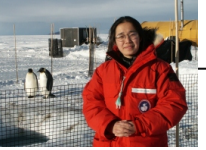
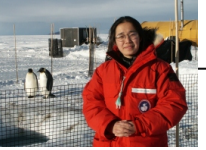


Lecture 35. Spectral Filters for LIDAR Applications

- Spatial filters

-- Considerations on beam divergence and FOV

- Interference filters
- Daytime filters: Fabry-Perot interferometers
- Daytime filters: Faraday filters
- Atomic and molecular absorption filters

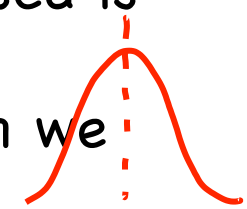


Spatial Filters
Considerations on Beam Divergence & FOV

Small laser beam divergence
→ small receiver field of view (FOV)

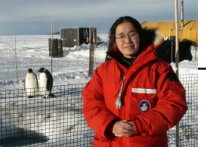
-- A very effective way to reduce daytime background

Whether a small beam divergence thus small FOV can be used is mainly determined by two factors –

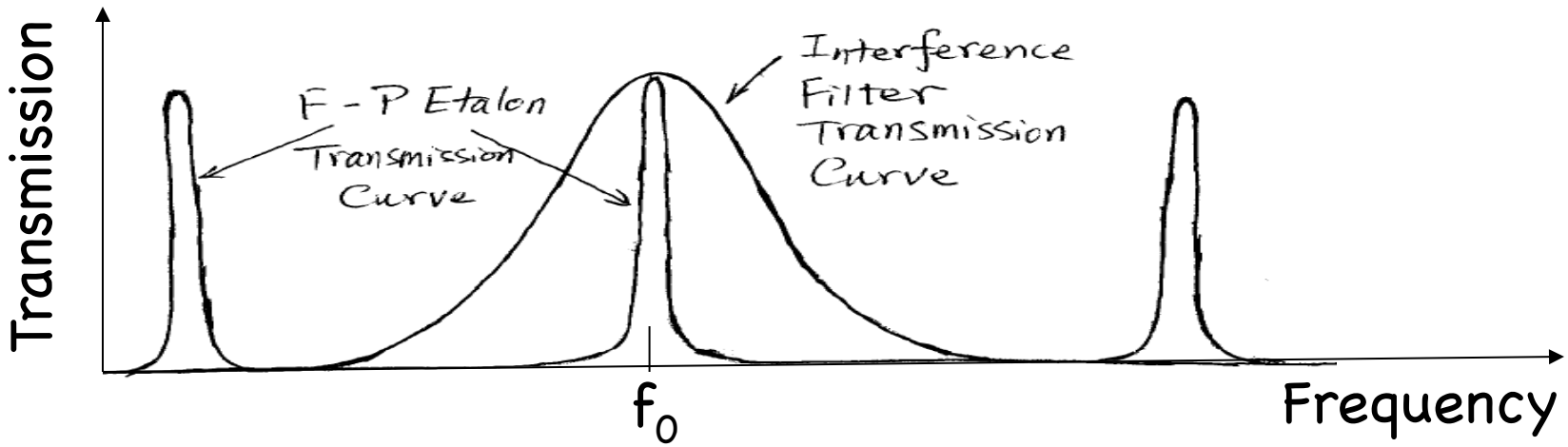


1) Will the atmosphere saturation be resulted? If yes, then we cannot use small divergence and FOV.
2) Is the laser spatial mode good enough (TEM00 mode) to achieve small beam divergence, enabling small FOV? TEM00

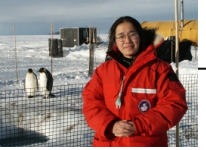
How much FOV is suitable? FOV is usually larger than the claimed beam divergence to tolerate the fluctuations in the beam pointing.



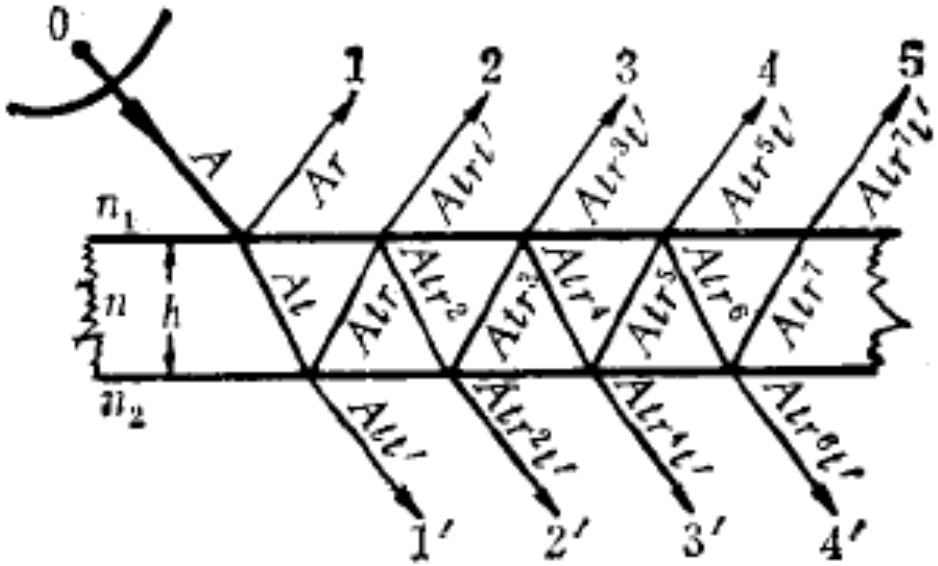
Spectral Filters: Interference Filters & Fabry-Perot Etalons



IF and FPI are based on multiple beam interference.



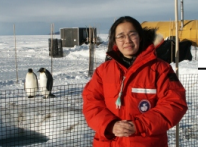
Multiple Beam Interference



- Phase difference between two adjacent beams is given by

$$\boxed{\delta = \frac{2\pi}{\lambda}\Delta L = \frac{2\pi}{\lambda} 2nh\cos i}$$

- In the figure, t and r are the amplitude-transmission and reflection coefficients. Intensity transmission and reflectivity are the square of t and r, i.e., $T = t^2$ and $R = r^2$.



Multiple Beam Interference

- Total amplitude is the sum of multiple beam amplitudes

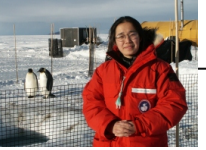
$$\tilde{U}_T = Att'(1 + r^2 e^{i\delta} + r^4 e^{2i\delta} + \ldots) = \frac{Att'}{1 - r^2 e^{i\delta}}$$

- Thus, the transmission intensity is

$$I_T = \tilde{U}_T \tilde{U}_T^* = \frac{A^2 (tt')^2}{\left(1 - r^2 e^{i\delta}\right)\left(1 - r^2 e^{-i\delta}\right)} = \frac{I_0 (1 - r^2)^2}{1 - 2r^2 \cos\delta + r^4}$$

- Recall R = r^2, therefore, we have

$$I_T = \frac{I_0}{1 + \dfrac{4R\sin^2(\delta/2)}{(1-R)^2}}$$



Multiple Beam Interference

- When $\delta = 2k\pi$, the transmission light reaches maximum, which determines the transmission wavelength or frequency.
- If incident angle i = 0, transmission wavelengths and frequencies are determined by

$$2nh = k\lambda_k$$

$$\nu_k = \frac{c}{\lambda_k} = \frac{kc}{2nh}$$

- Thus, the frequency spacing or Free-Spectral-Range is

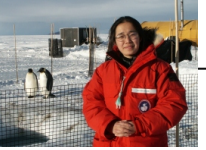
$$FSR = \frac{c}{2nh}$$

- Full-Width-at-Half-Maximum for each transmission line is

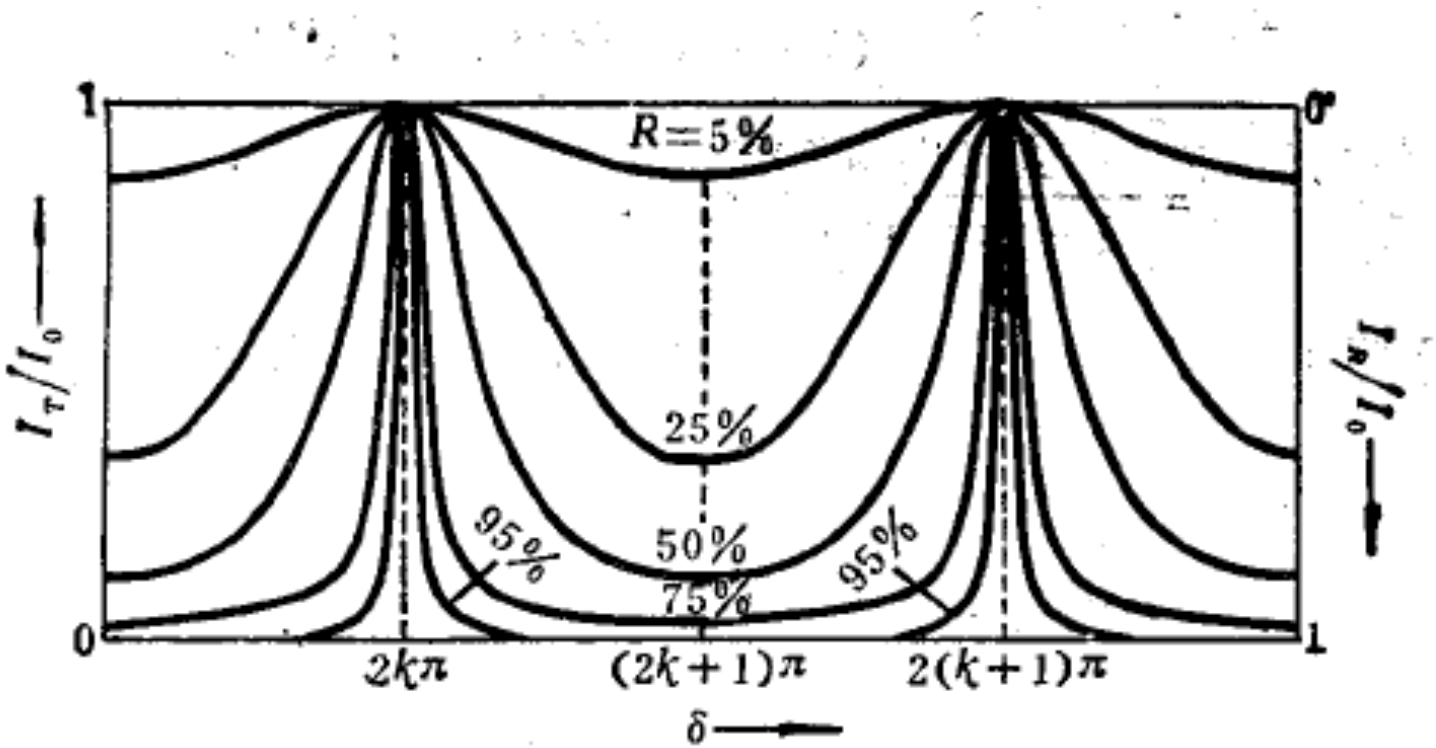
$$\Delta\nu_k = \frac{1-R}{\pi\sqrt{R}} \cdot \frac{c}{2nh}$$

- Finesse is defined as

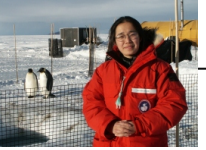
$$F = \frac{FSR}{\Delta\nu_k} = \frac{\pi\sqrt{R}}{1-R}$$



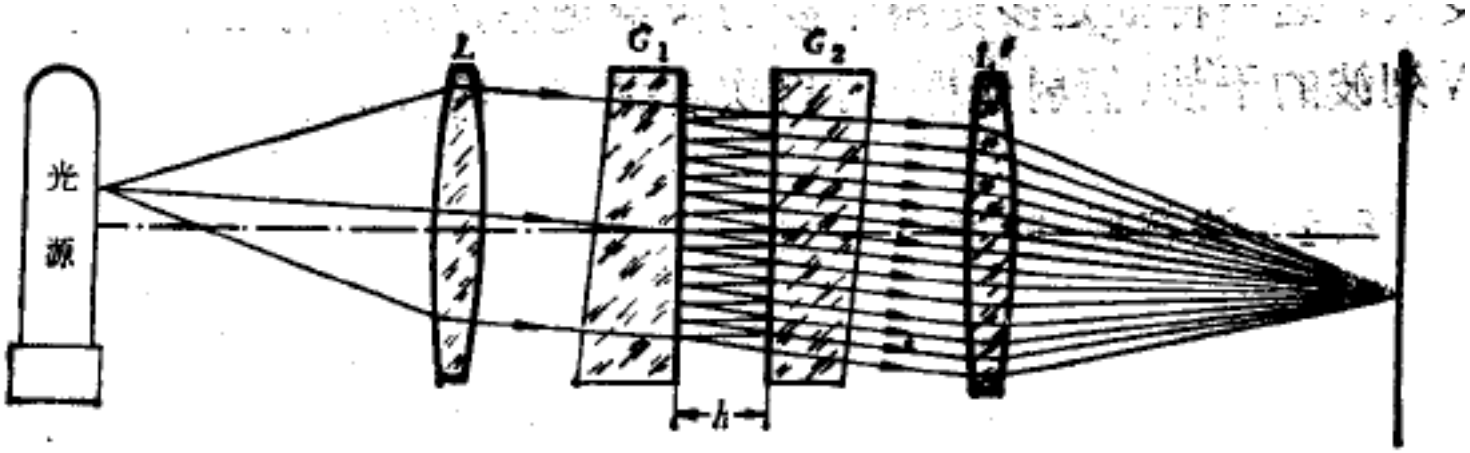
Interference Fringes

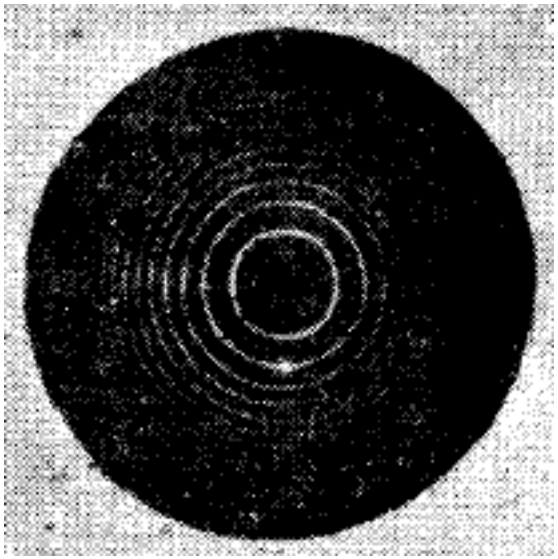


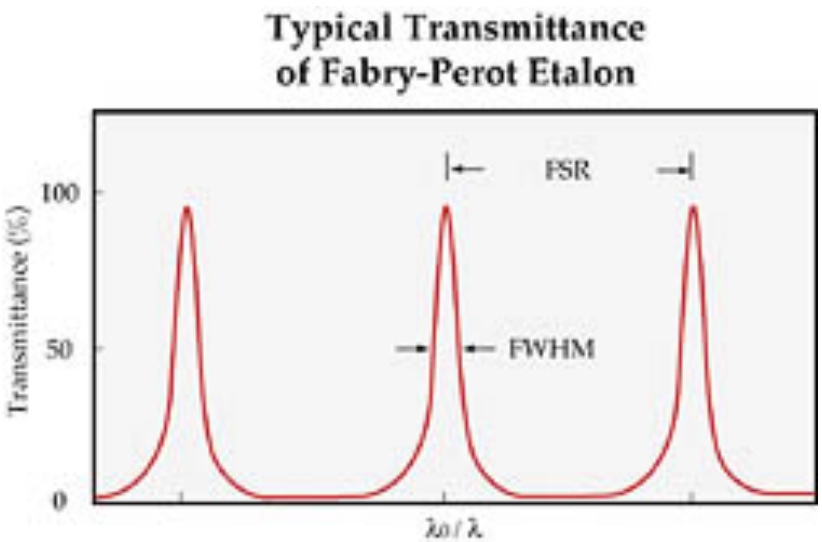
- Periodic transmission lines

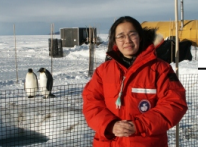


Fabry-Perot Etalon

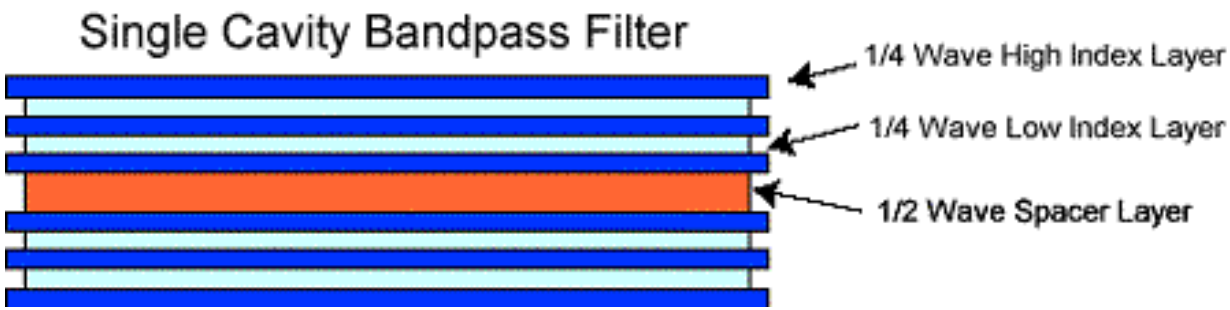


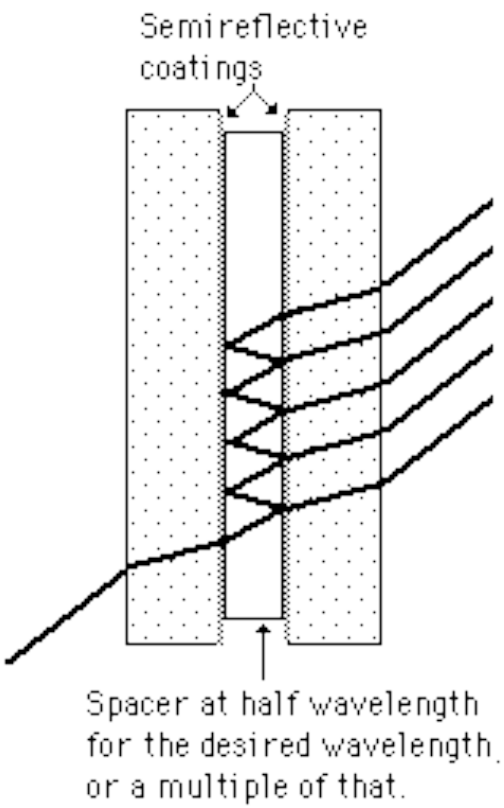






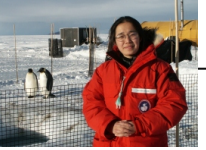
Interference Filter





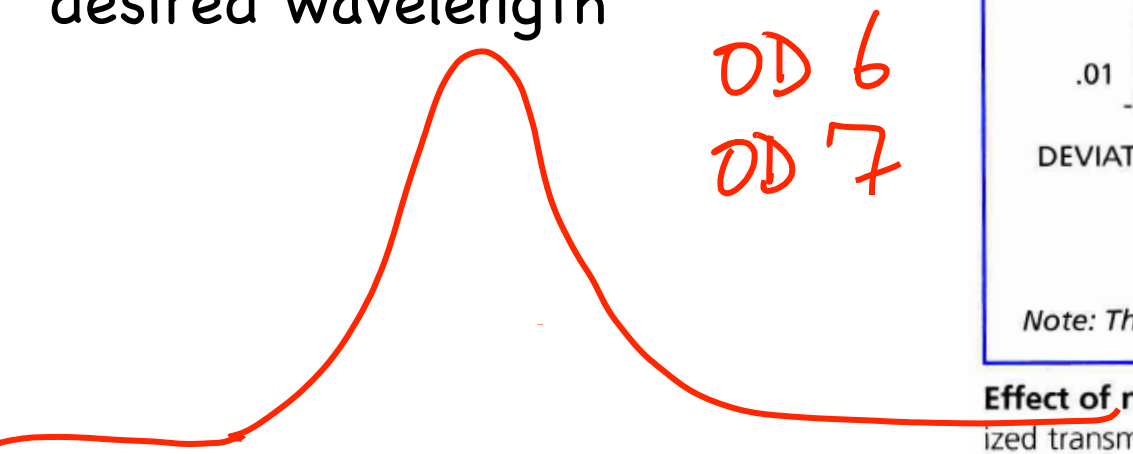
- Interference filters are multilayer thin-film devices, based on Fabry-Perot interferometer.
- Constructive interference at the desired wavelength (spacer $d = \lambda_0/2$)

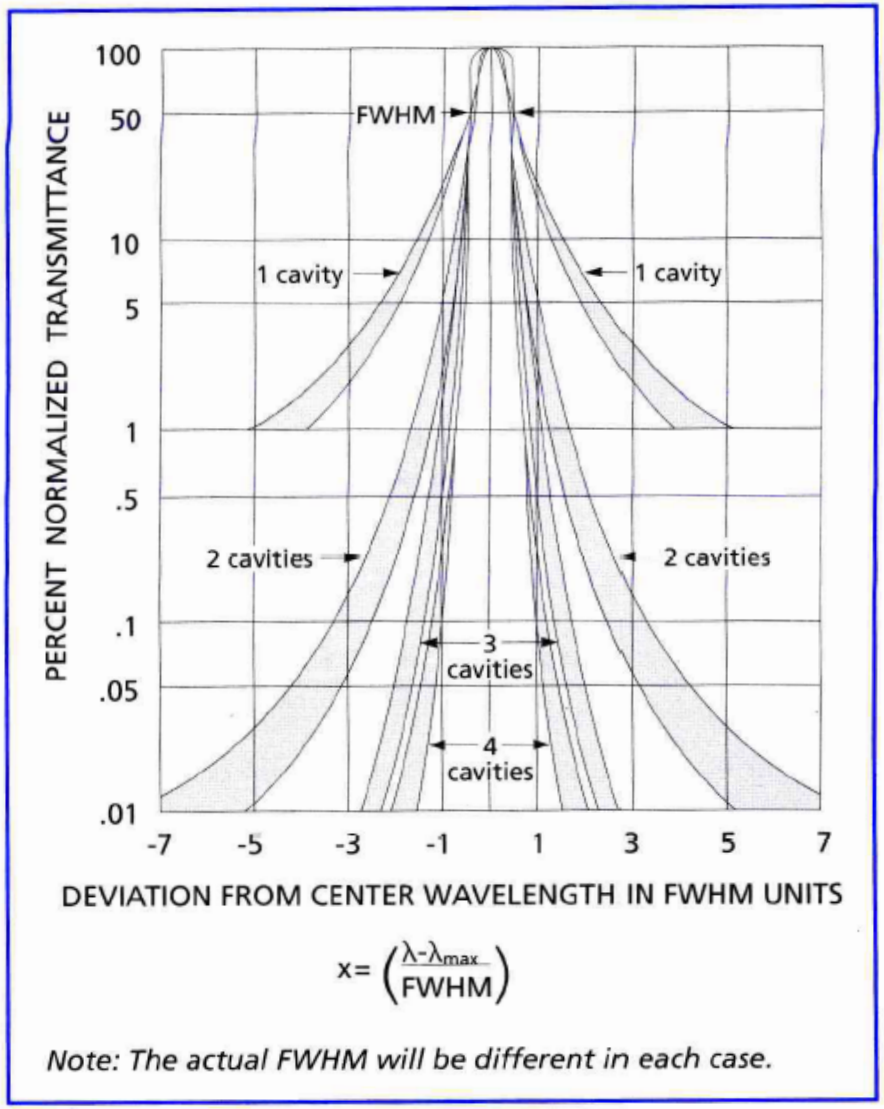
  - round trip $2d = \lambda_0$
- Destructive interference at other wavelengths to block them.



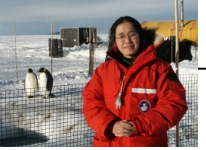
Multi-Cavity Interference Filter

- Multi-cavity interference filter gives better rejection to wavelengths other than desired wavelength

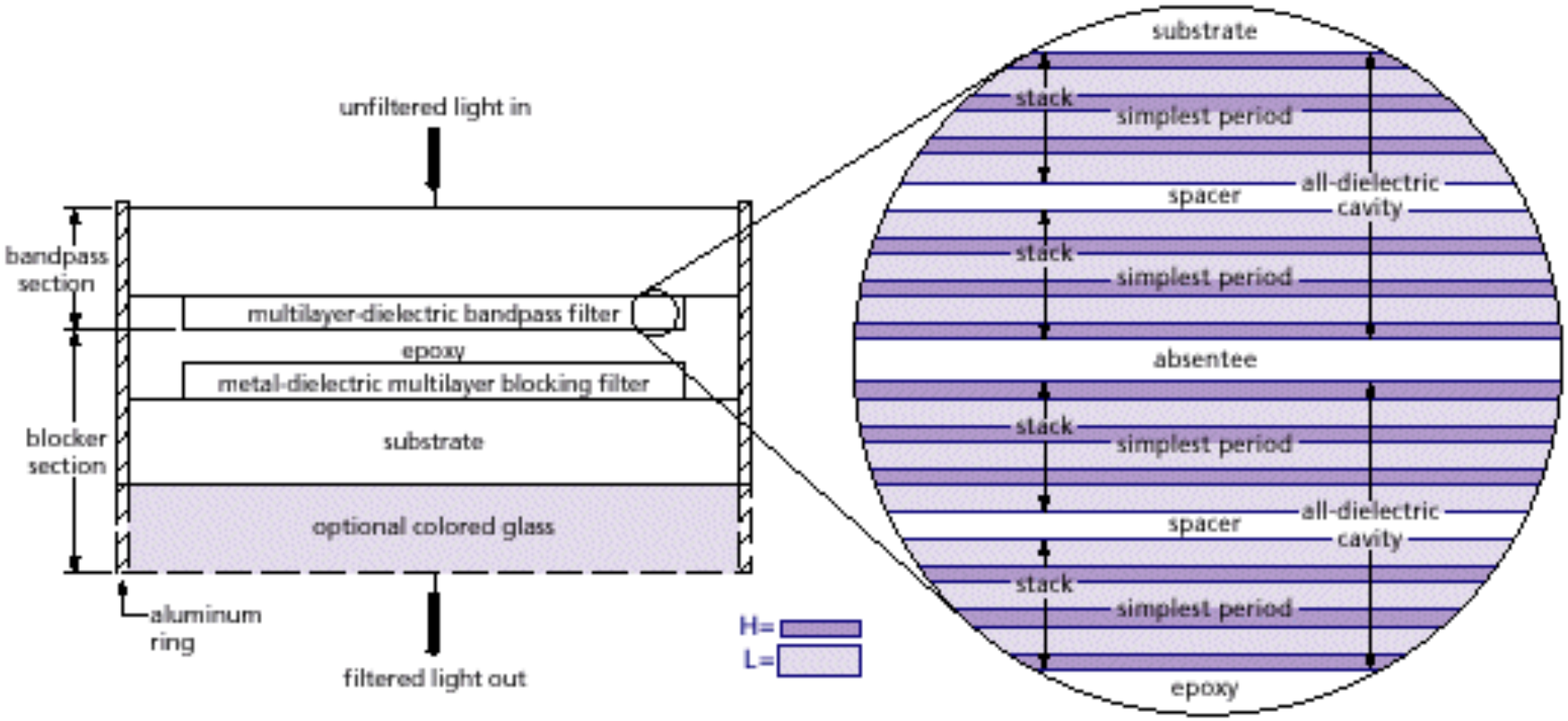




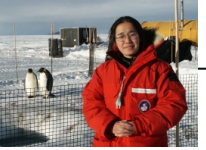
Effect of number of cavities on passband shape (normalized transmittance for ZnS/Na_3AlF_6 passband interference filters with 10-nm FWHM)



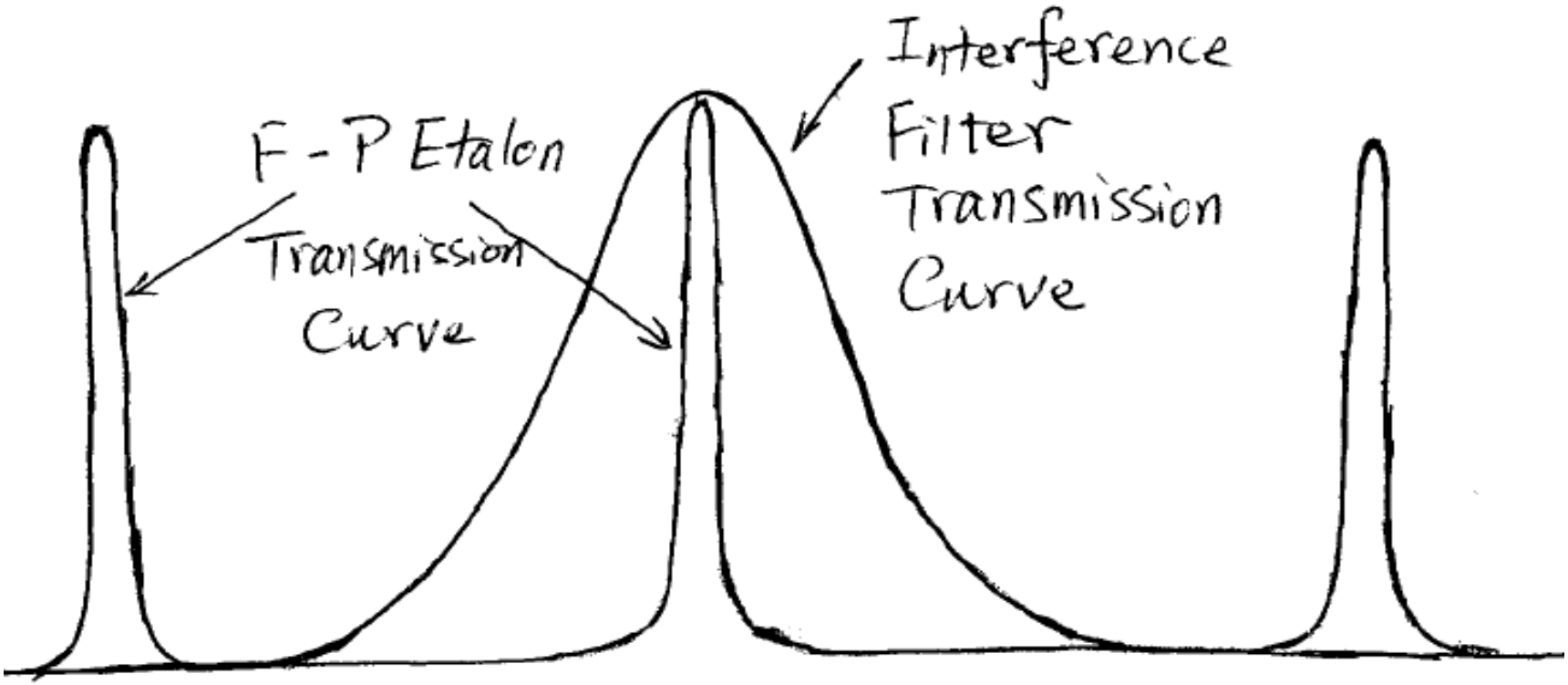
Interference Filter



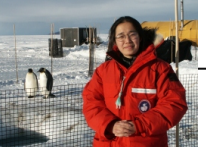
- Colored glass etc is optional to further block wavelengths far away from desired wavelength, especially at shorter end.



Combination of Interference Filter and Etalon in Lidar Receiver

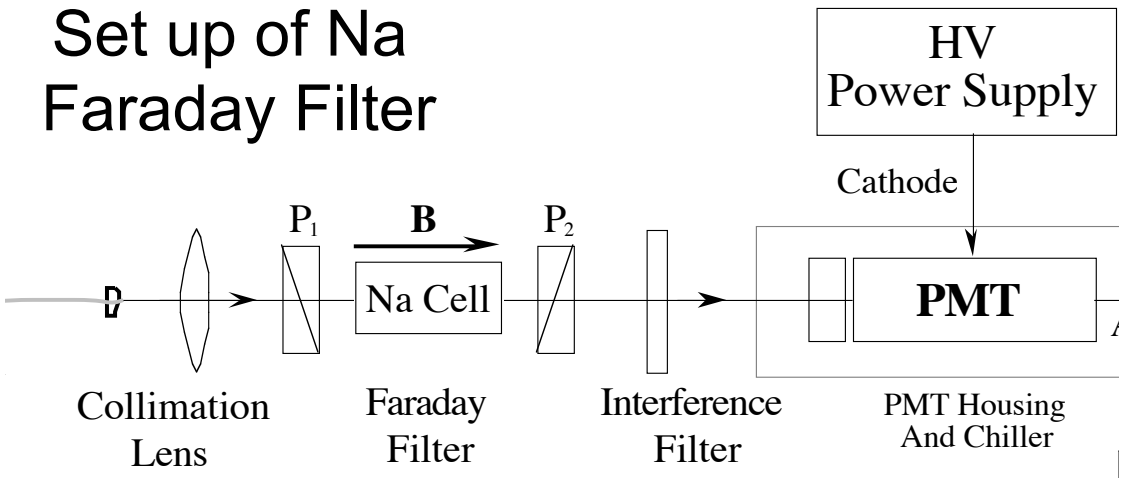


- Typical bandwidth of F-P etalon in lidar receiver is about 10-30 GHz.

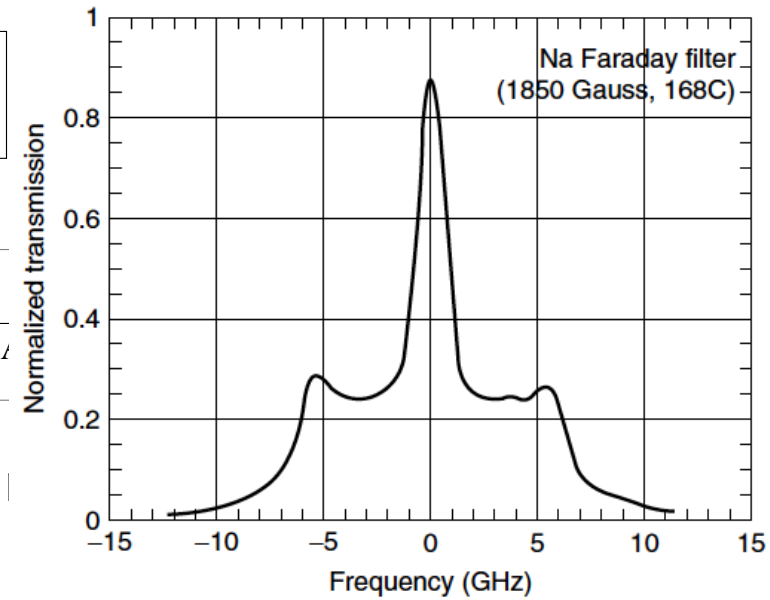


Spectral Filters: Faraday Filters

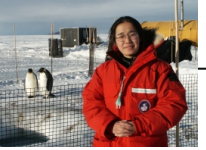
Set up of Na Faraday Filter



See textbook Chapter 5

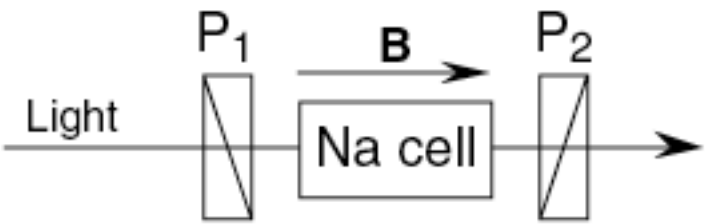


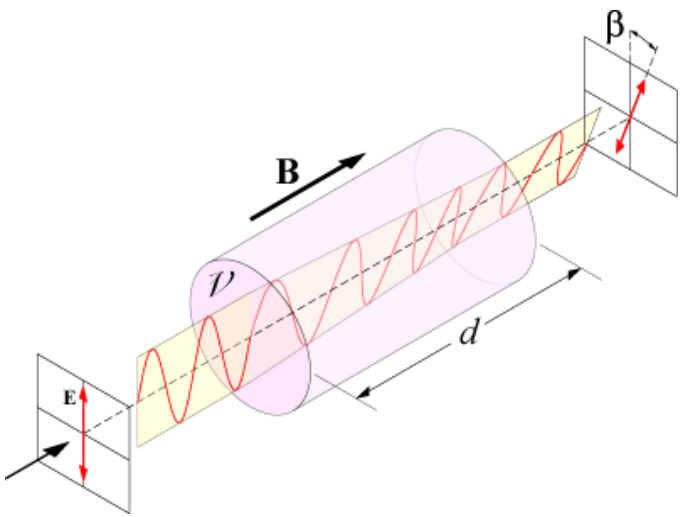
FADOFs (Faraday Anomalous Dispersion Optical Filters) are based on the magnetic-field induced Faraday rotation effect of linear polarization of light.



Faraday Effect

- Faraday effect is the rotation of light polarization by some media under magnetic field.

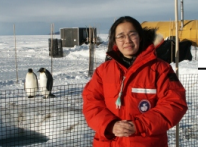




- Refraction index n of dilute Na vapor

$$n = \sqrt{1+\chi} \cong 1 + \frac{1}{2}\chi = 1 + \frac{1}{2}\chi' - \mathrm{i}\frac{1}{2}\chi'' \qquad (5.74)$$

χ is the electric susceptibility of Na vapor



Optical Activity vs. Waveplate Retardation

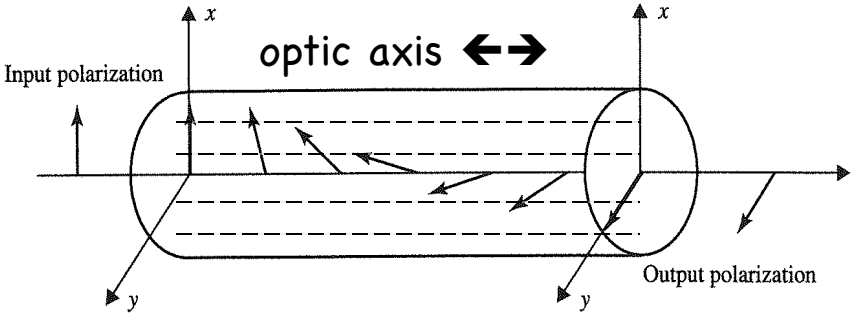
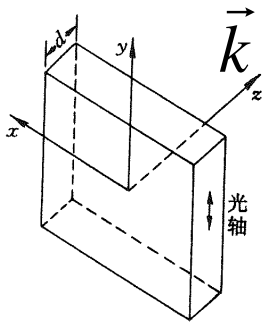
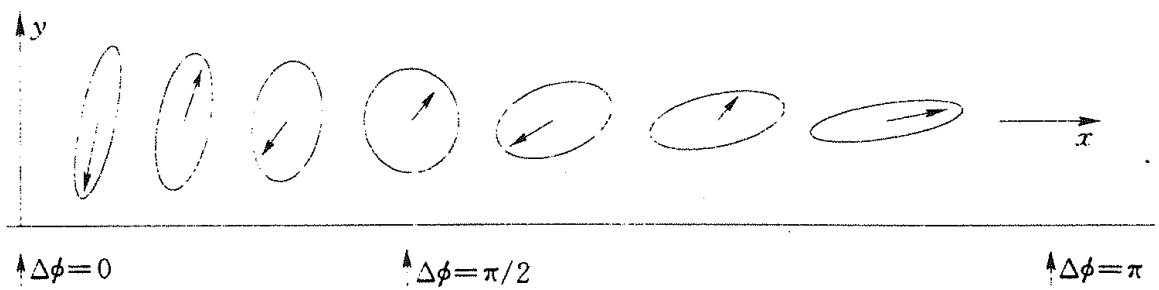


Figure 1.14 Rotation of the plane of polarization by an optically active medium.

Optical activity: linearly polarized light propagates along the optic axis with the linear polarization rotating along the way.
-- "Circular polarization birefringence"

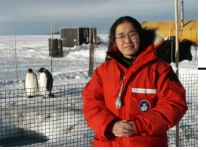




Wave plate z = 0 z(π/2) z(π)

Waveplate retardation: linearly polarized light propagates perpendicular to the optic axis and the polarization changes its state along the way.

The decomposition of linearly polarized light is based on the orthogonal eigenstates of a crystal. For example, optical activity has L and R circular polarizations as its eigen-vibrations, while wave plate has o and e linear polarization as its eigne-vibrations.



Faraday Rotator: Magnetic-Field-Induced Optical Activity

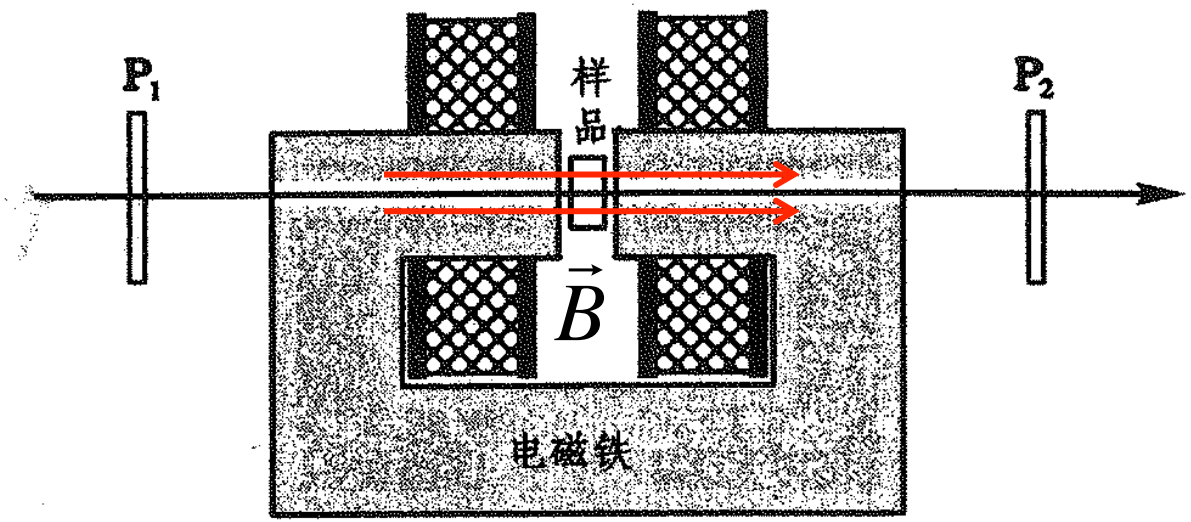
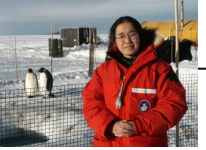


图 6 – 79 磁致旋光

Magneto-Optic (MO) crystal: Field-induced optical activity or magnetically induced optical activity (polarization rotation)

Light must propagate along the optic axis which is defined by the external magnetic field.



Faraday Rotator: Magnetic-Field-Induced Optical Activity

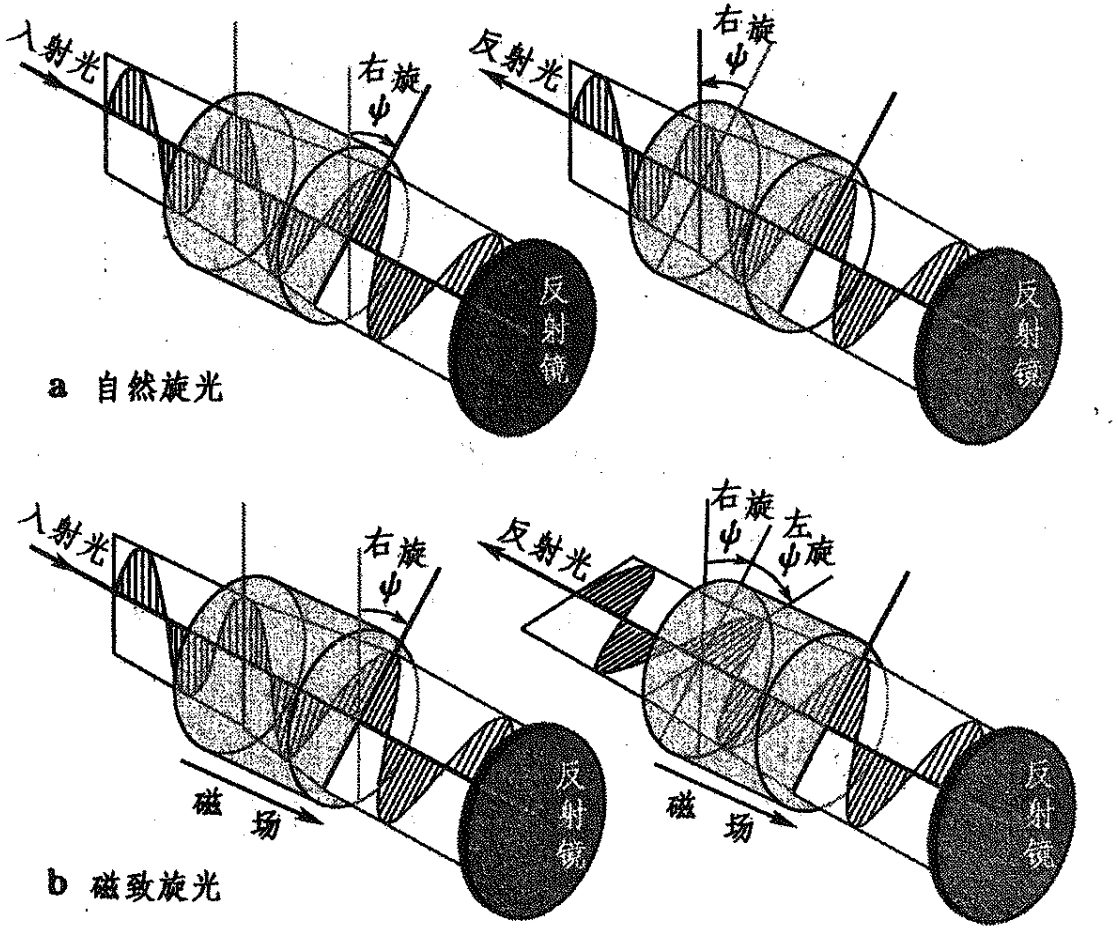
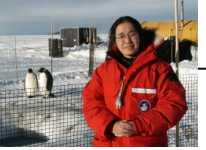


图 6 – 80 自然旋光与磁致旋光的比较

Naturally occurring optical activity

Faraday (B-field-induced) optical activity



Light Velocity vs. Refraction Index

The light speed in vacuum c is given by

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

ε_0 – dielectric constant in vacuum (the permittivity of a vacuum)

μ_0 – permeability in vacuum

The phase velocity of EM wave in medium v is given by

$$v = \frac{1}{\sqrt{\varepsilon_0 \varepsilon \mu_0 \mu}} = \frac{c}{n}$$

ε – relative dielectric constant

μ – relative permeability

The refraction index of the medium is given by

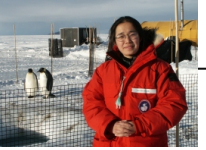
$$n = \sqrt{\varepsilon \mu}$$

Except for ferromagnetic materials, $\mu \approx 1$ is true for most materials, so

$$n = \sqrt{\varepsilon \mu} \approx \sqrt{\varepsilon} = \sqrt{1 + \chi}$$

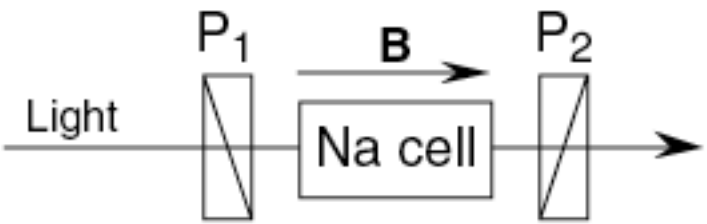
X – macroscopic electric susceptibility of the medium

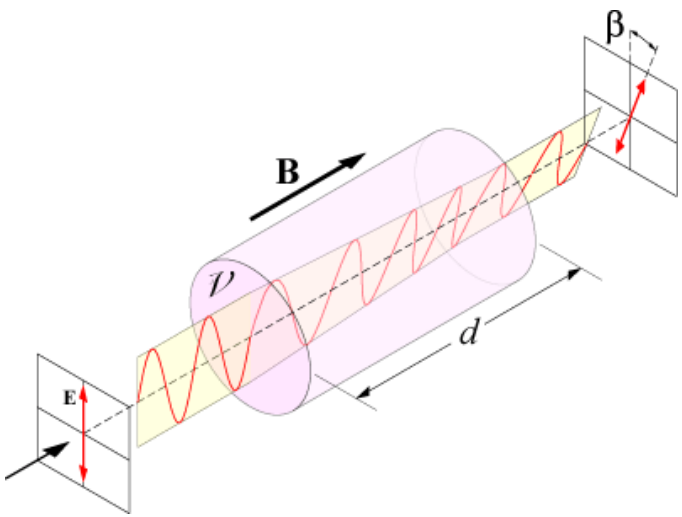
$\varepsilon_m = \varepsilon_0 \varepsilon$ – the dielectric constant (permittivity) of the medium



Faraday Effect

- Faraday effect is the rotation of light polarization by some media under magnetic field.



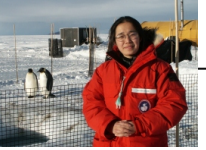


- Refraction index n of dilute Na vapor

$i^2 = -1$

$$n = \sqrt{1+\chi} \cong 1 + \frac{1}{2}\chi = 1 + \frac{1}{2}\chi' - \mathrm{i}\frac{1}{2}\chi'' \qquad (5.74)$$

χ is the electric susceptibility of Na vapor



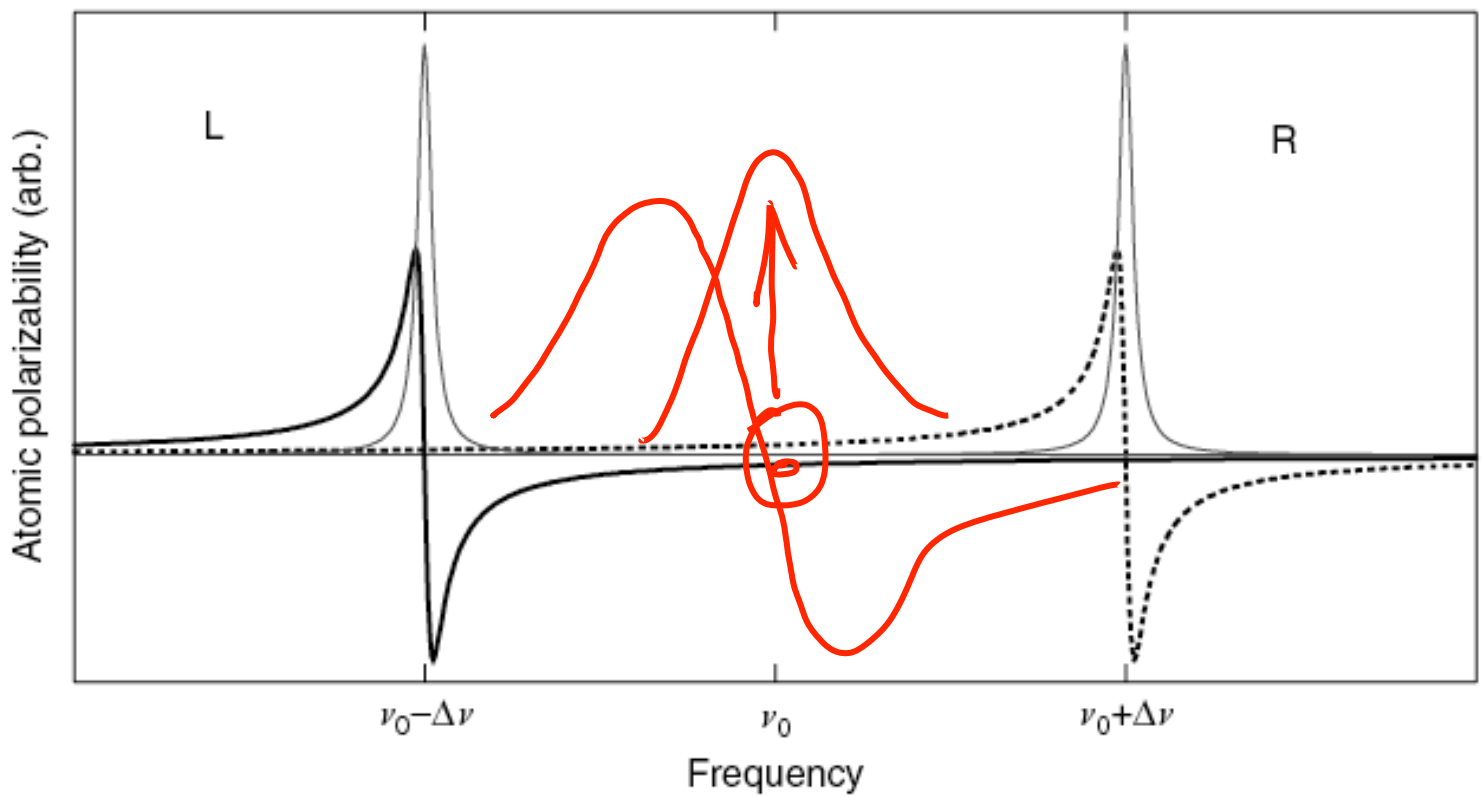
Faraday Effect under Zeeman Splitting

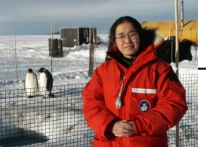
$$\chi' = \frac{Ne^2 f}{2m\omega\epsilon_0} \frac{\omega_0 - \omega}{(\omega_0 - \omega)^2 + (\gamma/2)^2}$$

Dispersion

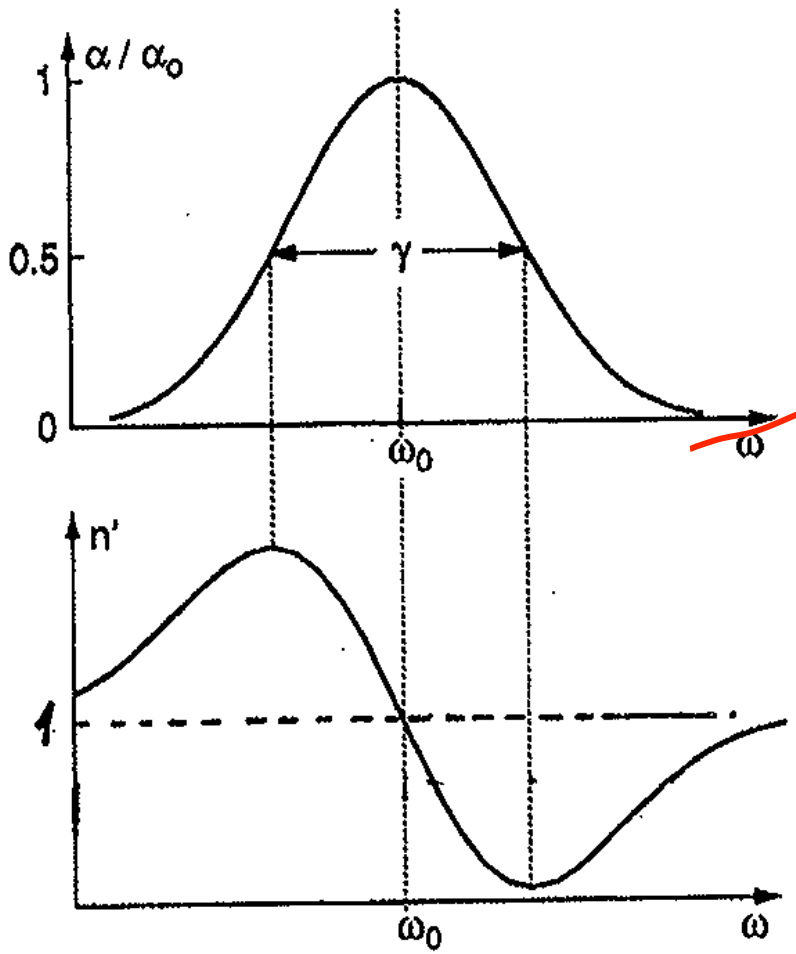
$$\chi'' = \frac{Ne^2 f}{2m\omega\epsilon_0} \frac{\gamma/2}{(\omega_0 - \omega)^2 + (\gamma/2)^2}$$

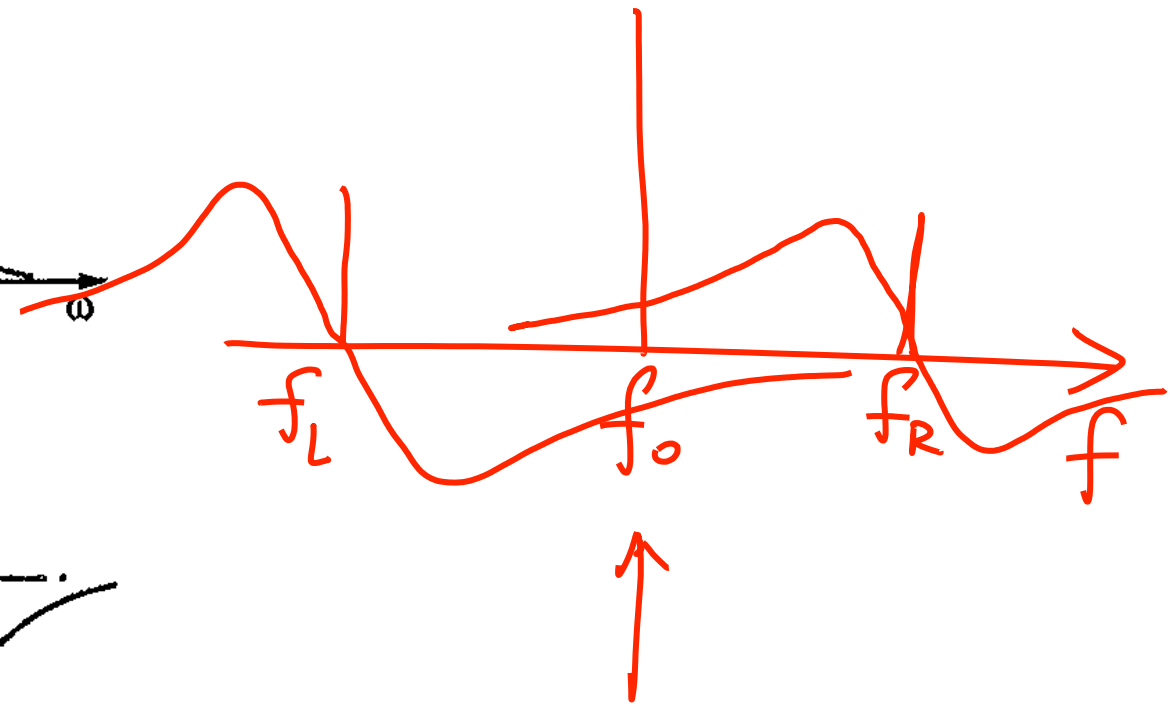
Resonance absorption

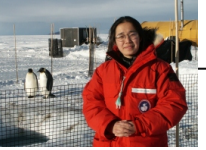




Resonance Absorption vs. Dispersion







Explanation of Optical Activity

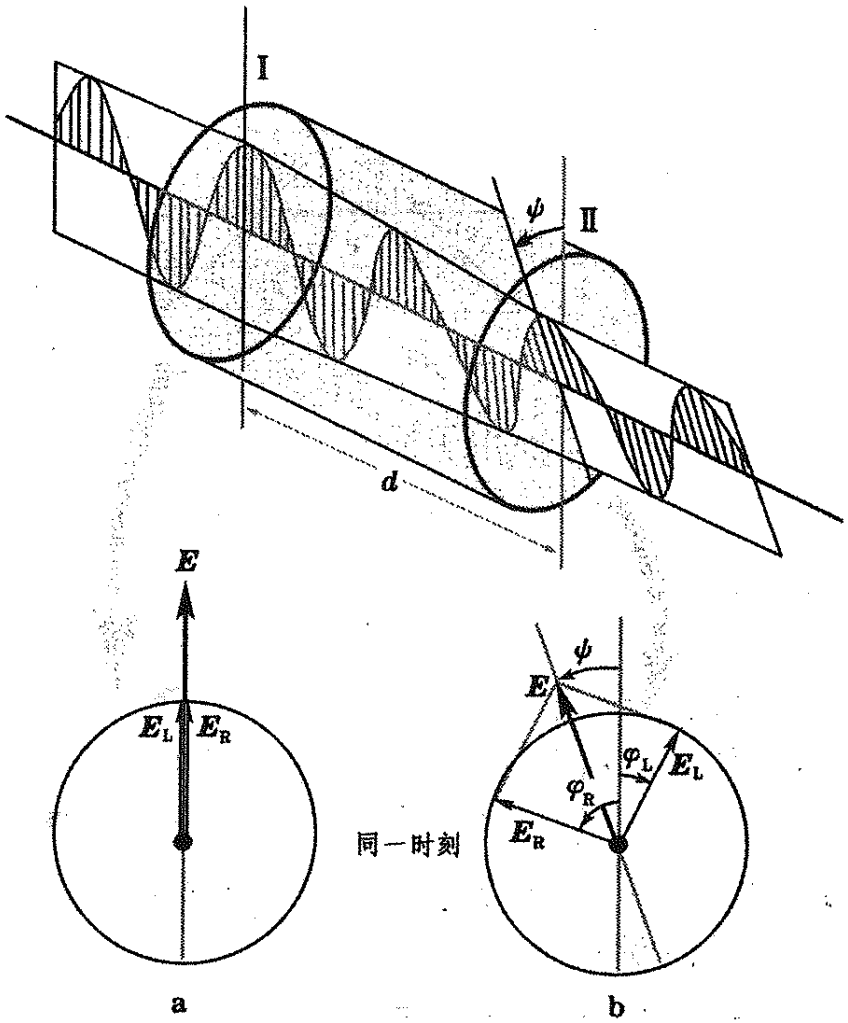


图 6－72 旋光性的解释

When light propagates along the optic axis, it can be decomposed to the superposition (synthesis) of a left and a right circularly polarized light.

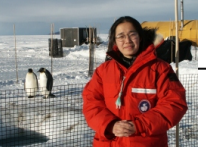
If two circular polarizations experience different refraction indexes, extra phase shift will be introduced.

Consequently, two circular polarizations recombine to form a linear polarization with its orientation rotated.

$$\varphi_L = \frac{2\pi}{\lambda} n_L d,$$

$$\varphi_R = \frac{2\pi}{\lambda} n_R d,$$

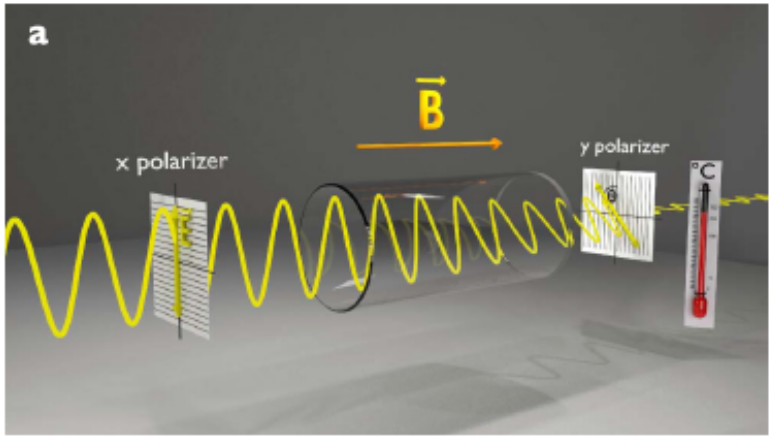
$$\psi = \frac{1}{2}(\varphi_R - \varphi_L) = \frac{\pi}{\lambda}(n_R - n_L) d.$$

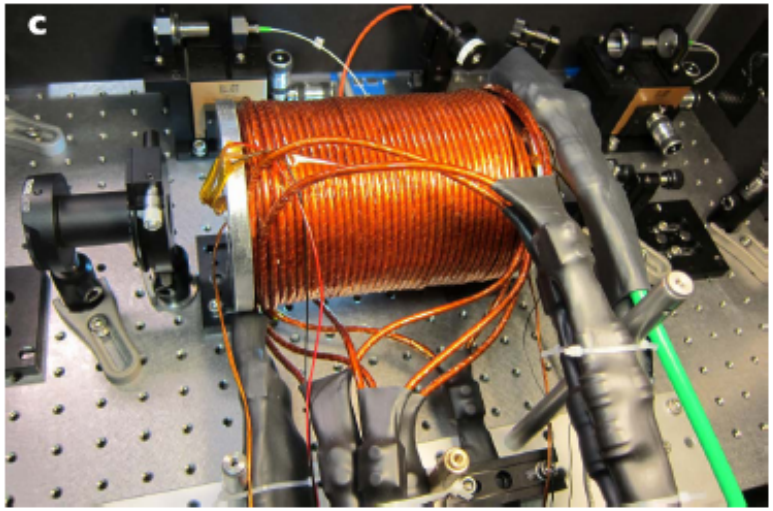


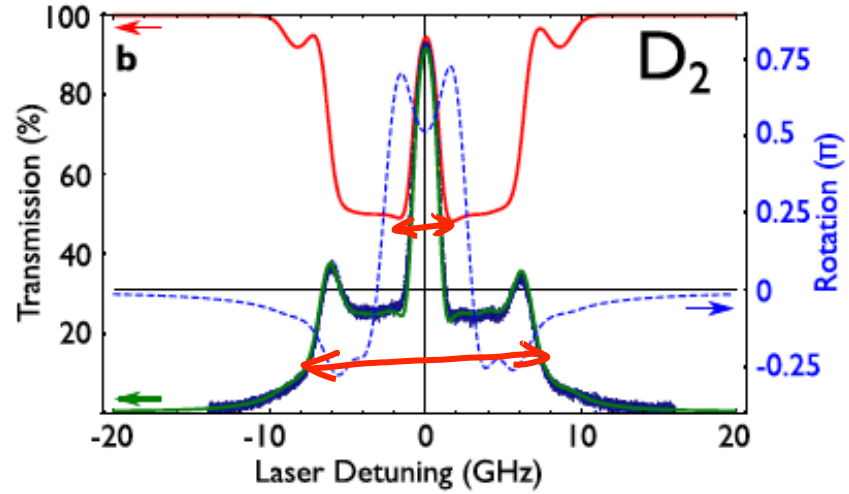
Faraday Filter

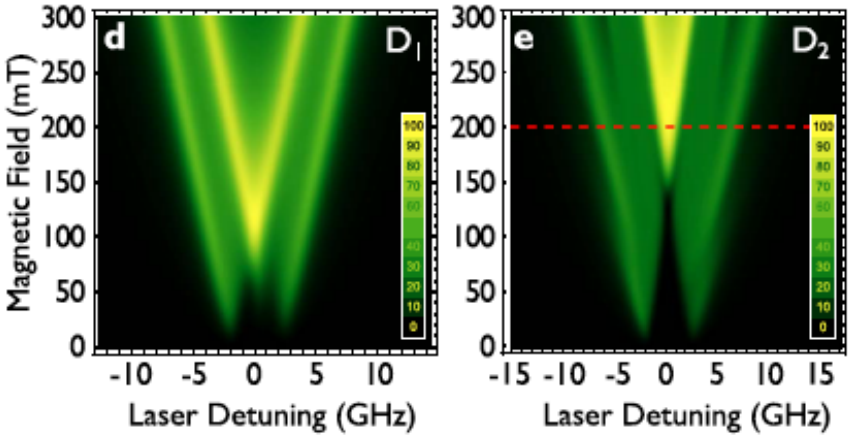
$$\Delta\varphi = 2\pi \frac{l\Delta n}{\lambda}$$

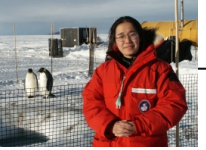
- Phase shift between two circular polarizations
- When the phase shift is π, the polarization is rotated by π/2



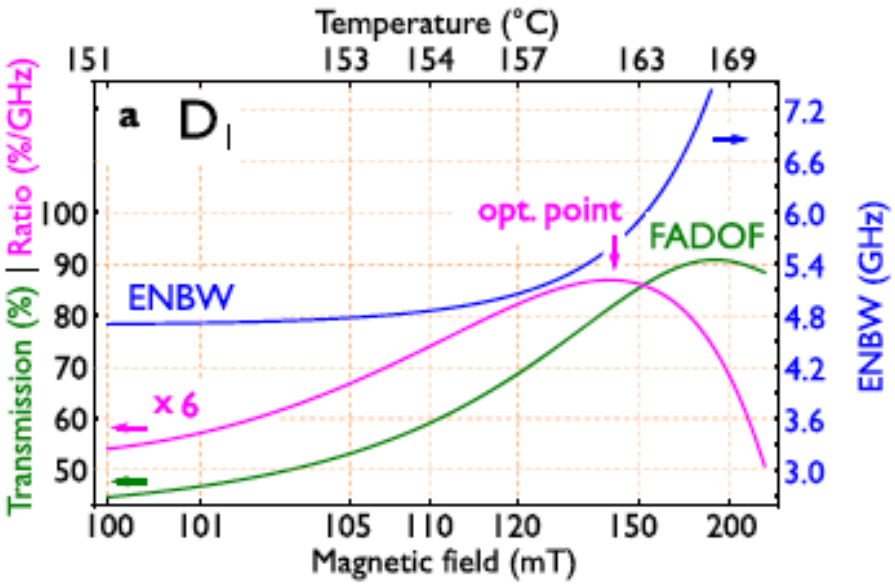


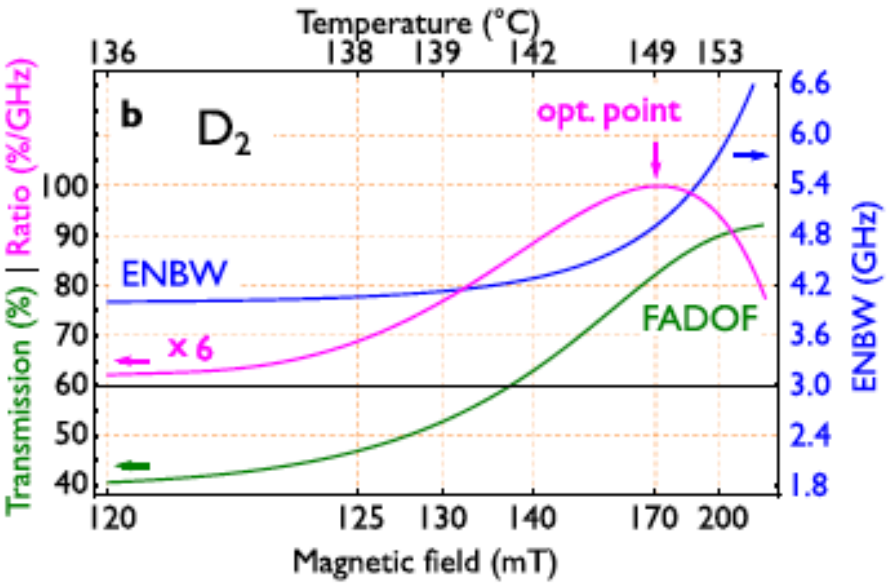




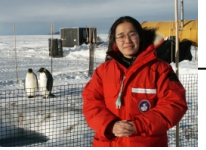


Narrowband Daytime Filter: Faraday Filter @ Different B and T

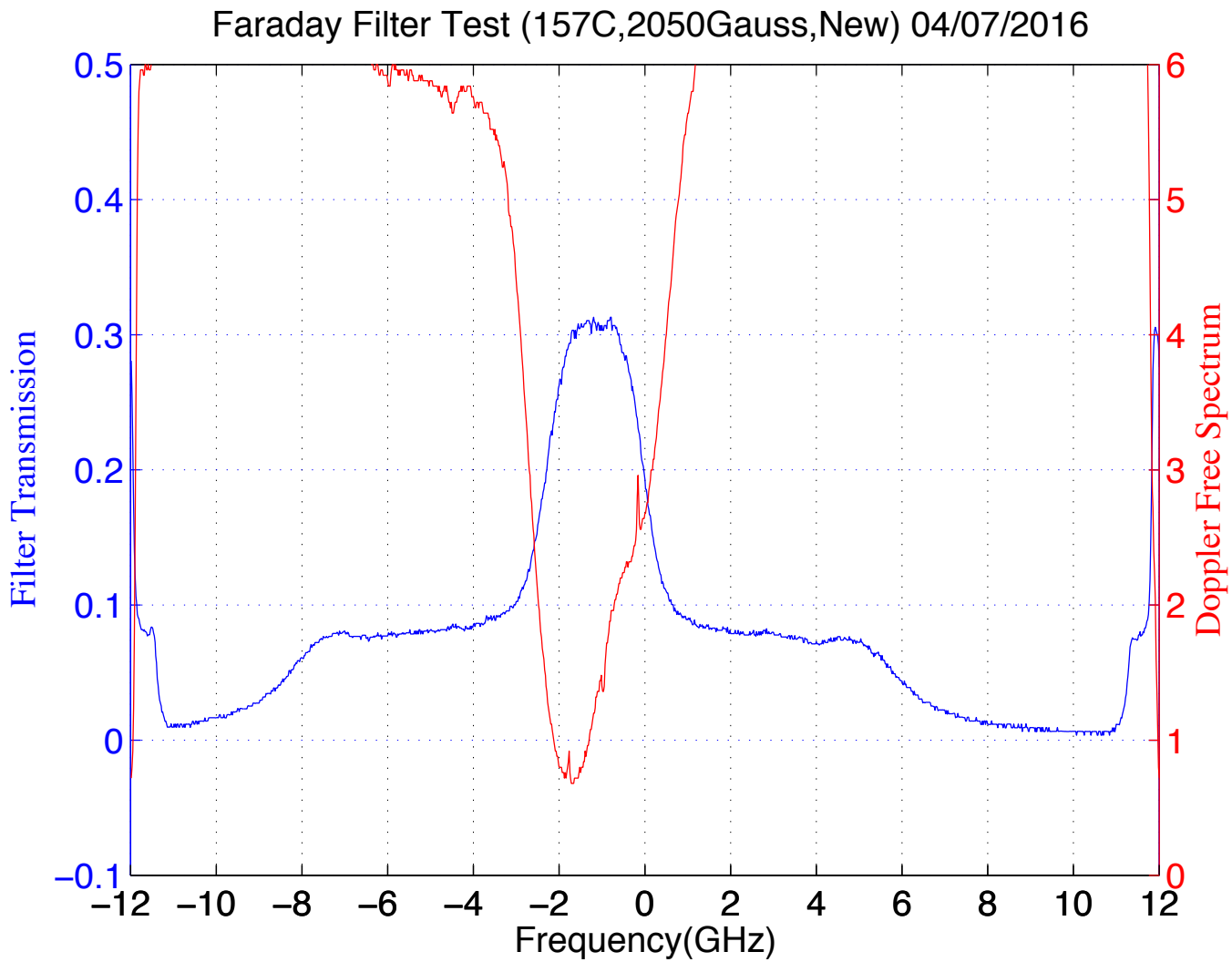


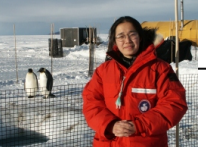


[Kiefer et al., Nature Scientific Reports, 2014]

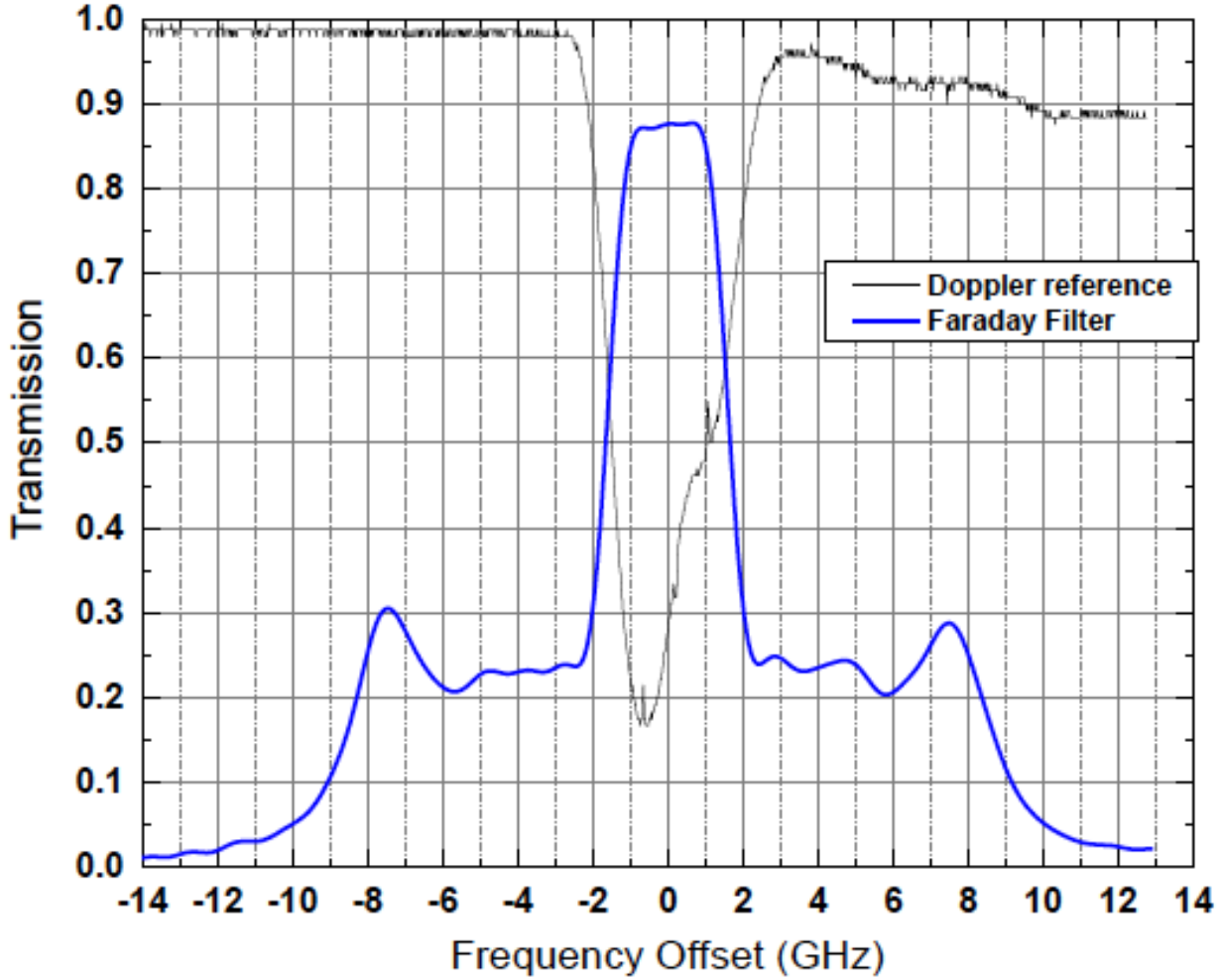


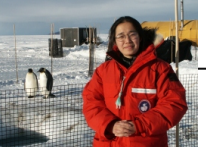
Narrowband Daytime Filter: Faraday Filter @ Different B and T



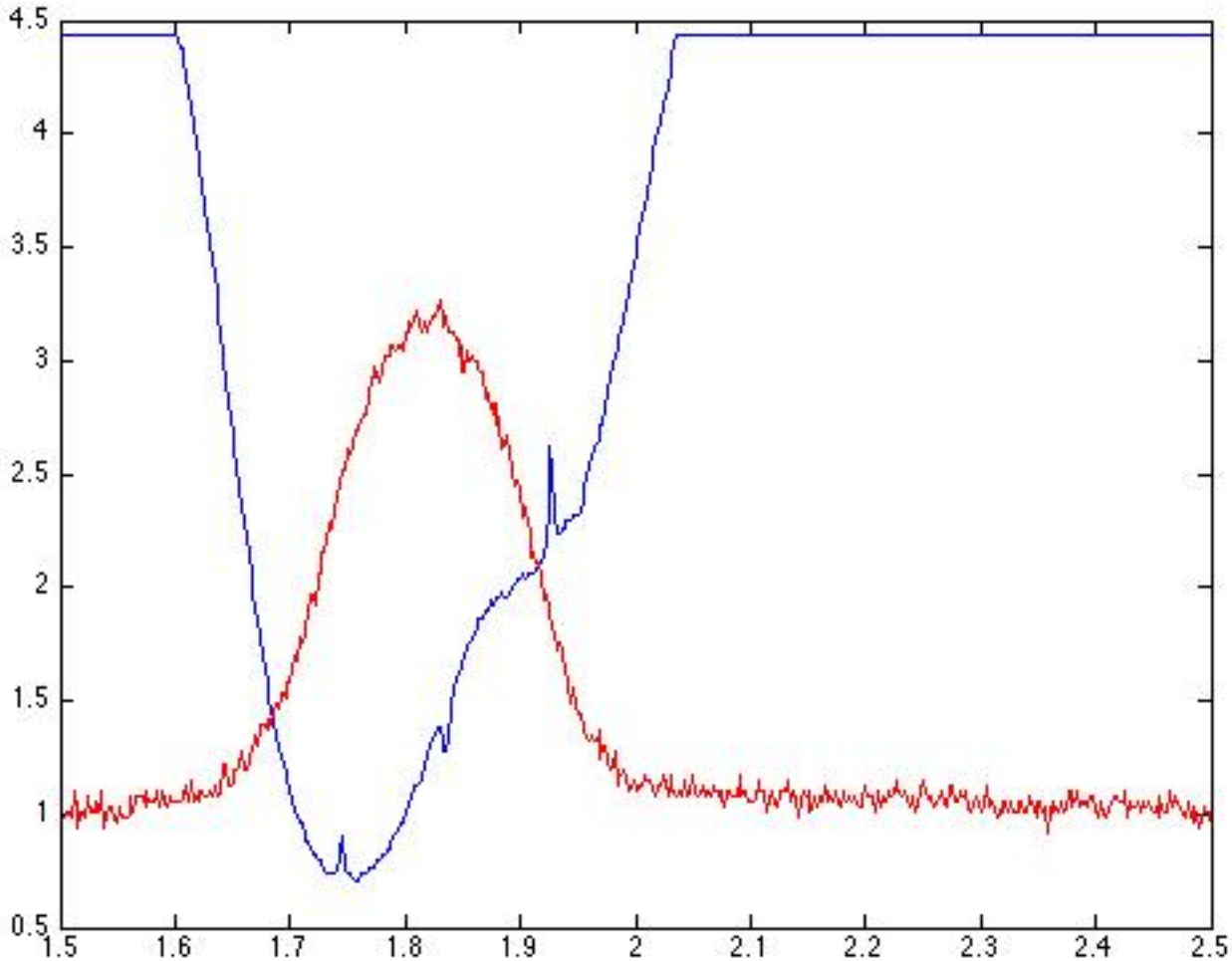


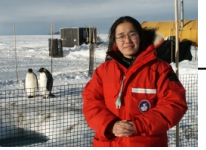
Narrowband Daytime Filter: Faraday Filter @ Different B and T





Fluorescence and Rayleigh Scattering vs. Doppler Shift





Atomic and Molecular Absorption Filter

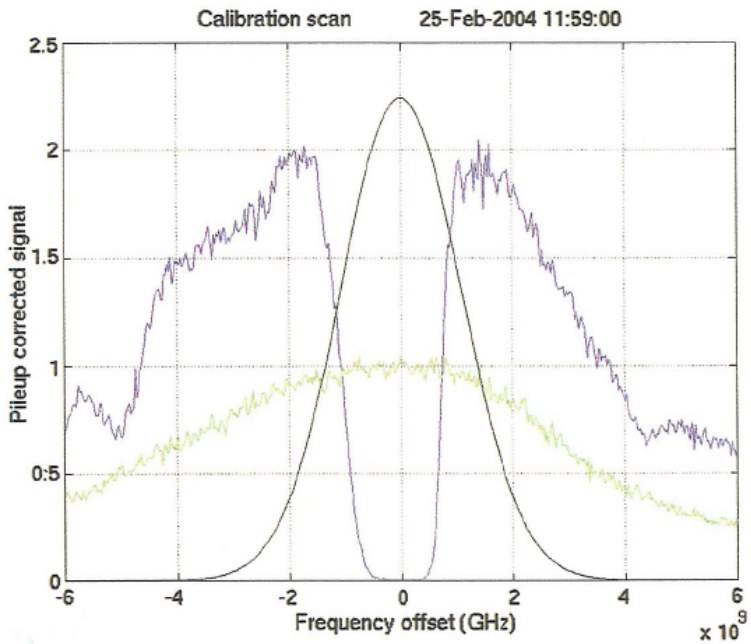


Fig. 5.5. Calibration scan showing the transmission of the molecular (blue) and combined (green) channels as a function of frequency. The Doppler broadened molecular spectrum for 300 K is also shown (black). Line 1109 of the iodine absorption spectrum (central notch) rejects most of the aerosol scattering and the central portion of the molecular scattering while passing the wings of the molecular line. The spectral transmission of the combined channel is determined by the pre-filter etalon.