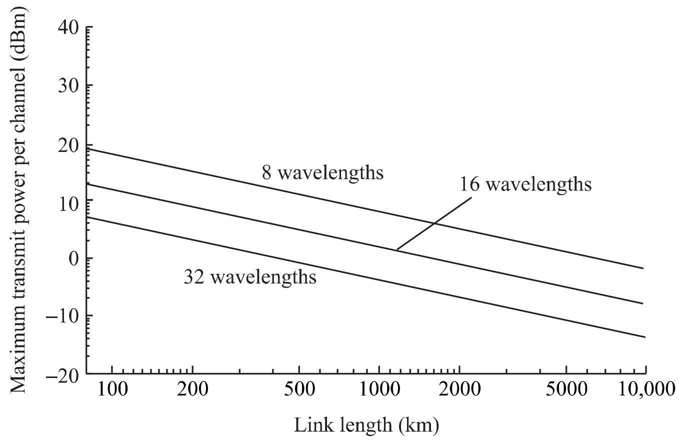

Figure 5.28 Limitation on the maximum transmit power per channel imposed by stimulated Raman scattering. The channel spacing is assumed to be 0.8 nm, and amplifiers are assumed to be spaced 80 km apart.

If the channel spacing is fixed, the power that can be launched decreases with W as $1/W^2$. For example, in a 32-wavelength system with channels spaced 0.8 nm (100 GHz) apart, and $L_e = 20$ km, $P \leq 2.5$ mW. Figure 5.28 plots the maximum allowed transmit power per channel as a function of the link length.The limit plotted here corresponds to $P_{\text{tot}}\Lambda L_e < 80{,}000$ mW-nm-km.

Although SRS is not a significant problem in systems with a small number of channels due to the relatively high threshold power, it can pose a serious problem in systems with a large number of wavelengths. To alleviate the effects of SRS, we can (1) keep the channels spaced as closely together as possible and/or (2) keep the power levels below the threshold, which will require us to reduce the distance between amplifiers.

5.8.4 Four-Wave Mixing

We saw in Section 2.5 that the nonlinear polarization causes three signals at frequencies ω_i, ω_j, and ω_k to interact to produce signals at frequencies $\omega_i \pm \omega_j \pm \omega_k$. Among these signals, the most troublesome one is the signal corresponding to

$$\omega_{ijk} = \omega_i + \omega_j - \omega_k, \; i \neq k, \; j \neq k. \tag{5.26}$$

Depending on the individual frequencies, this beat signal may lie on or very close to one of the individual channels in frequency, resulting in significant crosstalk to

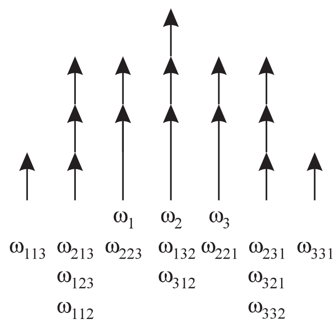

Figure 5.29 Four-wave mixing terms caused by the beating of three equally spaced channels at frequencies ω_1, ω_2, and ω_3.

that channel. In a multichannel system with W channels, this effect results in a large number ($W(W-1)^2$) of interfering signals corresponding to i, j, k varying from 1 to W in (5.26). In a system with three channels, for example, 12 interfering terms are produced, as shown in Figure 5.29.

Interestingly, the effect of four-wave mixing depends on the phase relationship between the interacting signals. If all the interfering signals travel with the same group velocity, as would be the case if there were no chromatic dispersion, the effect is reinforced. On the other hand, with chromatic dispersion present, the different signals travel with different group velocities. Thus the different waves alternately overlap in and out of phase, and the net effect is to reduce the mixing efficiency. The velocity difference is greater when the channels are spaced farther apart (in systems with chromatic dispersion).

To quantify the power penalty due to four-wave mixing, we will use the results of the analysis from [SBW87, SNIA90, TCF+95, OSYZ95]. We start with (2.37) from Section 2.5.8:

$$P_{ijk} = \left(\frac{\omega_{ijk}\bar{n}d_{ijk}}{3cA_e}\right)^2 P_i P_j P_k L^2.$$

This equation assumes a link of length L without any loss and chromatic dispersion. Here P_i, P_j, and P_k denote the powers of the mixing waves and P_{ijk} the power of the resulting new wave, $\bar{n}$ is the nonlinear refractive index (3.0×10^{-8} μm^2/W), and d_{ijk} is the so-called degeneracy factor.

In a real system, both loss and chromatic dispersion are present. To take the loss into account, we replace L with the effective length L_e, which is given by (5.24) for a system of length L with amplifiers spaced l km apart. The presence of chromatic dispersion reduces the efficiency of the mixing. We can model this by assuming a parameter η_{ijk}, which represents the efficiency of mixing of the three waves at frequencies ω_i, ω_j, and ω_k. Taking these two into account, we can modify the preceding equation to

$$P_{ijk} = \eta_{ijk} \left(\frac{\omega_{ijk} \bar{n} d_{ijk}}{3cA_e} \right)^2 P_i P_j P_k L_e^2.$$

For on-off keying (OOK) signals, this represents the worst-case power at frequency ω_{ijk}, assuming a 1 bit has been transmitted simultaneously on frequencies ω_i, ω_j, and ω_k.

The efficiency η_{ijk} goes down as the phase mismatch $\Delta\beta$ between the interfering signals increases. From [SBW87], we obtain the efficiency as

$$\eta_{ijk} = \frac{\alpha^2}{\alpha^2 + (\Delta\beta)^2} \left[1 + \frac{4e^{-\alpha l} \sin^2(\Delta\beta l/2)}{(1 - e^{-\alpha l})^2} \right].$$

Here, $\Delta\beta$ is the difference in propagation constants between the different waves, and D is the chromatic dispersion. Note that the efficiency has a component that varies periodically with the length as the interfering waves go in and out of phase. In our examples, we will assume the maximum value for this component. The phase mismatch can be calculated as

$$\Delta\beta = \beta_i + \beta_j - \beta_k - \beta_{ijk},$$

where β_r represents the propagation constant at wavelength λ_r.

Four-wave mixing manifests itself as intrachannel crosstalk. The total crosstalk power for a given channel ω_c is given as $\sum_{\omega_i + \omega_j - \omega_k = \omega_c} P_{ijk}$. Assume the amplifier gains are chosen to match the link loss so that the output power per channel is the same as the input power. The crosstalk penalty can therefore be calculated from (5.12).

Assume that the channels are equally spaced and transmitted with equal power, and the maximum allowable penalty due to FWM is 1 dB. Then if the transmitted power in each channel is P, the maximum FWM power in any channel must be $< \epsilon P$, where ϵ can be calculated to be 0.034 for a 1 dB penalty using (5.12). Since the generated FWM power increases with link length, this sets a limit on the transmit power per channel as a function of the link length. This limit is plotted in Figure 5.30 for both standard single-mode fiber (SMF) and dispersion-shifted fiber (DSF) for three cases: (1) 8 channels spaced 100 GHz apart, (2) 32 channels spaced 100 GHz apart, and (3) 32 channels spaced 50 GHz apart. For SMF the chromatic dispersion parameter is taken to be $D = 17$ ps/nm-km, and for DSF the chromatic dispersion zero is assumed to lie in the middle of the transmitted band of channels.

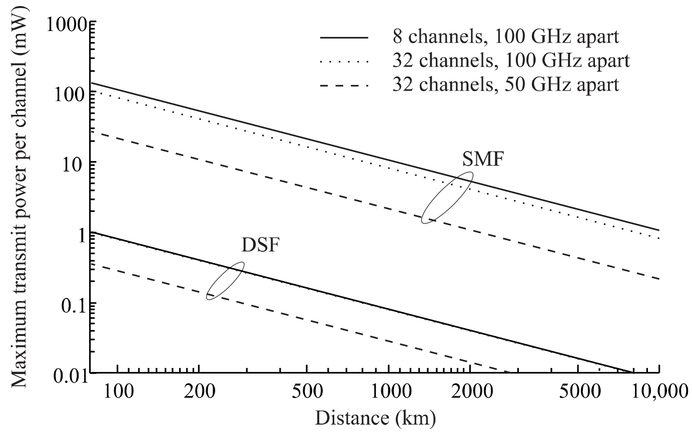

Figure 5.30 Limitation on the maximum transmit power per channel imposed by four-wave mixing for systems operating over standard single-mode fiber and dispersionshifted fiber. For standard single-mode fiber, D is assumed to be 17 ps/nm-km, and for dispersion-shifted fiber, the chromatic dispersion zero is assumed to lie in the middle of the transmitted band of channels. The amplifiers are assumed to be spaced 80 km apart.

The slope of the chromatic dispersion curve, $dD/d\lambda$, is taken to be 0.055 ps/nm-km^2. We leave it as an exercise (Problem 5.28) to compute the power limits in the case of NZ-DSF.

In Figure 5.30, first note that the limit is significantly worse in the case of dispersion-shifted fiber than it is for standard fiber. This is because the four-wave mixing efficiencies are much higher in dispersion-shifted fiber due to the low value of the chromatic dispersion. Second, the power limit gets worse with an increasing number of channels, as can be seen by comparing the limits for 8-channel and 32-channel systems for the same 100 GHz spacing. This effect is due to the much larger number of four-wave mixing terms that are generated when the number of channels is increased. In the case of dispersion-shifted fiber, this difference due to the number of four-wave mixing terms is imperceptible since, even though there are many more terms for the 32-channel case, the same 8 channels around the dispersion zero as in the 8-channel case contribute almost all the four-wave mixing power. The four-wave mixing power contribution from the other channels is small because there is much more chromatic dispersion at these wavelengths. Finally, the power limit decreases significantly if the channel spacing is reduced, as can be seen by comparing the curves for the two 32-channel systems with channel spacings of 100 GHz and 50 GHz. This decrease in the allowable transmit power arises because the four-wave mixing efficiency increases with a decrease in the channel spacing since the phase mismatch $\Delta\beta$ is reduced. (For SMF, though the efficiencies at both 50 GHz and 100 GHz are small, the efficiency is much higher at 50 GHz than at 100 GHz.)

Four-wave mixing is a severe problem in WDM systems using dispersion-shifted fiber but does not usually pose a major problem in systems using standard fiber. In fact, it motivated the development of NZ-DSF fiber (see Section 5.7). In general, the following actions alleviate the penalty due to four-wave mixing:

1. Unequal channel spacing: The positions of the channels can be chosen carefully so that the beat terms do not overlap with the data channels inside the receiver bandwidth. This may be possible for a small number of channels in some cases but needs careful computation of the exact channel positions.
2. Increased channel spacing: This increases the group velocity mismatch between channels. This has the drawback of increasing the overall system bandwidth, requiring the optical amplifiers to be flat over a wider bandwidth, and increases the penalty due to SRS.
3. Using higher wavelengths beyond 1560 nm with DSF: Even with DSF, a significant amount of chromatic dispersion is present in this range, which reduces the effect of four-wave mixing. The newly developed L-band amplifiers can be used for long-distance transmission over DSF.
4. As with other nonlinearities, reducing transmitter power and the amplifier spacing will decrease the penalty.
5. If the wavelengths can be demultiplexed and multiplexed in the middle of the transmission path, we can introduce different delays for each wavelength. This randomizes the phase relationship between the different wavelengths. Effectively, the FWM powers introduced before and after this point are summed instead of the electric fields being added in phase, resulting in a smaller FWM penalty.

5.8.5 Self-/Cross-Phase Modulation

As we saw in Section 2.5, SPM and CPM also arise out of the intensity dependence of the refractive index. Fluctuations in optical power of the signal causes changes in the phase of the signal. This induces additional chirp, which in turn, leads to higher chromatic dispersion penalties. In practice, SPM can be a significant consideration in designing systems at 10 Gb/s and higher, and leads to a restriction that the maximum power per channel should not exceed a few milliwatts. CPM does not usually pose a problem in WDM systems unless the channel spacings are extremely tight (a few tens of gigahertz). In this section, we will study the system limitations imposed by SPM.

The combined effects of SPM-induced chirp and dispersion can be studied by numerically solving (E.15). For simplicity, we consider the following approximate expression for the width T_L of an initially unchirped Gaussian pulse after it has propagated a distance L:

$$\frac{T_L}{T_0} = \sqrt{1 + \sqrt{2}\frac{L_e}{L_{NL}}\frac{L}{L_D} + \left(1 + \frac{4}{3\sqrt{3}}\frac{L_e^2}{{L_{NL}}^2}\right)\frac{L^2}{L_D^2}}. \tag{5.27}$$

This expression is derived in [PAP86] starting from (E.15) and is also discussed in [Agr95]. Note the similarity of this expression to the broadening factor for chirped Gaussian pulses in (2.13); L_e/L_{NL} in (5.27) serves the role of the chirp factor in (2.13).

Consider a 10 Gb/s system operating over standard single-mode fiber at 1.55 μm. Since $\beta_2 < 0$ and the SPM-induced chirp is positive, from Figure 2.11 we expect that pulses will initially undergo compression and subsequently broaden. Since the SPM-induced chirp increases with the transmitted power, we expect both the extent of initial compression and the rate of subsequent broadening to increase with the transmitted power. This is indeed the case, as can be seen from Figure 5.31, where we use (5.27) to plot the evolution of the pulse width as a function of the link length, taking into account the chirp induced by SPM. We consider an initially unchirped Gaussian pulse of width (half-width at $1/e$-intensity point) 50 ps, which is half the bit period. Three different transmitted powers, 1 mW, 10 mW, and 20 mW, are considered. As expected, for a transmit power of 20 mW, the pulse compresses more initially but subsequently broadens more rapidly so that the pulse width exceeds that of a system operating at 10 mW or even 1 mW. The optimal transmit power therefore depends on the link length and the amount of dispersion present. For standard single-mode fiber in the 1.55 μm band, the optimal power is limited to the 2–10 mW range for link lengths on the order of 100 km and is a real limit today for 10 Gb/s systems. We can use higher transmit powers to optimize other system parameters such as the signal-to-noise ratio (SNR) but at the cost of increasing the pulse broadening due to the combined effects of SPM and dispersion.

The system limits imposed by SPM can be calculated from (5.27) just as we did in Figure 5.31. We can derive an expression for the power penalty due to SPM, following the same approach as we did for chromatic dispersion. This is detailed in Problem 5.26. Since SPM can be beneficial due to the initial pulse compression it can cause, the SPM penalty can be negative. This occurs when the pulse at the end of the link is narrower due to the chirping caused by SPM than it would be in the presence of chromatic dispersion alone.

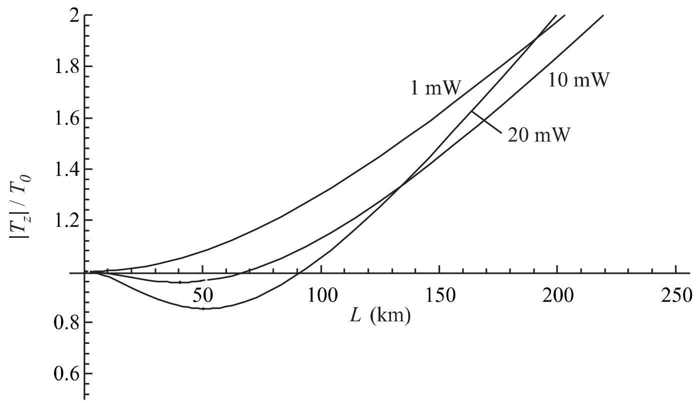

Figure 5.31 Evolution of pulse width as a function of the link length L for transmitted powers of 1 mW, 10 mW, and 20 mW, taking into account the chirp induced by SPM. A 10 Gb/s system operating over standard single-mode fiber at 1.55 μm with an initial pulse width of 50 ps is considered.

In amplified systems, as we saw in Section 5.5, two things happen: the effective length L_e is multiplied by the number of amplifier spans as the amplifier resets the power after each span, and in general, higher output powers are possible. Both of these serve to exacerbate the effects of nonlinearities.

In WDM systems, CPM aids the SPM-induced intensity dependence of the refractive index. Thus in WDM systems, these effects may become important even at lower power levels, particularly when dispersion-shifted fiber is used so that the dispersion-induced walk-off effects on CPM are minimized.

5.8.6 Role of Chromatic Dispersion Management

As we have seen, chromatic dispersion plays a key role in reducing the effects of nonlinearities, particularly four-wave mixing. However, chromatic dispersion by itself produces penalties due to pulse smearing, which leads to intersymbol interference. The important thing to note is that we can engineer systems with zero total chromatic dispersion but with chromatic dispersion present at all points along the link, as shown in Figure 5.20. This approach leads to reduced penalties due to nonlinearities, but the total chromatic dispersion is small so that we need not worry about dispersion-induced penalties.