CHAPTER 9

OTHER OPTICAL COMPONENTS

9.1 INTRODUCTION

In this chapter we describe optical phase-locked loops, optical directional couplers, ring resonators, optical equalizers, optical isolators, and polarizers, rotators, and circulators. Optical multiplexers and demultiplexers, as well as optical switches, are covered in subsequent chapters.

9.2 OPTICAL PHASE-LOCKED LOOPS

An *optical phase-locked loop* (OPLL) is a device based on a tunable laser source, a filter, and a photodiode bridge. Its principle of operation is similar to that of electronic PLLs. Ideally, the frequency from laser 1 ($\cos \omega t$) is in perfect quadrature with that from laser 2 ($\sin \omega t$). A balanced pin–diode bridge detects both frequencies. When the two frequencies are the same, the bridge is balanced at a quiescent state; otherwise, an unbalanced current is amplified and fed back through a low-pass filter to tunable laser 2 to adjust its frequency (Figure 9.1). Clearly, this arrangement assumes that both incoming light sources are at the same optical power level; if they are not, a compensating mechanism is incorporated.

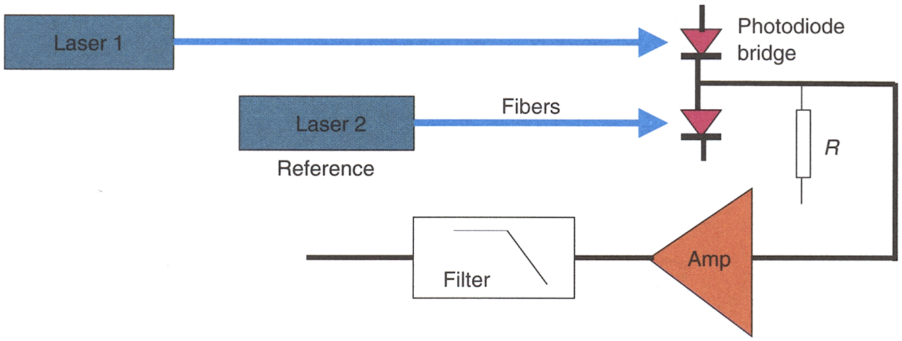

Figure 9.1 An optical phase-locked loop (OPLL) is a device based on a tunable laser source, a filter, and a photodiode bridge.

9.3 OPTICAL DIRECTIONAL COUPLERS

Optical directional couplers are devices that transfer the maximum possible optical power from one or more optical device(s) to another in a selected direction. Power transfer may be from a light source into a fiber, from fiber to fiber, from fiber to a device (such as to a filter, to a demultiplexer, etc.), and from a device to a fiber. The making of optical directional couplers employs filters and solid-state devices.

Single-mode fiber directional couplers use the evanescent property of integrated lightguides on a substrate to couple optical power (light) of a certain wavelength from one guide to another. Figure 9.2 illustrates two lightguides of coupling length L_0 separated by a distance d. When a voltage V_s is applied, optical power is guided through the same guide, but with a phase change. When the applied voltage is $V = 0$, power is transferred through the evanescent separation region to the adjacent guide. For maximum power transfer, certain conditions must exist:

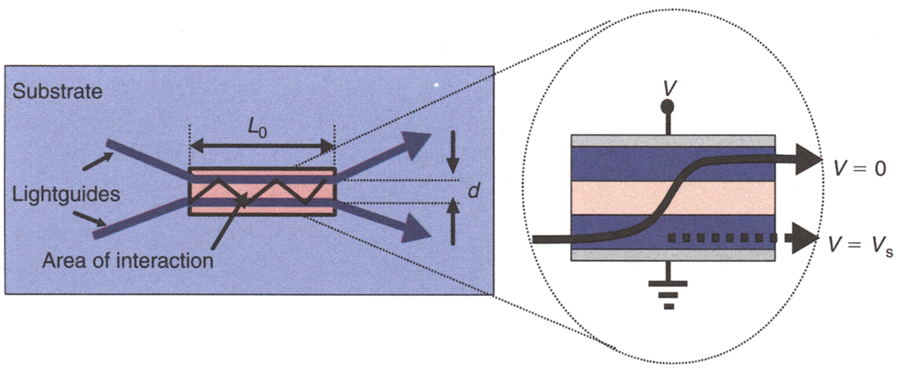

Figure 9.2 Couplers are characterized by the power coupled or lost at the coupling length, typically in terms of power loss Γ.

- The two lightguides must be in close proximity, separated by a distance d comparable to the wavelength λ to be coupled.
- The two phase velocities must be in perfect synchronization.
- The refractive index must be the same for both lightguides.
- The interaction (or coupling) length L_0 must precisely equal a coupling length [which is proportional to $\exp(d/d_0)$].

When the refractive index of one lightguide differs from the other, power is lost during optical power transfer. When the separation distance d or the equivalent optical isolation between the two guides at the coupling length L_0 increases, optical coupling decreases and at some distance d there is no coupling at all. Clearly, if the isolation between the two guides over the length L_0 is controlled, a device with some interesting applications may be made. Such controllable devices, in addition to being used as directional couplers, may be used as power attenuators, as signal modulators, as power splitters, or as on–off switches.

Couplers are characterized by the power lost, Γ. Typically, couplers are referred to as $(1 - \Gamma)^{1/2}$ or $(\Gamma)^{1/2}$ couplers. A typical power loss in couplers is about 3 dB at 1.5 μm. Power is lost under the following conditions:

- In the bulk of the lightguide material along the coupling length (because of scattering and absorption)
- At the sidewalls (because of structure irregularities)
- At the interface with the substrate (because of the form of scattering known as epitaxial interface scattering)
- At the edges (because of reflections and fiber-coupled insertion loss)

The most desirable characteristics of optical couplers are as follows:

- High isolation
- Low coupling power loss, Γ (in dB), and thus maximum power transfer
- No signal reflectivity
- No signal absorption
- No through-phase shift
- No signal distortion over the entire wavelength range of interest
- No added dispersion effects
- No added polarization effects
- No added noise
- Steady performance over a wide range of temperatures

Integrated lightguides are made from a variety of compounds, such as the following:

- GaAs doped (10^{15}) over a highly doped (10^{18}) GaAs substrate
- InP doped over a highly doped InP substrate
- GaAs over AlGaAs over a GaAs substrate
- InGaAsP over an InP substrate
- Ti diffused over a lithium niobate substrate (Ti:$LiNbO_3$)

The Ti:$LiNbO_3$ lightguide has the least loss, requires a relatively low voltage, and responds quickly. Thus, these devices are also used in photonic switching applications. However, InP and GaAs devices are better suited to monolithic optoelectronic integration with laser sources or detectors.

Couplers come in different flavors. Figure 9.3 illustrates three types. Directional couplers also act as isolators, and therefore a measure of goodness is the amount of power coupled in the desired direction with respect to the undesired (in dB). For maximum power transfer from a fiber, end faces are cut perpendicular to the longitudinal axis, they are highly polished and coated with antireflective film to prevent reflections and optical feedback, which could stimulate a laser effect. Finally, owing to the very small core diameter (~8 μm), the importance of fiber core alignment cannot be overemphasized.

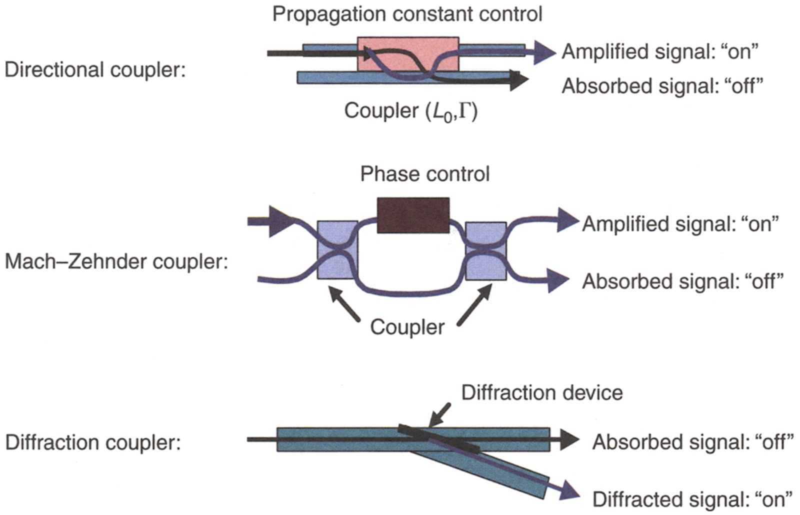

Figure 9.3 Couplers come in different types.

9.4 RING RESONATORS

Consider a fiber ring with its core in close proximity to the transmission fiber, thus forming a coupler with a coupling length L_0 and a coupler power loss Γ at the interaction region (Figure 9.4). The coupler is a $(1 - \Gamma)^{1/2}$ type (this describes the power coupled onto the ring). The ring has a circumference length L and attenuation constant α. Now, consider a lightwave traveling through the transmission fiber. When it reaches the coupler device, it is coupled onto the ring and travels around it. After a complete revolution around the ring, the coupled lightwave returns to the coupler with an attenuation α and a phase shift $\Phi = \beta L$, that which depends on the length ring L and on the wavelength λ.

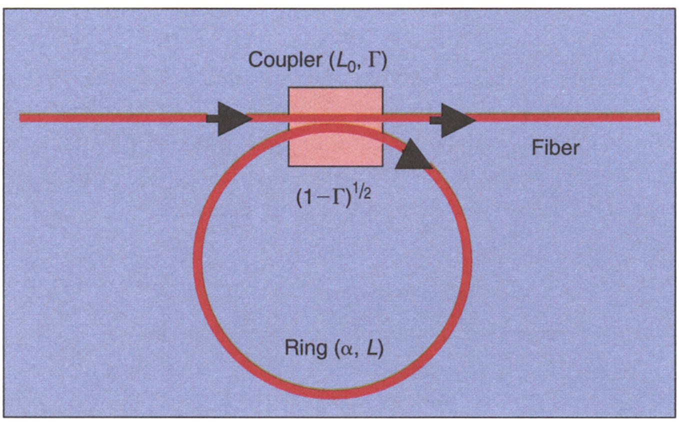

Figure 9.4 A ring resonator consists of a fiber ring with its core in close proximity to the transmission fiber.

At the coupler, the lightwaves from the ring and from the transmitting fiber interfere constructively or destructively, depending on which condition is valid, $\Phi = 2\pi N$ or $\Phi = 2\pi(N+1/2)$, respectively, where N is an integer.

The frequency difference Δf between the maximum and minimum of the transmitted power is obtained by

$$\Delta f = \frac{c}{2n_{\text{eff}} L}, \tag{9.1}$$

where n_{eff} is the effective refractive index. The effective refractive index in this case is defined as the weighted average of the refractive index of the waveguide and of the refractive index of the evanescent substrate.

The ring resonator acts like a pass-band filter with sharp cutoff characteristics and a high finesse (reported > 182). Its transmittance profile is depicted in Figure 9.5.

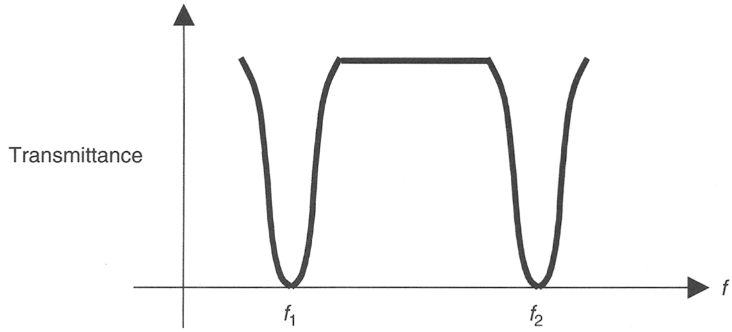

Figure 9.5 Transmittance profile of a ring resonator.

9.5 OPTICAL EQUALIZERS

The wavelengths of a generated spectral region are not all of the same amplitude. However, for proper transmission operation it is necessary to have a flat output power spectrum. Optical equalizers monitor each wavelength channel at the output and make selective amplitude adjustments to flatten the optical power of the spectrum within a band of wavelengths (Figure 9.6).

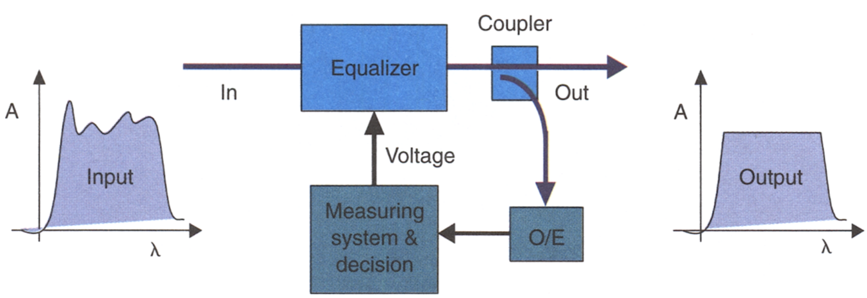

Figure 9.6 Optical equalizers flatten the optical power of a spectrum.

The equalizers operate as follows. At the output, each wavelength (with a given granularity) and over a wavelength range is (iteratively) measured, and based on each measurement, an appropriate adjustment is performed (by the application of an appropriate voltage) on the amplitude of the measured wavelength so that a flat spectrum is achieved. Figure 9.7 illustrates a typical output in the wavelength range of 1530–1565 nm with and without equalization.

Optical equalizers that perform equalization on a dynamic basis are also called dynamic wavelength equalizers (DWEs). Currently, optical equalizers are optoelectronic feedback control subsystems. A compact, all-optical equalizer with fast dynamic range is a device of the future.

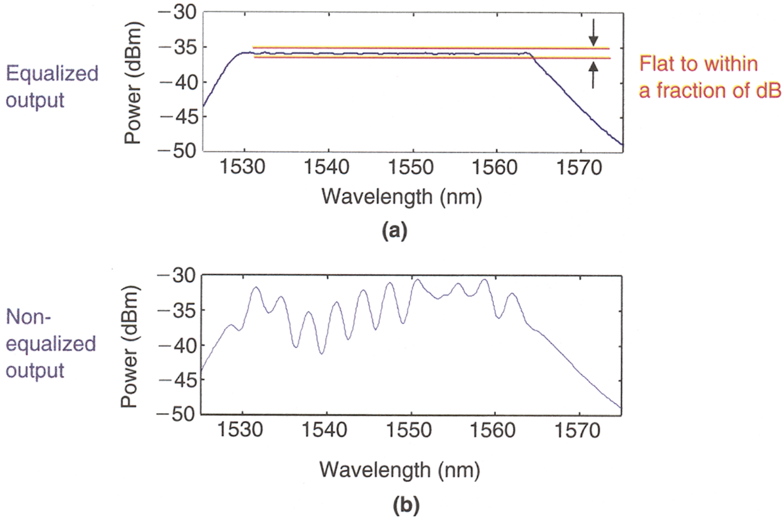

Figure 9.7 Typical power output (a) with equalization and (b) without. Bandwidth granularity is 0.5 nm.

The desirable characteristics of optical equalizers are

- Large wavelength range
- Low ripple of the spectrum amplitude (small peak-to-peak variation)
- High dynamic range
- Low loss
- Polarization independent
- Fast acquisition

9.6 OPTICAL ISOLATORS

Optical isolators are devices that transmit optical power (of a band of wavelengths) in one direction more than the other direction (Figure 9.8). Optical isolator devices are characterized by *insertion loss L*, or the loss of optical power through the device, and by *isolation I*, or the ratio of transmitted power in one direction to power in the other direction. Ideally, the isolator should allow transmission of all power in one direction and no power in the other direction; that is, $L = 0$ and $I =$ infinite.

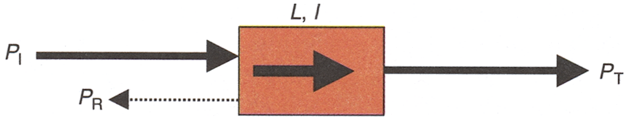

Figure 9.8 Optical isolators transmit optical power (of a band of wavelengths) in one direction more than the other.

The quantities L and I are expressed by

$$L = P_{\mathrm{I}} - P_{T2}\ (\mathrm{dB}) \tag{9.2}$$

and

$$I = P_{\mathrm{I}} - P_{\mathrm{R2}}\ (\mathrm{dB}) \tag{9.3}$$

where P_{I}, P_{T}, and P_{R} are the incident power, the transmitted power, and the reflected power, respectively, all expressed in decibel units.

9.7 POLARIZERS, ROTATORS, AND CIRCULATORS

Optical isolator devices are made with certain materials (formed in parallel plates or prisms) that allow one polarization direction of nonpolarized light to propagate through it. These devices are called *polarizers*. Birefringent materials can be used as polarizers.

Other materials rotate the polarization direction by an angle, and they are called *rotators*. Rotators are based on the Faraday effect. Rotators can be made with fibers doped with elements or compounds that have a large Verdet constant, such as terbium (Tb), YIG ($Y_3Fe_5O_{12}$): yttrium-iron-garnet), and TbBiIG ($Tb_{3-x}Bi_xFe_5O_{12}$: bismuth-substituted terbium-iron-garnet). Some compounds such as the YIGs, may require a strong magnetic field.

Polarizers and rotators can be combined to form isolators. Isolation is accomplished using polarizers and $\pi/4$ rotators in cascade, as shown in Figure 9.9.

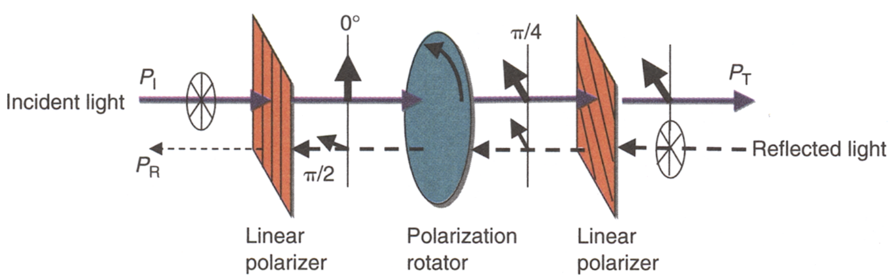

Figure 9.9 Isolation is accomplished by using polarizers and $\pi/4$ rotators in cascade.

Isolators may be viewed as two-port devices that allow unidirectional energy to flow from one terminal to the other. Now, if using a structure made with more than one isolator, a three-terminal device is constructed that permits unidirectional energy to flow from terminal 1 to 2, from 2 to 3, and from 3 to 1. This device is known as a circulator. Four-terminal circulators are also available.

Compactness of optical devices is a highly desirable feature in fiber-optic communications systems. Thus, devices with large Verdet values and strong magnetic fields would result in short lengths for a desirable angle of rotation.

For example, for 45° polarization shift (rotation) at $\lambda = 633$ nm, a terbium-doped glass fiber would be around 108 mm long [for $H = 1000$ Oe and a Verdet constant of $V = 0.25$ min/cm • Oe]. On the other hand, for 45° polarization shift at λ = 1300 nm, YIG devices placed in a strong (saturated) magnetic field are about 2 mm long. TbBiIG devices have also been used in the wavelength range of 1500 nm.

EXERCISES

1. What are the main components of an OPLL?
2. List five of the most desirable characteristics of optical couplers.
3. What is the fundamental principle on which a ring resonator operates?
4. What is an optical isolator?
5. What is a rotator?
6. Could a rotator be used to construct an isolator?