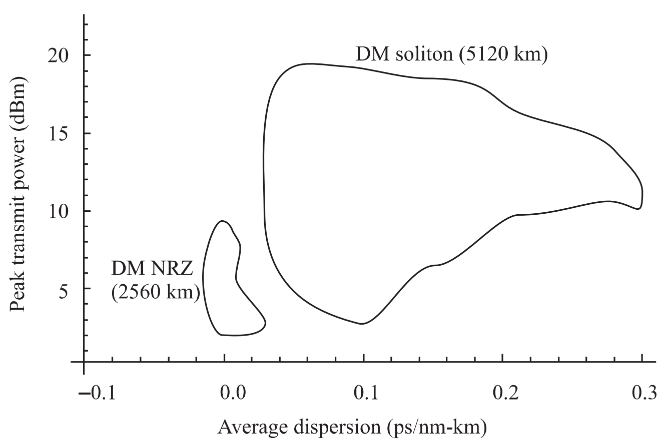

Figure 5.33 Typical contours of constant BER for a DM soliton and an NRZ modulated 10 Gb/s system. (After [Nak00].)

with 80 km spans is also shown. In both NRZ and DM soliton systems, the allowed transmit power has both a lower bound, determined by OSNR requirements, and an upper bound determined by fiber nonlinear effects. From Figure 5.33, note that not only is the DM soliton system capable of achieving regeneration-free transmission for twice the distance as the NRZ system, it is also able to tolerate a much wider range of variation in the transmit power and the average chromatic dispersion.

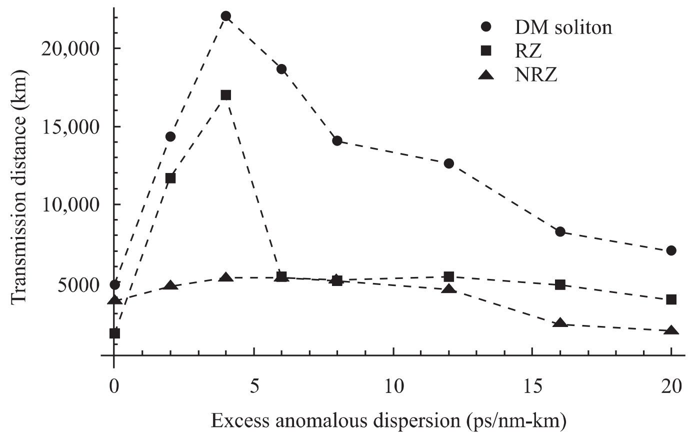

Figure 5.34 Performance of 10 Gb/s DM soliton systems compared with NRZ and (unchirped) RZ modulated systems. (After [Nak00].)

Another important factor influencing the performance of DM soliton systems is the peak-to-peak variation of the chromatic dispersion from the average over the span. In Figure 5.33, the peak-to-peak variation was chosen to be small (1.6 ps/nm-km), and thus both the anomalous and normal segments had very low chromatic dispersion. However, the achievable regeneration-free transmission distance is quite sensitive to the excess chromatic dispersion, relative to the average chromatic dispersion on the span, because of the delicate balancing of the chromatic dispersion against the nonlinearities in the fiber that occurs for soliton-like pulses. Figure 5.34 plots the maximum distance between regenerators as a function of the excess anomalous chromatic dispersion on the span, while maintaining a fixed value of the average chromatic dispersion, for DM solitons as well as NRZ and (unchirped) RZ systems. The excess anomalous chromatic dispersion is the excess of the chromatic dispersion in the anomalous segment over and above the average chromatic dispersion on the link, as indicated in Figure 5.32. Here we assume that the 80 km spans consist of a 50 km anomalous segment and a 30 km normal segment. The NRZ and RZ systems are assumed to be fully dispersion compensated so that the average chromatic dispersion on these spans is zero. For the DM soliton system, the average chromatic dispersion is 0.1 ps/nm-km, which is slightly anomalous. Since the average chromatic dispersion is zero for the NRZ and RZ systems, and quite small in the DM soliton case, the abscissa in Figure 5.34 is effectively the chromatic dispersion of the anomalous segment.

Note from Figure 5.34 that the NRZ system is not sensitive to the excess local chromatic dispersion. This is because the NRZ system essentially operates in the linear regime. Note also that the DM soliton system can achieve considerably higher transmission distances than NRZ and RZ systems for all values of the excess anomalous chromatic dispersion. Thus, DM soliton systems are superior to these systems over virtually all kinds of dispersion-managed fiber spans.

We saw in Section 5.7.4 that (unchirped) RZ systems have a smaller PMD penalty than NRZ systems. Chirped RZ, or DM soliton systems, have an even smaller PMD penalty and thus are more suitable for transmission rates of 40 Gb/s and above, from the PMD perspective as well.

5.12 Overall Design Considerations

We have seen that there is an interplay of many different effects that influence the system design parameters. We will summarize some of these effects in this section. In addition, two key issues in this regard, (1) the trade-off between higher bit rates per channel versus more channels, and (2) whether to use bidirectional or unidirectional systems, will be discussed in Chapter 13.

5.12.1 Fiber Type

Among the many issues facing system designers is what type of fiber should be deployed in new installations. This very much depends on the type of system that is going to be deployed. For single-channel systems operating at very high bit rates (10 Gb/s and above) over long distances, DSF is the best choice. However, DSF makes it much harder to use WDM for upgrading the link capacity in the future, primarily due to four-wave mixing, and thus is not a practical choice for most links. For WDM systems, the choice of fiber type depends on the distance and bit rate per channel. DSF is clearly a bad choice. If the system is not chromatic dispersion limited, then standard single-mode fiber is the best choice because such a system is least susceptible to degradation from nonlinearities. As the distance and bit rate increase in future upgrades, the system will eventually become chromatic dispersion limited (for example, over 600 km at 2.5 Gb/s), and chromatic dispersion compensation must be incorporated into the system. For WDM systems operating at high bit rates over long distances, NZ-DSF provides a good alternative to using standard single-mode fiber with dispersion compensation.

If the residual dispersion slope after chromatic dispersion compensation is the main problem, you can use reduced slope fiber, such as Lucent's TrueWave RS fiber.

On the other hand, if nonlinearities are the significant problem, large effective area fiber, such as Corning's LEAF, can be used. For terrestrial systems, NZ-DSF fiber with positive dispersion in the 1.55 μm band can be used in order to be able to upgrade the system to use the L-band wavelengths. For submarine systems, NZ-DSF with negative dispersion fiber can be used in order to avoid modulation instability.

The following are some transmission numbers. Using carefully dispersion-managed fiber spans, transmission of 120 channels, each running at 20 Gb/s over a distance of 6200 km, has been demonstrated [VPM01]. This experiment used only C-band EDFAs. Using both the C-band and the L-band, and combining distributed Raman amplification with EDFAs, transmission of 77 42.7 Gb/s channels over 1200 km has been demonstrated [Zhu01]. Over short distances, about 100 km, and using all three bands (S-band, C-band, and L-band), transmission of over 250 40 Gb/s channels has been demonstrated [Fuk01, Big01].

5.12.2 *Transmit Power and Amplifier Spacing*

The upper limit on the transmitted power per channel P is determined by the saturation power of the optical amplifiers, the effect of nonlinearities, and safety considerations. From a cost point of view, we would like to maximize the distance l between amplifier stages, so as to minimize the number of amplifiers. The transmitted power per channel, P, and the total link length L, along with the amplifier noise figure and receiver sensitivity, determine the maximum value of l possible. In addition, as l increases, the penalty due to nonlinearities also increases, which by itself may play a role in limiting the value of l.

The amplifier spacing in existing systems must also conform to the repeater hut spacing, typically about 80 km, though this is not an issue for new installations.

5.12.3 *Chromatic Dispersion Compensation*

In systems that have to operate over standard single-mode fiber, chromatic dispersion must be compensated frequently along the link, since the total chromatic dispersion usually cannot be allowed to accumulate beyond a few thousand ps/nm. Systems employing NZ-DSF can span longer lengths before chromatic dispersion compensation is required. In addition to chromatic dispersion compensation, chromatic dispersion slope also needs to be compensated. The ultimate limits of link lengths before the wavelengths need to be demultiplexed and compensated individually are set by the variation in dispersion slope since dispersion slope cannot usually be compensated exactly for all the channels. The use of reduced slope fiber increases this length. By careful span engineering using a large effective area fiber followed by a carefully tailored dispersion compensating fiber, to minimize the dispersion slope, transmission of 120 WDM channels at 20 Gb/s each over 6200 km has been demonstrated

[Cai01]. Using similar techniques, transmission of 101 WDM channels at 10 Gb/s each over 9000 km has also been demonstrated [Bak01].

5.12.4 *Modulation*

Most systems in use today employ NRZ modulation. However, chirped RZ modulation is being considered for ultra-long-haul systems, operating at 10 Gb/s and above. The main motivation for chirped RZ systems is that by the appropriate combination of chirping and chromatic dispersion compensation, such systems achieve very long, regeneration-free transmission. The penalties due to PMD are also lower for RZ modulation than they are for NRZ modulation.

Within NRZ systems, direct modulation is less expensive but leads to chirping, which in turn increases the chromatic dispersion penalties. External modulation is required in chromatic dispersion–limited systems, particularly 10 Gb/s systems. Today, most long-haul systems use external modulation. Metro WDM systems usually employ direct modulation up to bit rates of 2.5 Gb/s to keep costs low, and try to achieve distances of 100–200 km before reaching the chromatic dispersion limit.

Prechirping can be used to increase the link lengths by taking advantage of the pulse compression effects that occur when positively (negatively) chirped pulses are used in positive (negative) dispersion fiber.

5.12.5 *Nonlinearities*

Nonlinear effects can be minimized by using lower transmit powers. The use of a large effective area fiber allows the use of higher transmit powers, and hence longer links, in the presence of nonlinearities. The trade-off is the higher dispersion slope of these fibers.

Some nonlinear effects can actually be beneficial. For example, SPM can sometimes lead to longer link lengths since the positive chirping due to SPM over positive dispersion fiber leads to pulse compression.

5.12.6 *Interchannel Spacing and Number of Wavelengths*

Another design choice is the interchannel spacing. On the one hand, we would like to make the spacing as large as possible, since it makes it easier to multiplex and demultiplex the channels and relaxes the requirements on component wavelength stability. Larger interchannel spacing also reduces the four-wave mixing penalty if that is an issue (for example, in systems with dispersion-shifted fiber). It also allows future upgrades to higher bit rates per channel, which may not be feasible with very tight channel spacings. For example, today's systems operate with 100 GHz channel spacing with bit rates per channel up to 10 Gb/s. Such a system can be upgraded by introducing additional wavelengths between two successive wavelengths leading to 50 GHz channel spacing. Alternatively, the channel spacing can be maintained at 100 GHz and the bit rate per channel increased to 40 Gb/s. If the initial channel spacing is reduced to 50 GHz, it becomes much harder to upgrade the system to operate the channels at 40 Gb/s.

On the other hand, we would like to have as many channels as possible within the limited amplifier gain bandwidth, which argues for having a channel spacing as tight as possible. For a given number of channels, it is easier to flatten the amplifier gain profile over a smaller total bandwidth. Moreover, the smaller the total system bandwidth, the lesser the penalty due to stimulated Raman scattering (although this is not a limiting factor unless the number of channels is fairly large).

Other factors also limit the number of wavelengths that can be supported in the system. The total amplifier output power that can be obtained is limited typically to 20–25 dBm, and this power must be shared among all the channels in the system. So as the number of wavelengths increases, the power per channel decreases, and this limits the total system span. Another limiting factor is the stability and wavelength selectivity of the multiplexers and demultiplexers.

Two other techniques are worthy of mention in the context of designing high channel count systems. The first is the interleaving of wavelengths transmitted in the two directions. Thus, if λ_i^E and λ_i^W denote the wavelengths to be transmitted in the east and west directions, we transmit $\lambda_1^E, \lambda_2^W, \lambda_3^E, \ldots$ on one fiber, and $\lambda_1^W, \lambda_2^E, \lambda_3^W, \ldots$ on the other fiber. This technique effectively doubles the spacing between the wavelengths as far as the nonlinear interactions are concerned.

The second technique is similar but is applicable when both the C-band and L-band are used. In this case, the nonlinear interactions between the signals in the two bands can be avoided by transmitting the signals in one band in one direction over the fiber, and the signals in the other band in the other direction. If this is done, the nonlinear interactions effectively "see" only one of the bands.

Taking all this into consideration, 160-channel systems operating at 10 Gb/s per channel, with 50 GHz spacings, have been designed and are commercially available today. Even larger numbers of channels can be obtained by reducing the channel spacing and improving the stability and selectivity of the wavelength multiplexers and demultiplexers.

5.12.7 *All-Optical Networks*

All-optical networks consist of optical fiber links between nodes with all-optical switching and routing of signals at the nodes, without electronic regeneration. The various aspects of system design that we studied in this chapter apply to point-to-point links as well as all-optical networks, and we have attempted to consider several factors that affect networks more than point-to-point links. Designing networks is significantly harder than designing point-to-point links for the following reasons:

- The reach required for all-optical networks is considerably more than the reach required for point-to-point links, since lightpaths must traverse multiple links. In addition, loss, chromatic dispersion, and nonlinearities do not get reset at each node.
- The network is more susceptible to crosstalk, which is accumulated at each node along the path.
- Misalignment of multiplexers and demultiplexers along the path is more of a problem in networks than in links.
- Because of bandwidth narrowing of cascaded multiplexers and demultiplexers, the requirements on laser wavelength stability and accuracy are much higher than in point-to-point links.
- The system designer must deal with the variation of signal powers and signal-to-noise ratios among different lightpaths traveling through different numbers of nodes and having different path lengths. This can make system design particularly difficult. A common approach used to solve this problem is to equalize the powers of each channel at each node individually. Thus, at each node the powers in all the channels are set to a common value. This ensures that all lightpaths reach their receivers with the same power, regardless of their origin or their path through the network.
- Rapid dynamic equalization of the amplifier gains will be needed to compensate for fluctuations in optical power as lightpaths are taken down or set up, or in the event of failures.

5.12.8 *Wavelength Planning*

The International Telecommunications Union (ITU) has been active in trying to standardize a set of wavelengths for use in WDM networks. This is necessary to ensure eventual interoperability between systems from different vendors (although this is very far away). An important reason for setting these standards is to allow component vendors to manufacture to a fixed standard, which allows volume cost reductions, as opposed to producing custom designs for different system vendors.

The first decision to be made is whether to standardize channels at equal wavelength spacing or at equal frequency spacing. At $\lambda = 1550$ nm, $c = 3 \times 10^8$ m/s, a 1 nm wavelength spacing corresponds to approximately 120 GHz of frequency spacing. Equal frequency spacing results in somewhat unequal wavelength spacing. Certain components used in the network, such as AWGs and Mach-Zehnder filters,

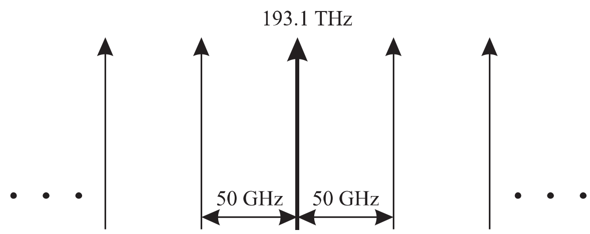

Figure 5.35 Wavelength grid selected by the ITU.

naturally accept channels at equal frequency spacings, whereas other components, including other forms of gratings, accept channels more naturally at equal wavelength spacings. There is no major technical reason to favor one or the other. The ITU has picked equal frequency spacing for their standard, and this is specified in ITU G.692. The channels are to be placed in a 50 GHz grid (0.4 nm wavelength spacing) with a nominal center frequency of 193.1 THz (1552.52 nm) in the middle of the 1.55 μm fiber and EDFA passband, as shown in Figure 5.35. For systems with channel spacings of 100 GHz or more, the frequencies are to be placed on a 100 GHz grid, with the same reference frequency of 193.1 THz. This latter grid was the first standard, before the 50 GHz grid was introduced.

The choice of the 50 GHz frequency spacing is based on what is feasible with today's technology in terms of mux/demux resolutions, frequency stability of lasers and mux/demuxes, and so on. As the technology improves, and systems with more channels become practical, the grid spacing may have to be reduced. Moreover, in systems that must operate over dispersion-shifted fiber, it may be desirable to have unequal channel spacings to alleviate the effects of four-wave mixing. This will also require a finer grid spacing since all these unequal spacings must be accommodated within the same total bandwidth, which in turn necessitates a finer grid. For example, a system using the channels 193.1, 193.2, 193.3, and 193.4 THz is spaced on a 100 GHz grid, and the channel spacings are all equal to 100 GHz. If the channel spacings are made unequal and are, say, 50, 100, and 150 GHz, we can use the channels 193.1, 193.15, 193.25, and 193.4 THz. This system occupies the same bandwidth from 193.1 to 193.4 THz as the equally spaced system, but the channels are on a 50 GHz grid instead of a 100 GHz grid. (If we do not place the channels on this finer 50 GHz grid but still use a 100 GHz grid, we will end up using more total bandwidth to achieve the unequal channel spacing; see Problem 5.27.) In fact, to tackle the unequal spacing requirement due to four-wave mixing on dispersion-shifted fibers, ITU allows such systems to have some wavelengths that are on a 25 GHz grid; see ITU G.692 for details.

That being said, a much more difficult decision is to pick a standard set of wavelengths for use in 4-, 8-, 16-, and 32-wavelength systems to ensure interoperability. This is because different manufacturers have different optimized channel configurations and different upgrade plans to go from a system with a small number of channels to a system with a larger number of channels. As of this writing, ITU is standardizing (ITU G.959) the set of 16 wavelengths starting with 192.1 THz, and spaced 200 GHz apart, for multichannel interfaces between WDM equipment.

It is not enough to specify the nominal center frequencies of the channels alone. A maximum deviation must also be specified because of manufacturing tolerances and aging over the system's lifetime. The deviation should not be too large; otherwise, we would get significant penalties due to crosstalk, additional loss, chirp, and the like. The deviation is a function of the interchannel spacing, Δf. For $\Delta f \geq 200$ GHz, the ITU has specifed that the deviation should be no more than $\pm\Delta f/5$ GHz.

5.12.9 Transparency

Among the advantages touted for WDM systems is the fact that they are transparent to bit rate, protocol, and modulation formats. It is true to a large extent that a wavelength can carry arbitrary data protocols. Providing transparency to bit rate and modulation formats is much more difficult. For instance, analog transmission requires much higher signal-to-noise ratios and linearity in the system than digital transmission and is much more susceptible to impairments. A WDM system can be designed to operate at a maximum bit rate per channel and can support all bit rates below that maximum. We cannot assume that the system is transparent to increases in the maximum bit rate. The maximum bit rate affects the choice of amplifier spacings, filter bandwidths, and dispersion management, among other parameters. Thus the system must be designed up front to support the maximum possible bit rate.

Summary

This chapter was devoted to studying the effects of various impairments on the design of the new generation of WDM and high-speed TDM transmission systems and networks. Although impairments due to amplifier cascades, dispersion, nonlinearities, and crosstalk may not be significant in lower-capacity systems, they play significant roles in the new generation of systems, particularly in networks, as opposed to point-to-point links. We learned how to compute the penalty due to each impairment and budget for the penalty in the overall system design. We also studied how to reduce the penalty due to each impairment. Transmission system design requires careful attention to each impairment because requirements on penalties usually translate into specifications on the components that the system is built out of, which in turn translate to system cost. Design considerations for transmission systems are summarized in the last section of this chapter.

Further Reading

We recommend the recent books by Kaminow and Koch [KK97a, KK97b] for an in-depth coverage of the advanced aspects of lightwave system design. For authoritative treatments of EDFAs, see [BOS99, Des94]. Gain equalization of amplifiers is an important problem, and several approaches have been proposed [Des94]. Amplifier cascades are discussed in several papers; see, for example, [Ols89, RL93, MM98]. Amplifier power transients are discussed in [Zys96, LZNA98]. The optical feedback loop for automatic gain control (AGC) illustrated in Figure 5.8 was first described in [Zir91].

Crosstalk is analyzed extensively in several papers. Intrachannel crosstalk is considered in [ZCC+96, GEE94, TOT96]. Interchannel crosstalk is analyzed in [ZCC+96, HH90]. Dilation in switches is discussed in [Jac96, PN87].

Chromatic dispersion and intermodal dispersion are treated at length in the aforementioned books. The different types of single-mode fiber have been standardized; see ITU G.652, ITU G.653, and ITU G.655. Polarization-mode dispersion is studied in [PTCF91, CDdM90, BA94, ZO94]; see also [KK97a, Chapter 6]. For recent work on PMD compensation, see [Kar01, PL01]. PMD compensation is analyzed in [SKA00], and the effects of PMD on NRZ and RZ pulses are compared in [SKA01].

Good surveys of fiber nonlinearities appear in [Chr90, Agr95, Buc95, SNIA90]. See also [TCF+95, FTC95, SBW87, Chr84, OSYZ95].

The standards bodies have given a lot of thought in defining the system parameters for WDM systems. The 50 GHz wavelength grid is specified in ITU G.692. It is instructive to read this and other related standards: ITU G.691, ITU G.681, ITU G.692, Telcordia GR-253, Telcordia GR-192, and Telcordia GR-2918, which provide values for most of the system parameters used in this chapter.

For a discussion of the design issues in achieving 40 Gb/s WDM transmission, see [Nel01]. The design of transoceanic WDM systems is discussed in [Gol00]. Our treatment of the design of DM soliton systems is based on [Nak00]. The Differential Phase Shift Keying (DPSK) modulation scheme discussed in [MLS+06] allows 40 Gb/s WDM transmission to be deployed on networks designed for 10 Gb/s WDM transmission and, at the time of this writing, is increasingly being deployed in long-haul networks.

Problems

5.1 In an experiment designed to measure the attenuation coefficient α of optical fiber, the output power from an optical source is coupled onto a length of the fiber and measured at the other end. If a 10-km-long spool of fiber is used, the received optical power is −20 dBm. Under identical conditions but with a 20-km-long spool of fiber (instead of the 10-km-long spool), the received optical power is −23 dBm. What is the value of α (in dB/km)? If the source-fiber coupling loss is 3 dB, the fiber-detector coupling loss is 1 dB, and there are no other losses, what is the output power of the source (expressed in mW)?

5.2 The following problems relate to simple link designs. Assume that the bit rate on the link is 1 Gb/s, the dispersion at 1.55 μm is 17 ps/nm-km, and the attenuation is 0.25 dB/km, and at 1.3 μm, the dispersion is 0 and the attenuation is 0.5 dB/km. (Neglect all losses except the attenuation loss in the fiber.) Assume that NRZ modulation is used.

(a) You have a transmitter that operates at a wavelength of 1.55 μm, has a spectral width of 1 nm, and an output power of 0.5 mW. The receiver requires −30 dBm of input power in order to achieve the desired bit error rate. What is the length of the longest link that you can build?

(b) You have another transmitter that operates at a wavelength of 1.3 μm, has a spectral width of 2 nm, and an output power of 1 mW. Assume the same receiver as before. What is the length of the longest link that you can build?

(c) You have the same 1.3 μm transmitter as before, and you must achieve an SNR of 30 dB using an APD receiver with a responsivity of 8 A/W, a gain of 10, an excess noise factor of 5 dB, negligible dark current, a load resistance of 50 Ω, and an amplifier noise figure of 3 dB. Assume that a receiver bandwidth of $B/2$ Hz is sufficient to support a bit rate of B b/s. What is the length of the longest link you can build?

(d) Using the same 1.3 μm transmitter as before, you must achieve an SNR of 20 dB using a *pin* receiver with a responsivity of 0.8 A/W, a load resistance of 300 Ω, and an amplifier noise figure of 5 dB. Assume that a receiver bandwidth of $B/2$ Hz is sufficient to support a bit rate of B b/s. What is the length of the longest link you can build?

5.3 Compute the dispersion-limited transmission distance for links with standard single-mode fiber at 1550 nm as a function of the bit rate (100 Mb/s, 1 Gb/s, and 10 Gb/s)