Birefringent Thin Films for LCDs

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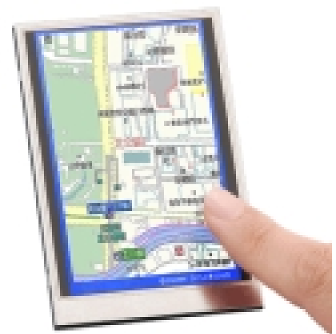
Outline

- Introduction
- Optical Transmission in Birefringent Networks
  - Phase retardation Γ depends on (λ,θ,ϕ)
  - Slow axis orientation depends on (θ,ϕ)
- Achromatic Wave Plates
- Wide Field-of-View Elements
- Applications in LCDs
- Summary

Birefringence in Optics

- Crystal Polarizers
- Polarization Interference
- Birefringent Spectral Filters
  - Narrow Passband
  - Wide Field of View
- Polarization Mode Dispersion (PMD) in Single Mode Fibers
- Birefringent Thin Films for LCDs

Displays in our Daily Life



- Notebook Computers
- Mobile Phones
- Computer Monitors
- Digital Cameras
- Televisions
- Personal Digital Assistants PDAs

Demand of Flat Panel Displays

- Military Applications
  - Cockpit Displays
  - AWACS Radar Signal Processing
- Civilian Aircraft Applications
  - Cockpit Displays
  - Personal Entertainment Displays
- Home and Personal Applications)
  - TVs, Digital Cameras, Cell Phones, Notebook Computers, etc.

Airborne Warning and Control System

- Equipped with 20 ~ 30 computers for signal processing and communications
- Computer Monitors
  - Cathode Ray Tubes, CRTs
  - Electro-luminescence Panels, ELPs
  - Liquid Crystal Displays, LCDs
- The light weight and small volume of LCDs offer more Payload and cruising Range

Cockpit Displays

- The Primary Display Units in front of each of the pilots display the horizon as well as essential navigation data
- Displays
  - Cathode Ray Tubes, CRTs
  - Electro-luminescence Panels, ELPs
  - Liquid Crystal Displays, LCDs
- The pilot and the copilot must cross check the data on the primary display units.
  - Large Viewing Angles needed

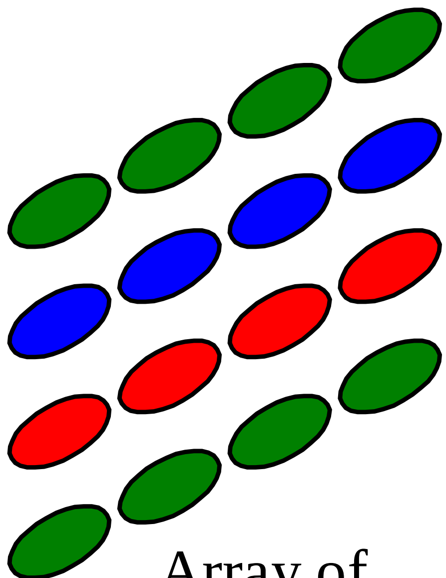
Commercial Aircrafts

- The advantages of LCDs offer the possibility of personal entertainment systems as well as more cruising range.

Display Systems

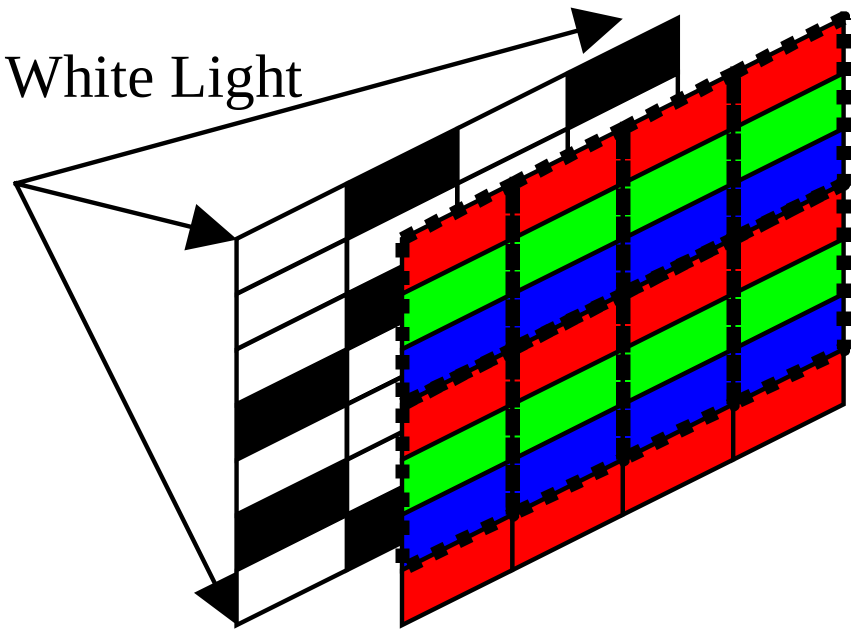
- Virtual Displays
  - No real image in space
  - Limited to one observer only
- Direct-view Displays
  - TVs, Computer monitors
  - CRTs, Plasmas, LCDs, DLPs, OLEDs
  - Transmission mode or reflective mode
- Projection Displays
  - Re-imaging (with Magnification) of direct-view displays: Large-area displays for large audience
  - Front-projection, Rear-projection
- 3D Displays, etc.

Direct and Indirect Displays



Array of
Light emitters

Examples: LED, OLED, PLED, CRT, Plasma
Each light emitter can be turned ON or OFF for information displays.

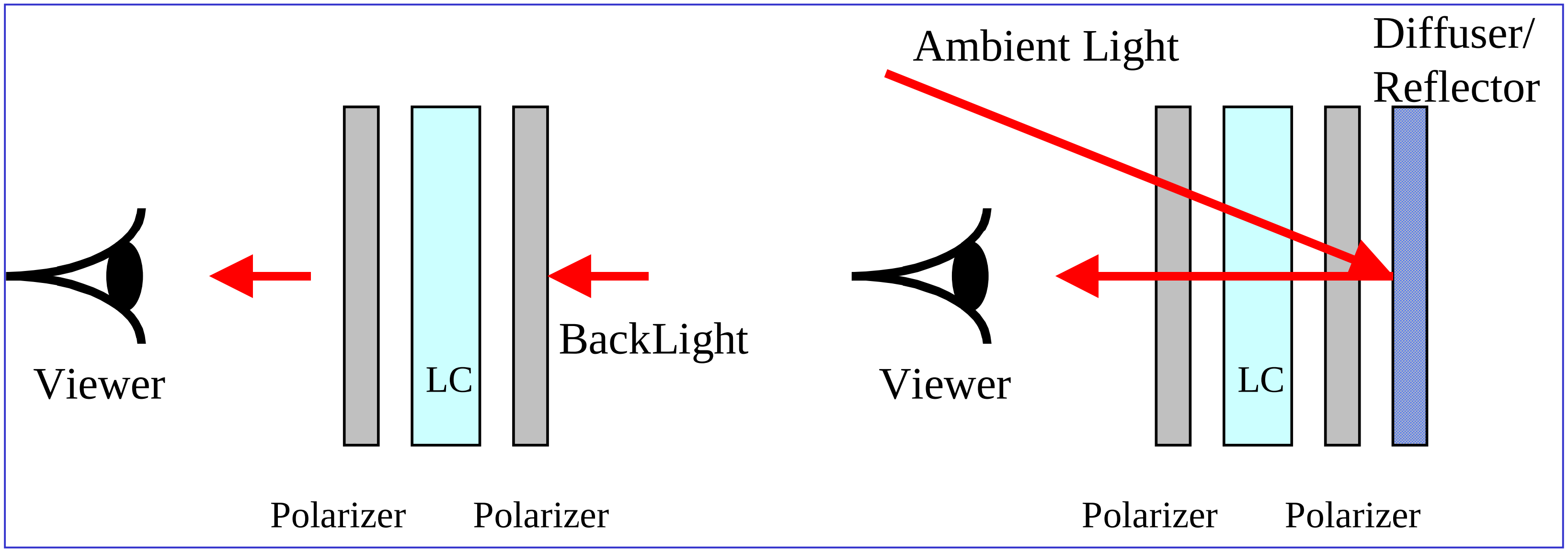


Array of
Lightvalves

Array of
Color Filters

Examples: LCD, DLP (digital light processor), GLV (grating Light valve), LCoS
Each light valve can be turned ON or OFF.

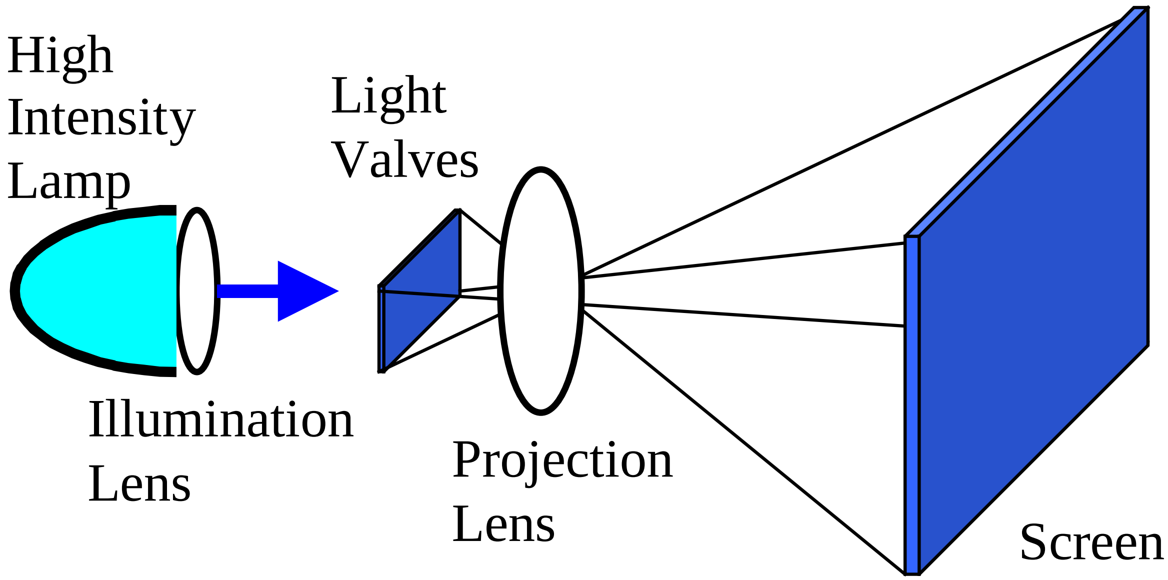
Transmissive and Reflective Displays



- High contrast
- Full color
- Poor outdoor readability

- Low power consumption
- Sunlight readability
- Poor contrast
- Poor brightness at dark ambient

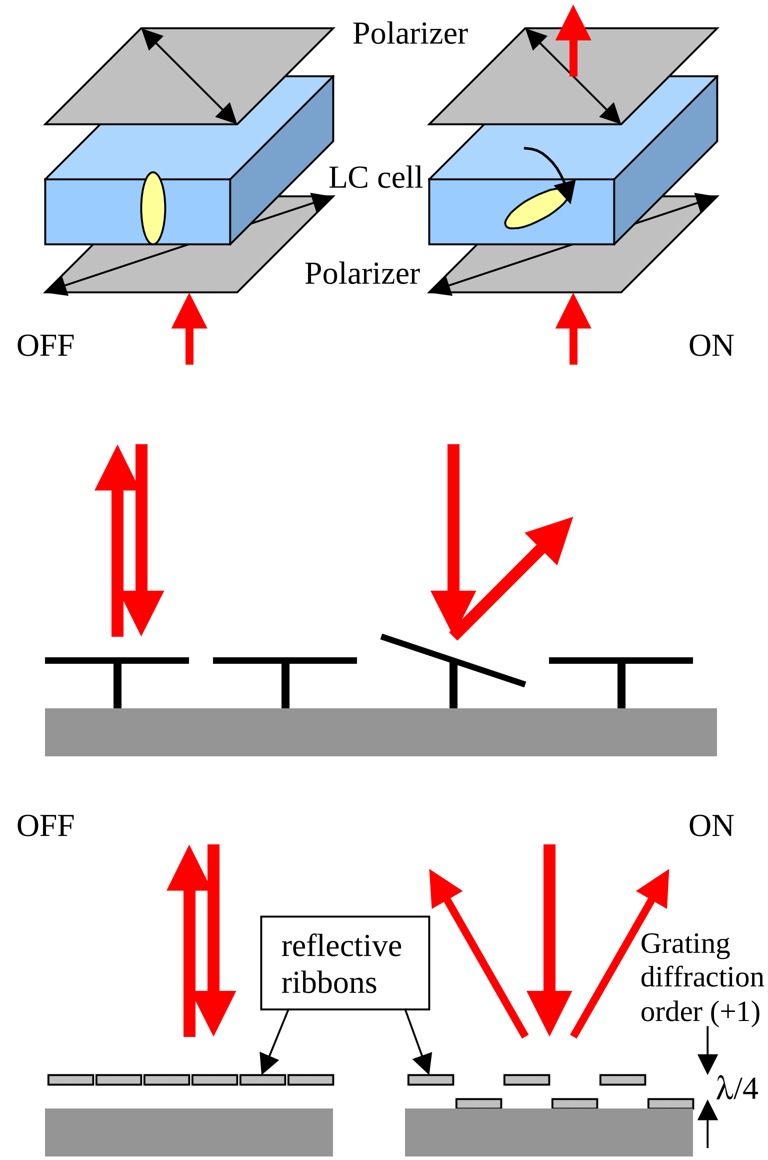
Projection Displays



- Large Area Displays for Large Audience
- High Intensity Light Sources needed
- 2-D Light Valves (or 1-D with Scanning)
- Light Valves can be LCD, DLP, GLV, etc.
- Dichoric mirrors, Lenses, prisms

Light Valves

- Liquid Crystal Light Valves
  - Electro-optical control of polarization state of light beam in conjunction with polarizers
- MEMS Light Valves
  - Electro-static control of micro-mirror orientation to deflect a beam of light
- Grating Light Valves (GLV)
  - Electro-static control of alternating elements of a parallel array of reflective micro-ribbons



Light Sources

Backlight (32” W)	**CCFL** (cold cathode)	**EEFL** (external electrode)	**LED**	**OLED**	**FFL** (flat FL)
Voltage	1~1.2 KV	1.5~2.5 KV	<10 V	<10 V	24 V
Lifetime (hours)	50 K – 60 K	> 60 K	50 K	12 – 15 K	100 K
Brightnes ($lm/m^2/sr$)	400-500	400-500	120-180	120	180
No. of units (32” W)	16	20	150	-	1

- Lasers and high intensity lamps are employed in projection displays.
- Ambient light is employed in reflective displays.

Characteristics of Displays

- Brightness
- Color and Grey Levels
- Contrast Ratio (CR), Speed, etc.
- Viewing angles, display area
- Quantum efficiency in direct displays
  - For each electron-hole recombination, what fraction of energy reaches the viewer?
- Optical efficiency in indirect displays
  - For each unit of optical energy at the backlight, what fraction of energy reaches the viewer?

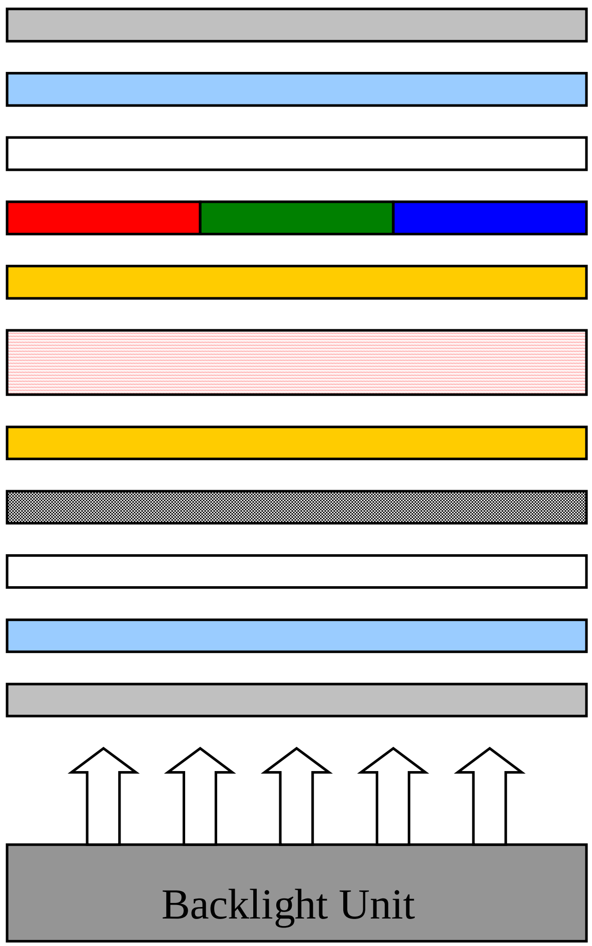
Brightness

(Units and Definition)

	Physical Measurement	Unit		Lighting & Display (Visual perception)	Unit
Power	**Physical power (power)**	**Watt**		**Visible power**	**Lumen**
Intensity	**Irradiance (intensity)**	**Watt/m^2**		**Illuminance**	**Lumen/m^2**
Brightness	**Radiance**	**Watt/m^2/sr**		**Luminance**	**Lumen/m^2/sr**

- 1 Candela = 1 Lumen/sr (visible power per solid angle)
- 1 Nit = 1 Candela/m^2 = 1 Lumen/m^2/sr (Brightness unit)
- 1 Watt (W):
  - = 25.9 Lumen @ 450 nm, = 220.0 Lumen @ 500 nm
  - = 679.0 Lumen @ 550 nm, **= 683.0 Lumen @ 555 nm**
  - = 430.0 Lumen @ 600 nm, = 73.0 Lumen @ 650 nm

Optical Components in Liquid Crystal Displays



Sheet Polarizer
Birefringent Thin Film Compensator
Glass Plate
Color Filters
Transparent Electrode (e.g., ITO)
Liquid Crystal
Transparent Electrode (e.g., ITO)
Thin Film Transistors (TFTs)
Glass Plate
Birefringent Thin Film Compensator
Sheet Polarizer
Backlight Unit, BLU

Optical Beams in Anisotropic Media

The dielectric "constant" of an anisotropic medium:

$$\varepsilon = \varepsilon_0 \begin{pmatrix} n_x^2 & 0 & 0 \\ 0 & n_y^2 & 0 \\ 0 & 0 & n_z^2 \end{pmatrix}$$

n_x, n_y, n_z **are the principal indices of refraction**

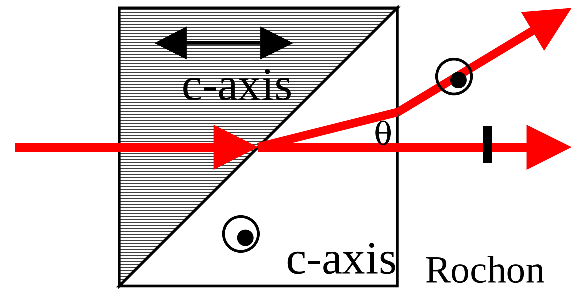
Isotropic media: $n_x = n_y = n_z$

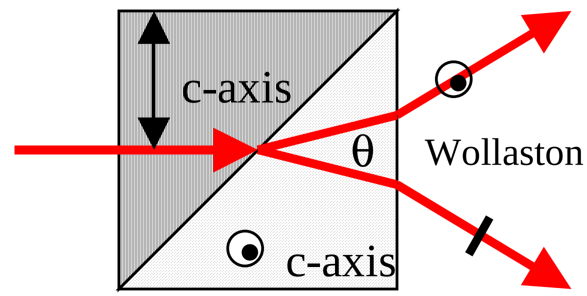
Uniaxial media: $n_x = n_y \neq n_z$

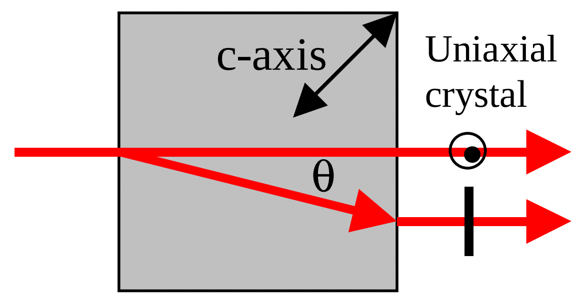
Biaxial media: $n_x \neq n_y \neq n_z$

Birefringent Crystal Polarizers

- Rochon prisms (e.g., calcite, n_e=1.486, n_o=1.658, $\theta \sim 7^o$)
- Wollaston prisms (e.g., calcite, n_e=1.486, n_o=1.658, $\theta \sim 13^o$)
- Uniaxial crystal (e.g., YVO_4, n_e=2.16, n_o=1.96, $\theta \sim 6^o$)
- Savart Plate – Two 45°-cut uniaxial crystal plates of equal thickness in series. The second plate is rotated 90-degree relative to the first one (to balance the phase shift).







Dichroic Crystal Polarizers

Optical Dichroism -

Example 1: Tourmaline (Sodium Aluminum Borosilicate) - a naturally occurring mineral
Ordinary mode is strongly absorbed.

Example 2: Sulfate of iodo-quinine (Dr. Herapath, 1852)
Extraordinary mode is strongly absorbed.

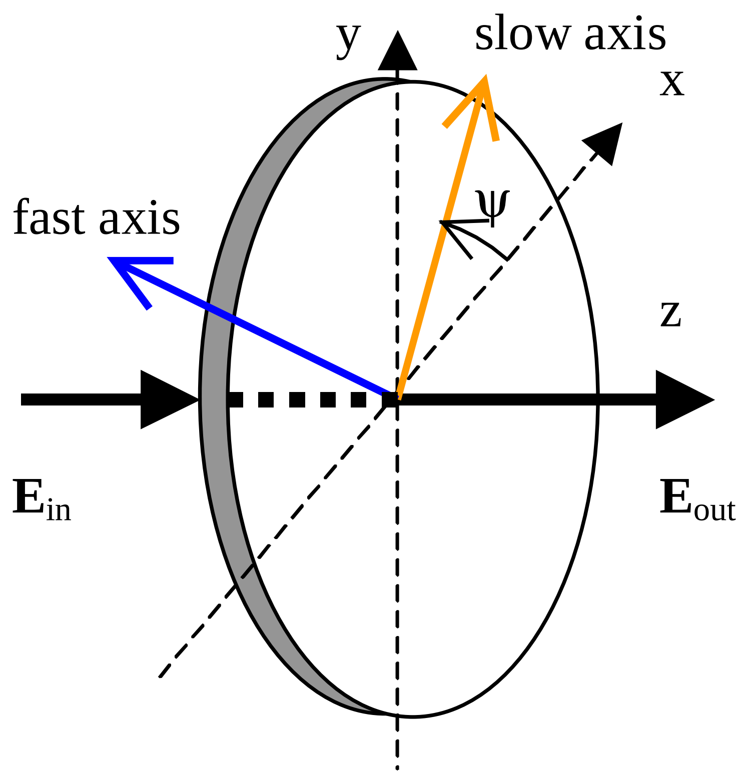
O-type Polarizers: O-mode is transmitted
E-type Polarizers: E-mode is transmitted

Polarization State Change due to Transmission

- In isotropic media (e.g., glass), the polarization state remains unchanged as the beam propagates through the media.
- In anisotropic media (e.g., liquid crystals), the two independent modes of propagation may propagate at different speeds. The difference in the speed of propagation leads to different phase shifts and thus a change of polarization state.

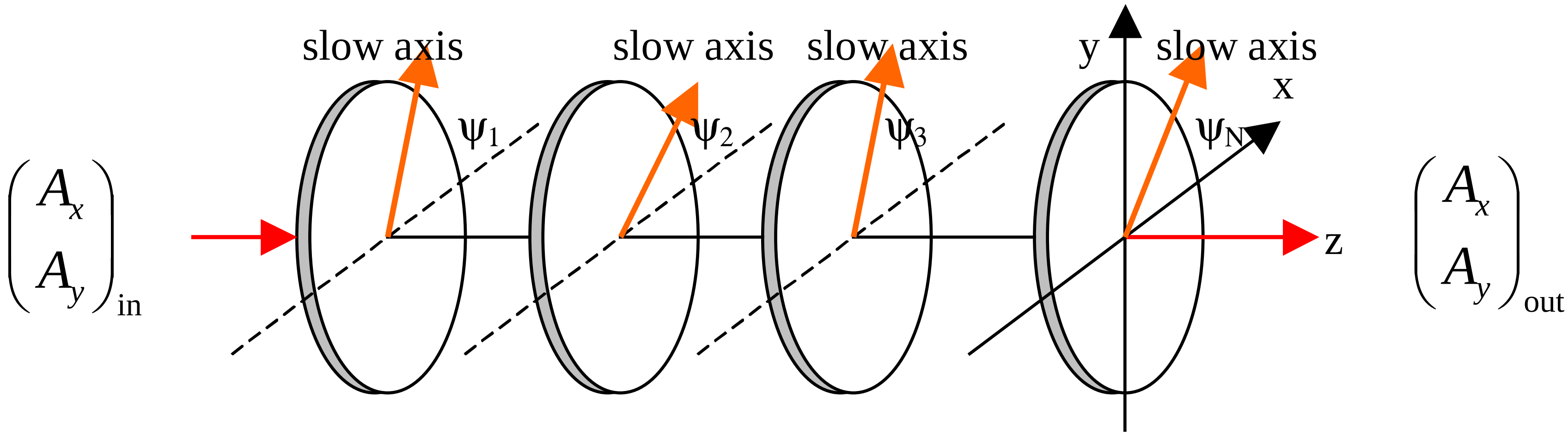
Phase Retardation in Birefringent Plates

- Slow mode and fast mode propagate at different speed, and hence different wavenumber: k_s, k_f
- Phase retardation
  - $\Gamma=(k_s - k_f)d$
- Polarization state changes due to Γ
- Jones vectors



$$\mathbf{E}_{\text{in}} = \begin{pmatrix} A_s \\ A_f \end{pmatrix} \qquad \mathbf{E}_{\text{out}} = \begin{pmatrix} A_s e^{-ik_s d} \\ A_f e^{-ik_f d} \end{pmatrix}$$

Jones Matrix Method

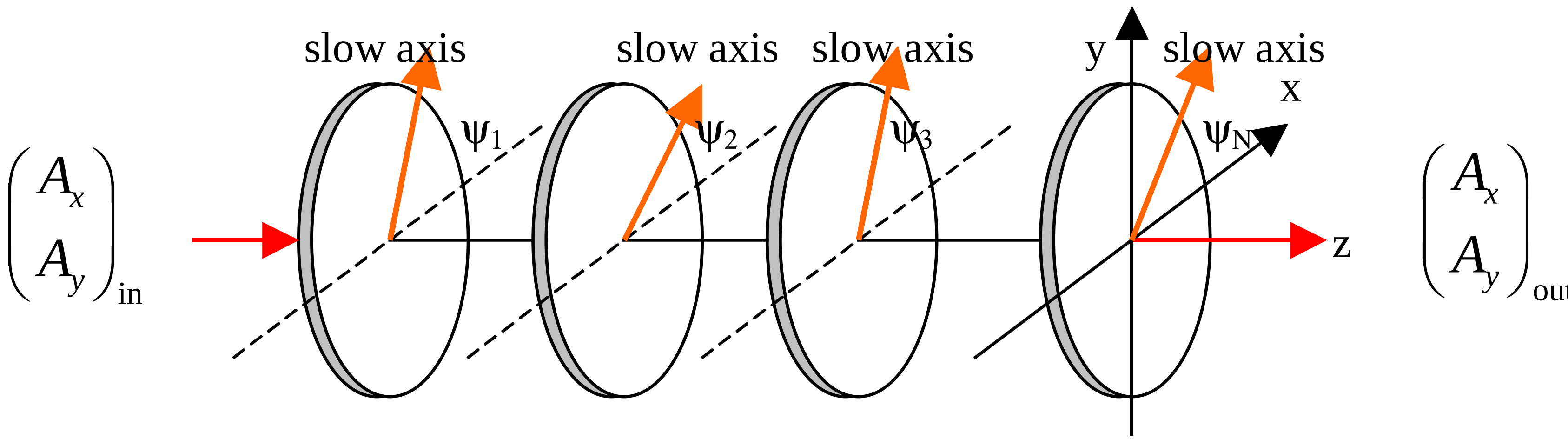


- Input-Output Matrix relationship in *xy*-coordinate
- Coordinate transformation from *xy*-coordinate to *sf*-coordinate

$$\begin{pmatrix} A_x \\ A_y \end{pmatrix}_{\text{out}} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} A_x \\ A_y \end{pmatrix}_{\text{in}}$$

$$\begin{pmatrix} A_s \\ A_f \end{pmatrix} = \begin{pmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{pmatrix} \begin{pmatrix} A_x \\ A_y \end{pmatrix} \equiv R(\psi) \begin{pmatrix} A_x \\ A_y \end{pmatrix}$$

Jones Matrix Method



$$\begin{pmatrix} A_x \\ A_y \end{pmatrix}_{\text{out}} = W(\Gamma_N, \psi_N) \;\; ..... \;\; W(\Gamma_3, \psi_3) W(\Gamma_2, \psi_2) W(\Gamma_1, \psi_1) \begin{pmatrix} A_x \\ A_y \end{pmatrix}_{\text{in}} = M \begin{pmatrix} A_x \\ A_y \end{pmatrix}_{\text{in}}$$

- The Jones matrix of each waveplate W is unitary.
- The 2x2 matrix M is also unitary.
  - $M_{22} = M^*_{11}$, $M_{21} = - M^*_{12}$
  - $M_{11} M_{22} - M_{12} M_{21} = 1$

Stokes Vectors & Poincaré Sphere

Jones vector:

$$\mathbf{E} = \begin{pmatrix} A_x e^{i\delta_x} \\ A_y e^{i\delta_y} \end{pmatrix}$$

A_x, A_y, δ_x, δ_y are all real

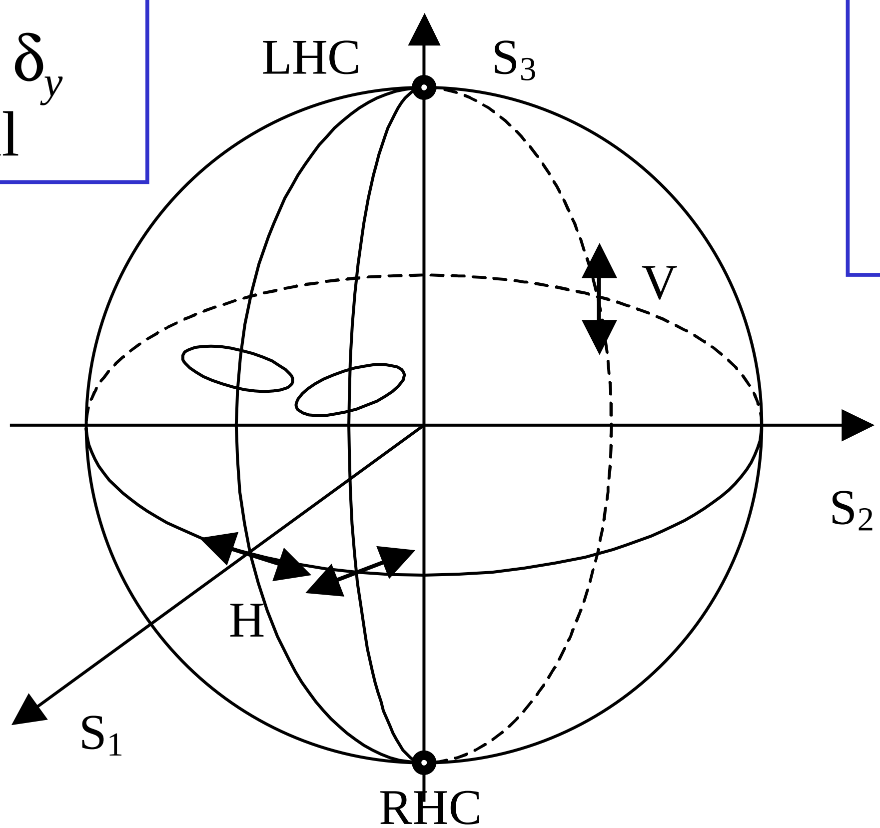
Stokes vector:
(Statistical Average)

$$S_0 = \langle A_x^2 + A_y^2 \rangle$$

$$S_1 = \langle A_x^2 - A_y^2 \rangle$$

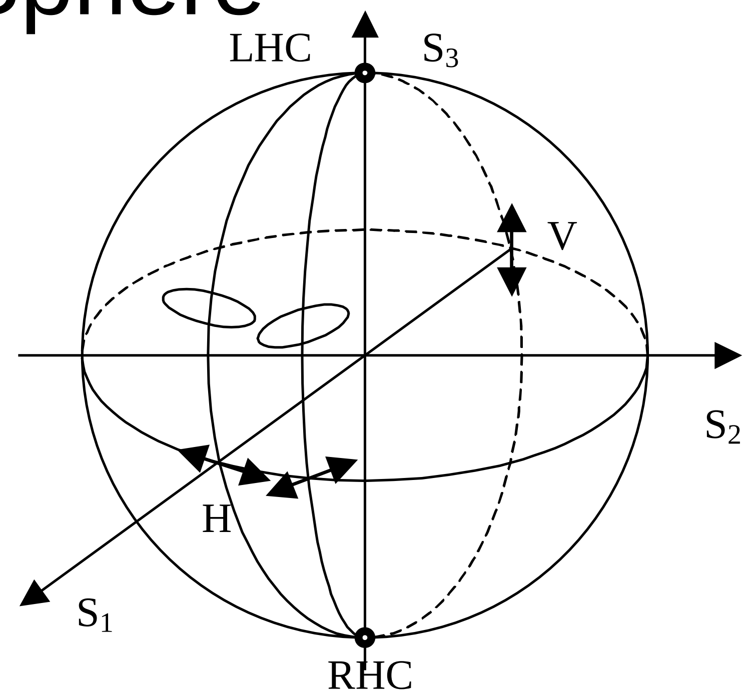
$$S_2 = 2\langle A_x A_y \cos(\delta_y - \delta_x) \rangle$$

$$S_3 = 2\langle A_x A_y \sin(\delta_y - \delta_x) \rangle$$



For polarized light, normalized the field so that S_0=1. The vector (S_1, S_2, S_3) is a point on the Poincaré sphere.

Poincaré Sphere



Each point on the sphere represents a polarization state. Each pair of antipodal points represents a pair of mutually orthogonal states.

Examples:

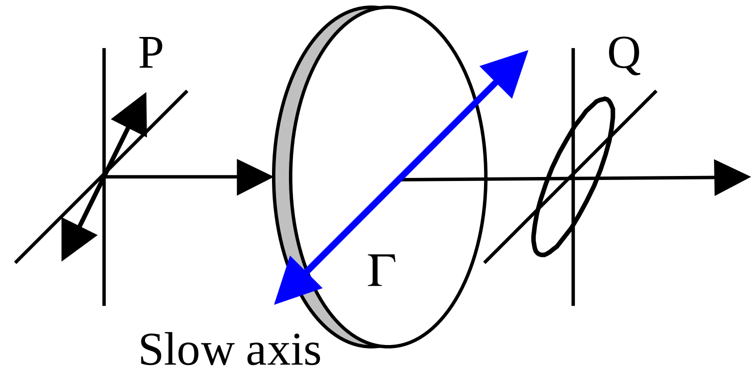
LHC on the North pole and RHC on the South pole.

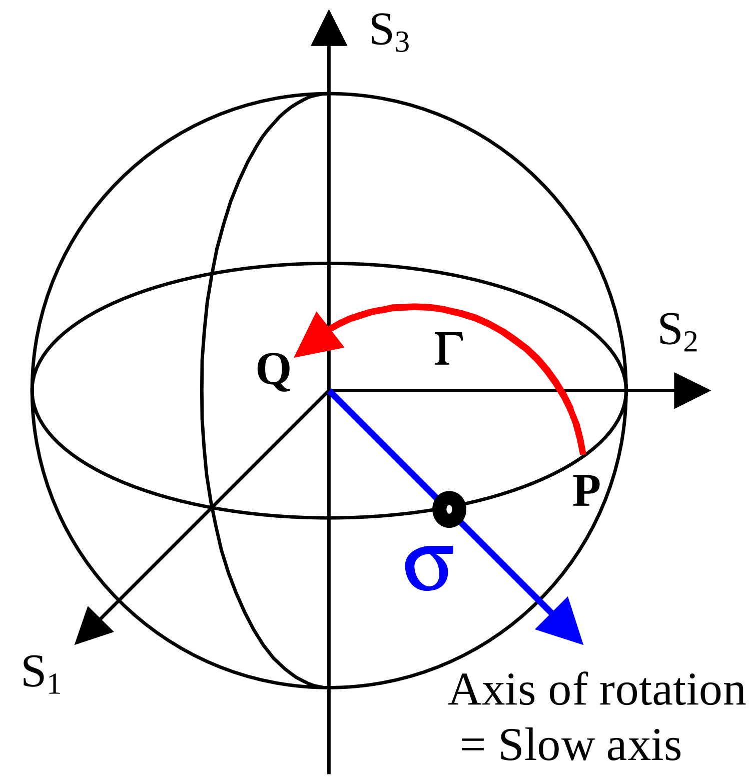
H: (1, 0, 0) and V: (-1, 0, 0) are a pair of linearly polarized orthogonal states (horizontal, vertical).

Points on equator represent linear polarization states.

Polarization Transformation on Poincaré Sphere

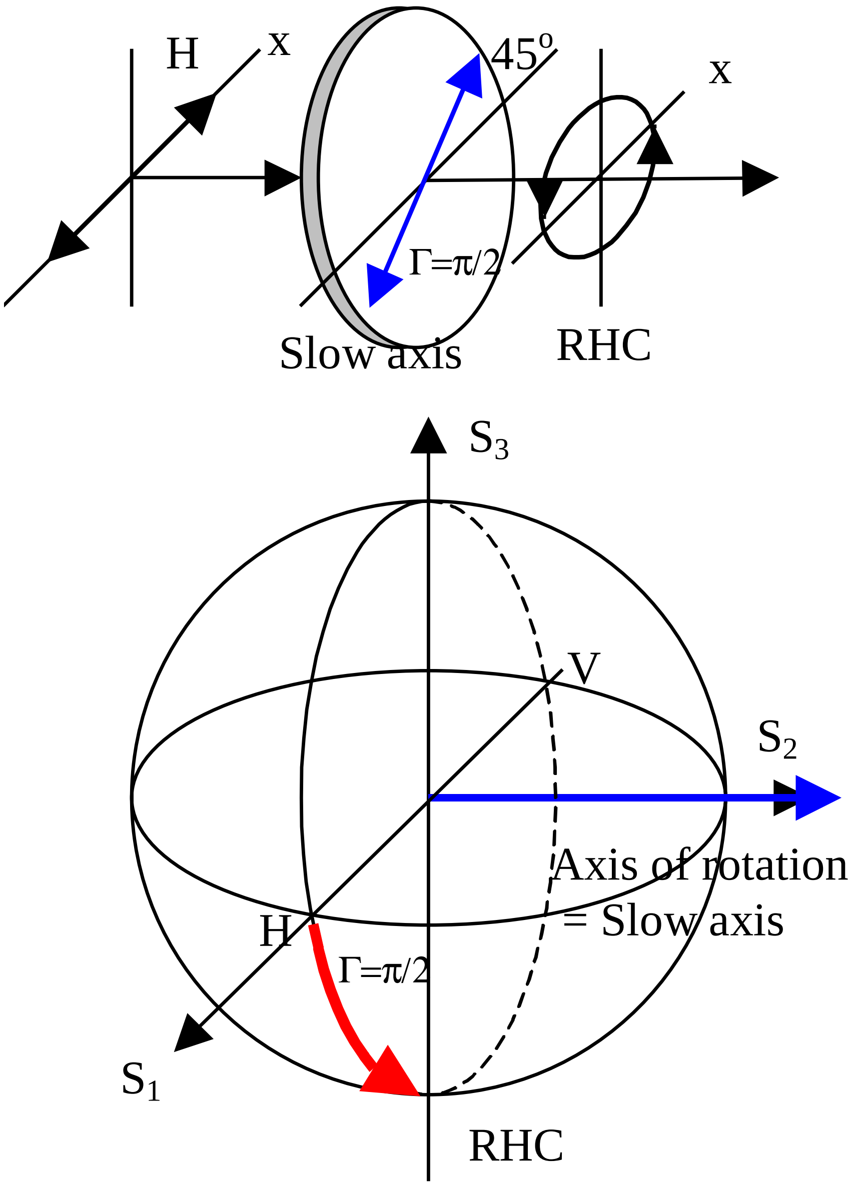
- The polarization state transformation by a wave plate can be easily obtained by using the Poincaré sphere.
- The output polarization state **Q** is obtained by a rotation of the input polarization state **P** around the slow axis of the wave plate by an angle equal to the phase retardation **Γ**.
- σ is the polarization state of the slow mode of wave plate.





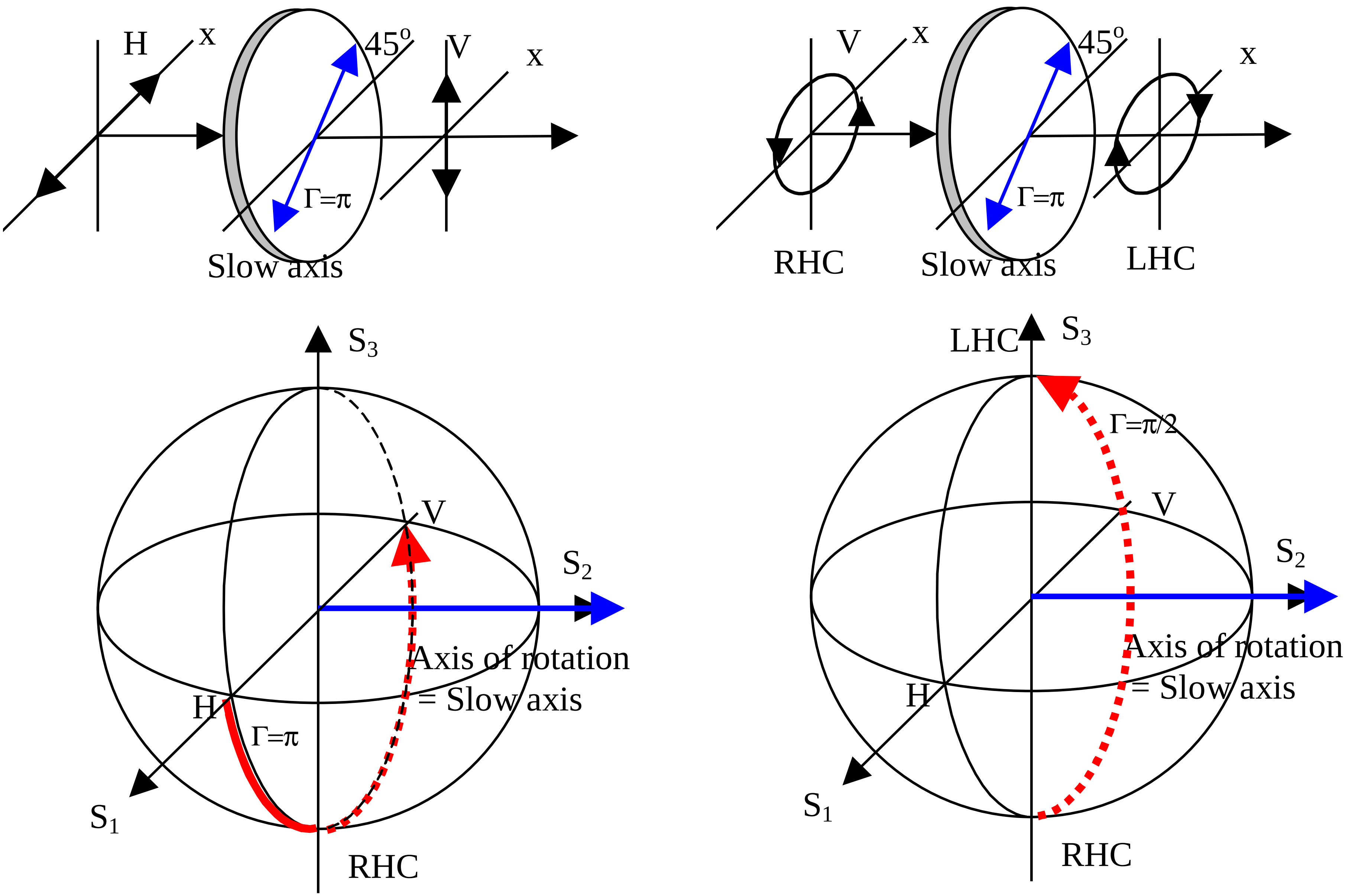
Examples of Polarization Transformation

(Quarter-wave plate, $\Gamma = \pi/2$)



Examples of Polarization Transformation

(Half-wave plate, $\Gamma = \pi$)



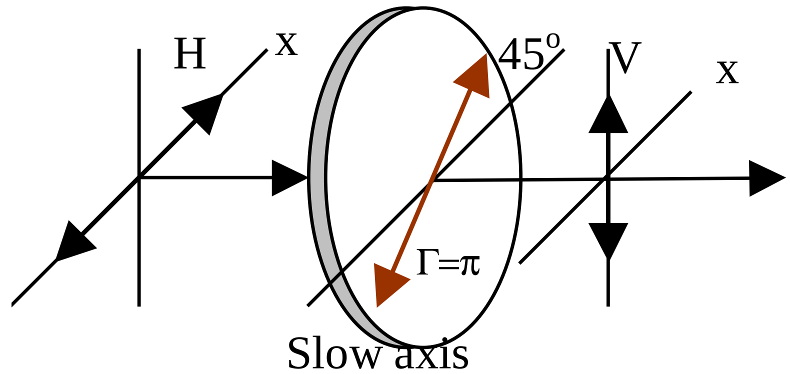
Wavelength Dependence

(Half-wave plate)

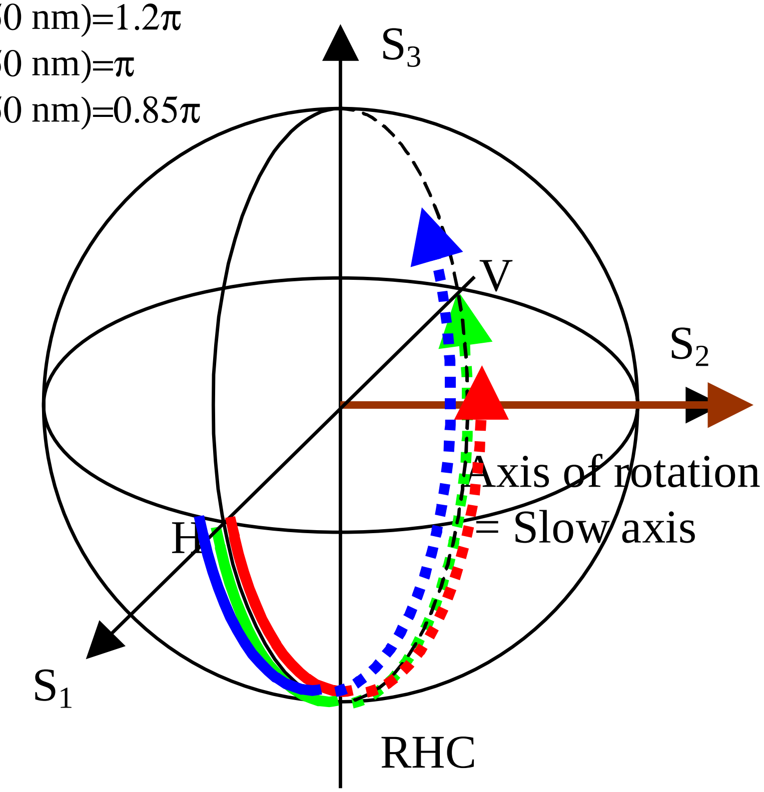
- The phase retardation Γ depends on wavelength:

$$\Gamma = \frac{2\pi}{\lambda}(n_e - n_o)d$$

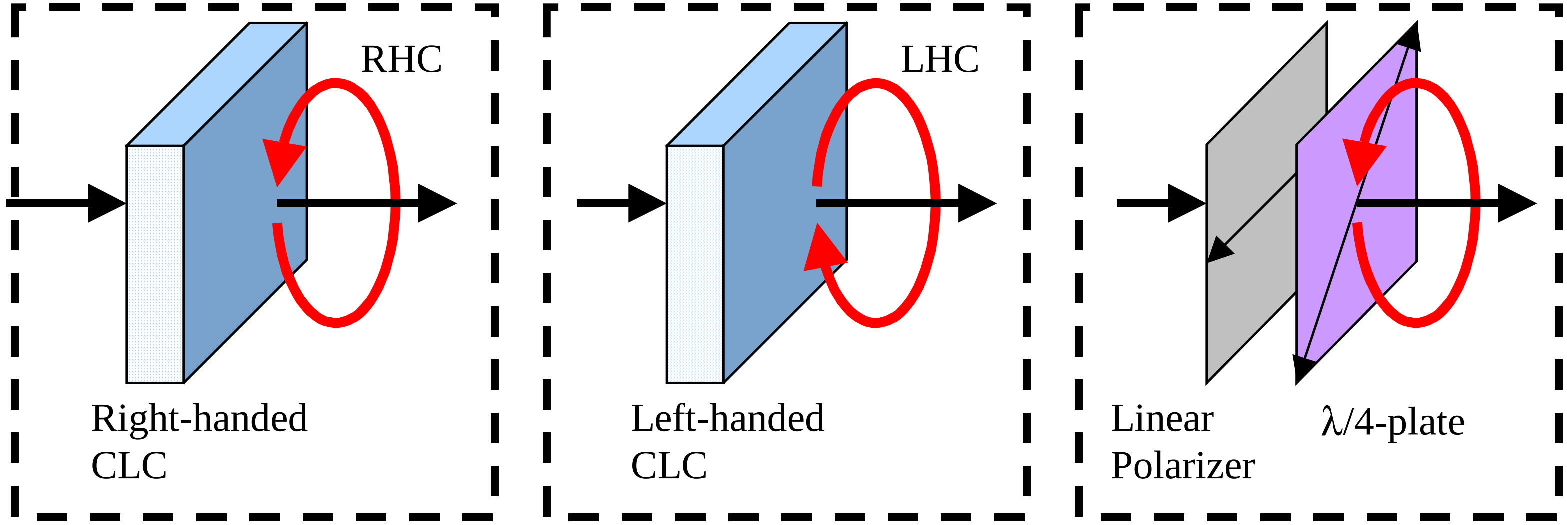
- The output polarization state for the three colors (R, G, B) are thus dependent on the color.
- Achromatic wave plates (Γ is independent of λ) are desirable.



Γ(450 nm)=1.2π
Γ(550 nm)=π
Γ(650 nm)=0.85π

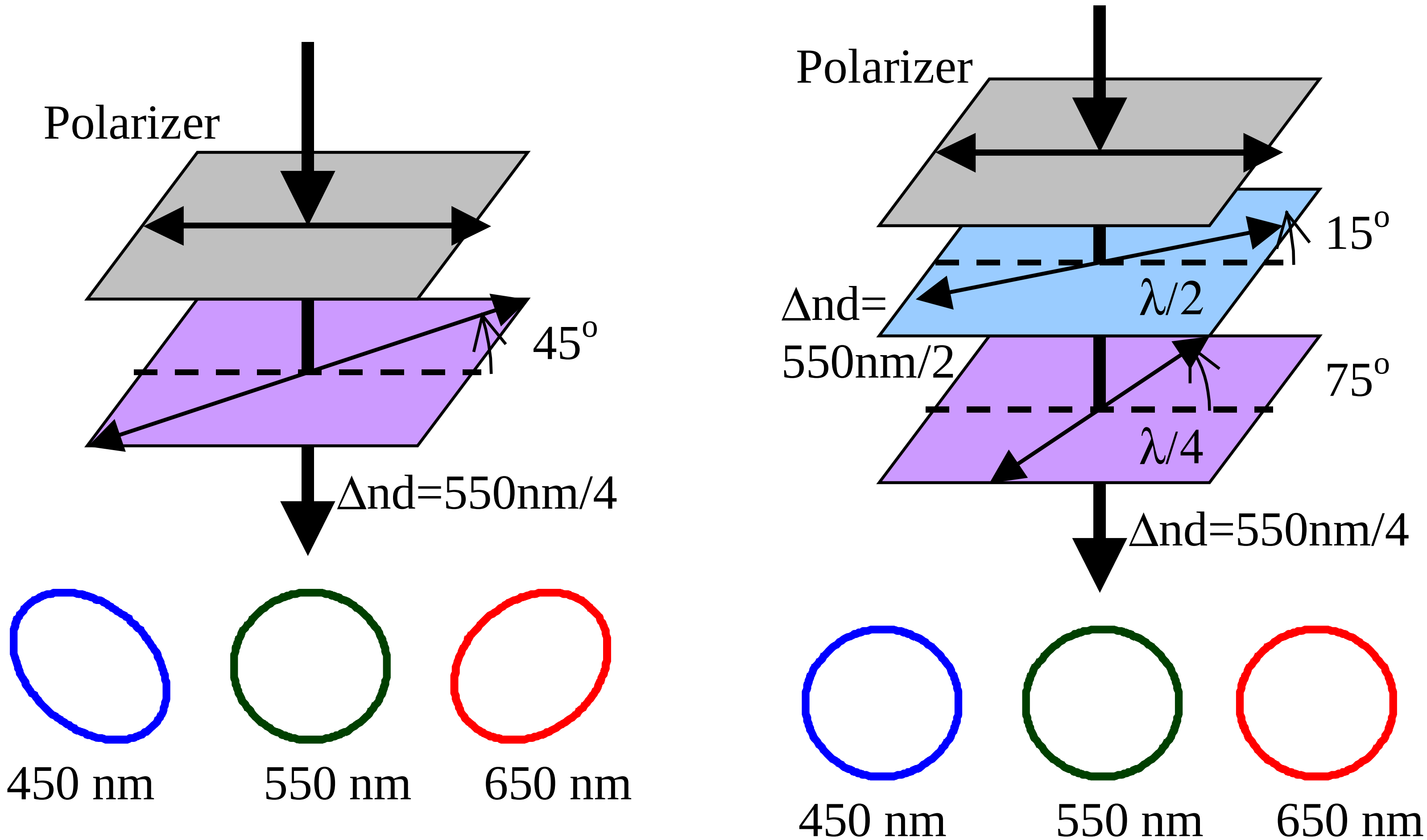


Circular Polarizers



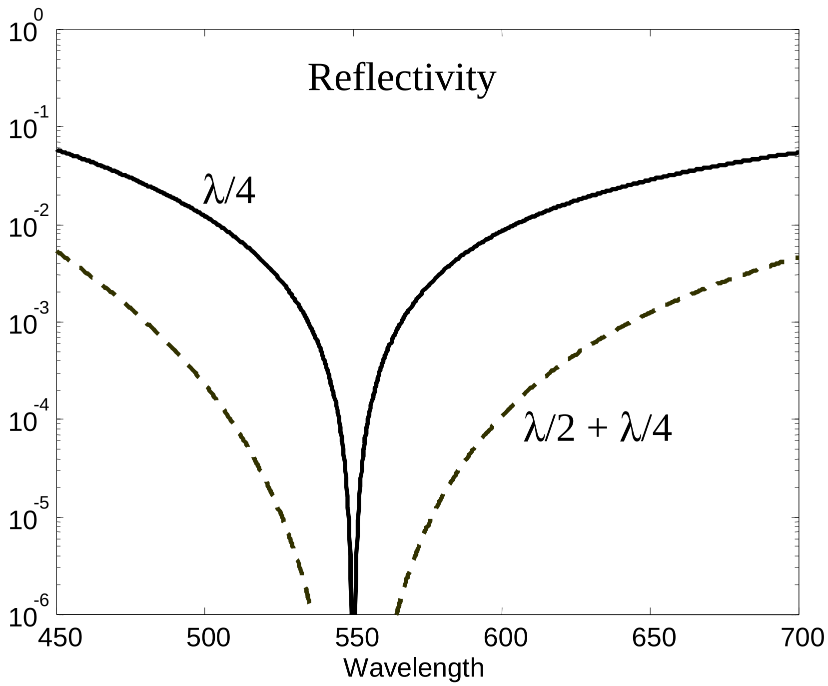
- There are two independent circular polarization states (right-handed, and left-handed).
- A circular polarizer can separate these two polarization states by eliminating or redirecting one of them.
- Cholesteric liquid crystal (CLC) can function as circular polarizers.
- A combination of a linear polarizer and a quarter-wave plate can function as quasi-circular polarizers.

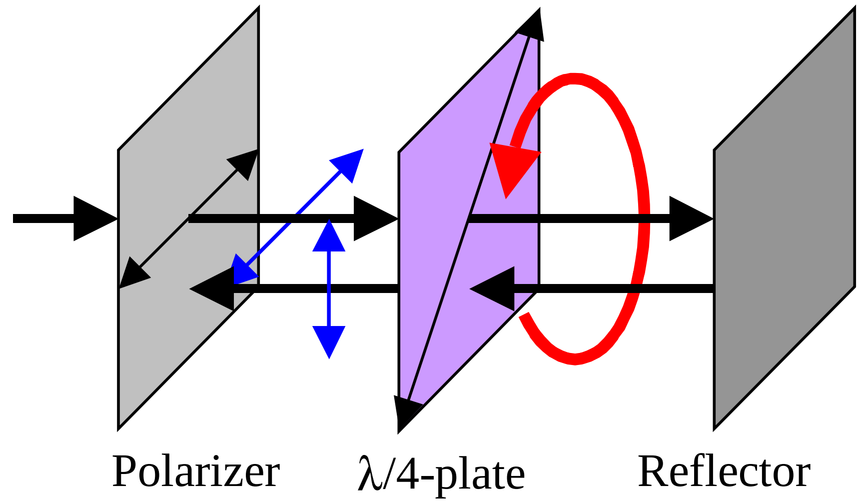
Achromatic Quasi-Circular Polarizers



- Using a combination of λ/2 and λ/4 plates, all three colors can be converted into circularly polarized light

Anti-reflection with Quasi-Circular Polarizers



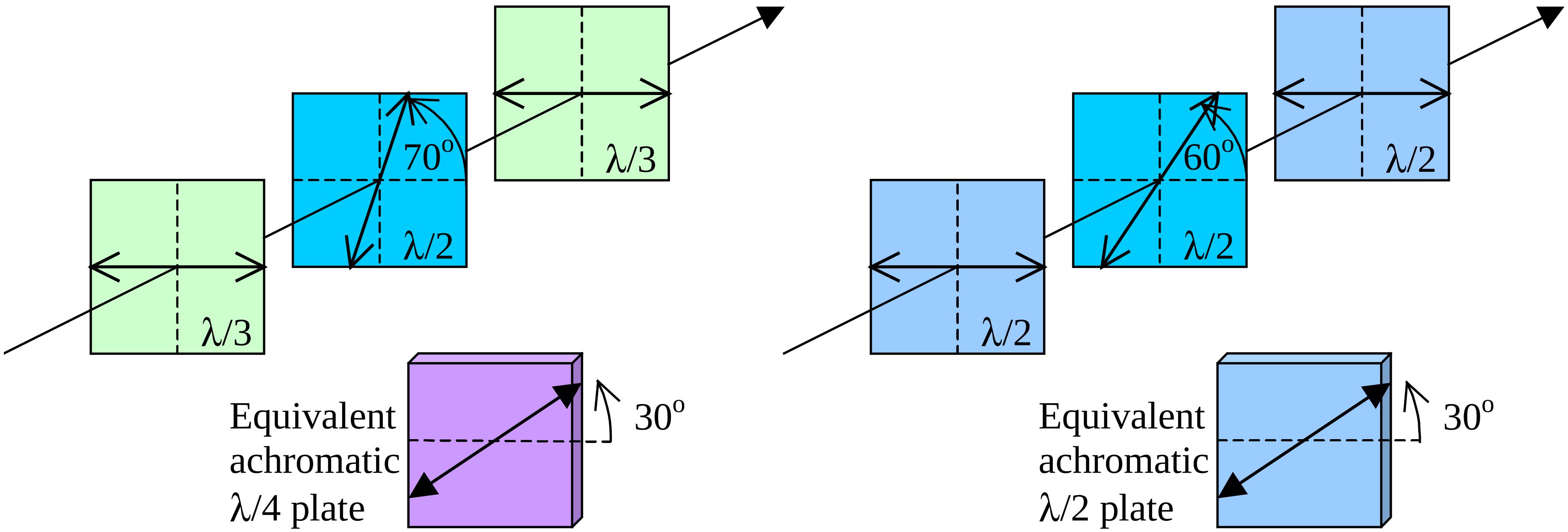


- A change of handedness occurs upon reflection from a reflector (mirror)
- The net result is a rotation of polarization by 90^o

Achromatic Wave Plates

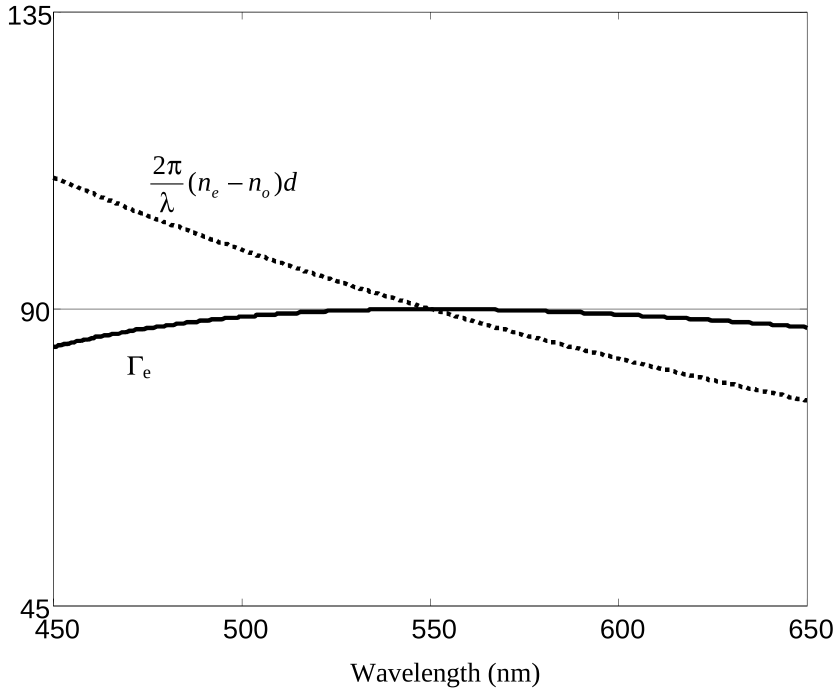
- Phase retardation G depends on wavelength λ and angle of incidence (θ, ϕ)
- Achromatic Wave Plates: $\left(\frac{\partial}{\partial\lambda}\Gamma(\lambda,\theta,\phi)\right)_{(0,0)} \approx 0$
  - Pancharatnam approach employs plates of the same material with different retardance and orientation of slow axes
  - Beckers approach employs plates of the same slow axis with different material dispersion

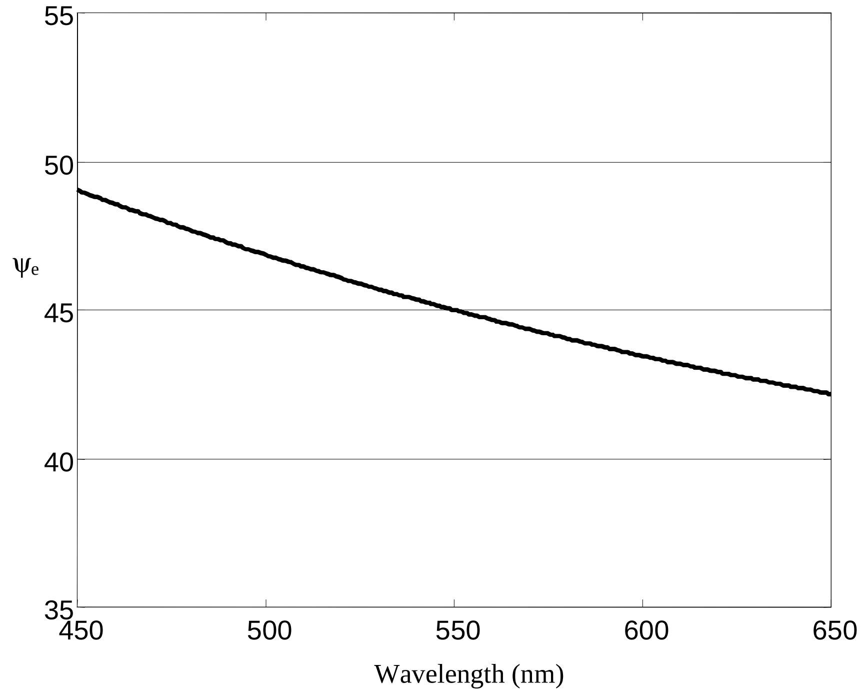
Achromatic Wave Plates



- A combination of wave plates can be designed to produce an achromatic wave plate that has a constant retardance (λ/4, or λ /2) within a broad spectral range (e.g., from 0.8 λ to 1.2 λ). The slow and fast axes of the equivalent wave plate must be fixed within the spectral range.
- References: S. Pancharatnam, Proc, of the Indian Academy of Sciences, Vol. 41, 1955 pp. 130-144; A.M. Title, Appl. Opt., Vol. 14, 229 (1975).

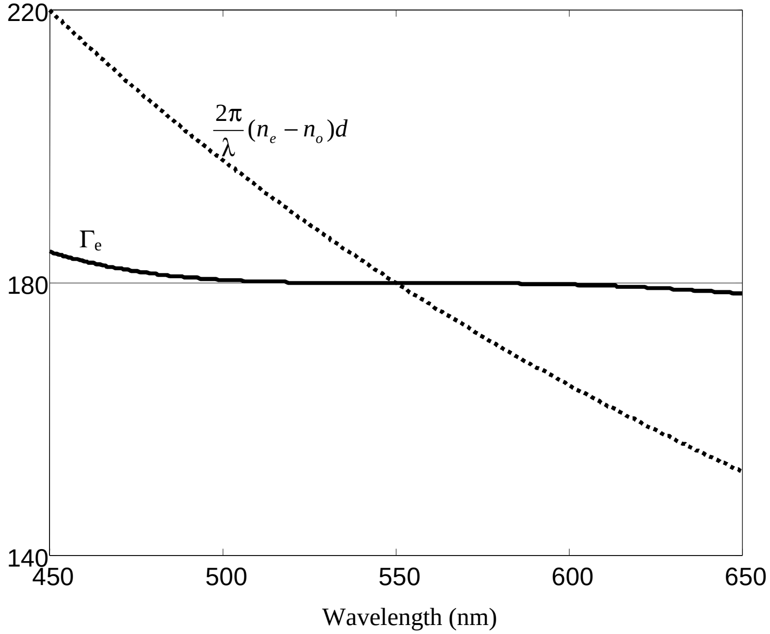
Achromatic Quarter-wave Plate (Q-H-Q)

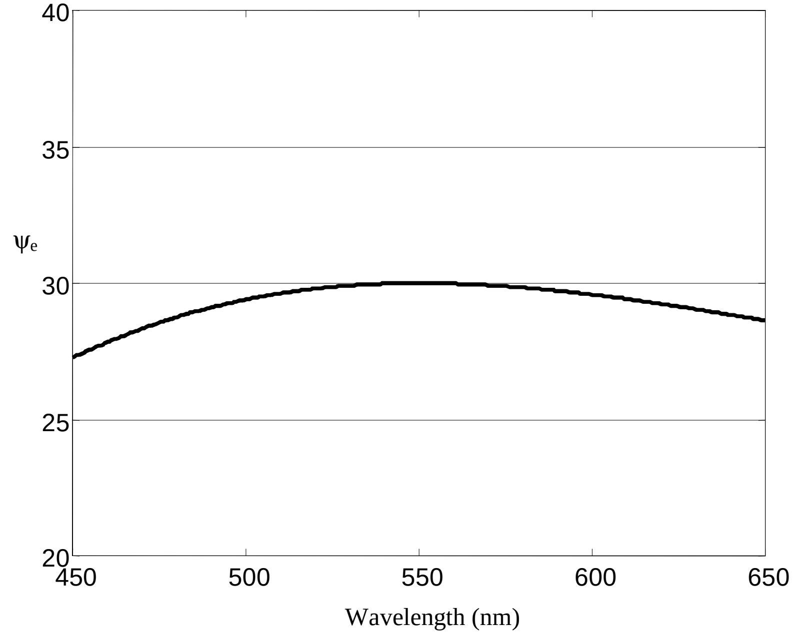




- Achromatic property is only limited to a small solid angle around normal incidence

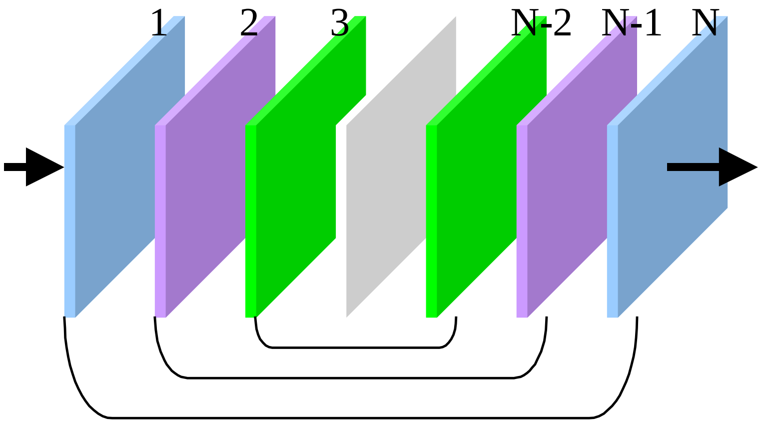
Achromatic Half-wave Plate (H-H-H)





- Achromatic property is only limited to a small solid angle around normal incidence

Achromatic Wave Plates



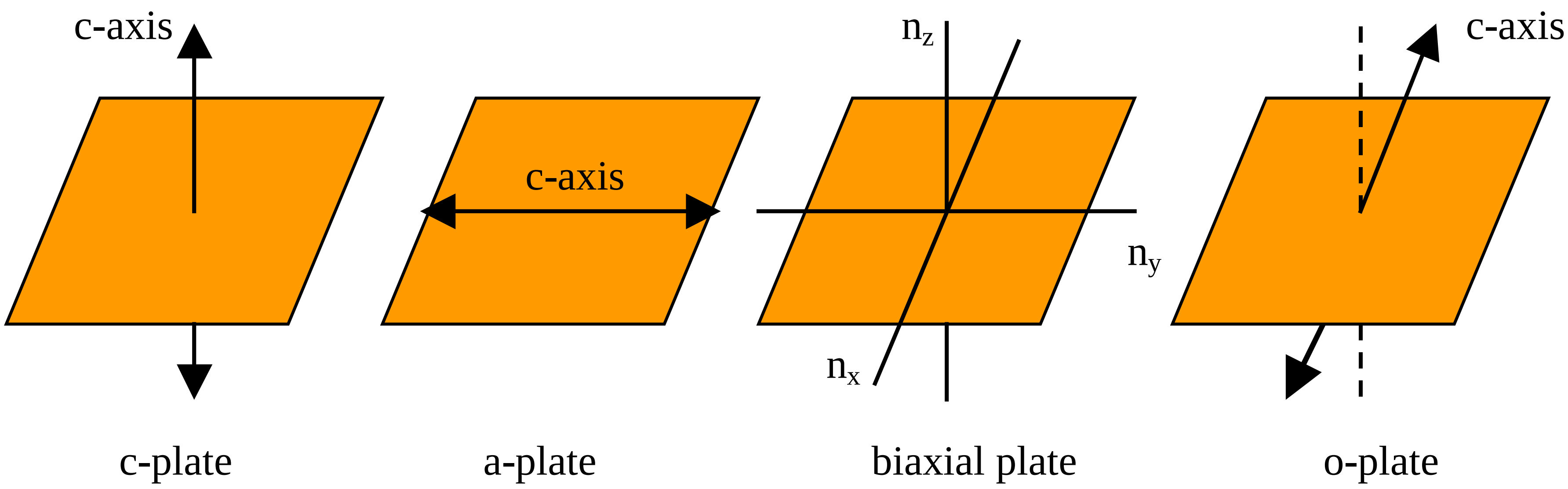
$$M = M_N M_{N-1} \cdots M_3 M_2 M_1$$

$$M\ \mathbf{V}_{\text{slow}} = e^{-i\Gamma/2}\ \mathbf{V}_{\text{slow}}$$

$$M\ \mathbf{V}_{\text{fast}} = e^{+i\Gamma/2}\ \mathbf{V}_{\text{fast}}$$

- Obtain the Jones matrix of the birefringent system (usually a series of wave plates)
- Find the eigenvectors and eigenvalues of the Jones matrix
- The system is equivalent to an achromatic wave plate provided the eigenvectors are linearly polarized and both the eigenvectors and eigenvalues are insensitive to wavelength variation.
- A symmetric system supports linearly polarized eigenvectors. ($M_N = M_1$, $M_{N-1} = M_2$, …..)

Typical Wave Plates in LCDs



In wave plates made of uniaxial films, the plates are characterized by their retardance $d(n_e\text{-}n_o)$ and the orientation of the c-axis.
In wave plates made of biaxial films, the plates are characterized by their retardance $d(n_x - n_z)$ and $d(n_y – n_z)$.
The actual phase retardation is a function of angle of incidence: $\Gamma(\theta,\phi)$.

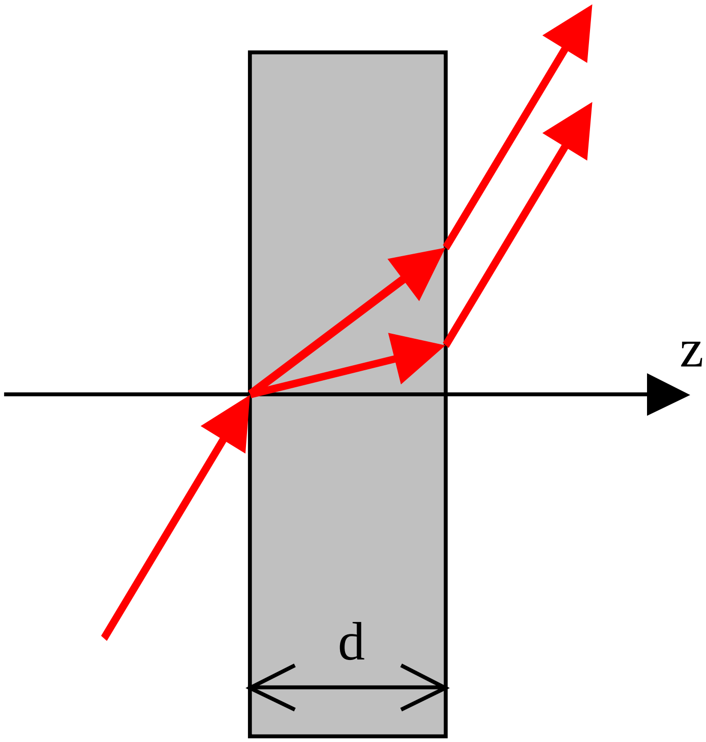
Phase Retardation at General Incidence

- At a general incidence, the wavevectors of the modes are:

  $\mathbf{k}_s=(k_x, k_y, k_{sz})$

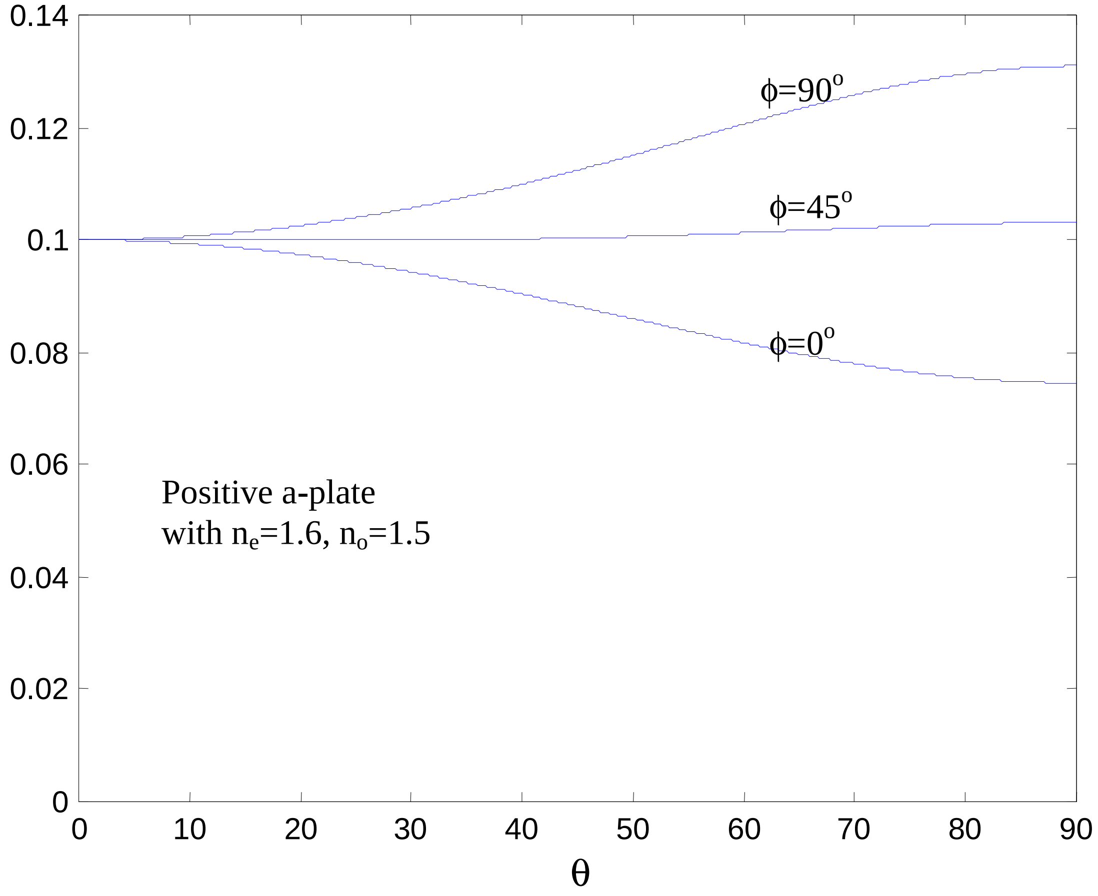
  $\mathbf{k}_f=(k_x, k_y, k_{fz})$

- Due to boundary conditions, the x- and y-component of the wavevectors of the two modes are the same
- Phase retardation
  - $\Gamma=(k_{sz} - k_{fz})d$



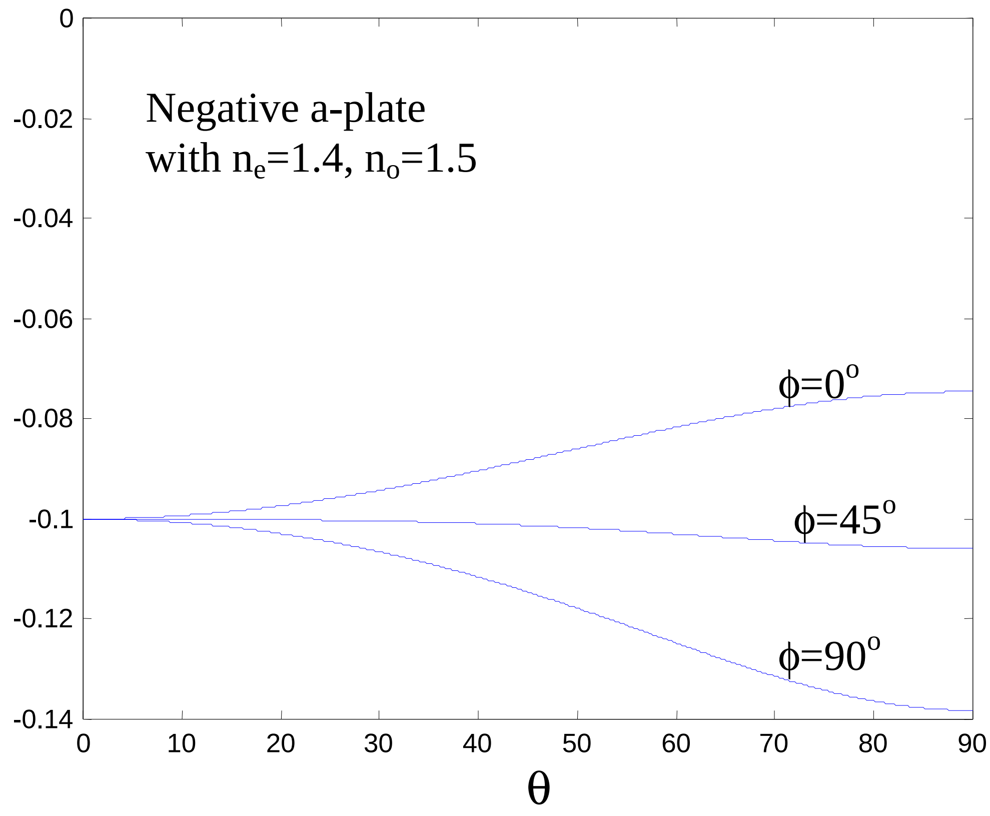
$$\mathbf{E}_{in} = \begin{pmatrix} A_s \\ A_f \end{pmatrix} \qquad \mathbf{E}_{out} = \begin{pmatrix} A_s e^{-ik_{sz}d} \\ A_f e^{-ik_{fz}d} \end{pmatrix}$$

Normalized Phase Retardation $\Gamma(\theta,\phi)$



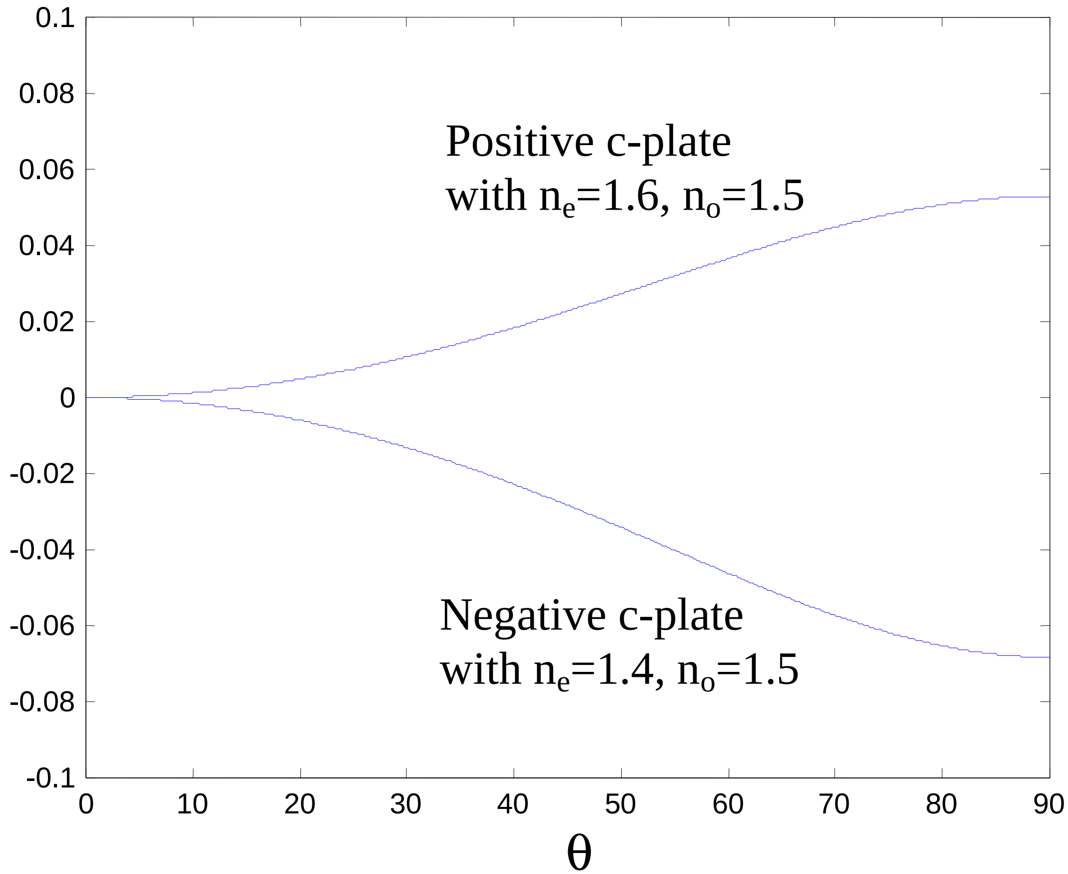
- Azimuth angle ϕ measured from c-axis.

Normalized Phase Retardation $\Gamma(\theta,\phi)$



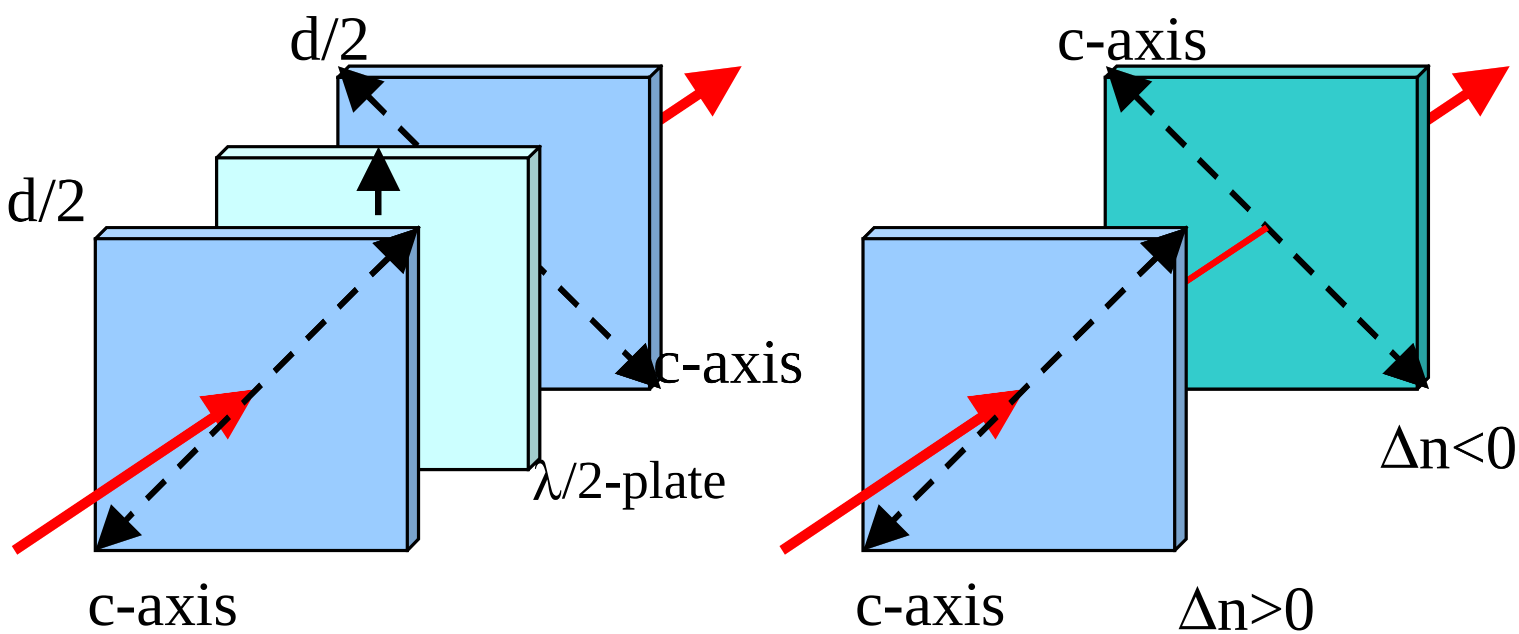
- Azimuth angle ϕ measured from c-axis.

Normalized Phase Retardation $\Gamma(\theta,\phi)$



- The phase retardation of c-plates is independent of the azimuth angle ϕ.

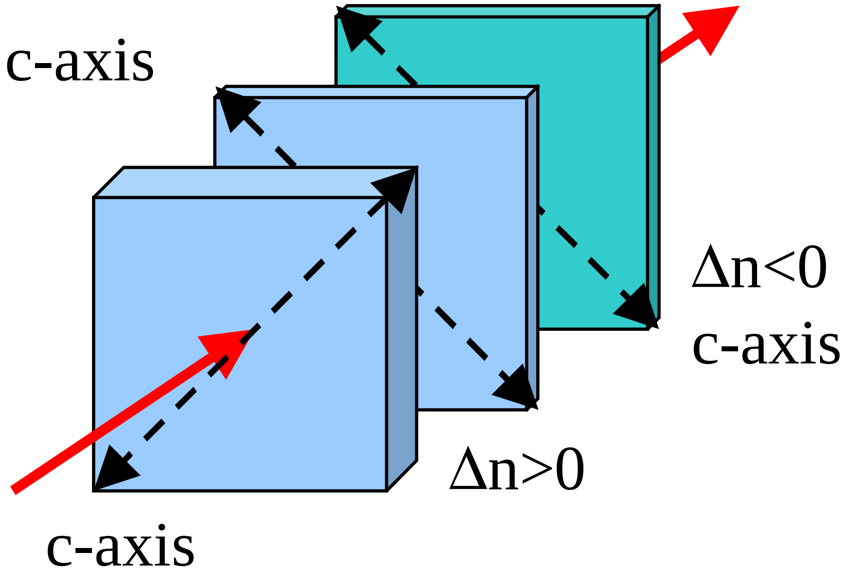
Wide Field-of-View Elements



Lyot-1:
Split elements with
a half-wave plate

Lyot-2:
Use two films of opposite
K-values (or Δn)
and crossed principal axes

Lyot 3 Wide Field Elements



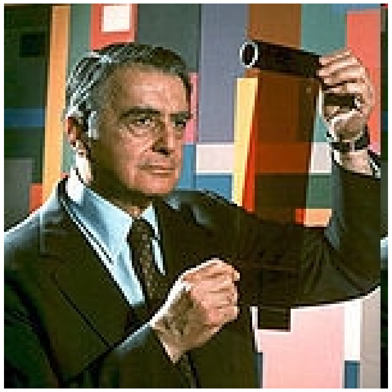
- Two plates of the same material with different thicknesses and crossed slow axes
- The third plate has an opposite *K* value (or Δn for uniaxial crystals)
- J.W. Evans, J. Opt. Soc. Am., 39, 229 (1949)

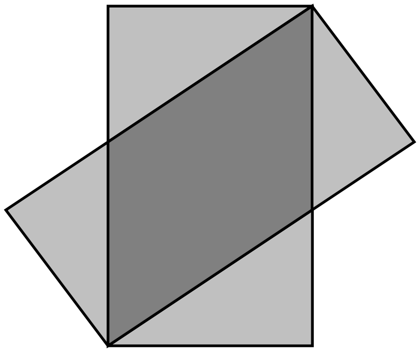
O-type Polarizers

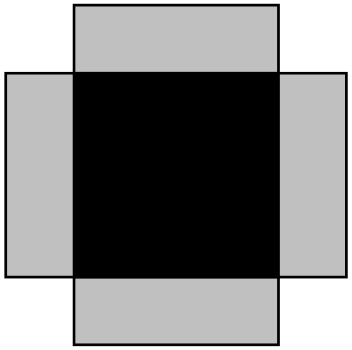
- In an O-type polarizer, the ordinary mode is transmitted, whereas the extraordinary mode is absorbed.
- The polarization state of the O-mode depends on the angle of incidence. This dependence can lead to a leakage of light through a pair of crossed polarizers.

Sheet Polarizers

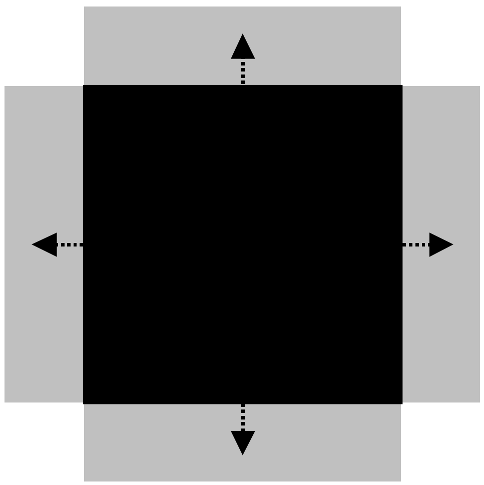
- Large Sheets of Dichroic Crystals are not available
- Erwin Land's Invention of Sheet Polarizers in 1920s
  - Single Crystal is Not Necessary
  - Multi-domain Crystal with Parallel Alignment is Adequate
- Polaroid Sheet Polarizers consist of Parallel Array of Submicroscopic Dichroic Crystals (Iodine)
  - O-type Sheet Polarizers: O-mode is transmitted.
  - E-type Sheet Polarizers: E-mode is transmitted. Attenuation occurs at oblique incidence.
- Large sheets (square miles) of polarizers are now available
- More than 10^8 square meters of polarizer needed in 2010



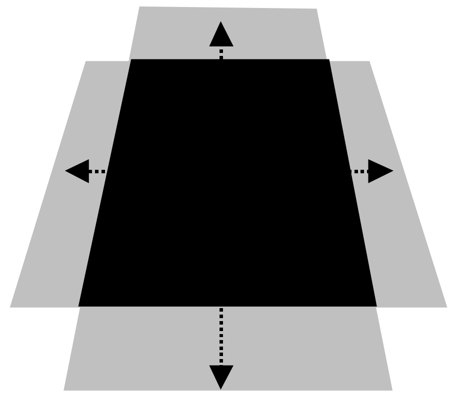




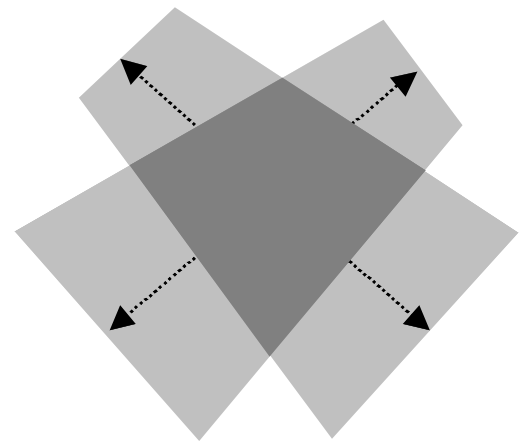
Leakage of Light through Crossed Polarizers



Normal Viewing
(θ=0°, ϕ=0°)



Oblique Viewing
(θ=60°, ϕ=0°)



Oblique Viewing
(θ=60°, ϕ=45°)

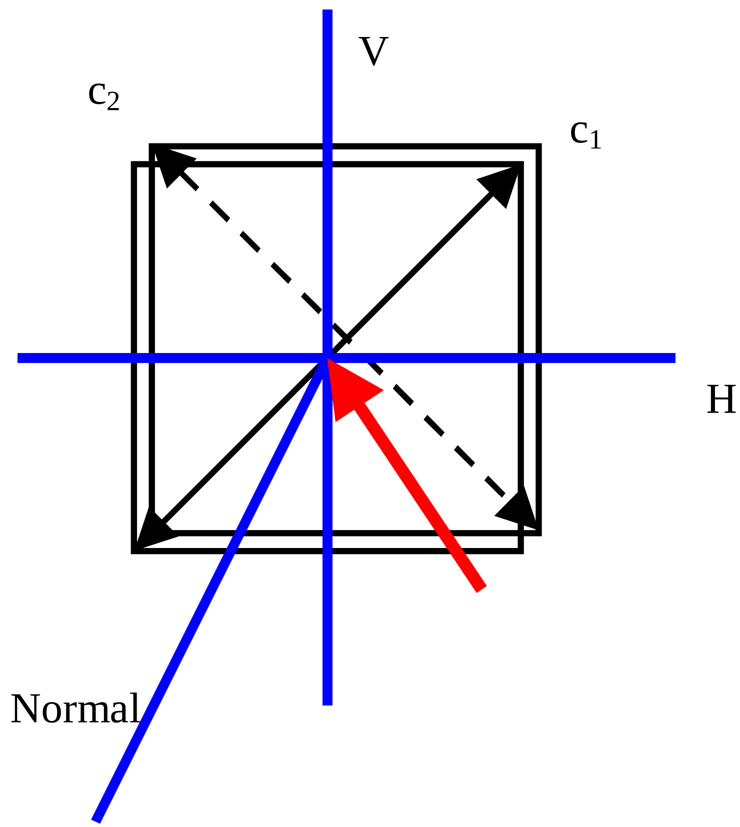
- Dark states of LCDs require polarizers with absorption axes that are mutually perpendicular
- Leakage of light occurs at oblique viewing
- The leakage can reach as high as 8%

Transmission through Crossed Polarizers

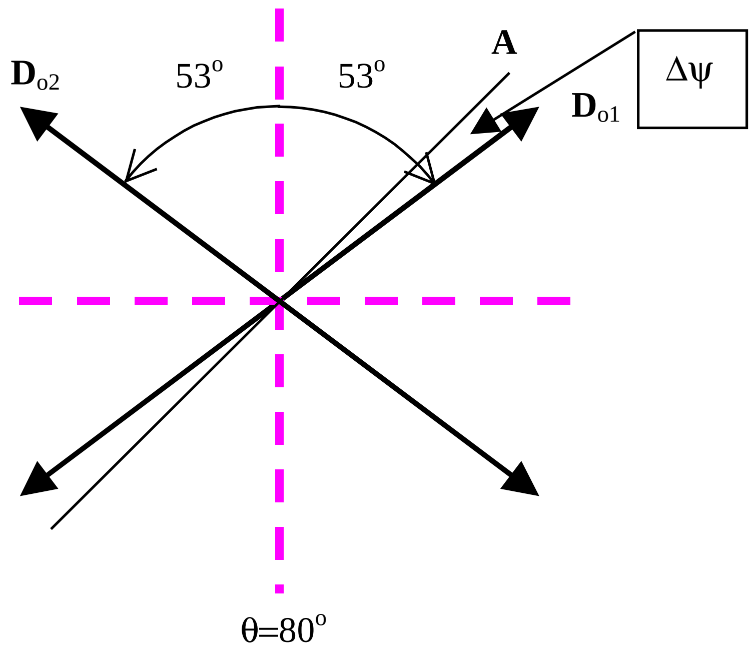
- Most sheet polarizers in LCDs are made of uniaxial materials which exhibit a strong attenuation for the extraordinary wave. Such polarizers, known as O-type polarizers, thus transmit ordinary wave and extinguish the extraordinary wave.
- The transmission of a beam of unpolarized light can be written

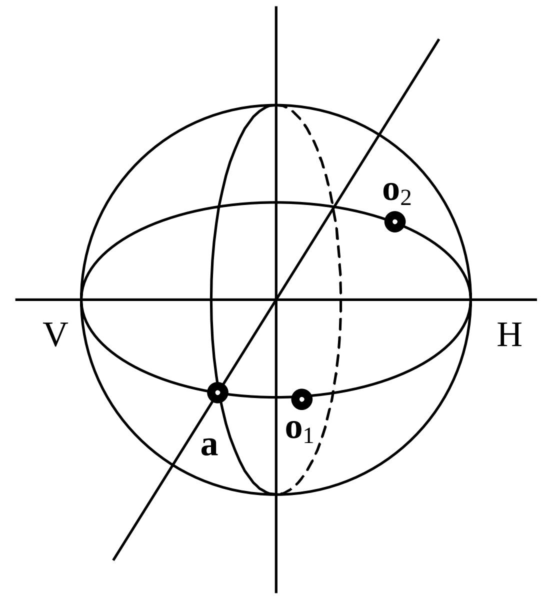
$$T = \frac{1}{2}\left|\mathbf{D}_{o1}\cdot\mathbf{D}_{o2}\right|^2 = \frac{1}{2}\left|\frac{(\mathbf{k}\cdot\mathbf{c}_1)(\mathbf{k}\cdot\mathbf{c}_2)}{|\mathbf{k}\times\mathbf{c}_1||\mathbf{k}\times\mathbf{c}_2|}\right|^2$$

- For normal incidence, the transmission is zero. Thus a completely dark state is obtained for normal incidence. However, for oblique incidence, the transmission is finite. The leakage is maximum when the viewing plane in 45 degrees from the absorption axes and is an increasing function of the angle of incidence (θ measured from the normal).



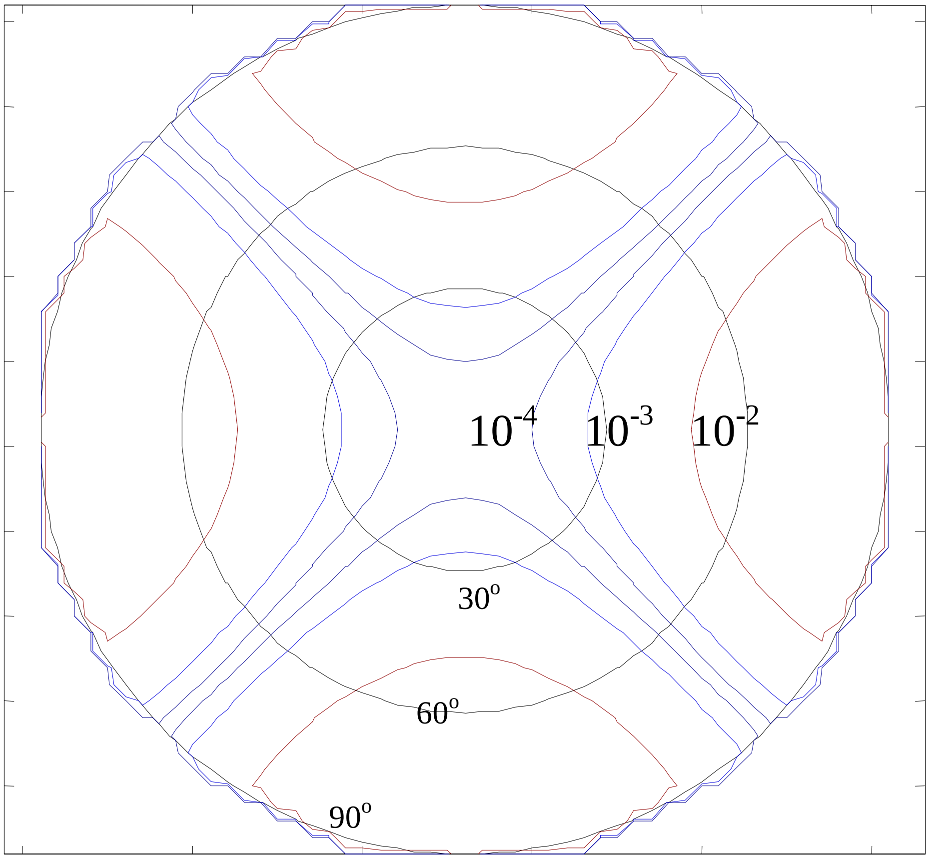
Transmission through Crossed Polarizers



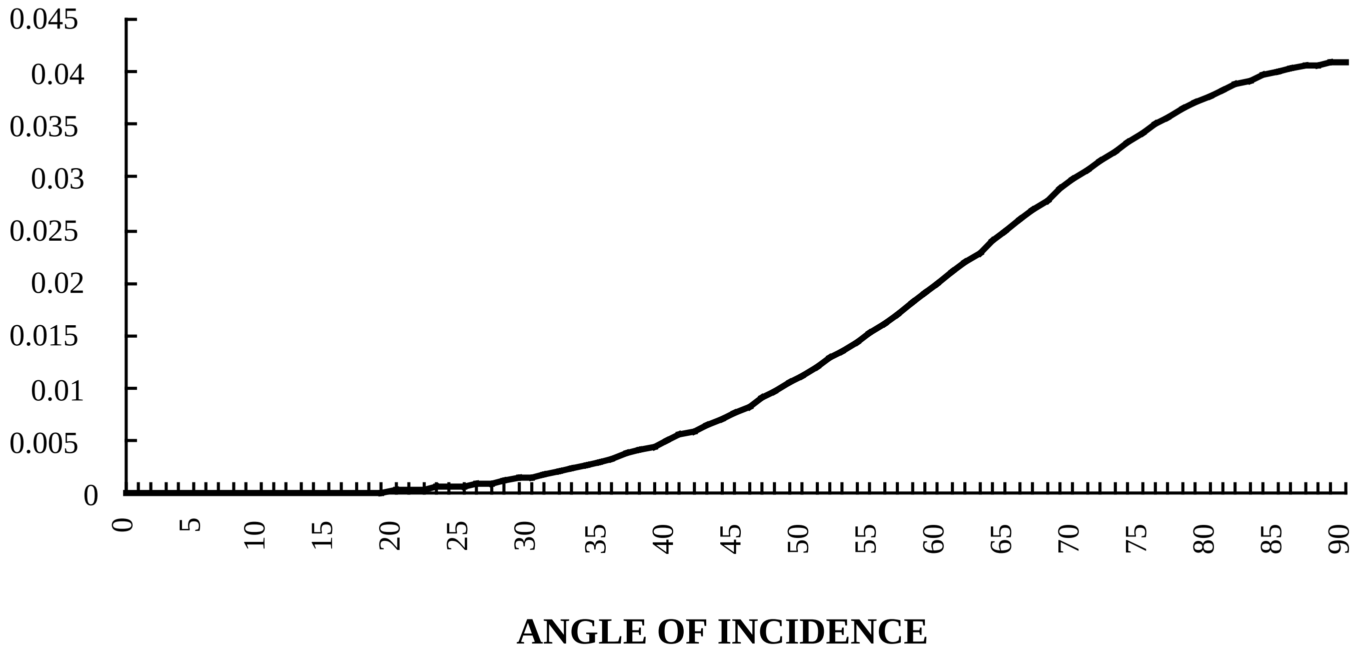


- We examine the orientation of $\mathbf{D}_{o1}$ and $\mathbf{D}_{o2}$. via the angle measured from the normal of the plane of incidence. For normal incidence, the angles are 45 degrees. When the plane of incidence in 45 degrees from the absorption axes of the polarizers, the angle between the unit vector $\mathbf{o}_1$ and the normal vector **s** is an increasing function of the angle of incidence. The deviation from 45 degrees $\Delta\psi$ can be as big as 8 degrees at $\theta=80^o$. This corresponds to a leakage of 3.8%. Figure 2a illustrates the orientation of the **D**-vectors of the transmitted polarization state in the polarizers and the Poincaré representation of the polarization states $\mathbf{o}_1$ and $\mathbf{o}_2$.

Equi-transmittance Contours
(Ideal crossed polarizers)



Leakage of Light through Crossed Polarizers

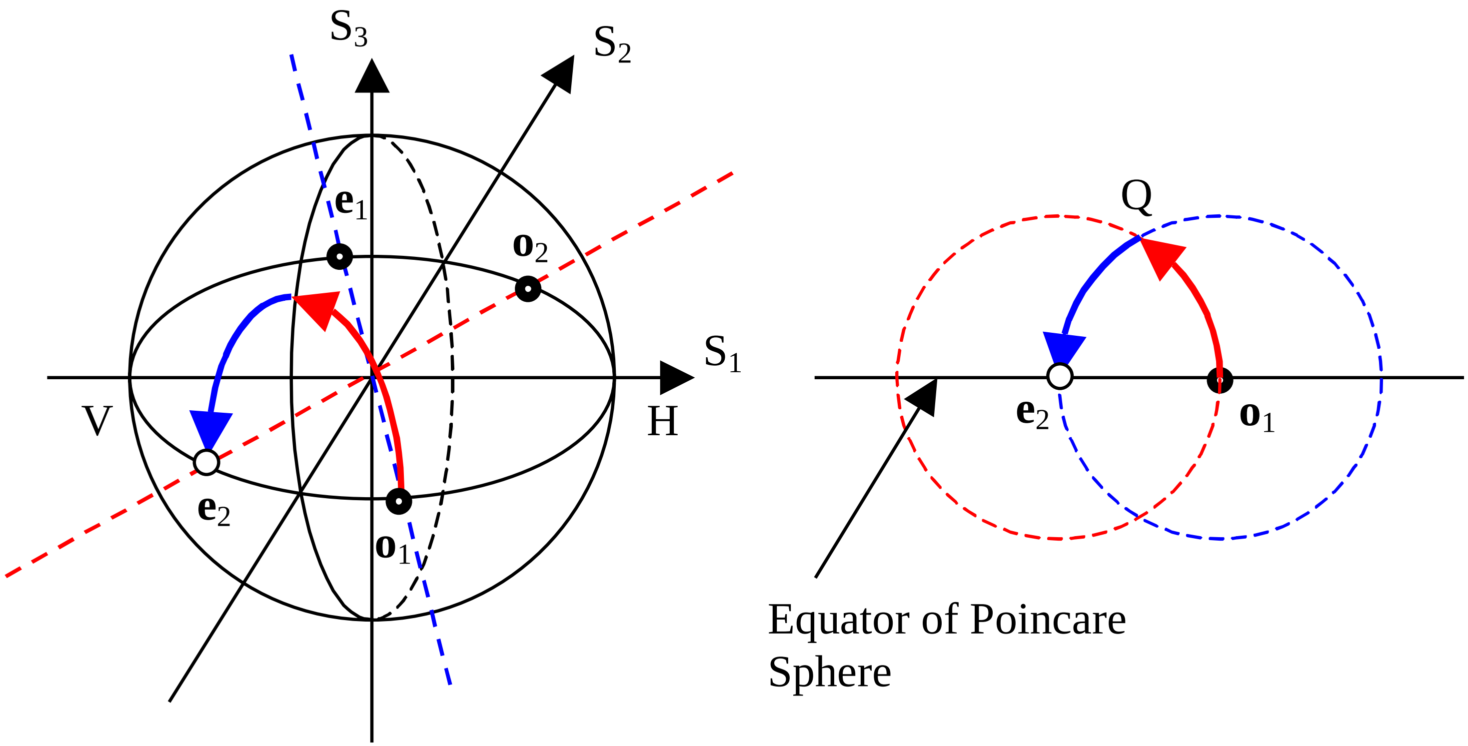


Angle of Incidence:	**0°**	**20°**	**40°**	**60°**	**80°**
Leakage of Light:	**0**	**0.04%**	**0.5%**	**2%**	**4%**

Leakage of Light Leads to Degradation of Contrast ratio

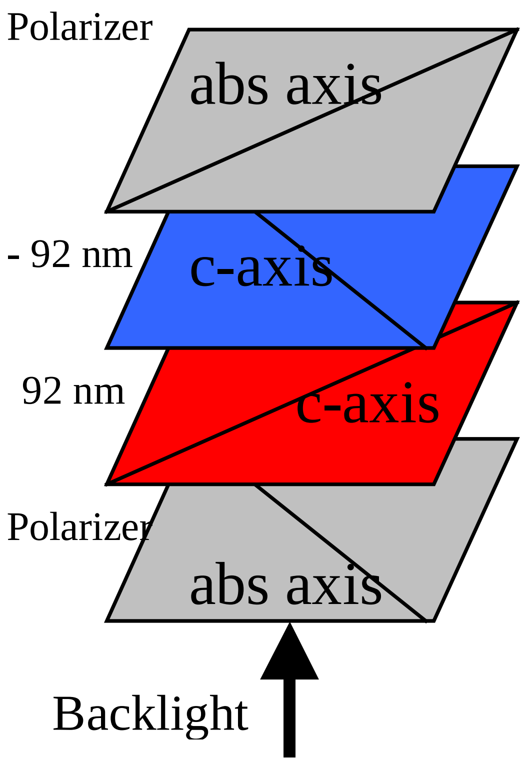
Example: with a 2% Leakage, the Maximum Contrast is 25.

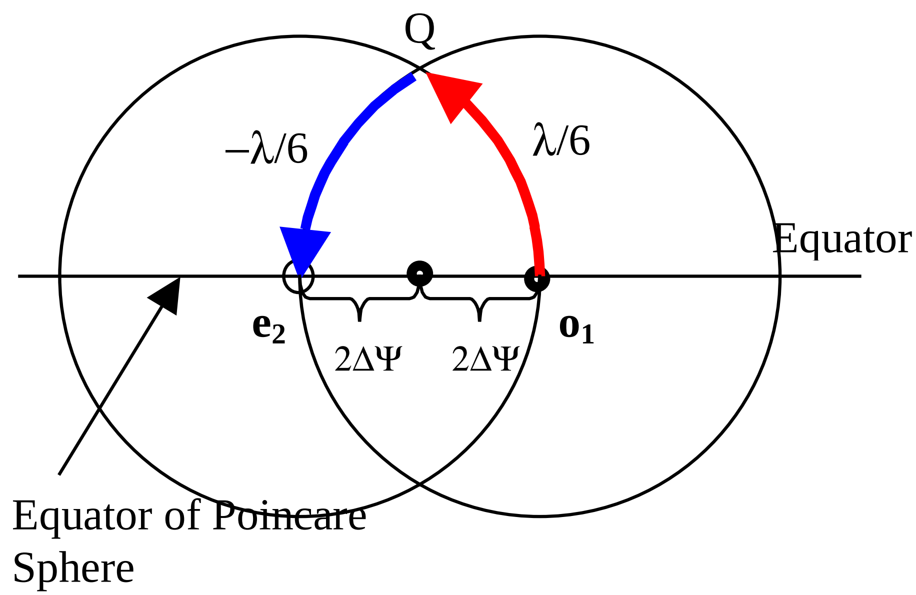
Leakage Elimination using Waveplates



- To eliminate the leakage, we must transform the polarization state from $\mathbf{o}_1$ (O-mode of 1st polarizer) to $\mathbf{e}_2$ (E-mode of 2nd polarizer) by using retardation plates.
- This can be achieved by using two a-plates each with a phase retardation of $\pi/3$ (six-th wave plates).

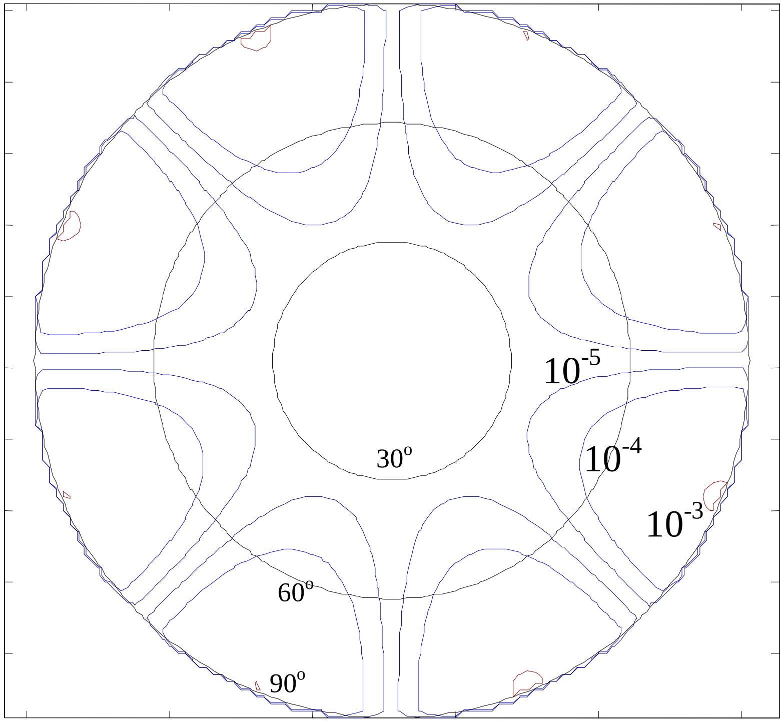
XA Compensators for Polarizers



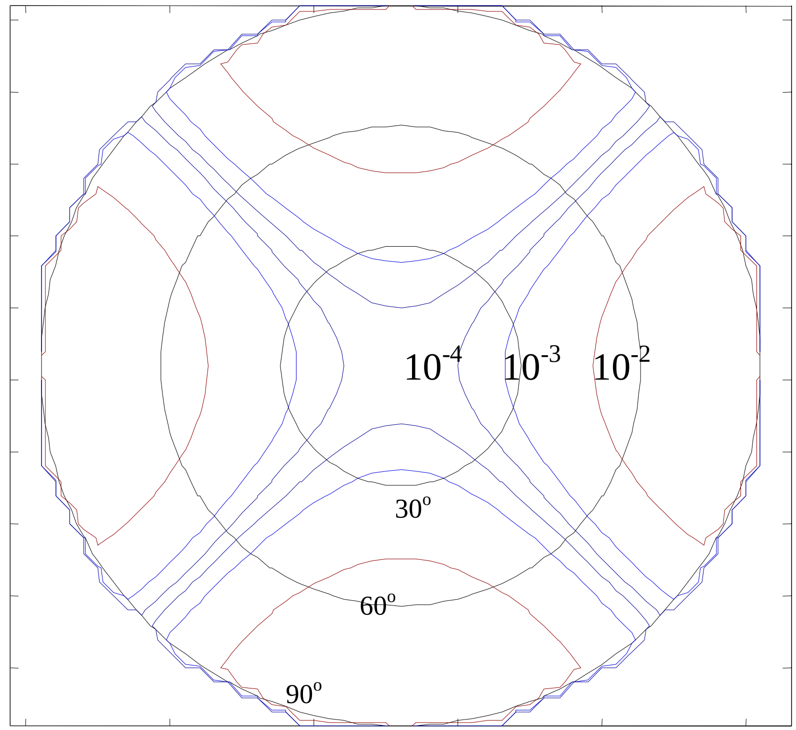


- The c-axes of a-plate compensators must be perpendicular to the absorption axis of the adjacent polarizer.
- A pair of crossed a-plates (XA) are needed.

Equi-transmittance Contours



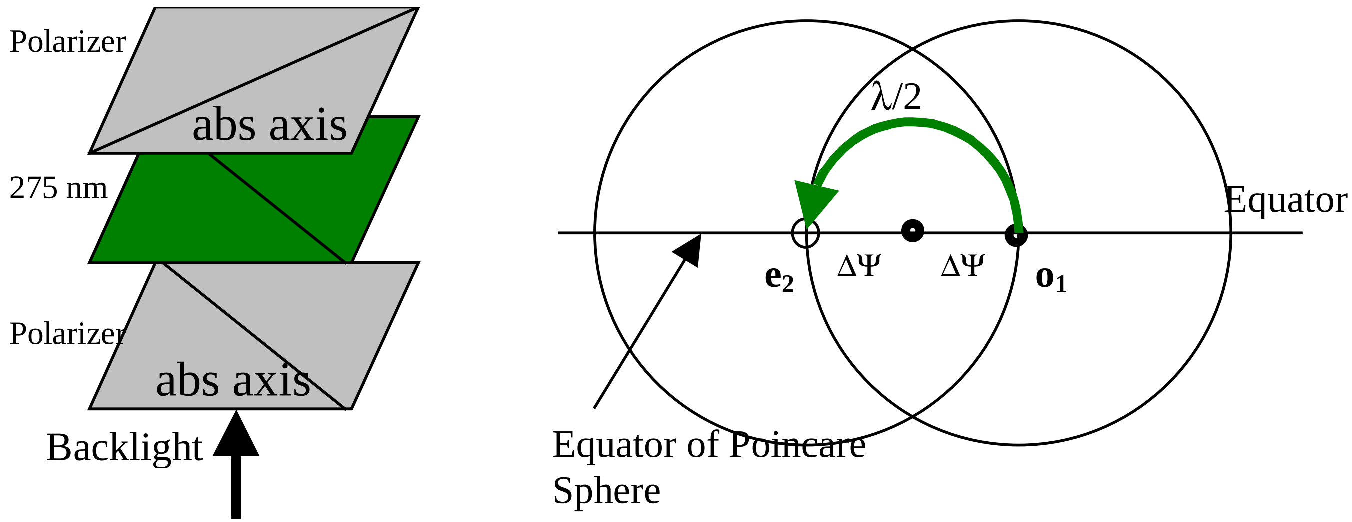
With (+a, -a) compensators



Without compensators

Without compensators, the leakage can be up to 10^{-3} for viewing at $\theta=30^{o}$.
With compensators, the leakage is cut to below 10^{-3} for viewing angle up to 80^{o}.

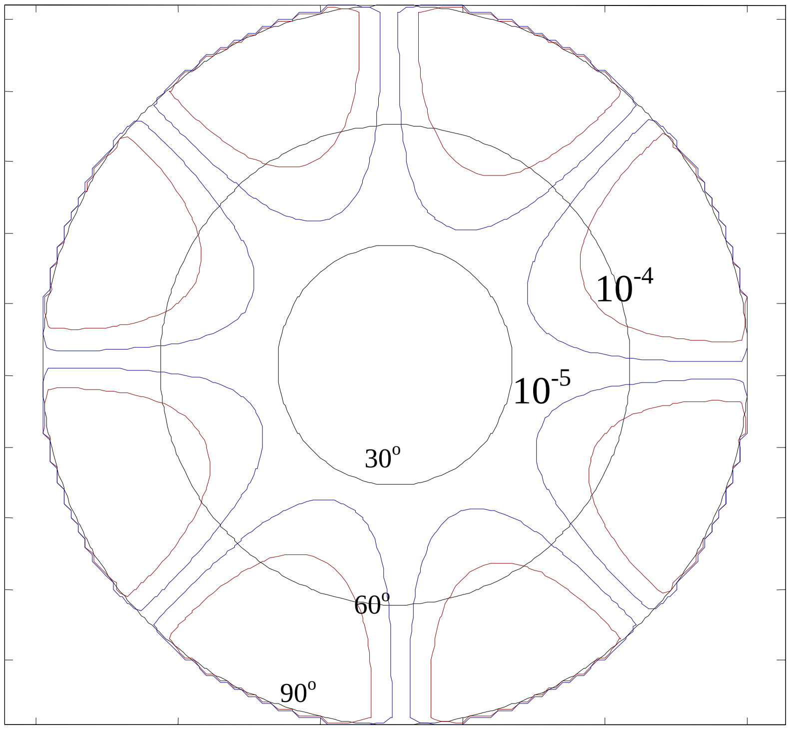
Biaxial Compensators for Polarizers



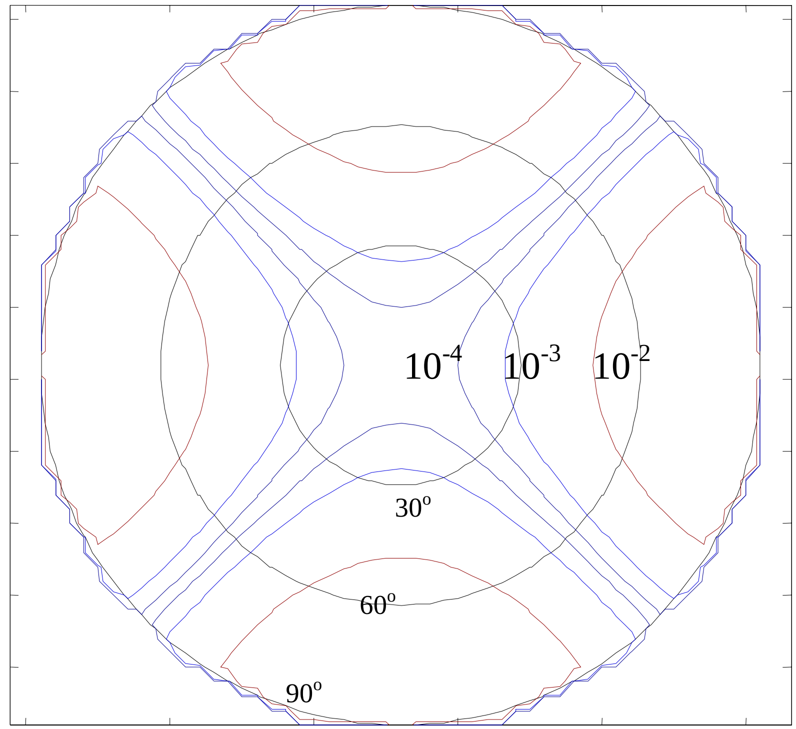
- A single biaxial plate with its principal axis of the largest index aligned parallel to the absorption axis of the first polarizer. Furthermore, the plate surface is parallel to OAP.
- The indices n_x , n_y , and n_z are chosen so that the slow axis is oriented at 45^o relative to plane of incidence. The retardance is $(n_x – n_y)d = \lambda/2$.

Takahiro Ishinabe, Tetsuya Miyashita and Tatsuo Uchida, Jpn. J. Appl. Phys. Vol.41 (2002) pp.4553-4558

Equi-transmittance Contours



With a biaxial compensator



Without compensators

- Biaxial compensator eliminates the leakage down to 10^{-4} for viewing angles up to 60°.

Origin of Leakage of Light in LCDs

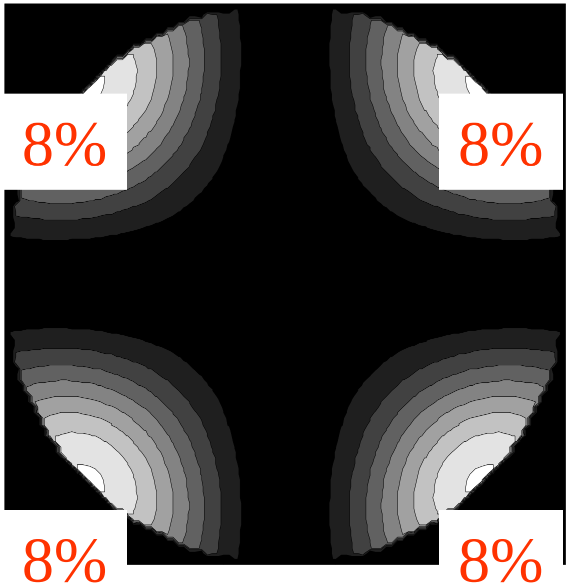
- **Leakage of light through crossed polarizers due to poor extinction ratios of polarizers.**
- **Leakage of light through crossed ideal polarizers at oblique incidence.**
- **Leakage of light at polarizer due to elliptical polarization state after transmitting through LC cell.**
- **Leakage of light leads to poor contrast ratios and color instability in Displays.**

Contrast Ratio of LCDs

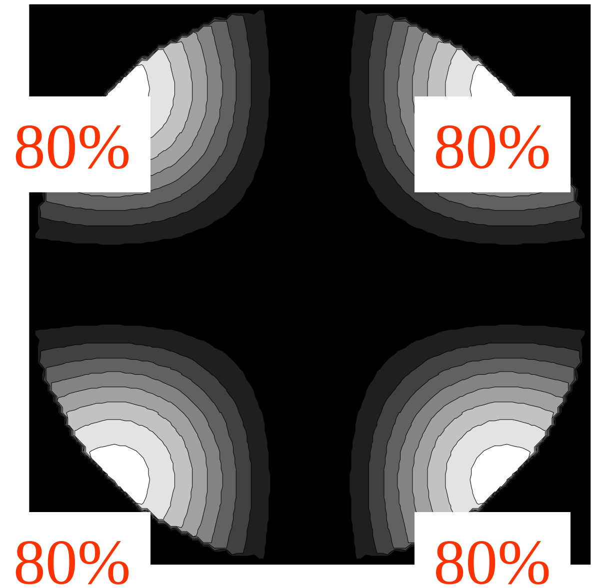
$$\text{Contrast ratio (CR)} = \frac{\text{Transimission at Bright State}}{\text{Transimission at Dark State}}$$

- High contrast ratios (CR) require a dark state with near zero transmission.
- Leakage of light at dark state leads to poor contrast ratios and color instability.

Leakage of Light in Dark State of VA-LCD



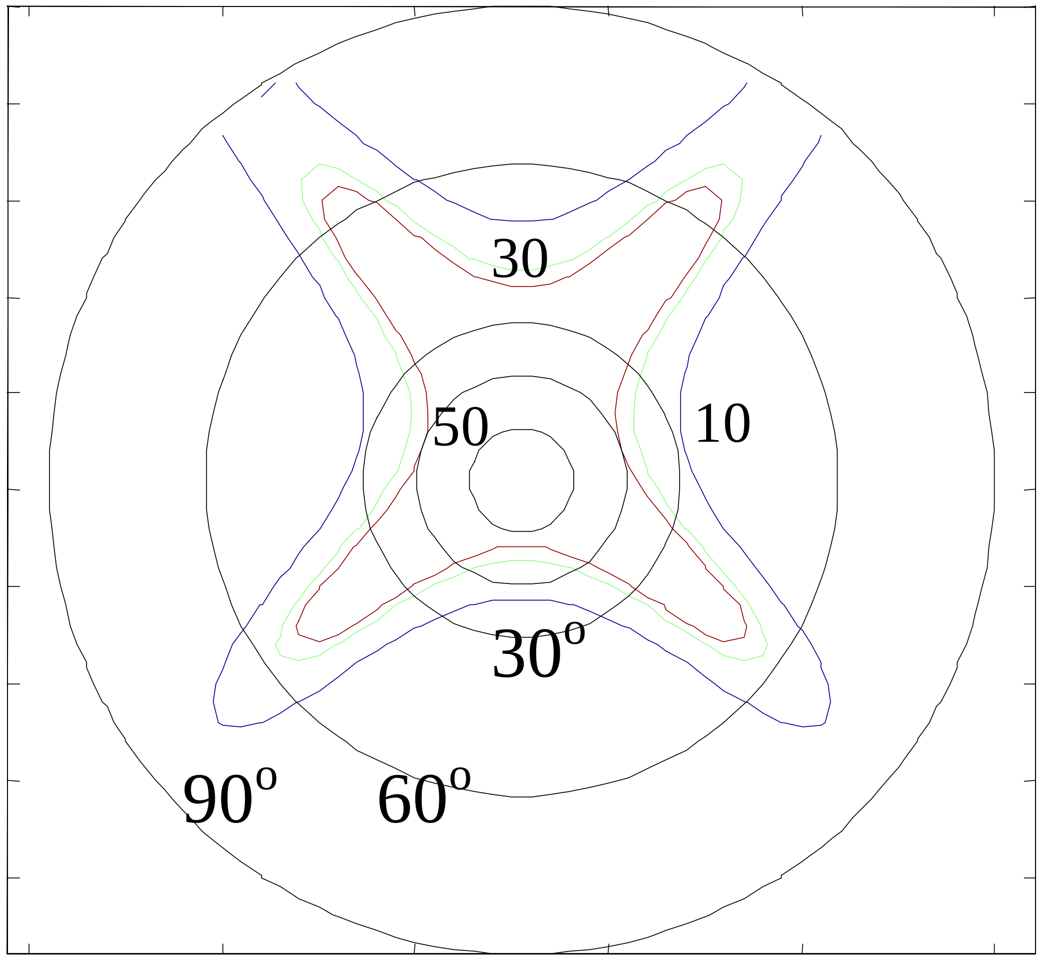
Crossed Polarizers



Crossed Polarizers with LC

- Leakage of light due to polarizers alone can reach 8%
- Linearly polarized light is transformed into elliptically polarized light after transmitting through the VA-LC cell, leading to even more leakage of light
- An overall leakage of light can reach as high as 80% in VA-LCDs
- The leakage leads to poor contrast ratios and color instability

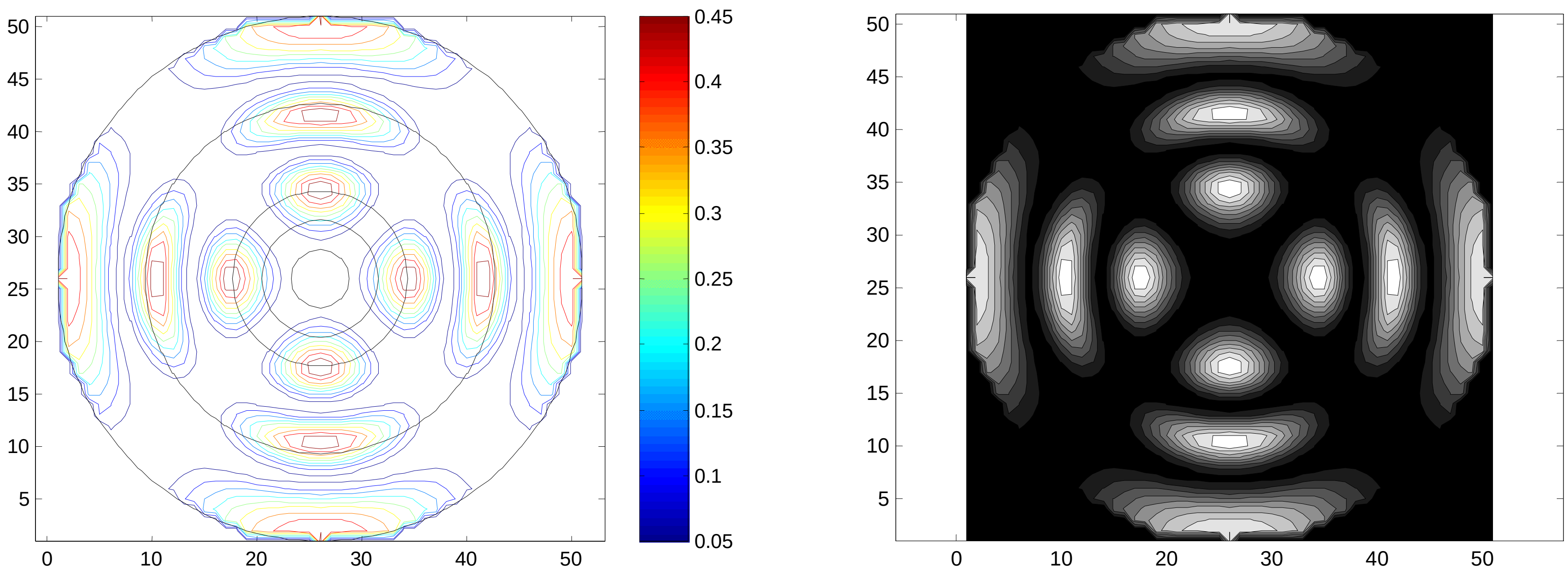
Equi-Contrast Contours in NW TN-LCDs



Poor contrast at large viewing angles due to leakage of light through polarizers and elliptical polarization states after LC cell.

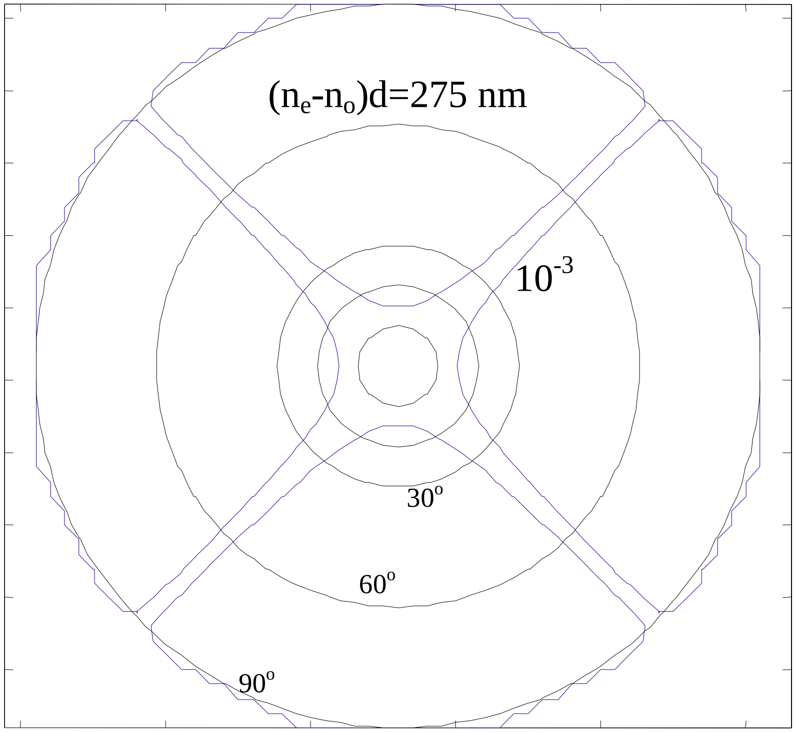
Equi-transmittance Contours

(A thick C-plate in crossed polarizers)

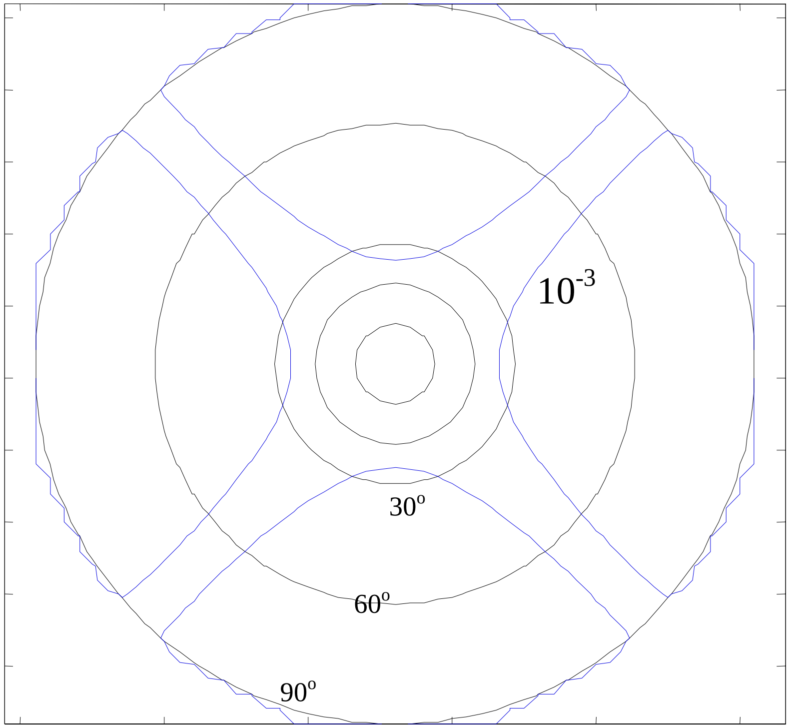


- Example: A thick c-plate with $(n_e-n_o)d=2.5\ \mu m$.
- Conoscopy consists of concentric bright rings with a dark cross along absorption axes of polarizers.

Equi-transmittance Contours



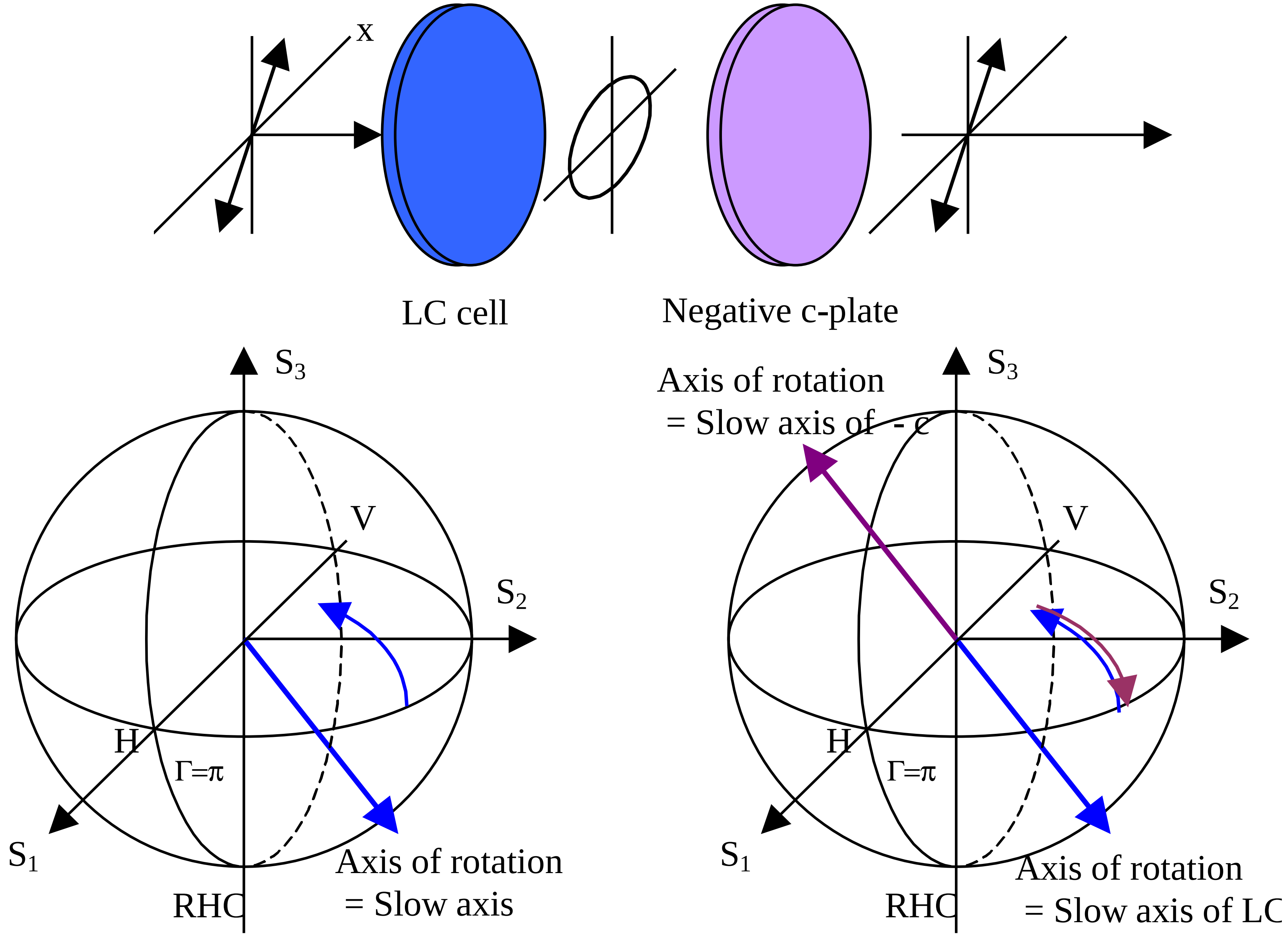
C-plate in crossed Polarizers



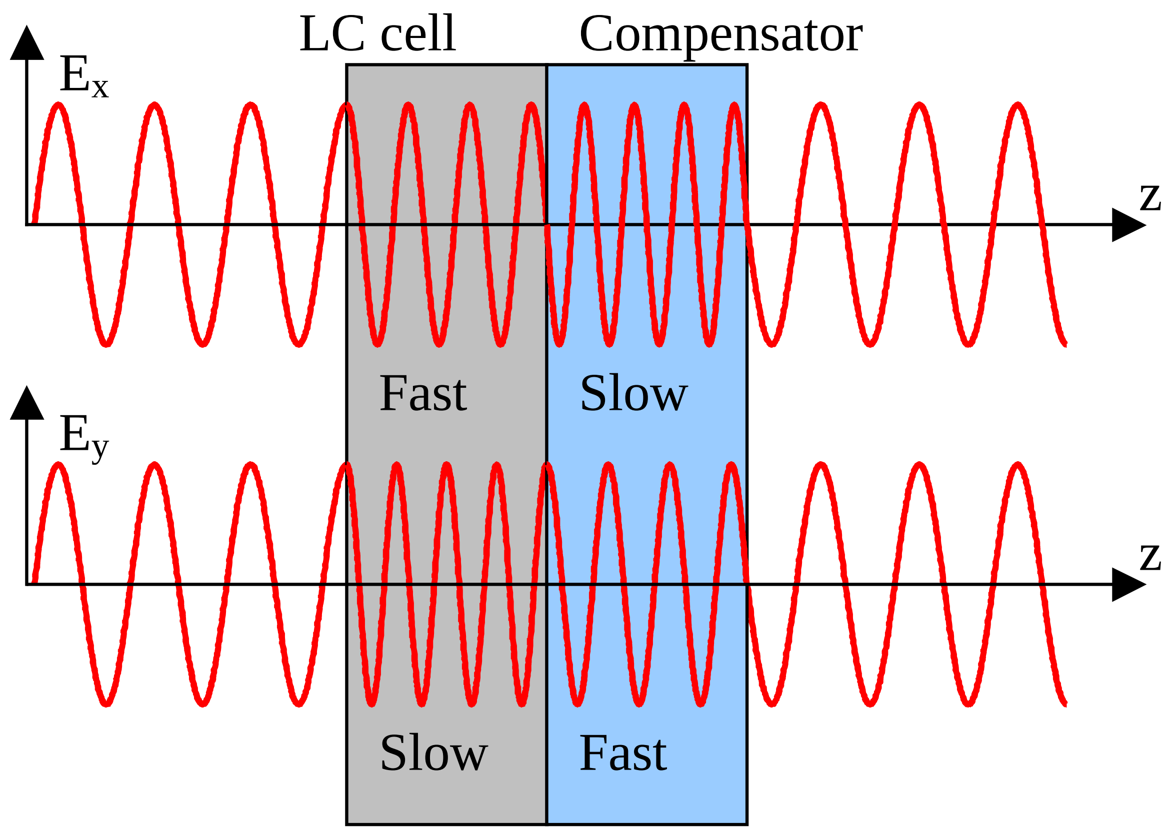
Crossed Polarizers

- The presence of a c-plate between crossed polarizers leads to further leakage due to the elliptical polarization state of light after transmitting through the c-plate.

Birefringence Compensation



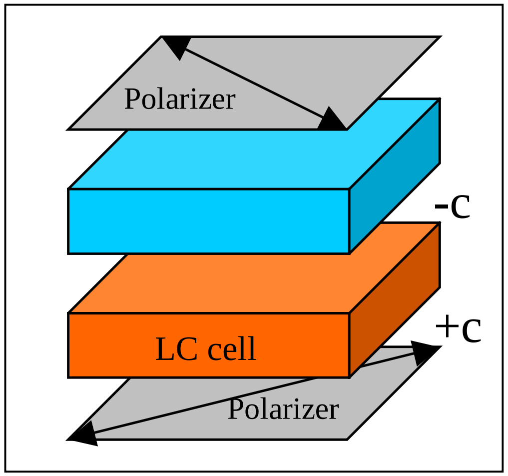
Birefringence Compensation

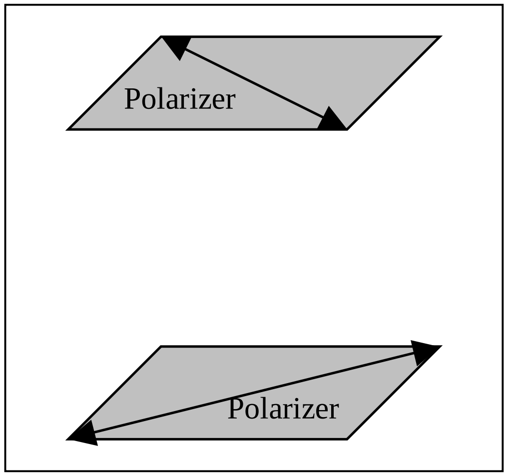


- The compensator is made of materials with an opposite sign of the birefringence.

Negative C-plate Compensators

- A negative c-plate can be employed to compensate the positive retardation due to the LC cell. The polarization state becomes linear after transmitting through the LC cell and the negative c-plate (provided $|n_e - n_o| << n_o$).
- The leakage due to elliptical polarization state is eliminated.
- The leakage due to crossed polarizers at oblique viewing remains.
- For high contrast in LCDs, we must also eliminate leakage due to crossed polarizers.





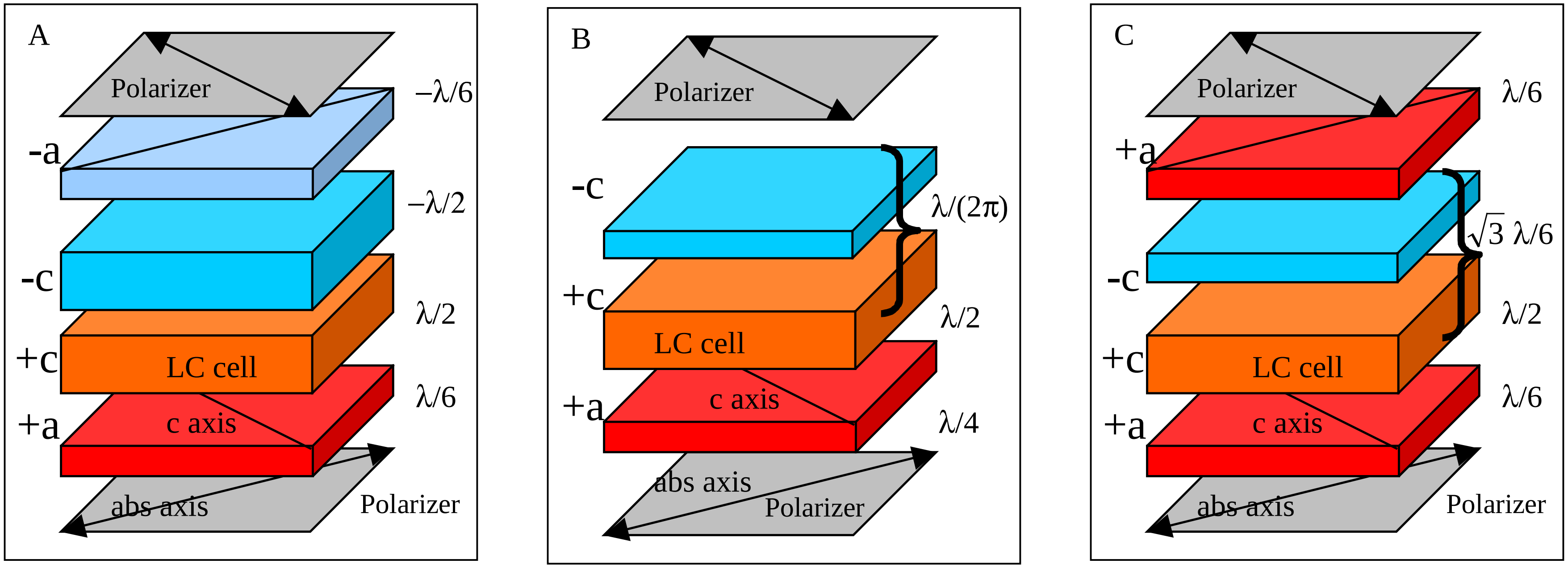
Compensators for LCDs

- Elimination of all possible sources of leakage of light in the dark state
- Leakage of light due to polarizers
  - Sixth-wave plates, quarter-wave plates
  - Biaxial plates
- Leakage of light due to LC cell
  - Negative c-plates
- Dispersion considerations
  - Matching of dispersion among the compensator materials and the LC material
- Broadband considerations
  - Achromatic wave plates

Dark States of LCDs

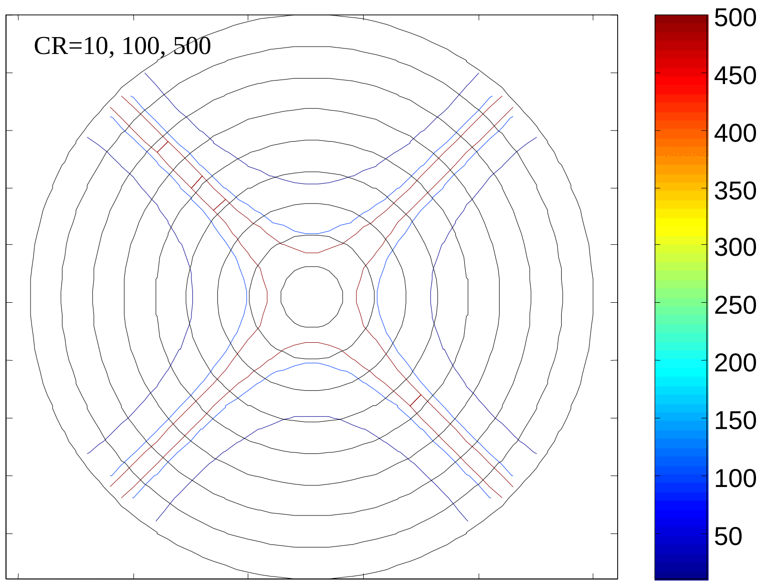
- Normally White (NW) TN-LCDs
  - Voltage is ON
  - LC is approximately a positive c-plate
  - Leakage due to polarizers and LC cell
- Normally Black (NB) VA-LCDs
  - Voltage is OFF
  - LC is a positive c-plate
  - Leakage due to polarizers and LC cell
- Normally Black (NB) IPS-LCDs
  - Voltage is OFF
  - LC is a positive a-plates
  - Leakage due to polarizers ONLY

VA LCD with Compensators

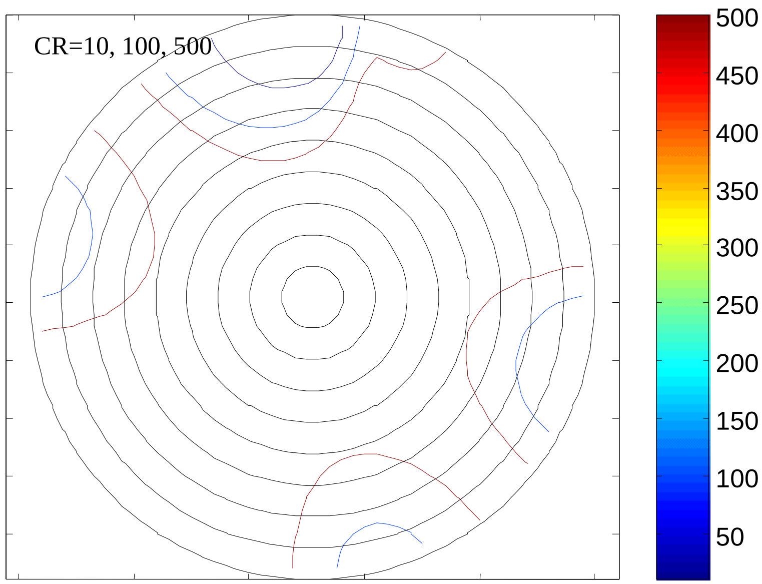


- For high contrast in LCDs, we must eliminate leakage due to crossed polarizers as well as birefringence of LC cell.
- Design A eliminates the leakage via the λ/6 (+a, -a) scheme.
- Design B eliminates the leakage via the (+a, +c) scheme.
- Design C eliminates the leakage via the (+a, +c, +a) scheme.

Viewing Angle Improvement in VA LCDs



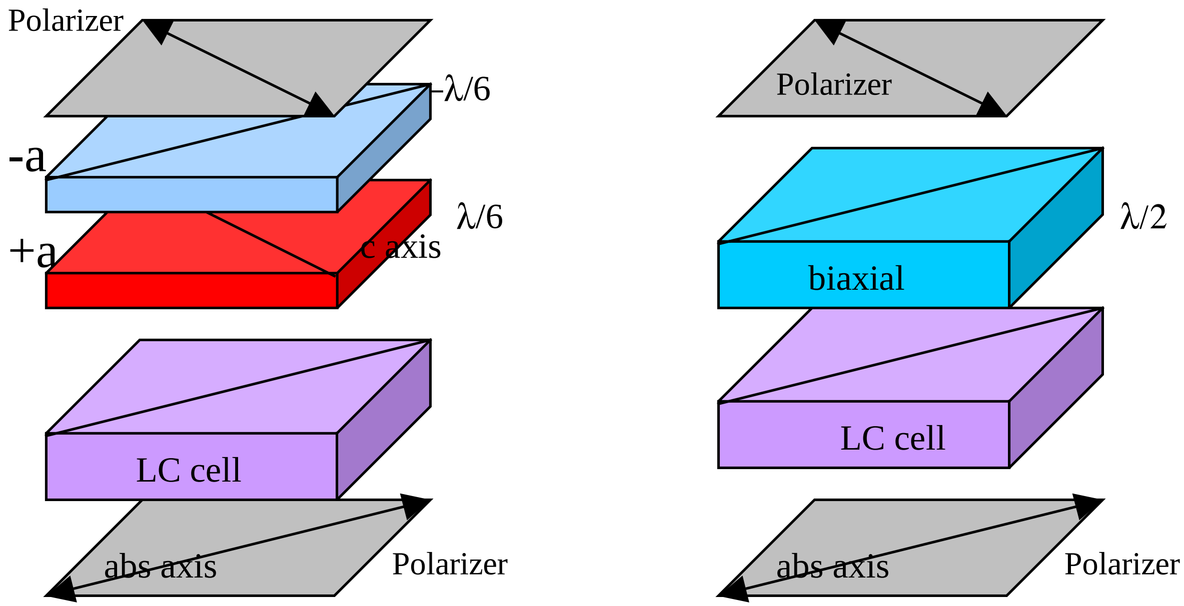
VA-LCD without Compensator



VA-LCD with AC Compensator

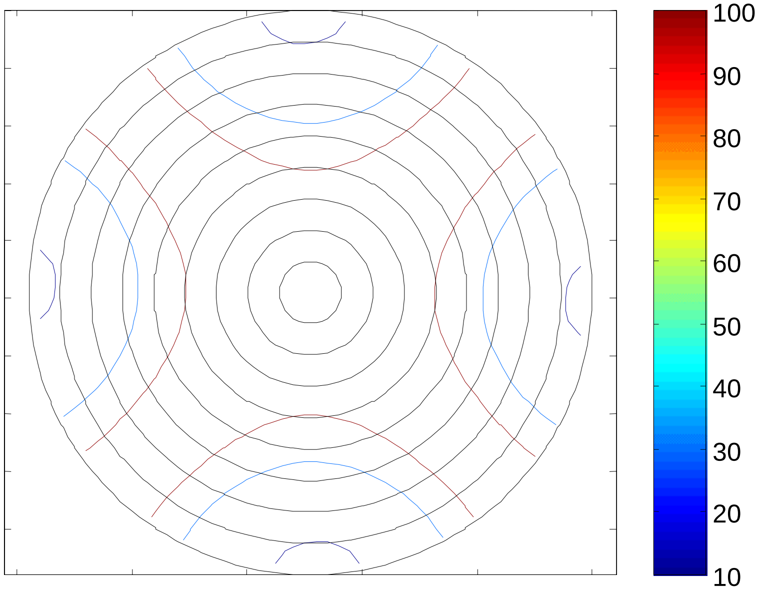
- Using (+a, +c) compensators, the viewing angles for contrast ratios of 500 increase from 30 degrees to 100 degrees.
- Similar improvement can be achieved with other compensator schemes, including biaxial films.

IPS LCD with Compensators

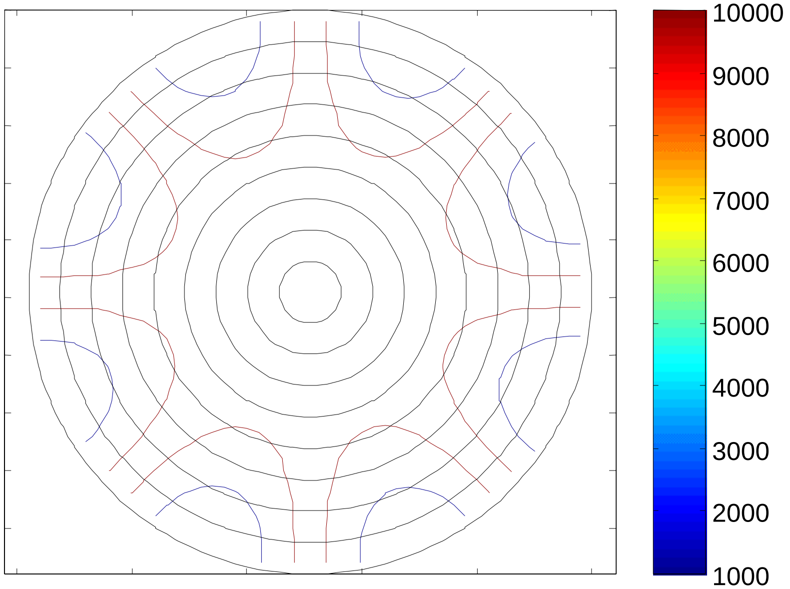


- Leakage of light at the dark state of IPS LCDs is due to crossed polarizers only.
- A combination of (+a, -a) plates eliminate the leakage of light due to crossed polarizers.
- A single biaxial plate with nz=(nx+ny)/2 can also eliminate the leakage of light due to crossed polarizers.

Viewing Angle Improvement in IPS LCDs



IPS-LCD without Compensator

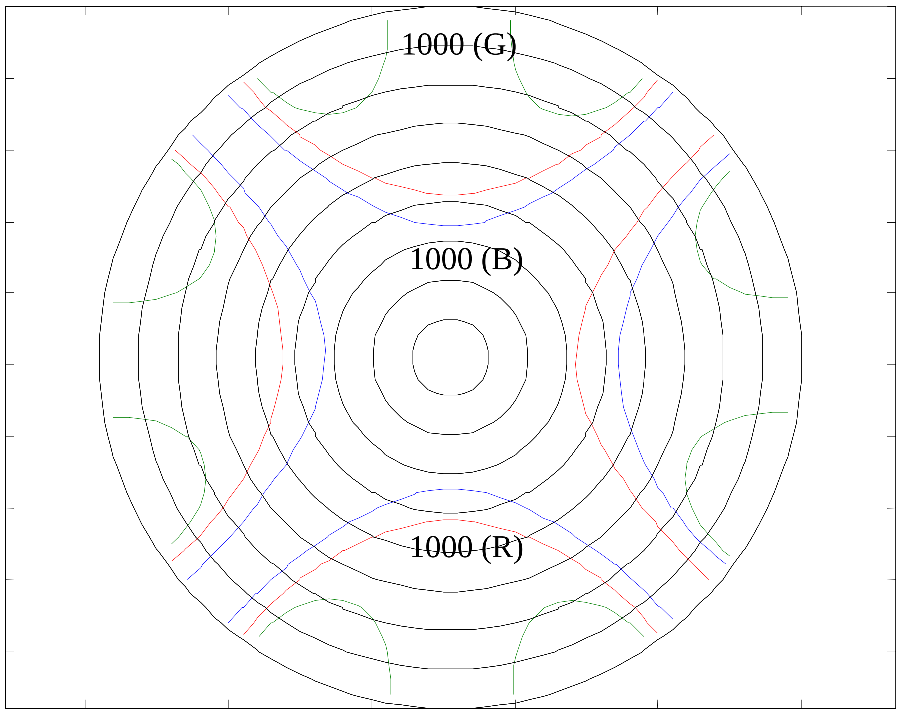


IPS-LCD with AA Compensator

- Using (+a, -a) compensators, the viewing angles for contrast ratios of 100 increase from ± 40 degrees to ± 90 degrees.
- Similar improvement can be achieved with other compensator schemes, including biaxial films.

Color Dependence of Compensators

(Example: IPS LCDs)



- Using (+a, -a) compensators designed for λ=550 nm, the viewing angles for contrast ratios of 1000 are up to ± 90 degrees.
- For red light (650 nm) and green light (450 nm), the viewing angles for CR=1,000 become ± 30, ± 40 degrees, respectively.

Summary

- Optical Transmission in Birefringent Networks
  - Phase retardation Γ depends on (λ,θ,ϕ)
  - Slow axis orientation depends on (θ,ϕ)
- Achromatic Wave Plates
  - Pancharatnam
  - Beckers
- Wide Field-of-View Elements
- Applications in LCDs
- Other Applications

Reference: P. Yeh and C. Gu, "Optics of LCDs, 2nd Ed." (Wiley 2010)

Thank You