Overall Fiber Dispersion

1. Multimode Fibers

The overall dispersion in multimode fibers comprises both chromatic and intermodal terms. The total rms pulse broadening σT is given by:

$$\sigma_T = (\sigma_c^2 + \sigma_n^2)^{\frac{1}{2}} \quad (2.44)$$

where σc is the intramodal or chromatic broadening and σn is the intermodal broadening caused by delay differences between the modes (i.e. σs for multimode step index fiber and σg for multimode graded index fiber). The chromatic term σc consists of pulse broadening due to both material and waveguide dispersion. However, since waveguide dispersion is generally negligible compared with material dispersion in multimode fibers, thenσc =σm.

2. Single-Mode Fibers

The pulse broadening in single-mode fibers results almost entirely from chromatic or intramodal dispersion as only a single-mode is allowed to propagate.* Hence the bandwidth is limited by the finite spectral width of the source. Unlike the situation in multimode fibers, the mechanisms giving chromatic dispersion in single-mode fibers tend to be interrelated in a complex manner. The transit time or specific group delay σg for a light pulse propagating along a unit length of single-mode fiber may be given as:

$$\tau_g = \frac{1}{c}\frac{d\beta}{dk} \quad (2.45)$$

where *c* is the velocity of light in a vacuum, β is the propagation constant for a mode within the fiber core of refractive index *n*1 and *k* is the propagation constant for the mode in a vacuum.The total first-order dispersion parameter or the chromatic dispersion of a single-mode fiber, *D*T, is given by the derivative of the specific group delay with respect to the vacuum wavelength λas:

$$D_T = \frac{d\tau_g}{d\lambda} \tag{2.46}$$

In common with the material dispersion parameter it is usually expressed in units of ps nm−1 km−1. When the variable λ is replaced by ω, then the total dispersion parameter becomes:

$$D_T = -\frac{\omega}{\lambda}\frac{d\tau_g}{d\omega} = -\frac{\omega}{\lambda}\frac{d^2\beta}{d\omega^2} \tag{2.47}$$

The fiber exhibits intramodal dispersion when β varies nonlinearly with wavelength. β may be expressed in terms of the relative refractive index difference Δ and the normalized propagation constant *b* as

$$\beta = kn_1[1 - 2\Delta(1 - b)]^{\frac{1}{2}} \tag{2.48}$$

The rms pulse broadening caused by chromatic dispersion down a fiber of length *L* is given by the derivative of the group delay with respect to wavelength as

$$\text{Total rms pulse broadening} = \sigma_\lambda L \left| \frac{d\tau_g}{d\lambda} \right| = \frac{\sigma_\lambda L 2\pi}{c\lambda^2}\frac{d^2\beta}{dk^2} \tag{2.49}$$

where σλ is the source rms spectral linewidth centered at a wavelength λ. When Eq. (2.44) is substituted into Eq. (2.45), detailed calculation of the first and second derivatives with respect to *k* gives the dependence of the pulse broadening on the fiber material's properties and the normalized propagation constant *b*. This gives rise to three interrelated effects which involve complicated cross-product terms. However, the final expression may be separated into three composite dispersion components in such a way that one of the effects dominates each terms. The dominating effects are as follows:

✓ The material dispersion parameter D_M defined by $\lambda/c \mid d^2n/d\lambda \mid$ where $n = n_1$ or n_2 for the core or cladding respectively.

✓ The waveguide dispersion parameter D_W, which may be obtained from Eq. (3.47) by substitution from Eq. (2.114) for τ_g, is defined as:

$$D_W = -\left(\frac{n_1 - n_2}{\lambda c}\right) V \frac{d^2(Vb)}{dV^2} \tag{2.50}$$

where *V* is the normalized frequency for the fiber. Since the normalized propagation constant *b* for a specific fiber is only dependent on *V*, then the normalized waveguide dispersion coefficient $V d^2(Vb)/dV^2$ also depends on *V*. This latter function is another universal parameter which plays a central role in the theory of singlemode fibers.

A profile dispersion parameter D_P which is proportional to $d\Delta/d\lambda$

This situation is different from multimode fibers where the majority of modes propagate far from cutoff and hence most of the power is transmitted in the fiber core. In the multimode case the composite dispersion components may be simplified and separated into two chromatic terms which depend on either material or waveguide dispersion. Also, especially when considering step index multimode fibers, the effect of profile dispersion is negligible. Strictly speaking, in single-mode fiber with a power-law refractive index profile the composite dispersion terms should be employed. Nevertheless, it is useful to consider the total first-order dispersion *D*T in a practical single-mode fiber as comprising:

$$D_T = D_M + D_W + D_P \qquad (\text{ps nm}^{-1}\text{ km}^{-1}) \tag{2.51}$$

Polarization

Cylindrical optical fibers do not generally maintain the polarization state of the light input for more than a few meters, and hence for many applications involving optical fiber transmission some form of intensity modulation of the optical source is utilized. The optical signal is thus detected by a photodiode which is insensitive to optical polarization or phase of the lightwave within the fiber. Nevertheless, systems and applications have been investigated which could require the polarization states of the input light to be maintained over significant distances, and fibers have been designed for this purpose. These fibers are single mode and the maintenance of the polarization state is described in terms of a phenomenon known as fiber birefringence.

1. Fiber Birefringence

Single-mode fibers with nominal circular symmetry about the core axis allow the propagation of two nearly degenerate modes with orthogonal polarizations. They are therefore bimodal supporting HE*x*11 and HE*y*11 modes where the principal axes *x* and *y* are determined by the symmetry elements of the fiber cross section. Hence in an optical fiber with an ideal optically circularly symmetric core both polarization modes propagate with identical velocities.Manufactured optical fibers, however, exhibit some birefringence resulting from differences in the core geometry (i.e. ellipticity) resulting from variations in the internal and external stresses, and fiber bending. The fiber therefore behaves as a birefringent medium due to the difference in the effective refractive indices, and hence phase velocities, for these two orthogonally polarized modes. The modes therefore have different propagation constants βx and βy which are dictated by the anisotropy of the fiber cross section. In this case βx and βy are the propagation constants for the slow mode and the fast mode respectively. When the fiber cross-section is independent of the fiber length L in the z direction, then the modal birefringence$B$F for the fiber is given by:

$$B_F = \frac{(\beta_x - \beta_y)}{(2\pi/\lambda)} \tag{2.52}$$

Where λ is the optical wavelength. Light polarized along one of the principal axes will retain its polarization for all L. The difference in phase velocities causes the fiber to exhibit a linear retardation $\Phi(z)$ which depends on the fiber length L in the z direction and is given by:

$$\Phi(z) = (\beta_x - \beta_y)L \tag{2.53}$$

assuming that the phase coherence of the two mode components is maintained. The phase coherence of the two mode components is achieved when the delay between the two transit times is less than the coherence time of the source. the coherence time for the source is equal to the reciprocal of the uncorrelated source frequency width ($1/\delta f$).It may be shown that birefringent coherence is maintained over a length of fiber Lbc (i.e. coherence length) when

$$L_{bc} \simeq \frac{c}{B_F \delta f} = \frac{\lambda^2}{B_F \delta \lambda} \tag{2.54}$$

where$c$ is the velocity of light in a vacuum and $\delta\lambda$ is the source linewidth.

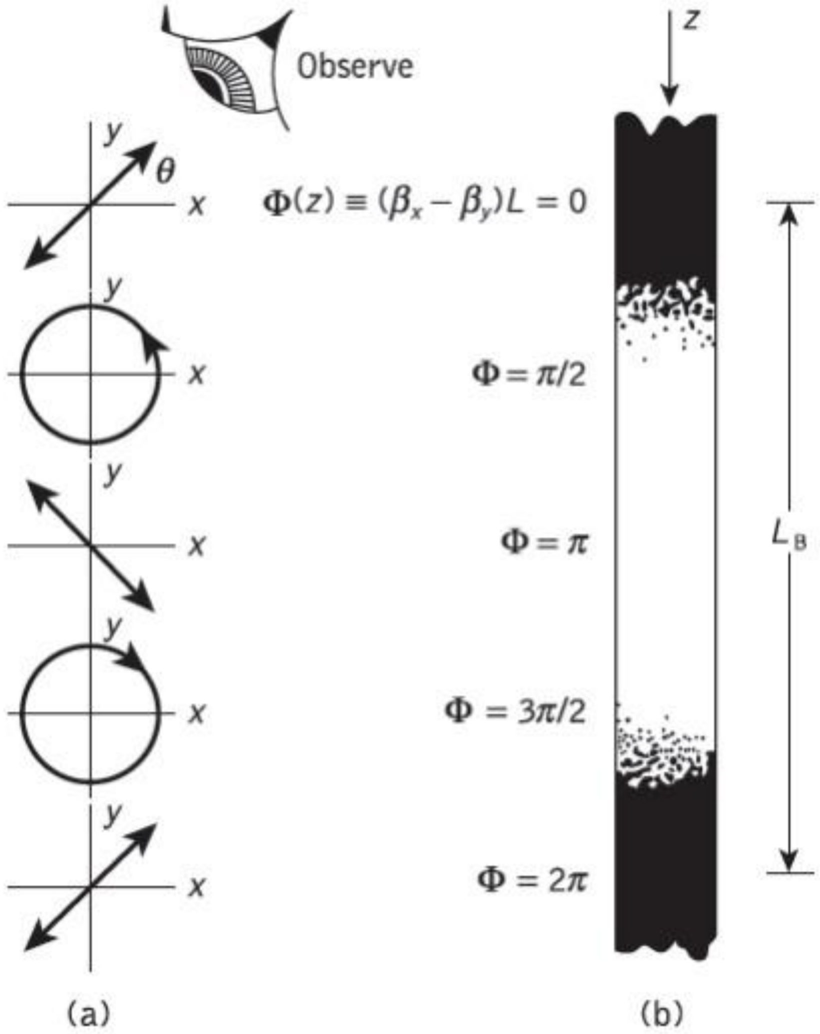

Figure 2.14 An illustration of the beat length in a single-mode optical fiber: (a) the polarization states against $\Phi(z)$; (b) the light intensity distribution over the beat length within the fiber

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However, when phase coherence is maintained (i.e. over the coherence length) Eq. (2.58) leads to a polarization state which is generally elliptical but which varies periodically along the fiber. This situation is illustrated in Figure 2.14(a) where the incident linear polarization which is at 45° with respect to the *x* axis becomes circular polarization at $\Phi = \pi/2$ and linear again at $\Phi = \pi$. The process continues through another circular polarization at $\Phi = 3\pi/2$ before returning to the initial linear polarization at $\Phi = 2\pi$. The characteristic length LB for this process corresponding to the propagation distance for which a 2π phase difference accumulates between the two modes is known as the beat length. It is given by:

$$L_B = \frac{\lambda}{B_F} \tag{2.55}$$

Substituting for *B*F from Eq. (2.47) gives:

$$L_B = \frac{2\pi}{(\beta_x - \beta_y)} \tag{2.56}$$

It may be noted that Eq. (2.56) may be obtained directly from Eq. (2.58) where:

$$\Phi(L_B) = (\beta_x - \beta_y)L_B = 2\pi \tag{2.57}$$

Typical single-mode fibers are found to have beat lengths of a few centimeters, and the effect may be observed directly within a fiber via Rayleigh scattering with use of a suitable visible source (e.g. He–Ne laser). It appears as a series of bright and dark bands with a period corresponding to the beat length, as shown in Figure 2.14.(b).

The modal birefringence *B*F may be determined from these observations of beat length. In a nonperfect fiber various perturbations along the fiber length such as strain or variations in the fiber geometry and composition lead to coupling of energy from one polarization to the other. These perturbations are difficult to eradicate as they may easily occur in the fiber manufacture and cabling. The energy transfer is at a maximum when the perturbations have a period Λ, corresponding to the beat length, and defined by:

$$\Lambda = \frac{\lambda}{B_F} \tag{2.58}$$

However, the cross-polarizing effect may be minimized when the period of the perturbations is less than a cutoff period Λc (around 1 mm). Hence polarization-maintaining fibers may be designed by either:

(a) high (large) birefringence: the maximization of the fiber birefringence, may be achieved by reducing the beat length *L*B to around 1 mm or less

(b) low (small) birefringence: the minimization of the polarization coupling perturbations with a period of Λ. This may be achieved by increasing Λc giving a large beat length of around 50 m or more.

2. Polarization-Maintaining Fibers

Although the polarization state of the light arriving at a conventional photodetector is not distinguished and hence of little concern, it is of considerable importance in coherent lightwave systems in which the incident signal is superimposed on the field of a local oscillator. Moreover, interference and delay differences between the orthogonally polarized modes in birefringent fibers may cause polarization modal noise and PMD respectively. Finally, polarization is also of concern when a single-mode fiber is coupled to a modulator or other waveguide device that can require the light to be linearly polarized for efficient operation. Hence, there are several reasons why it may be desirable to use fibers that will permit light to pass through while retaining its state of polarization. Such polarization-maintaining (PM) fibers can be classified into two major groups: namely, high-birefringence (HB) and low-birefringence (LB) fibers.

The birefringence of conventional single-mode fibers is in the range BF = 10-6 to 10-5. An HB fiber requires BF > 10-5 and a value better than 10-4 is a minimum for polarization maintenance. HB fibers can be separated into two types which are generally referred to as two-polarization fibers and single-polarization fibers. In the latter case, in order to allow only one polarization mode to propagate through the fiber, a cutoff condition is imposed on the other mode by utilizing the difference in bending loss between the two polarization modes.

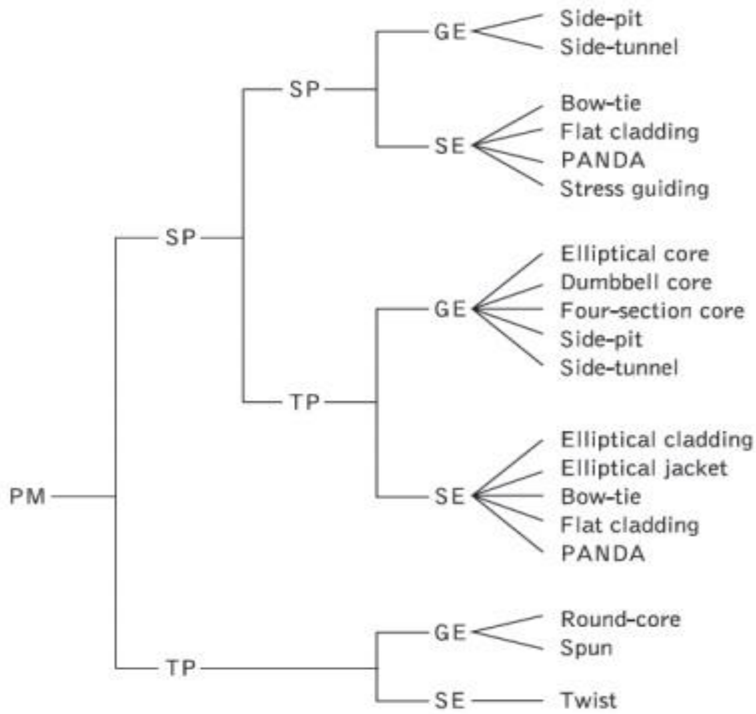

Figure 2.15 Polarization-maintaining fiber types classified from a linear polarization maintenance viewpoint. PM: polarization-maintaining, HB: high-birefringence, LB: low-birefringence, SP: single-polarization, TP: two-polarization, GE: geometrical effect, SE: stress effect

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The various types of PM fiber, classified in terms of their linear polarization maintenance.