Hale COLLAGE (NJIT Phys-780)
Topics in Solar Observation Techniques

Lecture 04: Solar Imaging Instruments

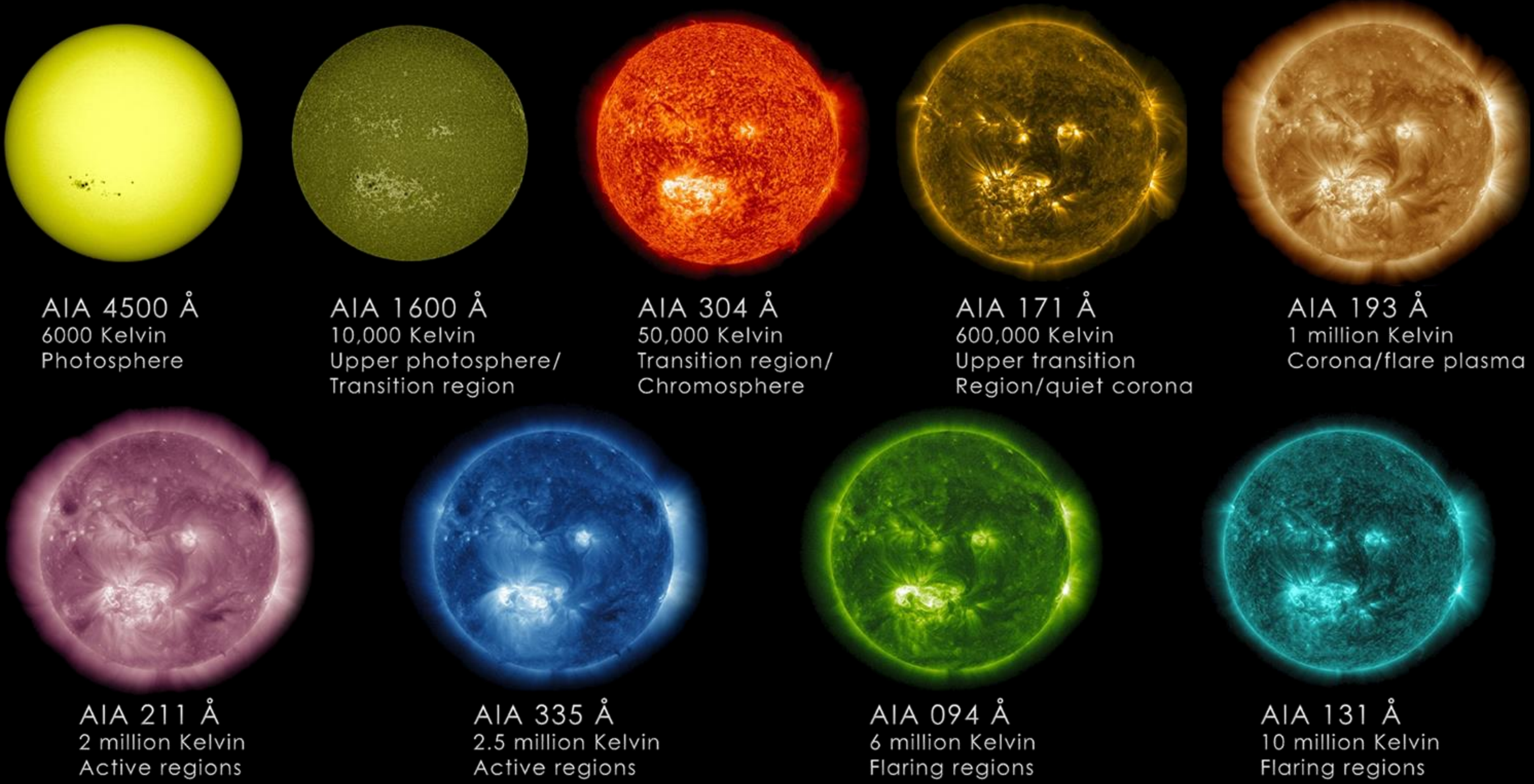
Wenda Cao

Big Bear Solar Observatory
New Jersey Institute of Technology

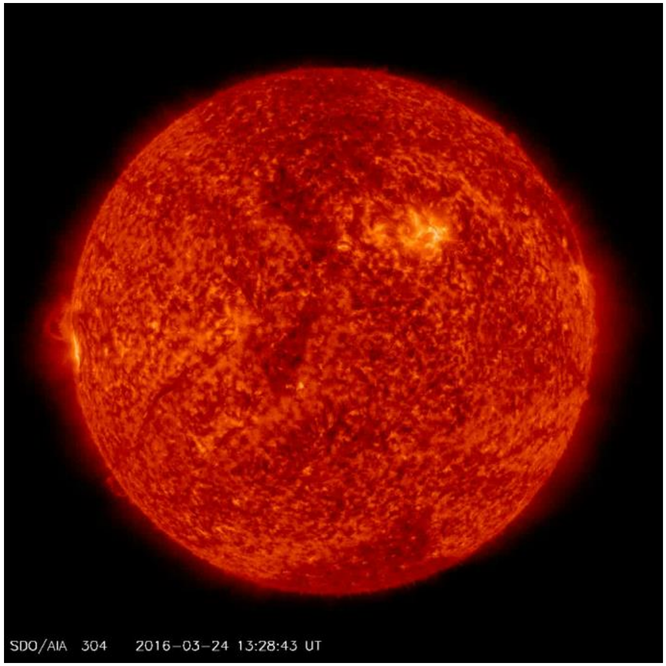
Valentin M. Pillet

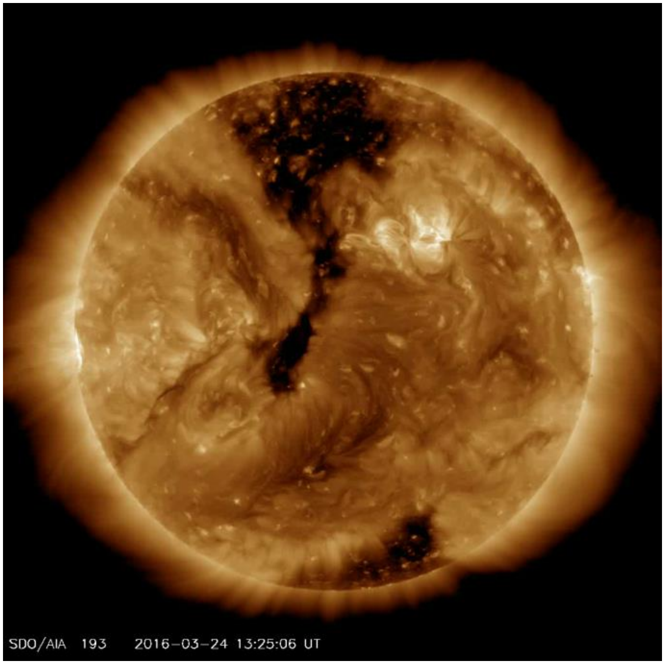
National Solar Observatory

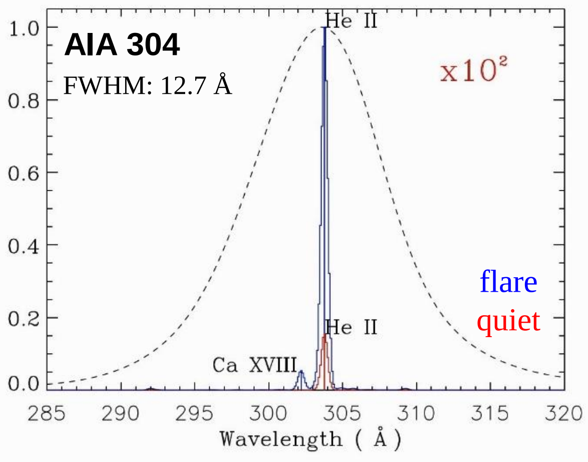
SDO – AIA Coronal Imaging

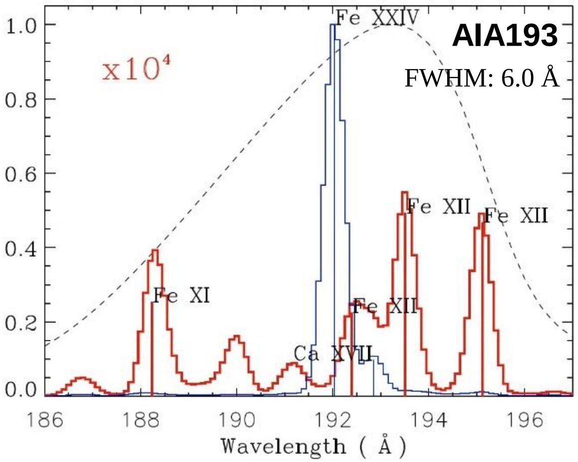


SDO – AIA Filters



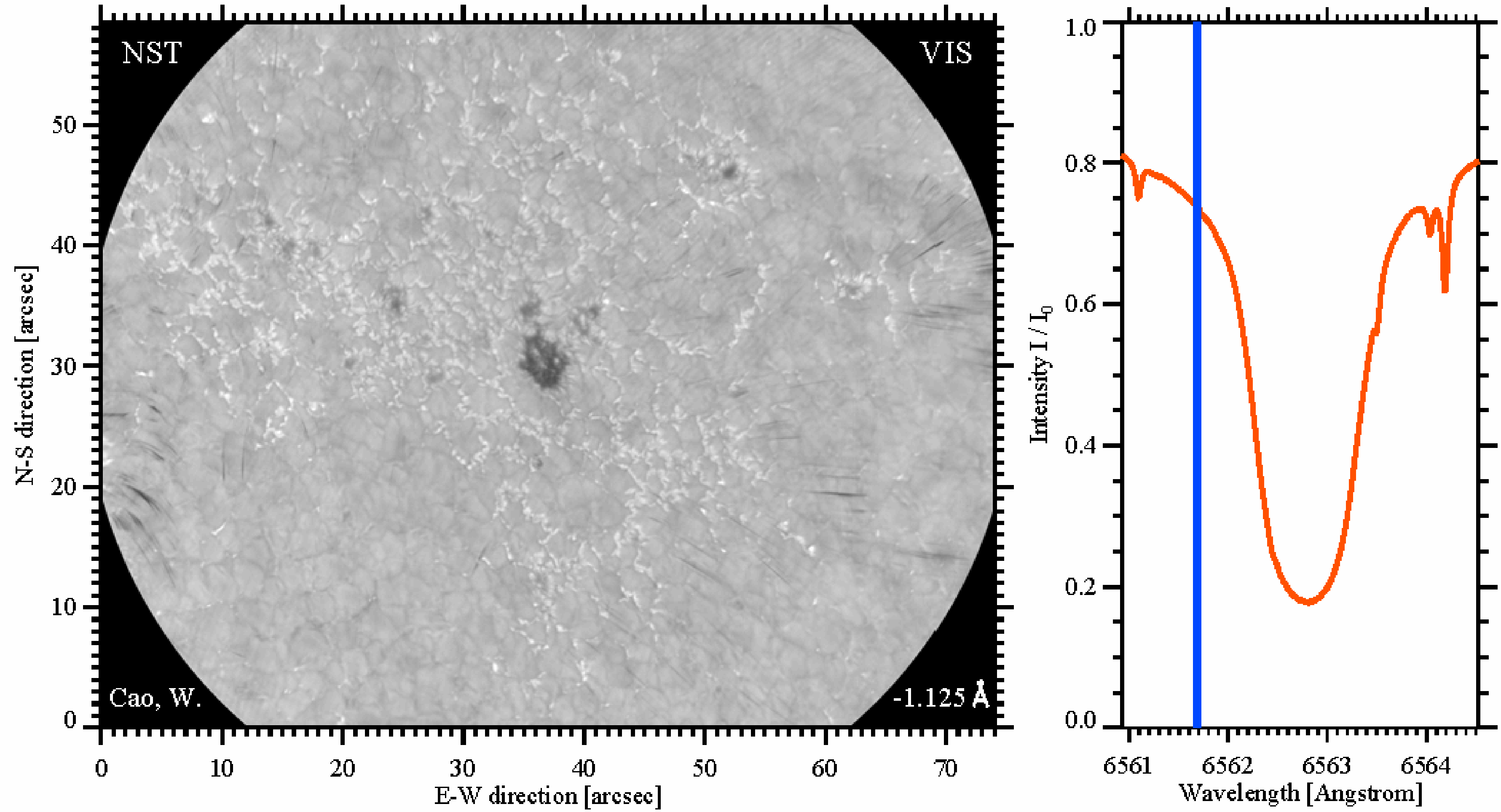






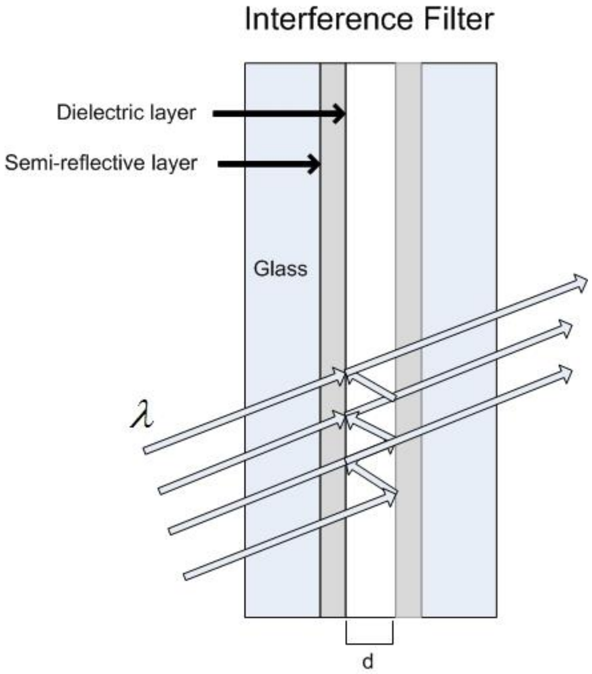
- *SDO/AIA passbands were chosen very carefully to sample a wide range of T*
- *Sometimes, though, there are still >>1 lines in the narrow pass bands …*

NST-VIS Spectroscopy



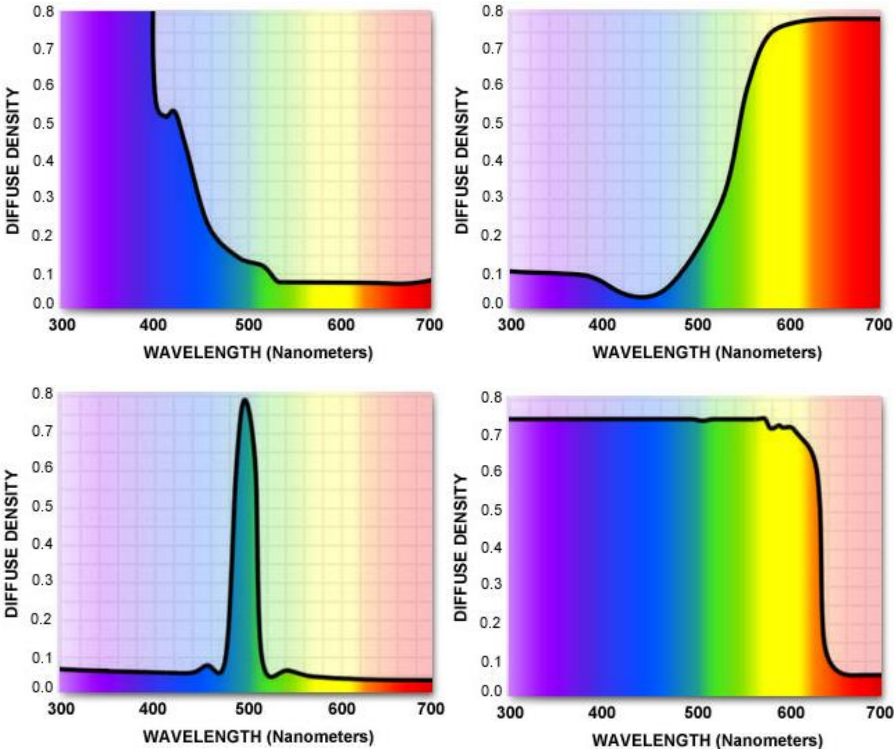
1. Interference Filters

- ❑ *Interference filters are multilayer thin-film devices. An optical filter consists of multiple layers of evaporated coatings on a substrate, whose spectral properties are the result of wavelength interference rather than absorption.*
- ❑ *Provide a passband of a few to hundreds angstroms*
  - ❑ *Interference filter category*
  - ❑ *Interference filter structure*
  - ❑ *Interference filter principal*
  - ❑ *Interference filter terminology*
  - ❑ *Use an interference filter in a right way*
  - ❑ *Choose a right interference filter*



Interference Filter Category

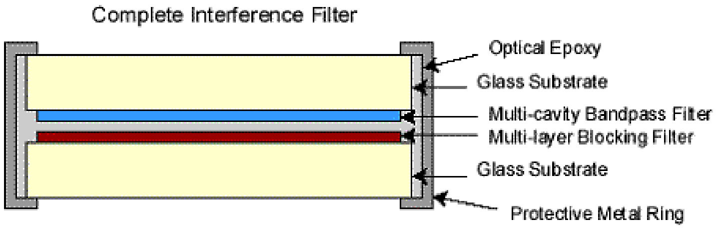
- ***Short Wavelength Pass:*** *transmits visible light of lower wavelengths and block light with higher wavelengths.*
- ***Long Wavelength Pass:*** *allows light of longer wavelengths to pass through it and effectively block shorter wavelengths.*
- ***Band Pass:*** *transmit one particular region (or band) of light spectrum. It passes only a very narrow region of wavelengths and blocks a majority of light incident upon the filter surface.*
- ***Sharp Cutting:*** *eliminates spectral regions, such as the infrared, "hot rejector".*
- ***Broad Band****: transmit one particular region (or band) of light spectrum. It usually has rather broad transmission characteristics and passes a significant number of wavelengths.*

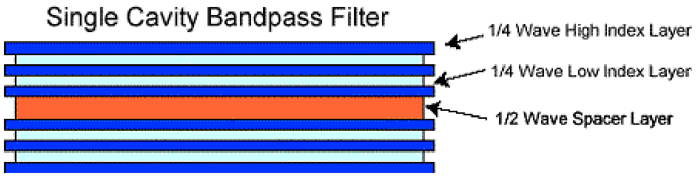


Courtesy: micro.magnet.fsu.edu

Interference Filter Structure

- *Interference filters are designed to provide constructive or destructive interference of light by taking advantage of the refraction of light through different materials.*
- *Glass substrates*
- *Multilayer thin-film coatings are applied to substrates.*
- *Single cavity bandpass filter*
  - *Spacer: the gap between the reflecting surfaces is a thin film of dielectric material, with a thickness of one-half wave at the desired peak transmission wavelength.*
  - *Reflection layers: consist of several film layers, each of which is a quarterwave thick.*
- *Multi-layer blocking filter*
- *Optical epoxy and protective metal ring*





Courtesy: micro.magnet.fsu.edu

Spacer – FP Resonator

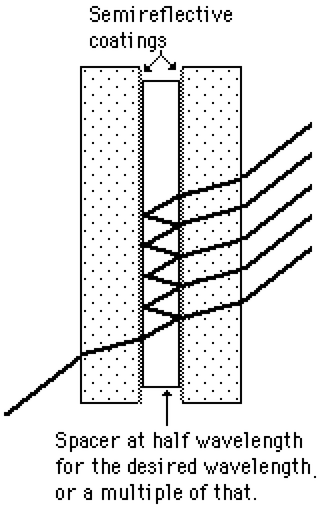
- *Spacer: the gap between the reflecting surfaces is a thin film of dielectric material, with a thickness of one-half wave at the desired peak transmission wavelength.* (d = $\lambda_0/2$)
- *Start from a Fabry-Perot etalon …* $2AB - CD = 2d\cos\alpha$

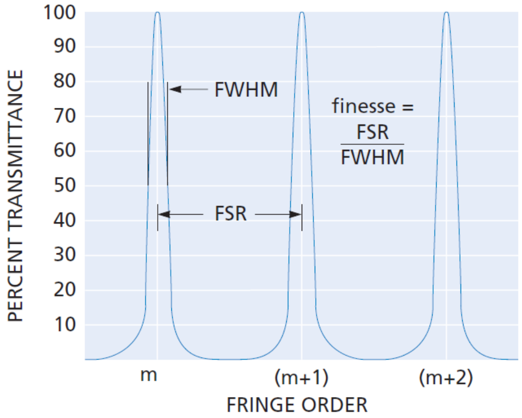
$$\varphi = 2\pi(2d\cos\theta)/\lambda = 2\pi m \qquad m = 2d\cos\alpha/\lambda$$

- *Constructive interference occurs when* $m = 1, 2, 3\ldots$
- *Zero transmission occurs when* $m = 1/2, 3/2, 5/2\ldots$
- *Consider d =* $\lambda_0/2$ *and the normal incidence*

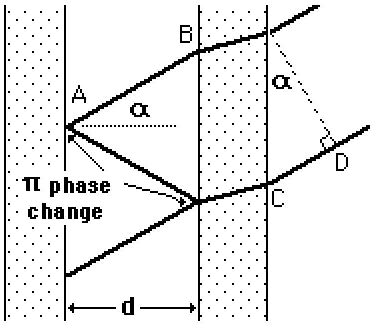
$$\lambda_{trans} = 2d\cos\alpha = 2\frac{\lambda_0}{2}\cos 0^\circ = \lambda_0$$

- *How about the light of* $\lambda \neq \lambda_0$ *?*

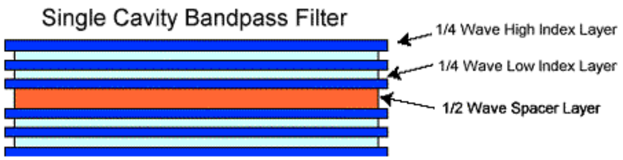




Pathlength difference for adjacent rays = 2AB - CD = 2d cos α



Reflection Layers - Thin-films



- *Reflection layers: consist of several film layers, each of which is a quarterwave thick (t = λ/4), acting as anti-reflection optical coating.*

- *Consider reflection by a film layer*

$$\varphi = 2\pi(2t\cos\theta)/\lambda = 2\pi m \qquad m = 2t\cos\alpha/\lambda$$

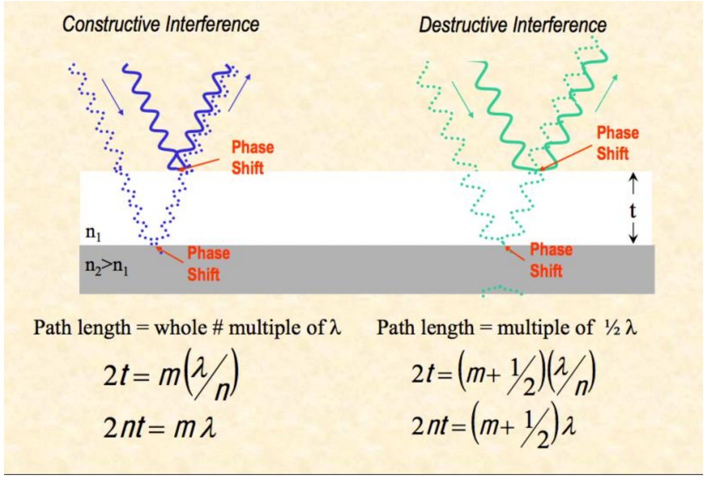
- *Constructive interference occurs when* $m = 1, 2, 3\ldots$

- *Destructive interference occurs when* $m = 1/2, 3/2\ldots$
- *Then*

$$m\lambda = 2t\cos\alpha = 2\frac{\lambda}{4}\cos 0^\circ = \frac{\lambda}{2} \qquad m = 1/2$$

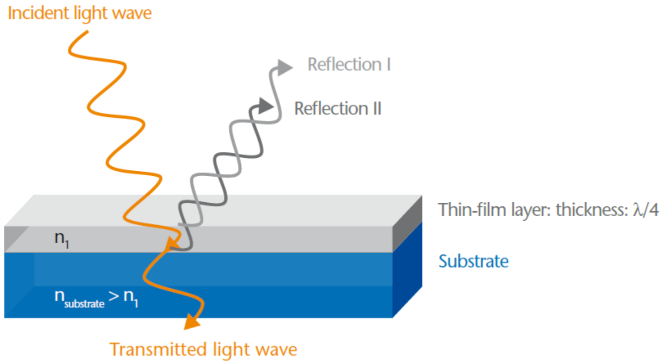
- *It is precisely this light cancellation that is exploited for anti-reflective (AR) coating, where no light is reflected (back), therefore all light is transmitted.*

- *How about the light of* $\lambda \neq \lambda_0$ *?*

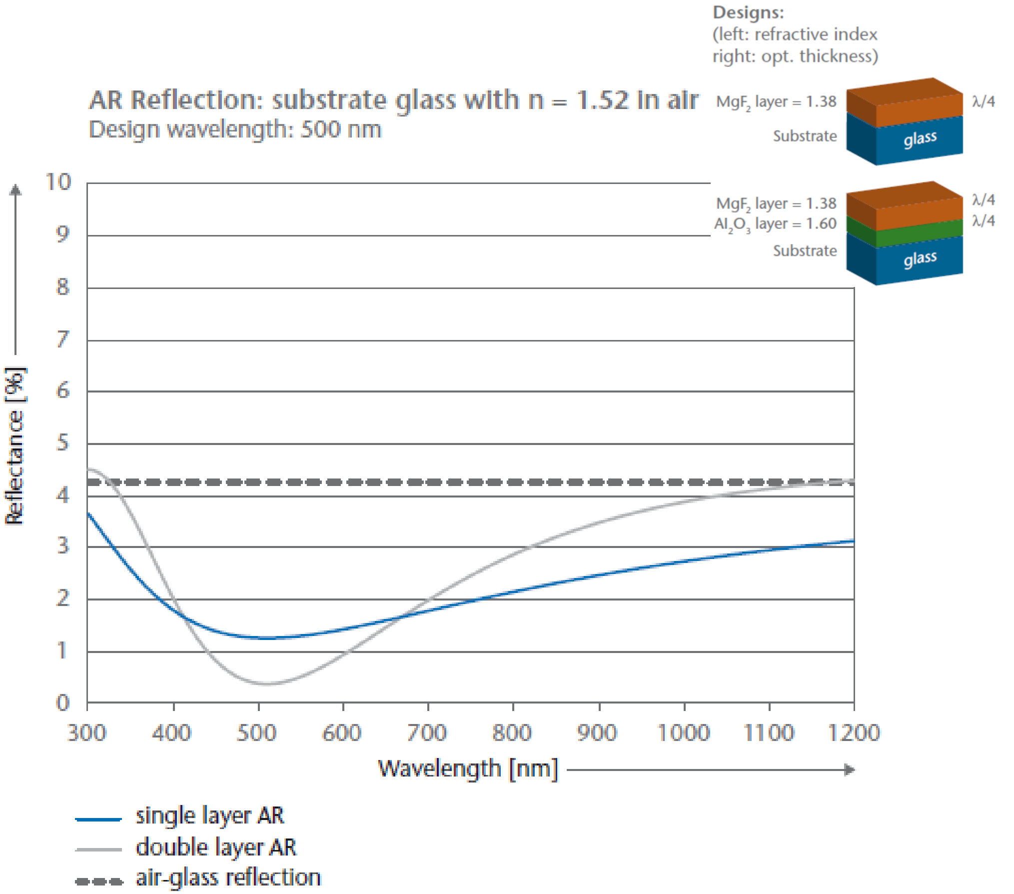


Thin-films act as AR Coating

- *It is precisely this light cancellation that is exploited for anti-reflective (AR) coating, where no light is reflected (back), therefore all light is transmitted.*
- *A thin-film layer coating of thickness λ/4 generates a phase difference of half a wavelength for the wave traveling backwards.*

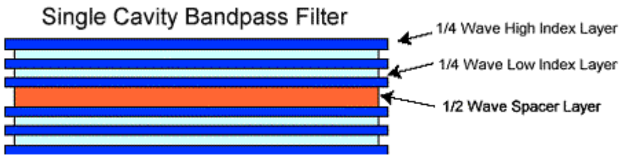


Courtesy: CVI Melles Griot

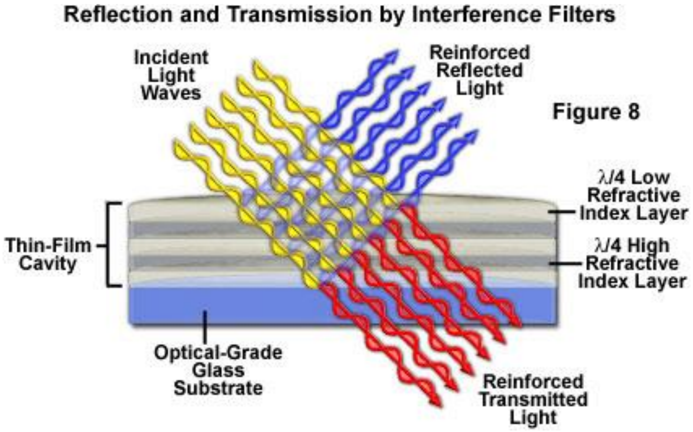


Principal Summary

- *Reflection layers: consist of several film layers, each of which is a quarter-wave thick (d = λ/4).*
- *With the reflected rays being effectively cancelled, a thin film of quarter-wave thickness functions as an anti-reflection optical coating.*

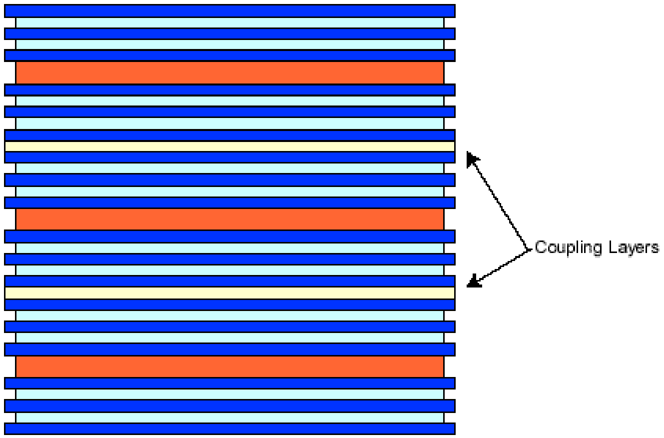


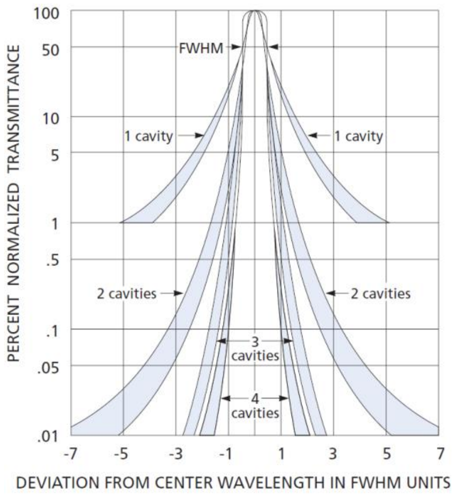
- *Spacer: the gap between the reflecting surfaces is a thin film of dielectric material, with a thickness of one-half wave at the desired peak transmission wavelength. (d = λ/2)*
- *The gap in spacer determines which wavelengths destructively interfere and which wavelengths are in phase and will ultimately pass through the coatings.*
- *This principle strongly attenuates the transmitted intensity of light at wavelengths that are higher or lower than the wavelength of interest.*



More Detail about Structure

- *Spacer is the gap between the reflecting surfaces, which is a thin film of dielectric material.*
- *On either side of this gap are the two reflecting layers, which actually consist of several film layers.*
- *This sandwich of quarter-wave layers is made up of an alternating pattern of high and low index material, usually ZnS (n=2.35) and cryolite (n=1.35). Together, they are called a stack.*
- *The number of layers in the stack is adjusted to tailor the width of the bandpass.*
- *To sharpen cutoff, it is common practice that several cavities are layered sequentially into a multicavity filter, which dramatically reduces the transmission of out-of-band wavelengths.*

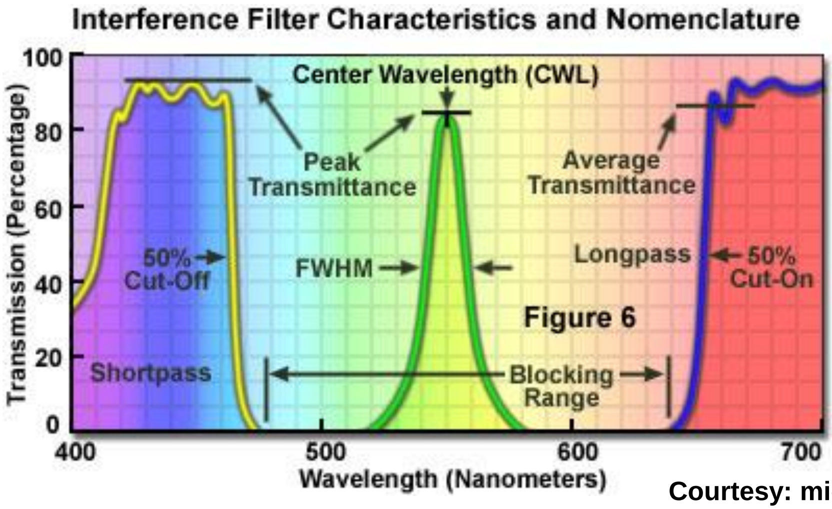

Three Cavity Bandpass Filter

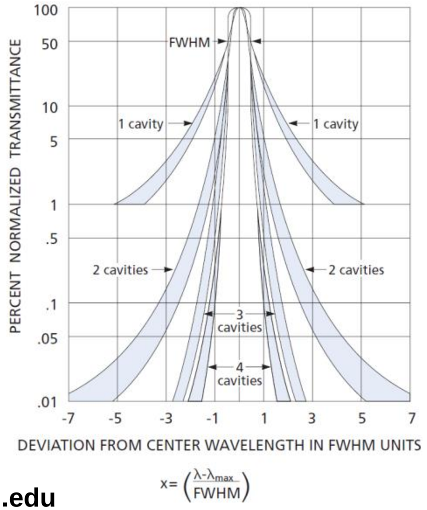


$$x = \left(\frac{\lambda - \lambda_{max}}{FWHM}\right)$$

Terminology

- **Bandpass:** *the range (or band) of wavelengths passed by a wavelength-selective optic.*
- **Blocking:** *the degree of light attenuation at wavelengths outside the passband of filter.*
- **Center Wavelength (CWL):** *the wavelength at the midpoint of the half power bandwidth (FWHM).*
- **Full-Width Half-Maximum (FWHM):** *the width of the bandpass at one-half of the maximum transmission.*
- **Peak Transmission:** *the maximum percentage transmission within the passband.*
- **Filter Cavity:** *An optical "sandwich" of two partially reflective substrate layers separated by an evaporated coating which forms the dielectric spacer layer.*





Courtesy: micro.magnet.fsu.edu

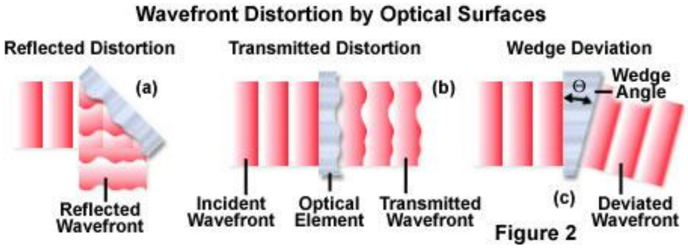
Performance

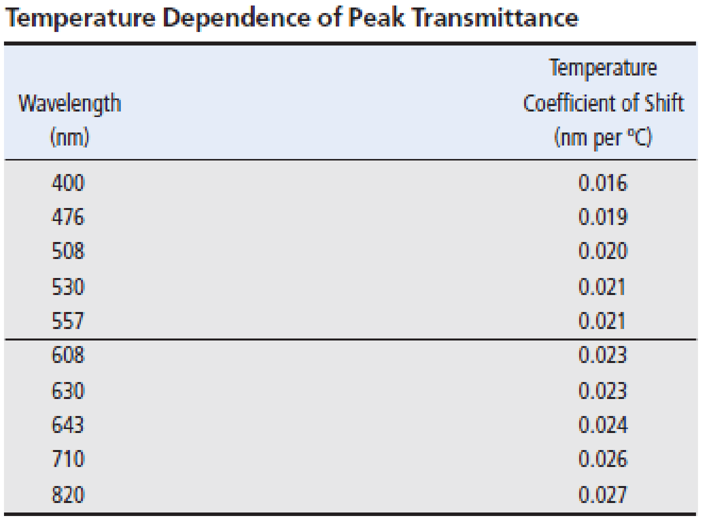
- ***Transmitted distortion:*** *the distortion of a plane wavefront passing through the filter, and is also measured in fractions or multiples of a wavelength.*
- ***Wedge:*** *angular deviation from parallelism between the outer filter surfaces, which is measured in are-second or are-minutes of the deviation angle.*
- ***Angle shift:*** *the wavelength of CWL at small angle* ϕ *from normal incidence is*

$$\lambda = \lambda_0 \sqrt{1-\left(\frac{n_0}{n_e}\right)^2 \sin^2 \phi}$$

where $n_0 = 1$ *in air,* n_e *is refractive index of spacer material.*

- ***Temperature:*** *an interference filter is slightly temperature dependent, causing transmission spectrum shifts slightly to longer wavelengths with increasing temperature.*
- ***Orientation:*** *the shiniest side toward the source.*

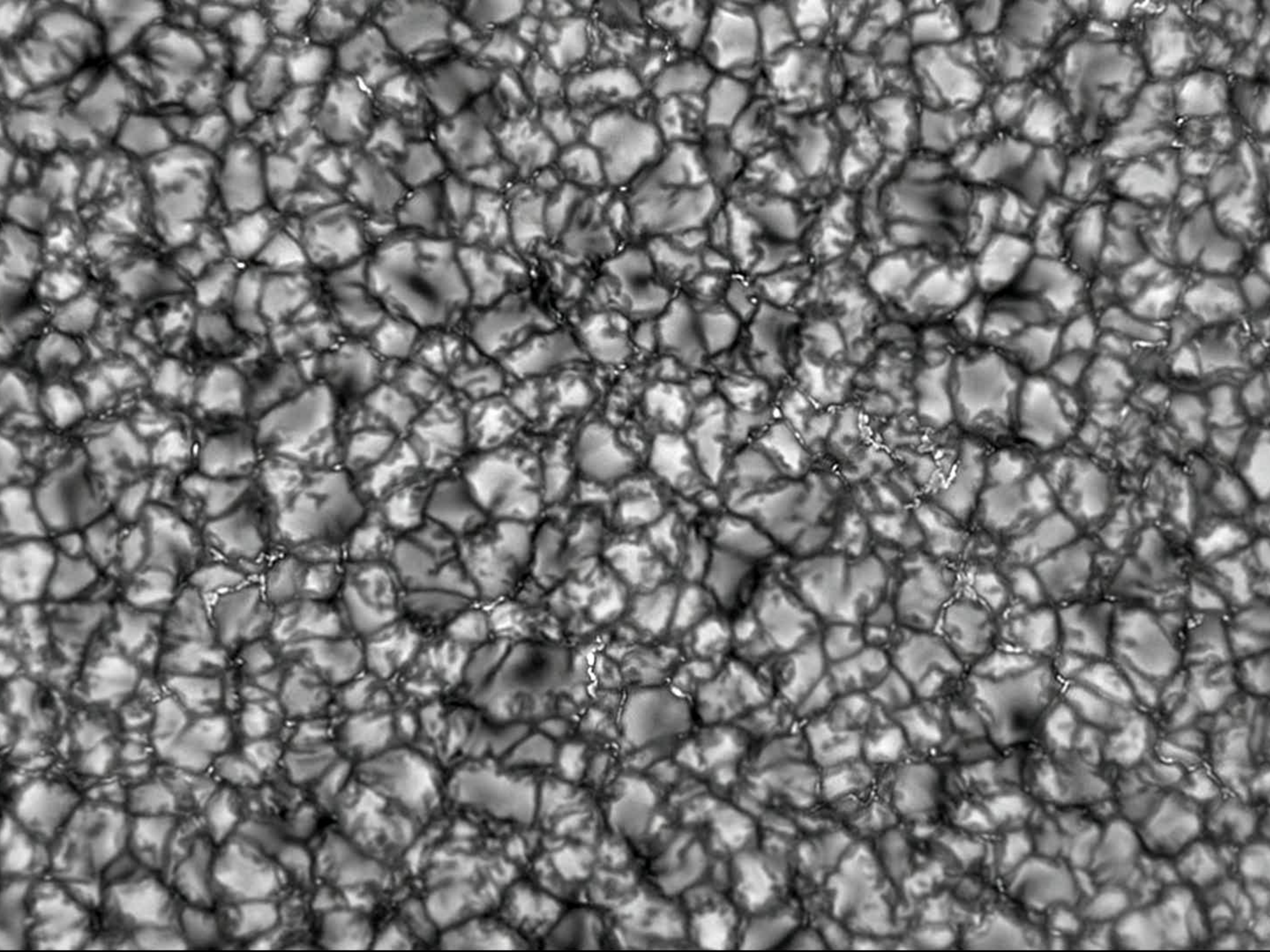




Temperature Dependence of Peak Transmittance

Wavelength (nm)	Temperature Coefficient of Shift (nm per °C)
400	0.016
476	0.019
508	0.020
530	0.021
557	0.021
608	0.023
630	0.023
643	0.024
710	0.026
820	0.027

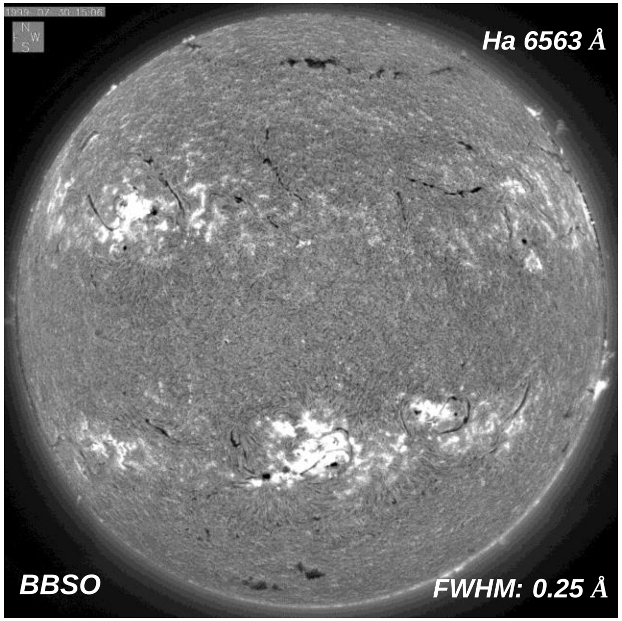
Courtesy: CVI Melles Griot

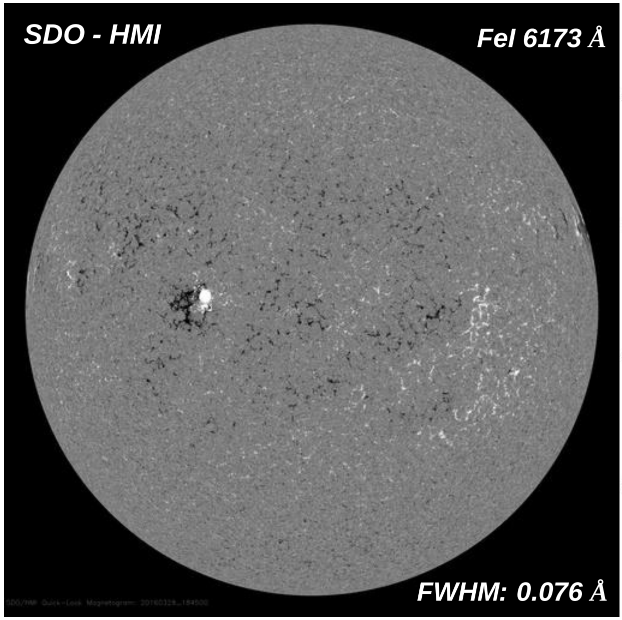


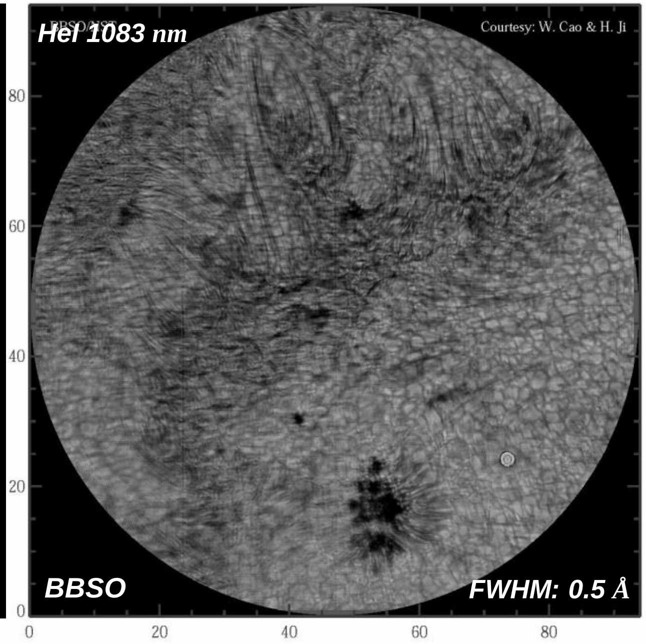
2. Lyot Filters

Bernard Lyot
1897-1952

- *Lyot filter, named for its inventor Bernard Lyot, is a type of optical filter that uses birefringence to produce a narrow passband of transmitted wavelengths.*
- *Lyot filters are often used in astronomy, particularly for solar astronomy.*
- *Provide a passband of a quarter to a few of angstroms*

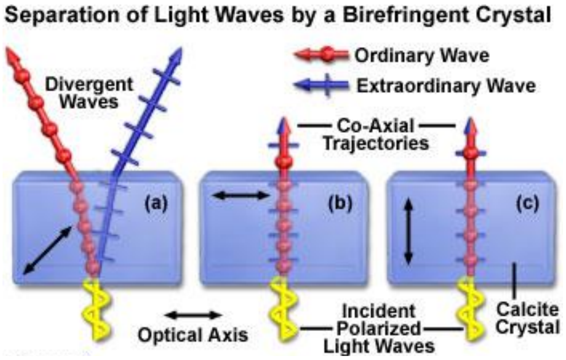




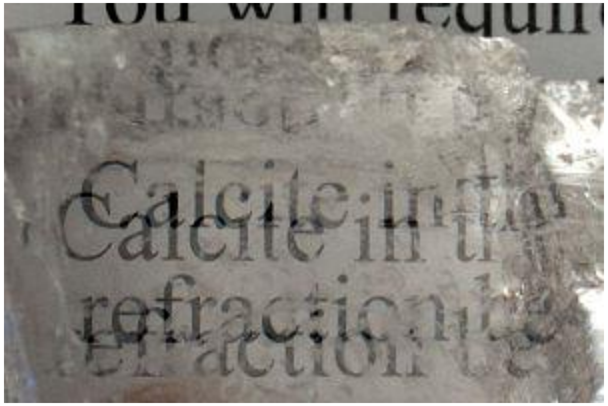


Birefringence

- ***Birefringence,*** *or* ***double refraction,*** *is the decomposition of a ray of light into two rays when it passes through certain anisotropic material (birefringent crystal), such as crystals of calcite.*
- *When a beam of light is incident on a birefringent crystal, the waves are split upon entry into orthogonal polarized components:* ***o****rdinary and* ***e****xtraordinary.*
- ***o and e*** *components travel through the molecular lattice along different pathways, depending on their orientation with respect to the crystalline optical axis.*
- *Light passing through a birefringent crystal*
- ***Parallel entry:*** *o and e wavefront coincide in amplitude, phase, and trajectory during their journey in the crystal.*
- ***Oblique entry:*** *o and e diverge and follow different pathways, and* ***o wave travels faster then e wave.***
- ***Perpendicular entry:*** *divergence between o and e is eliminated, but* ***o wave still travels at a higher speed than does e wave.***



www.olympusmicro.com



$$n_o \neq n_e$$

Birefringence and Interference

- ***Perpendicular entry:*** *the propagation speed of o and e wave differ. Birefringent index of a crystal is defined as*

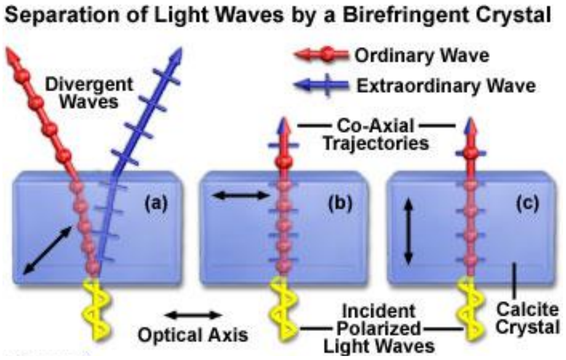
$$\mu = n_e - n_o$$

- ***o** and **e** wave travel through a crystal of thickness d with a phase delay*

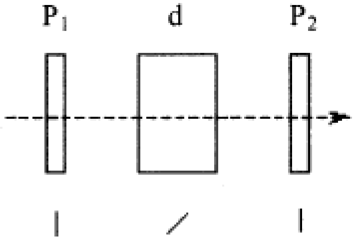
$$\delta = \frac{2\pi(\Delta OPL)}{\lambda} = \frac{2\pi d(n_e - n_o)}{\lambda} = \frac{2\pi\mu d}{\lambda}$$

- *Consider a birefringent crystal of a thickness of d, which is placed between two linear polarizers with the same polarization direction. Assume the optical axis of the crystal is 45 with respect to the polarization directions, then the transmitted light is given by*

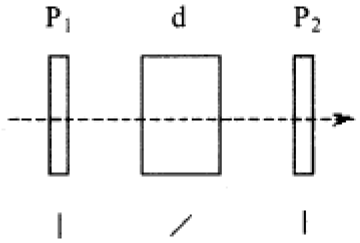
$$T = \cos^2(\frac{\delta}{2}) = \cos^2(\frac{\mu d}{\lambda}\pi) = \cos^2(\sigma\pi)$$



www.olympusmicro.com



Transmission Profiles



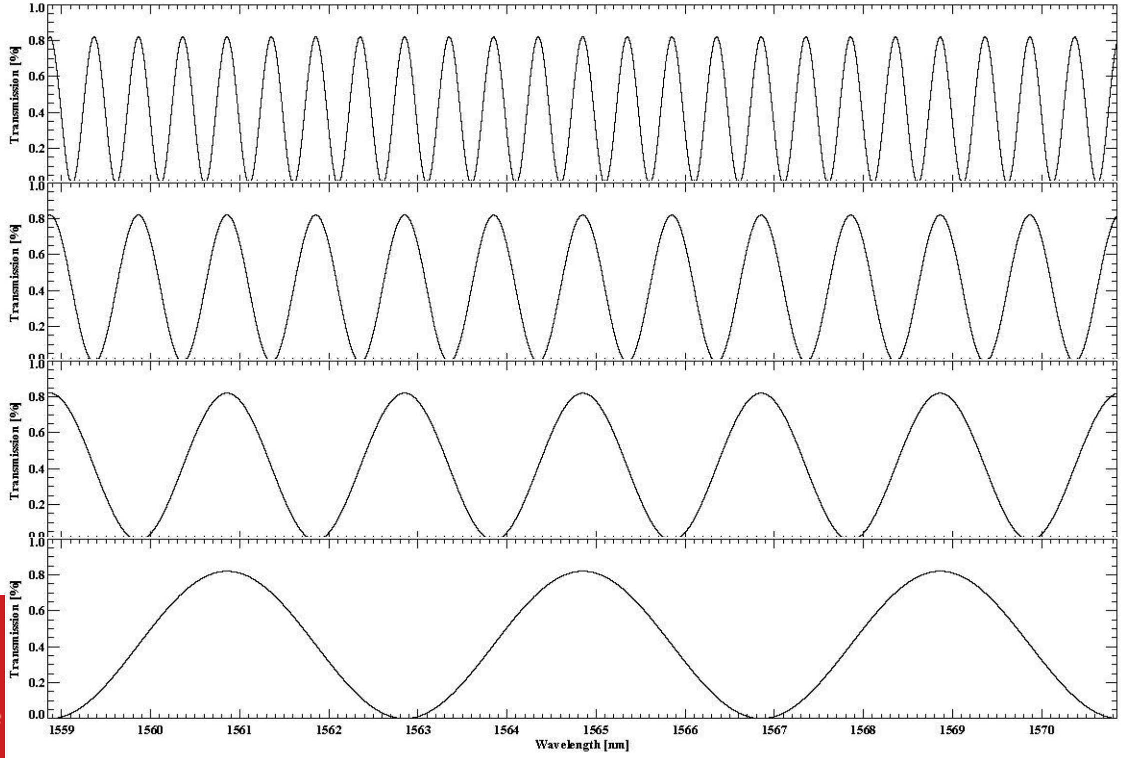
- ☐ *What does the transmission profile look like?*

$$T_1 = \cos^2\left(\frac{\delta_1}{2}\right) = \cos^2\left(\frac{\mu d_1}{\lambda}\pi\right) = \cos^2(\sigma_1\pi)$$

- ☐ *What does the transmission profile look like if $d_2 = 2d_1$?*

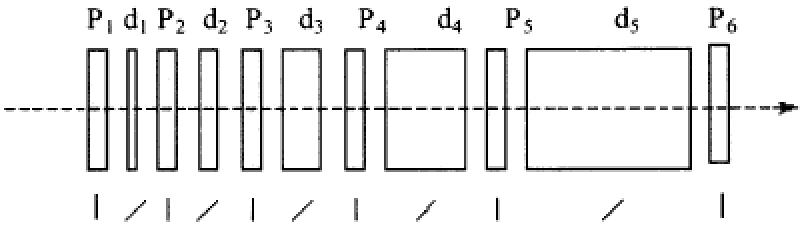
$$T_2 = \cos^2\left(\frac{\delta_2}{2}\right) = \cos^2\left(\frac{\mu d_2}{\lambda}\pi\right) = \cos^2(\sigma_2\pi) = \cos^2(2\sigma_1\pi)$$

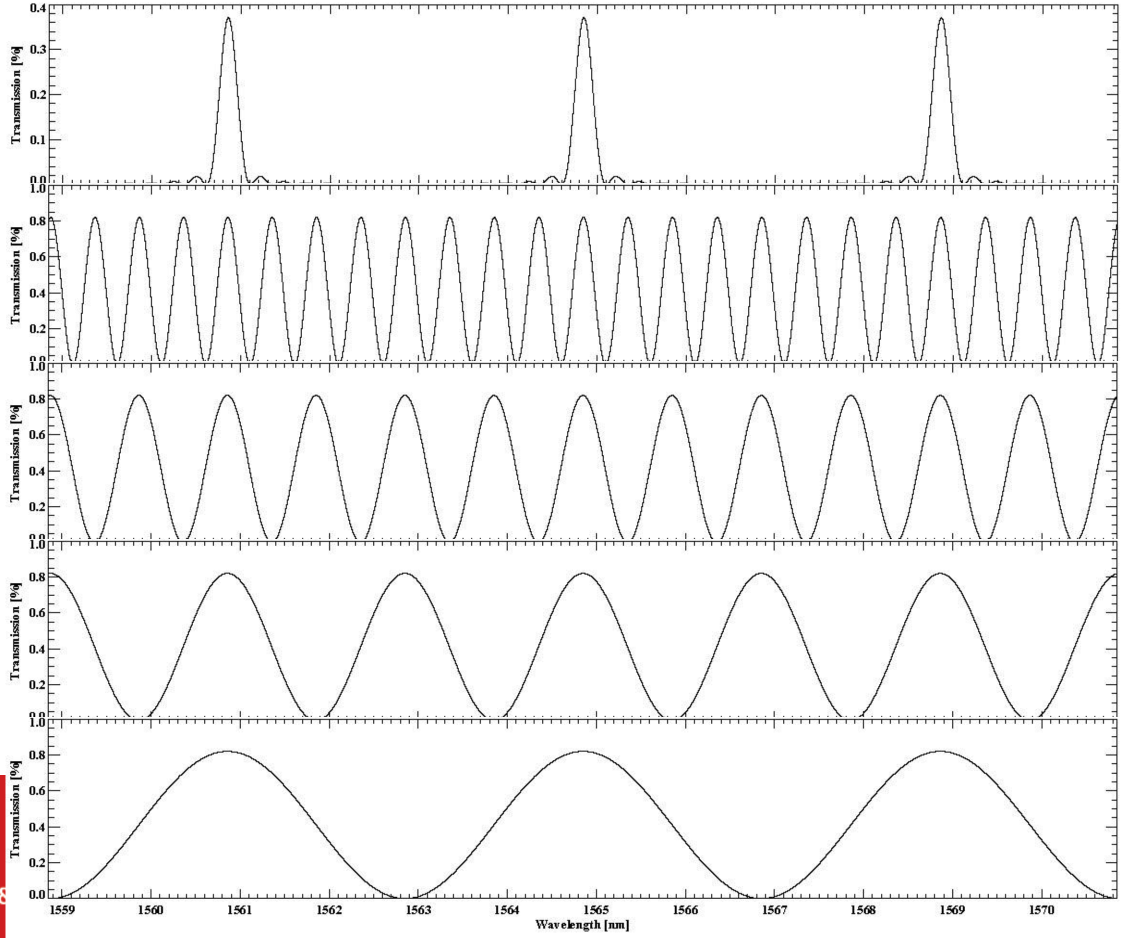
- ☐ *$d_3 = 2d_2 = 4d_1$?*
- ☐ *$d_4 = 8d_1$?*



Lyot Filter Transmission Profiles

$$
\begin{aligned}
T &= T_1 T_2 T_3 T_4 \\
&= \cos^2\left(\frac{\mu d_1}{\lambda}\pi\right)\cos^2\left(\frac{\mu d_2}{\lambda}\pi\right)\cos^2\left(\frac{\mu d_3}{\lambda}\pi\right)\cos^2\left(\frac{\mu d_4}{\lambda}\pi\right) \\
&= \cos^2(\sigma_1\pi)\cos^2(2\sigma_1\pi)\cos^2(4\sigma_1\pi)\cos^2(8\sigma_1\pi)
\end{aligned}
$$





FWHM and FSR

- ***Full Width at Half Maximum (FWHM):*** *is determined by the thickness of the thickest stage* d_{thick}.

$$\Delta\lambda_{FWHM} = \frac{\lambda^2}{2\mu d_{thick}}$$

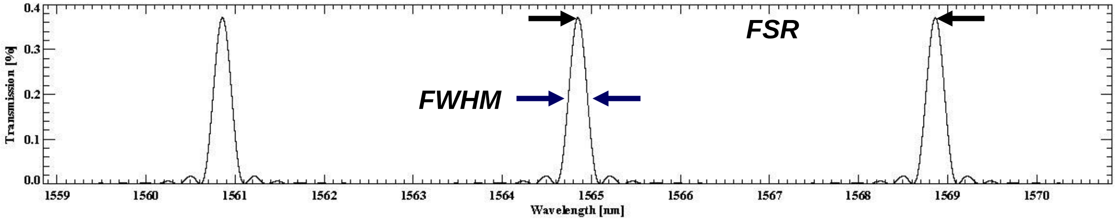
$\mu = 0.172 @ 590\text{nm}$
$\lambda = 590\text{ nm}$
$\Delta\lambda_{FWHM} = 0.025\text{ nm}$
$d_{thick} = ?$

- ***Free Spectral Range (FSR):*** *is determined by the thickness of the thinnest stage* d_{thin}.

$$FSR = \frac{\lambda^2}{\mu d_{thin}}$$

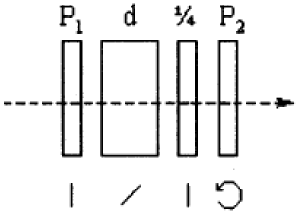
- *For a Lyot filter with n stages,* $d_{thick} = (2n)d_{thin}$, *so*

$$FSR = \frac{\lambda^2}{\mu d_{thin}} = (4n)\Delta\lambda_{FWHM}$$

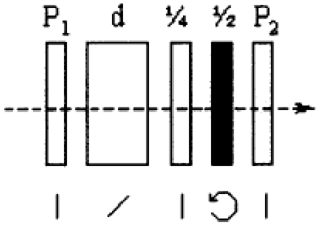


Lyot Filter Tuning

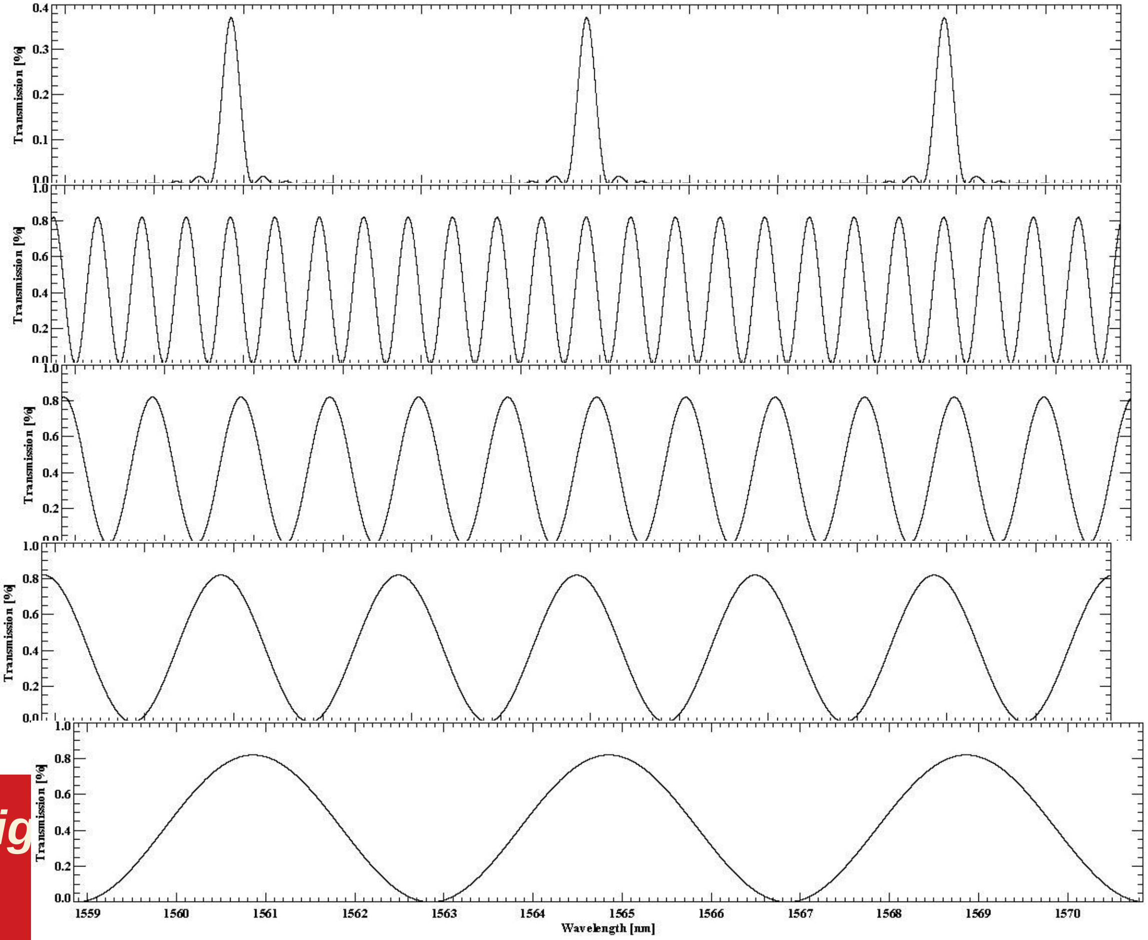
- *Wavelength tuning is a critical feature to calibration, fabrication and operation.*
- *Each stage needs its individual tuning system.*
- *A quarter waveplate, which follows the crystal to be 45° with respect to the optical axis, is followed by a rotating polarizer or a rotating half waveplate.*



$$T=\cos^2\left(\frac{\mu d}{\lambda}\pi+\alpha\right)=\cos^2(\sigma\pi+\alpha)$$



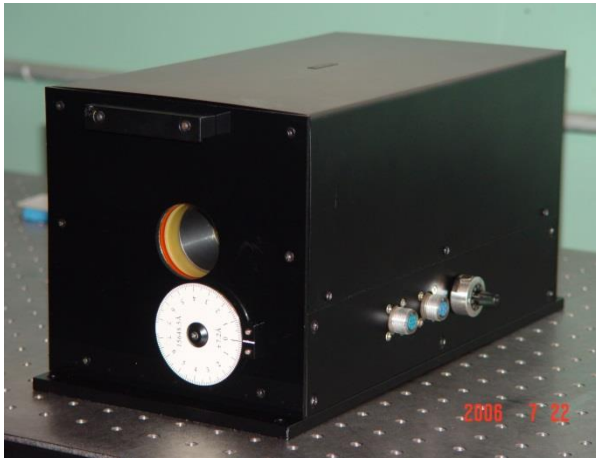
$$T=\cos^2\left(\frac{\mu d}{\lambda}\pi+2\beta\right)=\cos^2(\sigma\pi+2\beta)$$



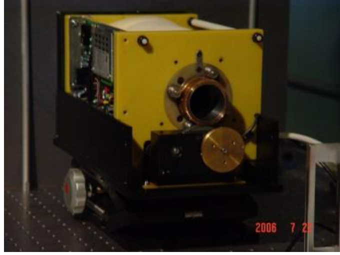
BBSO NIR Lyot Filter

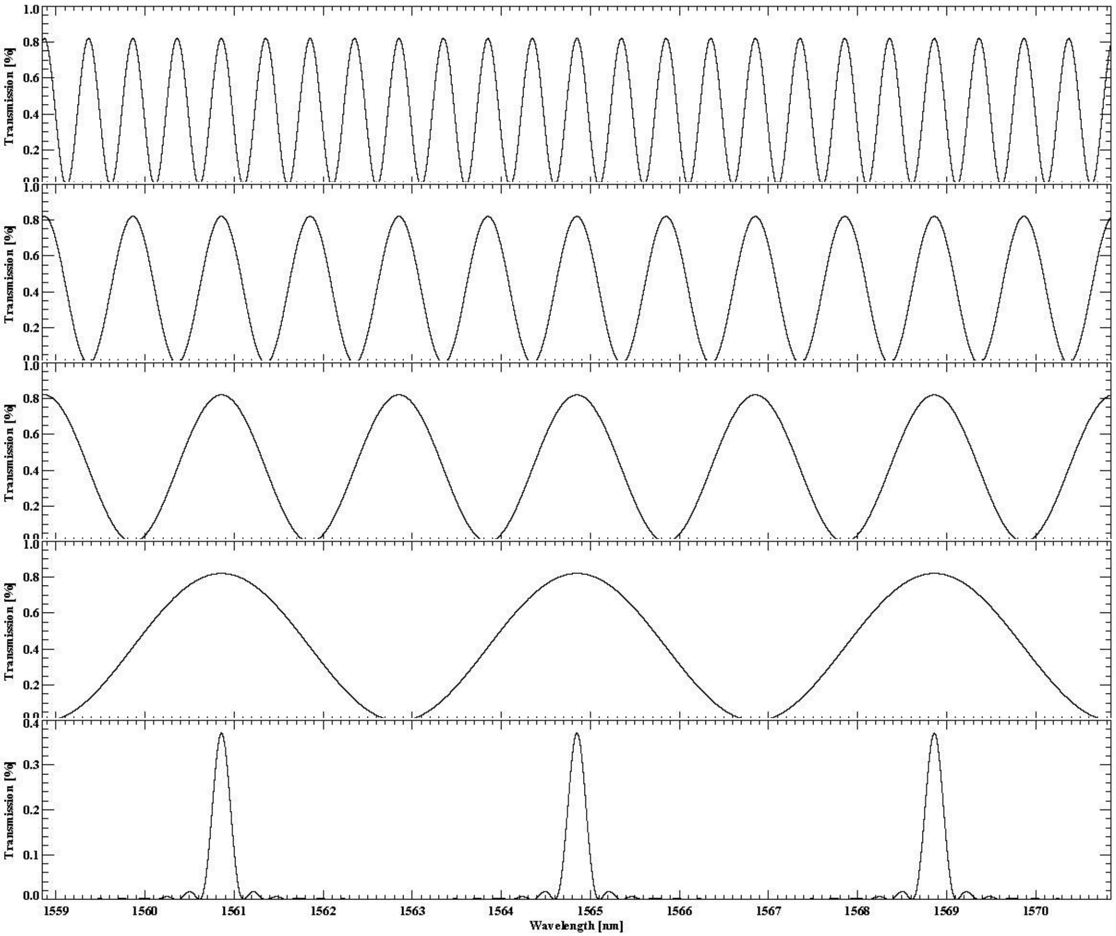
Design Requirement

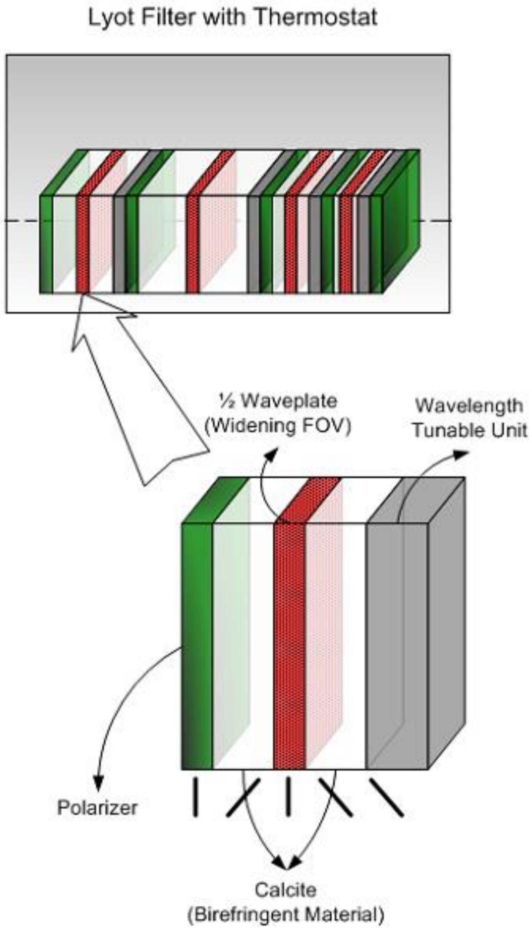
Working Wavelength:	Fe I 1.5648 & 1.5652 µm
Clear Aperture:	~ 37 mm
Passband FWHM:	2.5 Å
Tunable Range:	± 7 Å
Peak Transmission:	~ 8 % for non-polarized light
Internal Structure:	4-module
Thermal Controller:	35.000 ± 0.005° C
Minimum tunable step:	0.01 Å



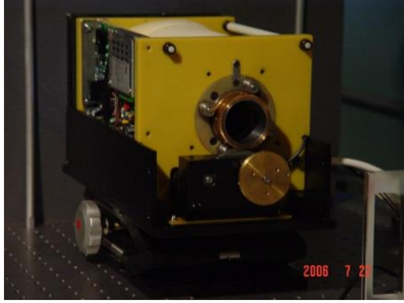
Optical and Mechanical Design







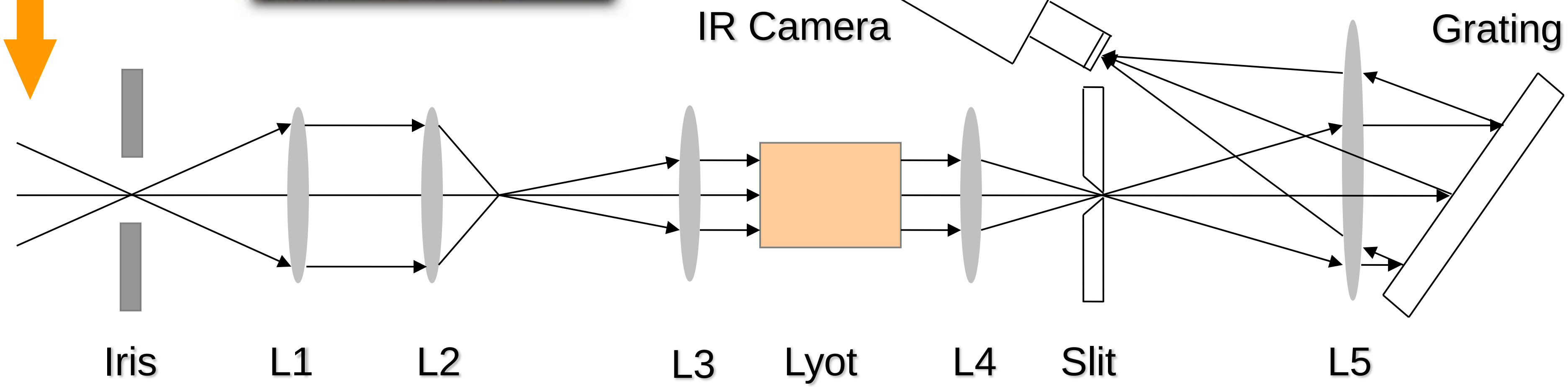
System Calibration



John W. Evans Solar Facility

National Solar Observatory/Sacramento Peak

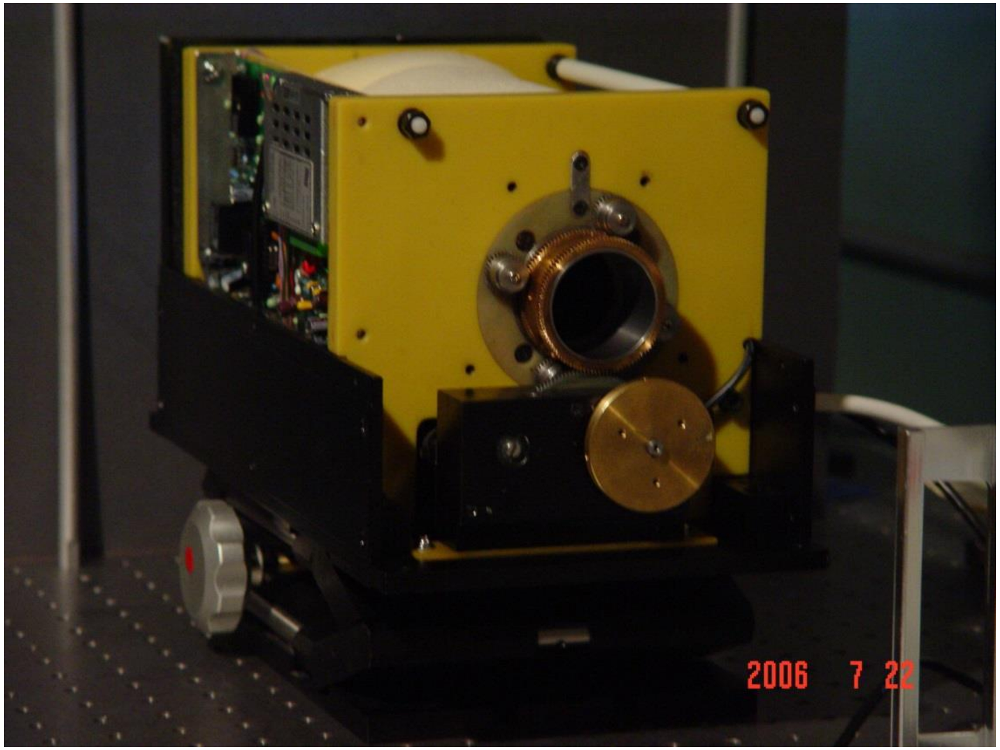
July 2006

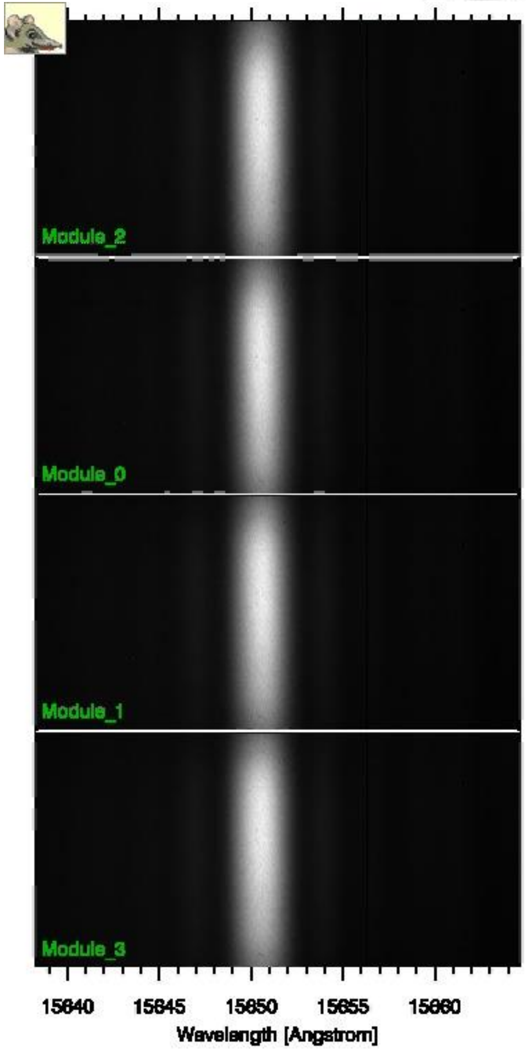


System Calibration

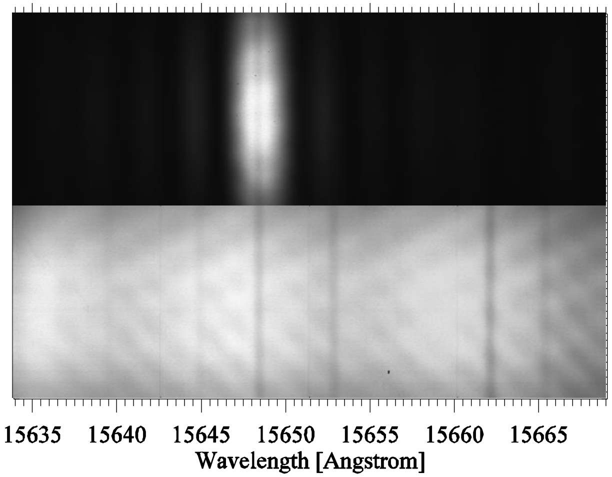
$$T = T_0 \cdot T_1 \cdot T_2 \cdot T_3$$

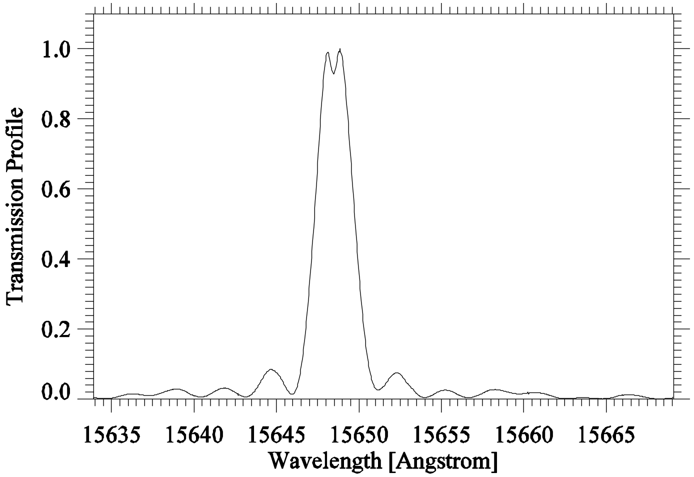
$$= \cos^2\left(\frac{\mu d}{2^0 \lambda}\pi + \delta_0\right) \cdot \cos^2\left(\frac{\mu d}{2^1 \lambda}\pi + \delta_1\right) \cdot \cos^2\left(\frac{\mu d}{2^2 \lambda}\pi + \delta_2\right) \cdot \cos^2\left(\frac{\mu d}{2^3 \lambda}\pi + \delta_3\right)$$

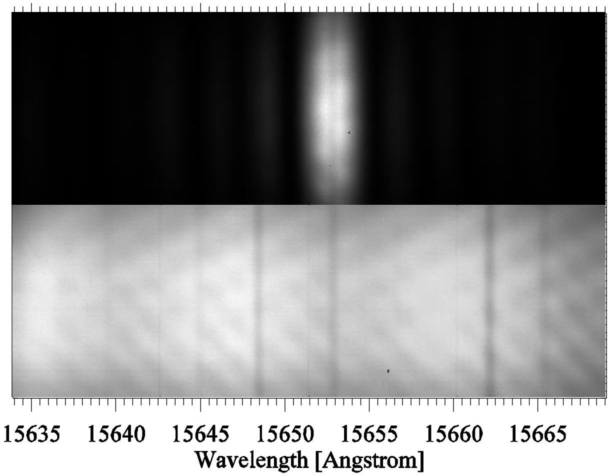


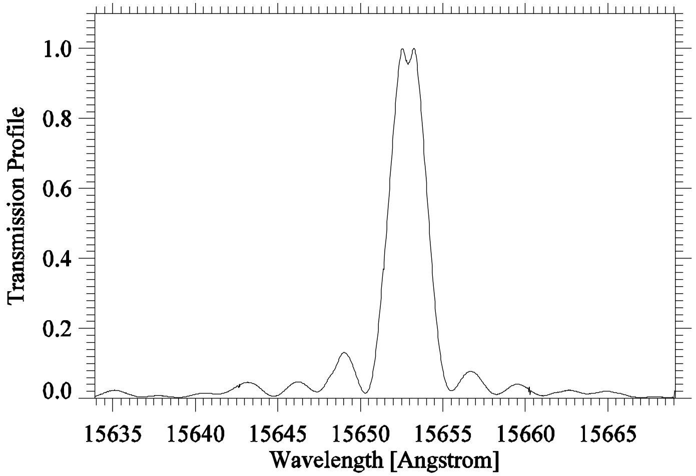


Transmission Profiles

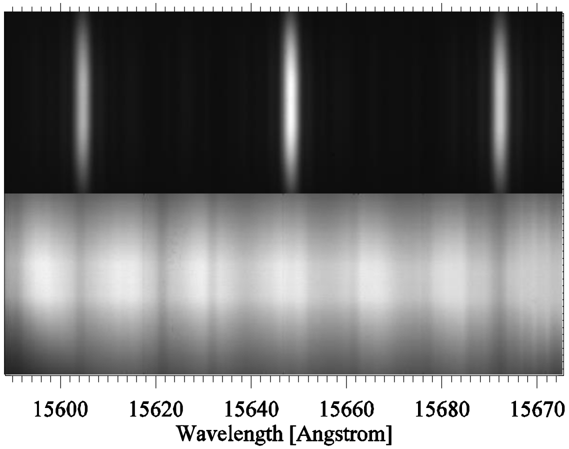


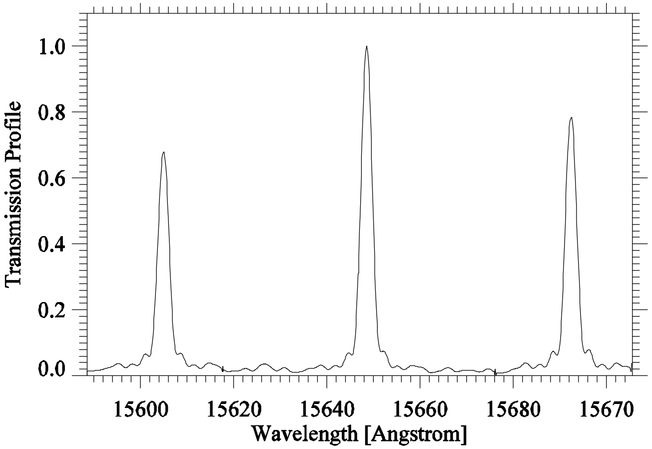


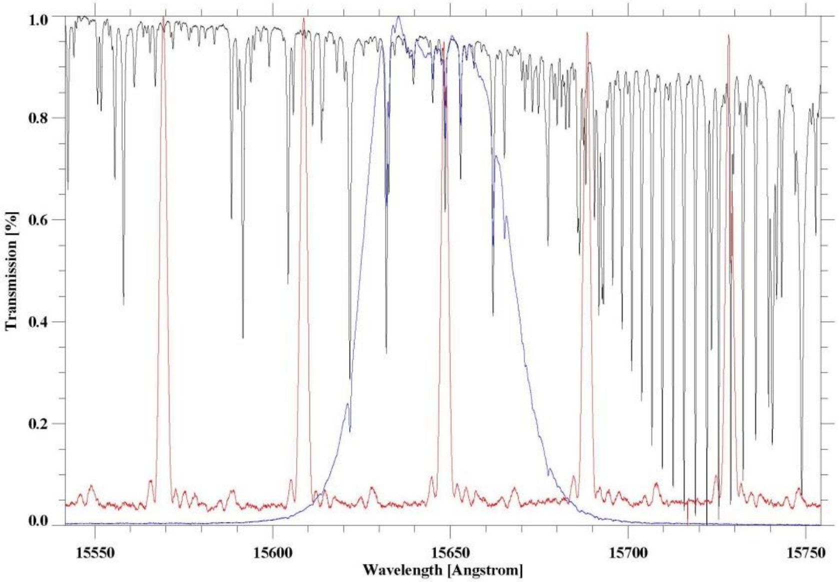




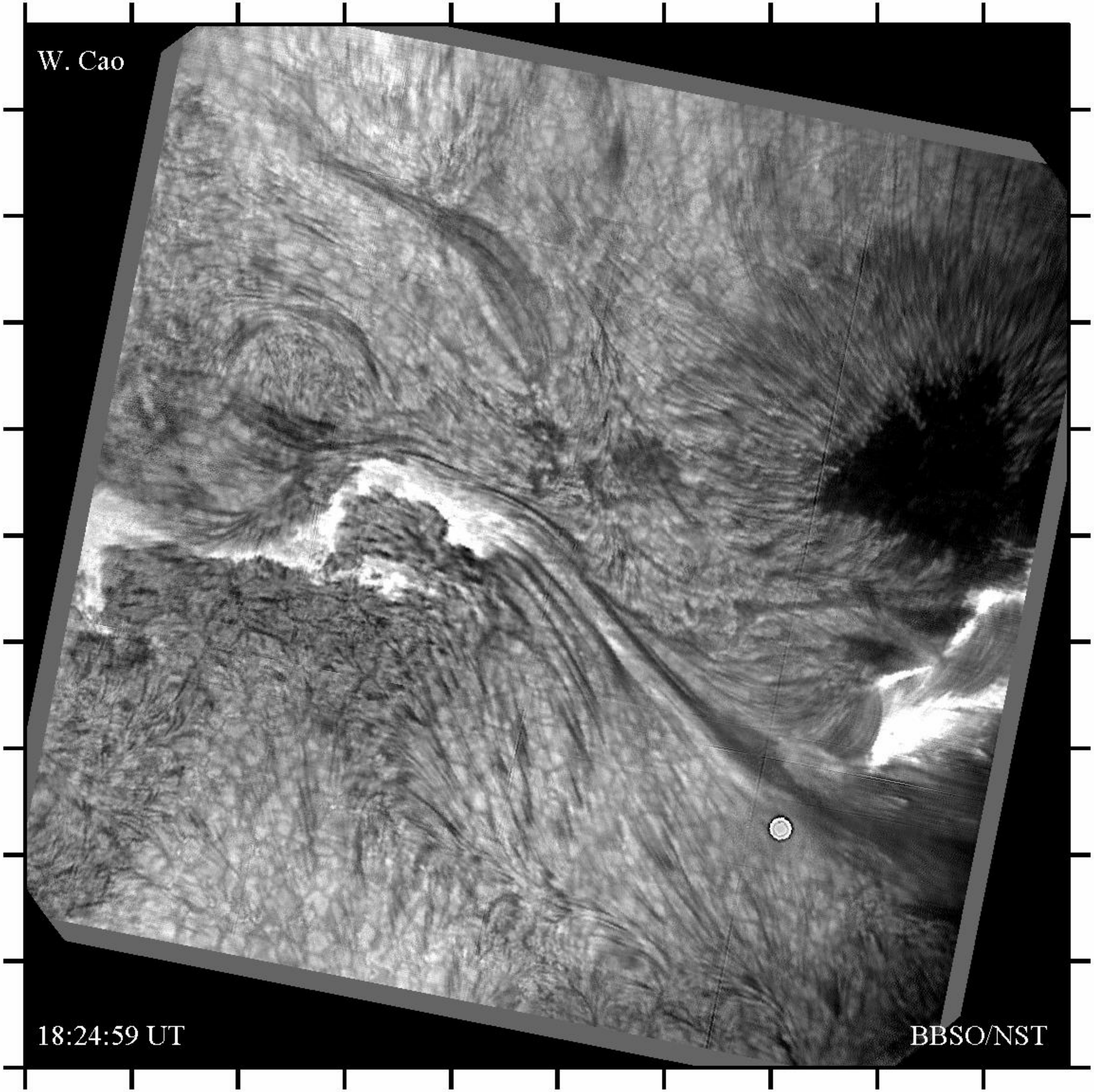
Order Sorting Filter





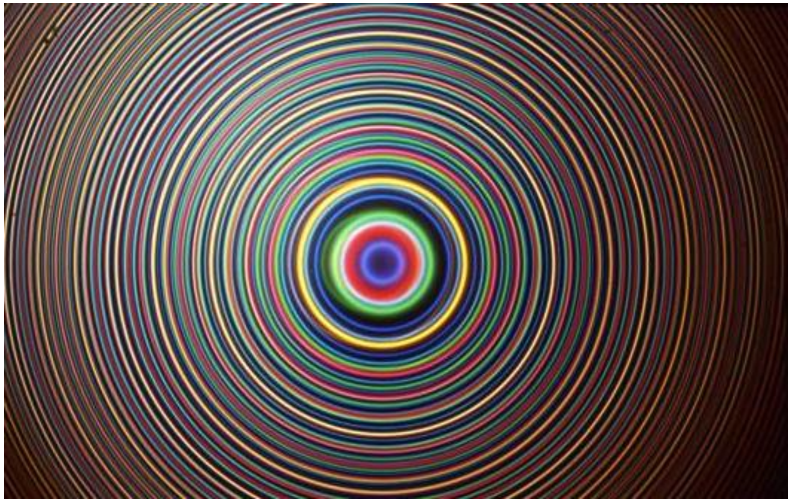


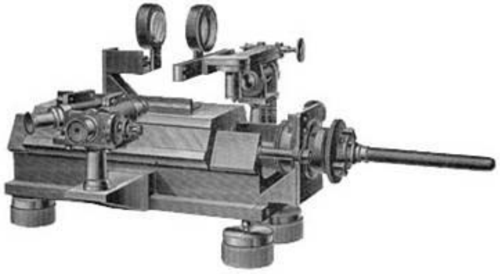
A M1.2 flare on August 17, 2013



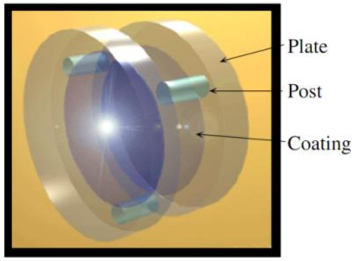
3. Fabry-Perot Interferometer

- *Fabry-Perot interferometer (FPI), also called Fabry-Perot etalon is made of two semi-reflecting plates of glass, parallel, producing an interference pattern.*





Collection Ecole polytechnique



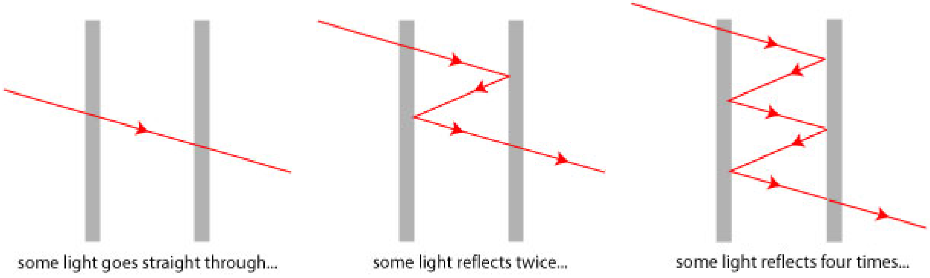
IC Optical System Ltd.

How does a FPI work ?

- *Start from a Fabry-Perot etalon …*

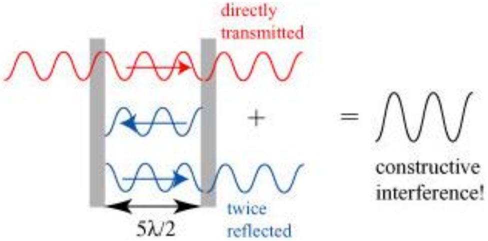
$$2AB - CD = 2nd\cos\alpha$$

$$m\lambda = 2nd\cos\alpha$$



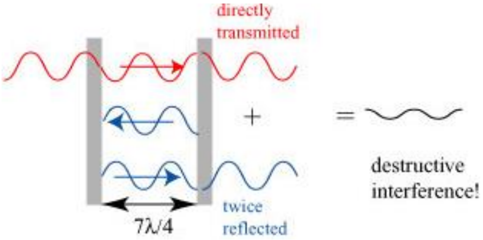
- *Constructive interference occurs when*

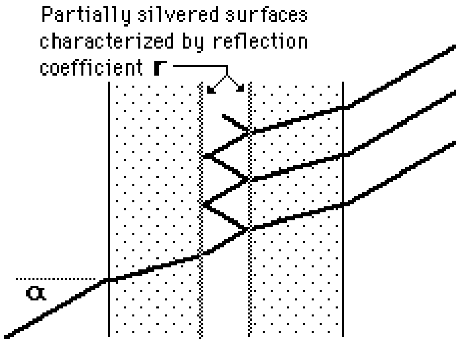
$$m = 1, 2, 3\ldots$$

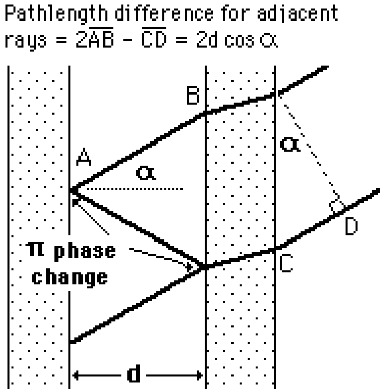


- *Destructive interference occurs when*

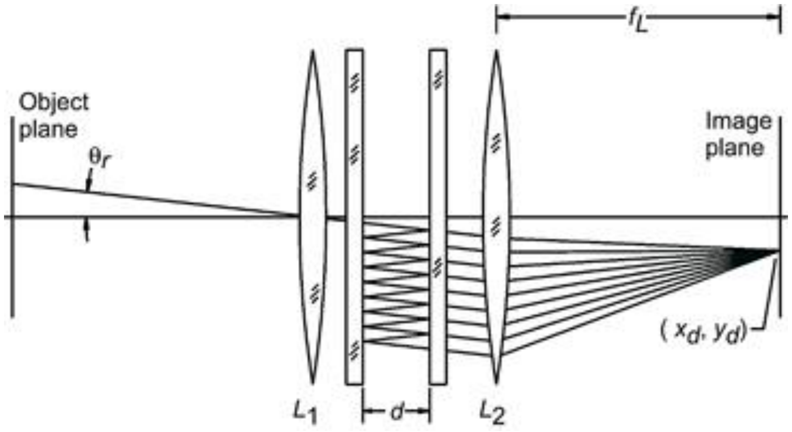
$$m = 1/2, 3/2, 5/2\ldots$$







Interference Fringe

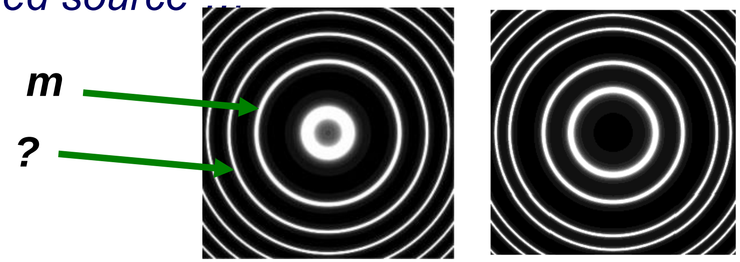


$$m\lambda = 2nd\cos\alpha$$

- Constructive interference occurs when

$$m = 1, 2, 3\ldots$$

- When a FPI is illuminated by a monochromatic extended source …



- When a FPI is illuminated by a polychromatic extended source …

- When incident angles are fixed, transmitted wavelength depends on the spacing of a FPI.

Transmission Profile

- The amplitude $E_t(m)$ of the resultant electric vector of transmitted light is given by

$$E_t(m) = t_1^+ t_2^+ [1 + r_1^- r_2^+ e^{i\varphi} + \ldots + (r_1^- r_2^+)^{m-1} e^{i(m-1)\varphi}]$$

$$E_t \to E_t(\infty) = t_1^+ t_2^+ / (1 - r_1^- r_2^+ e^{i\varphi})$$

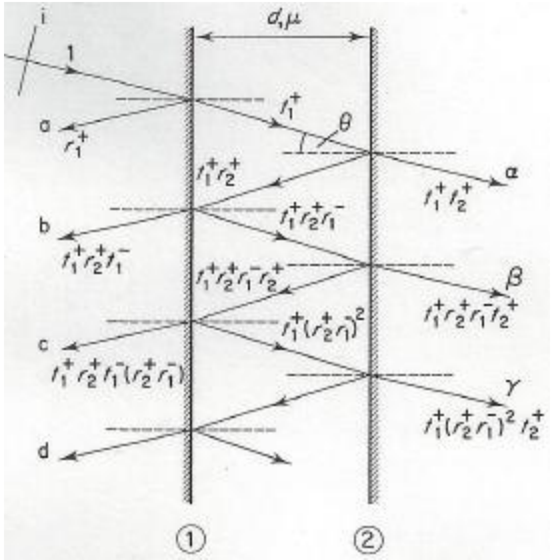
- The energy transmission coefficient for the pair of surfaces:

$$I_t = E_t E_t^* = \left|t_1^+ t_2^+\right|^2 \Big/ \left(1 + \left|r_1^- r_2^+\right|^2 - 2\left|r_1^- r_2^+\right| \cos\varphi\right)$$

$$I_T = T^2 \big/ (1 + R^2 - 2R\cos\varphi)$$
$$= \frac{T^2}{(1-R)^2} \left(\frac{1}{1 + [4R/(1-R^2)]\sin^2(\varphi/2)} \right)$$
$$= [T/(1-R)]^2 [1 + F\sin^2(\varphi/2)]^{-1}$$

- The energy reflection coefficient for the pair of surfaces:

$$I_R = F\sin^2(\varphi/2)[1 + F\sin^2(\varphi/2)]^{-1}$$



$$\varphi = 2\pi(2\mu d\cos\theta)/\lambda$$

$$T = t^+ t^-$$
$$R = (r^+)^2 = (r^-)^2$$
$$R + T = 1$$

$$F = 4R/(1-R)^2$$

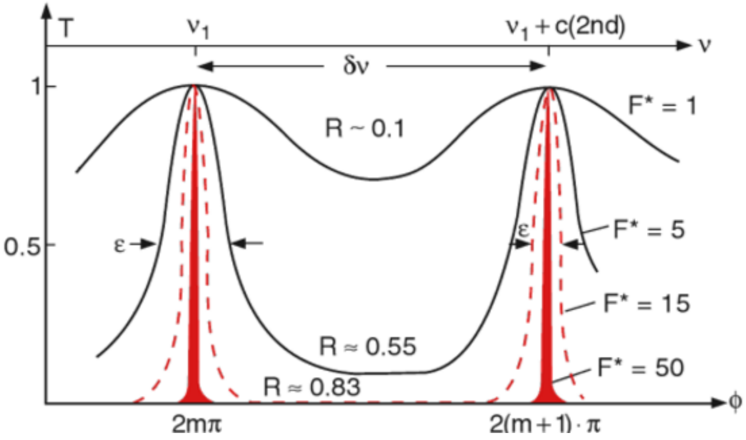
Transmission Profile

- Consider absorption $A+R+T=1$

$$\varphi = 2\pi(2nd\cos\theta)/\lambda$$

- The energy transmission coefficient for the pair of surfaces:

$$\frac{I_T}{I_0} = [T/(1-R)]^2[1+F\sin^2(\varphi/2)]^{-1}$$
$$= [(1-R-A)/(1-R)]^2[1+F\sin^2(\varphi/2)]^{-1}$$
$$= [1-A/(1-R)]^2[1+F\sin^2(\varphi/2)]^{-1}$$

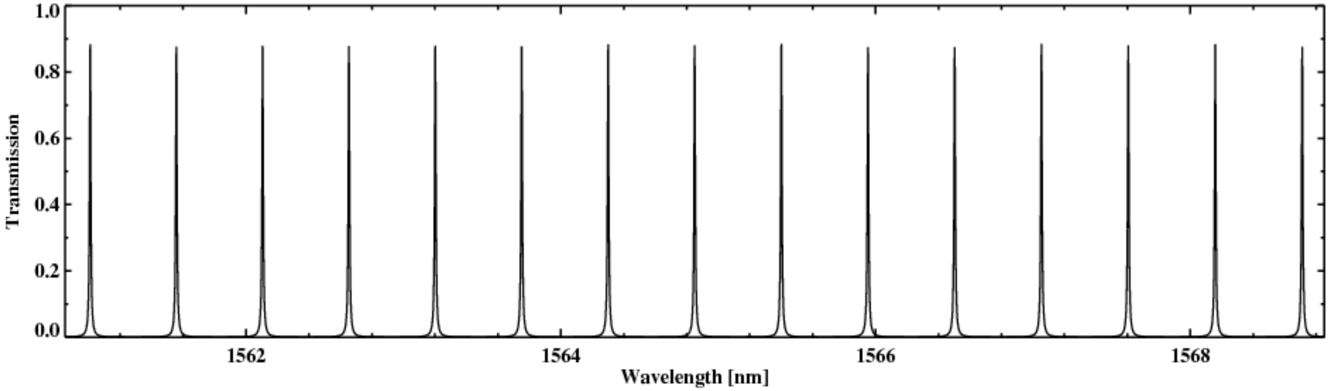


- When $\varphi = 2m\pi$, constructive interference occur

$$I_{\max} = I_0[1-A/(1-R)]^2 = I_0T^2/(1-R)^2$$

- When $\varphi = m\pi$, destructive interference occur,

$$I_{\min} = I_0[1-A/(1-R)]^2/(1+F) = I_0T^2/(1+R)^2$$



FWHM, FSR and Finesse

- *Full width at half maximum (FWHM):*

$$fwhm = \frac{(1-R)\lambda^2}{2\pi nd\cos\theta\sqrt{R}}$$

- *Free spectral range (FSR):*

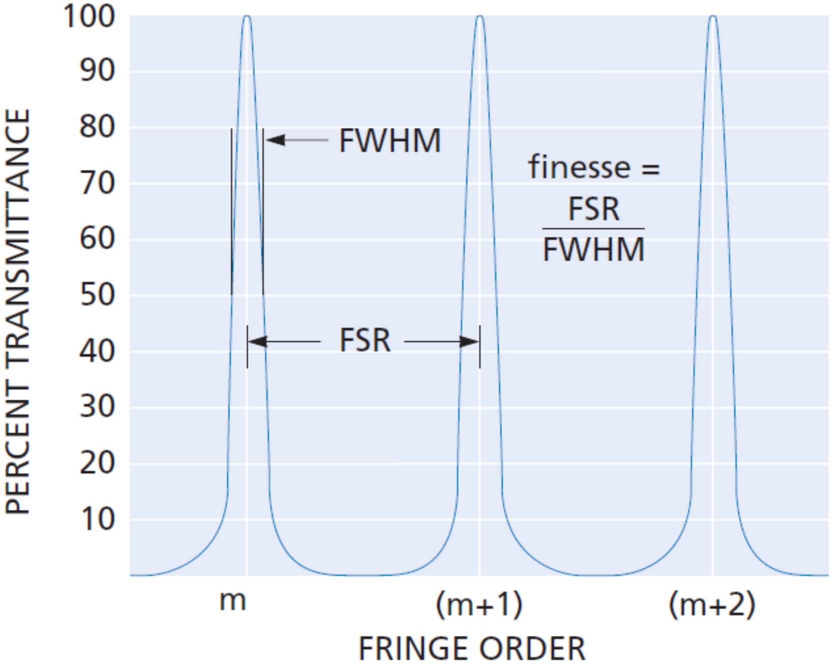
$$fsr = \frac{\lambda^2}{2nd\cos\theta} = \frac{\lambda}{m}$$

- *Finesse:*

$$N_R = \frac{fsr}{fwhm} = \frac{\pi\sqrt{R}}{1-R}$$

- *Resolving power:*

$$\Re = \frac{\lambda}{\Delta\lambda} = mN_R = \frac{2nd\cos\theta}{\lambda}N_R$$

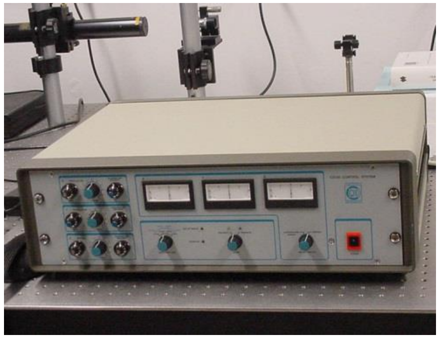


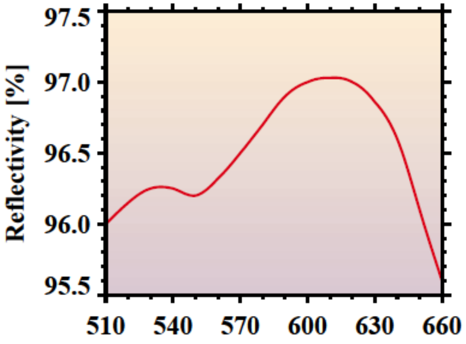
$$m\lambda = 2nd\cos\theta$$

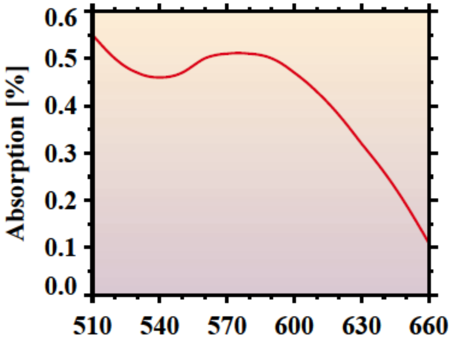
ICOS ET70FS-1024

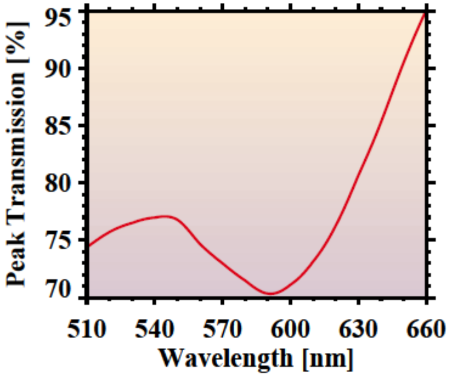
ICOS FPI Specification

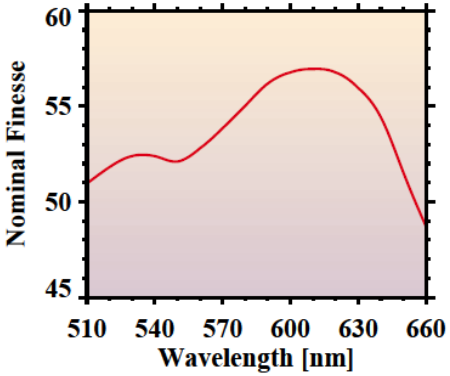
Etalon Model:	ET70FS-1024
Working Wavelength:	500 ~ 700 nm
Clear Aperture:	~ 70 mm
Nominal Finesse:	70 @ 6563 nm
Controller Model:	CS100-8099
Cavity Spacing:	d = 496 μm
Cavity Scan Range:	> 4 μm
Plate Flatness:	> λ / 200 before coating







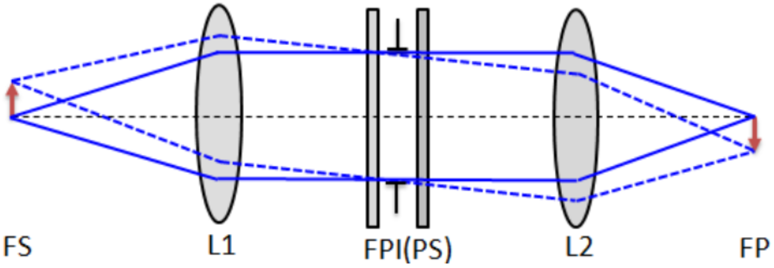




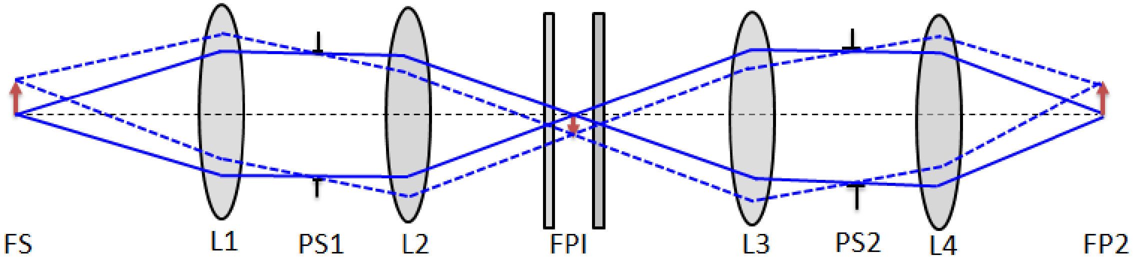
Optical Setup

$$m\lambda = 2nd\cos\alpha$$

Collimated mount



Telecentric mount

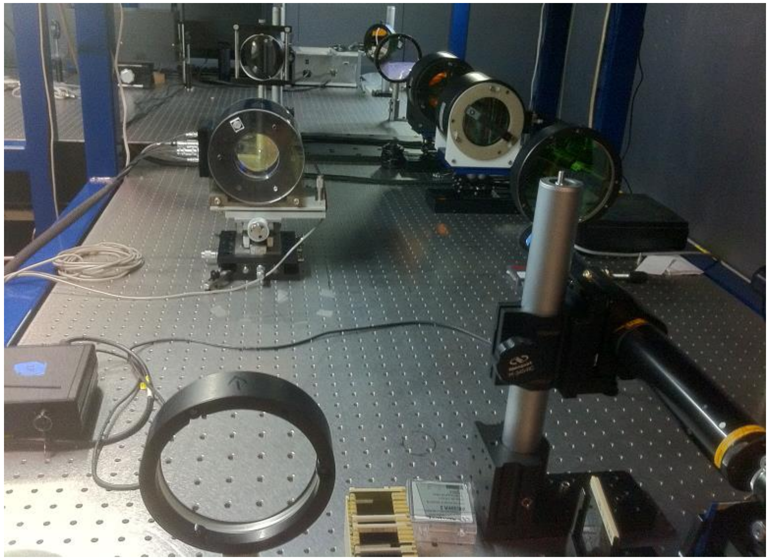


	Collimated	Telecentric
Broadening mechanisms	reflectivity plate shape	reflectivity f-number
Wavelength shift across FOV	yes	no
Wavefront distortion	large	low
Influence of Dust on the image	low	large
Alignment sensitivity	large	low
Blocking Ghost reflections	difficult	easy
Influence of plate shape	broadening	λ-shift

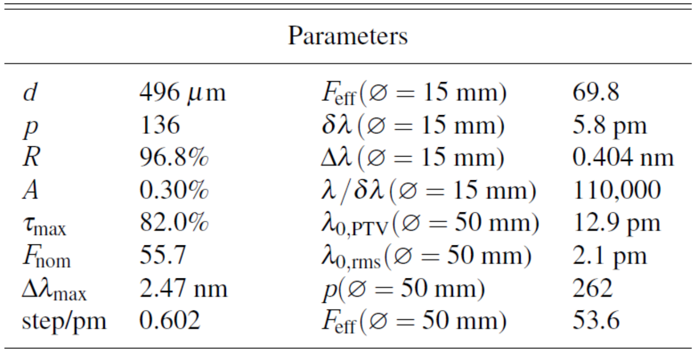
$$\delta\lambda = \left[\left(\frac{\lambda^2(1-R)}{2\pi nd\sqrt{R}}\right)^2 + \left(\frac{\lambda^2}{ndp}\right)^2 + \left(\frac{\lambda\beta^2}{8n}\right)^2\right]^{\frac{1}{2}}$$

Visible Imaging Spectrometer

- Single Fabry-Pérot etalon (D = 70 mm) plus narrow band interference filter
- Wavelength coverage: 550 – 700 nm
- Band pass: 5.8 pm
- Telecentric configuration with F/120
- Available spectral lines:
  - Hα (656.3 $\pm$ 0.15 nm)
  - Fe I (630.2 $\pm$ 0.15 nm)
  - NaD$_2$ (588.9 $\pm$ 0.15 nm)
  - more lines are coming as needed …
- Field of view: 75″(H) by 64″(V)
- High speed computer with SSD HDs
- Spectroscopy cadence: a 11 points scan with multi-frames selection: < 15 secs



CHARACTERISTIC PARAMETERS OF THE VIM FABRY-PÉROT ETALON AT 632.8 NM



Parameters			
d	496 μm	$F_{\mathrm{eff}}(\varnothing = 15\ \mathrm{mm})$	69.8
p	136	$\delta\lambda\,(\varnothing = 15\ \mathrm{mm})$	5.8 pm
R	96.8%	$\Delta\lambda\,(\varnothing = 15\ \mathrm{mm})$	0.404 nm
A	0.30%	$\lambda/\delta\lambda\,(\varnothing = 15\ \mathrm{mm})$	110,000
τ_{max}	82.0%	$\lambda_{0,\mathrm{PTV}}(\varnothing = 50\ \mathrm{mm})$	12.9 pm
F_{nom}	55.7	$\lambda_{0,\mathrm{rms}}(\varnothing = 50\ \mathrm{mm})$	2.1 pm
$\Delta\lambda_{\mathrm{max}}$	2.47 nm	$p(\varnothing = 50\ \mathrm{mm})$	262
step/pm	0.602	$F_{\mathrm{eff}}(\varnothing = 50\ \mathrm{mm})$	53.6