

## Chapter 2

# OPTICAL FIBER CHARACTERISTICS AND SYSTEM CONFIGURATIONS

One attractive aspect of optical fibers is their enormous bandwidth compared to other media, such as radio waves and twisted-pair wires. Still, an optical fiber is not ideal; it possesses some unwanted properties. Dispersion and nonlinearity are the major limiting factors in lightwave communication. Fiber dispersion causes different spectral components of a signal to travel at different speeds. Hence, for a given transmission distance different spectral components arrive at the destination at different times. This results in a pulse broadening effect when a pulse propagates along an optical fiber. However, the situation is different when the nonlinearity and dispersion are considered together. In some circumstances, the nonlinearity could counteract the dispersion. In addition, when multiple channels are considered, the fiber nonlinearity results in interactions among channels.

The purpose of this chapter is to discuss the effects of dispersion and nonlinearity in terms of their origins and corresponding impairments. Those impairments lead to various system designs intended to minimize deleterious effects caused by dispersion and nonlinearity. This chapter begins with a discussion of dispersion in single-mode fibers, and types of optical fibers based on the value of dispersion. It is then followed by the effects of nonlinearity and approaches to minimize such effects, in Section 2.2. The discussion of system configurations based on the types of transmission optical fiber is presented in Section 2.3. The benefits and trade-offs on different system configurations are also explained.

### 2.1 FIBER DISPERSION

When one considers an optical fiber, the first parameter of interest is the value of dispersion. This is simply because different types of optical fibers have different dispersions. For a single-mode optical fiber, the only source of dispersion is due to group-

velocity dispersion (GVD), or intramodal dispersion where the dispersion is the result of the wavelength dependence of the group velocity  $v_g$ . This causes different spectral components to propagate along an optical fiber with different group velocities. For an optical fiber of length  $z$ , the spectral component at a frequency  $\omega$  would exit the fiber at a time delay of  $T = z/v_g$  [1]. The group velocity  $v_g$  can be related to the phase (propagation) constant  $\beta$  by

$$v_g^{-1} = d\beta/d\omega. \quad (2.1)$$

Due to the frequency dependence of  $\beta$ , one can show that a pulse having the spectral width of  $\Delta\omega$  is broadened by

$$\Delta T = \beta_2 z \Delta\omega, \quad (2.2)$$

where  $\beta_2 = d^2\beta/d\omega^2$ , which is generally called the GVD parameter, with units of ps<sup>2</sup>/km. The GVD parameter  $\beta_2$  can be interpreted as the dispersion per unit transmission distance per unit frequency spread of the signal. In optical fiber communication systems, the wavelength unit is more commonly used than the frequency unit, and (2.2) can be rewritten as

$$\Delta T = Dz\Delta\lambda, \quad (2.3)$$

where  $\Delta\lambda$  is the signal spectral width in wavelength units, and  $D$  is the dispersion parameter in the units of ps/(km·nm), which can be related to  $\beta_2$  by

$$D = \frac{d}{d\lambda} \left( \frac{1}{v_g} \right) = - (2\pi c/\lambda^2) \beta_2, \quad (2.4)$$

where  $c$  is the velocity of light in vacuum, and  $\lambda$  is the wavelength. It should be noted that the dispersion parameter  $D$  rather than the GVD parameter  $\beta_2$  is generally used to indicate the amount of dispersion in fiber specifications.

When the fiber loss and nonlinearity are neglected, a single-mode optical fiber can be considered as an all-pass filter with nonlinear phase response, and the corresponding transfer function can be written as

$$H_o(\omega) = \exp \left\{ jz \left[ \beta_0 + \beta_1(\Delta\omega) + \frac{1}{2} \beta_2(\Delta\omega)^2 + \frac{1}{6} \beta_3(\Delta\omega)^3 + \dots \right] \right\}, \quad (2.5)$$

where  $\beta_m = \left( d^m \beta / d\omega^m \right)_{\omega=\omega_0}$ , and  $\omega_0$  is the operating frequency. It should be noted that (2.5) is derived under the assumption that  $\Delta\omega \ll \omega_0$ , so  $\beta(\omega)$  can be expanded about  $\omega_0$  by using a Taylor series. In terms of communication theory, the all-pass filter whose transfer function is given by (2.5) would cause waveform distortion due to the nonlinear phase response. This is commonly called dispersion in the fiber optic communication areas. When (2.5) is considered, the first term in the exponent causes only a constant phase shift while the second term results in a time delay. The third and following terms (the second-order and higher-order terms when  $\beta_2$  is considered) in (2.5) are the sources of dispersion. The second-order term is related to the dispersion parameter  $D$  by (2.4) whereas the third and higher-order terms are a result of the phase constant not being a quadratic function of frequency. For the third-order term, it can be related to the dispersion slope  $S$  by

$$S = \frac{dD}{d\lambda} = \left( 2\pi c / \lambda^2 \right)^2 \beta_3 + \left( 4\pi c / \lambda^3 \right) \beta_2. \quad (2.6)$$

In practice, the third and higher-order terms in (2.5) can be safely neglected as long as the operating wavelength is sufficiently far from the zero-dispersion wavelength so that the contributions of those terms are negligible. Thus, the quadratic dependence of the phase response on the frequency in (2.5) is the major source of dispersion.

### 2.1.1 Sources of Dispersion

One source of dispersion in a single-mode optical fiber comes from the fact that the refractive index of the material used to make an optical fiber is a function of the wavelength. This is commonly referred to as material dispersion  $D_M$  or chromatic dispersion [58]. Generally, an optical fiber consists of a core and cladding. The refractive index profile of core and cladding also gives rise to dispersion, which is called waveguide dispersion  $D_W$ . Shown in Fig. 2.1 are the material and waveguide dispersions as a function of wavelength for a single-mode optical fiber. It is clearly seen that the material dispersion increases with wavelength for silica based optical fibers in the wavelength range of interest. The wavelength  $\lambda_{zD}$  at which the material dispersion becomes zero is in the range of 1.27-1.29  $\mu\text{m}$  depending primarily on the materials used to control the index

of refraction of the core of the fiber [1]. Beyond this wavelength  $\lambda_{zD}$ , the material dispersion becomes positive. On the other hand for typical fiber designs the waveguide dispersion is negative in the entire wavelength range 0 – 1.6  $\mu\text{m}$  as shown in Fig. 2.1. Theoretically, the material dispersion and waveguide dispersion are interrelated; however, a good approximation of the total dispersion is simply the sum of both dispersions [58]. The effect of the waveguide dispersion is to shift the zero-dispersion wavelength to the longer wavelength. For a standard single-mode fiber the dispersion  $D$  is zero near 1.31  $\mu\text{m}$ . The typical value of  $D$  for a standard single-mode fiber is around 15 to 18 ps/(km-nm) in the 1.55- $\mu\text{m}$  wavelength window where the fiber attenuation is lowest. Such high values of  $D$  poses the major limitation on 1.55- $\mu\text{m}$  systems.

Although the material dispersion can be altered, significant changes are difficult to achieve in practice. On the other hand, waveguide dispersion can be modified fairly easily by changing the refractive index profile of core and cladding. Fig. 2.2 shows the refractive index profiles of a standard single-mode optical fiber and a dispersion-shifted fiber. By changing the refractive index profile of an optical fiber the variation of waveguide dispersion as a function of wavelength can be tailored so that the total dispersion is zero at 1.55  $\mu\text{m}$ . This type of optical fiber is generally called dispersion-shifted fiber. The dispersion-shifted fibers were particularly deployed in single-channel systems. Its minimum dispersion at 1.55- $\mu\text{m}$  wavelength region allows the effective use of the wavelength region where the fiber loss is minimum. Still, there is a problem associated with the nonlinear interaction between the signal and the noise as discussed below.

By employing dispersion-shifted fibers, the distance between the transmitter and the receiver can be enhanced considerably due to the small effect of dispersion. However, the distance cannot be extended indefinitely due to the fact that the optical fiber is not a lossless medium. Fortunately, the fiber attenuation can be compensated by employing in-line optical amplifiers to periodically boost up the signal power. Since the optical amplifiers also emit noise called amplified spontaneous emission (ASE) noise, the phase matching between the signal and the ASE noise results in the nonlinear four-wave mixing, which in effect transfers energy from the signal to ASE noise. In general, the efficiency of the four-wave mixing process decreases with the increase in the dispersion.

Hence, for single-channel systems employing dispersion-shifted fiber, the operating wavelength has to be sufficiently away from the zero-dispersion wavelength. It should be noted that the four-wave mixing process is not the only nonlinear effect in an optical fiber. The various nonlinear effects prevent the effective use of WDM technique in systems employing dispersion-shifted fibers. For example, the four-wave mixing among WDM channels generates new signals whose wavelengths might be collocated with the WDM signals themselves. This in effect causes a decrease in the signal power and cross talk among WDM channels.

Similar to the four-wave mixing process, the other nonlinear effects in general decrease with the increase in dispersion. In order to effectively suppress the nonlinear effects, the local dispersion of the transmission fibers has to be sufficiently large. Although standard single-mode optical fibers seem to be the answer for solving the problems caused by the nonlinear effects to enable the deployment of WDM techniques, large local dispersion implies that the dispersion compensation scheme is necessary for combating the large accumulated dispersion. This in turn increases the system complexity. In order to avoid such complexity, an optical fiber whose dispersion is the compromise between the standard single-mode fiber and dispersion-shifted fiber is desirable. This led to the development of a new type of optical fiber known as non-zero dispersion fiber (NZDF) in the early 1990s [59], [60]. Its purpose is to facilitate WDM deployment at the channel rate of 10 Gb/s without dispersion compensation. The dispersion of this type of fiber is designed so that it is sufficiently large to minimize the nonlinear effects while the effect of dispersion itself is not so strong as to cause severe waveform distortion. The non-zero dispersion fiber normally has a value of dispersion in the 1.55- $\mu\text{m}$  wavelength region of several ps/(km-nm). It is clearly seen that the fiber nonlinearity is not negligible, and has to be taken into account seriously. Systems have to be properly configured in order to minimize nonlinear effects, and in some special circumstance to cleverly use fiber nonlinearity as an advantage.

## **2.2 NONLINEAR EFFECTS IN OPTICAL FIBERS**

Although silica glass used as material for making optical fibers has very small nonlinear coefficients, the nonlinear effects in optical fibers are generally not negligible.

This is because the optical intensity of a propagating signal is high despite the fact that the signal power is rather low (several milliwatts to tens of milliwatts). The small cross section of an optical fiber causes the intensity to be very high, which in effect is sufficient to induce significant effects of nonlinearity. Furthermore, for optically amplified systems, the distance between regeneration is large, so the nonlinear effects may accumulate over long distances. The nonlinear effects can be divided into two cases based on their origins: stimulated scatterings and optical Kerr effects. The latter is the result of intensity dependence of the refractive index of an optical fiber leading to a phase constant that is a function of the optical intensity, whereas the former is a result of scattering leading to an intensity dependent attenuation constant. There are two stimulated scattering phenomena in an optical fiber: Raman scattering and Brillouin scattering.

The intensity dependence of refractive index results in self-phase modulation (SPM), cross-phase modulation (XPM or CPM), and four-wave mixing (FWM). Another difference between stimulated scatterings and the effects of nonlinear refractive index is that the former is associated with threshold powers at which their effects become significant. All of these effects are discussed in this section.

### 2.2.1 Stimulated Raman Scattering (SRS)

Stimulated Raman scattering (SRS) is the result of interaction between incident light and molecular vibration. Some portion of the incident light is downshifted in frequency by an amount equal to the molecular-vibration frequency, which is generally called the Stokes frequency. This in effect depletes the optical power of the incident light. When there is only a single light wave propagating along the optical fiber, Raman scattering results in the generation of spontaneous Raman-scattered light waves at lower frequency. In general, the criterion used to determine the level of scattering effects is the threshold power  $P_{th}$  defined as the input power level that can induce the scattering effect so that half of the power (3-dB power reduction) is lost at the output of an optical fiber of length  $z$ . For single-channel lightwave systems, it has been shown that the threshold power  $P_{th}$  is given by [15]

$$P_{th} = 32\alpha A_{eff} / g_R, \quad (2.7)$$

where  $\alpha$  and  $A_{eff}$  are the attenuation coefficient and effective core area of an optical fiber, respectively, and  $g_R$  is the Raman gain coefficient. Note that  $\alpha$  in (2.7) is the approximation of effective interaction length when  $z$  is large. For a 1.55- $\mu\text{m}$  single-channel system employing a standard single-mode optical fiber,  $P_{th}$  is found to be of the order of 1 W. Commonly, the transmitted power is well below 1 W; thus, the effect of SRS is negligible in single-channel systems.

The effect of Raman scattering is different when two or more signals travel along an optical fiber. When two optical signals separated by the Stokes frequency travel along an optical fiber, the SRS would result in the energy transfer from the higher frequency signal to the lower frequency signal. That is, one signal experiences excess loss whereas another signal gets amplified. The signal that is amplified is called the probe signal whereas the signal that suffers excess loss is called the pump signal. The effectiveness of the energy transfer depends on the frequency difference (Stokes frequency) between the pump and probe signals. Shown in Fig. 2.3 is the Raman gain coefficient for the probe signal as a function of Stokes frequency for a pump wavelength of 1  $\mu\text{m}$  [61]. Since the gain coefficient scales inversely with the wavelength, the peak gain coefficient shown in Fig. 2.3 becomes  $7 \times 10^{-12}$  cm/W at the pump wavelength of 1.55  $\mu\text{m}$ . It is clearly seen that the Raman gain bandwidth is very broad. The SRS can still happen even when two signals are separated by 15 THz ( $500 \text{ cm}^{-1}$ ).

In WDM systems, the channels at shorter wavelengths will act as pump signals and suffer excess loss. On the other hand, the channels at longer wavelengths acting as probe signals are amplified via SRS. This might cause SNR discrepancy among channels. Shown in Fig. 2.4 is the schematic explanation of the SRS in the case of two-channel systems. In this case the pump channel (channel 1) is located at  $\lambda_1$  whereas the probe channel (channel 2) is at  $\lambda_2$  ( $\lambda_2 > \lambda_1$ ). Here the effect of dispersion is neglected. Shown in Fig. 2.4 (a) are bit patterns of both channels without SRS. Under the presence of SRS, the signal in channel 1 is depleted and transferred to channel 2 whenever both channels carry bit 1 as shown in Fig. 2.4 (b). However, there is no SRS when either channel carries bit 0. It is clearly seen that the SRS affects the two channels differently. At the receiver

output, the eye opening of channel 1 would be smaller than that of channel 2 due to the energy depletion on some of bit 1 caused by SRS, which can be viewed as cross talk.

Practically, the situation is not as severe as the illustrated example. In WDM systems, the chance that all channels transmit bit 1 simultaneously decreases with the increase in the number of channels. This decreases the effect of SRS. It has been shown in [62] that when this statistical consideration is taken into account, the threshold power of the SRS to cause a noticeable effect is increased by 3 dB compared with that predicted by assuming all channels are continuous-wave. The effect of SRS is also reduced under the presence of dispersion [63]. Fiber dispersion causes the signals at different wavelengths to travel at different speeds, causing walk-off between bit sequences at different channels. The walk-offs among channels decreases the effect of SRS, hence increasing the threshold power. In general, SRS is not the limiting factor in lightwave communication systems compared with the other nonlinear effects due to its high threshold power.

### 2.2.2 Stimulated Brillouin Scattering (SBS)

This nonlinear effect is due to the interaction between the incident light and acoustic vibration in the optical fiber. Similar to SRS, stimulated Brillouin scattering (SBS) causes frequency down-conversion of the incident light, but the frequency shift in this case is equal to the frequency of the interacting acoustic wave. However, unlike Raman-scattered light, the Brillouin-scattered light propagates in the backward direction. This in effect causes excess loss on the incident light similar to SRS. For SBS, the threshold power is given by [64]

$$P_{th} = 42 \frac{\alpha A_{eff}}{g_B} \left( 1 + \frac{\nu_p}{\nu_B} \right) \quad (2.8)$$

where  $g_B$  is the Brillouin gain coefficient,  $\nu_p$  is the signal linewidth, and  $\nu_B$  is the Brillouin gain bandwidth. For a 1.55- $\mu\text{m}$  system employing a standard single-mode optical fiber,  $P_{th}$  can be as low as 2 mW when the signal is continuous-wave and has ideal zero linewidth ( $\nu_p \approx 0$ ).



This seems to suggest that the SBS is the major limiting factor in the allowable launched power. However, it should be noted that modulation broadens the signal spectral width considerably. In addition, for silica fiber the Brillouin gain bandwidth  $\nu_B$  is as small as 20 MHz at 1.55  $\mu\text{m}$  [65]. When the ratio between the signal spectral width  $\nu_p$  and the Brillouin gain bandwidth  $\nu_B$  in (2.8) is taken into account, the threshold power increases significantly, especially when the bit rate is high. Since the gain bandwidth  $\nu_B$  is very small, there are no nonlinear interactions among WDM channels due to SBS. Therefore, in order to avoid SBS the power of each WDM channels, not the total power of all transmitted channels, has to be kept below the threshold. Due to its high threshold power  $P_{th}$ , the effect of SBS is negligible when the operating bit rate is sufficiently high, which is generally satisfied in practice.

### 2.2.3 Self-Phase Modulation (SPM)

Self phase modulation (SPM) arises from the intensity dependence of the refractive index. SPM results in the conversion of intensity variation to phase variation. For a silica optical fiber, the refractive index  $n$  is given by [15]

$$n = n_0 + n_2 I(\tau), \quad (2.9)$$

where  $n_0$  is the linear refractive index of the material,  $n_2$  is the nonlinear refractive index, and  $I(\tau)$  is the optical intensity in units of  $\text{W}/\text{m}^2$ . The value of  $n_0$  is approximately 1.5 whereas  $n_2$  is around  $3 \times 10^{-20} \text{ m}^2/\text{W}$  [15]. Although the value of  $n_2$  seems very small, high signal intensity and long transmission distance make the effect of nonlinear refractive index not negligible. For a propagation distance of  $z$ , the phase of the signal is given by

$$\phi(z, \tau) = \frac{2\pi n_0 z}{\lambda} + \frac{2\pi n_2 I(\tau) z_{eff}}{\lambda}, \quad (2.10)$$

where  $z_{eff}$  is the effective transmission distance taking into account of the fiber attenuation, and it is given by

$$z_{eff} = \frac{1 - e^{-\alpha z}}{\alpha}. \quad (2.11)$$

Note that (2.10) is derived under the assumption that a plane wave propagates in an infinite uniform medium. The first term in (2.10) is just a linear phase shift, and depends only on the transmission distance  $z$ . On the other hand, the second term in (2.10) depends not only on the transmission distance  $z$  by way of  $z_{eff}$ , but also the intensity variation of the signal  $I(\tau)$  itself. Therefore, this effect is called self phase modulation (SPM). The intensity dependence of refractive index causes a nonlinear phase shift, which is proportional to the intensity of the signal  $I(\tau)$ . It should be noted that  $z_{eff}$  is less than  $z$ . This implies that fiber attenuation reduces the effect of nonlinear phase shift.

SPM alone broadens the signal spectrum, but does not affect the intensity profile of the signal. The spectral broadening effect can be understood from the fact that the time-dependent phase variation causes instantaneous frequency deviation  $\delta\omega(\tau)$ , which is given by

$$\delta\omega(\tau) = -\frac{\partial\phi}{\partial\tau} = -\frac{2\pi n_2 z_{eff}}{\lambda} \frac{\partial I(\tau)}{\partial\tau}. \quad (2.12)$$

(2.12) suggests that the magnitude of instantaneous frequency deviation increases with distance and the intensity variation of the signal. The spectrum broadening effect caused by SPM may result in interchannel cross talk among channels in WDM systems.

Although SPM alone does not affect the intensity profile of the signal, that is no longer true in the presence of dispersion. The combined effect of dispersion and SPM strongly depends on the sign of dispersion (the sign of  $D$ ). In terms of the sign of dispersion, the operating wavelength region is divided into two regimes: normal dispersion and anomalous dispersion regimes. The normal dispersion regime corresponds to the wavelength range in which dispersion  $D$  is negative ( $\beta_2$  is positive) whereas the anomalous dispersion regime is the wavelength region in which  $D$  is positive ( $\beta_2$  is negative). As seen from (2.12) the sign of SPM-induced instantaneous frequency variation is independent of the sign of dispersion; however, the sign of dispersion-induced instantaneous frequency variation depends on the sign of dispersion. For the propagation of an optical pulse, the SPM enhances the effect of dispersion when the operating wavelength is in the normal dispersion regime. That is, the pulse is broadened more severely than under the effect of dispersion alone in the normal dispersion regime.

This results from the fact that the sign of instantaneous frequency variation across the pulse induced by the SPM is identical to that induced by the dispersion [66]. Conversely, the SPM negates the effect of dispersion in the anomalous dispersion regime.

When the SPM is sufficiently strong, a pulse can be compressed during initial propagation. In addition, under ideal conditions the pulse shape can be continually preserved during propagation due to the balancing of the effects of dispersion and SPM in the anomalous dispersion regime. This type of pulse is called a soliton [8]-[10]. However, the effect of SPM decreases with transmission distance due to fiber attenuation, preventing soliton formation [67].

It is seen from (2.10) that the effect of nonlinear refractive index, causing nonlinear phase shift, is proportional to the signal intensity. When multiple channels are simultaneously transmitted, the nonlinear phase shift on a given channel depends not only on the intensity of that channel but also the intensities of the other channels. This is discussed in the next section

#### 2.2.4 Cross-Phase Modulation (XPM or CPM)

Similar to the SPM, cross-phase modulation (XPM) is due to the nonlinear behavior of the refractive index on the optical intensity. However, in this case the total nonlinear phase shift on a given channel is due to the combined intensities of all transmitted channels, which can result in cross talk among WDM channels. When  $N$  channels are transmitted in a single optical fiber, the nonlinear phase shift on the  $j^{\text{th}}$  channel is governed by [1]

$$\phi_j(z, \tau) = \frac{2\pi n_0 z}{\lambda} + \frac{2\pi n_2 z_{\text{eff}}}{\lambda} \left( I_j(\tau) + 2 \sum_{m \neq j}^N I_m(\tau) \right), \quad (2.13)$$

where  $I_m(\tau)$  is the optical intensity of the  $m^{\text{th}}$  channel. The first term in the parentheses on the right hand side of (2.13) corresponds to SPM discussed in the previous section whereas the second term is responsible for XPM. The factor of 2 in (2.13) suggests that the effect of XPM from a neighboring channel is two times stronger than that caused by SPM itself.

In the case of continuous-wave signals, XPM would dominate over SPM as suggested by (2.13). However, when pulses at different wavelengths are considered, the

effect of XPM depends on the relative temporal locations of those pulses. XPM is strongest when pulses completely overlap one another. Additionally, the probability that all channels transmit bit 1 has to be taken into consideration, similar to the case of SRS. The low probability of all channels simultaneously transmitting bit 1 reduces the effect of XPM on average. Under the presence of dispersion pulses at different wavelengths travel at different group velocities, which in effect causes pulses to walk off from one another, thus reducing the effect of XPM [68], [69]. The larger the dispersion discrepancies among channels, the more rapidly the pulses walk off from one another. In other words, the effect of XPM is inversely proportional to dispersion discrepancies among channels in WDM systems. Thus, in order to minimize the impairment caused by XPM, the channel separation and/or local dispersion have to be properly chosen in WDM systems, which can be achieved in practice.

### 2.2.5 Four-Wave Mixing (FWM)

The intensity dependence of refractive index not only causes nonlinear phase shift but also gives rise to the process by which signals at different wavelengths are mixed together producing new signals at new wavelengths. This process is known as four-wave mixing (FWM). The difference between the processes (SPM and XPM) causing the nonlinear phase shift and the FWM process is that energy transfer occurs in the FWM process. When signals at frequencies  $f_i$ ,  $f_j$  and  $f_k$  propagate along an optical fiber, the nonlinear interactions among those signals by mean of FWM result in the generation of new signals at [70]

$$f_{ijk} = f_i + f_j - f_k. \quad (2.14)$$

The energies from the interacting signals are transferred to those newly-generated signals at frequencies  $f_{ijk}$ . In the simplest case when only two signals at frequencies  $f_1$  and  $f_2$  are involved, the FWM generates new signals at  $2f_1 - f_2$  and  $2f_2 - f_1$  as demonstrated in Fig. 2.5 (a). The number of FWM-generated signals grows rapidly with the number of involved signals as shown in Fig. 2.5 (b), which corresponds to when three signals undergo FWM generating new signals at frequencies given by (2.14).

When  $N$  signals are involved in the FWM process, the number of FWM-generated signals is given by [70]

$$M = \frac{N^2(N-1)}{2}. \quad (2.15)$$

For example, when 10 signals are four-wave mixed together, 450 signals are generated. In WDM systems, not only does the FWM cause power depletion on the participating channels, but it also results in cross talk among channels. The cross talk comes from the fact that some of the FWM-generated signals can have the same frequencies as the WDM channels when all channels are equally spaced in frequency. One approach to avoid cross talk is to employ unequally spaced channel allocation (USCA) [28], [70]. In this method, all channels are allocated so that the FWM-generated signals do not have the same frequencies as the channels. The illustration of this method is shown in Fig. 2.5 (b) for the case of three transmitted channels. It should be noted that in this method only cross talk is avoided, but the signals still suffer excess power loss.

Mathematically, the power of a FWM-generated signal at the frequency  $f_{ijk}$  given by (2.14) is proportional to [71]

$$\eta = \frac{\alpha^2}{\alpha^2 + \Delta\beta^2} \left( 1 + \frac{4e^{-\alpha z} \sin^2(\Delta\beta z/2)}{(1 - e^{-\alpha z})^2} \right), \quad (2.16)$$

where  $\eta$  is called FWM efficiency and  $\Delta\beta$  is the phase mismatch, which is given by

$$\Delta\beta = \left( \frac{2\pi\lambda^2}{c} \right) |f_i - f_k| |f_j - f_k| \left\{ D + \frac{dD}{d\lambda} \left( \frac{\lambda^2}{2c} \right) (|f_i - f_k| + |f_j - f_k|) \right\}. \quad (2.17)$$

The phase mismatch  $\Delta\beta$  in (2.17) generally represents the difference of propagation constants  $\beta$  of the original signals and the FWM-generated signals. From (2.16), one can see that the FWM efficiency  $\eta$  decreases with the increase in the phase mismatch  $\Delta\beta$ .

The phase mismatch  $\Delta\beta$  is proportional to the frequency spacing between the original signals ( $|f_i - f_k|$  and  $|f_j - f_k|$ ), and the dispersion  $D$ . Hence, for systems employing optical fibers whose dispersion is small, the channel spacing has to be sufficiently large in order to avoid phase matching. On the other hand, channels can be packed closer together if the local dispersion  $D$  is large. Shown in Fig. 2.6 is the FWM efficiency  $\eta$  as

a function of channel spacing  $\Delta f$  when three interacting signals at frequencies  $f_i$ ,  $f_j$  and  $f_k$  are equally spaced. The solid line corresponds to a standard single-mode fiber (SSMF) with  $D = 16$  ps/(km·nm). The dash line represents a dispersion-shifted fiber (DSF) when  $D = 1$  ps/(km·nm). In the case of SSMF, the effect of FWM becomes negligible when channels are equally spaced apart by several tens of GHz. On the other hand, the effect of FWM is still not negligible even when the channel spacing is 50 GHz in the case of DSF. For WDM systems, large local dispersion is the preferred mean to suppress the FWM because the ultimate goal of employing WDM is to transmit as many channels as possible for a given available transmission bandwidth [72].

One may notice that nonlinear interchannel interactions discussed so far decrease with the increase in local dispersion of the transmission fiber. This appears to suggest that transmission fibers should have very large dispersion to make nonlinear effects negligible. The accumulated dispersion can be removed by concatenating the transmission fiber with an optical fiber having the opposite amount of dispersion. However, practical system implementations have to be taken into consideration. There exist trade-offs among different system implementations. This is presented in the next section.

## 2.3 SYSTEM CONFIGURATIONS

In terms of dispersion, transmission optical fibers can be divided into three categories: small, moderate, and large local dispersions. Each is designed for specific system applications. It is seen from the previous section that large local dispersion is beneficial in term of nonlinearity suppression. However, such large local dispersion results in large accumulated dispersion, which can make dispersion compensation difficult. Thus, in terms of practical implementations, every aspect of a system has to be considered, including suppression of impairments caused by dispersion and nonlinearity, and feasibility of such implementations.

Three types of transmission optical fibers are considered in this dissertation: a dispersion-shifted fiber (DSF), TrueWave™ reduced slope fiber (TRSF), and standard single-mode fiber (SSMF). Their characteristics are summarized in Table 2.1. Among the

three the DSF has lowest dispersion whereas the SSMF has largest dispersion in the 1.55  $\mu\text{m}$  wavelength window. For the TRSF, its dispersion is the compromise between the DSF and SSMF, and it is generally referred to as NZDF. In this dissertation, DSF represents the transmission fiber having small local dispersion whereas TRSF and SSMF are used to represent transmission fibers having moderate and large local dispersion, respectively. It should be noted that there are several optical fibers that have moderate dispersion in the market. All of them are comparable in terms of characteristics.

### **2.3.1 Small Local Dispersion**

The apparent advantage of the DSF is that it has low dispersion in the 1.55- $\mu\text{m}$  wavelength window. Hence, the effect of dispersion is not strong, but the nonlinear effects are no longer negligible. By choosing the operating wavelength so that it is in the anomalous dispersion regime ( $D > 0$  or  $\beta_2 < 0$ ), the pulse compression effect can be exploited to maximize the system performance. This is due to the fact that in the anomalous dispersion regime the effect of SPM counteracts the dispersion.

With a small local dispersion, dispersion compensation is not necessary; however, WDM deployment with this type of optical fibers is not efficient. This is because small local dispersions implies that the channel spacing between two WDM channels has to be large in order to suppress the interchannel nonlinear impairments; such as XPM and FWM. In addition, the operating wavelength of each channel has to be sufficiently far from the zero-dispersion wavelength in order that the dispersion on that channel is sufficient to suppress the FWM between the signal and the ASE noise in systems employing in-line optical amplifiers. This introduces an additional constraint on the utilization of available bandwidth, hence further limiting the number of channels that can be transmitted.

### **2.3.2 Moderate Local Dispersion**

Initially, the purpose of having moderate local dispersion in an optical fiber is to keep the effect of dispersion under control while the effect of fiber nonlinearity is minimized [59], [60], [73]. The TrueWave fiber enables the transmission of multiple 10-Gb/s channels up to several hundreds kilometers without the need of dispersion

compensation [59]. The specification of the TrueWave reduced slope fiber (TRSF) is shown in Table 2.1.

The effect of dispersion does not scale linearly with bit rate. In fact, the effect of dispersion grows quadratically with bit rate [1] since the pulse bandwidth grows linearly with bit rate. (This assumes, as is true in modern high speed fiber optic systems, that the linewidth of the signal source is small compared to the modulation bandwidth.) Hence, at a bit rate of 40 Gb/s the effect of dispersion is 16 times more severe than at 10 Gb/s, and dispersion compensation is necessary. In the case of single-span systems, the dispersion compensation is performed at the receiver by placing a negative-dispersion optical fiber, commonly called a dispersion compensating fiber (DCF), at the end of the fiber span as shown in Fig. 2.7 (a). On the other hand, in the case of multiple-span systems the accumulated dispersion is generally compensated periodically along the transmission link at the in-line amplifier sites as shown in Fig. 2.7 (b). Note that in the last span the DCF is at the receiver site. Periodic dispersion compensation is also known as dispersion management. In terms of accumulated dispersion for a given span length, optical fibers having moderate dispersion also provide another advantage compared with those having large local dispersion. Smaller accumulated dispersion implies that a shorter length of DCF is needed.

When DCF is considered, it is desirable that the DCF has large negative dispersion so that only a short length of DCF is required, assuming the transmission fiber (e.g. SSMF) has positive dispersion. The advantages of having a short length of DCF are that it does not take up much space at the in-line amplifier site, and that the additional loss introduced by the DCF is reduced. Note that the DCF commonly has higher loss than other types of optical fibers. In this dissertation, we choose the extra-high-slope dispersion compensating fiber (EHS-DK) as the dispersion compensating fiber due to its high dispersion. Its characteristics are shown in Table 2.1.

### **2.3.3 Large Local Dispersion**

In general, the larger the dispersion, the lesser are the effects of nonlinearity. This is the apparent advantage of employing optical fibers having large local dispersion because ideally a linear transmission fiber is desired. However, large local dispersion in



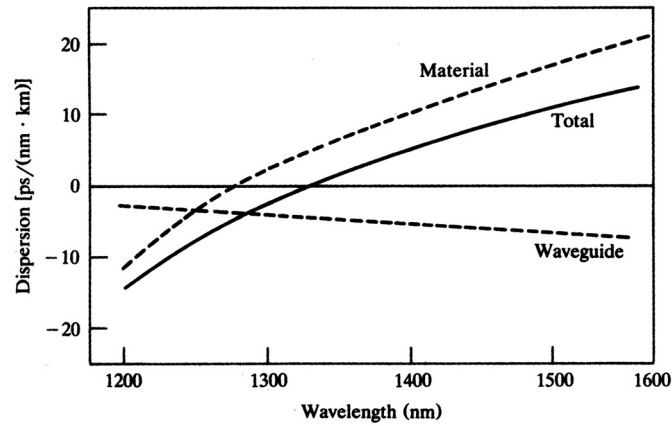
transmission fibers results in large accumulated dispersion, which requires long length of the DCF. Such long length of the DCF may cause problems in the practical implementations especially when the span length is large. In addition, long length of the DCF also introduces high additional loss. For example, if the span length is 160 km, the length of EHS-DK required is 11.72 km to manage the end-to-end dispersion back to zero when SSMF is employed as the transmission fiber. On the other hand, the length of EHS-DK needed is reduced to only 2.76 km in the case of TRSF.

One approach to take advantage of the optical fiber having large local dispersion, such as the SSMF, is to perform dispersion compensation within the transmission link instead of at in-line amplifier sites. In this approach the loss associated with the dispersion compensation is counted as transmission loss. The schematic diagram of this approach is shown in Fig. 2.7 (c) and (d) corresponding to single-span and multiple-span systems, respectively. As seen from Fig. 2.7 (c) and (d), there are two transmission fibers within a given span. When the SSMF is employed as the first transmission fiber, the dispersion compensation performed by the second transmission fiber is practically accomplished by using reverse-dispersion fiber (RDF). The RDF is designed for compensating the accumulated dispersion introduced by the SSMF. The characteristics of an RDF are listed in Table 2.1. Note that the RDF has larger absolute dispersion than the SSMF. This is beneficial since the RDF is more nonlinear than the SSMF due to its much smaller effective core area  $A_{eff}$ . Longer length of the SSMF deployed implies lower signal power entering the RDF fiber, hence reducing the unwanted effects of nonlinearity in the RDF fiber. One drawback of this approach is that any given span consists of two types of optical fibers, which may cause difficulties in installation and maintenance especially when a fiber cut happens. In addition, this approach cannot be deployed to upgrade already-installed systems which employ SSMFs as transmission fibers.

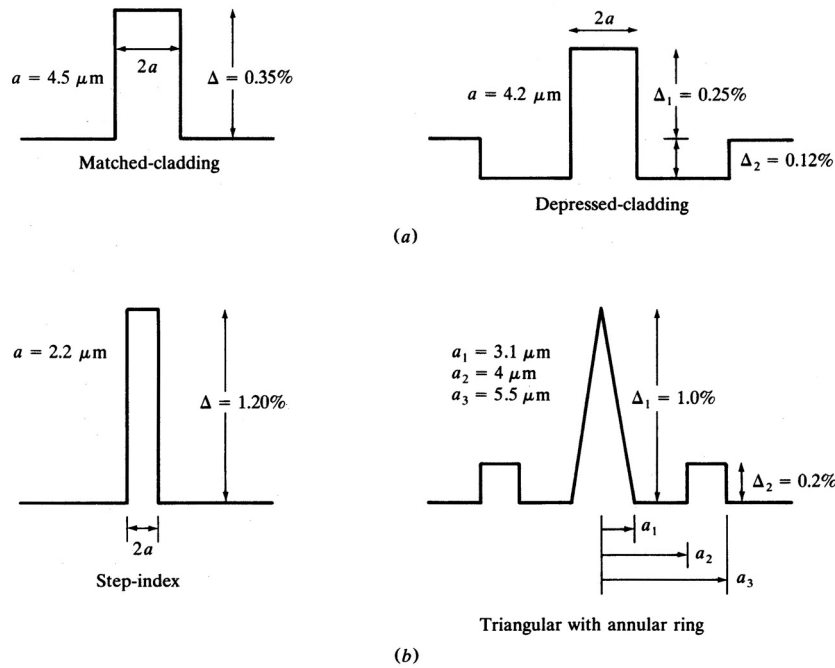
## 2.4 SUMMARY

In this chapter, the properties of optical fibers are discussed. When the nonlinearity is considered, their deleterious effects decrease with the increase in the local dispersion of the transmission fiber. Although large local dispersion is desirable in order to suppress nonlinear effects, large accumulated dispersion makes dispersion

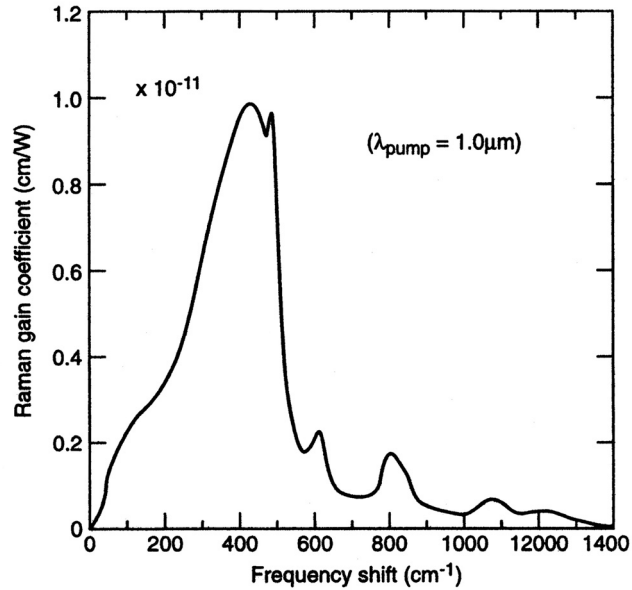
compensation necessary. However, dispersion compensation introduces additional loss and complexity to systems. This leads to various system configurations in terms of transmission fibers deployed. Each configuration has its own advantages and drawbacks. They are all discussed and explained. The system configuration is not the only key factor that improves system performance. The optical signal formats also play an important role in maximizing system performance. That is the subject of the remainder of this dissertation. The principal signal formats considered in the literature defined and compared in the next chapter.



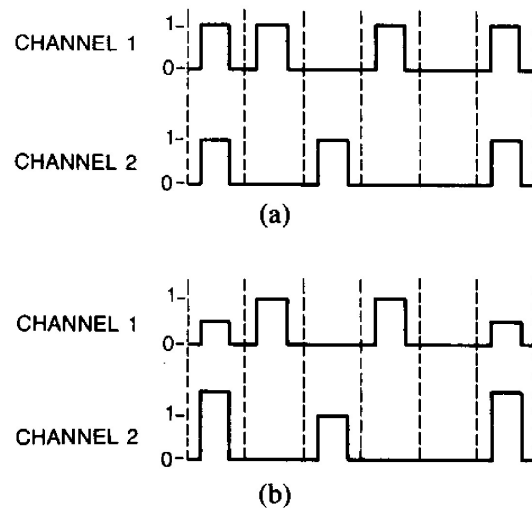
**Fig. 2.1:** The values of material and waveguide dispersions as a function of wavelength for a standard single-mode fiber [58].



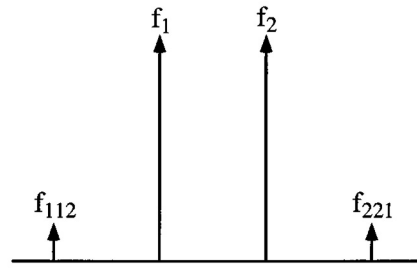
**Fig. 2.2:** Index profiles of core and cladding for various types of optical fiber. Vertical scale is refractive index, and horizontal scale is radius of optical fiber. Note that the center of fiber is at the middle of index profile. (a) Standard single-mode optical fiber, and (b) Dispersion-shifted fiber [58].



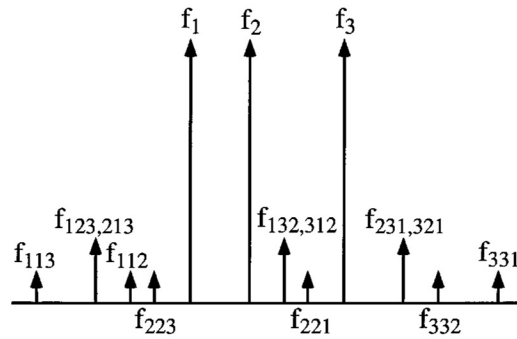
**Fig. 2.3:** Raman gain coefficient  $g_R$  as a function of Stokes frequency for fused silica at the pump wavelength of 1  $\mu\text{m}$ . Note that 1  $\text{cm}^{-1} = 30 \text{ GHz}$  [61].



**Fig. 2.4:** Schematic explanation of SRS for 2-channel system. Horizontal scale represents time, and vertical scale represents signal level. (a) Bit patterns of channel 1 and 2 without SRS. (b) Effects of SRS on both channels [15].

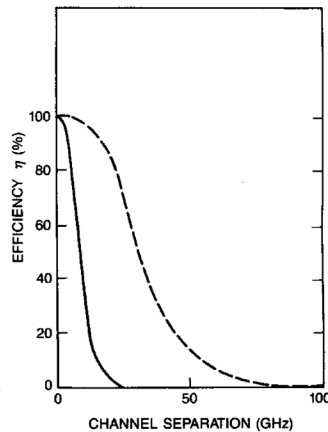


(a)



(b)

**Fig. 2.5:** Illustrations of FWM process. Horizontal axis is frequency. (a) FWM of two signals at frequencies  $f_1$  and  $f_2$ . (b) FWM of three signals at frequencies of  $f_1$ ,  $f_2$  and  $f_3$  [28].

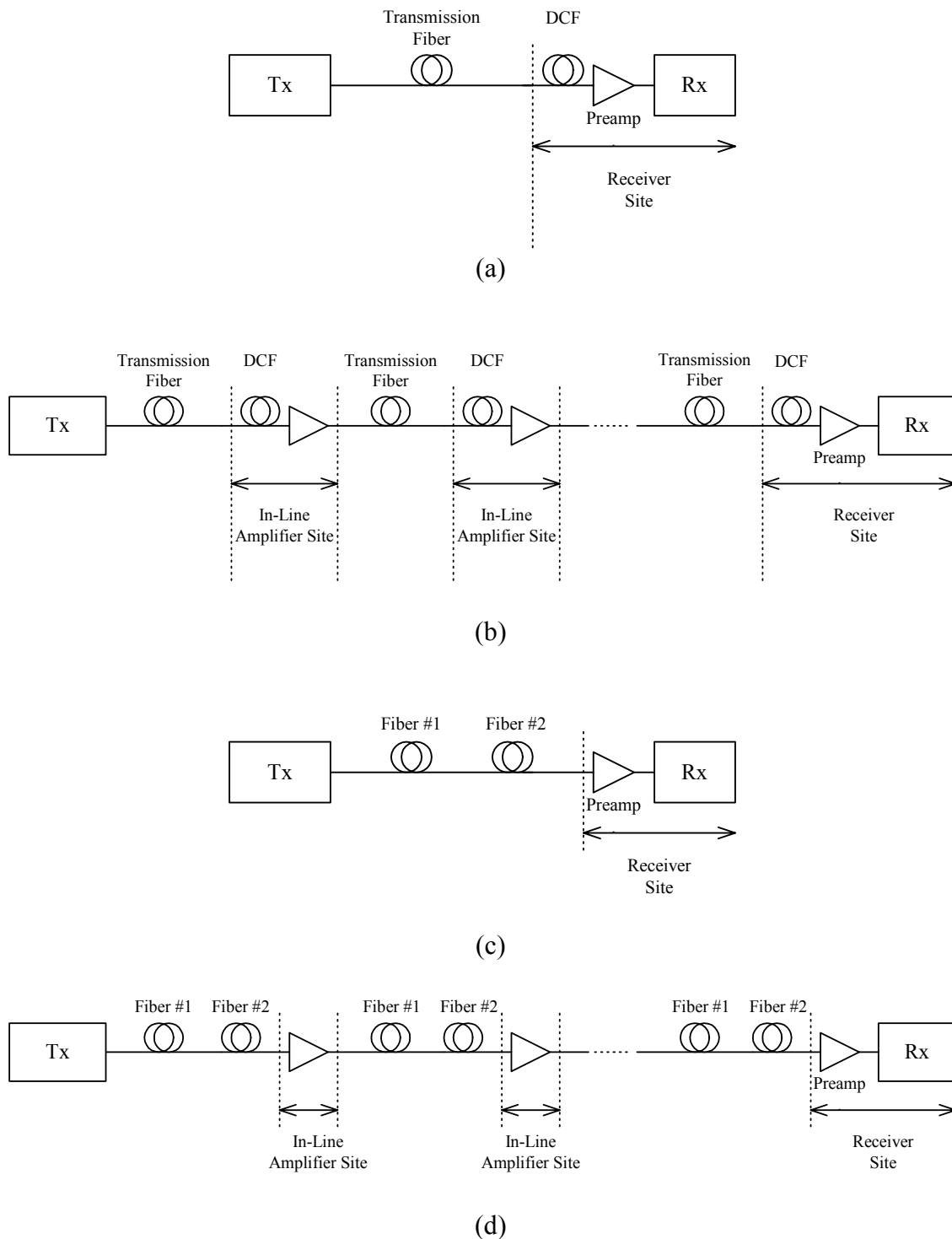


**Fig. 2.6:** Four-wave mixing efficiency  $\eta$  as a function of channel spacing  $\Delta f = |f_i - f_k| = |f_j - f_k|$  at  $1.55 \mu\text{m}$ . The solid line corresponds to standard single-mode optical fiber with  $D = 16 \text{ ps}/(\text{km}\cdot\text{nm})$ . The dash line represents dispersion-shifted fiber when  $D = 1 \text{ ps}/(\text{km}\cdot\text{nm})$  [15].

**Table 2.1:** Summary of fiber characteristics considered in this dissertation.

	Dispersion $D$ [ps/(km·nm)]	Effective Core Area $A_{eff}$ ( $\mu\text{m}^2$ )	Nonlinear Refractive Index $n_2$ ( $10^{-20} \text{ m}^2/\text{W}$ )	Attenuation $\alpha$ (dB/km)
Standard Single-Mode Fiber (SSMF)	+17	85	2.3	0.2
Dispersion- Shifted Fiber (DSF)	0	70	3.0	0.2
TrueWave Reduced Slope Fiber (TRSF)	+4	55	2.7	0.2
Reverse- Dispersion Fiber (RDF)	-26.91	25	2.3	0.22
Extra-High- Slope Dispersion Compensating Fiber (EHS-DK)	-232	19	2.7	0.59

Note: For DSF, it is also known as large effective area fiber (LEAF).



**Fig. 2.7:** Schematic diagrams of considered system configurations. (a) Single-span system with dispersion compensation at receiver. (b) Multiple-span (Dispersion-managed) system employing DCF. (c) Single-span system employing two types of transmission fibers. (d) Multiple-span (Dispersion-managed) system employing two types of transmission fibers.