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Features of spatially coupled optical fiber compact functional devices

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1. Introduction

In basic research on optics, especially using lasers as light sources, it has been a long time since experimental systems using optical fibers have been adopted in many cases. Not only the research subjects for optical communication fields, but also for sensing, quantum computing, spectroscopy, measurement, and even high-end processing using lasers, it is very convenient to use optical fibers to handle them, and the transverse mode is also stable, therefor, good characteristics can be obtained.

Optoquest manufactures high end optical fiber compact functional devices as research and experimental tools not only in the telecom field but also in various optical fields. Some of our recommended products are introduced in this paper.

2. Key technology is low-loss spatially coupled fiber optic in-out

It is not easy to couple the signal light with highly efficiency to the core of a generally used quartz glass single-mode optical fiber in devices that perform some function in spatial optics.

By using aspherical lenses that are well designed and selected considering aberrations (Fig. 1), the fiber collimator pair (Fig. 2) can be fabricated with the guaranteed optical coupling loss value ≤ 0.5 dB and the typical loss value ≤ 0.25 dB by using precise optical axis alignment equipment. In addition, our original YAG welded fixing technology (Fig. 3) provides the same high reliability as passive optical function modules that have passed the Telcordia GR-1221 test.

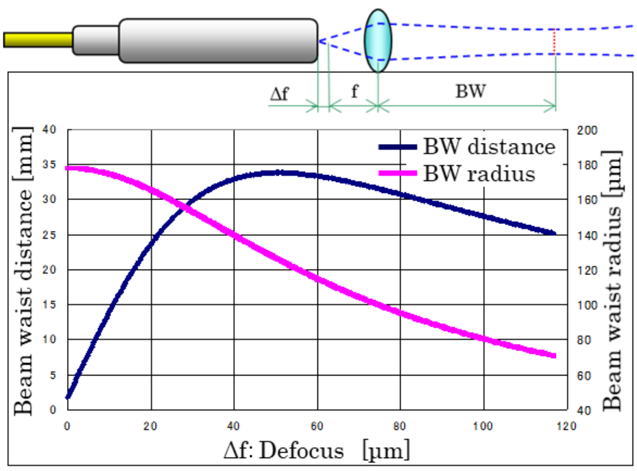


Fig. 1: Characteristics of defocus and beam waist radius

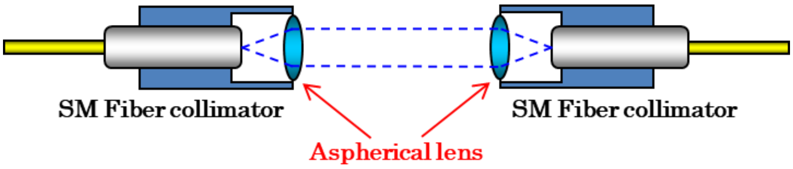


Fig. 2: Schematic diagram of Fiber collimator pair

Fig. 3: Photograph of YAG laser welded fixing

3. Polarization Controller

Commercially available optical fiber polarization controllers can be classified into the following three main types. (1) paddling type, (2) in-line stressing type, and (3) bulk type. In general, the order of cheapness is (1), (2), and (3), and the order of performance is (3), (2), and (1). Here we introduce the bulk type polarization controller in (3), which is fabricated by Optoquest.

3.-1) Abstract

By rotating some bulk polarizing elements in the spatial beam of a fixed fiber collimator pair (Fig. 4), any polarization states can be obtained according to the configuration of the elements.

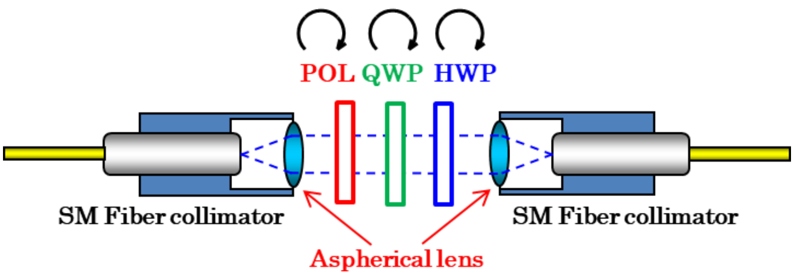
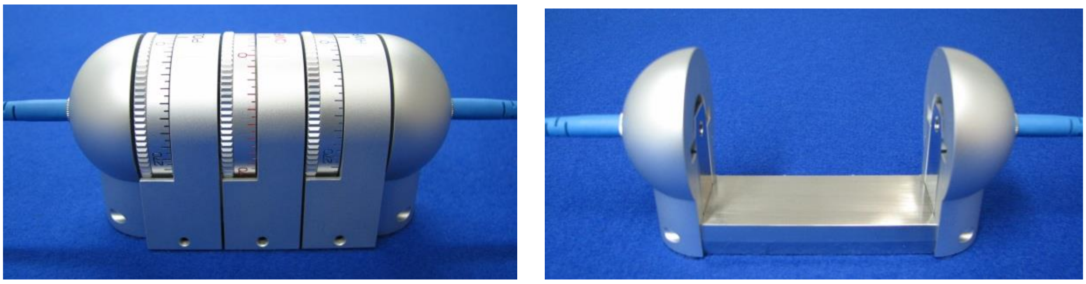


Fig. 4: Schematic diagram of bulk type Polarization Controller

The bulk type has more repeatability of the polarization state than the paddling type and the stressing type. Moreover, since this is a cartridge type, various experiments and inspections of the optical fiber system can be conveniently performed by simply inserting and removing the respective cassettes of the polarizing elements and the optical functional elements (Fig. 5).



(a) Example: Polarization Controller (b) fixed fiber collimator pair

(c) Polarizer Cassette, (d) Quarter Wave Plate Cassette, (e) Half Wave Plate Cassette

Fig. 5: (a)～(e): Photograph of cartridge type polarization controller and its component cassettes

3.-2) Overview of Polarization Control Principles

The principle is easy to explain since it is a bulk type. The polarizer is made of wire-grid type glass, and the QWP and HWP wave plates are made of quartz crystal. A polarizer transmits only linear polarization along its axis. By rotating QWP, the polarized ellipticity of the transmitted polarization can be changed. By rotating HWP, the polarized axis direction of the transmitted polarization can be changed.

・Role of the wave plates

A wave equation 'S' for linearly polarized light with amplitude 'a' (Fig. 6) is expressed as follows.

$S = a \sin(\omega \cdot t)$ 【'ω' is angular velocity and 't' is time】

Before the light 'S' enters the uniaxial crystal in the coordinate system of Fig. 6, it can be expressed as follows.

$X = a \cos\theta \cdot \sin(\omega \cdot t)$,

$Y = a \sin\theta \cdot \sin(\omega \cdot t)$

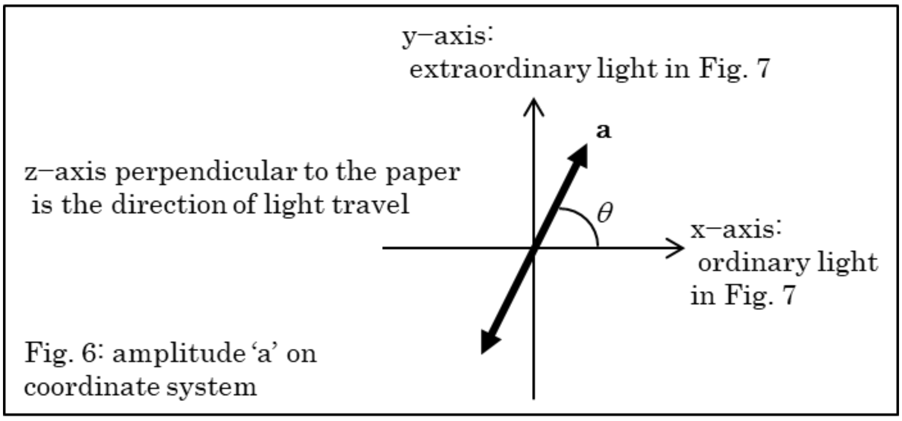


Fig. 6: amplitude 'a' on coordinate system

Now, let us consider the case in which a light with amplitude 'a' is transmitted through an optical crystal plate (for example, zero order quartz crystal waveplate) in Fig. 7 perpendicularly to the paper.

The linear polarization along the crystal axis is 'extraordinary light', and the refractive index is ne. The linear polarization perpendicular to the crystal axis is 'ordinary light', and the refractive index is no. In the case of quartz crystal, ne > no.

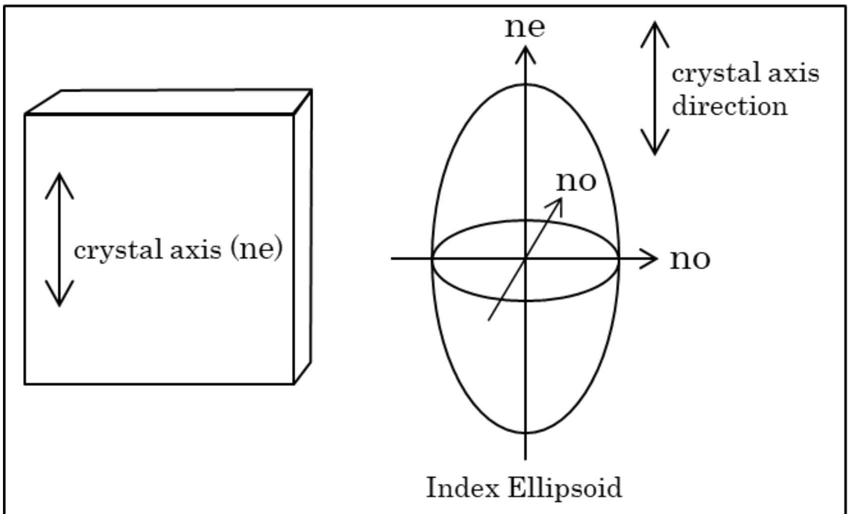


Fig. 7: Schematic diagram of uniaxial crystal

The equation for a wave transmitted through a uniaxial crystal can be expressed as follows.

$X = a \cos\theta \cdot \sin(\omega \cdot t + \delta o)$, $Y = a \sin\theta \cdot \sin(\omega \cdot t + \delta e)$

Since ne > no for the quartz crystal, the phase difference is $\delta o > \delta e$.

The phase difference δ can be expressed as $\delta o - \delta e = \delta$.

Since $\delta e = \delta o - \delta$, $Y = a \sin\theta \cdot \sin(\omega \cdot t + \delta o - \delta)$, so the phase of extraordinary light is delayed by 'δ' compared to ordinary light.

Incidentally, the phase difference between ordinal light and extraordinary light can be expressed as $\delta = \frac{2\pi}{\lambda} \cdot d \cdot (ne - no)$. 'd' is the thickness of the quartz crystal plate.

Some examples of polarization state that linear polarization can obtain before and after transmission through the quartz crystal plate are shown below.

Example (1): $\theta = 45^\circ$ and $\delta = 0$

$$X = \frac{a}{\sqrt{2}} \cdot \sin(\omega \cdot t + \delta o)$$

$$Y = \frac{a}{\sqrt{2}} \cdot \sin(\omega \cdot t + \delta o - \delta) = \frac{a}{\sqrt{2}} \cdot \sin(\omega \cdot t + \delta o)$$

$\therefore$ $Y = X$

→ Represents linear polarization before transmission

Example (2): $\theta = 45°$ and $\delta = \pi$

$$X = \frac{a}{\sqrt{2}} \cdot \sin(\omega \cdot t + \delta o)$$

$$Y = \frac{a}{\sqrt{2}} \cdot \sin(\omega \cdot t + \delta o - \delta) = \frac{a}{\sqrt{2}} \cdot \sin(\omega \cdot t + \delta o - \pi)$$

$$= -\frac{a}{\sqrt{2}} \cdot \sin(\omega \cdot t + \delta o)$$

$\therefore$ $Y = -X$

→ Represents linear polarization rotated 90° to the left after transmission as shown Fig, 8

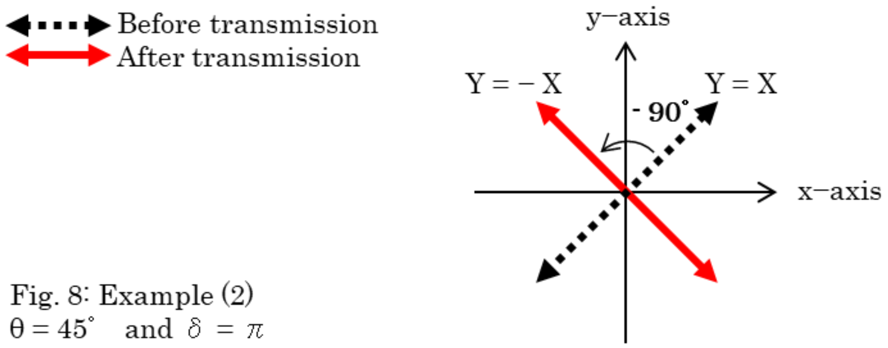


Fig. 8: Example (2)
$\theta = 45^\circ$ and $\delta = \pi$

Example (3): $\theta = 45^\circ$ and $\delta = \frac{\pi}{2}$

$$X = \frac{a}{\sqrt{2}} \cdot \sin(\omega \cdot t + \delta o)$$

$$Y = \frac{a}{\sqrt{2}} \cdot \sin(\omega \cdot t + \delta o - \delta) = \frac{a}{\sqrt{2}} \cdot \sin(\omega \cdot t + \delta o - \pi / 2)$$

$$= \frac{a}{\sqrt{2}} \cdot \cos(\omega \cdot t + \delta o)$$

$\therefore$ $X^2 + Y^2 = a^2 / 2$

→ Represents clockwise circular polarization after transmission as shown Fig. 9

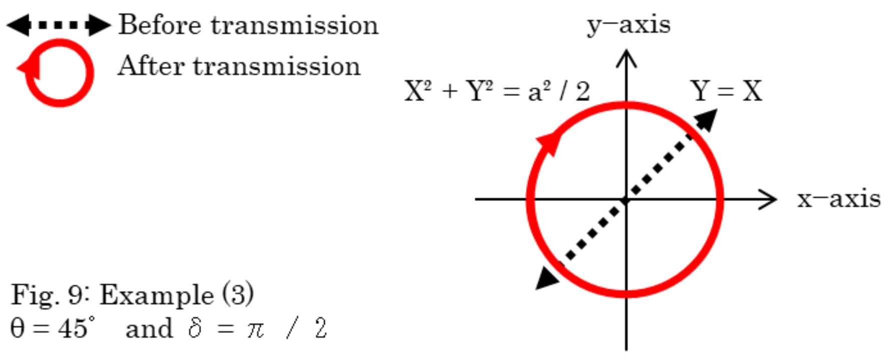


Fig. 9: Example (3)
$\theta = 45^\circ$ and $\delta = \pi / 2$

Example (4): $\theta = 45^\circ$ and $\delta = 3\frac{\pi}{2}$

$$X = \frac{a}{\sqrt{2}} \cdot \sin(\omega \cdot t + \delta o)$$

$$Y = \frac{a}{\sqrt{2}} \cdot \sin(\omega \cdot t + \delta o - \delta) = \frac{a}{\sqrt{2}} \cdot \sin(\omega \cdot t + \delta o - 3\pi / 2)$$

$$= -\frac{a}{\sqrt{2}} \cdot \cos(\omega \cdot t + \delta o)$$

$$\therefore X^2 + Y^2 = a^2 / 2$$

→ Represents counterclockwise circular polarization after transmission

・Conclusion of the bulk type polarization controller

A polarizer transmits only linear polarization along its axis, so high extinction ratio can be obtained.

By changing the angle θ of the polarized light axis incident on the HWP (i.e., $\delta = \pi$), an arbitrary polarization axis direction of -2θ can be obtained with a constant ellipticity as shown in Fig. 10.

By changing the angle θ of the polarized light axis incident on the QWP (i.e., $\delta = \pi/2$), an arbitrary polarization ellipticity can be obtained with a constant polarization axis direction as shown in Fig. 11.

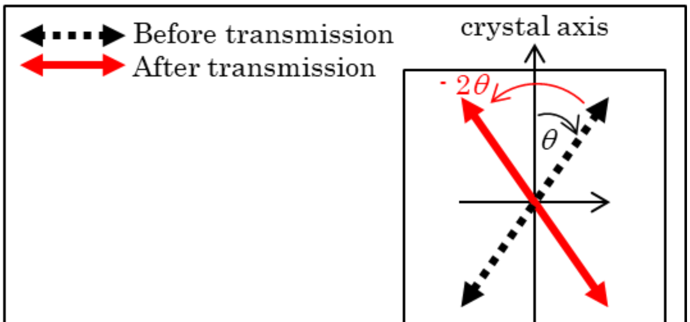


Fig. 10: Role of HWP

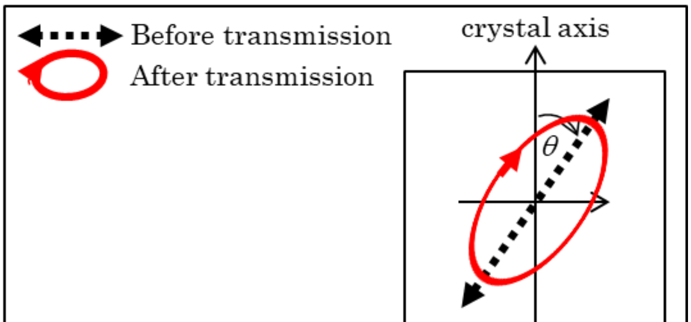


Fig. 11: Role of QWP

4. Variable Attenuator Module

This device is also a bulk type manually variable attenuator (Fig. 12 and Fig. 13) like the polarization controller.

There are three features.

(1) Can withstand 2W optical power input because it does not use light-absorbing material such as a knife edge in the optical path. It uses a prism.

(2) Equipped with an On/Off shutter. This also uses a prism.

(3) Variable attenuation uses a micrometer, so repeatability is very good.

Commercially available manually variable optical attenuators often use "screws" for attenuation. They require very careful fingering during frequent variable attenuation.

Since this device uses a micrometer for variable attenuation adjustment, you are free from the stress of fingerings. Of course, backlash is extremely low compared to the screw type.

Furthermore, PMF is in high demand for input and output fibers of this device.

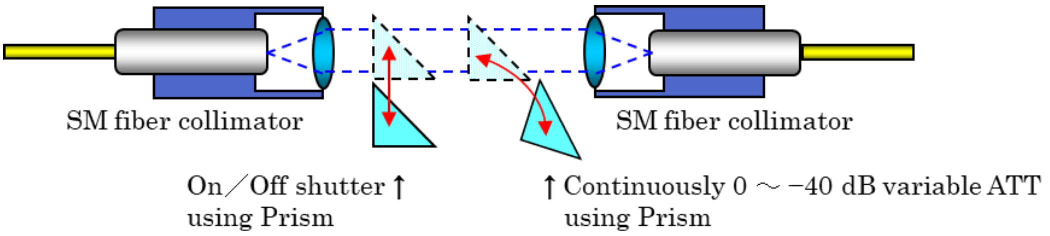


Fig. 12: Schematic diagram of bulk type Variable Attenuator Module

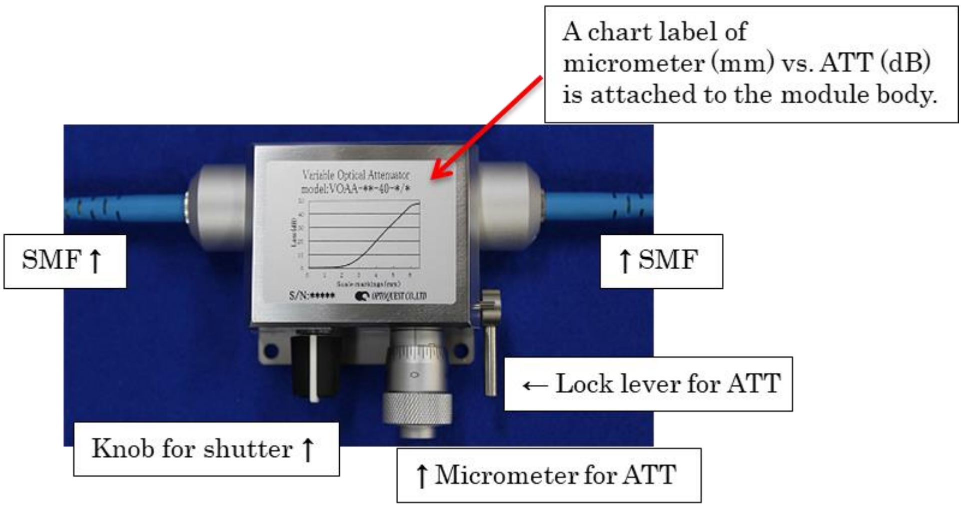


Fig. 13: Photograph of Variable Attenuator Module

5. Polarization Composition / Separation Coupler

This device is a 3-port module that can combine and separate polarizations (Fig. 14 and Fig. 15) with high extinction ratio. Also called PBS module, it is a bulk type device using optical crystal. It is not a polarization splitting or branching coupler.

Some commercially available polarization couplers are (1) PM fiber fusion type and (2) PBS module type applying Brewster's law using multilayer interference film. As is well known, the polarization separation ability of types (1) and (2) is limited to about 30 dB.

This device uses the uniaxial optical crystal which provides high polarization separation extinction ratio of ＞45dB. Ideal for high performance polarization diversity applications. It is often used as a polarization combination device for the purpose of TE and TM input to the polarization-dependent devices.

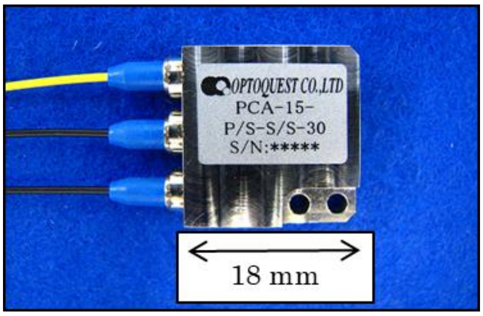


Fig. 14: Photograph of Polarization Composition / Separation Coupler

The mechanism of this device is briefly shown below (Fig. 15 and Fig. 16). The uniaxial optical crystal is used as a birefringent plate. Since a birefringent plate and a folding prism are used, it's a 3-port device with only one side.

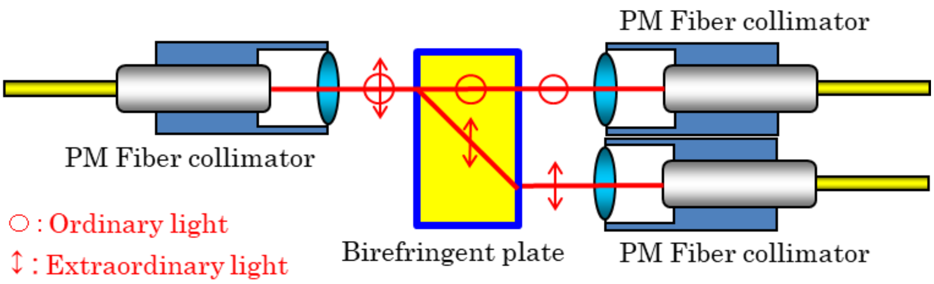


Fig. 15: Schematic diagram of bulk type Polarization Composition / Separation Coupler

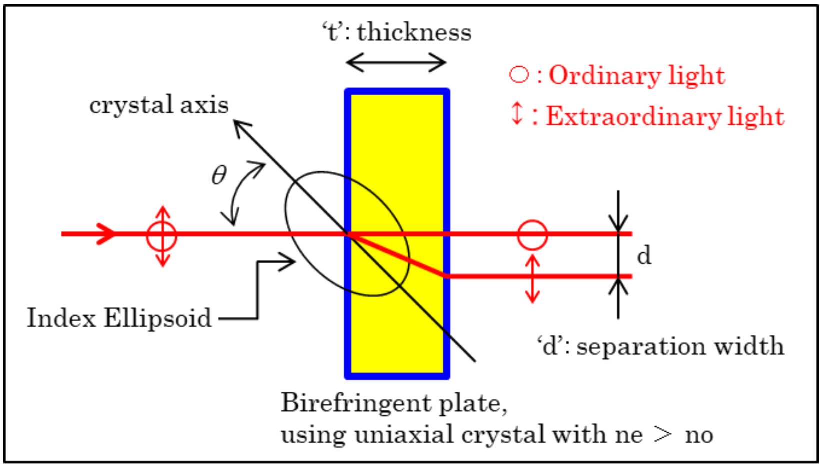


Fig. 16; Functional diagram of Birefringent plate

It is known that the separation width 'd' between ordinary light and extraordinary light is expressed as follows.

In the case of ne＞no,

$$d = \frac{(ne^2 - no^2) \cdot \tan\theta}{ne^2 \cdot \tan^2\theta + no^2} \cdot t$$

The separation width 'd' is the maximum when $\tan\theta = no / ne$.

In the case of ne ≒ no, $\theta = 45°$, it can be approximated as follows.

$$d = \frac{ne^2 - no^2}{ne^2 + no^2} \cdot t$$

For example, in the case of TiO2 (Rutile), ne≒2.69 and no≒2.44 at a wavelength of 1550nm. According to the above formula, θ max ≒ 42.2° . So 'd' max is calculated to be 0.098 ×t.

θ max ≒ 42.2° , d ≒ 0.098 × t

If $\theta = 45°$, d = 0.097 × t.

That is, the separation width per 1mm of thickness is about 0.1mm.

・Conclusion of the birefringent plate for this device

The separation width does not differ significantly whether the angle of the crystal axis is θ max or 45° . Considering also the reduction of reflected return light, θ is set to about 45°.

Furthermore, we are also good at handling PM fibers. As you know, PMF (polarization-maintaining fiber) maintains only linear polarization along the slow or fast axis.

There are two know-hows for evaluating high extinction ratio (Fig. 17).

(1) Deterioration of the extinction ratio of PMF depends on wavelength. By inputting broadband wavelength light into the PMF, wavelength-dependent phase differences can be evaluated without missing them.

(2) The extinction ratio can be measured with good repeatability by continuously rotating the linearly polarized broadband light and inputting it to the PMF, and monitoring the TE and TM power of the output polarized light respectively.

We have a system to handle the PMF with high extinction ratio using these know-hows. The extinction ratio of the PMF output of commercially available devices is at most 20 dB, but our devices can achieve ≥ 25 dB or ≥ 30 dB, depending on the class.

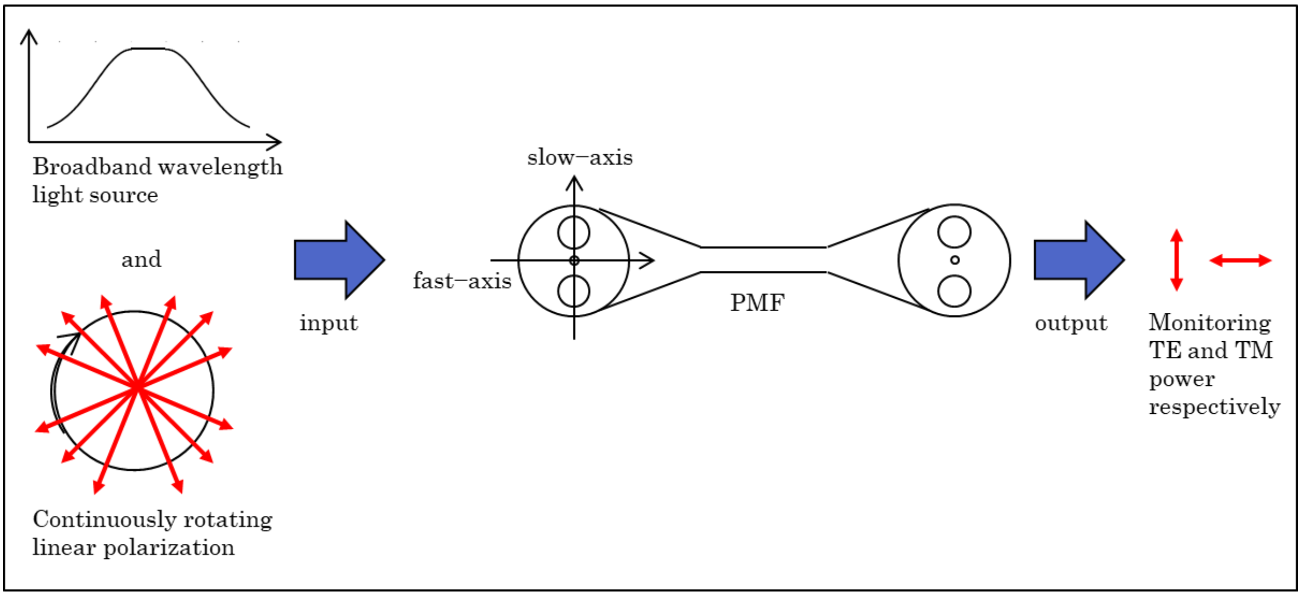


Fig. 17: Schematic diagram of the evaluating high extinction ratio of PM fibers

6. Devices for multi-core fiber

As mentioned at the beginning of this paper, we manufacture high-end spatially coupled optical fiber compact functional devices. In these days, multi-core fiber transmission systems have been a hot topic in advanced research on high-speed, large-capacity optical communications.

We have fabricated devices for multicore fiber such as FIFOs (Fan-in and Fan-out) (Fig. 18) and multi-functional devices for optical amplifiers using our specialized optical spatial coupling technology. These devices are characterized above all by low loss and low crosstalk.

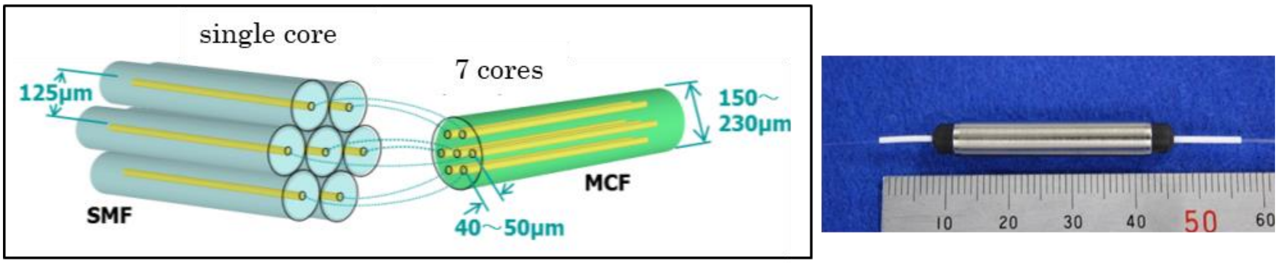


Fig. 18: Schematic diagram and photograph of FIFO

7. Super-continuum Light Source

This is a highly stable broadband light source using a unique pulse seeder specialized in super-continuum (SC) generation (Fig. 19). It has a flat spectral shape (Fig. 20) not found in conventional SC light sources and high stable output spectrum (Fig. 21) comparable to ASE light sources. Due to the dense output spectrum, even passive narrow band-pass filter modules can be evaluated with high dynamic range. The key technology to achieve flat shape and high spectral stability is in the special fiber laser we developed, and the generation of sub-nanosecond noise-like pulsed light (Fig. 22) from the fiber laser contributes to them.

This light source consists of single-mode optical fiber, and many optical fiber functional devices are used. These devises also contribute to reducing the temporal change in output spectrum.

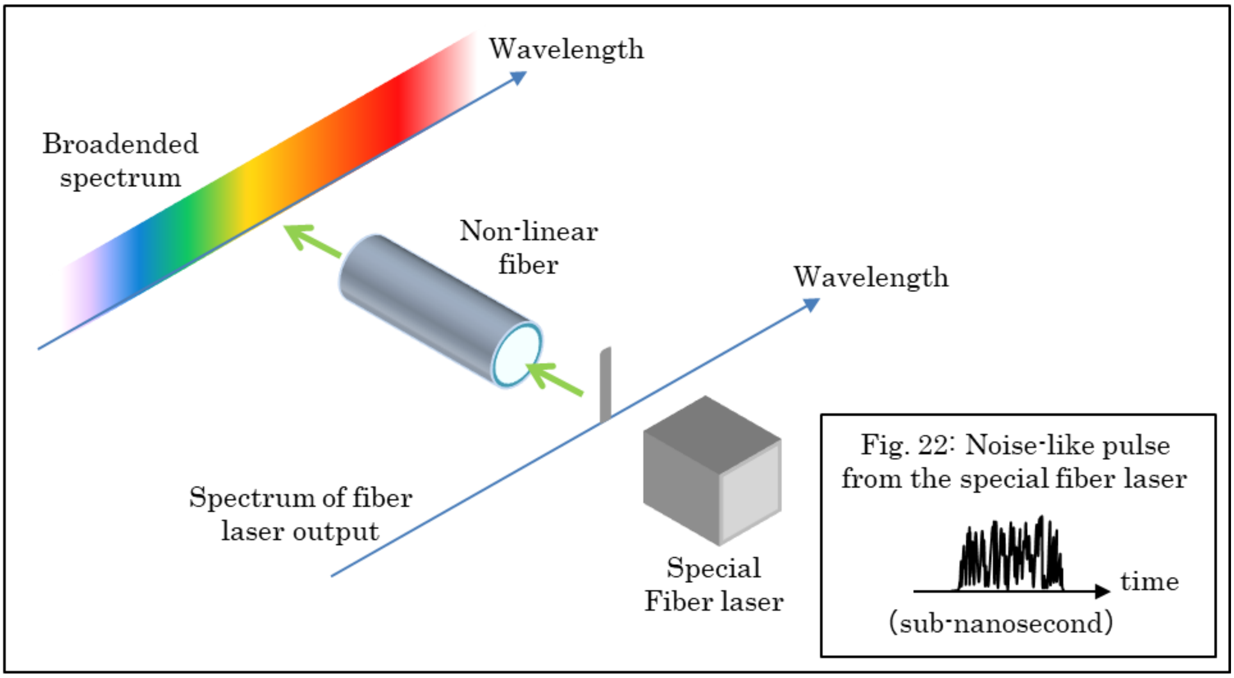
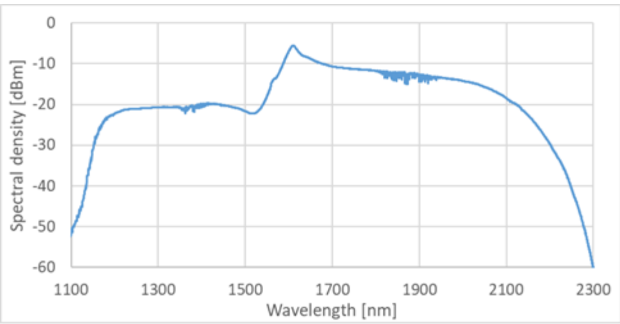


Fig. 19: Schematic diagram of Super-continuum (SC) Light Source



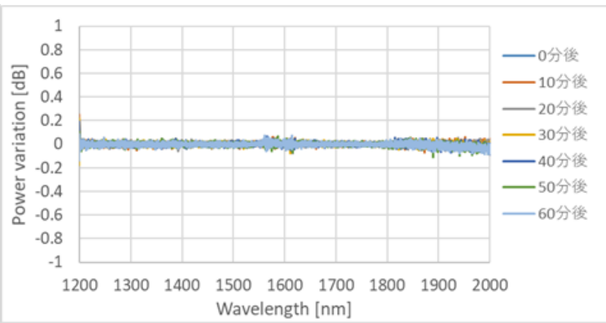


Fig. 20: Output spectrum

Fig. 21: Time stability of output spectrum

8. Conclusion

I introduced several spatially coupled optical fiber functional devices and a SC light source using them along with their features. I hope that this paper helps you understand the appeal of each device, which cannot be understood from only those leaflets.