Measurement tools for Polarized Light

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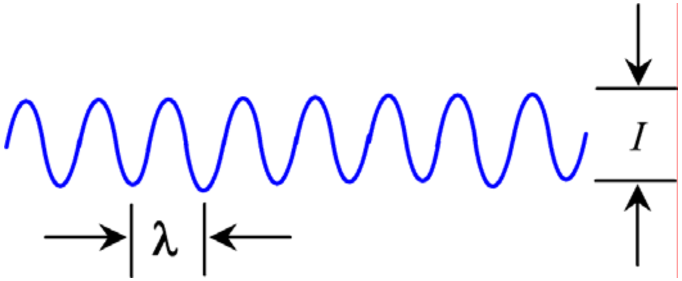
Basic description of light

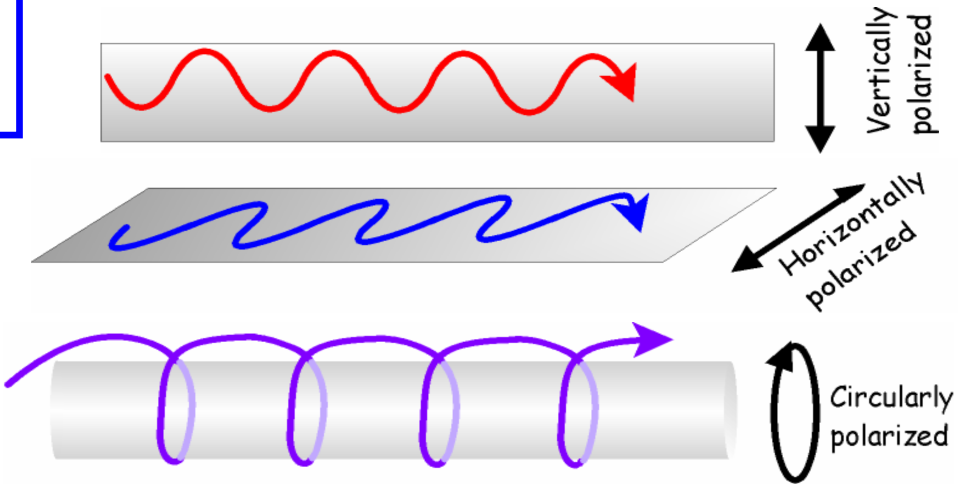
Three basic parameters describe light:



Wavelength: λ (color)

Intensity: I (brightness)

Polarization state: ***S*** (*subtle*)



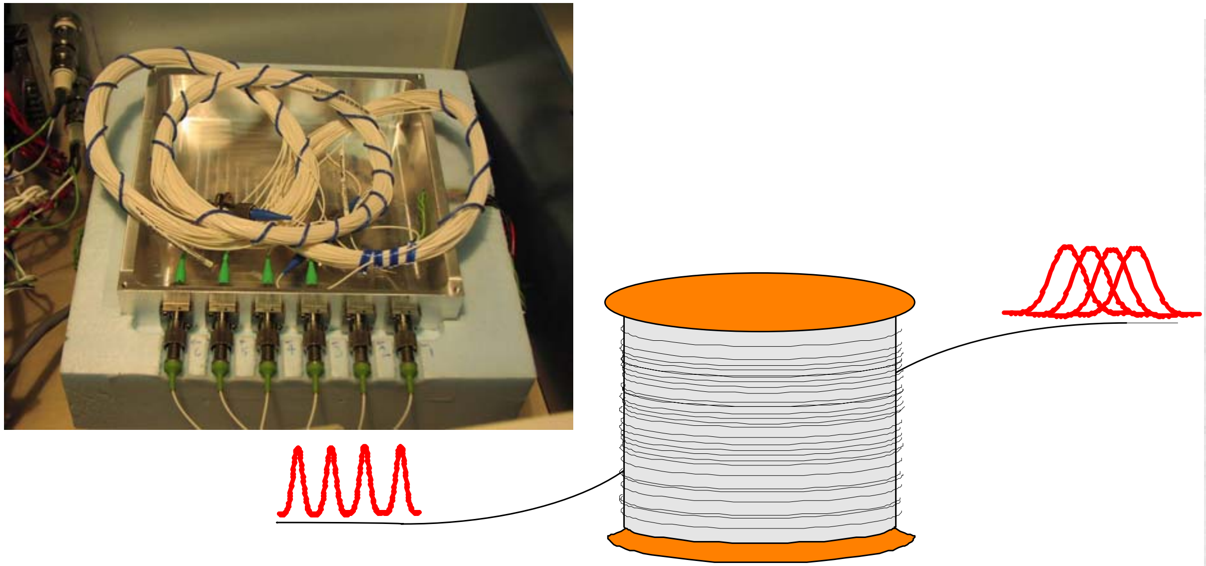
Polarized light in everyday life

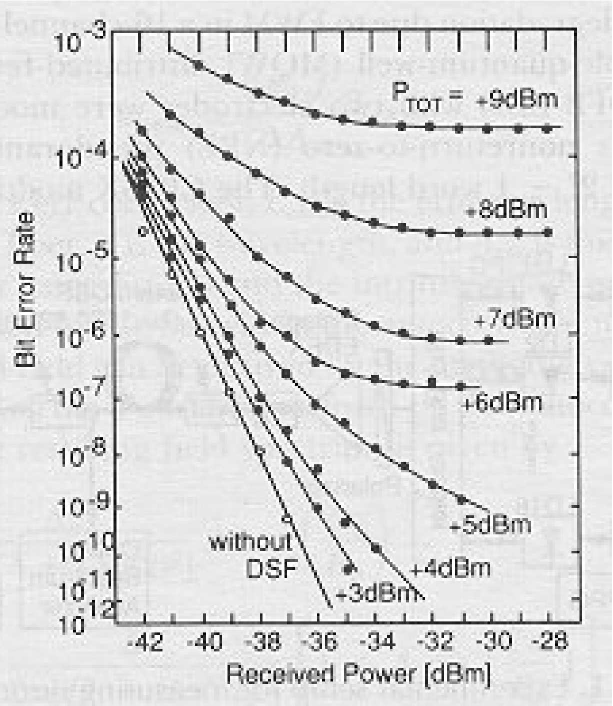
Bee navigation: Sunlight is polarized as it scatters from the atmosphere

Glare reduction: Light reflects from surfaces with a preferred polarization state

Flat panel display technology: Liquid crystal displays use to control pixel intensity

Polarized light in the lab





<u>Sources:</u> Lasers and LEDs emit polarized light

<u>Detectors:</u> Can be affected by polarization

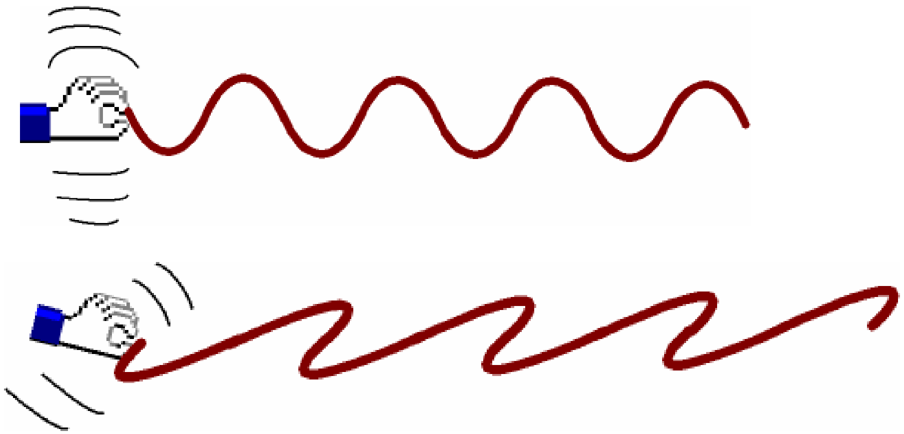
<u>Components:</u> Light propagation depends on polarization state

<u>Telecom Example:</u> System performance
bit error rate, power penalty strongly affected by polarization

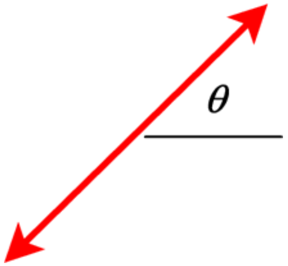
Outline

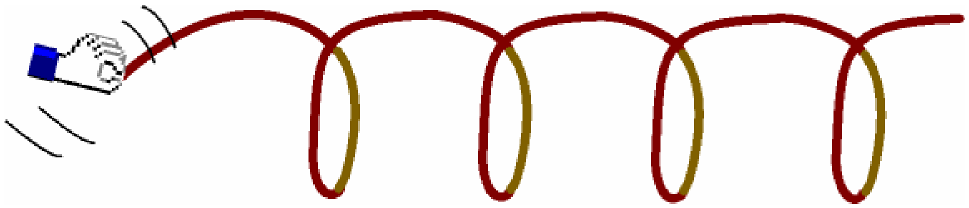
I. Describing polarized light (qualitative).
II. Describing polarized light (quantitative).
III. Generating and modifying polarized light.
IV. Polarization in optical fiber.

Describing polarized light (qualitative)

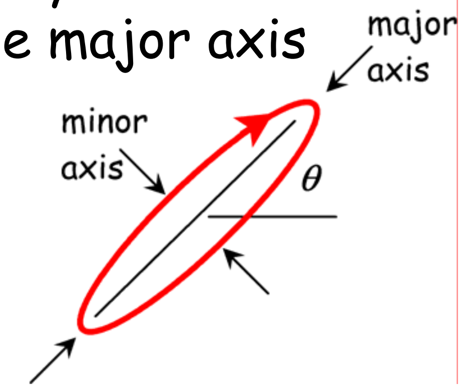


Linear: Orientation of the plane of vibration





Elliptical: Ellipticity and orientation of the major axis

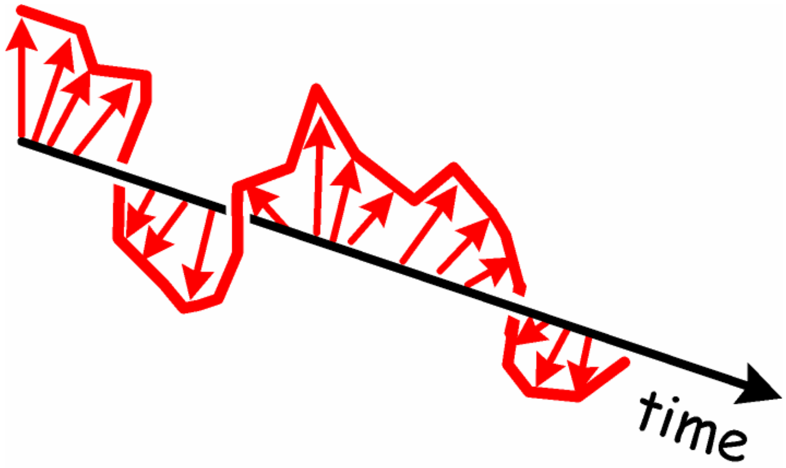


Abbreviations:

H (horizontal)	**+45** (+45 ° w/horizontal)	**RHC** (right-hand circular)
V (vertical)	**-45** (-45 ° w/horizontal)	**LHC** (left-hand circular)

"Unpolarized light"

Strictly speaking: There is no such thing as "unpolarized light"



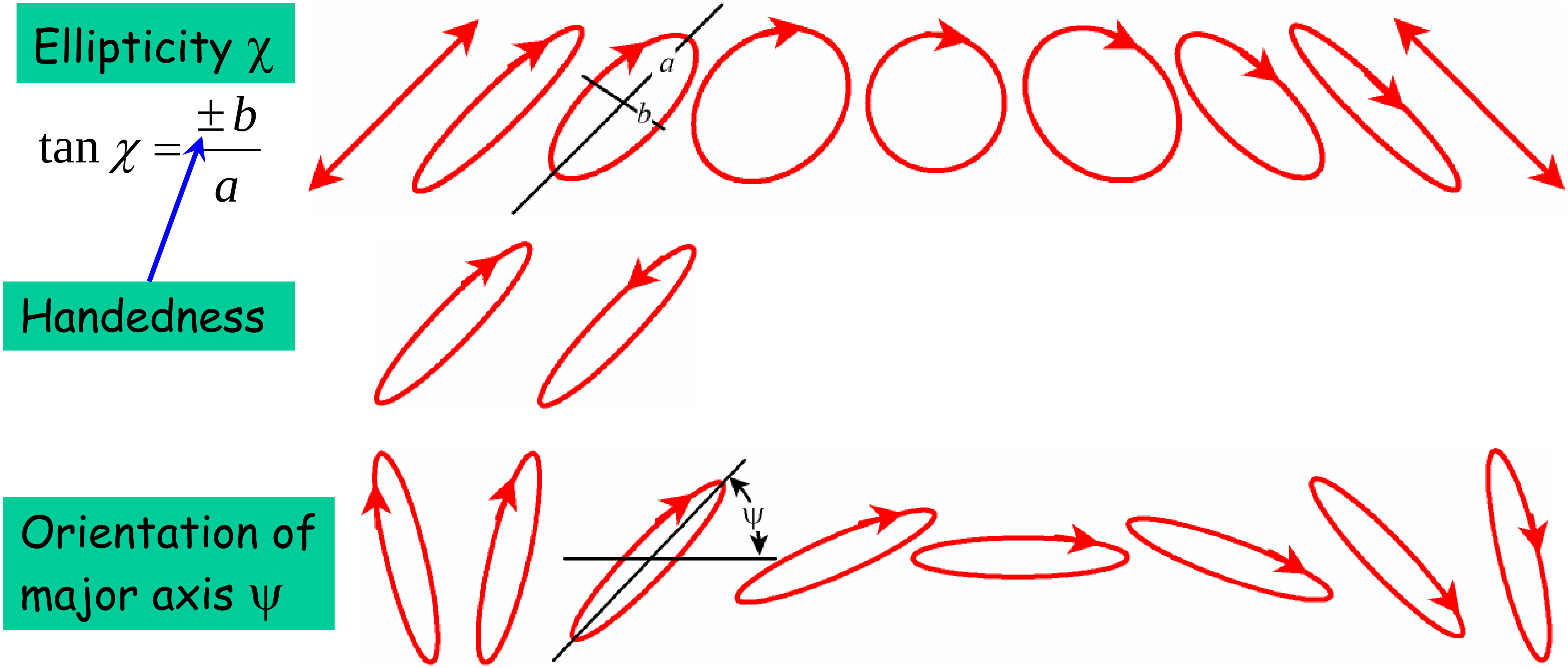
- At any instant all light is perfectly polarized
- "Unpolarized" or "depolarized" light means the polarization state changes too fast to measure.
- "It's just a matter of time" – Randy Travis

To generate "unpolarized" light:

- Make the polarization state change quickly with time
- Increase the time constant of your detector

Describing polarized light (quantitative)

It only takes 2 numbers to describe the state of polarization of light.



Ellipticity χ

$$\tan\chi = \frac{\pm b}{a}$$

Handedness

Orientation of major axis ψ

State of polarization is commonly described in one of two ways:

Jones vectors/matrices and Stokes vectors/Meuller matrices

Describing polarized light: Stokes vectors

$$\hat{\mathbf{S}} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix}$$

S_0 = Total intensity of light[*]

S_1 = Amount of light that is Horiz. or Vert. (linear)

S_2 = Amount of light that is ±45° (linear)

S_3 = Amount of light that is RHC or LHC

Stokes vectors describe the state of polarization using INTENSITY

- Easier to measure (based on observables)
- Includes “unpolarized” light
- Includes the total intensity of the light

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[*] Stokes vector often reported “normalized” (S_0=1).

Describing polarized light: Stokes vectors

$$\hat{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix}$$

Normalized intensity

Horiz. or Vert. (linear)

±45° (linear)

RHC or LHC

Horizontal

$$\hat{S}_H = \begin{pmatrix} 1 \\ +1 \\ 0 \\ 0 \end{pmatrix}$$

Vertical

$$\hat{S}_V = \begin{pmatrix} 1 \\ -1 \\ 0 \\ 0 \end{pmatrix}$$

+45 deg.

$$\hat{S}_{+45} = \begin{pmatrix} 1 \\ 0 \\ +1 \\ 0 \end{pmatrix}$$

-45 deg.

$$\hat{S}_{-45} = \begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix}$$

RHC

$$\hat{S}_{RHC} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ +1 \end{pmatrix}$$

-45 deg.

$$\hat{S}_{LHC} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ -1 \end{pmatrix}$$

General

$$\hat{S} = \begin{pmatrix} 1 \\ \cos 2\chi \cos 2\psi \\ \cos 2\chi \sin 2\psi \\ \sin 2\chi \end{pmatrix}$$

QUIZ: What kind of polarization states do we have here?

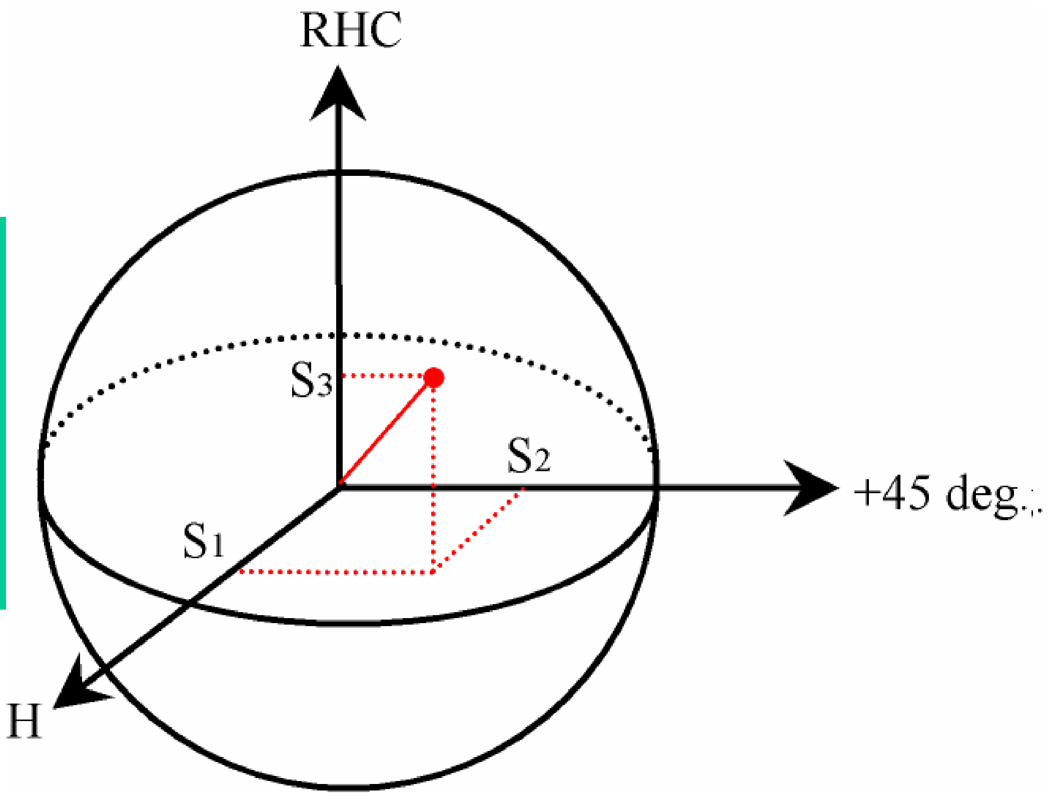
$$\hat{S}_? = \begin{pmatrix} 1 \\ 0.5 \\ 0.866 \\ 0 \end{pmatrix} \qquad \hat{S}_? = \begin{pmatrix} 1 \\ 0.482 \\ 0.835 \\ 0.286 \end{pmatrix} \qquad \hat{S}_? = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Stokes vectors: graphical approach

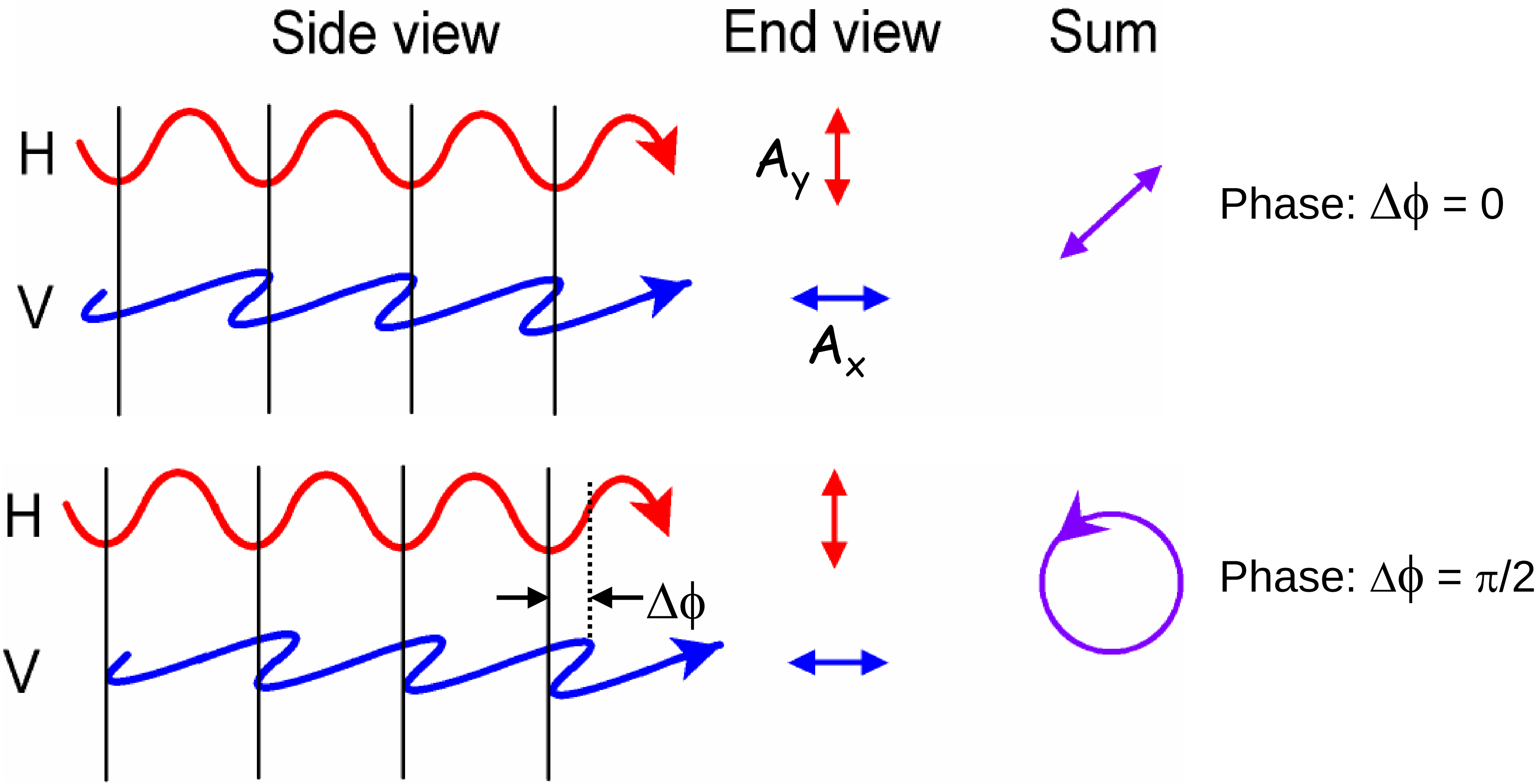
$$\hat{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} \begin{array}{l} \text{Normalized intensity} \\ \text{Horiz. or Vert. (linear)} \\ \pm 45^\circ \text{ (linear)} \\ \text{RHC or LHC} \end{array}$$

The Poincaré sphere:

- Plots Stokes vectors
- Linear states on the equator
- Elliptical states off the equator
- The poles are RHC and LHC



Where does “elliptical” polarization come from?



Relative amplitudes A_x and A_y determine axis orientation (ψ)

Phase (retardance) between H and V determines ellipticity (χ)

Important definition

Describing polarized light: Jones vectors

$$\hat{\mathbf{J}} = \begin{pmatrix} A_x e^{i\phi_x} \\ A_y e^{i\phi_y} \end{pmatrix}$$

A_x = Amplitude of horizontal component of electric field
ϕ_x = Phase of horizontal component of electric field

A_y = Amplitude of vertical component of electric field
ϕ_y = Phase of vertical component of electric field

Jones vectors describe state of polarization using ELECTRIC FIELD:

- Less intuitive to measure
- Simpler math but complex (real and imaginary parts)
- Includes absolute phase of light (only use Jones for interferometry)
- Ignores unpolarized light

Describing polarized light: Jones vectors

Horizontal

$$\hat{\mathbf{J}}_H = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

Vertical

$$\hat{\mathbf{J}}_V = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

+45 deg.

$$\hat{\mathbf{J}}_{+45} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

-45 deg.

$$\hat{\mathbf{J}}_{-45} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -1 \end{pmatrix}$$

RHC

$$\hat{\mathbf{J}}_{RHC} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ e^{i\pi/2} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ i \end{pmatrix}$$

LHC

$$\hat{\mathbf{J}}_{LHC} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ e^{-i\pi/2} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -i \end{pmatrix}$$

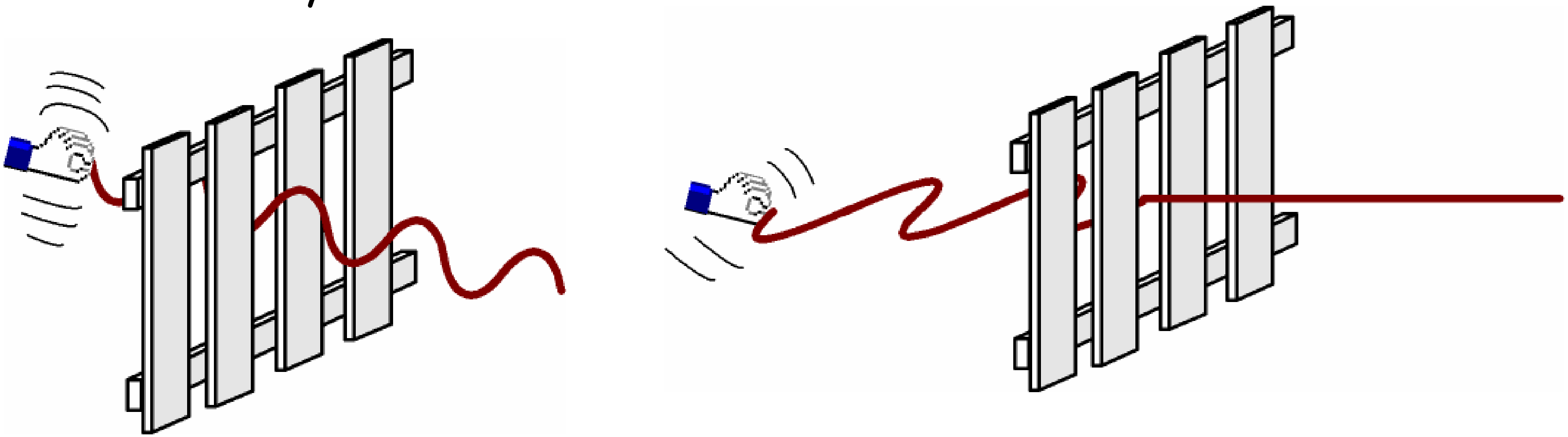
QUIZ:

Which state is linear and which vertical?

$$\hat{\mathbf{J}}_? = \begin{pmatrix} 0.8 \\ 0.2 + 0.57i \end{pmatrix} \qquad \hat{\mathbf{J}}_? = \begin{pmatrix} 0.3 \\ -0.95 \end{pmatrix}$$

How do you make polarized light?

Trick question: It's already polarized, you **USE A POLARIZER** to select the state you want.



QUIZ: In an optical polarizer, what do the slats of the fence represent?

- Absorption of polarized light
- Different paths for polarized light

Choosing a polarizer

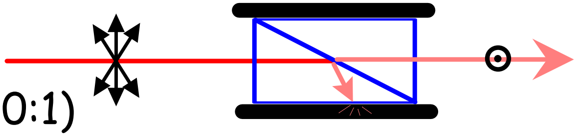
Important parameters:

- Operating wavelength (polarizer range and optical coating)
- Extinction ratio (min/max intensity transmission in dB)

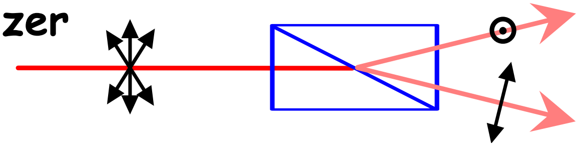
Optical polarizers:

- Crystals (calcite) range: 350-2300 nm

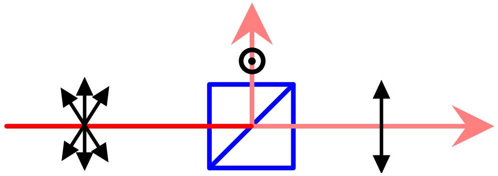
Glan-Thompson
Extinction ratios 50-70 dB (10,000,000:1)



Wollaston beam separating polarizer
50 dB extinction (both arms)



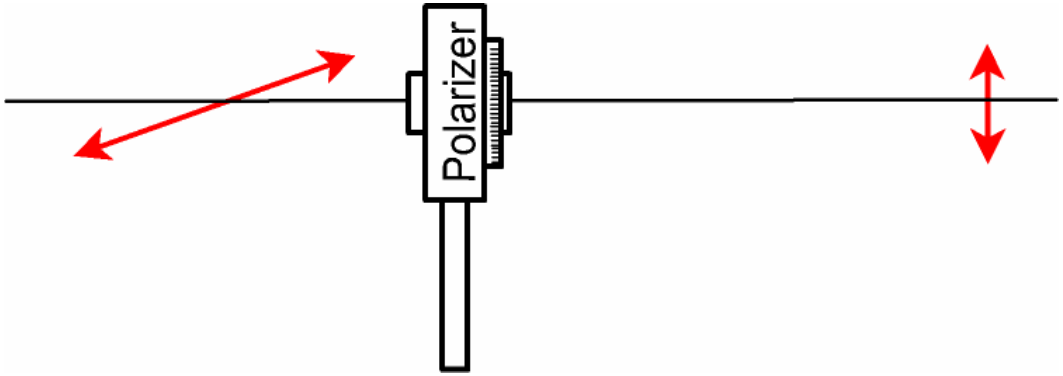
- Polarizing beam splitter (cube)
  27-30 dB on transmission (1000:1)
  ~ 15 dB reflection
  ~ 85 nm range



- Fiber optic inline polarizers
- Brewster mirrors

Modifying the polarization state: Polarizer

Some components require light of a certain polarization state. If you have the wrong state, how do you change it?

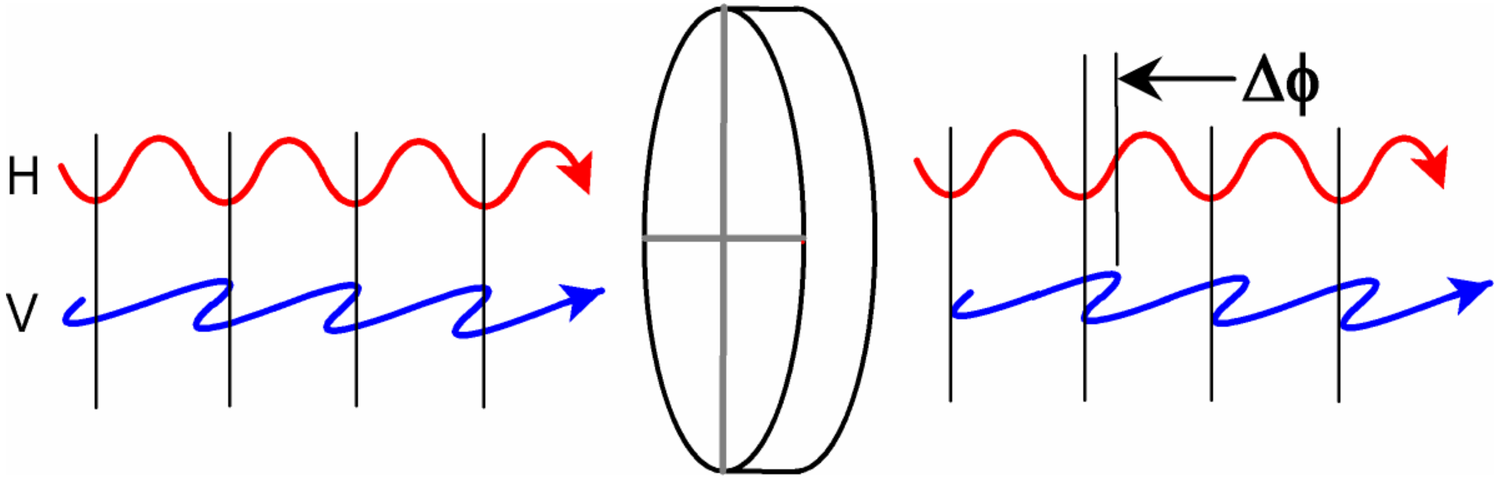


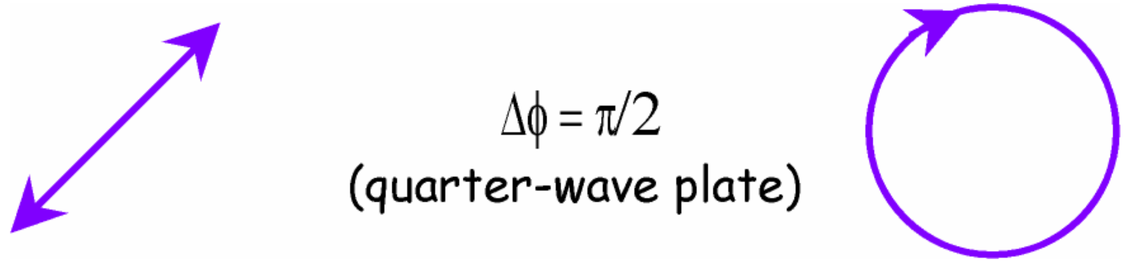
A polarizer extracts the desired state, but…

- The output power can be low
- Only linear states can be produced

Modifying polarization state: Retarder

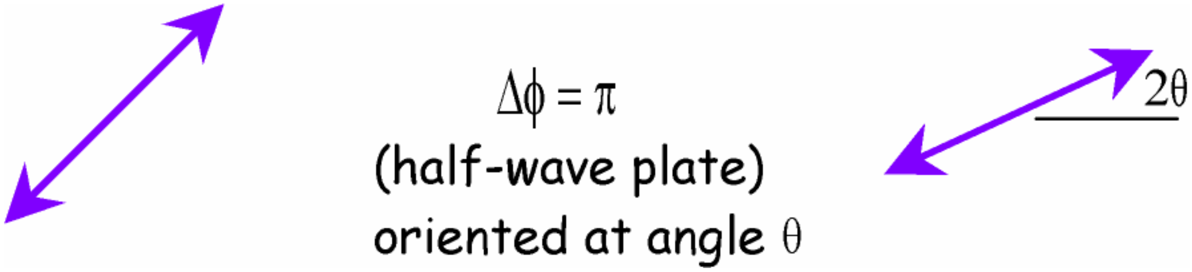
Retarders (waveplates): Materials that delay the light polarized along one axis more than that polarized along the orthogonal axis.





$\Delta\phi = \pi/2$

(quarter-wave plate)



$\Delta\phi = \pi$

(half-wave plate)

oriented at angle θ

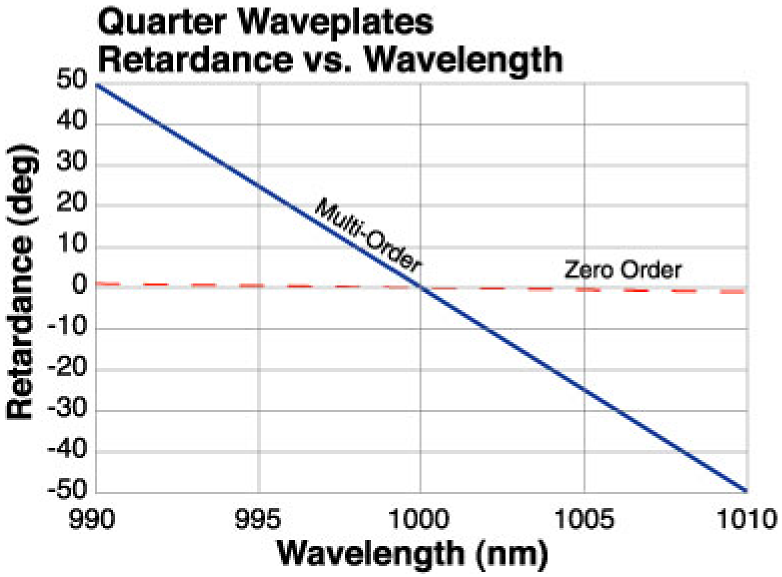
Choosing a retarder

Retardance: $\Delta\phi$ (tells you how the polarization state will be modified)
Birefringence: $\Delta n = (\Delta\phi/L)(\lambda/2\pi)$ is a material property (retardance per length).

Zero order: (retardance = $\Delta\phi$)
Best wavelength, entrance angle and temperature dependence

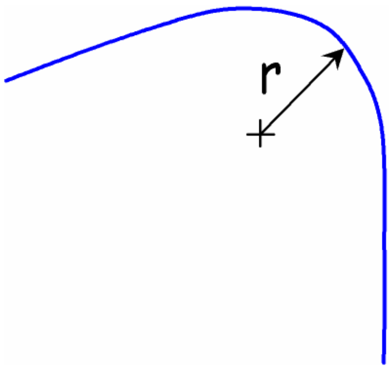
Multiple order: (retardance = $2\pi m + \Delta\phi$, m is a big number)
Inexpensive

Compound zero-order: (retardance = $(2\pi m + \Delta\phi) - 2\pi m = \Delta\phi$)
Poor entrance angle dependence



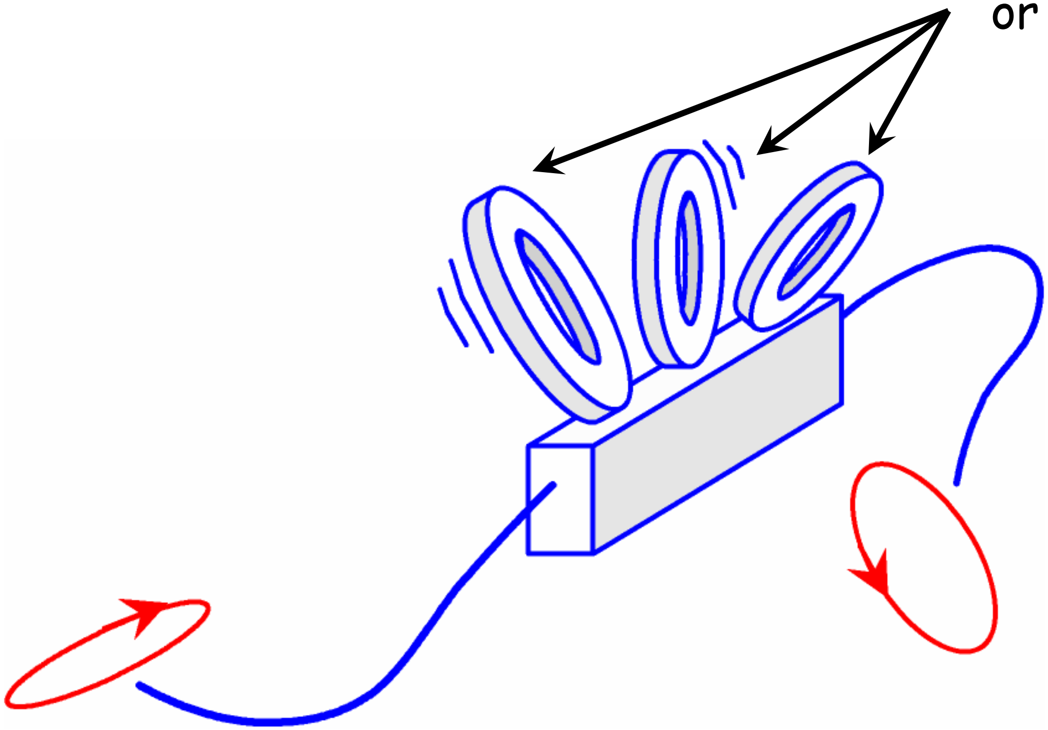
"Stability of Birefringent Linear Retarders (Waveplates)
P.D. Hale and G.W. Day, App. Opt., Vol. 27, 5146-5151, (1988)

Fiber polarization controller: “paddles”



Bending optical fiber induces a birefringence:

$$\Delta n \sim 1/r^2$$

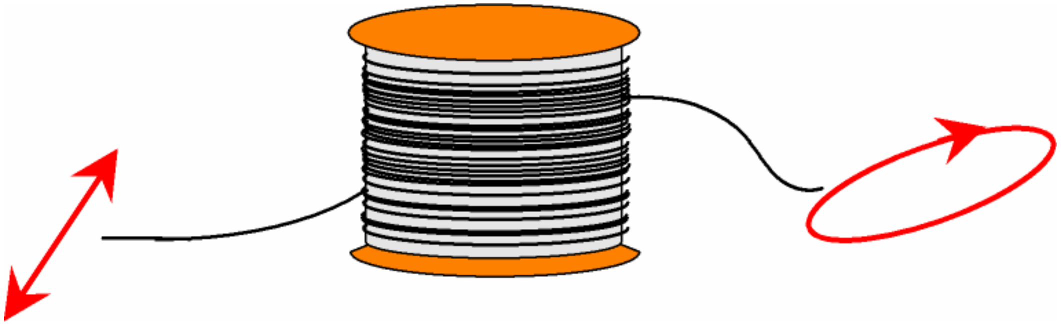


loops of fiber act like quarter- or half-wave retarder

- Accepts any input state
- Generates any output state
- Requires low-bend-loss fiber
- Output state not predictable

Polarization state and optical fibers

Think of optical fiber as one loooonnnngggg waveplate:



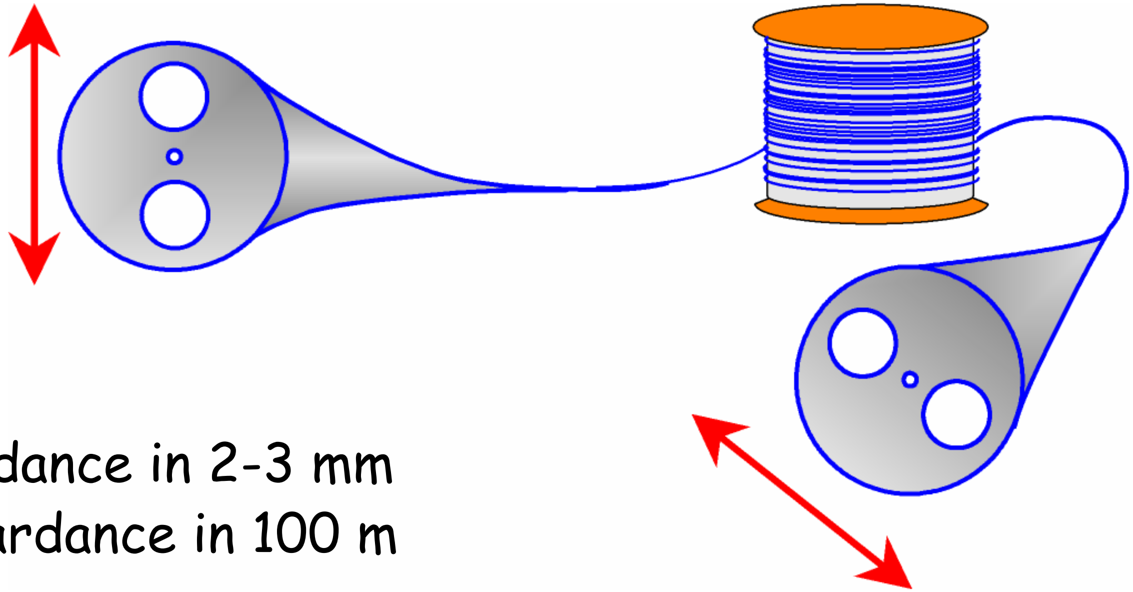
Output polarization state:
- Independent of input state
- Changes when fiber moves
- Changes with room temperature

If you require a **stable** output state:
- Tape the fiber down
- Re-adjust every several days

If you require a **particular** output state:
- Polarizer following the fiber (power fluctuations)
- Use polarization-maintaining fiber.

Polarization-maintaining fiber

Polarization-maintaining fiber (PMF) = High birefringence fiber (Hi-Bi)



Large birefringence:

PMF: $\pi/2$ retardance in 2-3 mm

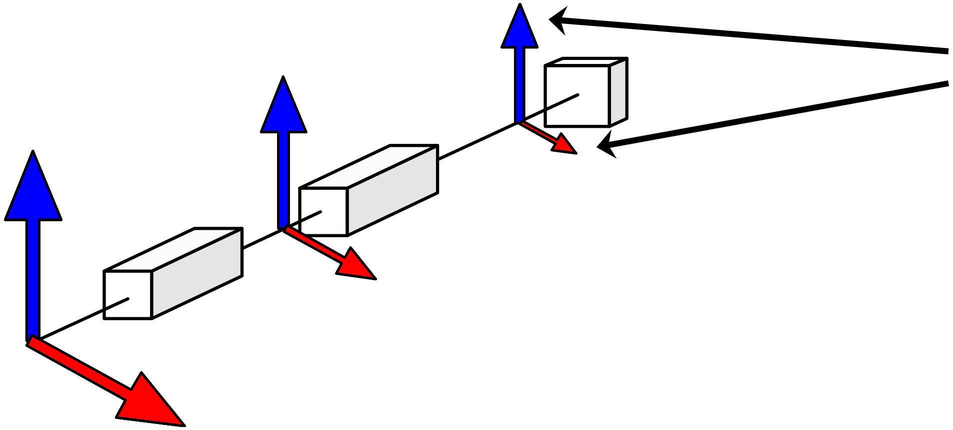
SMF *: $\pi/2$ retardance in 100 m

Maintains a <u>LINEAR</u> polarization state <u>only when aligned with the axes of the PMF</u>

- Input alignment accuracy determines the quality of the output state
- Be aware of alignment when splicing

*Single-mode fiber

Polarization-dependent loss (PDL)



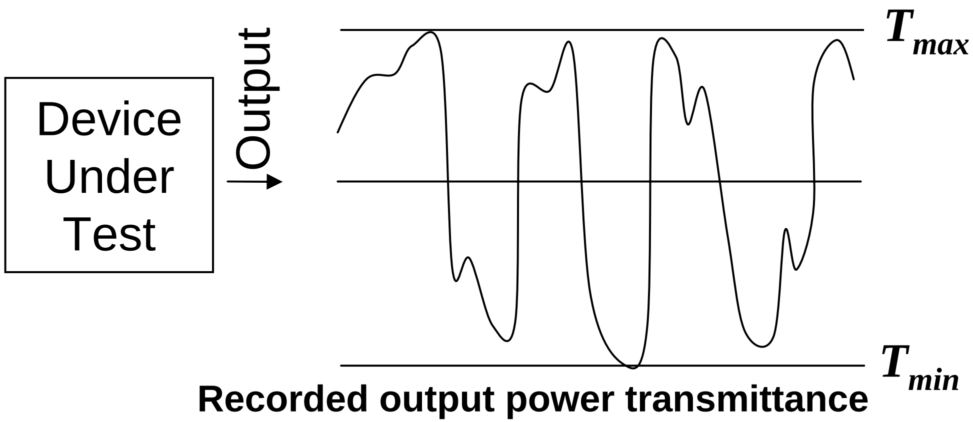
Attenuation depends on polarization state of the light

$$PDL = 10\log\frac{T_{\max}}{T_{\min}}$$

Two general measurement techniques

“All-states” technique

(Simple, slow)



Launch random (unknown) polarization states → Device Under Test

Recorded output power transmittance

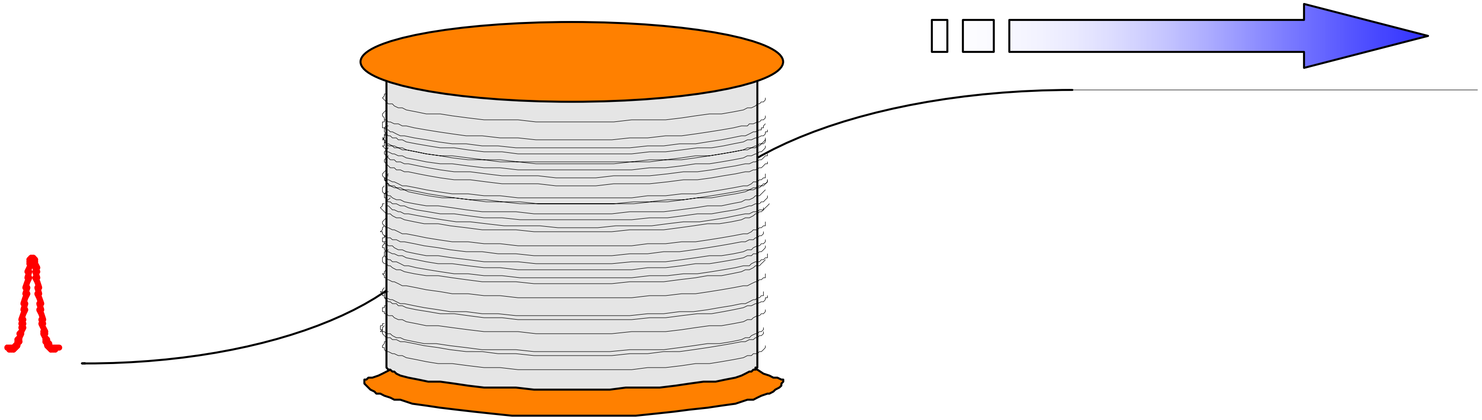
“Fixed-states”

(Fast, more complex)

- Launch 4 to 6 known polarization states
- T_{max} and T_{min} calculated from measured transmittances for each launch state

Fiber Bandwidth

How fast does light go down this fiber ?



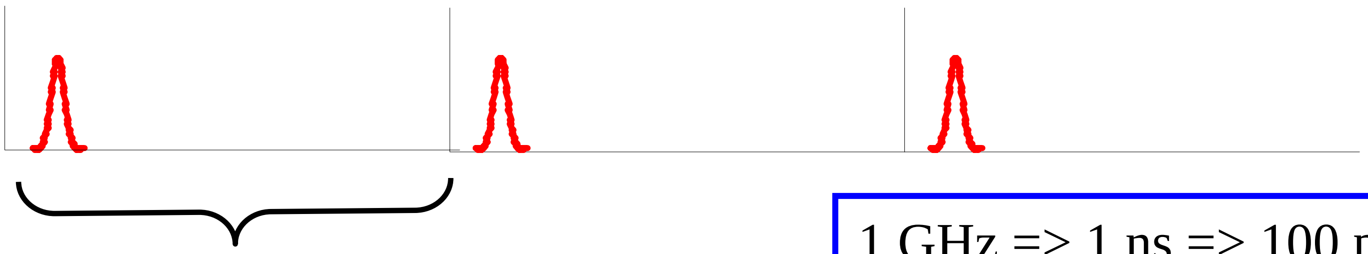
How fast can you send information down this fiber?

How close can you space the information bits?

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Dispersion

Rule of thumb: Pulse width < 0.1 T

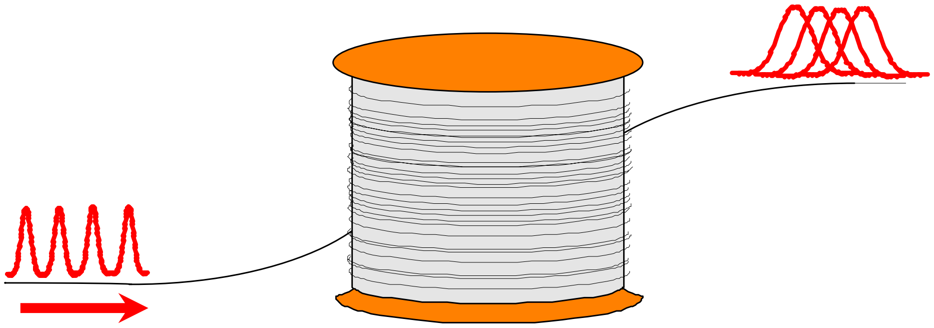


Bit period = T = 1 / frequency

1 GHz => 1 ns => 100 ps pulse width

40 GHz => 25 ps => 2.5 ps pulse width

If the entire pulse doesn’t propagate at the same velocity...
…pulses can disperse and bits become indistinguishable.



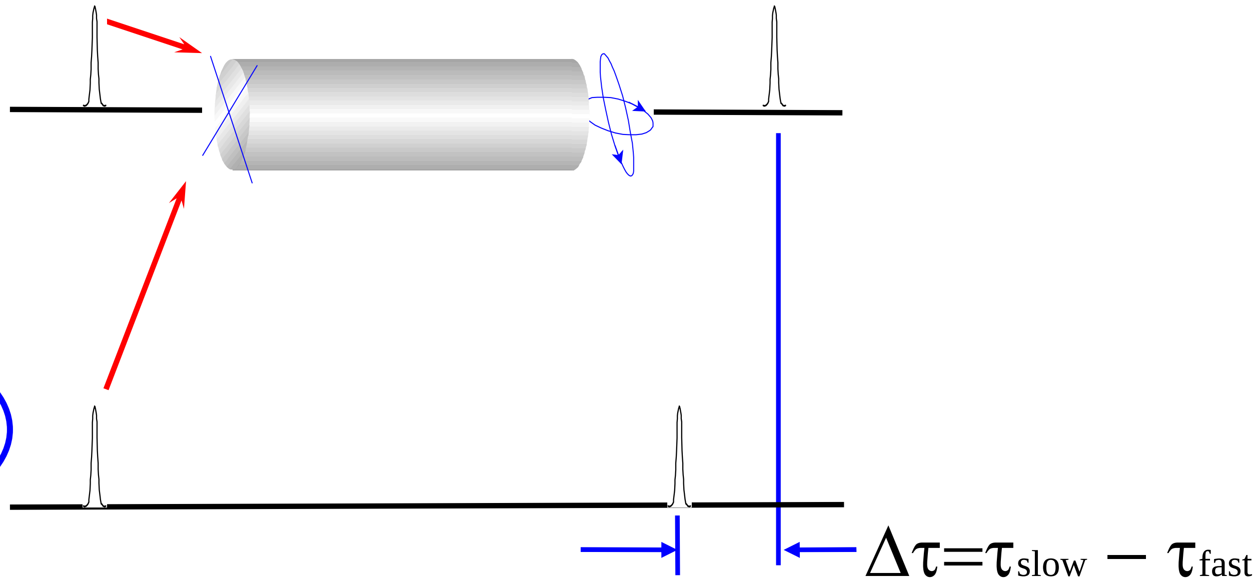
<u>Dispersion:</u> Propagation velocity depends on…
(wavelength, polarization state, propagation mode …)

Polarization-mode dispersion (PMD)

Simple birefringence yields pulse splitting

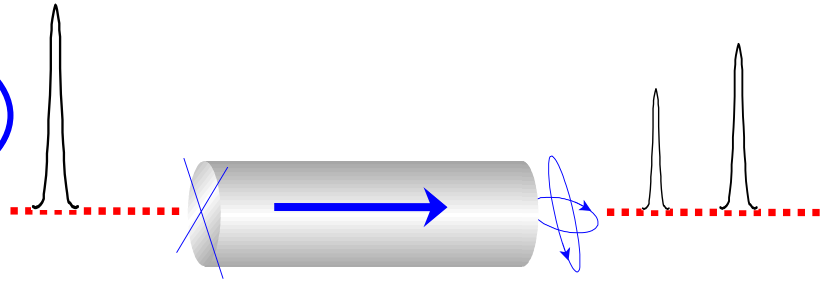
Polarized along
“fast” axis

Polarized along
“slow” axis



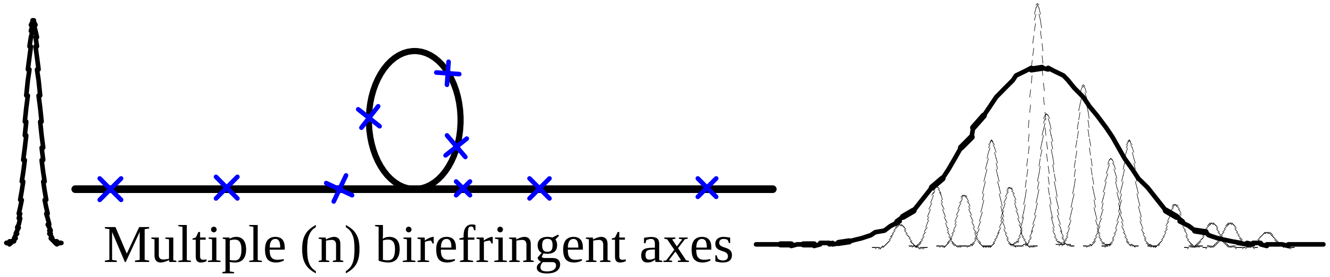
$\Delta\tau = \tau_{slow} - \tau_{fast}$

Arbitrarily-Polarized



PMD in fibers, causes pulse broadening

Polarization-mode coupling splits 1 pulse into 2^n



Single pulse in

2^n pulses out (Gaussian envelope)

“Mode-coupling” is a <u>statistical process</u>, this means…

- Big standard deviations

  (Longer measurement time, bigger uncertainty)

- Fiber PMD can’t be passively compensated

References

If you have any questions and want to discuss this with me…

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Or someone else…

Edward Collett, “Polarized Light: Fundamentals and Applications”, Marcel Dekker, Inc., New York , 1993.