Chapter 9
Birefringence in Optical Fibers: Applications

9.1 Introduction

As discussed in the previous chapter, the so-called single-mode fibers in fact support two modes simultaneously, which are orthogonally polarized. In an ideal circular-core fiber, these two modes will propagate with the same phase velocity; however, practical fibers are not perfectly circularly symmetric. As a result, the two modes propagate with slightly different phase and group velocities. Furthermore, environmental factors such as bend, twist, and anisotropic stress also produce birefringence in the fiber, the direction and magnitude of which keep changing with time due to changes in the ambient conditions such as temperature. These factors also couple energy from one mode to the other mode of the fiber, creating problems in practical applications.

The first issue we discuss is that as the magnitude of the birefringence mentioned earlier keeps changing randomly with time due to fluctuations in the ambient conditions, the output SOP also keeps fluctuating with time. The change in the output SOP is of little consequence in applications where the detected light is not sensitive to the polarization state. However, in many applications such as fiber optic interferometric sensors, coupling between optical fibers and integrated optic devices, coherent communication systems, and so on, the output SOP must remain stable. Secondly, since each mode propagates with different group velocities, the so-called polarization mode dispersion (PMD) can limit the ultimate bandwidth of a single-mode optical communication system.

We have already discussed the detrimental aspects of the random birefringence present in the practical fibers. However, a controlled and deliberate birefringence introduced in the fiber may be used to realize several in-line fiber optical components and devices. In this chapter, we will discuss this aspect, i.e., the applications of the controlled and deliberate birefringence introduced in the fiber. The detrimental aspect—namely, the PMD—will be discussed in the next chapter.

One of the most important applications of the deliberately introduced birefringence in optical fibers is the development of high-birefringence (Hi-Bi) fibers, which are realized by introducing a permanent high birefringence into the

fiber during the fabrication stage itself. Such fibers can maintain the SOP of the incident light over large distances and hence are also known as polarization-maintaining fibers (PMFs). In the next section, we will discuss different types of PMFs, their polarization characteristics, and their applications. Devices using controlled birefringence in conventional single-mode fibers are then discussed.

9.2 Polarization-Maintaining Fibers

Polarization-maintaining fibers can be broadly divided into the following two categories: (i) high-birefringence (Hi-Bi) fibers and (ii) single-polarization single-mode (SPSM) fibers.

9.2.1 High-birefringence (Hi-Bi) fibers

In the case of highly birefringent fibers, the propagation constants of the two orthogonally polarized modes are made quite different from each other so that the coupling between the two modes is greatly reduced. Thus, if the light is coupled to only one of the polarized modes, most of the light remains in the same polarized mode; hence, the SOP of the propagating light is maintained along the fiber. The polarization-holding capacity of a birefringent fiber is measured in terms of its beat length L_b, which is defined by

$$L_b = \frac{2\pi}{\beta_x - \beta_y} = \frac{\lambda}{\Delta n_{eff}},$$
(9.1)

where β_x and β_y and represent the propagation constants of the two orthogonally polarized (for instance, along the x and y directions) modes, and Δn_{eff} represents the difference between the effective indices seen by the x- and y-polarized modes at wavelength λ. A lower value of L_b means a higher value of $\beta_x - \beta_y$ and hence corresponds to a fiber with high polarization-holding capacity. Physically, L_b represents the distance along the fiber in which the phase difference between the two fundamental modes becomes 2π. Thus, if light is coupled to both fundamental modes of such a fiber, the SOP will be repeated after each distance L_b along the fiber, as shown in Fig. 9.1. The typical values of L_b for Hi-Bi fibers lie between 1 and 2 mm.

Cross talk (CT) is another important parameter of a Hi-Bi fiber that indicates its practical polarization-holding capacity. CT is a measure of the power coupled to the orthogonal polarization due to random coupling along the fiber when power is launched into one of the polarized modes at the input end. For example, if P_x represents the power launched into the x-polarized mode at the input end and P_y represents the power detected in the y-polarized mode at the output end, then the CT is defined as
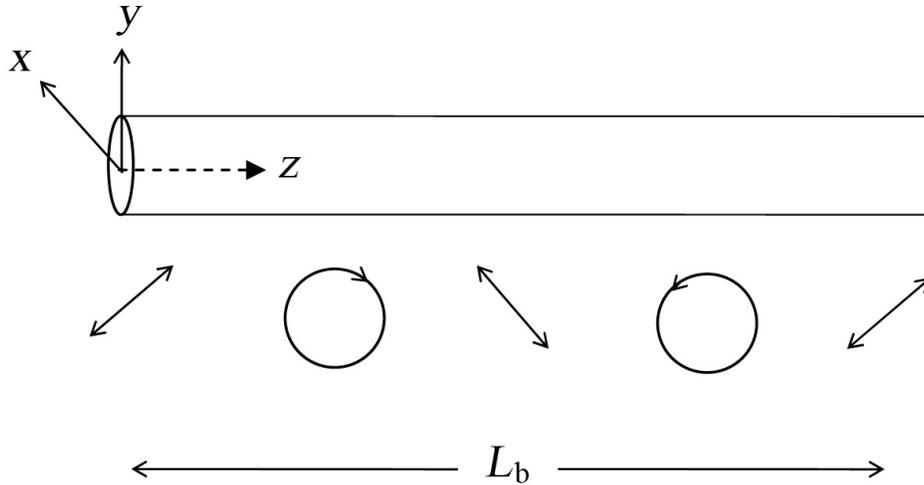
Figure 9.1 Evolution of the polarization state of light guided along a birefringent fiber when the *x*- and *y*-polarized modes are equally excited.

$$\mathrm{CT} = 10\log\left(\frac{P_y}{P_x}\right). \tag{9.2}$$

The unit of CT is decibels (dB), and it has a negative value. A higher absolute value of CT represents better polarization-holding capacity of the fiber.

Coupling between the two orthogonally polarized modes is also sometimes measured in terms of what is known as the *mode-coupling parameter κ* of a Hi-Bi fiber, which is defined as

$$\frac{P_y}{P_x} = \tanh(\kappa L), \tag{9.3}$$

L being the length of the fiber. The various types of popular Hi-Bi fibers are discussed in the remainder of Section 9.2.1.

9.2.1.1 Elliptical-core fibers

Elliptical-core fibers have an elliptical core embedded in a circular cladding, as shown in Fig. 9.2. The elliptical core of such fibers creates both geometrical anisotropy and asymmetrical stress in the core. As a result, the propagation constants β_x and β_y of the two fundamental modes polarized along the major axis (*x* direction) and minor axis (*y* direction), respectively, become different. The total birefringence is thus the sum of the geometrical birefringence B_g (due to the noncircular shape of the core) and stress-induced birefringence B_s (due to the asymmetrical stress produced by the elliptical core).
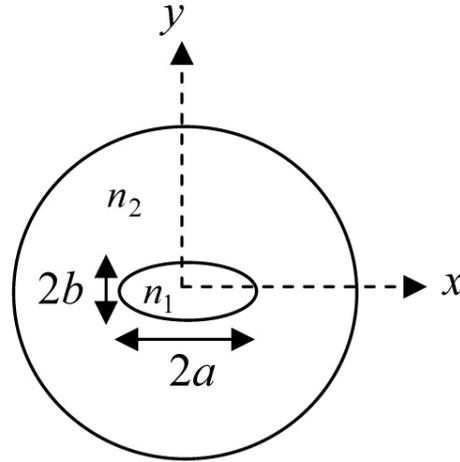
Figure 9.2 Transverse cross section of an elliptical core fiber.

9.2.1.1.1 Geometrical birefringence B_g

The geometrical birefringence of such fibers depends on the aspect ratio a/b of the core as well as on the refractive index difference $\Delta n = (n_1 - n_2)$ between the core and the cladding. In the vicinity of the first higher-mode cutoff, the birefringence for fibers with small core ellipticities ($a/b < 1.2$) is approximately given by[1]

$$B_g = (\beta_x - \beta_y) = 0.2 k_0 \left(\frac{a}{b} - 1 \right)(\Delta n)^2 . \tag{9.4}$$

Equation 9.4 shows that the birefringence of such fibers can be increased by increasing either the core ellipticity or Δn. However, it should be mentioned that neither a/b nor Δn can be increased beyond a certain limit due to the following:

(i) The birefringence is not a sensitive function of a/b for $a/b \gg 2$; it saturates to a value that is approximately given by (as obtained by curve fitting from Fig. 1 of Ref. 2)

$$B_g \simeq 0.32 (\Delta n)^2 . \tag{9.5}$$

(ii) For very large values of Δn, the core dimensions required for single-mode operation of the fiber become extremely small, and the fabrication of the fiber becomes very difficult. This is why such fibers were initially not considered of much use. However, the shift to longer wavelengths for long-distance communication systems has generated a great deal of interest in such fibers.

The exact calculation of B_g in elliptical-core fibers is quite difficult, as the wave equation must be solved in the elliptical coordinates, and the eigenvalue equation so obtained is in the form of an infinite determinant.[3] Dyott et al.[4] obtained the birefringence of different elliptical-core fibers by truncating the infinite determinant to a finite order. Numerical techniques such as the finite-element method[5] and the point-matching method[6] have also been used by various authors; however, these approaches involve time-consuming numerical calculations. A number of approximate methods[7–9] have also been reported, among which the one proposed by Kumar et al.[9] is relatively simple and gives reasonably accurate values of B_g in the region of practical interest. This approach, which approximates the elliptical core by an equivalent rectangular core, is discussed in the following section.

9.2.1.1.2 Equivalent rectangular waveguide model

Kumar and coworkers[9] have shown that the birefringence of an elliptical-core fiber closely matches that of a rectangular-core waveguide having the same core area, aspect ratio, and core and cladding refractive indices. Thus, the birefringence of an elliptical-core fiber with major and minor axes as $2a$ and $2b$, respectively, is approximately equal to that of a rectangular-core waveguide with major and minor axes given by

$$2a' = \sqrt{\pi}a \text{ and } 2b' = \sqrt{\pi}b, \tag{9.6}$$

with the same core and cladding refractive indices, n_1 and n_2, respectively. The propagation constants β_x and β_y for the two fundamental modes of this rectangular core waveguide can be obtained by using an accurate perturbation approach[10] and are given by

$$\beta_i^2 = (\beta_{1i}^2 + \beta_{2i}^2) + k_0^2(n_1^2 - n_2^2)P_i^2, \tag{9.7}$$

where i stands for x or y, and β_{1i} and β_{2i} are obtained by solving the two following simple transcendental equations:

$$\mu_1 \tan \mu_1 = \alpha_i \sqrt{V_1^2 - \mu_1^2}, \tag{9.8}$$

and

$$\mu_2 \tan \mu_2 = \frac{1}{\alpha_i} \frac{n_1^2}{n_2^2} \sqrt{V_2^2 - \mu_2^2}, \tag{9.9}$$

where $\qquad \alpha_i = \dfrac{n_1^2}{n_2^2}$ (or 1), for $i = x$ (or y),