Chapter 3

Passive fiber components

1. Introduction

The fiber optic components can be broadly classified as follows:

Amplitude/intensity components
Couplers, Attenuators, Reflectors
Phase components
Phase shifters, Phase modulators
Polarization components
Polarizers, Polarization splitters, Polarization controllers
Wavelength components
Wavelength filters, Wavelength division multiplexers/demultiplexers
Frequency components
Frequency shifters, Filters

Passive fiber components

Definition: Don't need any external drivers

Types:
Optical fiber connector; Optical fiber coupler;
Wavelength division multiplexer(WDM)
Optical attenuator; optical filter;
Optical insulator and circulator;
Polarizer, Fiber grating; etc

Active fiber components

Definition: Need external drivers

Types:
Fiber laser
Fiber amplifier
Optical wavelength converter(XGM,XPM,FWM)
Optical modulator
Optical switcher/ router

Analogy between optical components and electric components

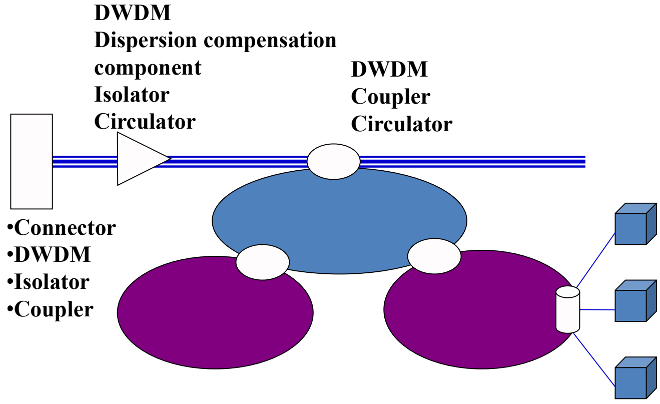
Electric wire	Optical fiber	Modulator	Optical modulator
Resistance	Optical isolator	Tee coupling	Optical coupler
Diode	Optical amplifier	Mixer	WDM
Amplifier	Optical amplifier	Frequency convector	Wavelength convector
Filter	Optical filter	Electric source	Light source
Electrical connector	Optical connector	Detector	Photodetector
Switcher	Optical switcher	Integrated circuit	Integrated optical circuit

Here, we focus on the some fiber components below

- **Self-focusing lens**
- **Optical connector**
- **Coupler**
- **Isolator**
- **Circulator**
- **WDM**
- **Fiber grating**

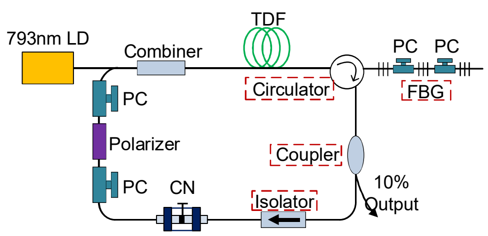
Application of optical components

These components are widely applied in fiber communication systems

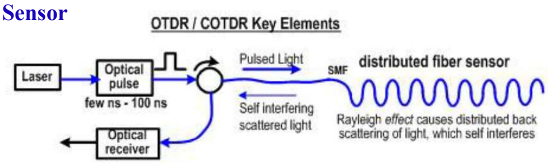


These components are widely applied in fiber communication systems, fiber laser and fiber sensors.

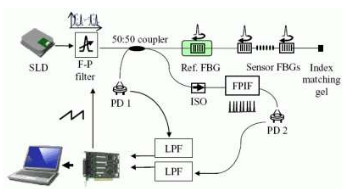
Fiber laser (mode-locked fiber laser)



Fiber Sensor



Circulator, Connector

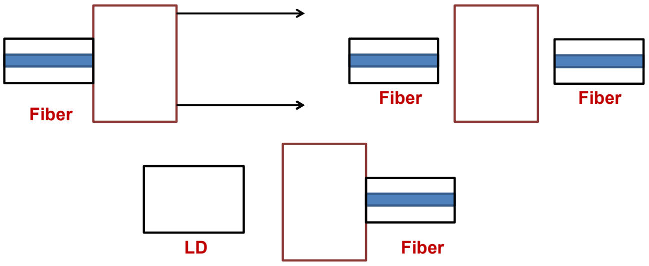


Connector, Coupler, FBG, Isolator

2. Self-focusing lens

(1) The application of self-focusing lens:

Collimating the light from fiber and coupling the free space light into fiber

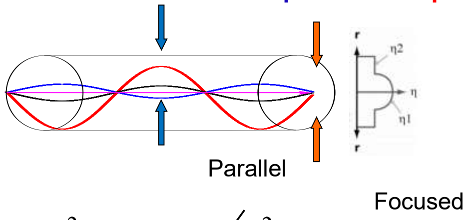


(2) Structure and mechanism of the self-focusing lens

The structure of the self-focusing lens is same as that of self-focusing fiber (one type of graded index fiber).

What is the self-focusing fiber?

Self-focusing fiber: fiber with square law index profile ⟹ light ray transmission trace is a sin curve ⟹ the light rays are focused at a same point after a period



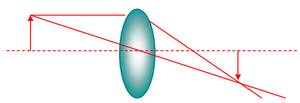
$$n^2(r) = n_1^2[1 - 2\Delta(r/a)^2]$$

self-focusing lens can be regarded as a section of self-focusing fiber.

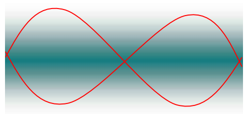
Differences between them:

self-focusing lens have
- larger core (~2mm)
- shorter length (only 1~2 period)
- larger NA (0.2~0.6)
- different fabrication processes

Comparison of globe lens and self-focusing lens



1. Uniform refractive index profile
2. Imaging by bended interface
3. To improve the imaging quality by careful aspheric design thus removing the spherical aberration



1. Graded refractive index profile
2. Imaging based on the bended light ray trace
3. To improve the imaging quality by optimizing refractive index profile

Compared to conventional globe lens, the self-focusing lens has a series of advantages.

Advantages:
1. Tiny
2. Smooth surface and ease of optical processing
3. The focal length and imaging characteristic can be flexibly changed by varying its length and refractive index profile
4. Its aberration can be controlled by optimizing the refractive index profile

(3) Refractive index of self-focusing lens

Transmission trace of the light ray:

Self -focusing lens usually satisfies the square law index profile:

$$n^2(r) = n_0^2(1 - Ar^2)$$

Compared to the fiber with a square law index profile:

$$n^2(r) = n_1^2[1 - 2\Delta(r/a)^2]$$

thus

$$A = \frac{2\Delta}{a^2}$$

Δ——Relative refractive index;
a——Radius;
n_0——Refractive index at the fiber axis

(4) Types of self-focusing lens

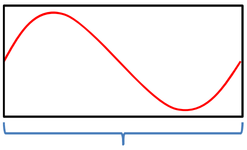
(1) Collimating lens 准直透镜
Transforming the light from fiber to parallel light

(2) Coupling lens 耦合透镜
Coupling the light from LD or fiber to the other fiber.

An important parameter of self-focusing lens

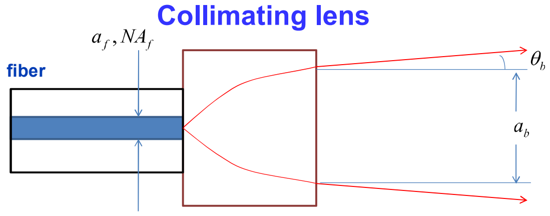
Pitch (P)

- It represents the transmission period of the light.



- Any input light rays can be also transformed to parallel light rays by carefully adjusting P.

Collimating lens



The fiber is placed at the focal point of the self-focusing lens

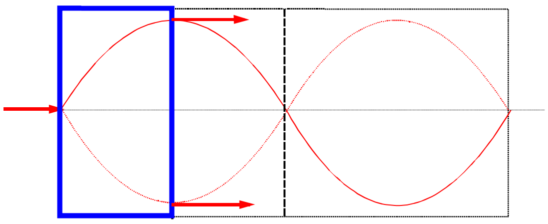
$$a_b = \frac{NA_f}{n_0\sqrt{A}\sin(\sqrt{A}L)} + a_f\cos(\sqrt{A}L)$$

$$\theta_b = \arcsin\left[(-a_f\sin(\sqrt{A}L)n_0\sqrt{A}\right]$$

$$A = \frac{2\Delta}{a_l^{\,2}}$$

Collimating lens

0.25P lens



For 0.25 P lens:

$$\sqrt{A}L = \frac{\pi}{2} \Rightarrow a_b = \frac{NA_f}{n_0\sqrt{A}}$$

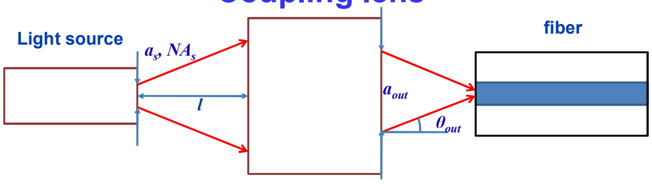
$$\theta_b = \arcsin(-a_f n_0\sqrt{A}) \approx -a_f n_0\sqrt{A}$$

- Beam width is proportional to NA, and the divergence is to fiber radius.

e.g.

- Single mode fiber (NA=0.1, a=10 um), beam width=0.67 mm, beam divergence=1.5×10^{-3} rad
- Multimode fiber (NA=0.2, a=50 mm), beam width=1.33 mm, beam divergence=7.5×10^{-3} rad

Coupling lens



$$a_{out} = a_s\cos(\sqrt{A}L) - NA_s\left[l\cos(\sqrt{A}L) - \sin\frac{\sqrt{A}L}{n_0\sqrt{A}}\right]$$

$$\theta_{out} = arc\sin\left\{NA_s\left[l\ n_0\sqrt{A}\sin(\sqrt{A}L) + \cos(\sqrt{A}L)\right] - a_s n_0\sqrt{A}\sin(\sqrt{A}L)\right\}$$

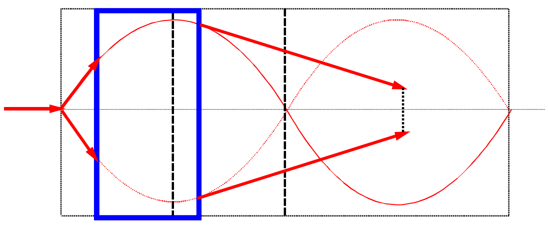
l is the distance between the source and the end face of the lens, a_{out} is the maximum spot radius of the output beam from the lens, θ_{out} is the flare angle of the output beam from the lens, a_s is the beam radius of the source, NA_s corresponds to the numerical aperture of the source.

Coupling lens

Coupling light from one fiber to the other fiber

Coupling lens

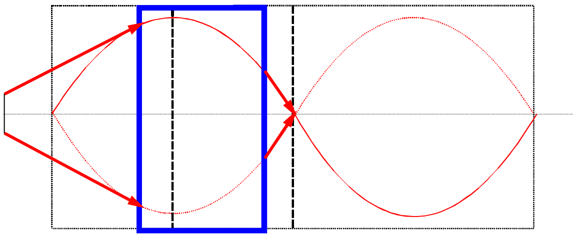
0.23P lens



Coupling lens

Coupling light from LD to fiber

0.29P lens



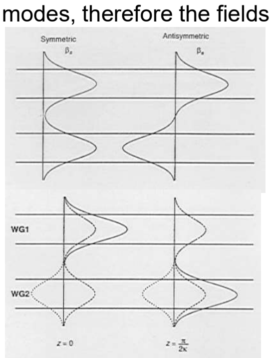
2. Fiber directional coupler

Introduction

Coupler:
It is a passive component used for dividing the signals, and is one of the most important in-line fibre components.The light is inputted from one port and then outputted from another one or more ports.

The operation principle of coupler [定向耦合器原理]
Single mode fiber：modes coupling theory；
Multimode fiber：bending theory.

Mechanism：when two fibers are closer, the waveguide field of one fiber will polarize the other fiber thus inducing the guided modes, therefore the fields overlap.



Directional coupler - formed by a pair of identical symmetric single-mode planar waveguides
At $z = 0$, power launched into WG1, exciting symmetric and antisymmetric modes $\beta_s \neq \beta_a$

- Two modes developing a phase difference, $\Delta\phi$, as they propagating
- $\Delta\phi = \pi$, the superposition cancelling in WG1 and adding in WG2
- $\Delta\phi = 2\pi$, leading to a power transfer back to WG1
- Power exchanging periodically between WG1 and WG2

Power exchange

If $P_1(0)$ is the power launched into fiber 1 at $z = 0$, then the power propagating in the two fibers are

$$\frac{P_1(z)}{P_1(0)} = 1 - \frac{\kappa^2}{\gamma^2}\sin^2 \gamma z$$

$$\frac{P_2(z)}{P_1(0)} = \frac{\kappa^2}{\gamma^2}\sin^2 \gamma z$$

$$\gamma^2 = \kappa^2 + \frac{1}{4}(\Delta\beta)^2 \quad \text{and} \quad \Delta\beta = \beta_1 - \beta_2$$

κ – coupling coefficient, a measure of the interaction strength between the two fibers, depending on

fiber parameters
separation between the fiber cores
operation wavelength

(i) $P_1(z) + P_2(z) = P_1(0)$ independent of z.

(ii) $\kappa = 0 \rightarrow P_1(z) = P_1(0) \quad P_2(z) = 0$

no coupling between two fibers – no exchange of power

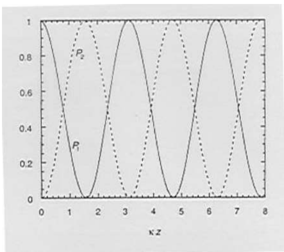
Phase-match case

A coupler made up of two identical fibers

$$\Delta\beta = 0 \quad (\beta_1 = \beta_2, \quad \gamma = \kappa)$$

$$P_1(z) = P_1(0)\cos^2 \kappa z$$

$$P_2(z) = P_1(0)\sin^2 \kappa z$$



Variation of powers in the two fibers in a directional coupler as a function of z when the two fibers $\beta_1=\beta_2$.

Interaction length L_c

The minimum distance at which the power completely transferred from the input fiber to the other fiber.

$$z = L_c = \frac{\pi}{2\kappa}$$

For typical single mode fibers operating at 1.3mm
$\kappa \sim$ 0.8 mm^{-1} to 0.3 mm^{-1}
$L_c \sim$ 2-5 mm

3-dB (50%) coupler:

$$L = \frac{\pi}{4\kappa}$$

$$P_1 = \frac{1}{2}P_0, \qquad P_2 = \frac{1}{2}P_0$$

By appropriately choosing the value of $\kappa{\cdot}L$, we can fabricate couplers with an arbitrary splitting ratio.

Practical parameters of a coupler

① Coupling ratio T_{ij}

The ratio of the input power at the port i to the output power from the port j

$$T_{ij} = \frac{P_j}{P_i}$$

② Excess loss α

The ratio of the total output power from all the ports to the input power at the port i

$$\alpha = -10\lg\left[\sum_j P_j / P_i\right] \quad \text{(dB)}$$

③ Insertion loss α_{ij}

The ratio of the output power from the port j to the input power at the port i

$$\alpha_{ij} = -10\lg\frac{P_j}{P_i} = -10\lg(T_{ij})$$

④ Directivity：方向性

The ratio of the output power from the undesired port k to the input power from the port i

$$\alpha_{ik} = -10\lg\frac{P_k}{P_i}$$

Good directional couplers should have low excess loss and high directivity.

Commercial directional couplers:

Coupling ratio: 50/50 - 1/99

Excess loss $\leq$ 0.1dB

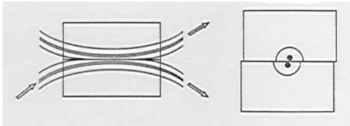
Insertion loss $\leq$ 3.4dB (for 3-dB coupler)

Directivity $\geq$ 55dB

Fabrication of directional couplers

(a) Polished fiber couplers

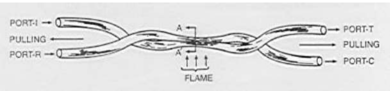
Fiber directional coupler made up of two side-polished fiber half blocks. Tuning is achieved by one lock against the other.

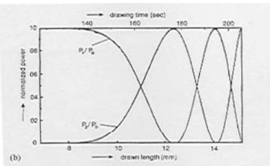


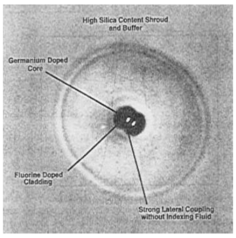
Standard technique for PM fiber couplers;
Disadvantage: time-consuming operation, high cost.

(b) Fused couplers 熔铸耦合器

Fused couplers —— fabricated by twisting two single-mode fibers (after removing their protective coating) and then heating and pulling them - two fibers fused laterally with one another and also tapered





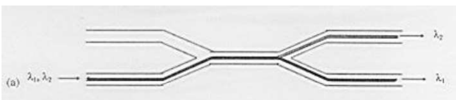


Experimentally measured normalised power exiting the two fibres versus the drawn length.

- The coupling ratio is monitored on line as the fibers are fused and drawn.
- Fused fiber couplers widely used for WDM network systems.
- Loss < 0.1dB with directivity in excess of 55dB.[超过]

Applications

(a) Power dividers - one of the most important and common applications.
(b) Wavelength division multiplexer/demultiplexer

P_i  P_2 P_1

Multiplexer principle:

Considering a directional coupler of length L made of identical fibers and κ_1 and κ_2 be the coupling coefficients at wavelengths λ_1 and λ_2

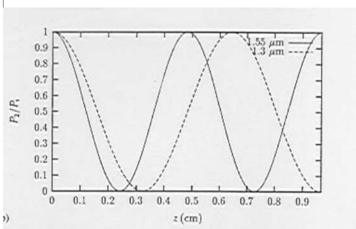
$$\kappa_1 L = m\pi \quad \text{and} \quad \kappa_2 L = \left(m - \frac{1}{2}\right)\pi$$

In such a case, if light beams λ_1 and λ_2 are launched simultaneously in the input fiber

$$\text{For } \lambda_1, \quad P_2(\lambda_1, L) = P_1 \sin^2(\kappa_1 L) = 0$$

$$\text{For } \lambda_2, \quad P_2(\lambda_2, L) = P_1 \sin^2(\kappa_2 L) = P_i$$

λ_1 exiting port B; λ_2 exiting port A - wavelength demultiplexing



1.3 mm / 1.55 mm WDM:

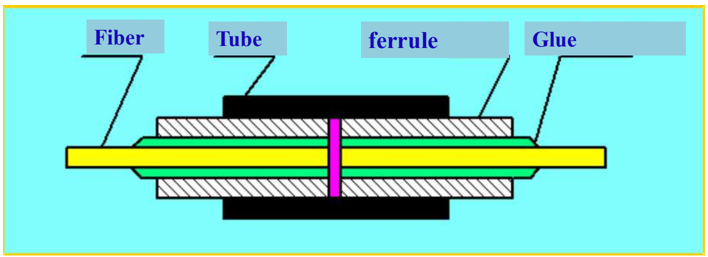
If light of 1.55 mm and 1.3 mm launched on the same fiber at the input of the coupler, light 1.3 mm will exit from the **same** fiber, whereas light 1.55 mm will exit from the **other** fiber.

3. Fiber-optic connectors

What is fiber-optic connector?

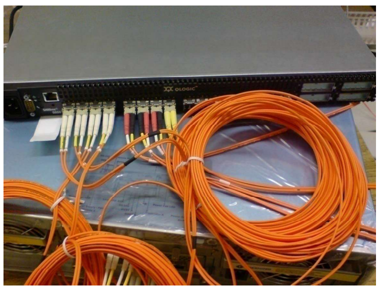
An optical fiber connector terminates端接/终止 the end of an optical fiber, and enables quicker connection and disconnection than splicing.

The typical structure of a fiber-optic connector



The application of fiber-optic connector

It is usually applied in the connection between fibers, equipments, or fiber and equipment.



The performance of the fiber-optic connector

(1) Optical loss

- Insertion loss
- Return loss

(2) Interchangeability 互换性

(3) Tensile strength 抗张强度

(4) Temperature

(5) Lifetime

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(1) Optical loss

- **Insertion loss**

  Introduction by the connector

  Typically <0.5 dB.

- **Return loss** [越大越好]

  It describes the ability of the connector to restrain the reflection

  Typically larger than 25 dB.

  If the polish is performed, it can be improved to larger than 45 dB.

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(2) Interchangeability

For the same type connectors, they can be replaced arbitrarily.

(3) Tensile strength

It is usually larger than 90 N.

(4) Temperature

Normally operates at the temperature range of -40^{0}C~70^{0}C.

(5) Lifetime

Good connector is required to be plugged beyond 1000 times.

Types of fiber-optic connector

There are a series of different classification standards.

- fiber materials
- structures
- shapes of the fiber ends
- numbers of the fiber cores
- ……

Connectors with different fiber materials

- Silica fiber based connectors (including single mode and multimode fibers)
- Plastics fiber based connector
- ……

Connectors with different structures

- FC connector(fiber channel) (screw thread connection)
- ST connector (bayonet socket connection)
- SC connector (snap-in)
- MT connector (multifiber)
- ……

Connectors with different shapes of the fiber ends

- PC connector (the connector surface is slightly curved)
- APC connector (the endface is at an 8 degree angle)
- ……

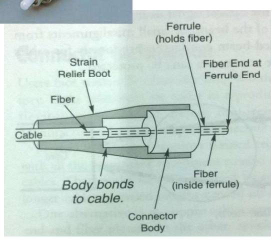
Connectors with different numbers of the fiber cores

- Single core connector
- Multi core connector
- ……

The commonly used fiber-optic connectors

(1) FC connector

This type of connectors are widely applied in datacom, telecommunications, measurement equipment, and EDFA

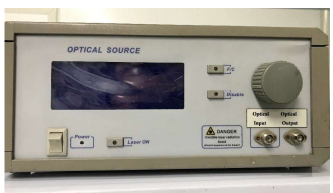


Typical structure of the FC connector

•The fiber is mounted in a long, thin cylinder called a ferrule which is typically made of ceramic and with 2.5 mm diameter.

•FC connector is connected with the help of the screw thread. 螺纹

• FC connector is simple with an easy operation and fabrication, but the fiber end is sensitive to dust.

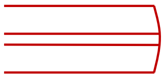


The commonly end type of the FC connector

(1)FC/FC

Flat Contact (FC). A back reflection of about -16 dB (4%).

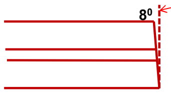
(2)FC/PC



Physical Contact (PC). A slightly curved end surface and a back reflections of -30 to -40 dB.

(3)FC/APC

Question: Why is the angle is 8^0?



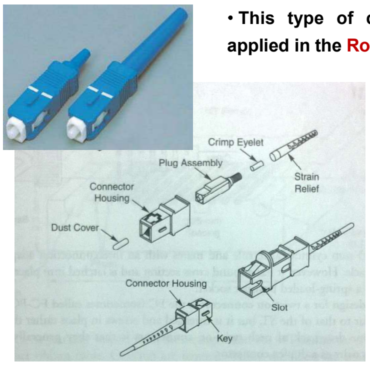
Angled PC (APC) adds an 8° angle to the end surface. A back reflections of <-60 dB can routinely be accomplished with this polish

Question: Why is the angle is 8^0?

Because when the end face of the APC connector is inclined by 8 degrees, the return loss will be higher than that of the plane.

This kind of oblique 8 degree fiber patch cord is mainly used in analog transmission, high-power ports and other places that are particularly sensitive to end-face reflection, and its advantage is that the end-face reflection is small and the return loss is large. The return loss of the general PC or UPC jumper is 50~55dB, and the APC is generally 60~65dB. But this does not mean that there is no reflection at all, but the reflection is particularly small.

(2) SC connector

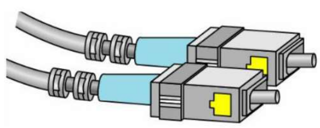


- This type of connectors are widely applied in the Router and Switch.

Typical structure of the SC connector

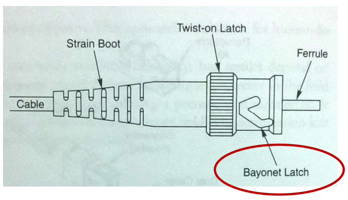
SC connector is built up around a cylindrical 2.5 mm ferrule that holds the fiber.

- The cross section of the outermost shell is rectangular.
- It is fastened using the rectangular latch and cannot be rotated.
- This type of connectors can be divided into the simplex type and duplex type.



(3) ST connector

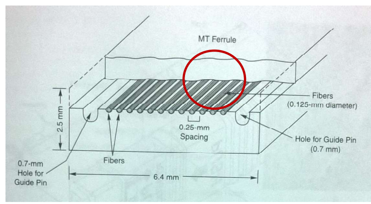
This type of connectors are widely applied in the 10-Mbps Ethernet system.



Typical structure of the ST connector

- ST connector is similar to the SC connector.
- It has a 2.5 mm ferrule made up of metal.
- It is fastened by a bayonet latch.
- It is only simplex.

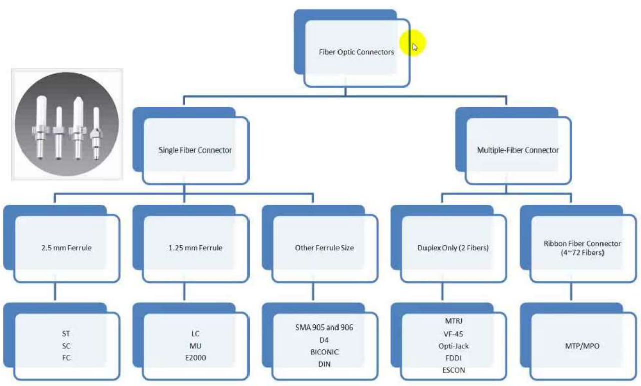
(4) MT connector



Typical structure of the MT connector

- This type of connector area widely applied in the multichannel signal transmission system.
- It is built up around the non-cylindrical ferrule which aligns many fibers parallel to each other.
- The ferrules include a pair of 0.7-mm holes, parallel to fibers (Guide Pin).
- These holes accommodate precision metal guide pins, which align the two elements with matched fibers

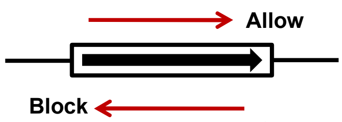
Common Fiber Connectors List

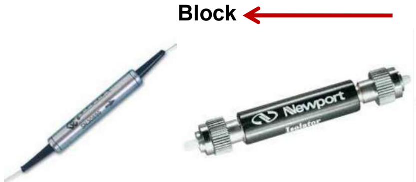


4. Fiber optic isolator

What is fiber optic isolator?

- It is a fiber optic component that only allows the transmission of light in only one direction.
- The light is completely blocked in the other direction.





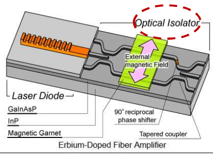
Application

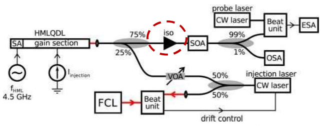
①To avoid the feedback in the semiconductor laser thus reduce the error rate；

②To avoid the returned light in a semiconductor amplifier thus improve the stability；

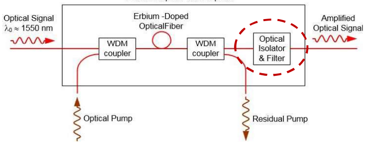
③Rare earth ions doped fiber amplifier（e.g., EDFA）；

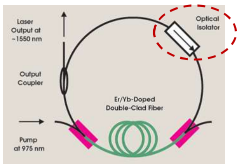
④To ensure the unidirectional operation of the fiber lasers





Erbium-Doped Fiber Amplifier





The inside structures of fiber optic isolators

There are two types of typical fiber optic isolators:

(1) Polarization dependent isolator (PDI)
Only available for special linearly polarization light.

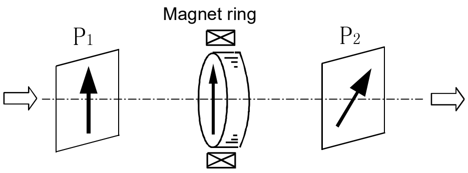
(2) Polarization independent isolator (PIDI)
Available for the light with random polarizations.

(1) Polarization dependent isolator (PDI)

It consists of

1) a pair of polarizing filters whose polarization directions have an angle of 45^0

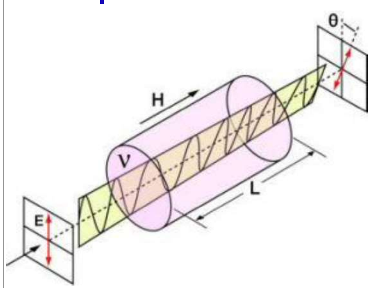
2) a Faraday rotator.



偏振旋转 右手定则

Faraday magneto-optical effect

Principle



•Light transmits through the Faraday rotator in a magnetic field.

•Polarization of the light always rotates along the right–hand–thread direction with respect to the magnetic field H.

•The rotation direction is not relative to the light transmission direction.

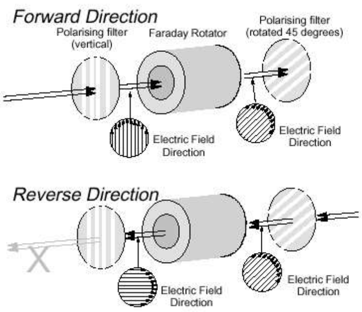
•The rotation angle *θ* is only related to the magnetic intensity *H*, Faraday rotator length *L* and material Verdet constant *ν*

Basic Material:

Yttrium-Iron-Garnet (YIG), Corning No.8363 Glass, etc.

In a fiber optic isolator, the rotation angle θ is chosen to be 45º

顺时针转



Forward：the polarization direction rotates 45° thus being parallel to the second polarizing filter, therefore the light transmission is allowed.

Reverse： the polarization direction rotates 45° but being perpendicular to the second polarizing filter, therefore the light transmission is blocked.

Disadvantages of the PDI:

•It is polarization dependent.

•For the input light with the random polarization states, there is a 50% optical power loss

•If the input light has a fixed polarization state, the optical power maybe lost totally.

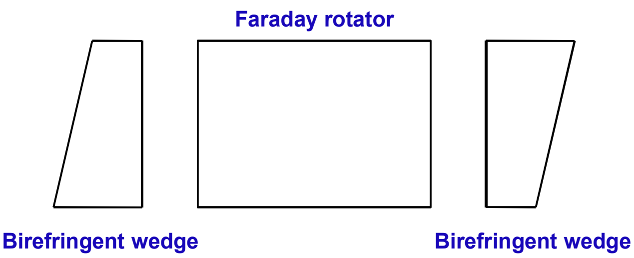
•If the polarization state varies as time, the light will also experience the loss. 损耗也会随时间变化

(2) Polarization independent isolator (PIDI)

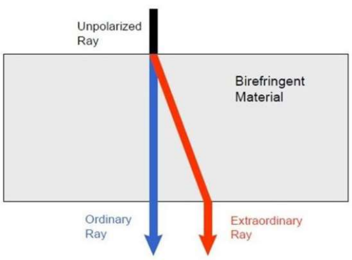
It consists of

1) a pair of birefringent wedges

2) a Faraday rotator.



What is the briefingence?



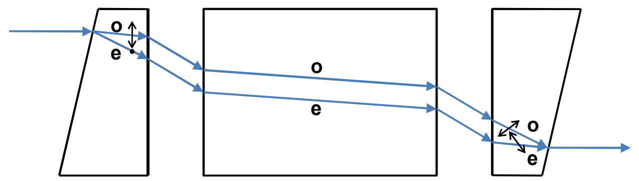
•For some birefringent materials, there would be different refractive indexes for the perpendicularly polarized lights.

•They have a lower refractive index for the o ray and a higher refractive index for the e ray.

•正单轴晶体Positive uniaxial crystal / 负Negative uniaxial crystals

•The polarizations are specially separated.

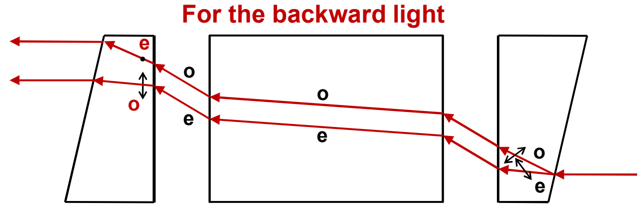
For the forward light



- The input light is separated into o beam and e beam by the birefringent wedge I.
- Both beams are rotated 45° by the Faraday rotator.
- The two beams are combined to be a single beam by the birefringent wedge II.

The forward light is allowed.

For the backward light



- The input light is also separated into o beam and e beam by the birefringent wedge II.
- Two beams are rotated 45° by the Faraday rotator.
- The o beam becomes the e beam, the e beam becomes the o beam for the birefringent wedge I.
- The two beams are diverged after passing through the birefringent wedge I

The backward light is blocked

The performance parameters of the fiber optic isolators

Insertion loss: $a = -10\lg (P_{out}/P_{in})$ (forward)

Isolation ratio: $I = -10\lg(P'_{out}/P'_{in})$, (backward)

Return loss: $I_b = -10\lg(P_{back}/P_{in})$

Operation bandwidth: Dl

For a commercial fiber optic isolator (Item: IO-H-1550)

Insertion loss: 0.5-0.7 dB

Isolation ratio: ≥29 dB

Return loss: ≥55 dB

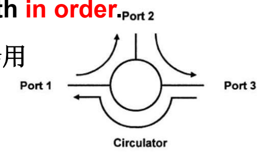
Operation bandwidth: 40 nm

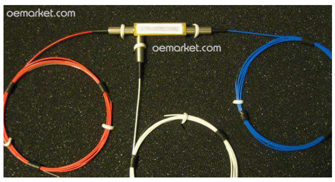
5. Fiber optic circulator

What is fiber optic circulator?

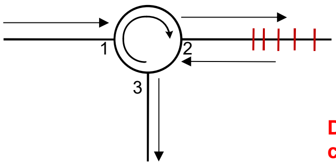
- **It is a fiber optic component that allows the light to transmit along the required path in order.**
- **Port 1 →Port 2 → Port 3**

Port 3到Port 1也有，但一般不会用

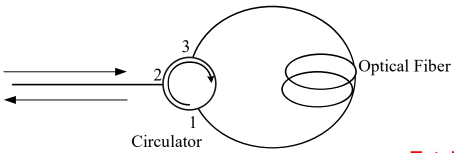




Application

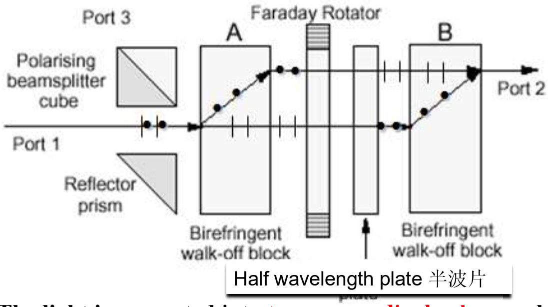


Dispersion compensation combined with CFBG



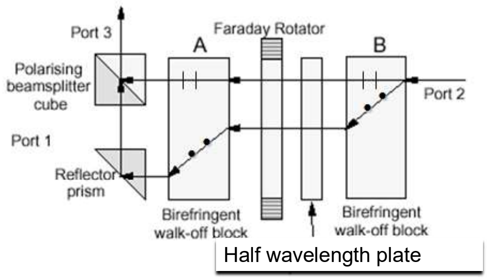
Total reflection mirror

Port 1 →Port 2



- **The light is separated into two perpendicular beams by the block A.**
- **The polarizations of the two beams are rotated 90° after passing through 45° Faraday rotator and phase retardation plate.**
- **The two beams are combined by the block B thus outputted from port 2.**

Port 2 →Port 3



- **Light is separated into two perpendicular beams by the wedge B.**
- **The polarizations of the two beams are kept unchanged after passing through 45° Faraday rotator and phase retardation plate.**
- **The two beams are combined by the reflector prism and the polarizing beam splitter cube thus outputted from port 3.**

The performance parameters of the fiber optic circulators:

Insertion loss: $a = -10\lg (P_{2,3}/P_{1,2})$, (order)

Isolation ratio: $I = -10\lg(P_{1,2}/P_{2,3})$, (reverse order)

Return loss: $I_b = -10\lg(P_{back}/P_{in})$

Operation bandwidth: Dl

For a commercial fiber optic circulator (Item: 6015-3)

Insertion loss: 0.8 dB

Isolation ratio: ≥40 dB

Return loss: ≥50 dB

Operation bandwidth: 85 nm