1

Optical Fiber and Optical Devices

1.1 Optical Fiber

Optical fibers are used most often as a flexible medium to transmit light. The external diameter of optical fibers is several hundreds of microns, and the most commonly used optical fiber in communication has a tiny diameter of only 125 μm. It makes optical fiber have inherent dimension advantage compared with other information transmission medium. As a cylindrical waveguide, the optical fibers usually have two layers with different refractive indices to achieve total internal reflection. The refractive index (RI) of fiber core n_{core} is higher than that of fiber cladding n_{clad}; hence the light energy is kept in the thinner core and transmitted along the fiber. Figure 1.1 shows the cross section and RI profile of a typical step-index fiber with the core/cladding diameter of r_{core}/r_{clad}. The relative RI difference Δ between the fiber core and cladding can be expressed as

$$\Delta = \frac{n_{core} - n_{clad}}{n_{core}} \tag{1.1}$$

The normalized frequency V of fiber defined as

$$V = \frac{2\pi r_{core}}{\lambda}\sqrt{n_{core}^2 - n_{clad}^2} \tag{1.2}$$

where λ is the wavelength of light. If $V < 2.405$, the optical fiber supports a single transmission mode, which is called as single-mode fiber (SMF). Increasing the diameter of optical fiber core can construct multi-mode fiber (MMF) to support more modes, and the core diameter of common MMF can be up to 62.5 or 105 μm with cladding diameter of 125 μm, but the core diameter of SMF is only 5–9 μm. In addition, by using the multi-mode interference effect in MMF, many physical parameters can be measured by optical fiber sensor, such as surrounding RI and temperature.

The propagation of light in optical fiber will produce inevitable transmission loss due to material absorption and Rayleigh scattering dominantly. The transmission loss α_{dB} of a fiber of L length can be expressed as

$$\alpha_{dB} = -\frac{10}{L}\log\left(\frac{P_1}{P_0}\right) \tag{1.3}$$

where P_1 and P_0 are the injected light power and the transmitted light power, respectively. In order to achieve ultra-low transmission loss, optical fibers are fabricated

Optical Fiber Sensing Technologies: Principles, Techniques, and Applications, First Edition.
Tiegen Liu, Junfeng Jiang, Kun Liu, and Shuang Wang.

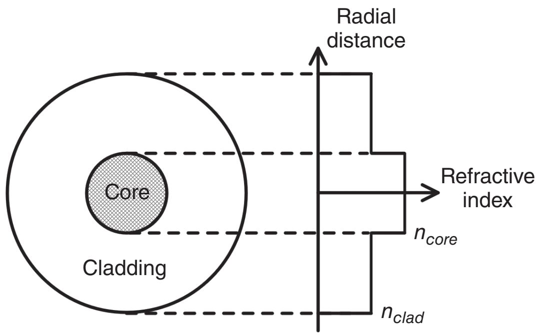


Figure 1.1 Cross-section refractive index profile of typical optical fiber. Source: Junferg Jiang.

by pure silica (SiO_2) or plastic. During the fabrication process, the dopants, such as GeO_2 and P_2O_5, are doped into the fiber core to increase the RI. Nowadays, the SMF have a minimum loss of ~0.2 dB/km at a communication window of 1550 nm. In fact, the fiber losses depend on the wavelength of transmitted light. But the loss is not necessarily detrimental to fiber sensing. The distributed optical fiber sensing can be realized by combining the Rayleigh scattering effect and nonlinear effects in the fiber.

In addition to the common silica fiber with single core and cladding, there are many special optical fibers with various compositions and structures for sensing, as shown in Figure 1.2. No-core fiber (NCF) only has a major core and uses the

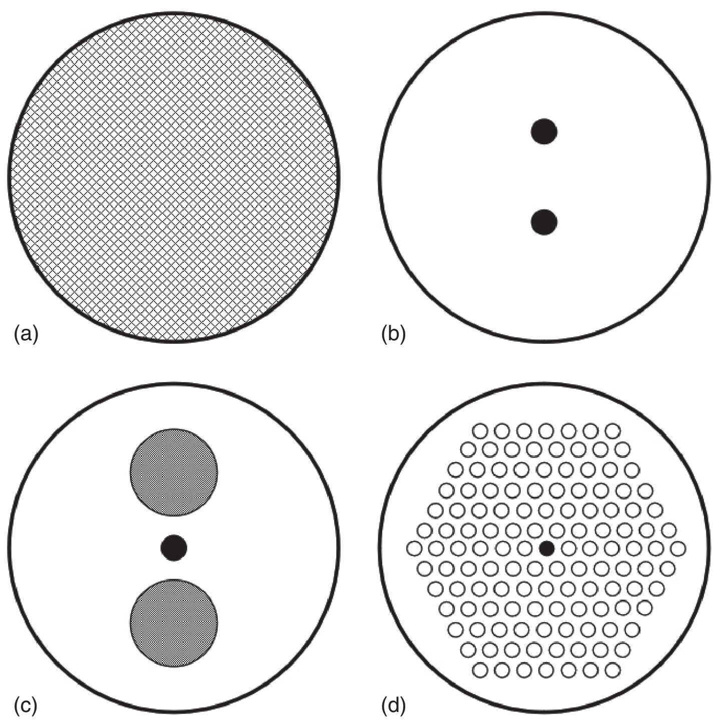


Figure 1.2 Scheme of special optical fibers: (a) NCF, (b) TCF, (c) PMF, and (d) PCF. Source: Junferg Jiang.

surrounding media as its cladding, so NCF is very sensitive to change of surrounding RI and can be selected to provide the self-image effect for RI measurement [1, 2]. Twin core fiber (TCF) has two thin cores in the same cladding, and the in-line Mach–Zehnder interferometers (MZIs) are easy to be constructed by it for multi-parameter sensing [3, 4]. Polarization-maintaining fiber (PMF) uses high-ellipticity fiber core and stress rods to realize the high birefringence and provides fixed polarization state and bending resistance characteristics. Photonic crystal fiber (PCF) is different from the traditional solid optical fiber with single medium, which has unique microstructure air holes in two-dimensional direction. Due to the microfluidics channel and high nonlinear effects, the PCF attracts great interests in biochemical sensing [5, 6]. According to the properties of the parameters to be measured, the sensitivity and detection limit of optical fiber sensors can be improved by selecting sensing optical fibers with appropriate geometric structures and optical characteristics.

1.2 Light Source

In optical fiber sensing system, the optical fiber sensor or sensing optical fiber can be simply regarded as a modulator affected by the parameters to be measured, and the light source is an unmodulated signal source, so its main purpose is to provide light. For different sensing targets and applications, the choice of light source is very important. The intensity, wavelength range, and stability of light source may affect the sensing performance. Moreover, it is necessary to balance performance and cost in practical engineering application. At present, the most commonly used light sources can be divided into two categories: semiconductor laser and optical fiber laser.

1.2.1 Semiconductor Laser

With the development of semiconductor device technology in 1960s [7, 8], the semiconductor laser is one of the first lasers to enter the field of civil consumption, which is widely used in consumer electronics and optical communication. Generally, the semiconductor laser obtains energy through electric pump. The laser output with high energy conversion efficiency (more than 50%) can be realized with a small pump current (15 mA at 2 V is typical), and the high-speed communication with a rate of more than 20 GHz can be achieved by direct modulation. In addition, semiconductor laser has inherent advantages in size and can be easily integrated with electronic devices. With the mature semiconductor processing technology, it can be produced on a large scale at low cost. These advantages make semiconductor laser the most widely used laser.

The semiconductor material is a covalent crystal composed of a large number of atoms arranged periodically and orderly. In this kind of crystal, due to the interaction of the neighboring atoms, the energy states of the electrons expand into the energy band with continuous energy level distribution. On the basis of atomic energy level, the energy level spectrum of a crystal is divided into several groups according to the different co-existence motion. The middle energy levels of each group are close to each other and form a band with a certain width, which is called energy band. The energy band occupied by the valence electrons forming the covalent bond is called the valence band (low energy band), while the adjacent empty band (free electron occupied energy band) above the valence band is called the conduction band (high energy band). The area between them is called the forbidden gap. For semiconductor lasers, the coherent optical emission arises from the stimulated transition from a higher energy band (conduction band) to a lower energy band (valence band) in the semiconductor materials.

The inversion distribution of particle number is a necessary condition for the generation of stimulated radiation, but it cannot produce laser yet. When the active material is placed in the optical resonator, the frequency and direction of the light are selected, and the continuous optical amplification and laser oscillation output can be obtained. The basic optical resonator consists of two parallel mirrors with different reflectivity and is called the Fabry–Perot resonator. Because the active material in the resonant cavity has a population inversion distribution, the spontaneous radiation produced by it can be used as the incident light. The incident light is reflected by the reflectors, the light propagating along the axis direction is amplified, and the light along the non-axis direction is weakened. After multiple feedback, the reflected light is continuously amplified, the directivity is continuously improved, and the gain is greatly improved. In addition, due to the absorption of the active material in the resonant cavity and scattering of the mirrors, the light suffers certain loss. When the gain and loss are equal (satisfying the condition of amplitude balance), a stable laser oscillation will be established in the resonant cavity.

The emission wavelength λ of a semiconductor laser depends on the energy released when the electrons in the conduction band transition to the valence band, which is approximately equal to the bandgap width, which can be expressed as

$$\lambda = \frac{hc}{E_g} \approx \frac{1.24}{E_g} \tag{1.4}$$

where $h = 6.626 \times 10^{-34}$ J s is the Planck constant and c is the light speed in vacuum.

As a cost-effective choice, the superluminescent diode (SLD) without reflection facet can provide broadband light, which has near Gaussian or flat-topped spectrum with relatively high average power. The optical bandwidth of SLD is usually tens of nanometers, sometimes even higher than 100 nm. Therefore, SLDs are particularly suitable for testing the transmission characteristics of optical fiber sensors. Using two SLDs with different wavelength ranges together can obtain a wider bandwidth high-power light source. Figure 1.3 shows the spectrum of a combined SLDs light source. It should be noted that optical feedback will reduce the output power or damage the SLD, and the SLD should not be used directly with reflective components, such as ferrule connector/physical contact (FC/PC) connectors. Figure 1.4 shows a photo of a benchtop SLD light source.

Unlike SLD with broadband light, the distributed feedback (DFB) laser is a narrow linewidth with single-frequency light source. In the active region of DFB laser, the periodic corrugated waveguide is equivalent to a distributed reflector, which

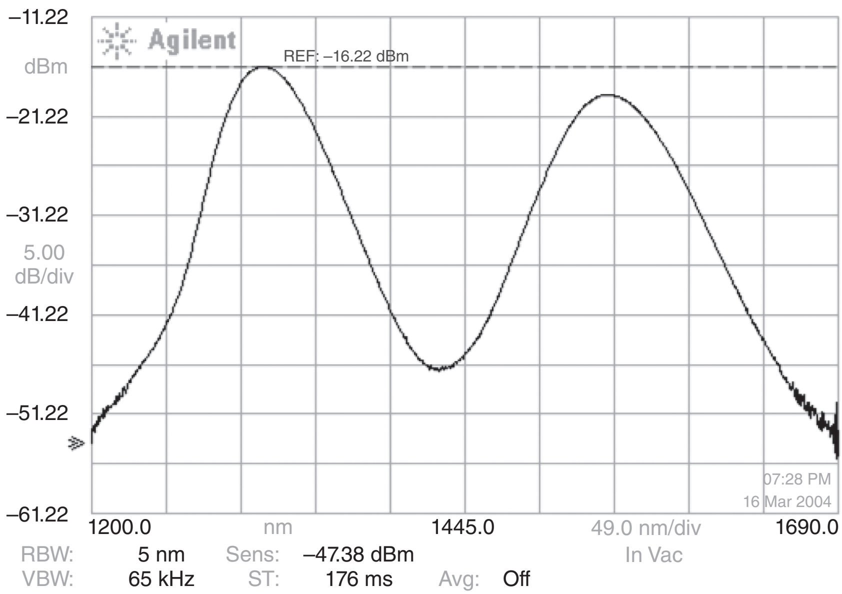


Figure 1.3 Spectrum of a combined SLDs light source. Source: Junferg Jiang.

Figure 1.4 Photo of a benchtop SLD light source. Source: Junferg Jiang.

provides optical feedback and wavelength selection. In this way, the DFB laser can achieve a typical linewidth of 2 MHz and a high side-mode suppression ratio (SMSR) of 40 dB. With the advantages of high stability and monochromaticity, the DFBs are suitable as investigation light sources in the distributed fiber sensing.

Commercial semiconductor lasers provide an extensive collection in package. The transistor outline (TO) can lasers are small in size and are easily embedded in the

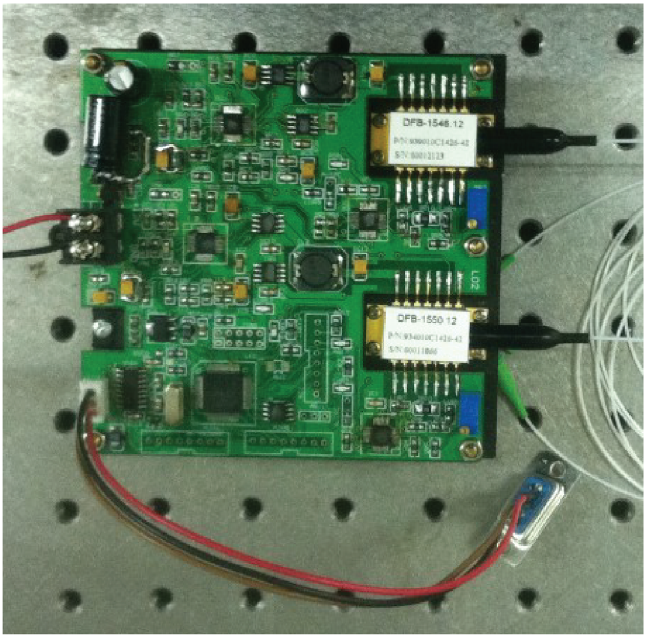


Figure 1.5 Photo of OEM light source with two pigtailed DFB lasers. Source: Junferg Jiang.

optoelectronic system, which can be packaged with and without pigtails. Another common packaging method is the butterfly package. The butterfly laser has more pins (14 pins compared with 3 pins of TO can) to provide accessional control and monitor functions. Moreover, the thermo-electric cooler (TEC) can be employed to maintain the stability of the laser under long-term working condition, but it also makes the butterfly laser slightly larger than the TO laser, as shown in Figure 1.5.

1.2.2 Optical Fiber Laser

The optical fiber laser is a kind of solid-state lasers that uses rare-earth-doped fiber doped with rare-earth elements such as erbium, ytterbium, neodymium, dysprosium, praseodymium, thulium, and holmium, as gain medium. However, unlike the traditional solid-state lasers with block Nd: YAG gain mediums, the fiber lasers with all-fiber structure can effectively avoid the interference of space environment, thermal-lens effect, and thermal-birefringence effect under high power and improve the coupling efficiency and beam quality. According to the working mode, optical fiber lasers can be divided into two types: continuous-wave (CW) oscillation lasers and pulse oscillation lasers. Moreover, nonlinear effects of optical fiber, such as stimulated Raman scattering, stimulated Brillouin scattering, and four-wave mixing can also provide gain and thus serve as gain media for a fiber laser.

Figure 1.6a gives the basic schematic diagram of the optical fiber laser with linear cavity. In order to realize laser oscillation and output, optical fiber laser is composed of three main parts: pump source, gain medium, and resonator. The semiconductor

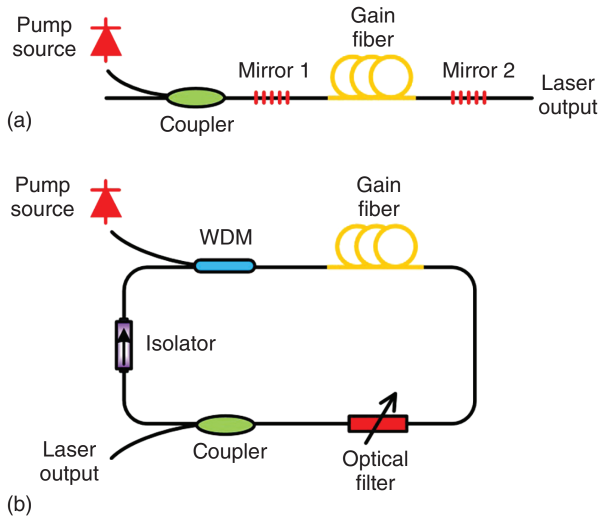


Figure 1.6 Schematic diagrams of the optical fiber lasers with (a) linear cavity and (b) ring cavity. Source: Junferg Jiang.

laser diode is usually used as the optical pump for pumping energy to realize particle number inversion in gain fiber, and the pump light is injected into the gain fiber through the optical coupler or wavelength division multiplexer (WDM). The gain fiber is the optical fiber added with rare-earth elements artificially in the manufacturing process. The linear cavity resonator is composed of mirrors with different reflectivity at both ends of the gain fiber. In the all-fiber laser, the fiber Bragg gratings (FBGs) are often used as the mirrors. The seed light is generated by the pump light, which enters the gain fiber to generate stimulated emission. Through the mode selection and optical oscillation of the resonator, most of the amplified light is reflected into the gain fiber after reaching the mirror 2 of the laser-output end, so the stimulated emission amplification occurs again in the gain fiber. The pump-input end of the resonator is a mirror 1 with higher reflectivity, so the light is reflected and magnified again. Between the two mirrors, the laser will produce an amplification process every time. Until the light intensity reaches the oscillation threshold of laser, a small part of the amplified laser is output through the mirror 2 with lower reflectivity, while the other 95% of the light continues to be reflected back to produce light amplification.

In addition to fiber linear cavity, fiber ring cavity configuration is also commonly used to realize fiber laser, as shown in Figure 1.6b. A positive feedback optical path is formed by closing the input and output ends of the resonator, which can realize multiple amplification and laser oscillation without the use of a mirror. However, in order to avoid the laser in a free-running state, it is usually necessary to insert an optical filter into the ring cavity to achieve specific wavelength or stable tunable wavelength laser output.

Broadband light can be realized by using amplified spontaneous emission (ASE) characteristics of rare-earth-doped fiber. Figure 1.7 shows a typical ASE spectrum

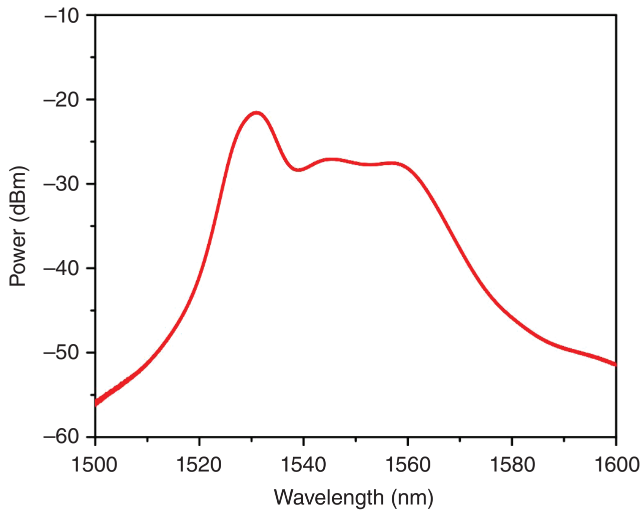


Figure 1.7 Typical ASE spectrum of an EDF. Source: Junferg Jiang.

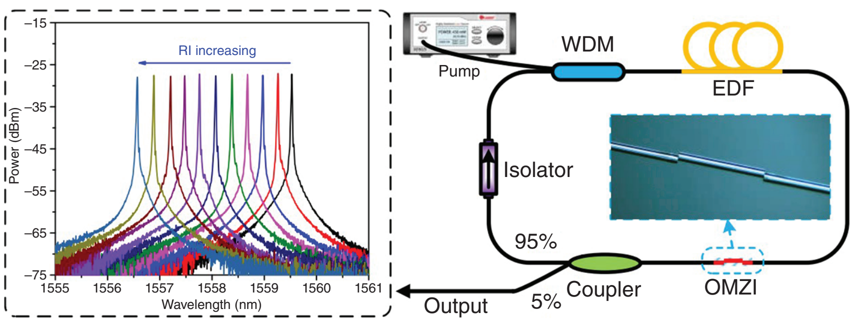


Figure 1.8 Scheme of a tunable fiber ring laser based on OMZI. Source: Junferg Jiang.

of an erbium-doped fiber (EDF). In addition, by inserting a filter into a closed ring cavity, single- or multi-wavelength laser can be generated. As shown in Figure 1.8, an open microcavity Mach–Zehnder interferometer (OMZI) provides a wavelength selector for a fiber ring cavity, which has compact in-line fiber structure and high RI sensitivity. The tunable single-wavelength laser can be obtained by changing the surrounding RI. At the same time, it can also be used for RI measurement with high detection limit due to the narrow full width at half maxima (FWHM) and high optical signal-to-noise ratio (OSNR) of laser spectra.

Because there is no optical lens in the resonant cavity of the fiber laser, optical fiber lasers have the advantages of free adjustment, free maintenance, and high stability, which is incomparable to the traditional solid/gas/dye-state lasers. In addition, the low cost, resistance, and flexibility of silica fiber provide the advantages of miniaturization and intensification of fiber laser devices. The power of the commercialized high-power fiber laser can reach 6 kW. Owing to the excellent beam quality, optical fiber lasers are gradually replacing other lasers in industrial applications such as mechanical cutting, marking, rust and paint removal, micro–nano processing, etc. In recent years, the tunable fiber lasers with broadband and high-power fiber lasers are still the research hotspots. In addition, due to the unique application prospects in biochemical medicine and special processing fields, thulium-doped fiber lasers in 2 μm wavelength region has attracted more and more attention.

1.3 Optical Amplifier

As mentioned in Section 1.1, the transmission of light in optical fiber will produce losses. Although the current advanced optical fiber manufacturing technology can reduce the actual transmission loss to the theoretical limit, in the complex long-distance optical communication and sensing systems, the additional losses caused by various factors such as insertion losses of devices may significantly reduce the intensity of optical signal, so that it cannot be accurately demodulated or detected. Different from the previous photon–electron–photon relay amplifiers, optical amplifiers do not require complex regeneration process of light signals, which can provide cost-effective optical gain and compensate for the decrease in optical power.

1.3.1 Erbium-Doped Fiber Amplifier

Erbium is a rare-earth element. In the manufacturing process of optical fiber, EDF can be made by doping erbium ion Er^{3+} into the fiber core, which is the main gain medium of the erbium-doped fiber amplifier (EDFA). EDFA can provide optical amplification at the low-loss window of 1550 nm due to the stimulated emission caused by electron transition of Er^{3+} between $^4I_{15/2}$ and $^4I_{13/2}$ state level, and it greatly promoted the development of optical fiber communication in the late 1980s. Owing to the homogeneous and inhomogeneous broadening of Er^{3+} state level, EDFA has excellent broadband amplification capability covering almost the entire C-band (1530–1565 nm) and L-band (1565–1625 nm), so it is widely used in wavelength division multiplexing system. EDFs are usually pumped by laser diode (LD) with the center wavelength of 980 or 1480 nm. The green fluorescence of EDF can be observed due to the excited state absorption effect of Er^{3+} when 980 nm light pump is used, as shown in Figure 1.9.

EDFAs can be simply modeled using the Giles model [9]. The pump light is coupled into EDF via WDM, the Er^{3+} of EDF absorbs the optical pumping energy and then it produces population inversion in EDF. The 1480 nm optical pumping lifts the electrons of Er^{3+} to $^4I_{13/2}$ state directly, as shown in Figure 1.10, but the 980 nm optical pumping makes electrons transit to upper state of $^4I_{11/2}$, and the excited electrons at $^4I_{11/2}$ state will rapidly decay to $^4I_{13/2}$ state with a relaxation time of ~1 μs. The spontaneous lifetime of metastable $^4I_{13/2}$ state is ~10 ms in general. In an EDFA system, the original light signal injected into the EDF can be amplified with a gain about 20–30 dB. The optical pump power is usually hundreds of milliwatts, and the length of the EDF is a few meters or more than 10 m; it can be reduced to less than

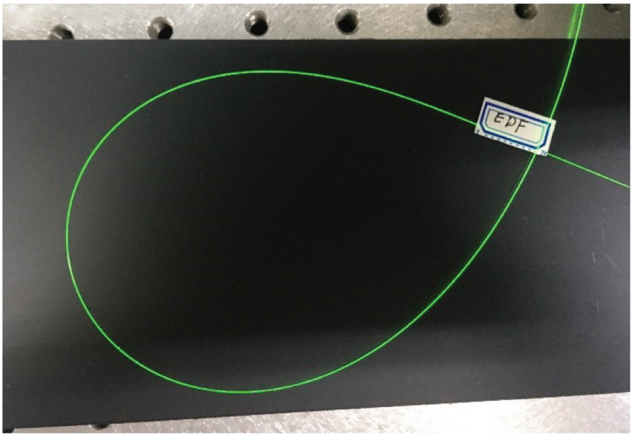


Figure 1.9 Green fluorescence of EDF pumped by 980 nm light. Source: Junferg Jiang.

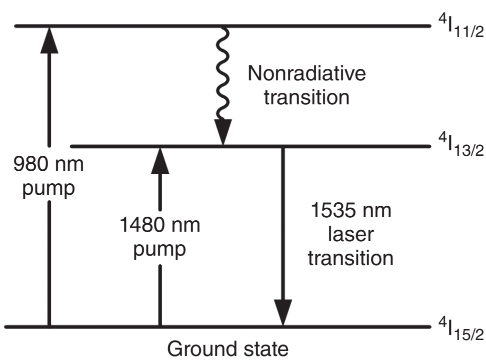


Figure 1.10 The pertinent energy diagram of Er^{3+}. Source: Junferg Jiang.

1 m by using EDF with high doping concentration. Due to the absorption effect of Er^{3+}, the intensity of pump light linearly attenuates along the EDF. If the pump light is exhausted, the EDF that does not absorb the pump energy will produce undesired loss. Therefore, in order to maximize the gain, the length of EDF needs to be optimized during the formation of EDFA.

Figure 1.11 gives a schematic of typical EDFA with three pumping methods. Figure 1.11a shows forward pumping, that is, the pump light and the signal light enter EDF in the same direction, and it has lower noise level. In contrast to forward pump light, backward pump light enters EDF in the direction opposite to signal light, as shown in Figure 1.11b, and higher output power can be obtained by using this method. Dual-directional pump combines forward pump and backward pump to inject pump light at both ends of EDF at the same time, as shown in Figure 1.11c. In this way, the problem of pump light attenuation along the EDF can be solved effectively, so that the EDF is fully pumped to maximize the gain. But there is no doubt that it will also increase the complexity and cost of the EDFA.

The common commercial EDFAs include rack, benchtop, and modular types. The rack EDFA can provide high gain and is suitable for long-distance communication

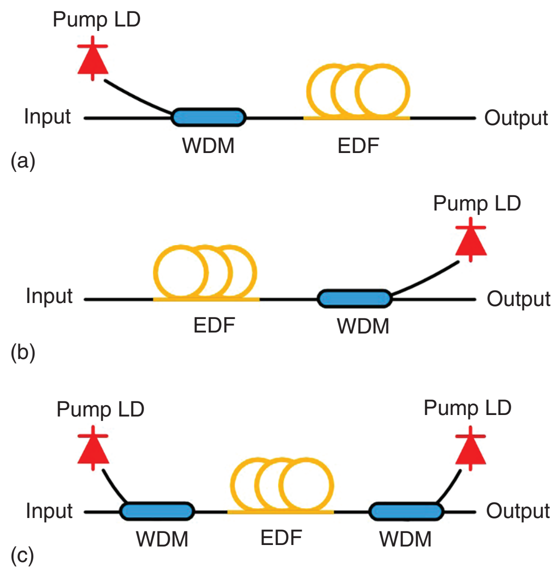


Figure 1.11 Schematic diagrams of EDFA with three optical pumping methods: (a) forward pump, (b) backward pump, and (c) dual-directional pump. Source: Junferg Jiang.

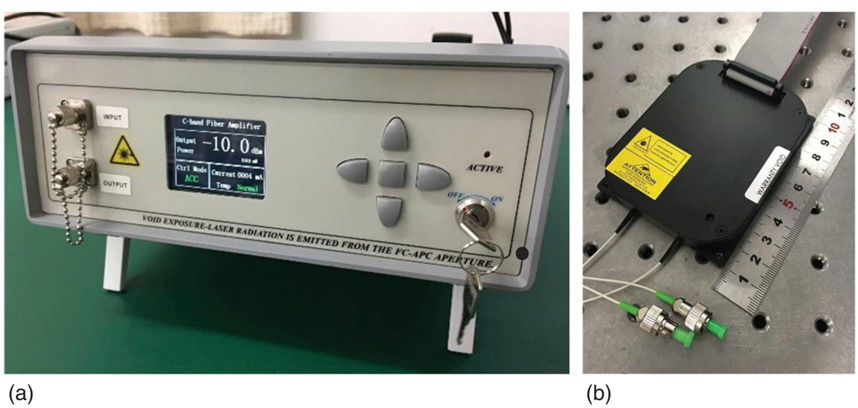


Figure 1.12 Photos of (a) a benchtop EDFA and (b) a modular EDFA. Source: Junferg Jiang.

network. The benchtop EDFA, as shown in Figure 1.12a, is the most commonly used type in laboratories because it is easy to operate and takes into account both performance and cost. The compact modular EDFA has the characteristics of small size and low power consumption, which can be easily installed in various application systems according to the use requirements. Figure 1.12b gives the photos of a modular EDFA. The EDFA can amplify the signal light and provide gain for the system conveniently; for example, in fiber loop ring-down sensing system, EDFA can compensate for the excessive cavity loss, increase the number of decay sensing pulses, and then improve the measurement range and accuracy. In distributed optical fiber sensing system, EDFAs are usually required to amplify the modulated interrogation pulses for longer sensing distance.

The original gain provided by EDFA is different for light with different wavelengths. In other words, the gain depends on wavelength. In a cascade amplification link or multi-channel system, it is necessary to flatten the gain spectrum, and the simplest and most effective way is to use passive optical filters, such as long-period grating (LPG) and thin-film filter (TFF). As mentioned earlier, the spontaneous emission and stimulated radiation will be produced in EDFA at the same time, and therefore power amplification will cause ASE noise. Accordingly, the gain cannot be infinitely provided by cascading amplifiers, and the signal-to-noise ratio will be reduced. Even so, EDFA is still a cost-effective optical amplifier with low noise level and low crosstalk. Due to the geometric symmetry of optical fiber, EDFA can be served as a polarization-insensitive amplifier. Furthermore, as an all-fiber amplifier, EDFA can be easily connected into the optical system, which is convenient for maintenance and upgrading. However, EDFA still has inherent disadvantages such as wavelength dependence, low dynamic response, and optical surge. The research on eliminating these problems and improving the performance of EDFA is continuing.

1.3.2 Semiconductor Optical Amplifier

The basic structure of the semiconductor optical amplifier (SOA) is similar to that of the semiconductor laser, as shown in Figure 1.13. The amplification of light is due to the inversion distribution of particle number in the semiconductor gain medium of active layer with the injection of electrons. However, in order to prevent self-excited oscillation, the mirrors with high reflectivity are replaced by the antireflection coating, and the inclination angle of the emitting cavity surface is increased. In addition, an isolator is needed to avoid the instability of amplification and additional noise caused by the reflected light. Compared with optical fiber amplifier, SOA adopts electric pump and can provide more than 20 dB gain on solid-state chip with hundreds of microns.

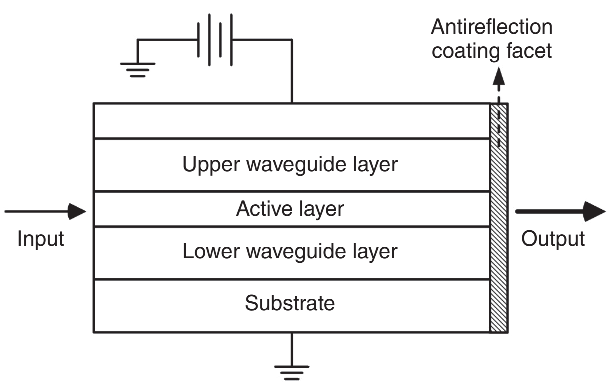


Figure 1.13 Schematic diagram of SOA. Source: Junferg Jiang.

SOA can be divided into two categories: Fabry–Perot amplifier (FPA) and traveling wave amplifier (TWA). The facet reflectivity of FPA is higher than that of TWA. For FPA, the signal light is reflected multiple times in the active layer of the semiconductor, and gain is obtained. Because of the low reflectivity resonator, self-oscillation will not emerge in FPA, but the gain spectrum is multi-peaked. A single gain peak provides a gain bandwidth of 2–10 GHz with gain of 10–20 dB. The TWA with lower facet reflectivity has a wider gain bandwidth of 5 THz, but the gain is only a few dB. In fact, due to the wavelength dependence of the reflectivity of the antireflection coating, a SOA can work in FPA or TWA state at different operating wavelengths, which depends on the one-time round-trip amplitude value of the light.

Like the gain fiber used by EDFA, the active layer of SOA will also be saturated, and the gain provided is related to the pump parameters. The gain saturation is the result of the decrease of the number of inversion particles formed by the increase of stimulated radiation recombination at high optical power. Due to the short lifetime of carriers in semiconductor materials, the gain is easily modulated by high bit rate optical signals. Especially in the wavelength division multiplexing system, the gain may also be affected by the beat frequency when two optical signals are amplified at the same time, and resulting in the amplification of the new frequency optical signal generated by beat frequency, it is called gain-induced four-wave mixing [10]. Consequently, if the frequency interval of multiplexing channel is not limited, SOA will cause channel crosstalk in optical communication system. Despite the disadvantage of coupling loss and high-speed signal crosstalk, the commercial SOAs with high integration and high gain is still the good choice for low-cost optical links, which usually adopt the compact 14-pin butterfly package. A comparison of typical features between the EDFA and the SOA is listed in Table 1.1. In other words, SOA is a bidirectional optical amplifier, which has the advantages of wide gain bandwidth, high gain, high conversion efficiency, high integration, and small size.

Table 1.1 A comparison of typical features between the EDFA and the SOA.

Features	EDFA	SOA
Active medium	Erbium-doped fiber	InP/InGaAsP semiconductor
Pumping	Light	Electric current
Operating wavelength	1530–1565 nm	1528–1562 nm
Gain	10–50 dB	10–30 dB
Relaxation time	100–1000 ps	1–100 ps
Gain bandwidth	20–80 nm	50–200 nm
Insertion loss	<1 dB	4–6 dB
Noise figure	<5 dB	7–11 dB
Size	90 mm × 70 mm × 15 mm	30 mm × 15 mm × 10 mm

1.4 Detector

In the optical fiber sensing, the detection of light is necessary in order to demodulate the parameters to be measured from the optical signals, photon–electron conversion is also conducive to digitalize, process, and store the information. Photodetector is an important device to realize photoelectric conversion, which should be selected with appropriate parameters according to the actual detection requirements. Common photodetectors include photodiodes, avalanche photodiodes (APD), photomultipliers, and photoconductive detectors.

Semiconductor photodiode detectors are the most widely used detector, which can provide efficient and economic optical detection. Its key detecting element is the semiconductor p–n junction. When the p-type semiconductor (p region) of the p–n junction absorbs an incident photon, it will produce a hole and a free electron. The electrons within the diffusion length of the depletion layer will reach the boundary of the depletion layer approximately and drift through it under the action of the electric field in the junction. Each electron passing through the junction will provide a charge, which can generate current in the external circuit of the p–n junction. If the absorption of incident photons takes place in the n-type semiconductor (n region) of p–n junction, the generated holes will have a similar process and also make the charge flow in the external circuit. If the absorption of photons occurs in the neutral region, the generated holes and electrons drift into the p region and the n region, respectively under the action of the electric field. In this case, the drift distance of each carrier is smaller than the whole physical width of the p–n junction, each photon absorbed will produce a charge, and the current response delay caused by the finite diffusion time of the carriers is avoided. But in fact, the depletion layer of p–n junction is only a few microns in general, and most of the incident photons are absorbed by the neutral region, so the photoelectric conversion efficiency is low, and the response speed is slow. Therefore, the practical photodiode detectors generally adopt the p–i–n semiconductor structure, that is, an intrinsic high resistivity material (usually n-type semiconductor with low doping concentration) layer i is sandwiched between the p-type and n-type semiconductor layers with high doping concentration. The i-layer is thick, and the absorption coefficient of it is low, the incident light is easy to enter the material and produce a large number of electron–hole pairs, thus greatly improving the photoelectric conversion efficiency. The drift component dominates the photocurrent, which greatly improves the response speed. In addition, the response speed of the device can be controlled by changing the width of the depletion layer.

According to the photoelectric effect mentioned earlier, when light is radiated on the p–n junction of the photodiode, photons are absorbed to produce electron–hole pairs. When the reverse voltage on the p–n junction is increased, the electric field in the depletion layer is correspondingly enhanced, and the initial electrons are accelerated under the action of high electric field. The high-speed electrons collide with the lattice atoms, which ionize the lattice atoms and produce new electron–hole pairs. The resulting new electrons collide with the atoms again. In this process, there is a chain reaction and the number of carriers will be multiplied by avalanche [11].

The detectors using this principle to achieve high-sensitivity light capture are called avalanche photodiodes. The structure of APD is similar to that of general photodiode, and its response frequency is also affected by the characteristics of depletion layer and load capacitance. As the avalanche gain of photocurrent increases by M times, the measured light signal power will increase by M^2 times. However, the avalanche gain has the same effect as the secondary electron multiplication gain. Theoretically, the power of APD will increase by M^2 times. In practice, the shot noise will increase M^n times, where $2 < n < 3$.

Semiconductor photodiodes can only be used to detect the light radiation whose photon energy is larger than the bandgap width of the semiconductor. If the energy of the incident photon is overpowered, the light absorption in the semiconductor increases with the frequency. A small number of carriers generated by the absorbed photons compound with most carriers before they diffuse to the depletion layer, which leads to the decrease of the response of photodiodes. Therefore, the frequency response of photodiodes is related to their own materials and the wavelength (frequency) of incident light. The wavelength responses of Si- and InGaAs-based photodiodes are shown in Figure 1.14. Silicon has high absorptivity and quantum efficiency, and the response wavelength of Si-based photodiodes ranges from visible light to ~1 μm. InGaAs can provide a wider response wavelength range, especially the C-band commonly used in optical fiber sensing. The ratio of photon-generated electron–hole pairs to incident photon number can be defined by the quantum efficiency, which can be used to characterize the light response of photodiodes. The most commonly used InGaAs-based photodiode is a kind of direct bandgap semiconductor, which has stronger absorption capacity and higher response rate than direct bandgap. Rate, bandwidth, sensitivity, and noise should also be considered when selecting photodiodes.

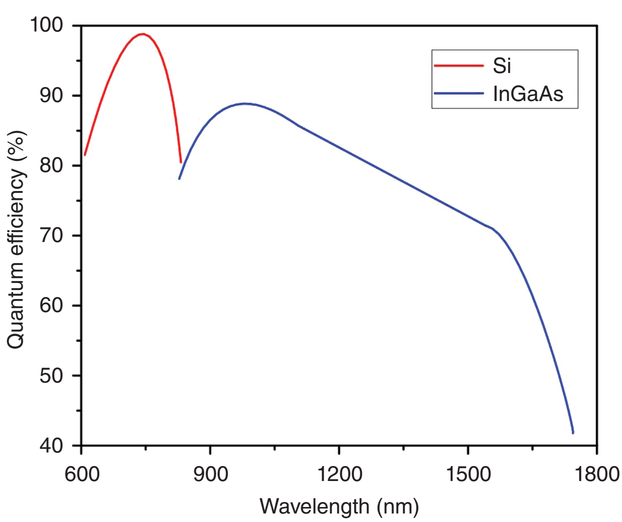
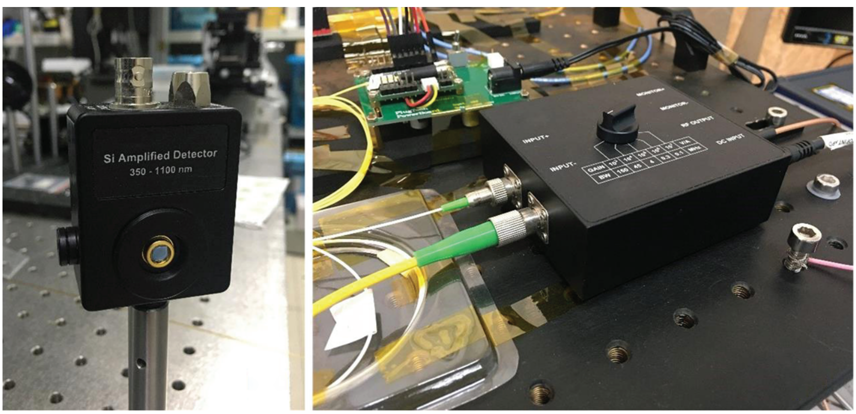


Figure 1.14 Wavelength responses of Si- and InGaAs-based photodiodes. Source: Junferg Jiang.

According to requirements and applications, commercial photodetectors also have a variety of options. Figure 1.15a shows a Si-amplified photodetector, the photodetector provides a Bayonet Neill-Concelman (BNC) connector for electrical signal output, and the light response ranges from ultraviolet to near infrared. Additionally, a fiber adapter can be used with the detectors for added functionality and flexibility. The balanced photodetector can eliminate common-mode noise by subtracting two optical input signals, which is equivalent to a balanced receiver. In this way, the weak change of optical signal path can be extracted from the interfering noise floor. Therefore, balanced detectors are often used for coherent detection in distributed optical fiber sensing, as shown in Figure 1.15b. Moreover, the cost-effective photodiodes with unmounted package are flexible to construct an optical signal demodulation system, which are suitable for high-speed photometry and monitoring applications. Figure 1.16 shows a TO can pigtailed photodiode and its use in a demodulation circuit.



(a) (b)

Figure 1.15 Photos of (a) a Si-amplified photodetector with space coupling input and (b) a balanced photodetector with two fiber inputs. Source: Junferg Jiang.

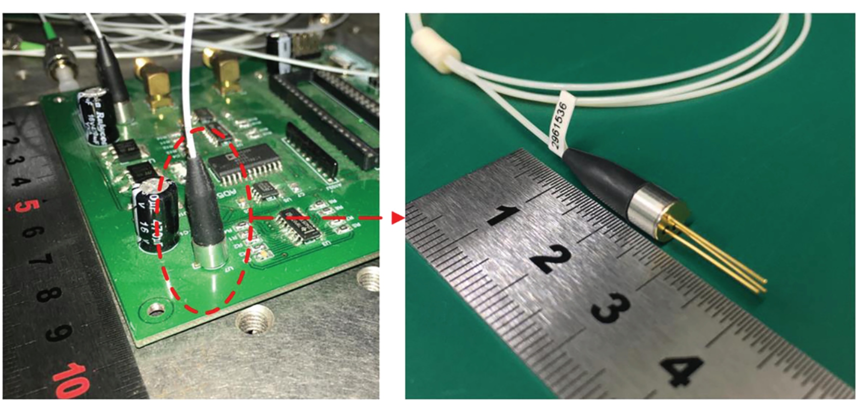


Figure 1.16 TO can pigtailed photodiode and its use in a demodulation circuit. Source: Junferg Jiang.

1.5 Optical Fiber Passive Device

The optical passive device that consists of traditional bulky components possesses many disadvantages, such as large space requirement, difficult adjustment, and large loss accompanying coupling light into with optical fiber. To overcome the disadvantages, optical fiber compatible passive devices, especially all-fiber optical passive devices, are developed.

1.5.1 Optical Fiber Coupler

Optical fiber coupler can be used for splitting or inserting of optical signals into an optical fiber link. When optical fiber coupler is independent of wavelength, it is called splitter or combiner. When optical fiber coupler is related to wavelength, it is called a wavelength division multiplexer (WDM).

The optical fiber coupler can be made with traditional optical beam splitting technology. Another method is to use the evanescent field coupling to extract optical power from the fiber. Due to the compact size of optical fiber, practical directional couplers are most based on evanescent field. With the help of evanescent field, the optical power is transmitted from one fiber to the other by overlapping the electromagnetic fields between the two cores. Because the evanescent field of an optical fiber is an exponentially decaying field, the cores of the two optical fibers must be close.

There are many types of couplers. The most basic coupler realizes two-wave coupling. It has two input channels and an output channel (Y-coupler), as shown in Figure 1.17a. When light is coupled from one fiber to another, the coupling coefficient depends on the distance between two fiber cores, diameter of fiber core, and working wavelength. The coupling ratio can be controlled by changing the length

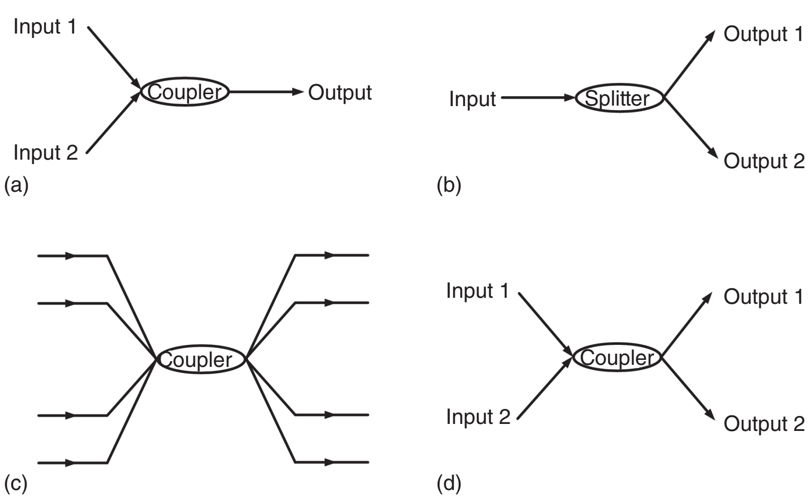


Figure 1.17 Coupler port configuration. (a) Y-coupler (b) optical fiber splitter (c) star coupler (d) X-coupler. Source: Junferg Jiang.

of coupling area. A 50 : 50 coupling ratio is more common and is often referred to as a 3 dB coupler. In fact, the coupling ratio of the coupler can be any value from 1 : 99 to 50 : 50. In addition, the uniformity and the operating wavelength window are also important parameters of optical fiber coupler. Uniformity is defined as the difference between the insertion loss of two specified output channels, whereas the operating wavelength window usually characterizes the relationship between channel coupling ratio and wavelength. If the input and output channels are reversed, it can be a wave splitter, as shown in Figure 1.17b.

$N \times N$ star coupler is commonly used in networks. The function of $N \times N$ star coupler is to mix and superimpose the input optical power of N fibers and distribute it evenly to the N output fibers. The star coupler can be used as a wavelength-independence multi-end power splitter or power combiner. The number N of the output end and the input end is not necessarily the same, which is generally the case in local area network (LAN) applications. The star coupler is shown in Figure 1.17c. The simplest coupler has two input channels and two output channels, also known as X-coupler, as shown in Figure 1.17d.

The optical fiber coupler is usually fabricated by three methods: the mechanical polishing method, chemical corrosion method, and fusion tapering method. Fusion tapering method is the main method for practical manufacturing. The process of fusion tapering is as follows. First, two or more bare fibers with the coating layer removed need to be installed side by side on the holding stages. Then, the fiber is stretched with flame heating continuously, and a fiber power meter is applied to monitor the optical power ratio of the two output ends in real time. The process stops until the coupling coefficient meets the requirements. Finally, the prepared optical fiber coupler is packaged carefully. A typical processed and packaged 2×2 fiber coupler is shown in Figure 1.18.

1.5.2 Optical Fiber Polarizer

Polarization is another basic physical quantity of light beams. An optical fiber polarizer is an optical element in an optical fiber system that generates polarized light.

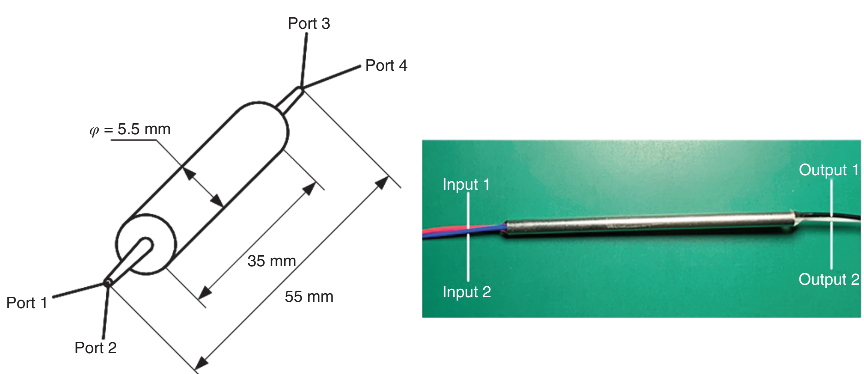


Figure 1.18 (a) Schematic diagram and (b) photo of 2×2 optical fiber coupler. Source: Junferg Jiang.

SMF support the fundamental mode having two polarization direction. Ideally, the two polarization modes degenerate. However, external stress and process defects make it impossible for the fiber geometry and structure to achieve standardization and symmetry. Therefore, the degenerated polarization mode is degraded into two orthogonal polarization modes.

Polarizers can be divided into three main types: the prism polarizer based on birefringence crystal, the polarizer based on anisotropic absorption of film or different mode attenuation of special fiber structure, and the polarizer based on reflective Brewster angle. Many commercial in-line optical fiber polarizers integrate these optical micro-components with optical fiber [12].

Typical optical fiber polarizer parameters include insertion loss (<0.5 dB), minimum extinction ratio (>30 dB), return loss (50 dB), and bandwidth (±50 nm).

1.5.3 Optical Fiber Isolator

The input and output of most passive devices are interchangeable, that is, reciprocal devices. However, nonreciprocal devices are also needed in fiber-optic sensing systems such as optical fiber isolator and optical fiber circulator. An optical fiber isolator is a device that only allows beam to be transmitted in one direction. The loss is low when the light in fiber is transmitted in the forward direction, and the loss is large when the light is transmitted in the reverse direction. In this reason, the optical fiber isolator can block the unwanted reflected light resulting from end faces or scatters. Some optical devices, especially lasers and optical amplifiers, are very sensitive to light reflected back from connectors, splices, modulators, or filters. The reflected light will degrade their stability and even damage them. Optical fiber isolators are a necessary protect components for these optical devices.

Optical fiber isolators can be divided into polarization-independent type and polarization-dependent type. An optical fiber polarization-dependent isolator consists with fiber collimator (graded-index lens), polarizer, analyzer, and Faraday rotator. The working principle of Faraday rotator is based on the Faraday magneto-optical effect. Originally isotropic media become optically active substances under the action of an external magnetic field, and the polarization direction of the polarized light rotates when passing through the substance. For a given magneto-optical material, the rotation angle θ of the light vibration plane is

$$\theta = vBL \tag{1.5}$$

where v is the characteristic constant of the material, called Verdet constant, L is the distance the light passes through, and B is magnetic induction intensity. The Faraday rotator is nonreciprocal optics, which means that changes in the properties of light passing through the device are not reversed when the light passes through in the opposite direction.

The principle of an optical fiber polarization-dependent isolator is shown in Figure 1.19. The vertical polarization component of the incident light passes the polarizer, and by adjusting the magnetic field intensity of the Faraday rotator, the polarization plane of incident light can be rotated by 45° and passes the analyzer.

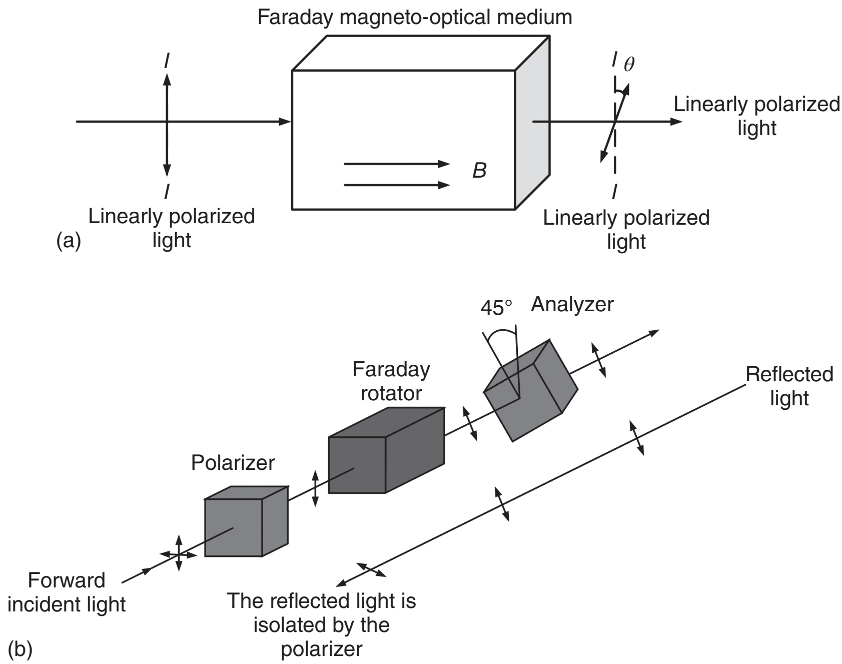


Figure 1.19 Schematic diagram of (a) Faraday magneto-optical effect and (b) optical fiber polarization dependent isolator. Source: Junferg Jiang.

When the reflected light returns, it is rotated 45° again by the Faraday rotator, which is exactly orthogonal to the polarization direction of the polarizer, so it is isolated.

The principle of an optical fiber polarization-independent isolator is shown in Figure 1.20. The parallel incident beam emitted by the collimator is divided into ordinary light (o-light) and extraordinary (e-light) light when passing through the birefringent crystal wedge 1; the polarization direction of o-light and e-light is vertical, and the propagation direction of the two lights has a small angle. The polarization direction of o-light and e-light is rotated 45° after passing through the Faraday rotator. The optical axes of birefringent crystal wedge 2 and wedge 1 are at an angle of 45°. After passing through wedge 2, the two lights are combined into one light. The reflected light is divided into o-light and e-light through the wedge 2 and then passes through the Faraday rotator. After passing through the wedge 1, o-light and e-light cannot be combined, so the reflected light is isolated.

Typical optical fiber isolator is shown in Figure 1.21, whose parameters include the bandwidth (±20 nm), the maximum insertion loss (~1.3 dB), and the minimum isolation (~16 dB).

1.5.4 Optical Fiber Circulator

The optical fiber circulator works similarly to an optical fiber isolator except that it has multiple ports. It is also a unidirectional transmission device. It is mainly used in single-fiber bidirectional transmission systems and optical add/drop multiplexers.

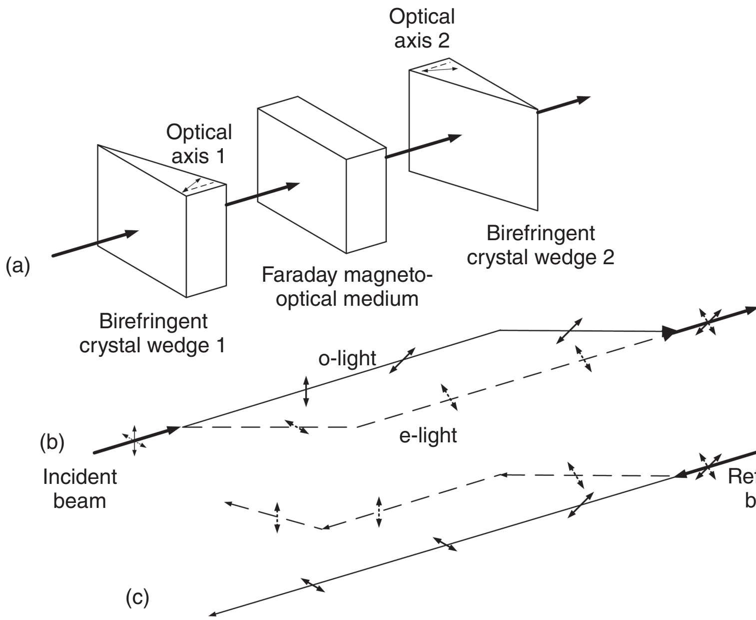


Figure 1.20 (a) Schematic diagram of optical fiber polarization-independent isolator. Light path of (b) incident light and (c) reflected path (top view). Source: Junferg Jiang.

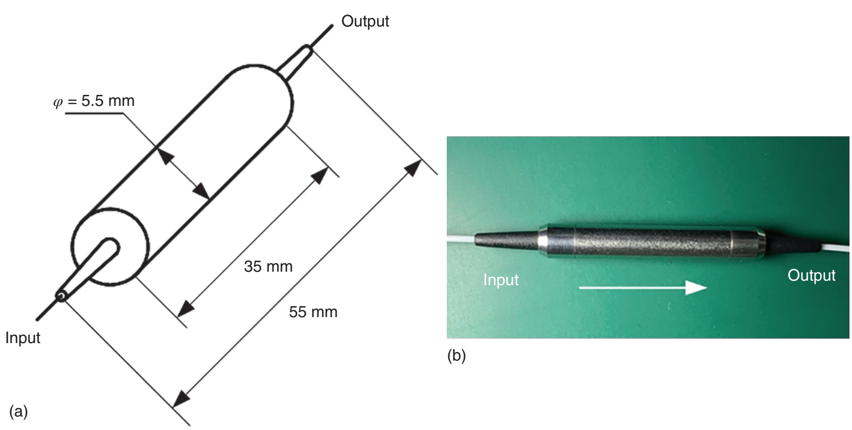


Figure 1.21 (a) Schematic diagram and (b) photo of 2 × 2 optical fiber isolator. Source: Junferg Jiang.

The most commonly used optical circulators are three-port devices, as shown in Figure 1.22a. Due to high isolation and low insertion loss, fiber circulators are widely used in advanced communication systems, such as branch multiplexers, bidirectional pumping systems, and dispersion compensation devices.

The working feature of the optical fiber circulator is that when the light is input from any port, it can only be transmitted in a single direction in the circulator and is output at the next port. The optical signal must pass through each port in turn

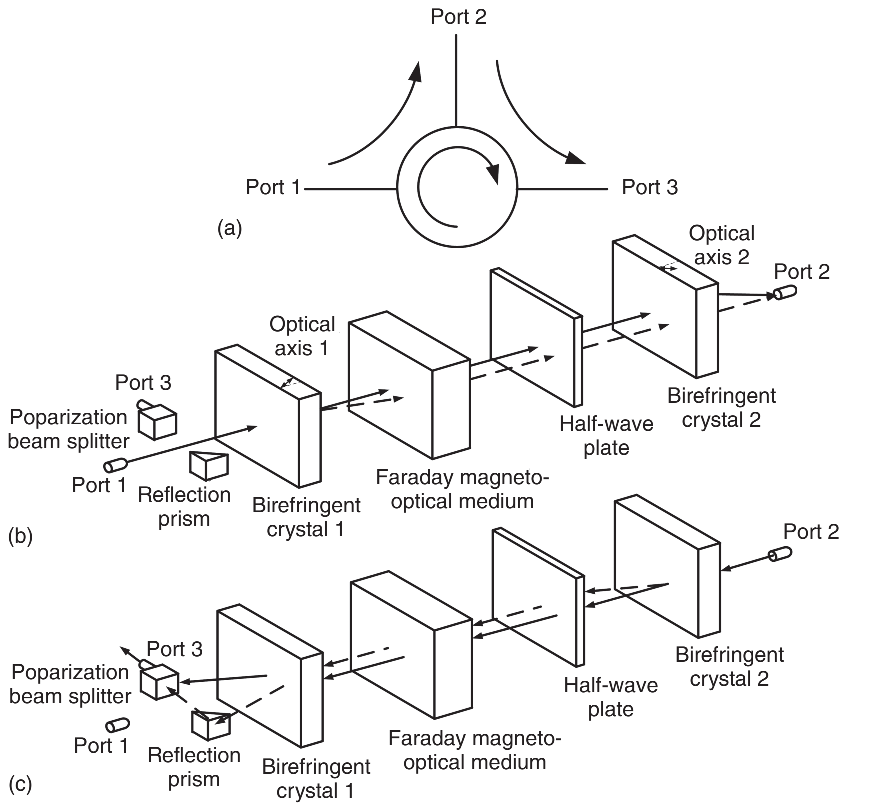


Figure 1.22 (a) Schematic of three-port optical fiber circulator, (b) optical path from port 1 to port 2, and (c) optical path from port 2 to port 3. Source: Junferg Jiang.

(that is, it must pass through ports 1 and 2 in turn before reaching port 3). The working principle of the optical fiber circulator is the same as that of the optical isolator, and both use Faraday rotators, as shown in Figure 1.22b. But the structure of the optical fiber circulator is more complicated. The reverse transmission light wave is transmitted to the third output port instead of being directly discarded. In fiber-optic sensing system, optical fiber circulators frequently replace the optical fiber coupler for low insertion loss light redirection, as shown in Figure 1.22c.

Typical optical fiber circulator is shown in Figure 1.23, whose parameters include insertion loss (<0.6 dB), isolation (70 dB), polarization sensitivity (<0.05 dB), and bandwidth (±10 nm).

1.5.5 Optical Fiber Switcher

Optical fiber switcher has one or more selectable transmission paths. Optical fiber switcher can be divided into two categories. One is a mechanical optical fiber switcher, which has the advantages of low insertion loss and high isolation. Meanwhile, the mechanical optical fiber switcher is polarization independent and

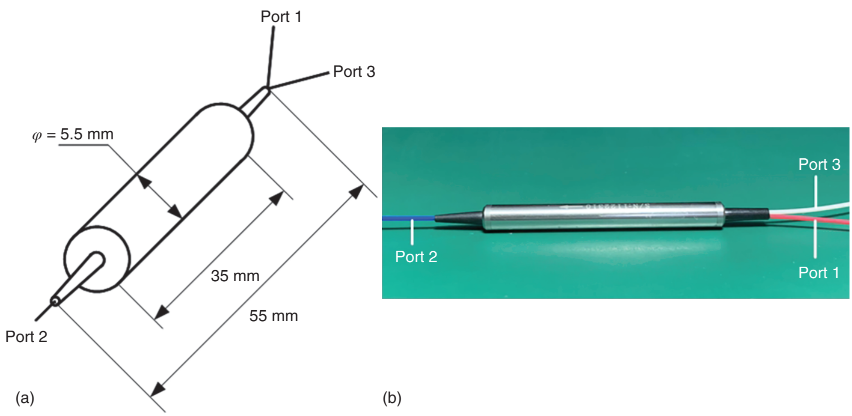


Figure 1.23 (a) Schematic diagram and (b) photo of optical fiber circulator for bidirectional transmission system. Source: Junferg Jiang.

wavelength independent. The disadvantages are long switching time (on the order of milliseconds) and poor repeatability. The other is optical fiber switcher based on solid physical effects, such as electro-optic, magneto-optical, thermo-optic, and acousto-optic effects. The advantages of these optical fiber switchers are short switching time (on the order of microseconds, even to nanoseconds) and small size.

1.5.5.1 Mechanical Optical Fiber Switcher

The diagrams of two traditional mechanical optical fiber switchers are shown in Figure 1.24. The optical fiber switcher in Figure 1.24a realizes the function of switching the optical path by controlling the magnet to move to the position of the movable optical fiber [13]. The optical fiber switcher in Figure 1.24b adjust the attitude of micro-reflector to select output fiber to realize the function of the optical switching [14].

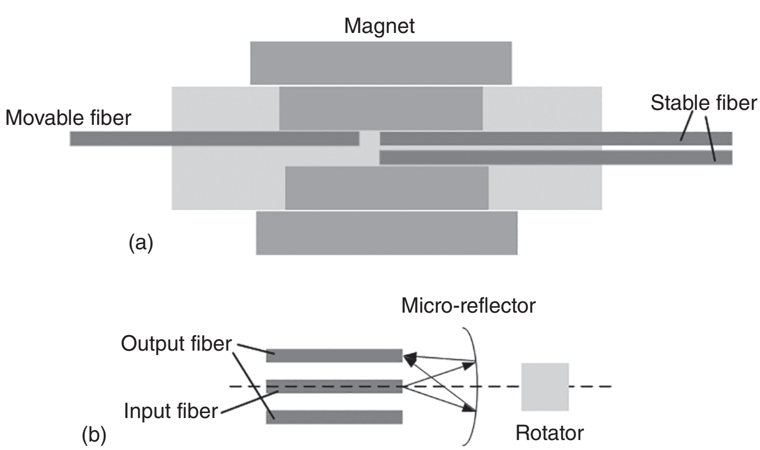


Figure 1.24 Mechanical optical fiber switchers based on (a) magnet and (b) reflector. Source: Junferg Jiang.

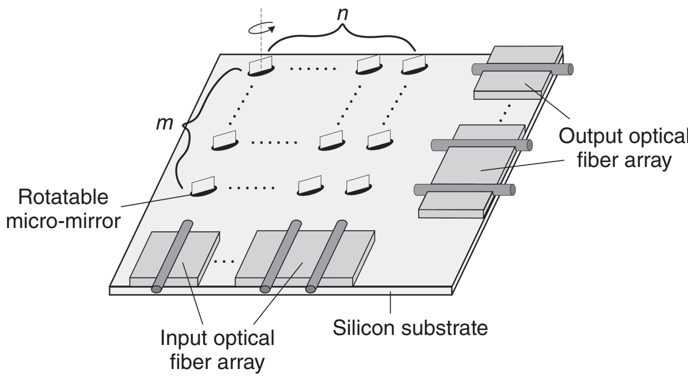


Figure 1.25 MEMS $m \times n$ optical fiber switcher matrix. Source: Junferg Jiang.

However, the traditional optical fiber switcher is bulky and difficult to integrate. In recent years, an integrated micro-electro-mechanical system (MEMS) optical fiber switcher is being vigorously developed. By using micro-processing technology, a large number of rotatable micro lens arrays are arranged on the silicon wafer. MEMS optical fiber switcher has the same principle as mechanical optical fiber switcher, but it is easy to integrate and has a large switching channel. Figure 1.25 shows a MEMS optical fiber switcher matrix. It consists of a two-dimensional micro-mirror array controlled by static electricity and many input and output optical fibers. The beams are transmitted in two-dimensional space. The collimated beams and rotating micromirrors form a multi-port optical switch matrix [15].

The mechanical optical fiber switcher has the advantage of simple principle, but the return loss will be affected due to the reflection of the fiber end face. In addition, the mechanical optical fiber switcher would bounce back, resulting in poor repeatability and reliability. Due to mechanical movement, high switching delay is inevitable.

1.5.5.2 Solid Physical Effect-Based Optical Fiber Switcher

In order to reduce switching delay, reduce loss, and facilitate integration, researchers have developed optical fiber switchers based on solid physical effects. Electro-optical fiber switcher and magneto-optical fiber switcher are mainly used.

The principle of electro-optical fiber switcher is generally uses the electro-optical effect (Pockels effect) or electro-absorption effect (Franz–Keldysh effect) of materials, such as ferroelectrics, organic polymers, or compound semiconductors. The RI of the material and the phase of light change under the action of electric field and then change of the light intensity or the light path is realized by interference or polarization. A 1×2 electro-optical fiber switcher is shown in Figure 1.26a; this type of switcher is based on bifurcated (Y-branch) waveguide. There is a small branching angle between the two bifurcated branches (generally less than 1 rad) [16]. When there is no external voltage, the incident light will be transmitted

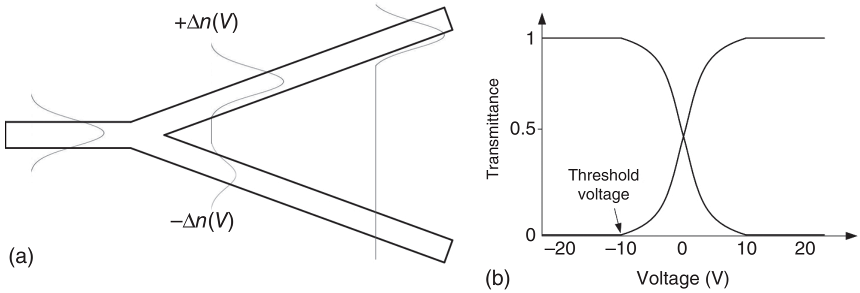


Figure 1.26 Electro-optical fiber switcher (a) structure and (b) numerical characteristics [16]. Source: Modified from Silberberg et al. [16].

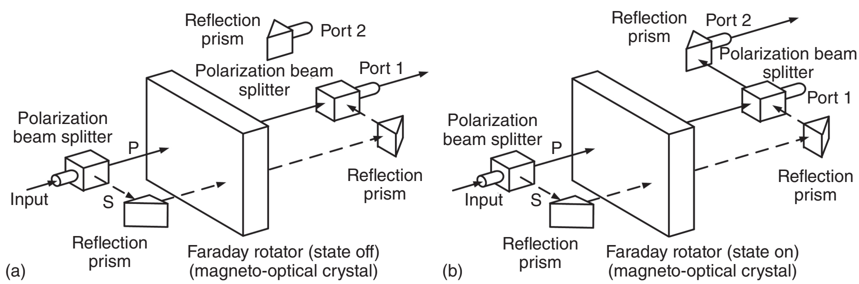


Figure 1.27 Schematic of 1×2 magneto-optical fiber switcher. (a) Optical path from input to port 1. (b) Optical path from input to port 2. Source: Junferg Jiang.

into the two branches with equal intensity. When a voltage is applied to one branch of the waveguide, the RI of the waveguide branch will increase, thus increasing the optical output power in the waveguide branch. When the external voltage reaches a certain threshold, the optical field will be suddenly guided to the waveguide with increased RI. The light transmittance on the waveguide will change suddenly as shown in Figure 1.26b. The electro-optical fiber switcher is characterized by low energy consumption (voltage below 10 V), independent of polarization, fast switching speed (nanosecond order), high repetition rate, long service life, and small size. The disadvantage is that the preparation process is complicated, and it is difficult to form an array composed of multiple optical fiber switchers.

The magneto-optical fiber switcher utilizes the Faraday rotation effect. The effect of the magneto-optical crystal on the polarization state of incident-polarized light changes when the external magnetic field changes. A 1×2 magneto-optical fiber switcher is shown in Figure 1.27. A beam is divided into two beams with P polarization and S polarization by a polarization beam splitter (PBS). When the Faraday rotator is on, the polarization planes of the two beams are rotated by 90°. The two beams are combined in another PBS and output from the port 2. When the Faraday rotator is off, two beams are combined and output from port 1. Therefore, the optical path is switched. Compared with other solid physical effect optical fiber switcher, it has the advantages of low driving voltage and small crosstalk.

1.6 Optical Fiber Modulator

Optical fiber modulation is a technology that loads signals on an optical carrier by phase, frequency, polarization, and intensity. The functional device that achieves this modulation effect is called an optical modulator. The general requirements for optical fiber modulators are that the device has a large bandwidth, good stability performance, lower loss, and high modulation efficiency.

Generally, the modulation mechanism of the optical fiber modulator can be divided into two types. The first modulation mechanism is to interrupt the optical path by physical methods such as stretch, end separation, tilt deviation, and lateral offset of the fiber. The second modulation mechanism is to insert an absorption or reflection material into the optical path to form a modulation medium. Such materials include birefringent crystals, polymers, and other tunable materials. Optical fiber modulators based on the previously mentioned two modulation mechanisms have been developed, such as piezoelectric optical fiber modulator and electro-optical fiber modulator. Optical phase modulation and intensity modulation techniques are commonly used in optical fiber sensing systems, and these two optical fiber modulators are mainly introduced.

1.6.1 Optical Fiber Phase Modulator

Optical fiber phase modulators include piezoelectric modulator based on piezoelectric transducer (PZT) and electro-optical fiber modulator based on lithium niobate.

The PZT modulator is a PZT tube wrapped with a few meters of optical fibers. The PZT tube is driven by a signal generator. The principle is that under the action of an external electric field, the circumferential change of the phase modulator is directly coupled to the change of the fiber length. This results in a phase change of the guided light. The PZT optical fiber phase modulator can be applied to coherent synthesis, large-scale Fourier scanning, laser phase locking, differential interference, and other application fields. The PZT phase modulator is widely used because of its simple structure, easy manufacture, and low cost.

The modulation frequency of electro-optical fiber modulator based on lithium niobate can reach tens of gigahertz. When an electric field is applied to a specific direction of the lithium niobate crystal, the RI of the crystal changes due to the electro-optic effect, which in turn causes an additional phase change of the transmitted light wave in the crystal, thereby achieving the purpose of modulating the light wave.

The linearly polarized light incident along the Z-axis can be decomposed into E_x and E_y, and the corresponding RIs are n_x and n_y, respectively, as shown in Figure 1.28. After propagation through the crystal of L length, the phase delay between E_x and E_y is

$$\text{Delay} = \frac{2\pi}{\lambda}\Delta nL = \frac{\pi {n_0}^3 \gamma L}{\lambda d} V \tag{1.6}$$

where V is the voltage applied to the lithium niobate crystal, n_0 is the RI of crystal when $V = 0$, and γ is linear electro-optic coefficient.

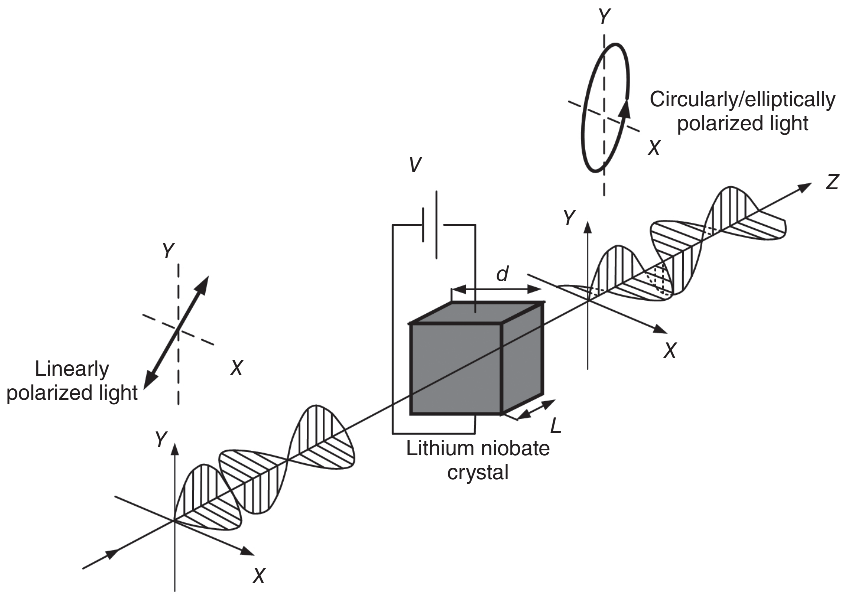


Figure 1.28 Schematic of electro-optical fiber modulator based on lithium niobate. Source: Junferg Jiang.

The integrated electrodes of lithium niobate electro-optical fiber phase modulator make its half-wave voltage extremely low, and it still has strong stability at high temperatures. The modulators are ideal devices for optical fiber sensing applications in harsh environments. At the same time, the modulator has the characteristics of high input impedance and low-frequency performance optimization, making it easier to use. The lithium niobate phase modulators can also be applied to quantum optics, interferometric sensing, fiber-optics sensors, chirping-frequency modulation, and spectrum broadening.

1.6.2 Optical Fiber Intensity Modulator

The lithium niobate crystal can also be processed into optical fiber intensity modulator. The lithium niobate intensity modulator modulates the optical output power of the device through the MZI. It consists of two 3 dB couplers cascaded. The structure is shown in Figure 1.29.

Two voltages V and $-V$ are applied to the electrodes of the two optical waveguide arms, respectively, and corresponding electric fields E_1 and E_2 are generated. The RI change of the waveguide arm is

$$\Delta n = \frac{1}{2} {n_0}^3 \gamma (E_1 - E_2) = {n_0}^3 \gamma \frac{V}{d} \tag{1.7}$$

For a symmetrical MZI $L_1 = L_1 = L$. The phase difference between the two arms can be obtained by Eq. (1.6). Let the voltage be a half-wave voltage when $\Delta\varphi = \pi$:

$$V_\pi = \frac{\lambda}{{n_0}^3 \gamma} \frac{d}{L} \tag{1.8}$$

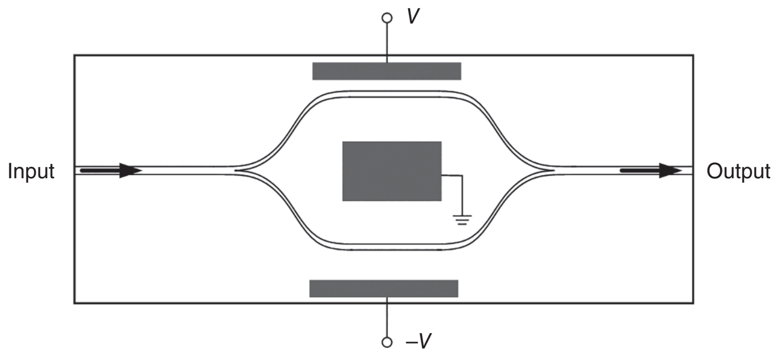


Figure 1.29 MZI optical fiber intensity modulator. Source: Junferg Jiang.

The phase difference between the two branches can be expressed as

$$\Delta\phi = \pi \frac{V}{V_\pi} \tag{1.9}$$

If the input optical power is evenly distributed to two branches at the input bifurcation point. The output optical intensity is related to $\Delta\phi$:

$$I_{output} \propto A \cos \omega t + A \cos(\omega t + \Delta\phi) = 2A \cos \omega t \cos \frac{\Delta\phi}{2} \tag{1.10}$$

where A is the amplitude of light field on two branches. When $\Delta\phi$ is 0, the output optical power of the optical fiber modulator reaches maximum. When $\Delta\phi$ is π, the light transmitted by the two branches of the optical fiber modulator interferes and cancels each other, and the output power reaches minimum, which is zero under ideal conditions.

References

1 Zhou, X., Chen, K., Mao, X. et al. (2015). A reflective fiber-optic RI sensor based on multimode interference in a coreless silica fiber. *Optics Communications* 340: 50–55.

2 Zhao, J., Wang, J., Zhang, C. et al. (2016). Refractive index fiber laser sensor by using tunable filter based on no-core fiber. *IEEE Photonics Journal* 8 (5): 6805008.

3 Yang, X., Yu, W., Liu, Z. et al. (2018). Optofluidic twin-core hollow fiber interferometer for label-free sensing of the streptavidin-biotin binding. *Sensors and Actuators B: Chemical* 277: 353–359.

4 Kang, Z., Sun, J., Bai, Y. et al. (2015). Twin-core fiber-based erbium-doped fiber laser sensor for decoupling measurement of temperature and strain. *IEEE Sensors Journal* 15 (12): 6828–6832.

5 Wu, C., Tse, M.L.V., Liu, Z. et al. (2013). In-line microfluidic refractometer based on C-shaped fiber assisted photonic crystal fiber Sagnac interferometer. *Optics Letters* 38 (17): 3283–3286.

6 Wu, J., Day, D., and Gu, M. (2008). A microfluidic RI sensor based on an integrated three-dimensional photonic crystal. *Applied Physics Letters* 92 (7): 071108.

7 Hall, R.N., Fenner, G.E., Kingsley, J.D. et al. (1962). Coherent light emission from GaAs junctions. *Physical Review Letters* 9 (9): 366.

8 Nathan, M.I., Dumke, W.P., Burns, G. et al. (1962). Stimulated emission of radiation from GaAs p–n junctions. *Applied Physics Letters* 1 (3): 62–64.

9 Giles, C.R. and Desurvire, E. (1991). Modeling erbium-doped fiber amplifiers. *Journal of Lightwave Technology* 9 (2): 271–283.

10 Yariv, A. and Yeh, P. (2006). *Photonics: Optical Electronics in Modern Communications*. Oxford: Oxford University.

11 McKay, K.G. (1954). Avalanche breakdown in silicon. *Physical Review* 94 (4): 877.

12 Lu, J., Dai, Y., Li, Q. et al. (2019). Fiber nanogratings induced by femtosecond pulse laser direct writing for in-line polarizer. *Nanoscale* 11 (3): 908–914.

13 Yeow, T., Law, K., and Goldenberg, A. (2001). MEMS optical switches. *IEEE Communications Magazine* 39 (11): 158–163.

14 Kozhevnikov, M., Basavanhally, N., Weld, J. et al. (2003). Compact 64×64 micromechanical optical cross connect. *IEEE Photonics Technology Letters* 15 (7): 993–995.

15 Cheng, Q., Rumley, S., Bahadori, M. et al. (2018). Photonic switching in high performance datacenters. *Optics Express* 26 (12): 16022–16043.

16 Silberberg, Y., Perlmutter, P., and Baran, J. (1987). Digital optical switch. *Applied Physics Letters* 51 (16): 1230–1232.