Lecture 07:
Filters

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Big Bear Solar Observatory
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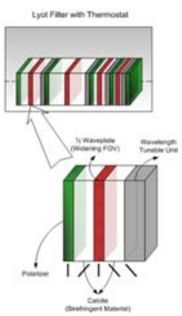
Outline

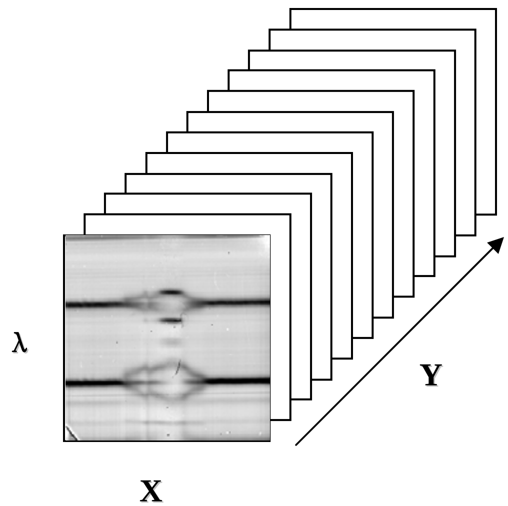


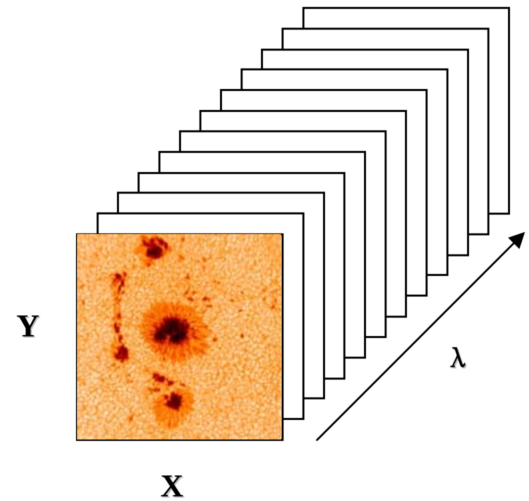
- ***Spectroscopy: spectrographs vs filters***
- ***Interference Filters***
- ***Lyot Birefringent Filters***
- ***Fabry-Perot Interferometers***
- ***Application in Astronomical Observation***

Textbook: The Fabry-Perot Interferometer: History, Theory, Practice and Application, J M Vaughan

1. Imaging Spectroscopy

- ***Spectrographs vs Filters***



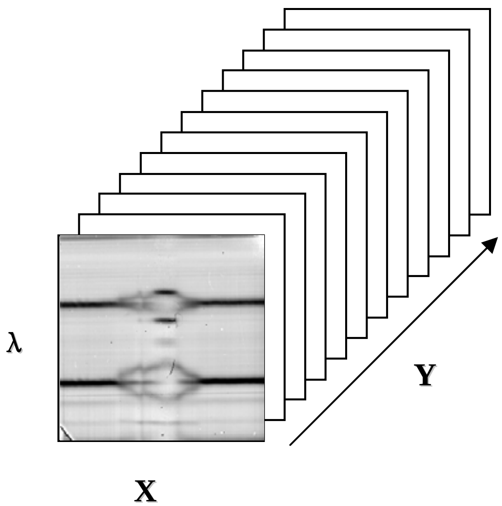


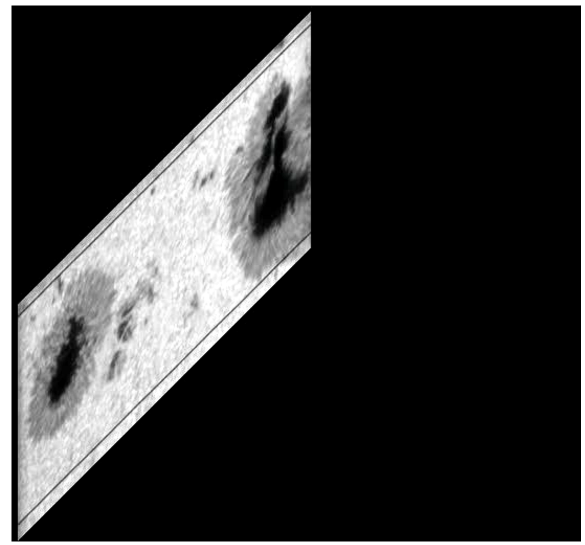
Need x, y, λ observations, can observe 2 simultaneously

Spectrograph observes x, λ
Filter observes y, x

If the spatial/spectral resolution and throughputs are the same and $N_x = N_y = N_\lambda$, then the two methods have same photons/time. Generally, $N_\lambda << N_x$ and filter is more efficient by a factor of $N_x/N_\lambda \sim 100$.

Spectrograph Spectroscopy





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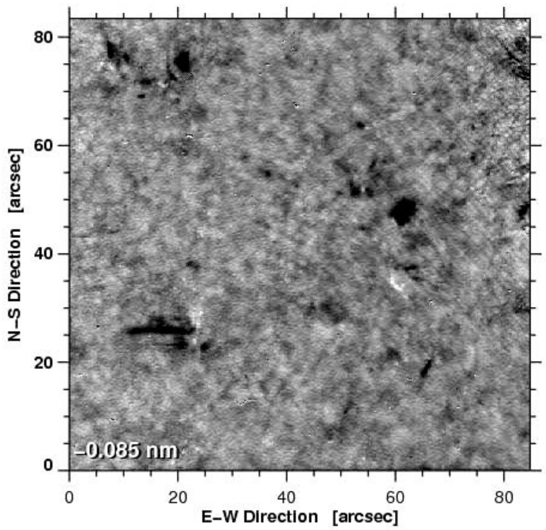
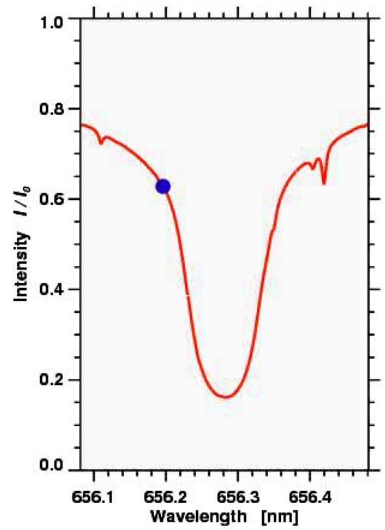
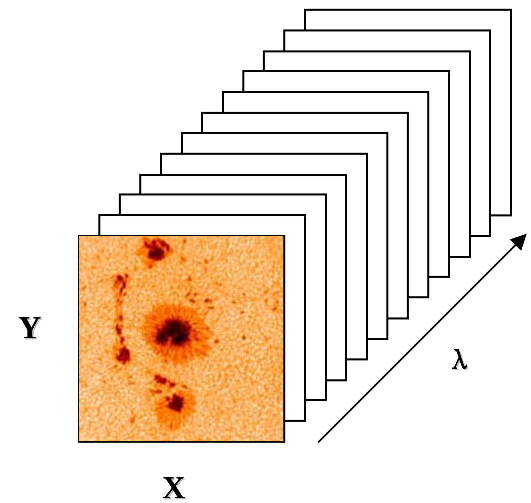
Filter Spectroscopy







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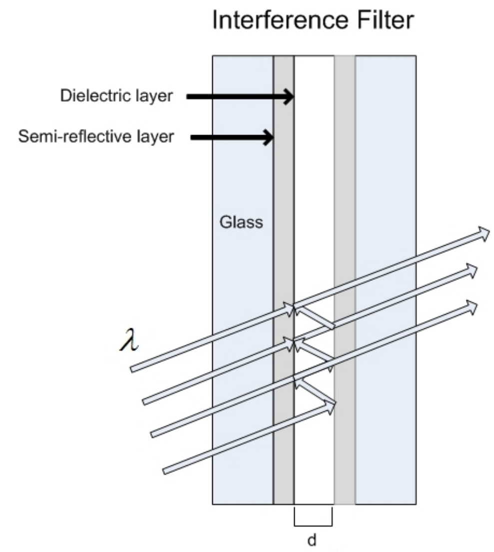
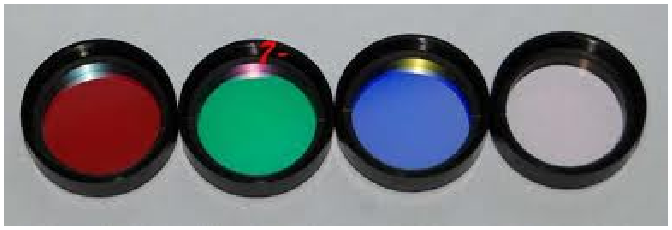
2. Interference Filters

- *Interference filters are multilayer thin-film devices. An optical filter consisting of multiple layers of evaporated coatings on a substrate, whose spectral properties are the result of wavelength interference rather than absorption.*

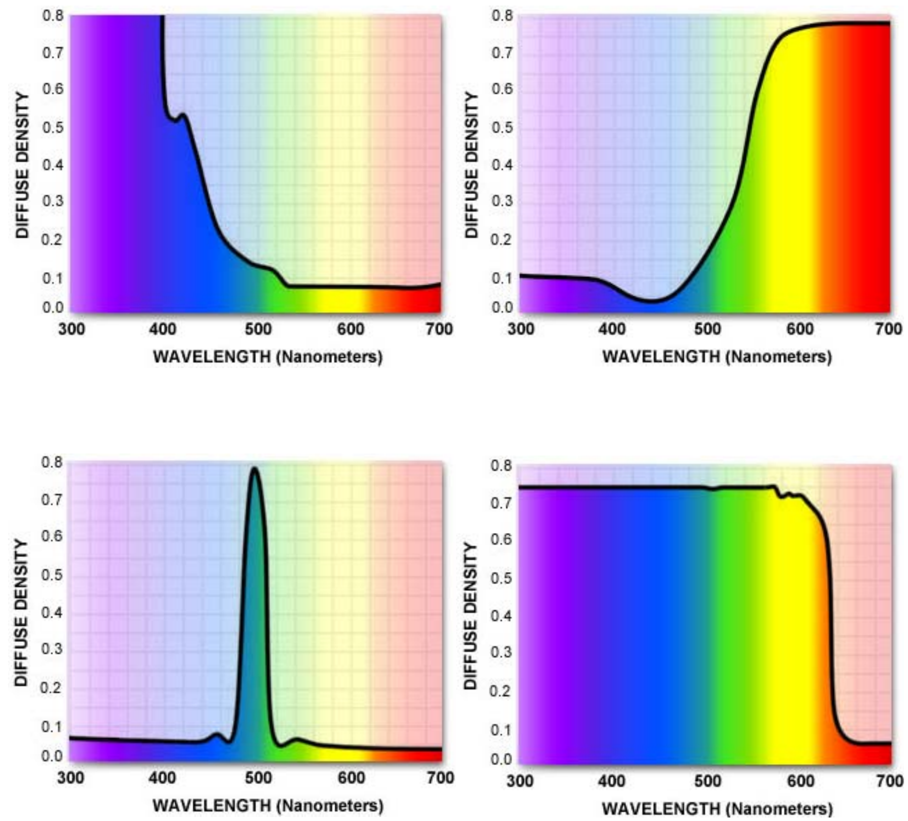
  - *Interference filter classes*
  - *Interference filter structure*
  - *Interference filter principal*
  - *Interference filter terminology*
  - *Choose a right interference filter*





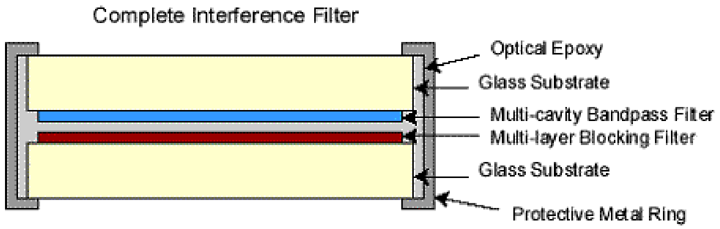
Filter Classes

- **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.*



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

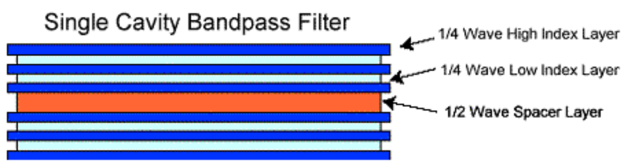


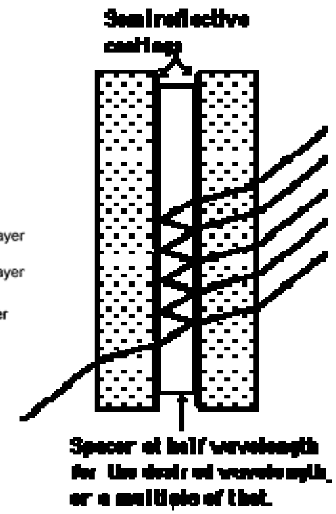
How does it work ?

- 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. ($d = \lambda/2$)
- Start from a Fabry-Perot etalon …

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

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





- Constructive interference occurs when

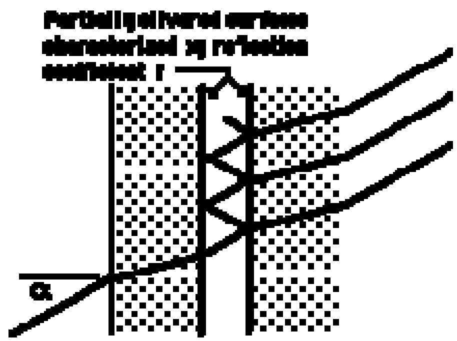
$$m = 1, 2, 3 \ldots$$

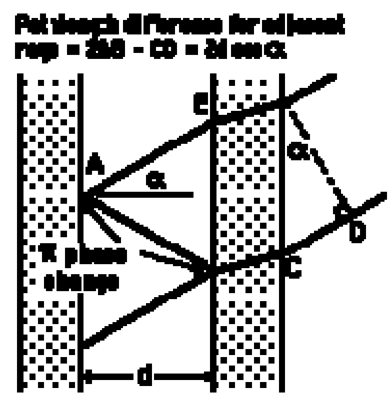
- Zero transmission occurs when

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

- Consider $d = \lambda/2$ and the normal incidence

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





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

How does it work ?

- *Reflection layers: consist of several film layers, each of which is a quarterwave thick (d = λ/4).*

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

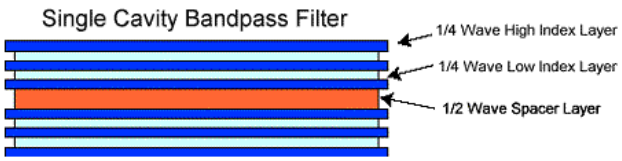
- *Total reflectance on interface R for the normal incident light*

$$R = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2$$

- *Consider n_1 = 1 and n_2 = 1.5 and 16 surfaces, R = ?*
- *Constructive interference occurs when* $m = 1, 2, 3\ldots$
- *Zero reflection occurs when* $m = 1/2, 3/2, 5/2\ldots$
- *Then*

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

- *So, zero reflection occurs and the light pass through the reflective surfaces if the reflected beam are in phase.*



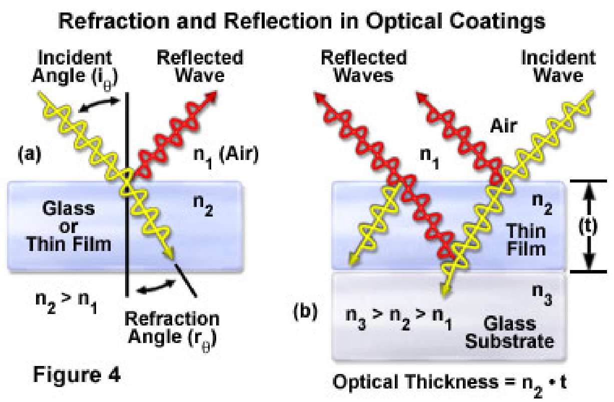
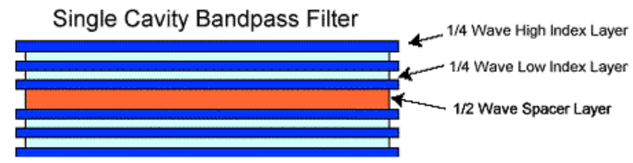


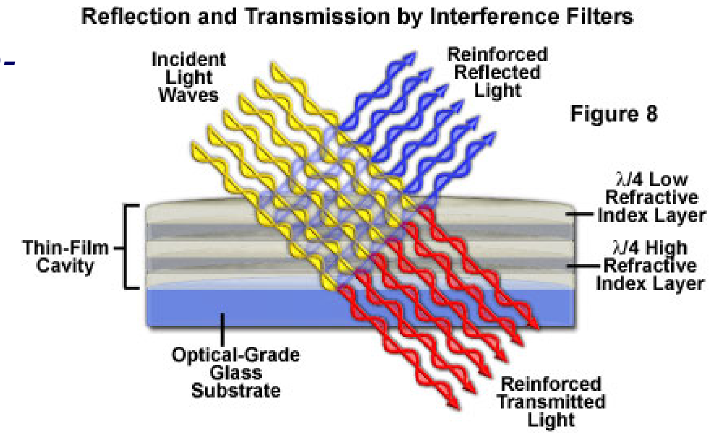
Figure 4

Principal Summary

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

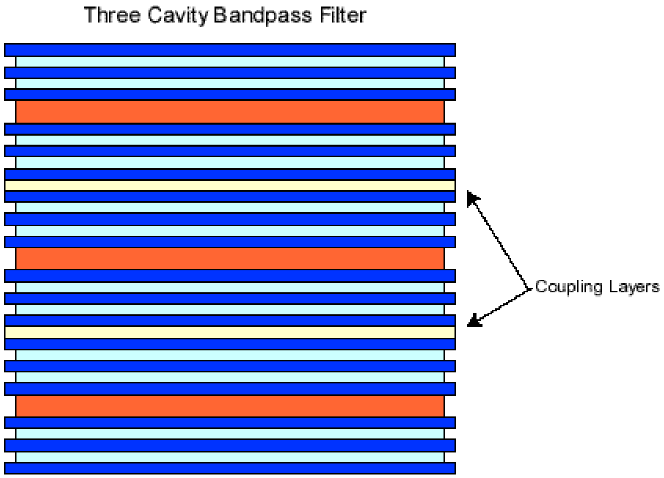


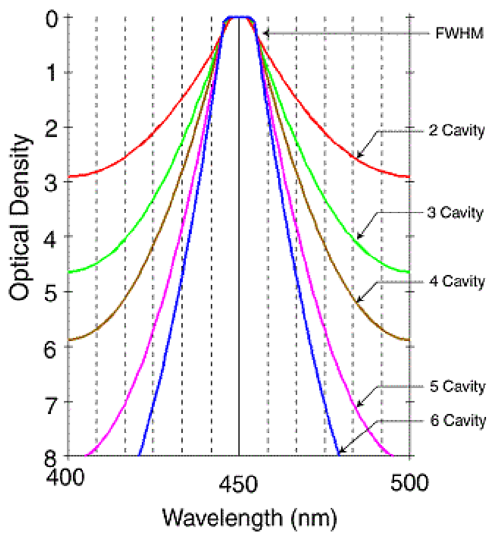
- *Spacer: the gap between the reflecting surfaces is a thin film of dielectric material, with a thickness of one-half wave at the desired peak transmission wavelength. ($d = \lambda/2$)*
- *The gap in spacer determines which wavelengths destructively interfere and which wavelengths are in phase and 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.





Interference Filter Anatomy

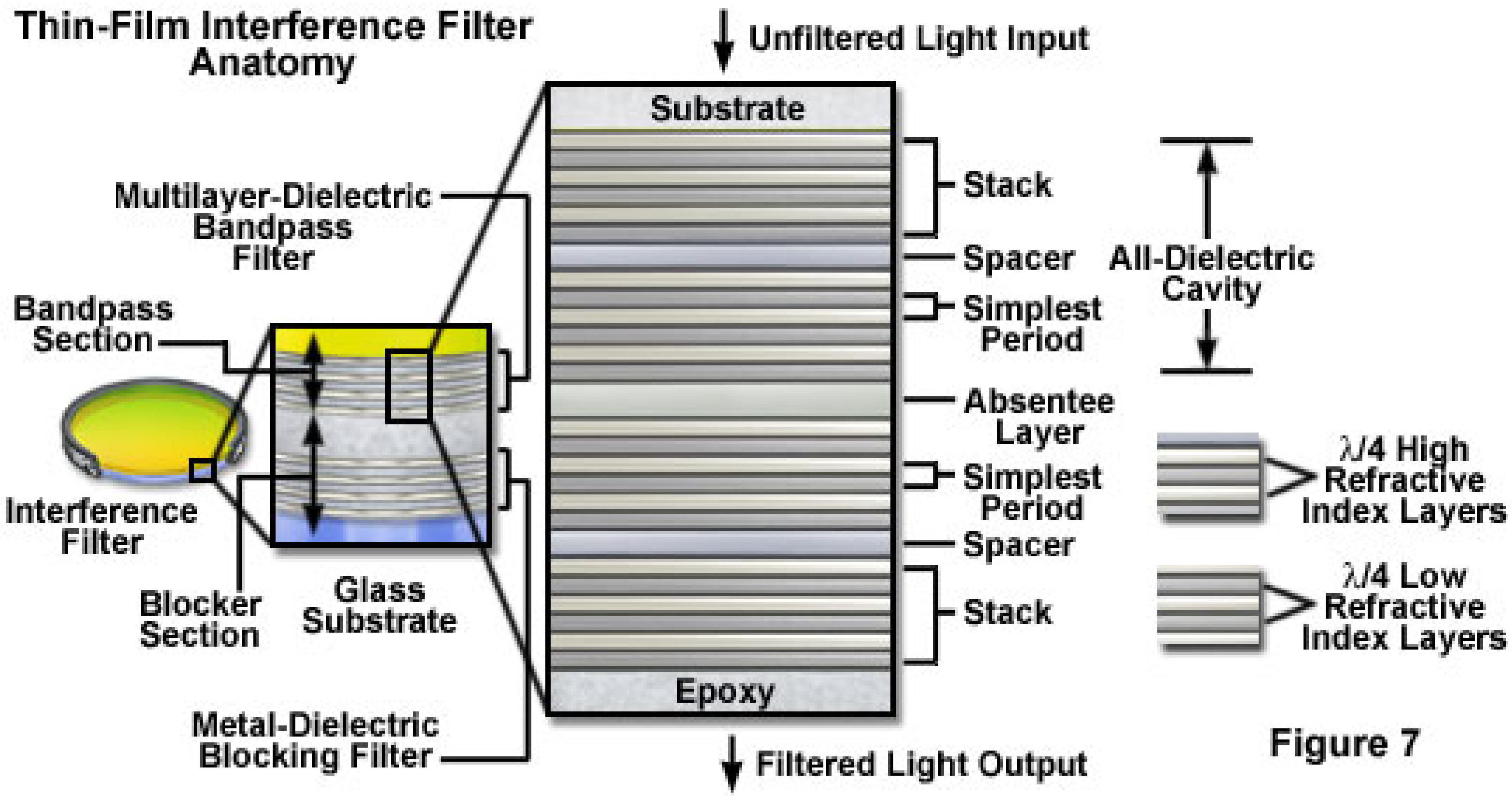
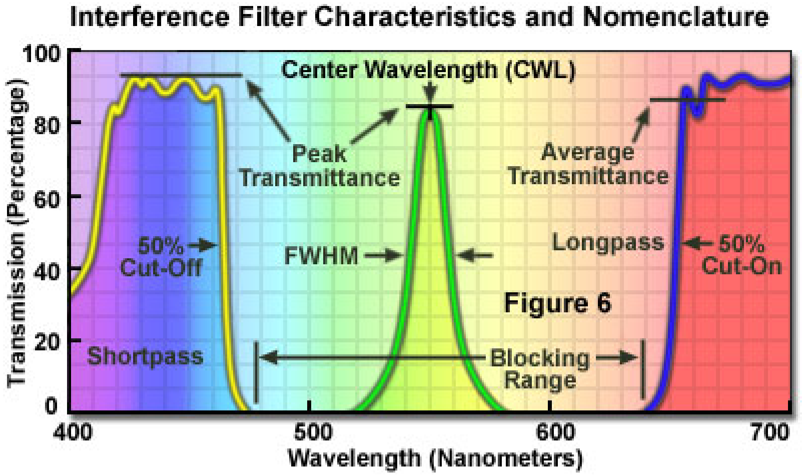


Figure 7

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.*



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.*

Wavefront Distortion by Optical Surfaces

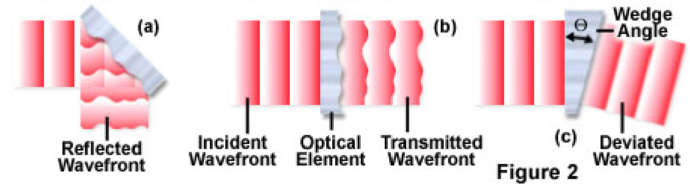


Figure 2

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

Select a Right Filter

Quotation

For: **Wenda Cao**
Big Bear Solar Observatory
Address: New Jersey Institute of Technology
40386 North Shore Lane
Big Bear City, CA 92314-9672
Phone:
Fax:
E-Mail: wcao@email.noao.edu

See Attached

From: **Kyle Bushong**
Phone: 978-692-7513 x3658
Fax: 978-692-7443
E-Mail: kyle_bushong@beminc.com

Item	Description	Qty	Unit Price	Total Price
1	CWL: 430.5 +0.2/-0nm FWHM: 1.0 ± 0.2nm Peak %T: > 60% Out of band blocking: E-5 from 200-1200nm Transmitted wavefront: ≤ 1/4wv PV per 1" CA @ 632.8nm Size: 50mm diameter nominal Clear aperture: 45mm minimum Thickness: unspecified Angle of incidence: 0° Operating temp: -10 to 30°C Surface quality: 60/40 per MIL-C-48497A Multiple substrate air-spaced construction, laminated into Al ring Air gap ~0.5-0.6mm Parts will be tested in air @ ~23°C with a collimated beam	2	$ 3,720.00	$ 7,440.00
2	Estimated shipping/insurance charge Shipping: ~$25 Insurance: ~$40	1	$ 65.00	$ 65.00
	Minimum order value: $5000.00 USD Deliverable Data: 1) In-band evaluation per filter, confirm peak T%, CWL, FWHM 2) Out-of-band blocking from 200-1200nm on 1 filter per batch ONLY 3) One scan per filter to confirm TWF, ≤ 1/4wv per 1" clear ap. Air-space worst case: add TWF of both components Pricing above does NOT include freight. All freight will be prepaid & added to invoice.			

Select a Right Filter

Prepared for: Wenda Cao
NJIT

USA

Fax:
Phone:
e-mail: wcao@email.noao.edu

Quotation # **28307**

Issue Date: 5/12/2010
Quote Validity: 90 days from date
Payment Terms: Pending
F.O.B.: Salem, NH

All prices are quoted in U.S. dollars

Prepared by: Phillip Clark
phil.clark@andovercorp.com

Re.: RFQ dated May 10th

Item #	Description	Qty	Unit price	Extended Item price	Delivery
1		1	$3,995.00	$3,995.00	3-4 weeks ARO
		2	$3,295.00	$6,590.00	3-4 weeks ARO

Wavelength: 430.5 nm +0.1/-0
Bandwidth: 0.5 nm ±0.1
Transmission: 40%
Blocking: 1 x 10-4 avg. X-Ray to 1200nm
Construction: 2 cavity

Size: 50.0 mm +0/-0.25
Thickness: 7.0 mm maximum
Clear Aperture: 45.0 mm

Temp. (° C.): 23.0
Operating Angle: 0

Substrate Mat'l: BK7 & Filter Glass
TWF: 1/4 wave per inch or better
Parallelism: 30 arc seconds or better
Scratch/Dig: 60/40
Polarization: Random
Effective Index: 1.45

Comments:

1. Exterior surfaces will be A/R coated
2. Filter will be mounted in a ring

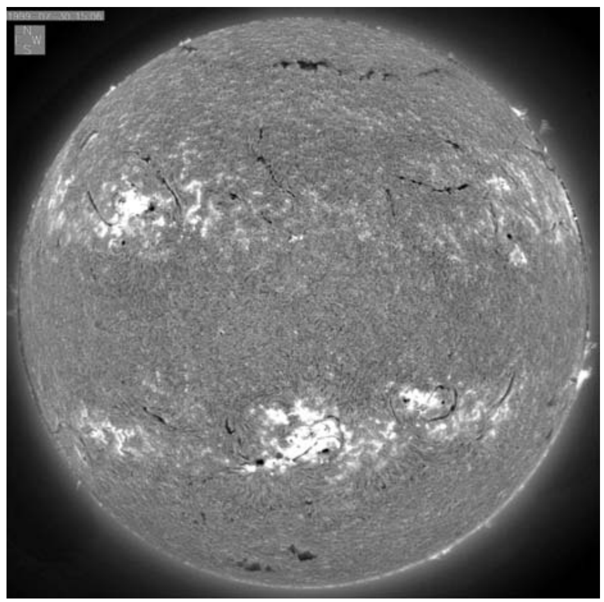
- **SCRATCH:** *Any marking or tearing of the part surface.*
- **DIG:** *A small rough spot on the part surface similar to a pit in appearance. A bubble is considered a dig.*

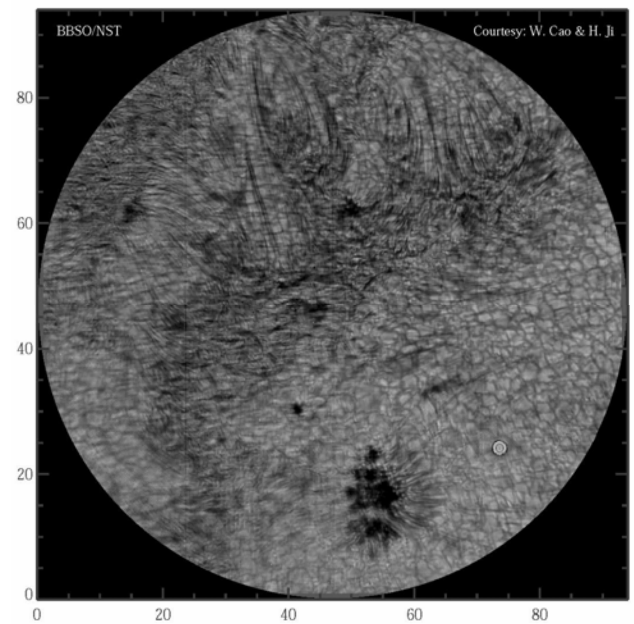
Scratch or Dig Number	Maximum Scratch Width		Maximum Dig or Bubble Diameter		Dig or Bubble Separation Distance	
#	mm	inch	mm	inch	mm	inch
120	0.12	0.0047	1.20	0.0473	20	0.787
80	0.08	0.0031	0.80	0.0315	20	0.787
60	0.06	0.0024	0.60	0.0236	20	0.787
50	0.05	0.0020	0.50	0.0196	20	0.787
40	0.04	0.0016	0.40	0.0158	20	0.787
30	0.03	0.0012	0.30	0.0118	20	0.787
20	0.02	0.0008	0.20	0.0079	20	0.787
15	0.015	0.0006	0.15	0.0059	20	0.787
10	0.010	0.0004	0.10	0.0039	1.0	0.040
5	0.005	0.0002	0.05	0.0020	1.0	0.040
3	0.003	0.00012	0.03	0.0012	1.0	0.040

3. Lyot Filters

Bernard Lyot 1897-1952

- *A 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.*





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.***

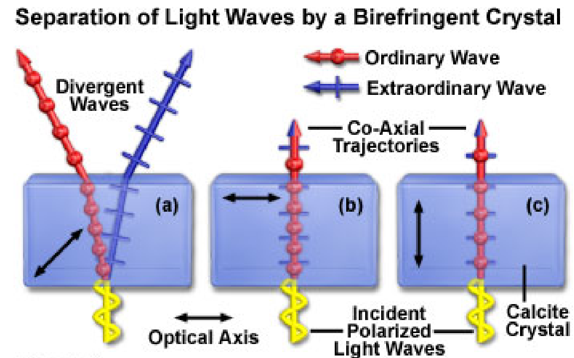
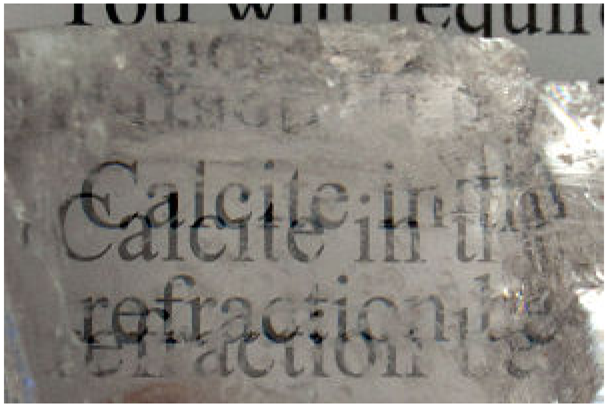


Figure 1



$$n_o \neq n_e$$

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*

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

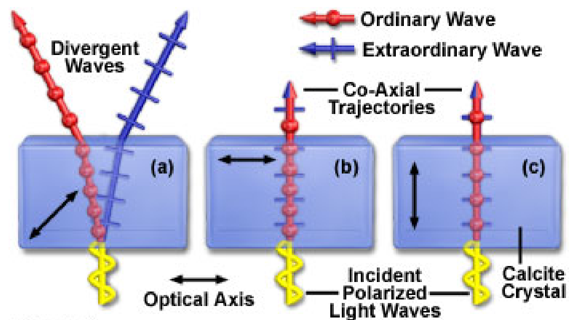
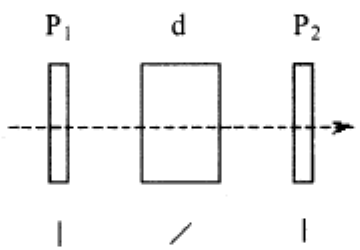


Figure 1



Transmission Profiles

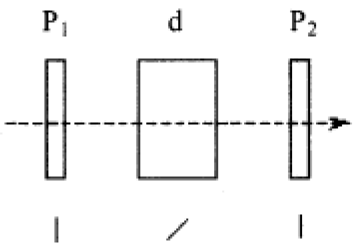
- *What does the transmission profile look like?*

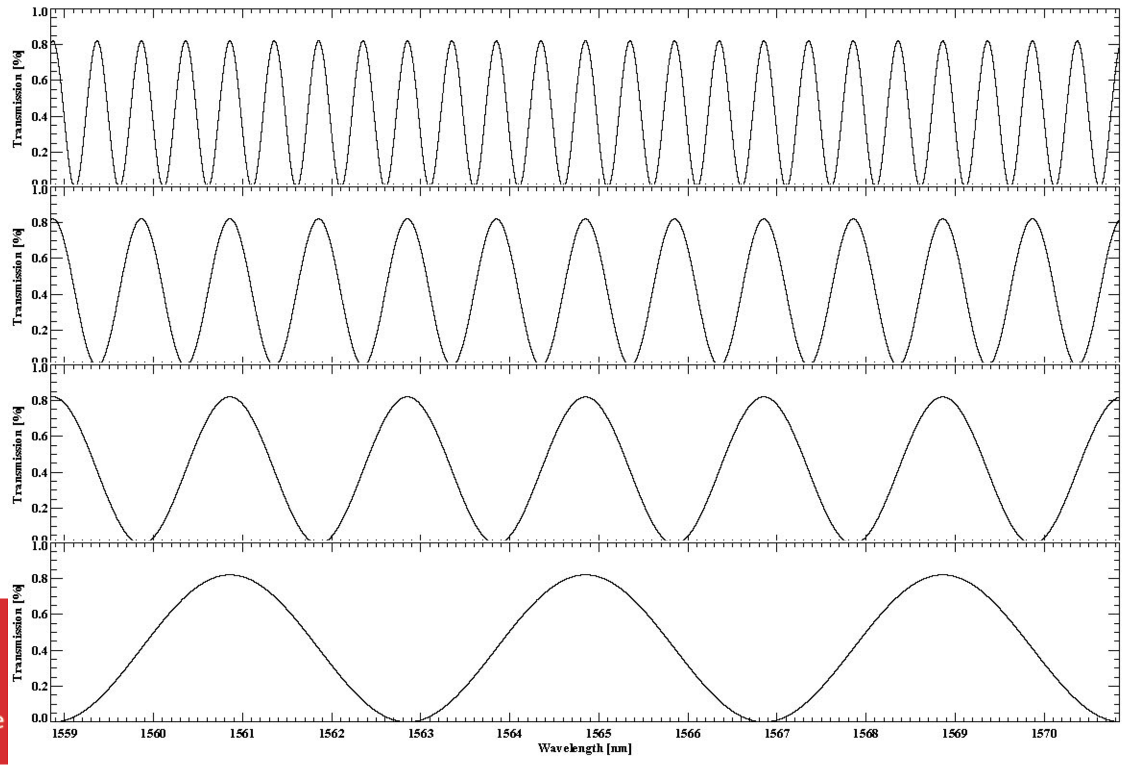
$$T_1 = \cos^2(\frac{\delta_1}{2}) = \cos^2(\frac{\mu d_1}{\lambda}\pi) = \cos^2(\sigma_1 \pi)$$

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

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

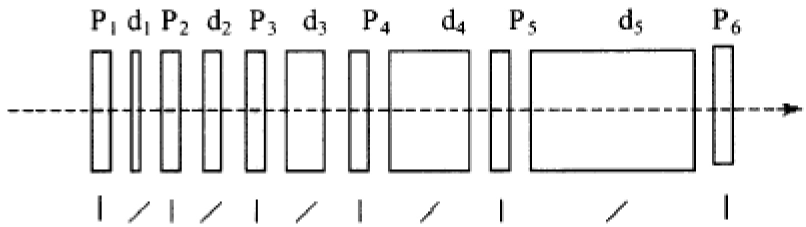
- *$d_3 = 2d_2 = 4d_1$?*
- *$d_4 = 8d_1$?*

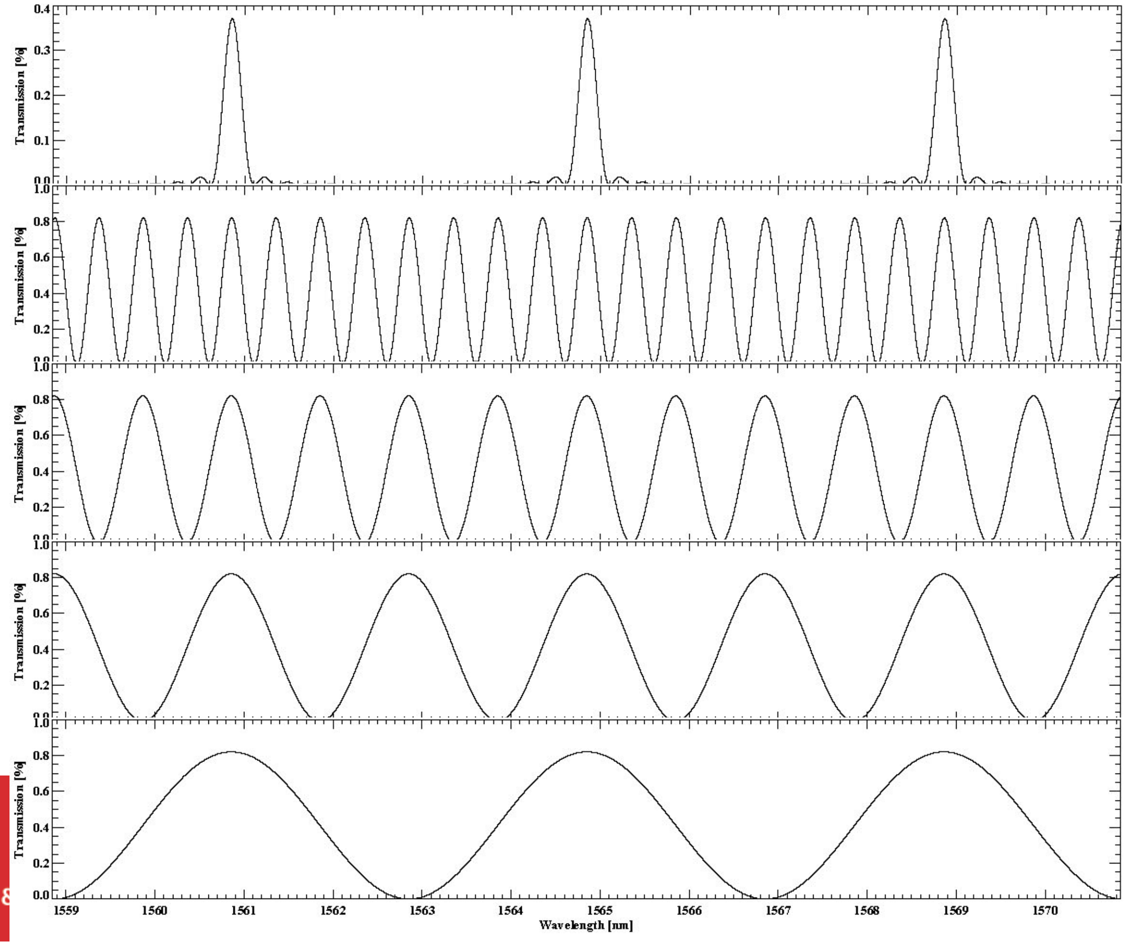




Lyot Filter Transmission Profiles

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





FWHM and FSR

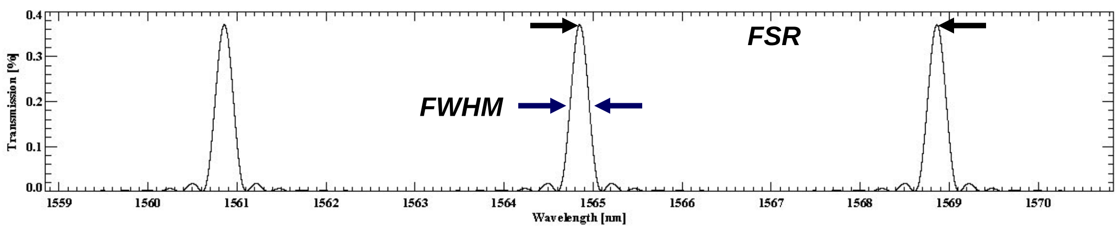
- ***Full Width at Half Maximum (FWHM):*** *is determined by the thickness of the thickest stage d_{thick}.*

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

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

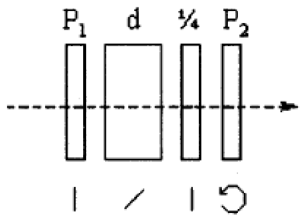
$$FSR = \frac{\lambda^2}{\mu d_{thin}}$$

- *For a Lyot filter with n stages, $d_{thick} = (2n)d_{thin}$, so* $$FSR = \frac{\lambda^2}{\mu d_{thin}} = (4n)\Delta\lambda_{FWHM}$$

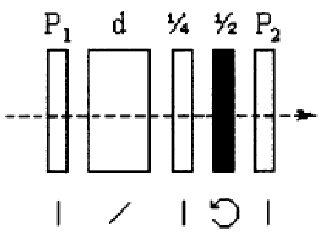


Lyot Filter Tuning

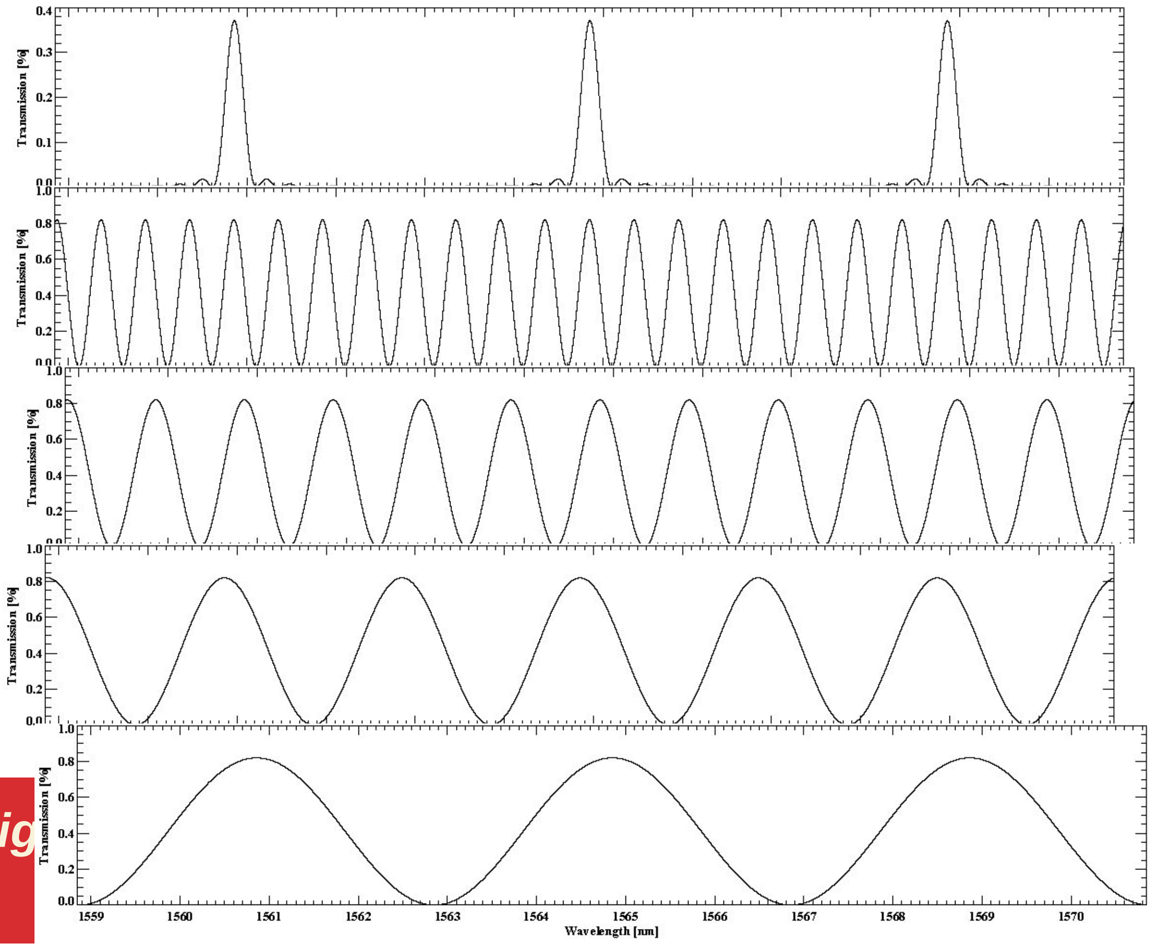
- *Wavelength tuning is a critical feature to calibration, fabrication and operation.*
- *Each stage needs its individual tuning system.*
- *A quarter waveplate, which follows the crystal to be 45° with respect to the optical axis, is followed by a rotating polarizer or a rotating half waveplate.*



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



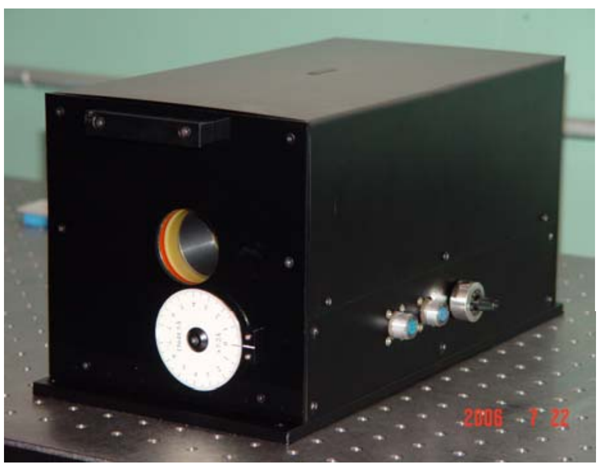
$$T = \cos^2(\frac{\mu d}{\lambda}\pi + 2\beta) = \cos^2(\sigma\pi + 2\beta)$$

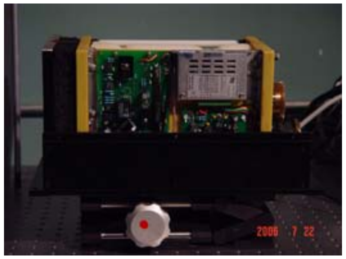


BBSO NIR Lyot Filter

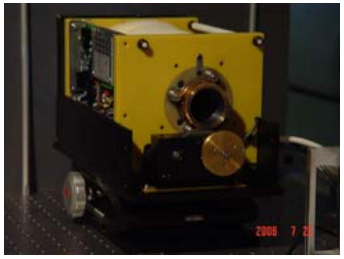
Design Requirement

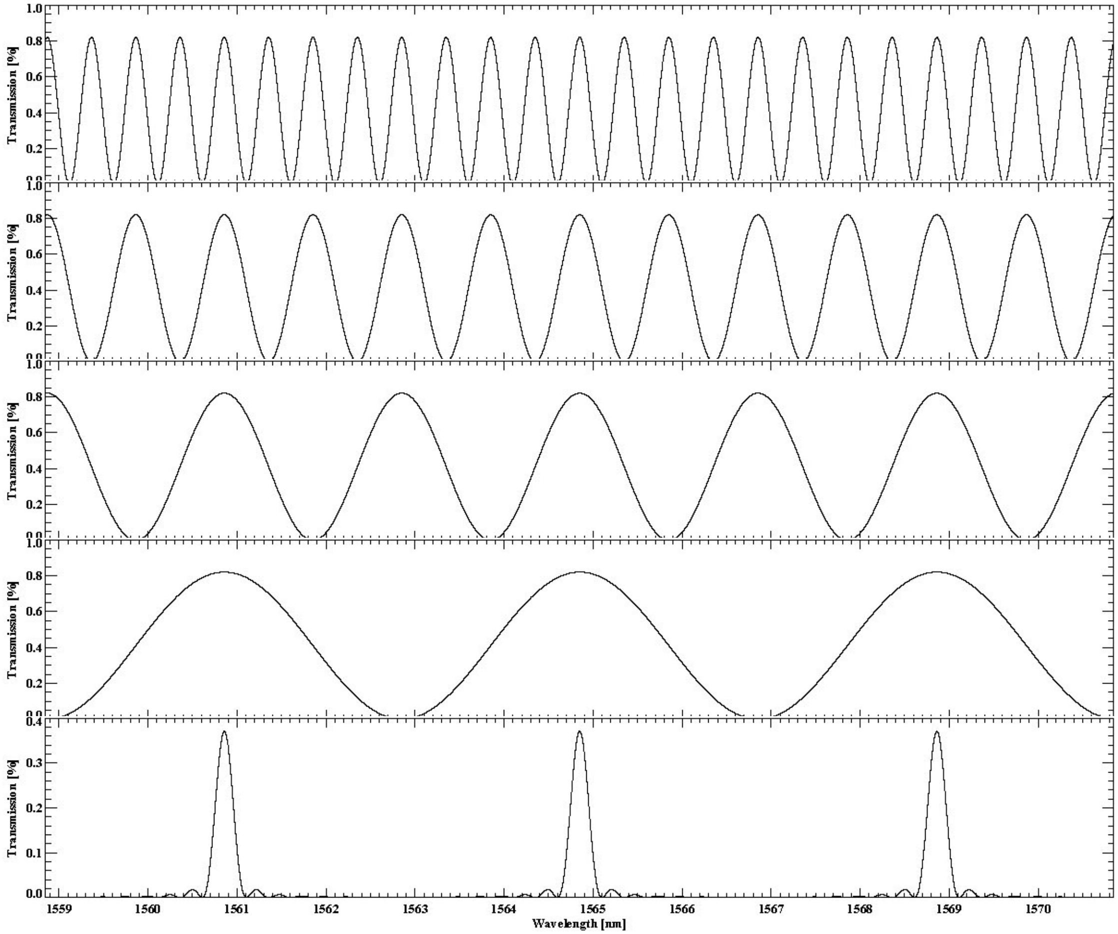
- Working Wavelength: Fe I 1.5648 & 1.5652 μm
- Clear Aperture: ~ 37 mm
- Passband FWHM: 2.5 Å
- Tunable Range: ± 7 Å
- Peak Transmission: ~ 8 % for non-polarized light
- Internal Structure: 4-module
- Thermal Controller: 35.000 ± 0.005° C
- Minimum tunable step: 0.01 Å

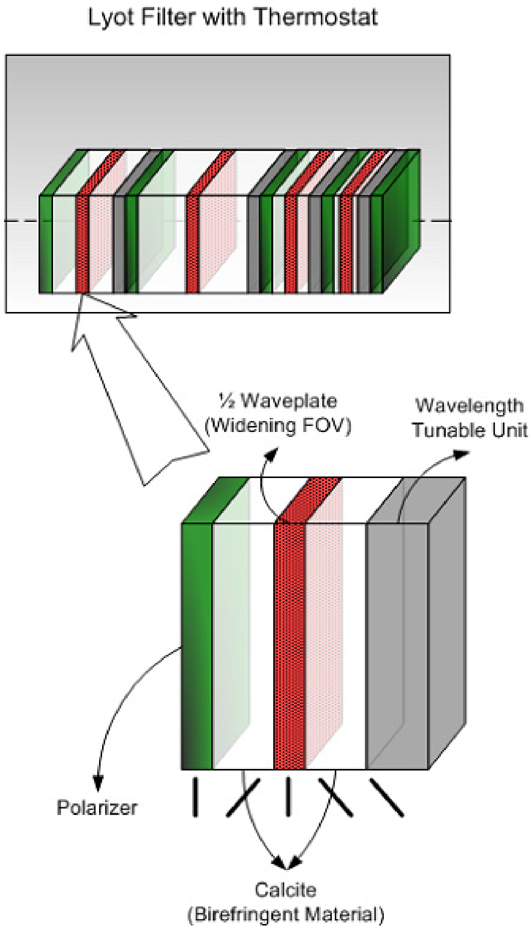




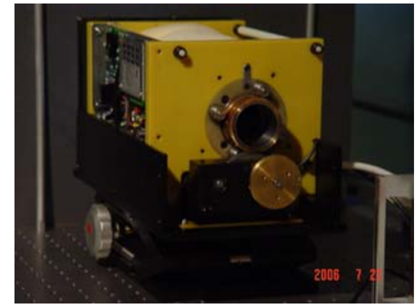
Optical and Mechanical Design







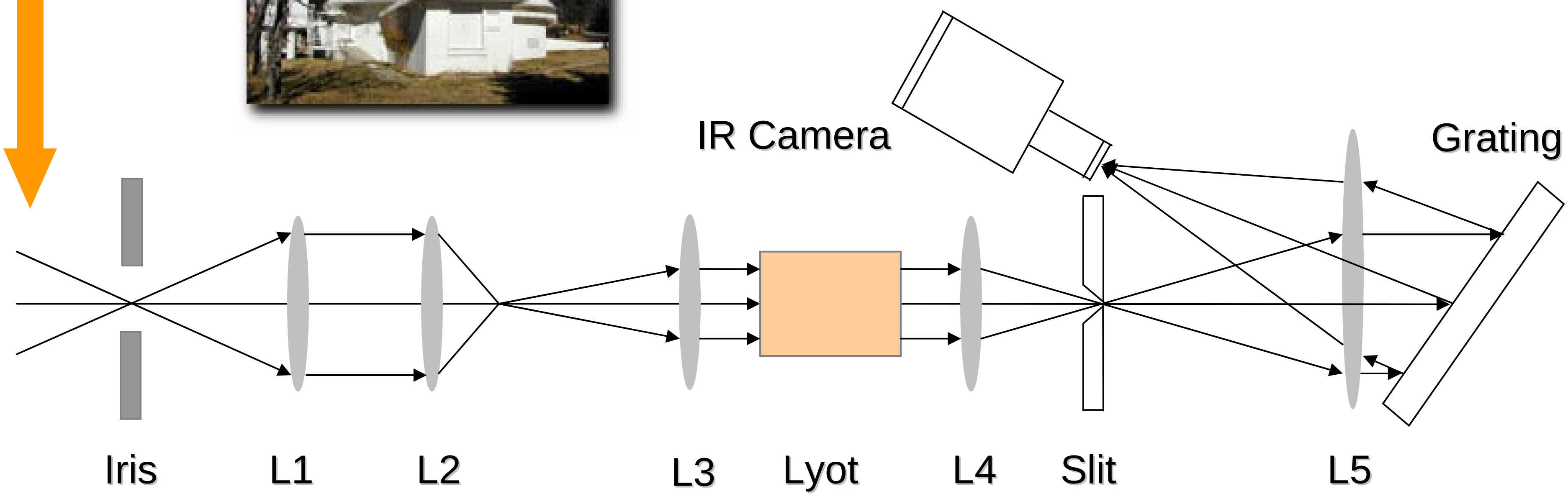
System Calibration



John W. Evans Solar Facility

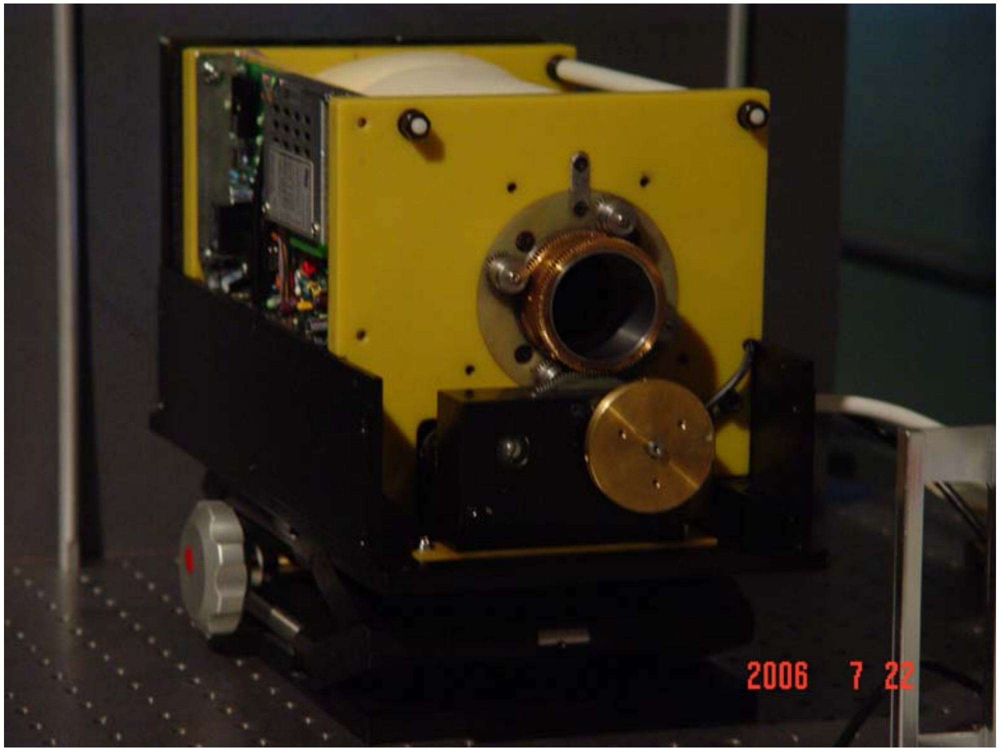
National Solar Observatory/Sacramento Peak

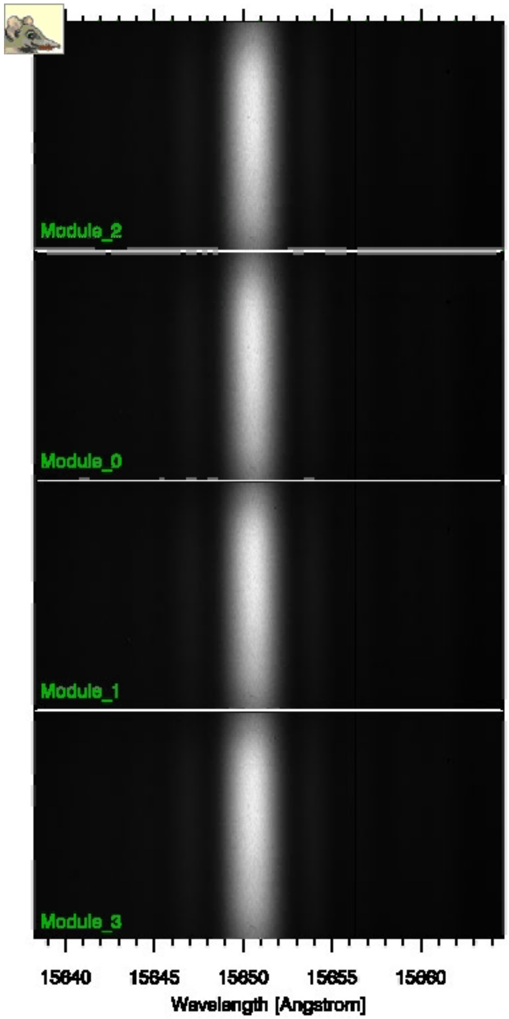
July 2006



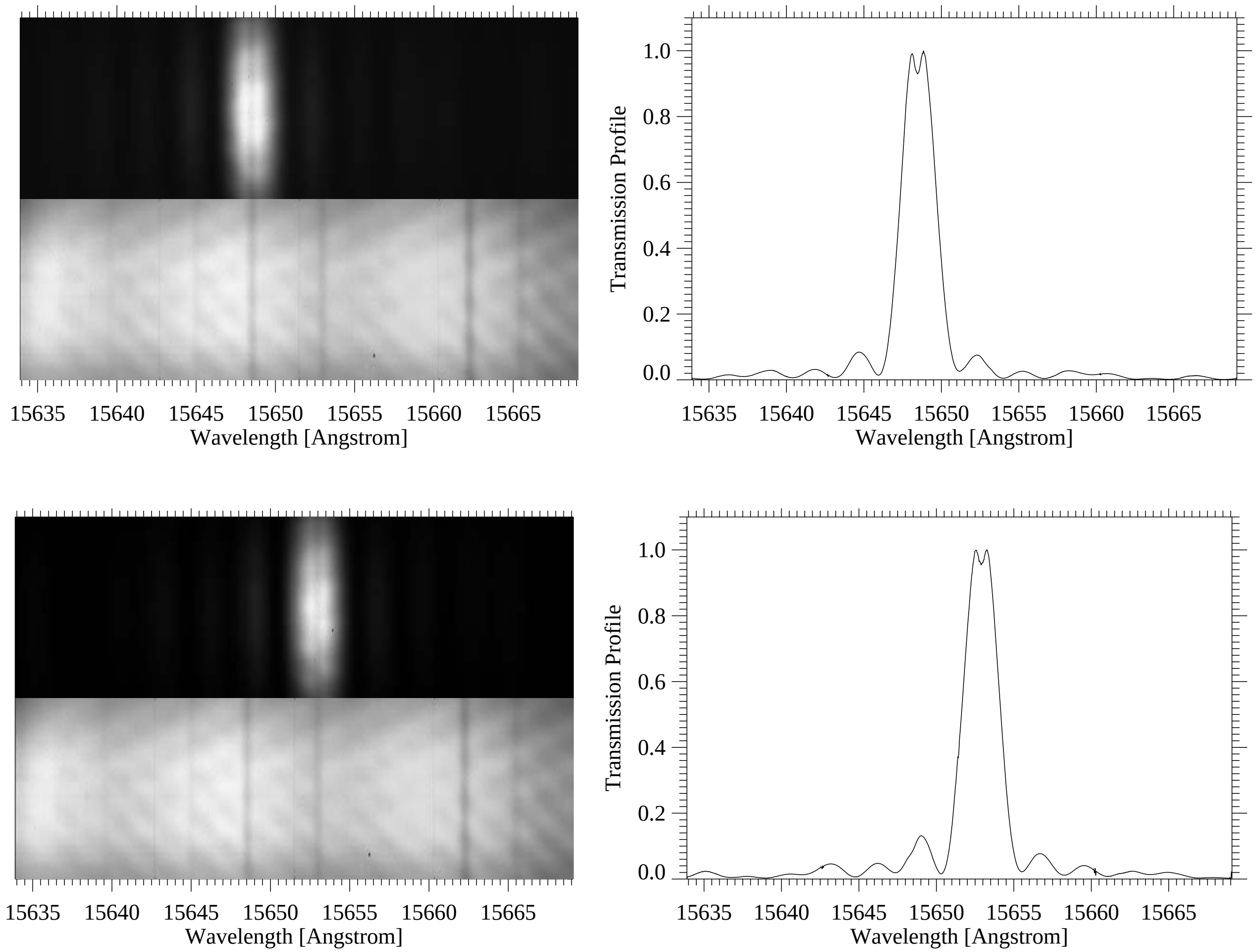
System Calibration

$$T = T_0 \cdot T_1 \cdot T_2 \cdot T_3$$
$$= \cos^2\left(\frac{\mu d}{2^0 \lambda}\pi + \delta_0\right) \cdot \cos^2\left(\frac{\mu d}{2^1 \lambda}\pi + \delta_1\right) \cdot \cos^2\left(\frac{\mu d}{2^2 \lambda}\pi + \delta_2\right) \cdot \cos^2\left(\frac{\mu d}{2^3 \lambda}\pi + \delta_3\right)$$

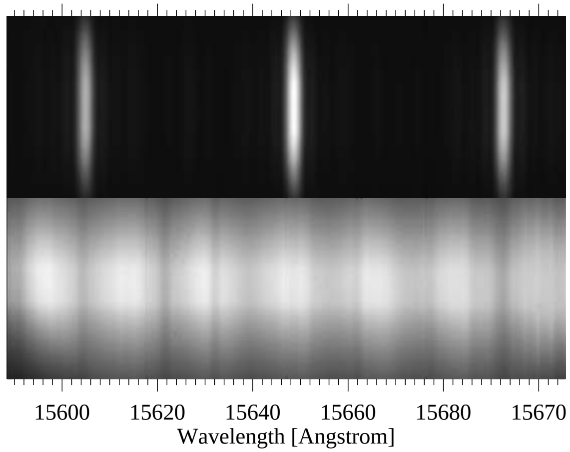


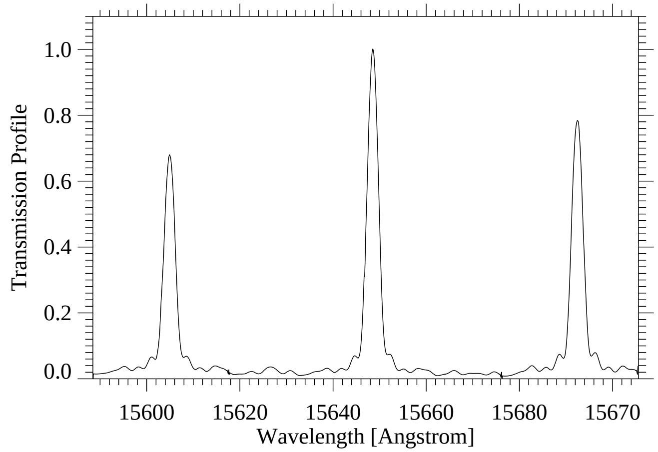


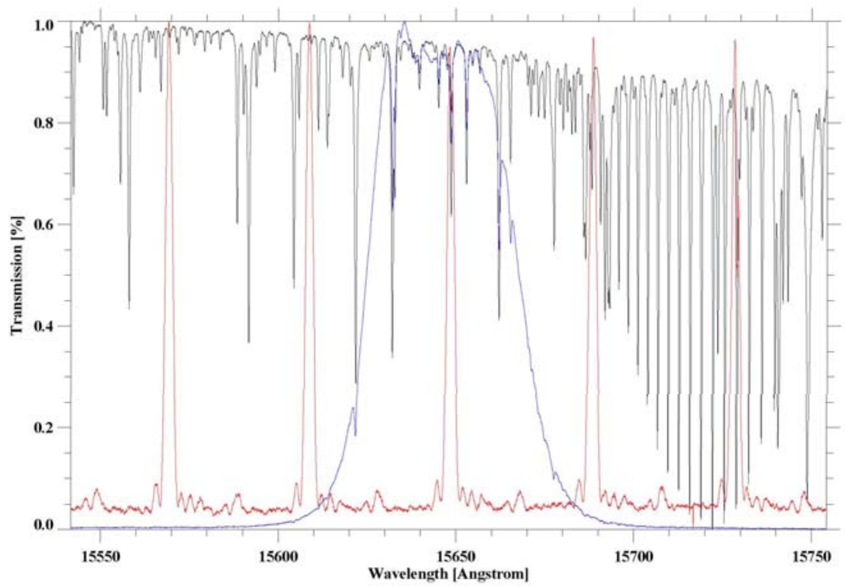
Transmission Profiles



Order Sorting Filter

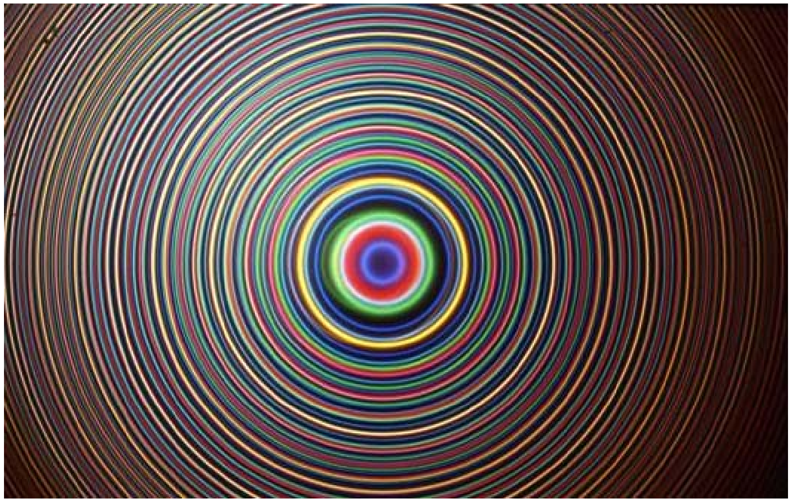


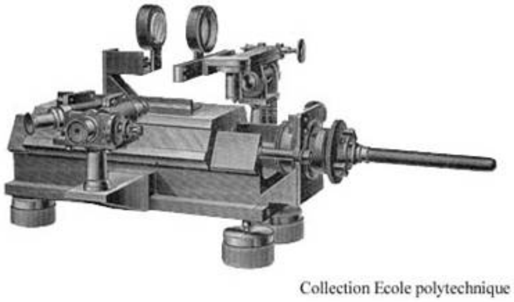




4. Fabry-Perot Interferometer

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



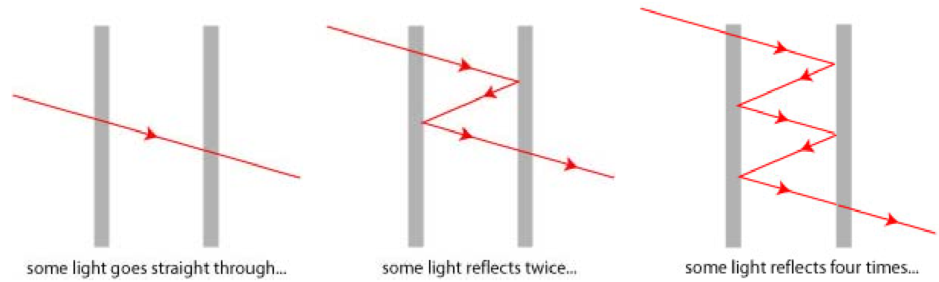


How does a FPI work ?

- *Start from a Fabry-Perot etalon …*

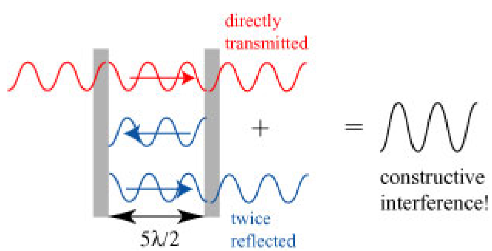
$$2AB - CD = 2\mu d \cos\alpha$$

$$m\lambda = 2\mu d \cos\alpha$$



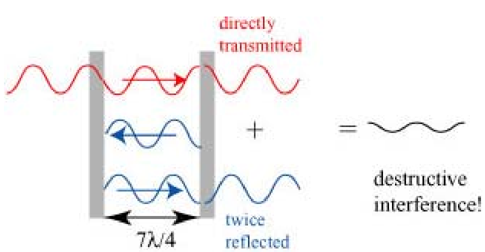
- *Constructive interference occurs when*

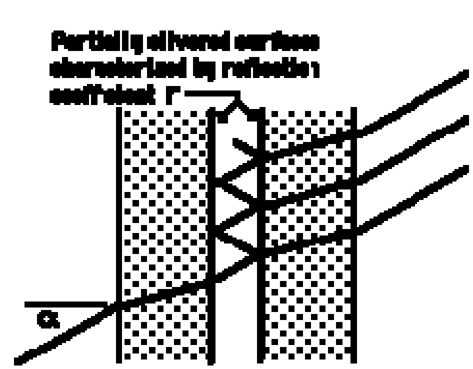
$$m = 1, 2, 3\ldots$$

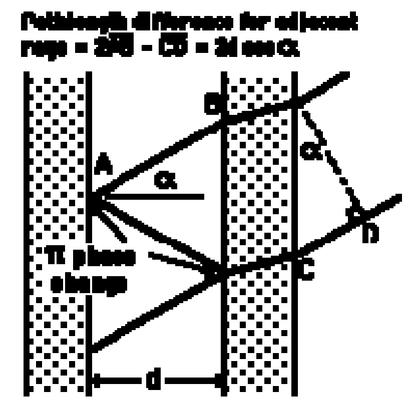


- *Destructive interference occurs when*

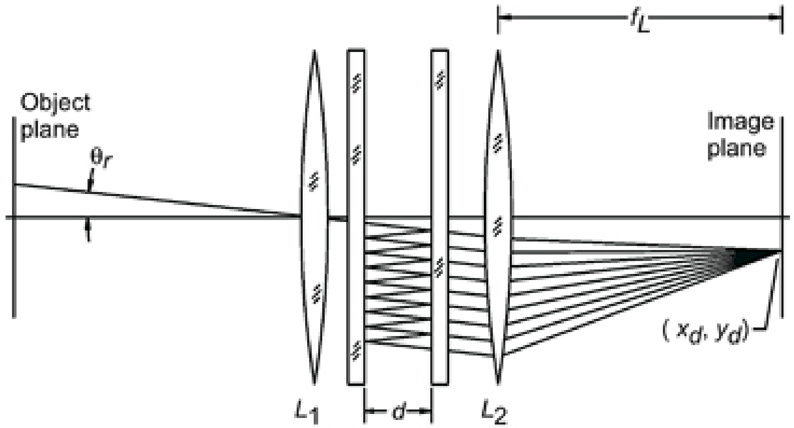
$$m = 1/2, 3/2, 5/2\ldots$$







Interference Fringe

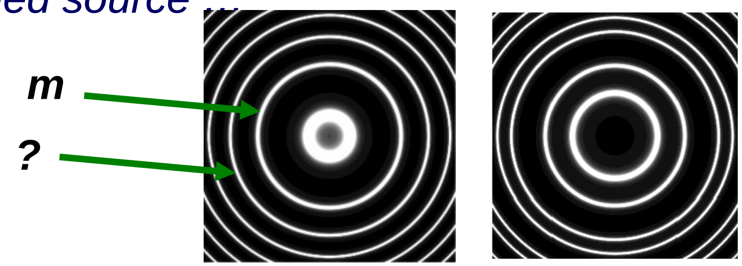


$$m\lambda = 2\mu d \cos\alpha$$

- *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*

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

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

- *The energy transmission coefficient for the pair of surfaces:*

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

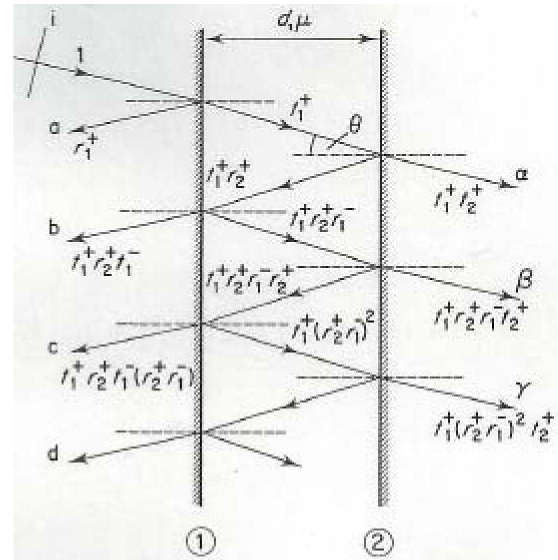
$$I_T = T^2 \big/ (1 + R^2 - 2R\cos\varphi)$$

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

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

- *The energy reflection coefficient for the pair of surfaces:*

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



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

$$T = t^+ t^-$$

$$R = (r^+)^2 = (r^-)^2$$

$$R + T = 1$$

Transmission Profile

- *Consider absorption* $A + R + T = 1$
- *The energy transmission coefficient for the pair of surfaces:*

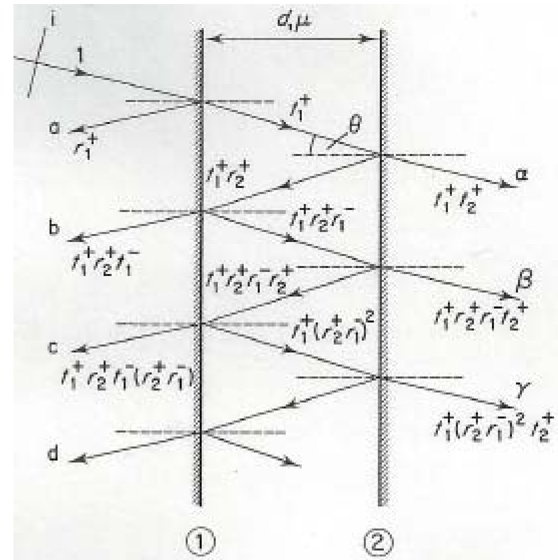
$$I_T = [T/(1-R)]^2[1+F\sin^2(\varphi/2)]^{-1}$$
$$= [(1-R-A)/(1-R)]^2[1+F\sin^2(\varphi/2)]^{-1}$$
$$= [1-A/(1-R)]^2[1+F\sin^2(\varphi/2)]^{-1}$$

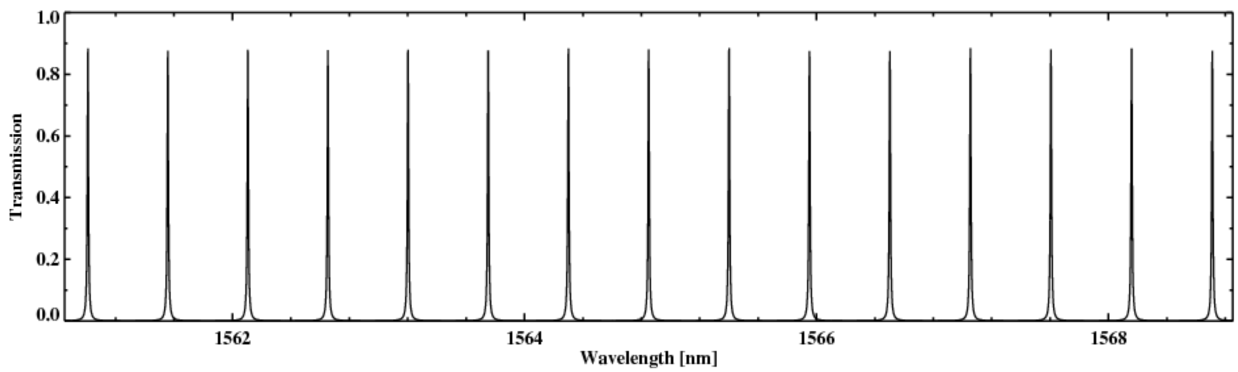
- *When* $\varphi = 2m\pi$*, constructive interference occur*

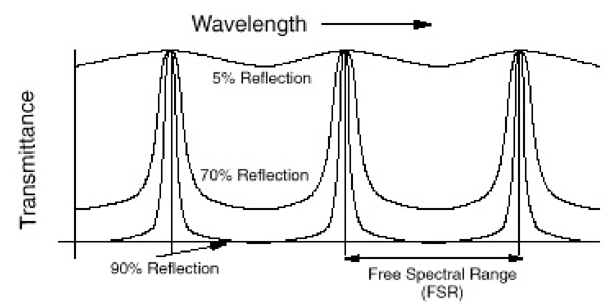
$$I_{\max} = I_0[1-A/(1-R)]^2 = I_0T^2/(1-R)^2$$

- *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):*

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

- *Free spectral range (FSR):*

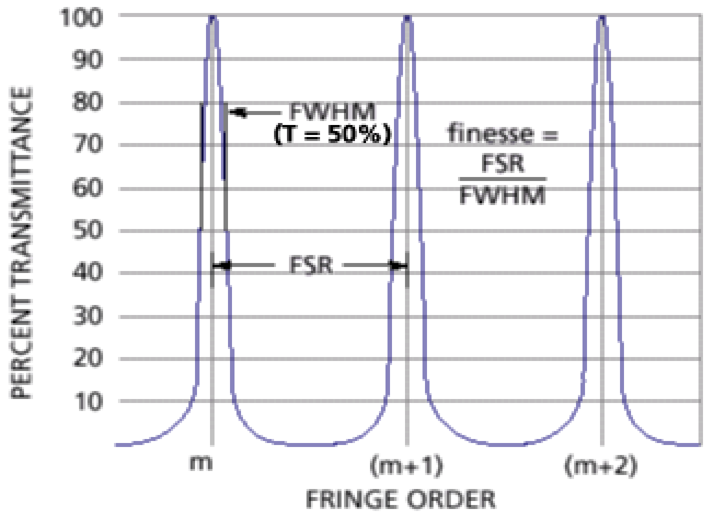
$$fsr = \frac{\lambda^2}{2\mu d \cos\theta} = \frac{\lambda}{m}$$

- *Finesse:*

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

- *Resolving power:*

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

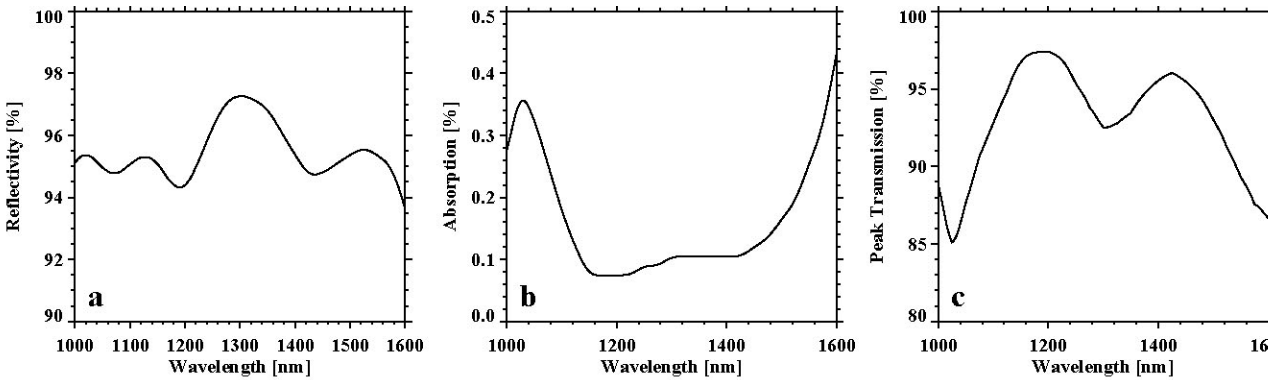


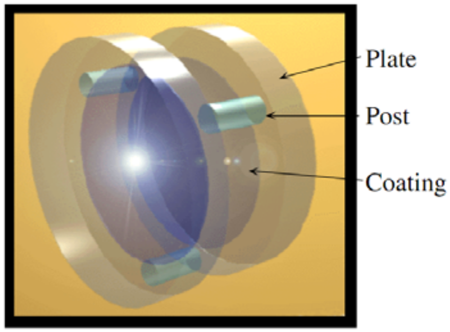
$$m\lambda = 2\mu d \cos\theta$$

An Example

Queensgate FPI Specification

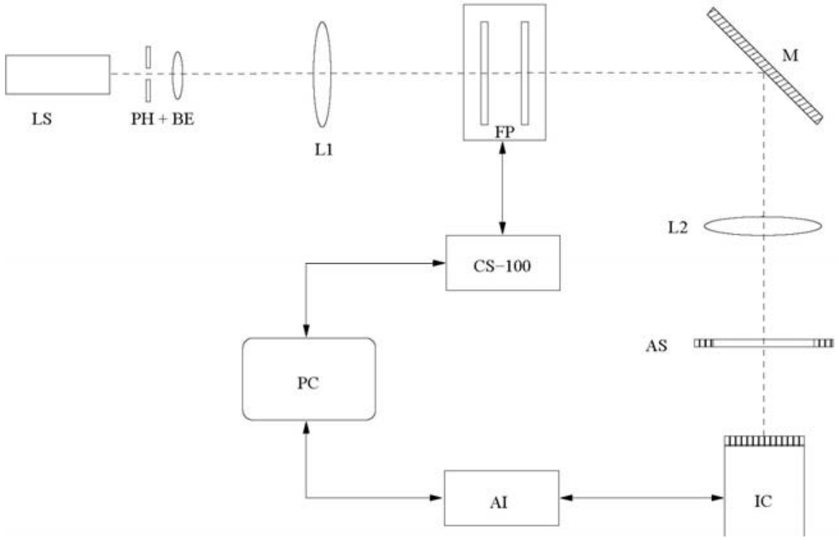
Etalon Model:	ET70FS-1041
Working Wavelength:	1 ~ 1.6 μm
Clear Aperture:	~ 70 mm
Nominal Finesse:	60 @ 1523 nm
Controller Model:	CS100-8105
Cavity Spacing:	2226 μm
Cavity Scan Range:	> 4.1 μm
Plate Flatness:	> λ / 100 @ 546.1 nm

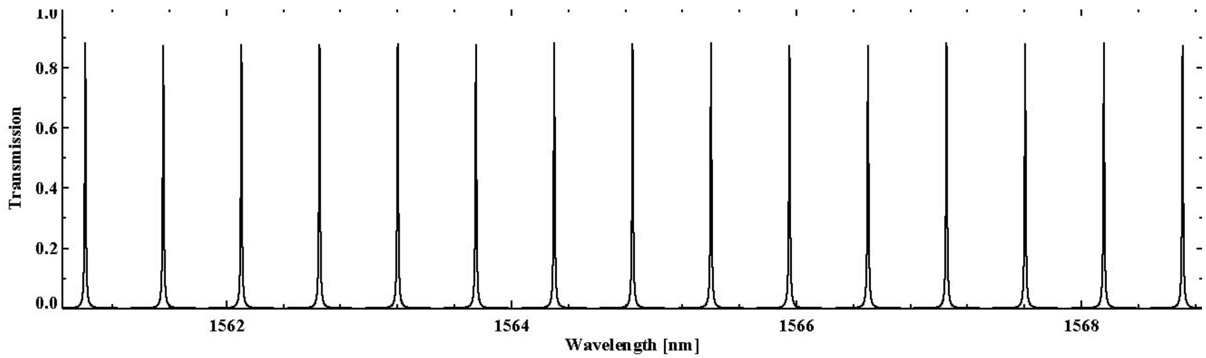




FPI Characteristic Evaluation

- *Bandpass (FWHM)*
- *Free Specral Range*
- *Finesse*
- *Resolving Power*
- *Plate Flatness*
- *Plate Roughness*
- *Transmission*
- *Stability & Repeatability*
- *Scan Step*





FPI Testing Results

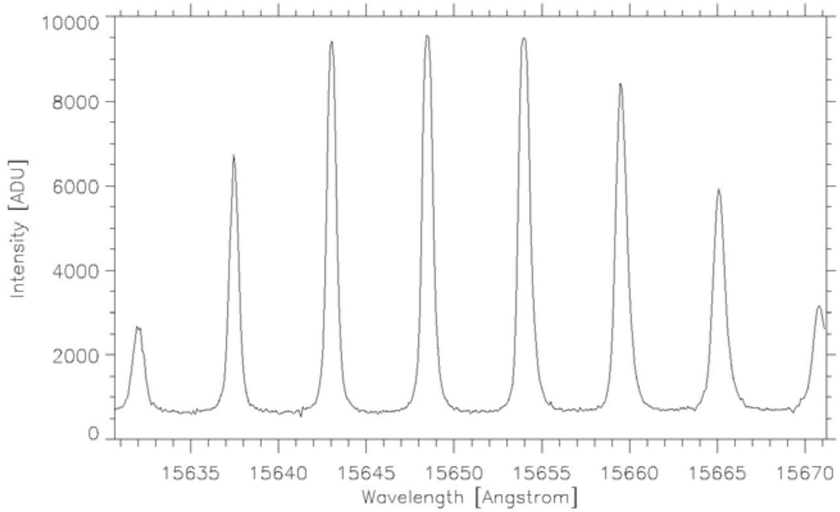
- FSR, FWHM, and Finesse:

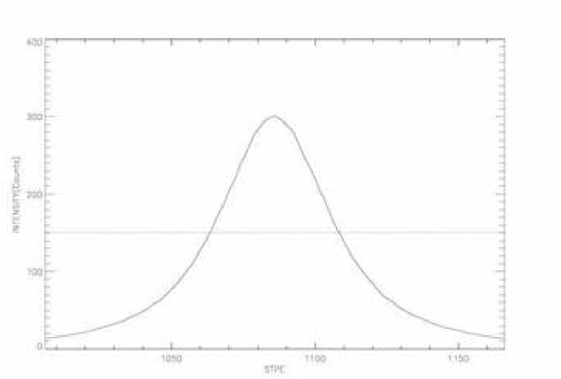
fsr = 5.505 ± 0.104 Å

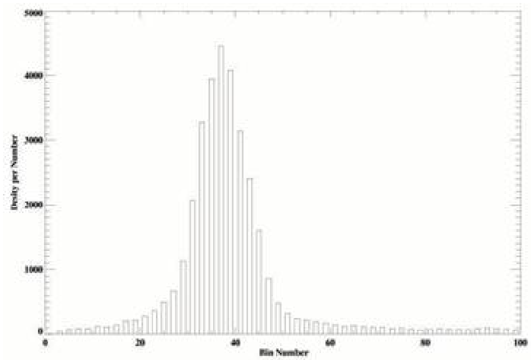
fwhm = 1.0 pm = 0.01 Å

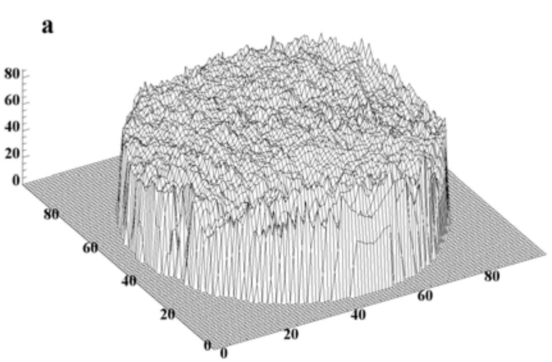
$$N_R = \frac{FSR}{FWHM} = 55$$

$$\Re = mN_R > 1.5\times10^5$$



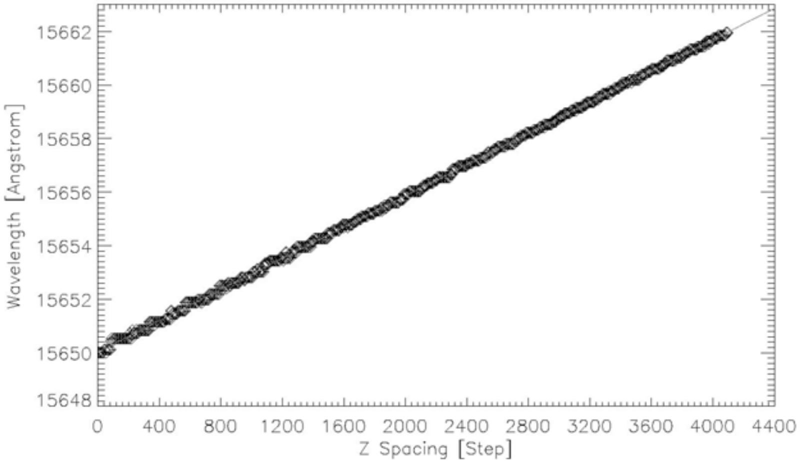


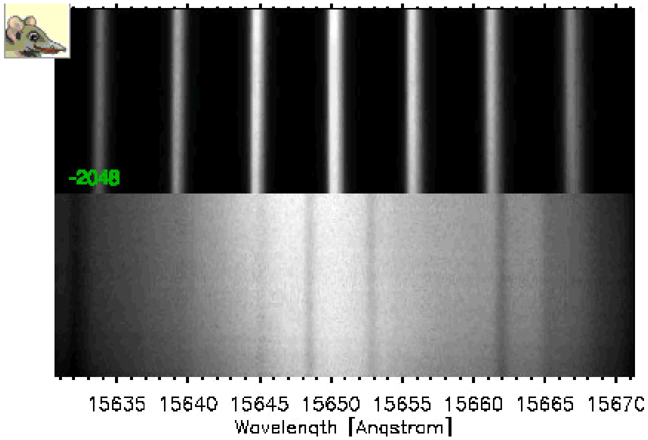




FPI Testing Results

- FPI Control & Scan Step: ~ 0.00292 Å / Step

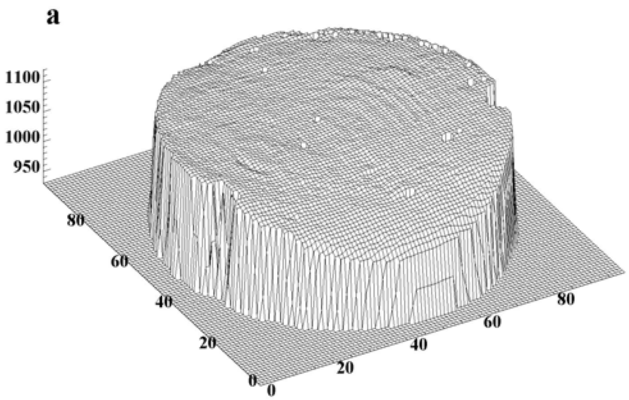




- Plate Flatness & Roughness:

  Flatness ~ λ / 306 @ 1523 nm

  Roughness ~ λ / 1842 @ 1523 nm

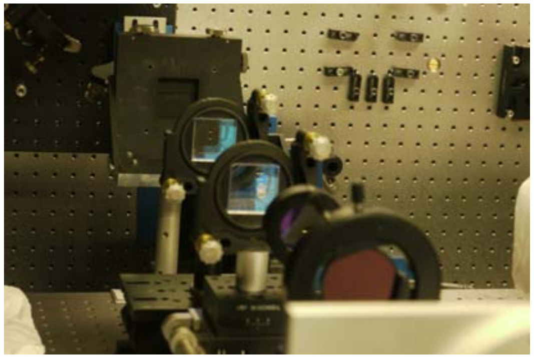


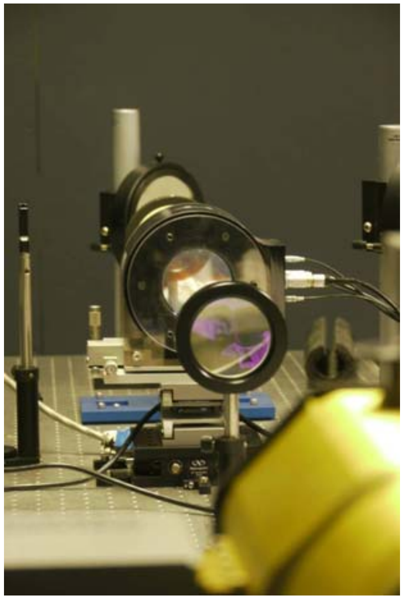
- Peak Transmission:

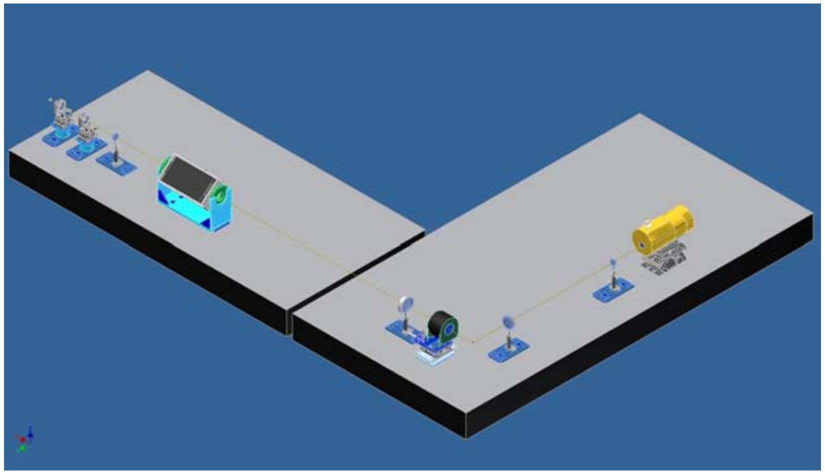
  ~ 90.5 % @ 1523.1 nm

Application I – IRIM

InfraRed Imaging Magnetograph







Application II – Measuring Neutral Winds in the Upper Atmosphere