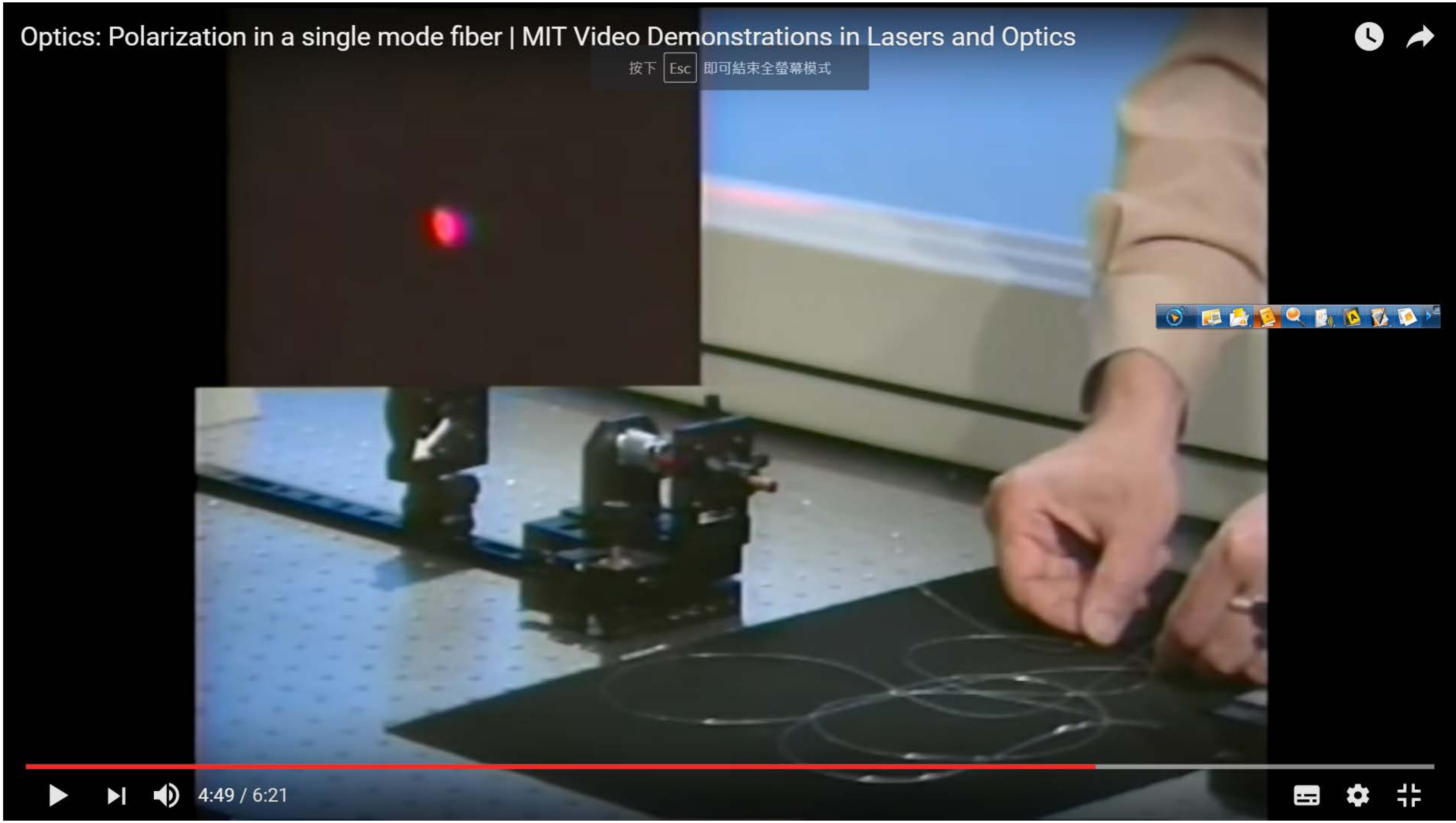
# 1.2.4 Polarization-Mode Dispersion

- A **single mode fiber** is not a truly single mode fiber because it can support **two degenerate modes** that are that are **polarized** in two orthogonal directions
- Under **ideal conditions** (perfect **cylindrical symmetry** and a **stress-free fiber**),
  - a mode excited with its polarization in the ***x* direction** would not couple to the mode with the orthogonal **y-polarization state**.
- In **real fibers**, small **departure**s from cylindrical symmetry, occurring because of **random variations** in the **core shape** along the fiber length,
  - result in a mixing of the **two polarization states** by **breaking the mode degeneracy**.
- The **stress-induced anisotropy** can also break this degeneracy.

# Polarization in a single mode fiber

- https://www.youtube.com/watch?v=kuht5Nv3Iio




# Polarization controller

- **Modal birefringence:** the **mode-propagation constant** $\beta$ becomes slightly different for the **modes polarized in the *x* and *y* directions**.

- **The strength of modal birefringence** is defined by

$$\boxed{B_m = \frac{|\beta_x - \beta_y|}{k_0} = |n_x - n_y|}$$

- For a given value of $B_m$, the **two modes** exchange their powers in a **periodic fashion** as they propagate inside the fiber with the period.

$$\boxed{L_B = \frac{2\pi}{|\beta_x - \beta_y|} = \frac{\lambda}{B_m}}$$

$L_B$ **:** the beat length

**Fast axis:** the axis along which the **mode index is smaller** because the group velocity is larger for light propagating in that direction.

**Slow axis:** the axis with the **larger mode index**

- In **standard optical fibers**, $B_m$ is **not constant** along the fiber but changes randomly because of fluctuations in the **core shape** and **anisotropic stress**.
  - light launched into the fiber with a **fixed state of polarization** changes its polarization in a **random fashion**.

- This change in **polarization** is typically harmless for continuouswave (CW) light because most photodetectors do not respond to **polarization changes** of the incident light.

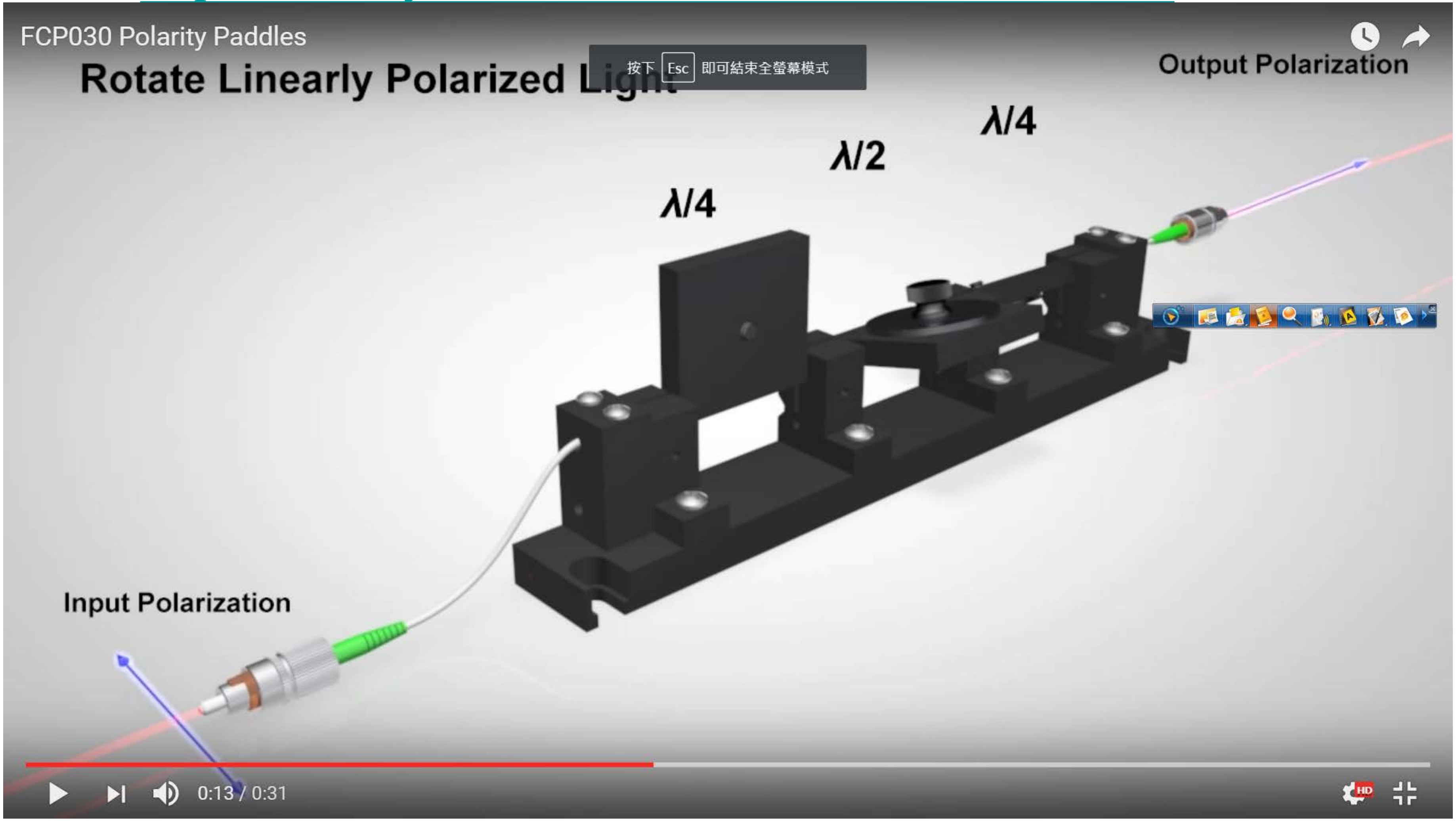
- It becomes an issue for **optical communication systems** when **short pulses** are transmitted over long lengths.
  - If an input pulse excites both polarization components, the **two components** travel along the fiber **at different speeds** because of their **different group velocities**.

# General Description

- These manual polarization controllers utilize stress-induced birefringence to alter the polarization in single mode fiber that is looped around two or three independent spools to create two or three independent fractional wave plates (fiber retarders).
- To transform an arbitrary input polarization state into an arbitrary output polarization state, a combination of
  - three paddles (a quarter-wave plate, a halfwave plate, and a quarter-wave plate) or
  - two paddles (quarter-wave plate and a quarter-wave plate) is used.


# Polarization Controller

- https://www.youtube.com/watch?v=I9kvcN1Ew1k

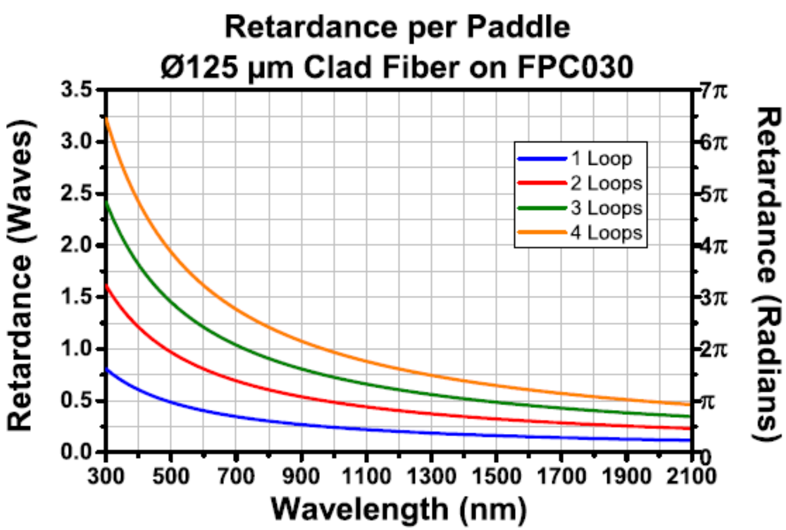


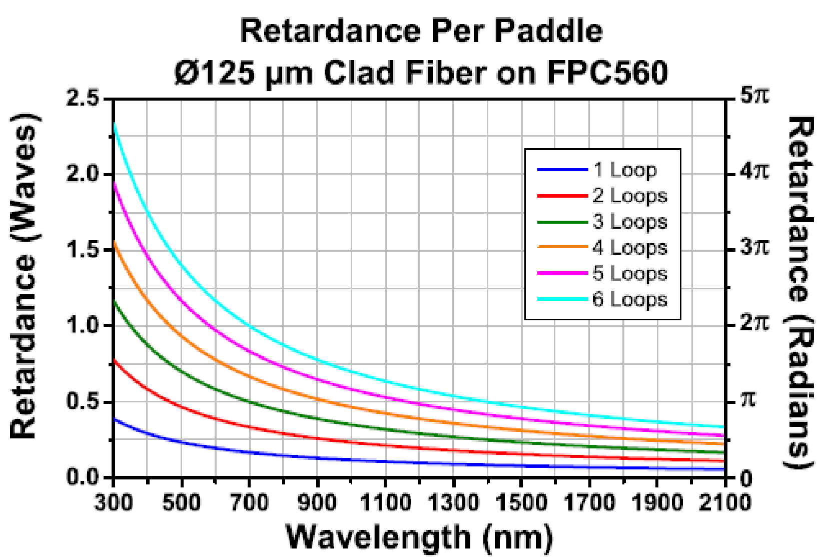
- The retardance of each paddle may be estimated from the following equation:

$$\boxed{\varphi(Radians) = \frac{2\pi^2 a N d^2}{\lambda D}}$$

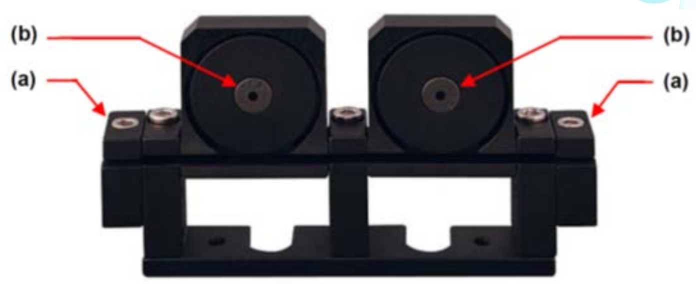
  - φ is the retardance,
  - *a* is a constant (0.133 for silica fiber),
  - *N* is the number of loops,
  - *d* is the fiber cladding diameter,
  - $\lambda$ is the wavelength, and
  - *D* is the loop diameter

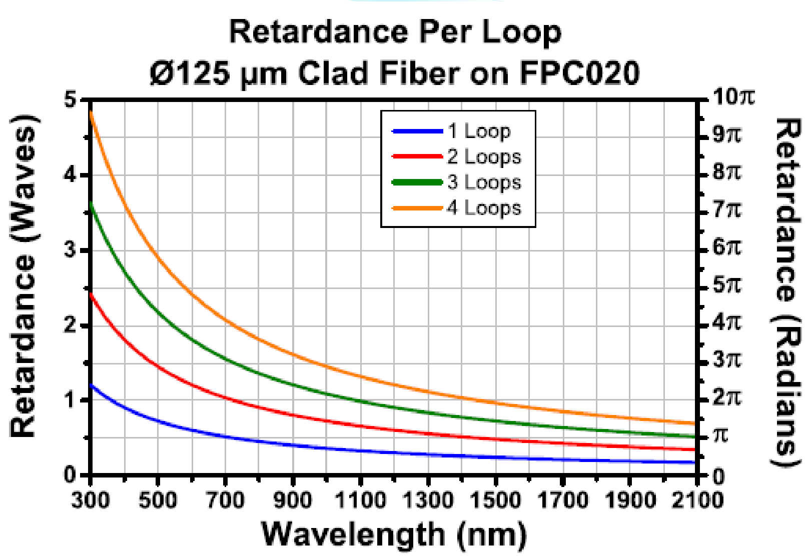
# 3-Paddle Fiber Polarization Controllers




# 2-Paddle Fiber Polarization Controllers



| Item # | FPC030 | FPC031 | FPC032 |
|---|---|---|---|
| Paddle Material | Black Delrin | | |
| Number of Paddles | 3 | | |
| Loop Diameter | 1.06" (27 mm) | | |
| Paddle Rotation | ±117.5° | | |
| Foot Print (L x W) | 8.5" x 1.0" (215.9 mm x 25.4 mm) | | |
| Fiber | None | CCC1310-J9 | |
| Operating Wavelength Range[a] | N/A | 1260 - 1625 nm | |
| Design Wavelength[b] | N/A | 1310 nm | |
| Mode Field Diameter | N/A | 8.6 ± 0.4 µm @ 1310 nm<br>9.7 ± 0.5 µm @ 1550 nm | |
| Cladding Diameter | N/A | 125 ± 0.7 µm | |
| Coating Diameter | N/A | 242 ± 5 µm | |
| Tubing Diameter | N/A | Ø900 µm Tight Buffer | |
| Numerical Aperture | N/A | 0.14 | |
| Loop Configuration[c] | N/A | 2-3-2 | |
| Connectors | N/A | FC/PC | FC/APC |
| Bend Loss | N/A | ≤0.1 dB | |

a. Retardance varies as a function of wavelength. Refer to Chapter 2 for more information.
b. Devices with preloaded fiber are optimized for this wavelength.
c. For polarization controllers with fiber preinstalled.

| Item # | FPC560 | FPC561 | FPC562 |
|---|---|---|---|
| Paddle Material | Black Delrin | | |
| Number of Paddles | 3 | | |
| Loop Diameter | 2.2" (56 mm) | | |
| Paddle Rotation | ±117.5° | | |
| Foot Print (L x W ) | 12.5" x 1.0" (317.5 mm x 25.4 mm) | | |
| Fiber | None | SMF-28-J9 | |
| Operating Wavelength Range[a] | N/A | 1260 - 1625 nm | |
| Design Wavelength[b] | N/A | 1310 nm | |
| Mode Field Diameter | N/A | 9.2 ± 0.4 µm @ 1310 nm<br>10.4 ± 0.5 µm @ 1550 nm | |
| Cladding Diameter | N/A | 125 ± 0.7 µm | |
| Coating Diameter | N/A | 242 ± 5 µm | |
| Tubing Diameter | N/A | Ø900 µm Tight Buffer | |
| Numerical Aperture | N/A | 0.14 | |
| Loop Configuration[c] | N/A | 3-6-3 | |
| Connectors | N/A | FC/PC | FC/PC |
| Bend Loss | N/A | ≤0.1 dB | |

a. Retardance varies as a function of wavelength. Refer to Chapter 2 for more information.
b. Devices with preloaded fiber are optimized for this wavelength.
c. For polarization controllers with fiber preinstalled.

**Loop diameter $\phi$=27 mm**

# Recommended Number of Loops

- The retardation of multi-order (including zero order) **quarter-wave plate** is given by the following equation:

$$\frac{(2m+1)\pi}{2}$$

where m is an integer.

- The retardation of multi-order (including zero order) **half-wave** plate is given by:

$$(2m+1)\pi$$

The retardation of each paddle should be close to any number.

| Order | m | Quarter-Wave Plate Retardation | Half-Wave Plate Retardation |
|---|---|---|---|
| Zero | 0 | $\frac{\pi}{2} \approx 1.57$ | $\pi \approx 3.14$ |
| 1st | 1 | $\frac{3\pi}{2} \approx 4.71$ | $3\pi \approx 9.42$ |
| 2nd | 2 | $\frac{5\pi}{2} \approx 7.85$ | $5\pi \approx 15.71$ |
| 3rd | 3 | $\frac{7\pi}{2} \approx 11.00$ | $7\pi \approx 21.99$ |
| 4th | 4 | $\frac{9\pi}{2} \approx 14.14$ | $9\pi \approx 28.27$ |
| 5th | 5 | $\frac{11\pi}{2} \approx 17.28$ | $11\pi \approx 35.56$ |

- The number of recommended loops and recommended fiber for several wavelengths is given in the following tables. These combinations come close to the desired **quarter-wave retardation**:

| Wavelength | # of Loops for ~1/4λ Retardation | | | Recommended Fiber |
|---|---|---|---|---|
| | Ø18 mm | Ø27 mm | Ø56 mm | |
| 480 nm | 3 loops | N/A | 3 loops | 460HP, S450, S460 |
| 630 nm | 3 loops | 2 loops | 4 loops | 630HP or S630 |
| 850 nm | 3 loops | 6 loops | 2 loops | 780HP, SM800-5.6 |
| 980 nm | 2 loops | 3 loops | 2 loops | 980HP, HI1060-J9, HI980-J9 |
| 1060 nm | 2 loops | 3 loops | 2 loops | 980HP, HI1060-J9, HI980-J9 |
| 1310 nm | 3 loops | 2 loops | 3 loops | SMF28e+ and CCC1310-J9 |

**FPC030**

- These combinations come close to the desired half-wave retardation:

| Wavelength | # of Loops for ~1/2λ Retardation | | | Recommended Fiber |
|---|---|---|---|---|
| | Ø18 mm | Ø27 mm | Ø56 mm | |
| 480 nm | 2 loops | 3 loops | 2 loops | 460HP, S450, S460 |
| 630 nm | 1 loop | 4 loops | 3 loops | 630HP or S630 |
| 850 nm | 1 loop | 2 loops | 4 loops | 780HP, SM800-5.6 |
| 980 nm | 4 loops | 2 loops | 4 loops | 980HP, HI1060-J9, HI980-J9 |
| 1060 nm | 3 loops | 2 loops | 5 loops | 980HP, HI1060-J9, HI980-J9 |
| 1310 nm | 2 loops | 3 loops | 6 loops | SMF28e+ and CCC1310-J9 |

**FPC560**

# Electronic Polarization Controller

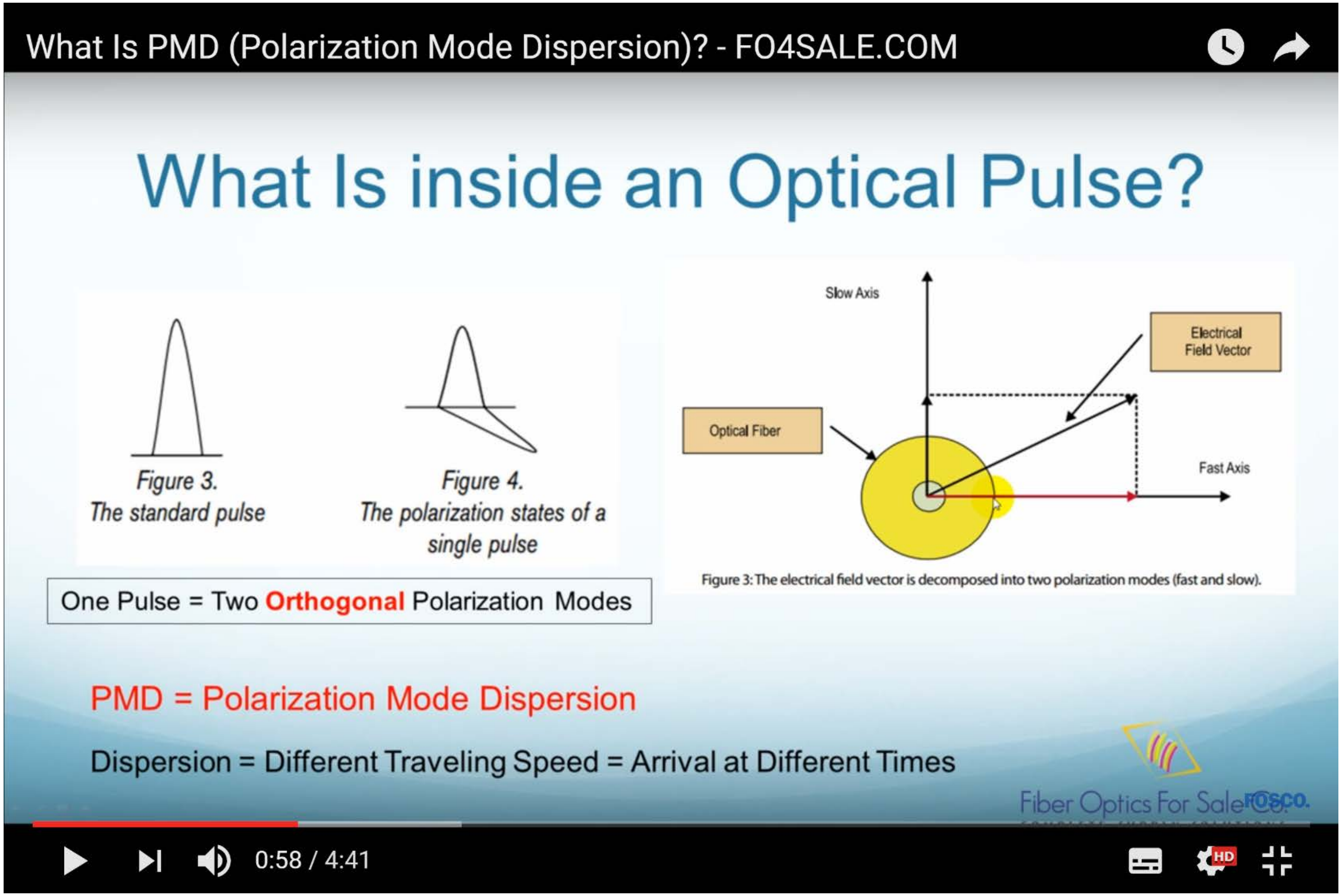
- https://www.youtube.com/watch?v=hcrZvtm-k2Y

- The pulse becomes **broader** at the output end because **group velocities change randomly** in response to random changes in **fiber birefringence** (analogous to a **random-walk problem**).

- This phenomenon, referred to as **polarization-mode dispersion** (PMD 偏振模色散), has been studied extensively because of its importance for **long-haul lightwave systems**.

# Polarization Mode Dispersion

➢ https://www.youtube.com/watch?v=J4-wCa_VNfA




**From YouTube**

- The **extent of pulse broadening** can be estimated from the **time delay** $\Delta T$ occurring between the **two polarization components** during propagation of an optical pulse.
- $\Delta T$ is given by:

$$\Delta T = \left| \frac{L}{v_{gx}} - \frac{L}{v_{gy}} \right| = L\left|\beta_{1x} - \beta_{1y}\right| = L(\Delta\beta_1) \tag{1.2.16}$$

$\Delta\beta_1$: related to group-velocity mismatch
$L$ : fiber of length
$B_m$: constant birefringence.

- Equation (1.2.16) cannot be used directly to estimate PMD for **standard telecommunication fibers** because of **random changes** in birefringence occurring along the fiber.
- These changes tend to equalize the **propagation times** for the **two polarization components**.

- PMD is characterized by the **root-mean-square** (RMS 均方根) value of $\Delta T$ obtained after averaging over **random perturbations**.
- The variance of $\Delta T$ is found to be.

$$\boxed{\sigma_T^2 = \left\langle (\Delta T)^2 \right\rangle = 2(\Delta\beta_1 l_c)^2[\exp(-L/l_c) + L/l_c - 1]}$$

  - $\Delta\beta_1 \equiv \Delta\tau/L$,
  - $\Delta\tau$ : the **differential group delay** along the **principal states** of polarization,
  - $l_c$ (correlation length): the **length** over **which two polarization components remain correlated**;

- For $L$ > 0.1 km, we can use $l_c$ (typical order of 10 m) <<L to find that

$$\boxed{\sigma_T \approx \Delta\beta_1\sqrt{2l_c L} \equiv D_p\sqrt{L}}$$

$D_p$ : PMD parameter

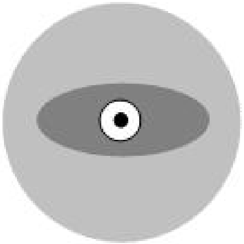
# Polarization-maintaining or polarization preserving fibers:

– It is desirable that fibers **transmit light** without changing its **state of polarization** for some applications

– A large amount of **birefringence** is introduced intentionally in these fibers through design modifications so that **relatively small birefringence fluctuations** are masked by it and **do not affect** the **state of polarization** significantly.

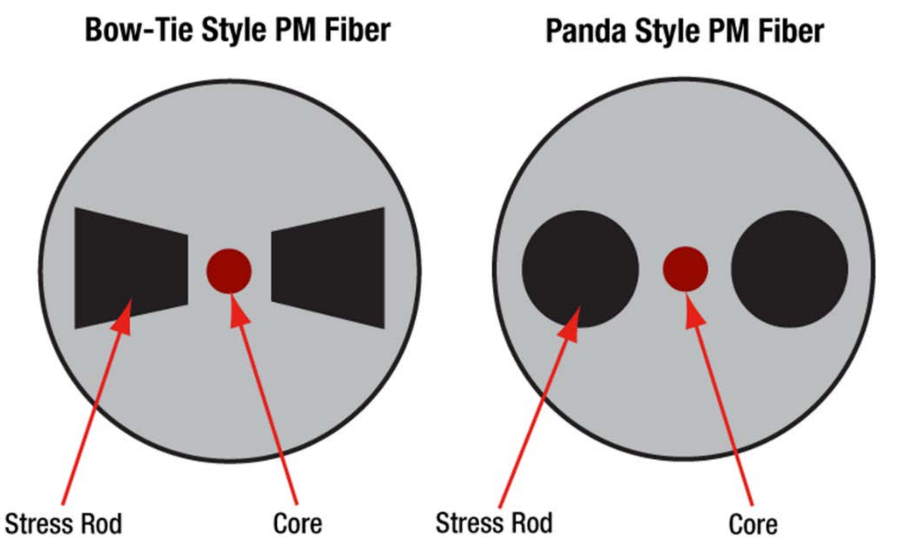
– One scheme **breaks** the **cylindrical symmetry** by making the fiber **core elliptical** in shape.

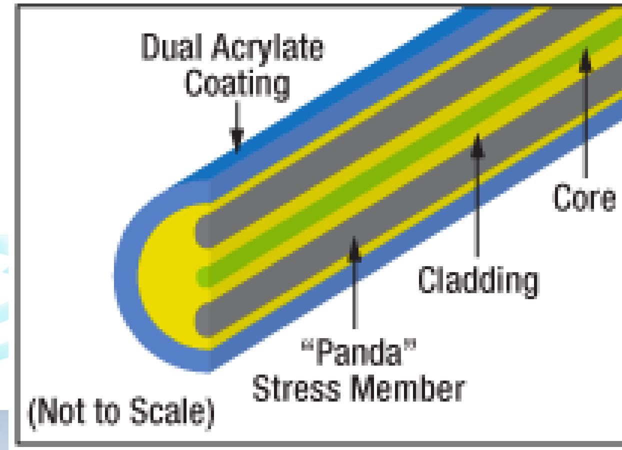
(The **degree of birefringence** is typically $\sim 10^{-6}$.)



– An **alternative scheme** makes use of **stress-induced birefringence** (permits $B_m \sim 10^{-4}$.)

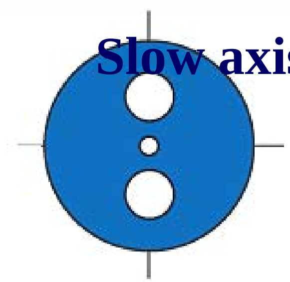
# Schematic setup of PM fiber




Bow-Tie" Style PM Fiber

Slow axis

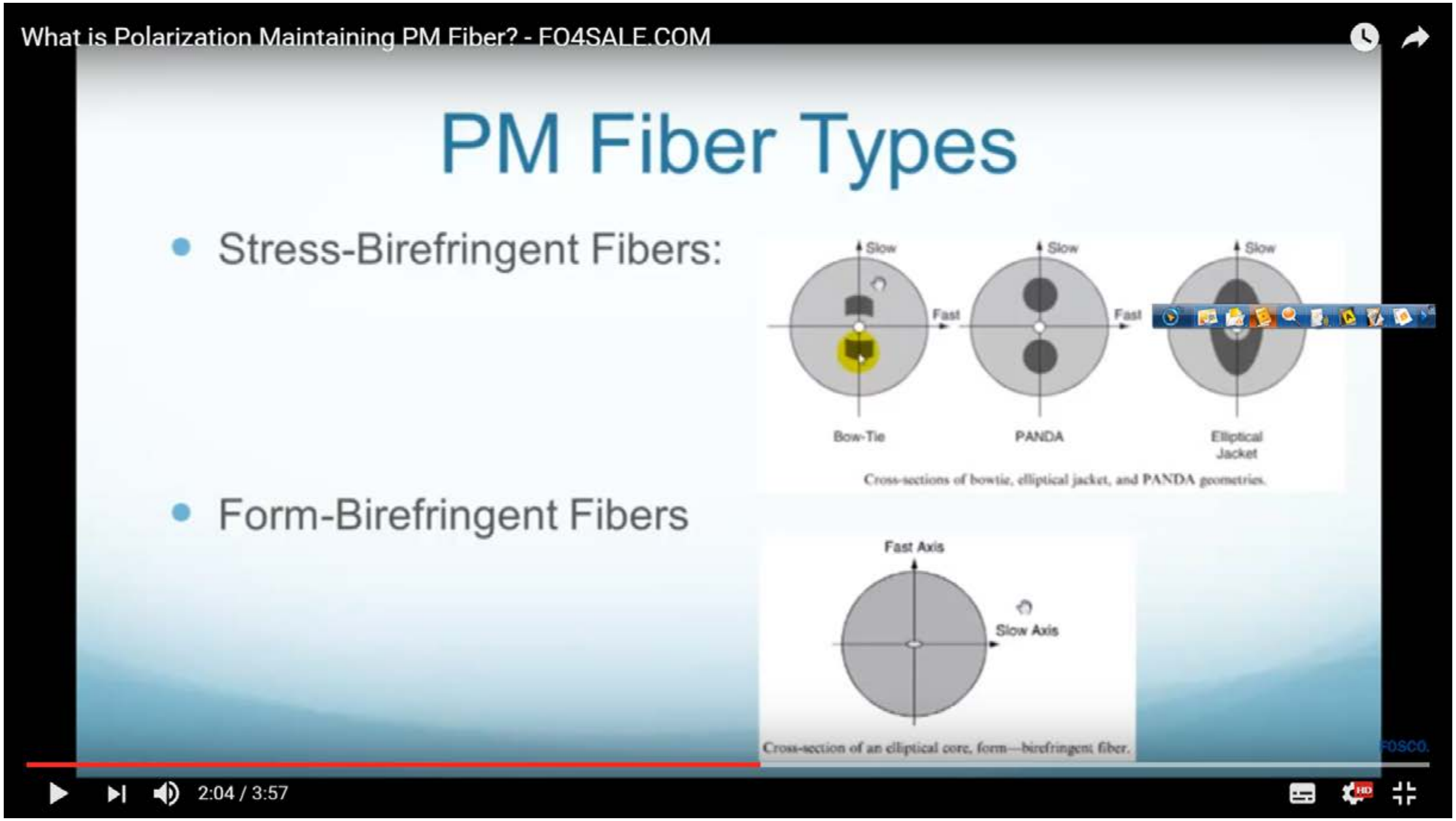


fast axis

https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=1596&pn=PS-PM980#7707 Thorlabs website Link

# PM fiber

- https://www.youtube.com/watch?v=7rrb-_Iin-g



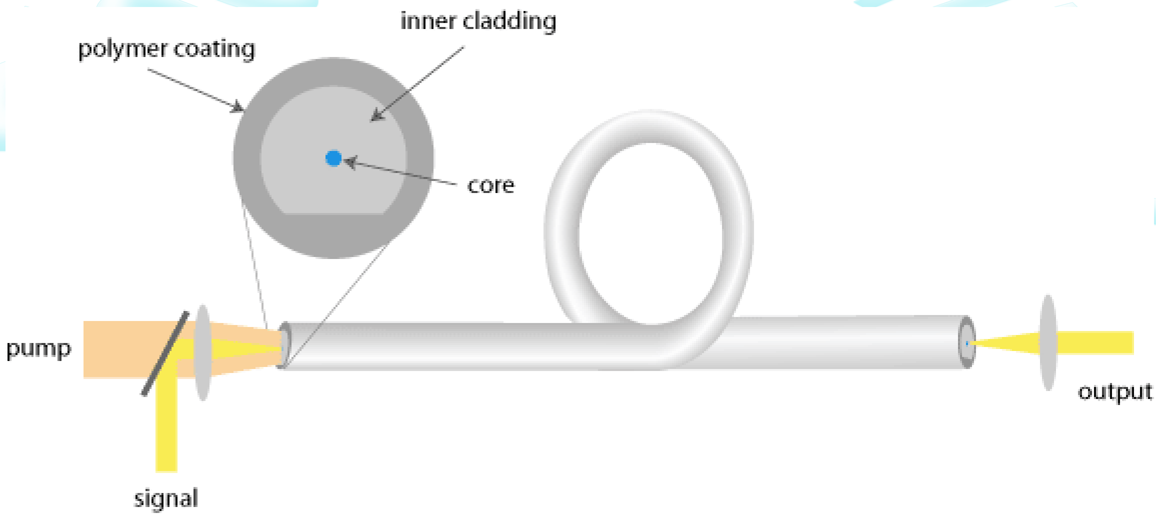
# PM980 XP

## Specifications

| Geometrical & Mechanical | |
|---|---|
| Core Diameter | 5.5 µm |
| Cladding Diameter | 125 ± 2 µm |
| Coating Diameter | 245 ± 15 µm |
| Core-Clad Offset | <0.5 µm |
| Coating Concentricity | ≤5 µm |
| Coating Material | UV Cured, Dual Acrylate |
| Operating Temperature | -40 to 85 °C |
| Proof Test Level | 200 kpsi (1.4 GN/m²) |

| Optical | |
|---|---|
| Numerical Aperture | 0.12 |
| Attenuation | ≤2.5 dB/km @ 980 nm |
| Operating Wavelength | 970 - 1550 nm |
| Second Mode Cut-off | 920 ± 50 nm |
| Mode Field Diameter ($1/e^2$ fit - near field) | 6.6± 0.7 µm @ 980 nm |
| Beat Length | ≤2.7 mm @ 980 nm |
| Normalized Cross Talk | ≤-40 dB @ 4 m<br>≤-30 dB @ 100 m (nominal) |

- The use of **polarization-maintaining fibers (保偏光纖)** requires **identification of the slow** and **fast axes** before an optical signal can be launched into the fiber.
  - **Structural changes** are often made to the **fiber** for this purpose.
  - **D fiber**: cladding is flattened in such a way that the **flat surface** is parallel to the **slow axis** of the fiber.




**Cladding-pumped fiber amplifier** based on a **double-clad fiber**. The signal light is launched into the doped core, while the pump light is launched into the inner cladding. The core is **D-shaped** for more efficient pump absorption.

- When the **polarization direction** of the **linearly polarized light** coincides with the **slow** or the **fast axis**, the **state of polarization** remains unchanged during propagation.

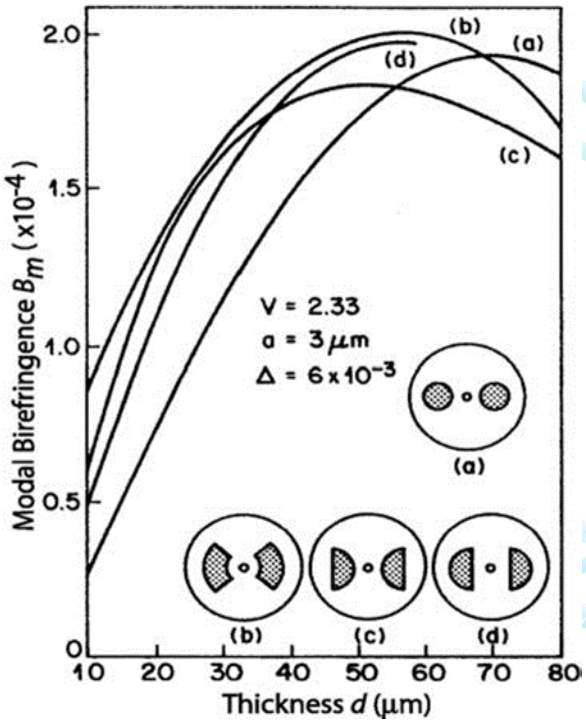
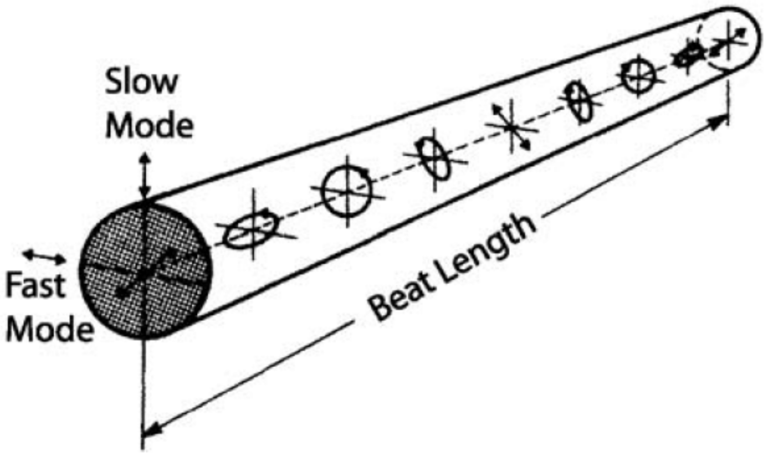



Figure 1.8: Variation of birefringence parameter $B_m$ with thickness $d$ of the stress-inducing element for four different polarization-maintaining fibers.

Different shapes of the stress-applying elements (shaded region) are shown in the inset.

- If the **polarization direction** makes an angle with these axes, polarization changes continuously along the fiber in a **periodic manner** with a period equal to the **beat length** [see Eq. (1.2.15)].

- The **state of polarization changes** over **one-half** of the **beat length** from **linear** to **elliptic**, **elliptic** to **circular**, **circular** to **elliptic**, and then back to linear but is rotated by 90° from the incident linear polarization.



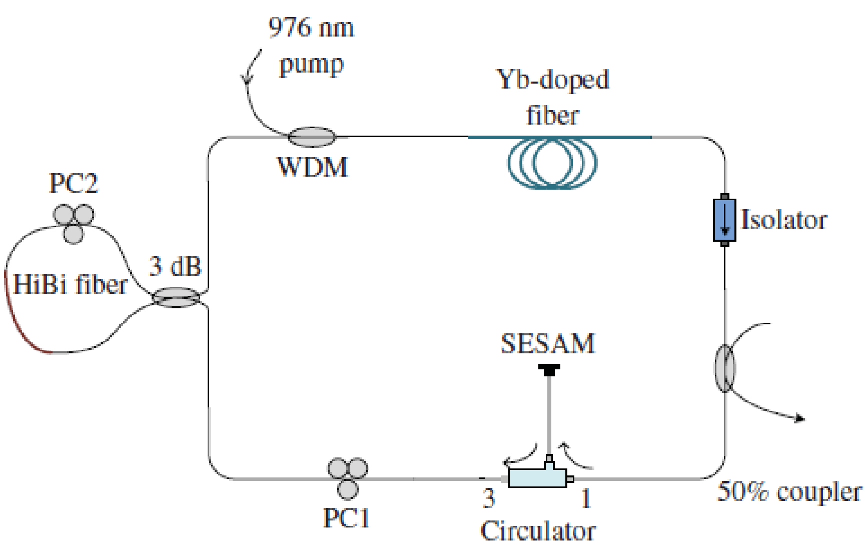

Evolution of state of polarization along a polarization-maintaining fiber when input signal is linearly polarized at 45 ◦ *from the slow axis.*

# Wavelength-Tunable High-Energy All-Normal-Dispersion Yb-Doped Mode-Locked All-Fiber Laser with a HiBi Fiber Sagnac Loop Filter

- The resulting **transmission spectrum** of the HiBi fiber Sagnac loop is approximately a periodic function of the wavelength given as

  $T = (1/2)[1 - \cos(2\pi BL/\lambda)]$

- L, B, and λ are the length of the HiBi fiber the HiBi fiber birefringence, and the wavelength in vacuum



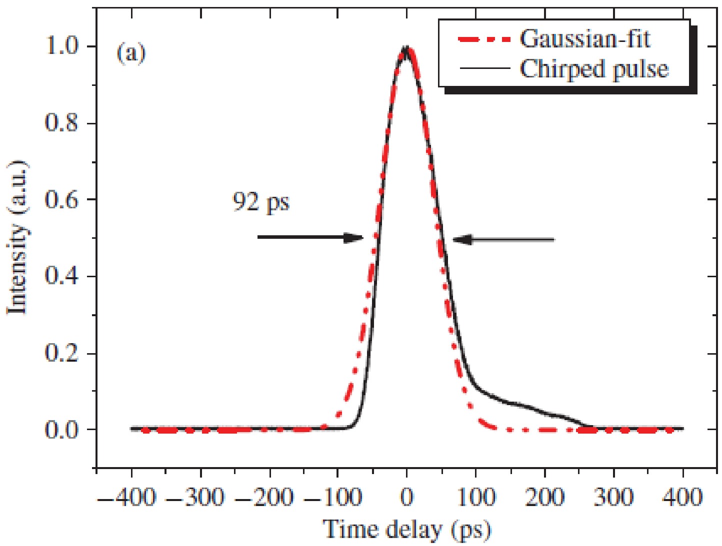

- The birefringence can be expressed as

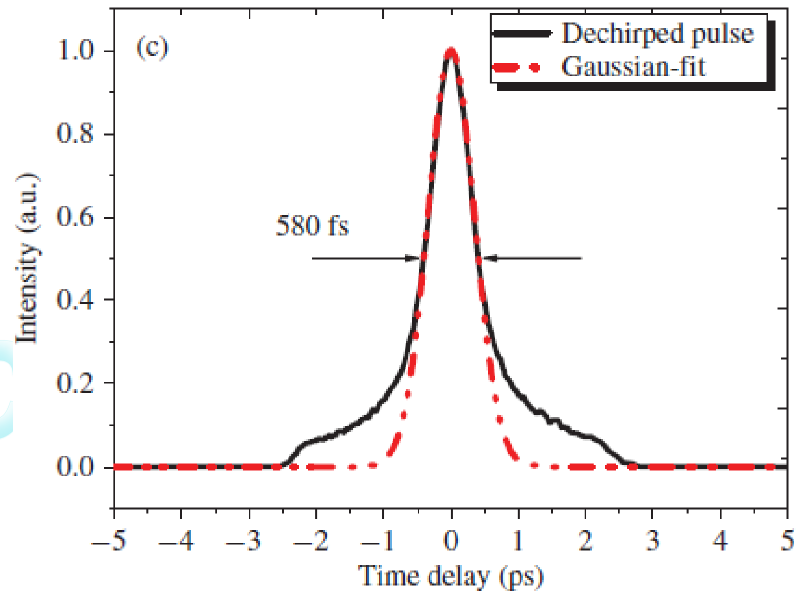
  $B = \lambda_0/L_B$,

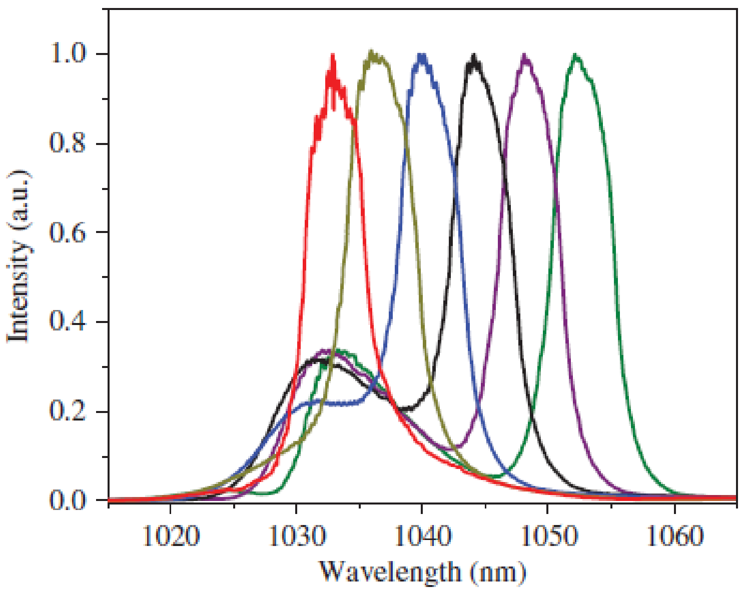
  $L_B$ : beat length measured at wavelength $\lambda_0$.

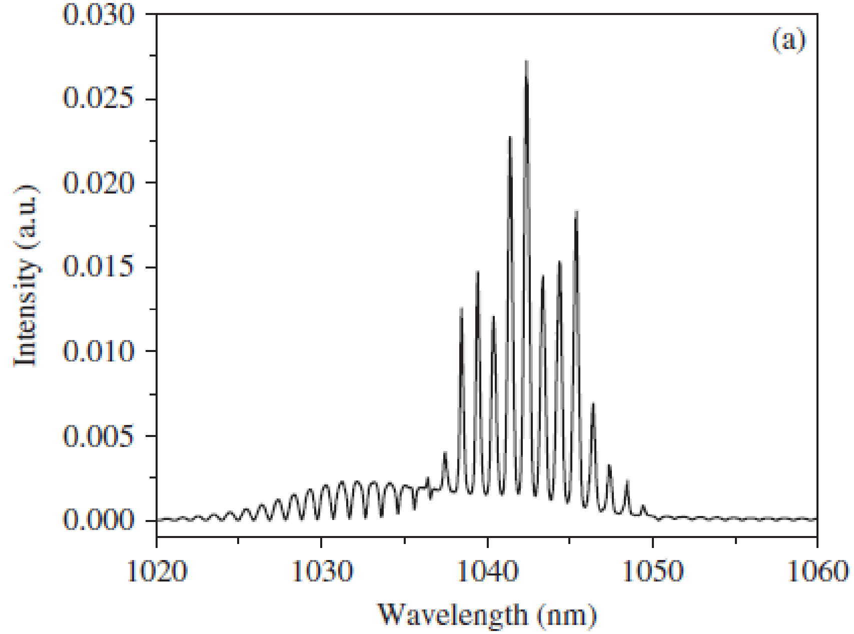
- The peak spacing is given as

  $\Delta\lambda = \lambda^2/(BL)$


(a)
Gaussian-fit
Chirped pulse
92 ps
Intensity (a.u.)
Time delay (ps)


(c)
Dechirped pulse
Gaussian-fit
580 fs
Intensity (a.u.)
Time delay (ps)


Intensity (a.u.)
Wavelength (nm)


(a)
Intensity (a.u.)
Wavelength (nm)

# Lyot Filter in sensor [1]

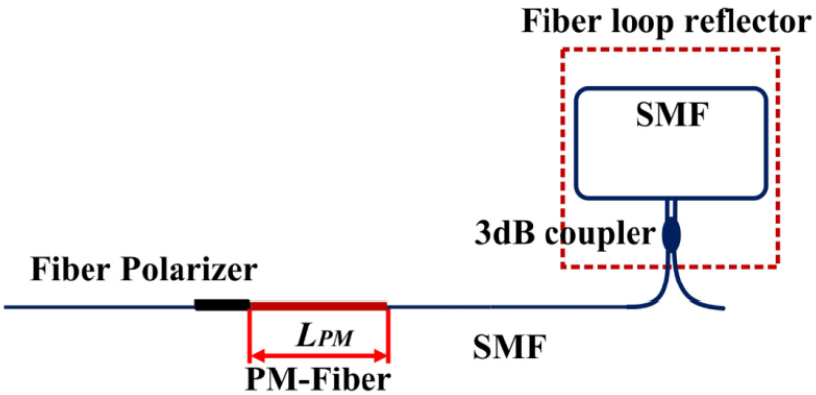
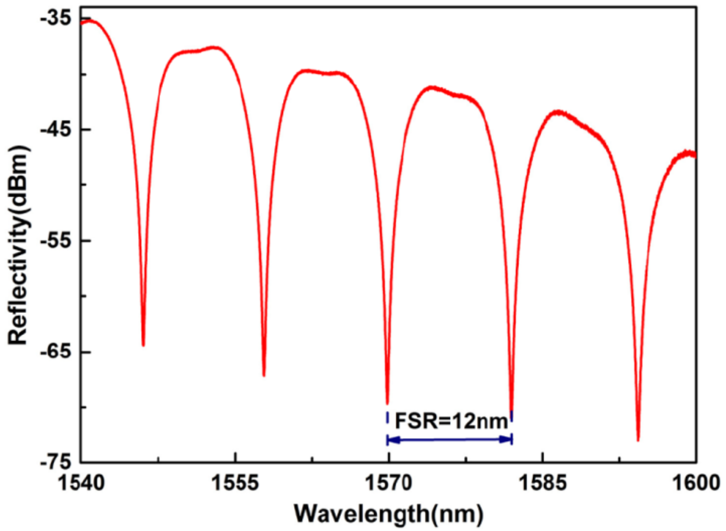



Fig. 1. Schematic configuration of the reflective all-fiber Lyot filter.




PM fiber (Corning Panda PM15-U2A)

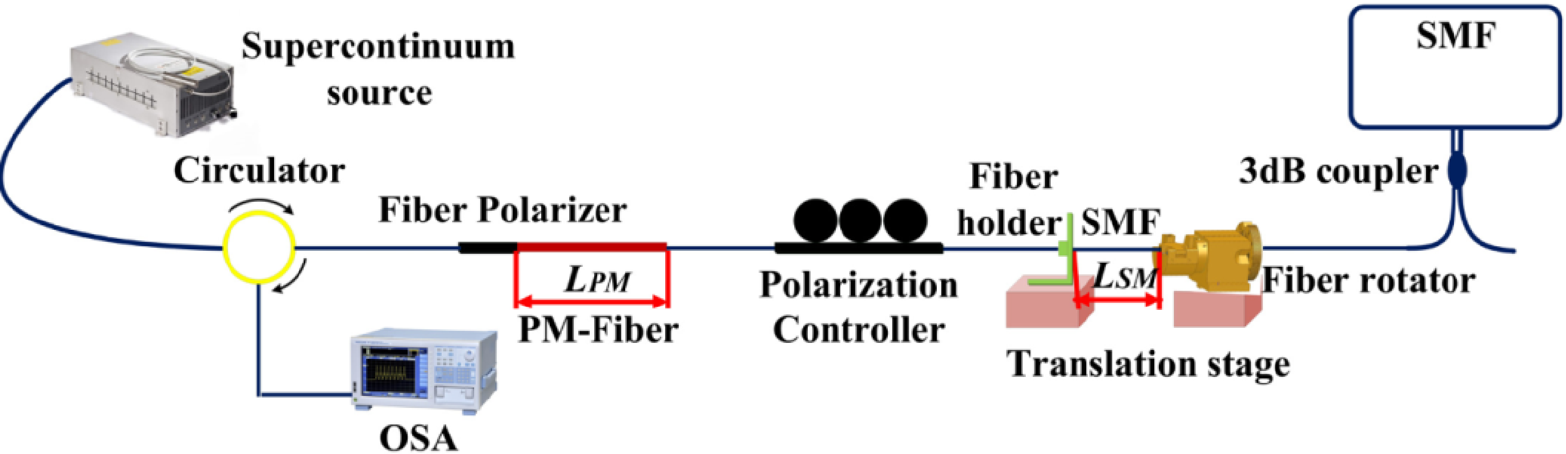
Length = 50 *cm*

B(birefringence)=$n_e$-$n_o$= $1.95 \times 10^{-4}$

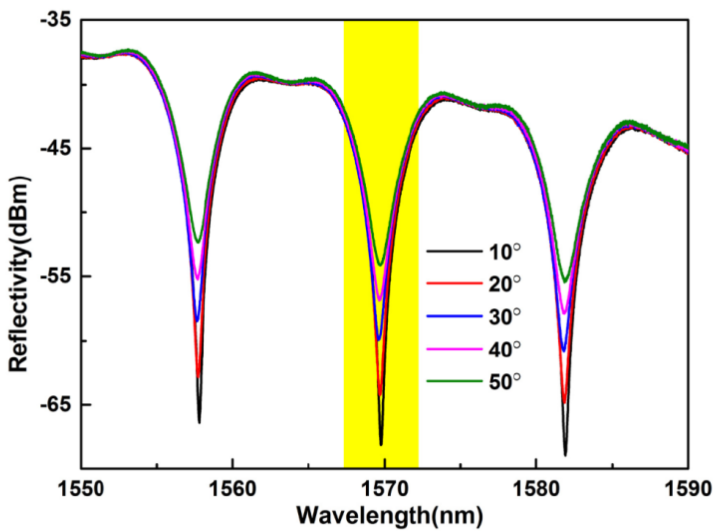
FSR (free spectral range) =$\Delta\lambda = \lambda^2/(BL) \sim 12$ nm

[1] Huang et al, "Intensity modulated torsion sensor based on optical fiber reflective Lyot filter Opt. Express, 25, 5081 (2017)

# Intensity modulated torsion sensor




Schematic diagram of the experiment setup for the reflective all-fiber Lyot filter-based torsion sensing system.




Reflection spectra of the Lyot filter under torsion of 10°, 20°, 30°, 40°, 50°.

**High Precision Bare Fiber Rotator**

# 1.3 Fiber Nonlinearities

- The response of any **dielectric** to **light** becomes nonlinear for **intense electromagnetic fields**, and optical fibers are no exception.

- The origin of **nonlinear response** is related to **aharmonic motion** of **bound electrons** under the influence of an applied field.

- The **total polarization *P*** induced by **electric dipoles** is **not linear** in the electric field ***E***, but satisfies the more general relation.

$$P = \varepsilon_0 (\chi^{(1)} \cdot E + \chi^{(2)} \vdots EE + \chi^{(3)} \vdots EEE + \cdots)$$

$\varepsilon_0$ :the vacuum permittivity

$\chi^{(j)}$: $j_{th}$ order susceptibility (a tensor of rank j+1)