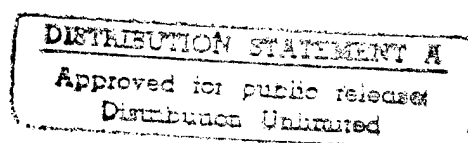# ULTRA-NARROW LINEFILTERING USING A CS FARADAY FILTER AT 455 nm

J. Menders, P. Searcy, K. Roff, S. H. Bloom and Eric Korevaar
Thermo Electron Technologies Corporation

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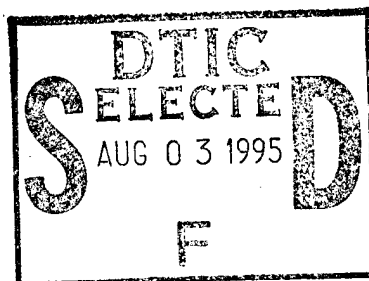DTIC QUALITY INSPECTED 5

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# ULTRA-NARROW LINEFILTERING USING A Cs FARADAY FILTER AT 455 nm

J. Menders, P. Searcy, K. Roff, S. H. Bloom and Eric Korevaar
Thermo Electron Technologies Corporation
9550 Distribution Avenue
San Diego, CA 92121-2305

## Abstract

We measured and modelled the ultra-narrowband transmission spectrum of a Cs Faraday filter at 455 nm. When optimized to achieve the narrowest passbands, we observed near unity transmission peaks of 0.7 GHz bandwidth with an integrated transmission of about 3 GHz. Using a filter model confirmed by close agreement with the measurements, we present a catalog of filter spectra for a wide range of magnetic fields and vapor temperatures. We predicted a wide field of view for the filter using a generalization of the on-axis model to three dimensions. The generalized model was confirmed experimentally by comparison to off-axis spectrum measurements for the cesium passband near 852 nm. We devised a new ultranarrow magneto-optic linefilter, which we call the "Voigt filter," that uses a transverse magnetic field.

## Introduction

To achieve quantum noise limited performance, background limited laser receivers require narrowband optical filters. Development of narrowband filters for underwater communications and sensing has provided a strong impetus for the development of a variety of filters that operate in the blue-green region of the visible spectrum, where sea water transmission is highest. Among these filters, absorptive-reemissive atomic line filters (ALFs) matched to the cesium absorption line at 455 nm have been used to obtain ultra-narrowband optical filtering,[1] achieving bandwidths of about 1 GHz. Another type of atomic line filter, referred to as the Faraday filter,[2,3,4] the magneto-optic filter,[5] the dispersive magneto-optic filter[6] or the FADOF[7] can also provide a bandpass of about the same width. Like the absorptive-reemissve ALFs, Faraday filters provide an optical passband at fixed wavelengths associated with strong atomic absorption lines; in particular, the Cs Faraday filter described here and a new calcium Faraday filter[5] provide ultranarrow passbands near the blue 455 nm cesium and 423 nm calcium absorption lines. Like other members of the Faraday filter family, the cesium Faraday filter offers the advantages of near unity peak transmission, image preservation[8] and real time operation (no excited state decay delays) over the absorptive-reemissive ALF.

The filters can provide passbands either at or in the wings of the resonance, for high (1 kG) or low (100 G) magnetic fields, respectively. In this paper we present the first transmission spectrum measurements of a Cs Faraday filter operated in the wings of the resonance near 455 nm. For an optimally chosen field and temperature, the spectrum exhibited two narrow strongly peaked 0.7 GHz passbands on either side of each of two hyperfine atomic resonance. At higher temperatures and fields, rapid modulations appeared in the spectra. We found close agreement between transmission measurements and the results of a detailed calculation. Having anchored the calculations, we generated a series of transmission spectra for a range of fields and temperatures. The general approach of our analysis, given in Ref. 4 for the case of the Cs Faraday filter at 852 nm, was also used here. A detailed description of a calculation similar to ours was recently published.[9] We also calculated the transmission spectra associated with the nearby 459 nm transition, finding that the leakage at 459 nm was relatively small for the optimal narrowband operating conditions.

We have determined through a combination of measurements and calulations that the magneto-optic aspects of the filter do not limit the filter field of view; instead the field of view is limited by the clear aperture of the filter and vignetting. To investigate the filter field of view, we first generalized our transmission calculation to account for arbitrary angles of incidence. We then validated the calculation experimentally for the case of a Cs Faraday filter at 852 nm for a range of propagation angles with respect to the magnetic field direction. Using our validated model, we showed that the passband width and position was largely independent of the field up to angles of 45°.

A new type of magneto-optic filter that uses a transverse magnetic field, which we call the Voigt filter (after the Voigt effect[10]), was demonstrated to provide bandpasses as narrow as that of the Faraday filter. We observed Cs Voigt filter spectra at both 852 and 455 nm. The Voigt filter transmisson spectra were calculated as a special case of the generalized transmission calculation.

The construction of a Faraday filter is shown as a part of the experimental set up in Fig. 1. The filter consists of Cs vapor in a magnetic field between crossed polarizers. As described in Ref. 4, the magnetic field Zeeman splits the energy levels, resulting in circular dichroism and birefringence in the immediate vicinity of an absorption line. Light is transmitted by the filter when its net polarization is parallel to the exit polarizer axis. A simple peaked transmission spectrum is obtained when the filter parameters (i. e. field, vapor density and cell length) are adjusted to provide a maximum rotation of 90°; at higher vapor densities

and/or fields, multiple rotations lead to rapid modulations in the transmission spectrum. Away from the absorption line, the filter provides an out of band rejection determined by the extinction ratio of the crossed polarizers (typically $>10^5$).
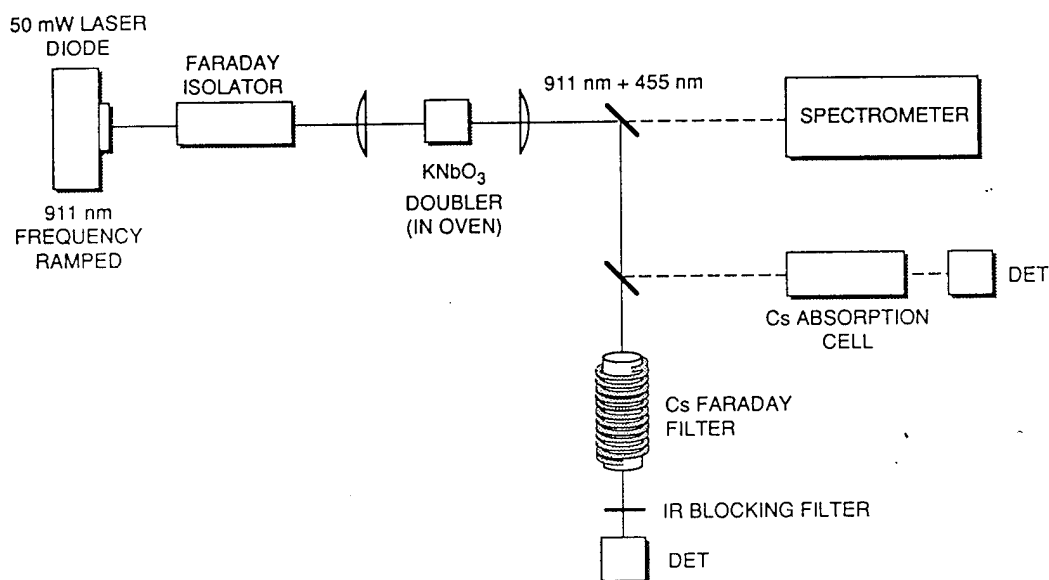


Fig. 1. Set up for the blue 455 nm Cs Faraday filter transmission measurement.

## Cs 455 nm Faraday Filter Spectra

### Set Up

Faraday filter tranmission spectra were measured for a range of fields and vapor densities using the set up shown in Fig. 1. A narrowband probe beam was provided by a doubled diode laser operating near 911 nm. The frequency ramped, narrowband beam of about 50 mW was provided by a current modulated diode laser (Spectra Diode Labs device type S9130). The laser was isolated and focused into a 7 mm long $KNbO_3$ doubling crystal mounted in a temperature controlled cell. The doubler produced about 1 $\mu$W of blue light which was split between the filter and a reference absorption cell. The filter consisted of an inch long cell containing Cs vapor in a magnetic field provided by a coaxial solenoid sandwiched between two Glan-Thompson polarizers. The vapor density was determined by the regulated (0.1°C) temperature of a coldfinger in the cell, which ranged between 120 and 200°C, giving densities between 4.7 x $10^{13}$ and 1.8 x $10^{15}$ atoms/$cm^3$. The field was determined from a measure of the solenoid current, using a calibration factor. We varied the current between 2 and 18 A to obtain fields up to 200 G. The filter and reference cell throughputs were monitored by silicon photodiodes or photomultipliers, whose outputs were simultaneously displayed on an oscilloscope and dumped to a plotter.

### Transmission Spectra

Two Faraday filter transmission spectrum measurements are presented along with corresponding calcualtions in Fig. 2. An example of a useful transmission spectrum for laser receiver applications is represented by the data shown in Fig. 2a. The cell was operated with a magnetic field of 200 G, at 140°C. The tallest peak in the spectrum has a bandwidth of 0.7 GHz. The four passbands correspond to two pairs of passbands, one pair for each of the lines in the ground state hyperfine doublet. The shape of the corresponding theoretical transmission corresponds to the measured spectrum very closely. From the calculated spectrum shown in 2b, the transmission peak is 70% for this particular operating point. Finer tuning of the filter operating point should produce a peak transmission much closer to 100%. In practice, the filter transmission is somewhat reduced by transmisson losses at the optical surfaces.

At higher temperatures, a broadening in the absorption lines appears to reduce the peak transmission. Experimental and calculated spectra for 200 G and 200°C are shown in Fig. 2c and d, respectively. The two calculated spectra, labelled by their linewidths $\Gamma$, were calculated for homogeneous broadening of 1 (dotted) and 20 (solid) times the natural linewidth $\Gamma_N$ of the transition. A comparison between the two plots shows how increasing the Lorentzian broadening leads to a reduction in the height of the secondary peaks, matching that exibited by the data. Possible causes for additional Lorenzian broadening include various collisional processes such as those with other Cs atoms, contaminant gases or the cell walls.
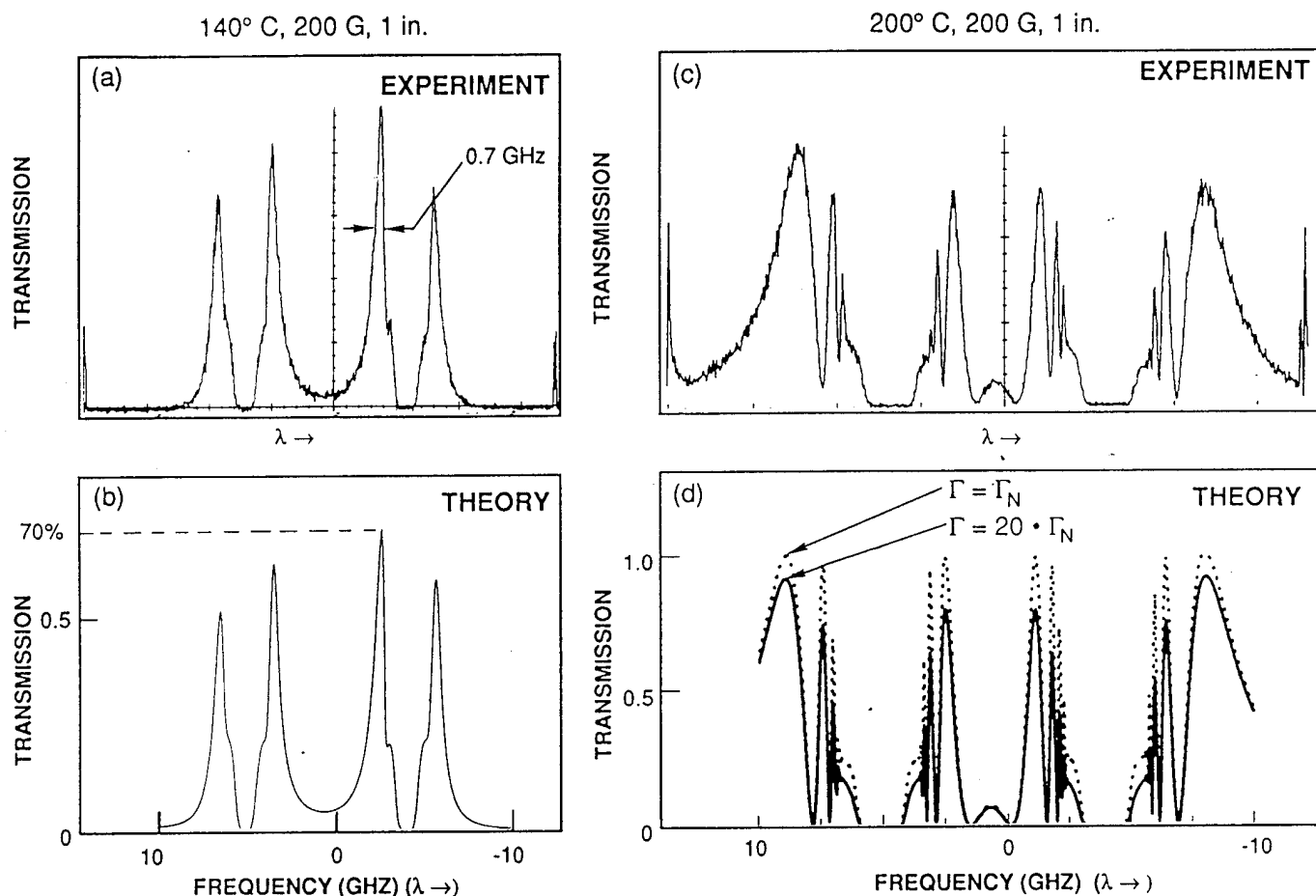
Fig. 2. Experimental and calculated blue 455 nm Cs Faraday filter transmission spectra.

A catalog of calculated 455 and 459 nm Faraday filter spectra for a 0.5 inch thick cell are shown in Figs. 3 and 4. Each of the figures shows plots for temperatures ranging between 120 and 200°C and fields ranging up to 400 G. From the array of calculated spectra shown in Fig. 3, it is apparent that a filter designer can trade 20°C for a factor of two in field and retain roughly the same spectrum. The integrated transmission given just above each plot can be used to estimate the noise equivalent bandwidth for each filter due to inband noise. The 459 nm filter plots displayed in Fig. 4 show that the inband noise near the passbands at 459 nm is insignificant for narrowest 455 nm passband conditions such as 160°C at 100 G.

<u>Filter Field of View</u>

An analysis of the the filter field of view showed that the 455 nm passband bandwidth and position was largely independent of field angle up to 45°. The results of our attempts at direct measurements of the field of view using our test filter was confused by Fresnel reflections from uncoated glass surfaces. Instead, the field of view was analyzed using a combination of measurements and calculations. Our calculation of the on-axis Faraday filter transmission spectrum was generalized to include off-axis rays. Then, off-axis transmission experiments were performed where the cell was fixed at near normal incidence to the probe beam, and the magnetic field was rotated to examine off axis propagation. These measurements validated the model for off-axis transmission spectra. Finally, using the validated model, we calculated the transmission spectra over the Faraday filter field of view.

<u>Extension of model to off-axis propagation</u>

We developed a calculation for the transmission of oblique rays propagating at angle $\theta$ with respect to the field for any linear polarization as an extension of our on-axis calculation. The transmission is easily determined by resolving the input polarization
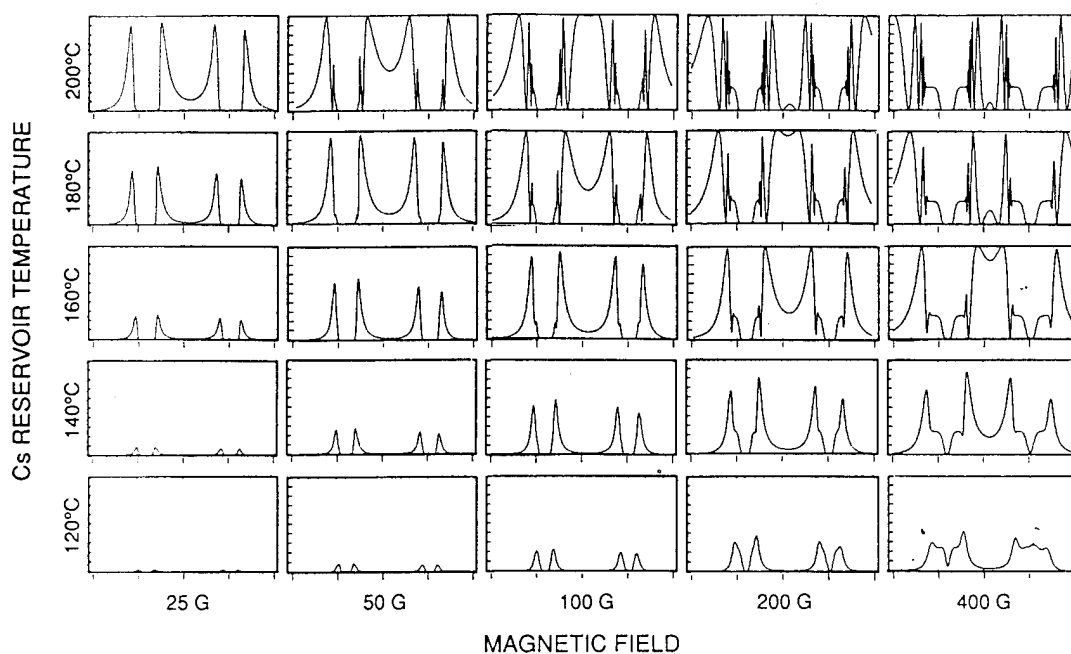
Fig. 3. Calculated blue 455 nm Cs Faraday filter transmission spectra for a 0.5 " cell.
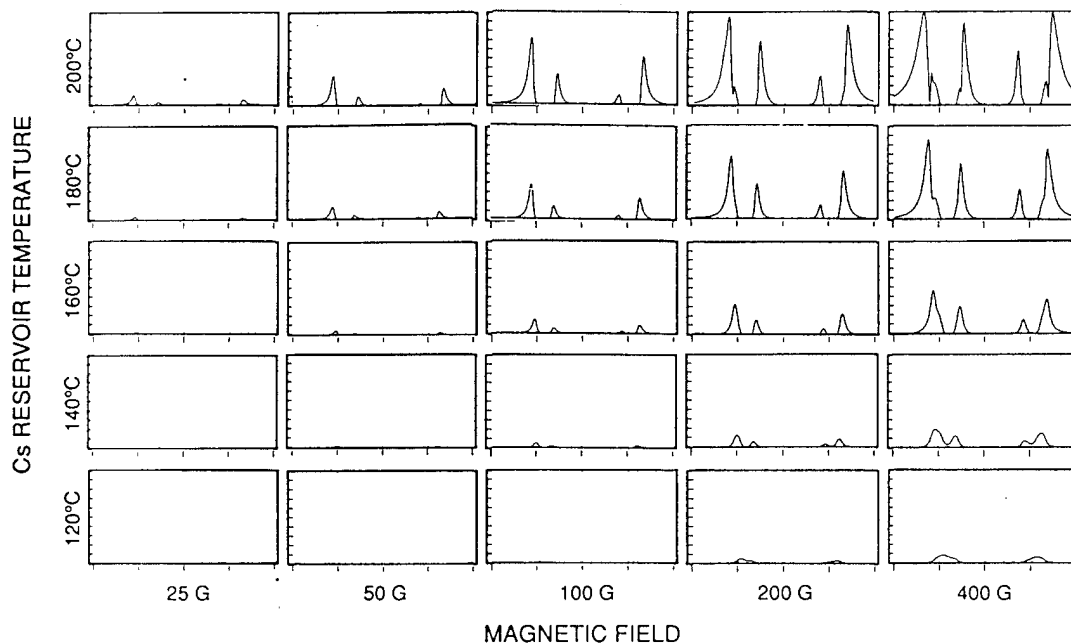


Fig. 4. Calculated blue 459 nm Cs Faraday filter transmission spectra for a 0.5" cell.

into the eigen-polarizations of the birefringent vapor, accumulating phase in each component over the vapor pathlength and recombining the components to obtain the field at the analyzing polarizer. The on-axis case is an instance of this type of analysis where the eigenpolarizations and indices are the circular polarizations and indices. The right and left circular indices, corresponding to the $\sigma_+$ and $\sigma_-$ transitions, were determined directly from a few atomic parameters. With the additional calculation of the index of refraction for the $\pi$ transition, enough information is provided to evaluate the dielectric tensor by using the simple on-axis and transverse case as boundary conditions. An example of the absorption and dispersion for the three transitions is given in Fig. 5. The wave equation for propagation in the vapor establishes eigenvector equations for the polarizations with indices as eigenvalues which are parameterized by the propagation angle $\theta$. Transmission calculations can then proceed in analogy to the on-axis case.
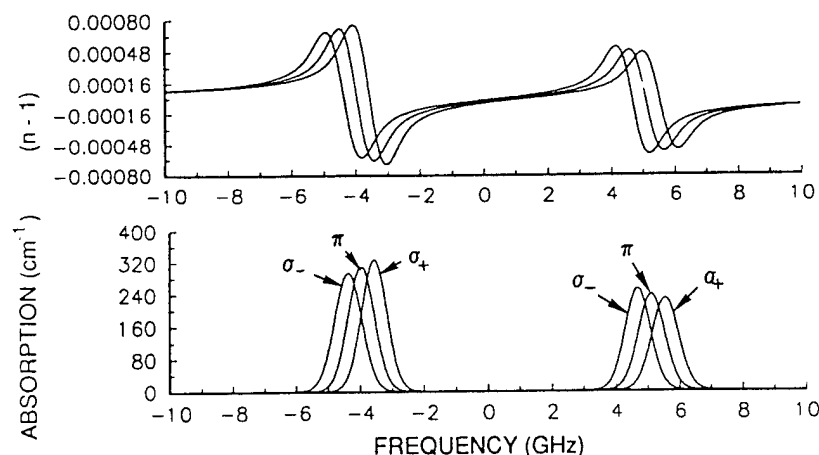
Fig. 5. The absorption and refractive index spectra for $\sigma_+$, $\sigma_-$ and $\pi$ polarized light in Cs vapor, at 200°C in a filed of 200 G.

## Off Axis Transmission Experiments

Off axis transmission measurements of the Cs Faraday filter passband at 852 nm were used to verify the transmission calculations described above. Notice that in these experiments, the propagation length through the vapor remains fixed, whereas in a wide field of view cell, the propagation distance increases by $1/\cos\theta$. Also, these experiments ignore the effects of large field angle on polarizer performance, since we use a pair of high quality Glan-Thompson prisms well inside their field of view of only a few degrees.

As shown in Fig. 6, we used a fixed Cs cell with respect to the probe beam. Transmission spectra at various field angles were obtained by rotating the magnetic field ($\theta$) and rolling the polarizers ($\phi$) (while maintaining crossed polarizers). For a fixed angle of propagation with respect to the magnetic field, rolling the polarizers simulated scanning a cone about the filter input. With the input polarizer fixed in the vertical direction, we made a series of transmission measurements for $\theta$ ranging up to 50° shown in the top part of Fig. 7. As the value of $\theta$ is increased, the position of the outside peaks move inward. Also, the transmission band between the peaks, which is nearly level for the on axis case, begins to sag as $\theta$ increases. Similar results were generated by the filter model. To compare them quantitatively, notice that the peak shift between the on axis case and the 50° case was measured to be about 7% of the hyperfine splitting. The calculated spectra show a 5% shift in the peak, comparable to the experimentally measured shift. The difference may be attributable to an error in the vapor temperture.

## Blue Passband Sensitivity to Field Angle

Off axis transmission spectra calculations showed that the bandpass width and position was largely insensitive to the field angle. This study considered a single peak of the Cs 455 Faraday filter as shown in Fig. 8, with a peak transmission of 83%. To model a Faraday filter field of view, the thickness of the cell was increased by a factor of $\cos\theta$. The transmission contour plot shown in Fig. 9 summarizes the spectra out to a field angle of 50°. The contours are labelled with relative transmission. In the plot horizontal slices for fixed angles can be used to reconstruct transmission spectra. The contours show that the position of maximum transmission migrates about 100 MHz between 0 and 50°, which is small compared to the approximate width of 700 MHz. We also see that the peak transmission falls only about 15% from its 83% peak on axis.

### The Voigt Filter

We invented a new magneto-optic ultra-narrowband filter, the "Voigt filter," in which the magnetic field is applied transverse to the filter axis. The rectilinear magnet designs for the Voigt filter may have packaging advantages over the cylindrical designs for the Faraday filter. However, as a rule of thumb, a Voigt filter requires about twice the magnetic field of a comparable Faraday filter to provide a similar transmission spectra.

The Voigt filter can be easily understood as a resonant half wave plate. For light propagating through the vapor at right angles to the magnetic field, the eigenpolarizations are purely linear, and are oriented along the magnetic field and perpendicular to it. The eigenindices are given by $n_\pi$ and $(\frac{1}{2}) \cdot (n_+ + n_-)$ respectively. This situation is similar to that of an ordinary birefringent
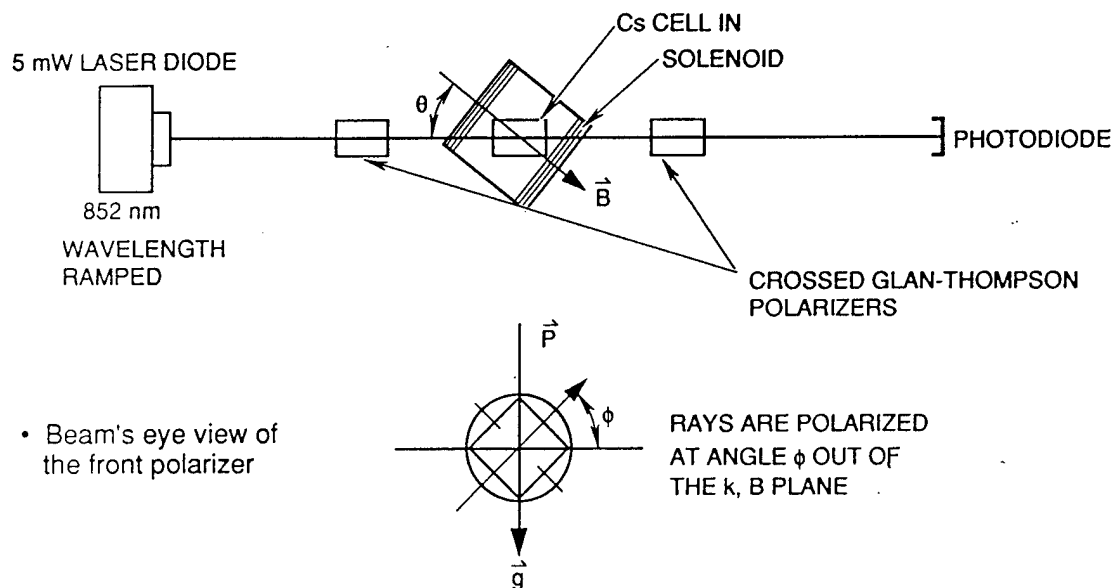
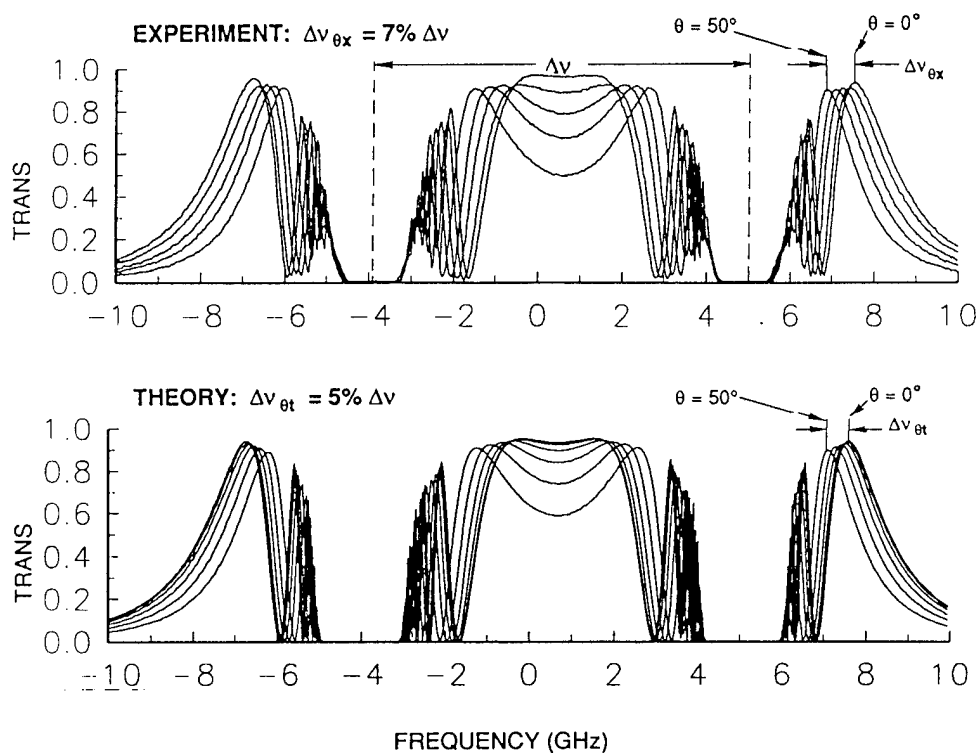Fig. 6. Set up for off-axis transmission spectrum measurements.



Fig. 7. Off-axis transmission spectrum measurements and calculations for $\phi=0°$ and $\theta=0, 10, 20, 30, 40$ and $50°$. The peak shift between the 0 and 50° spectra is $\Delta v_{\theta x}$ and $\Delta v_{\phi t}$ for the experimental and theoretical spectra, respectively.
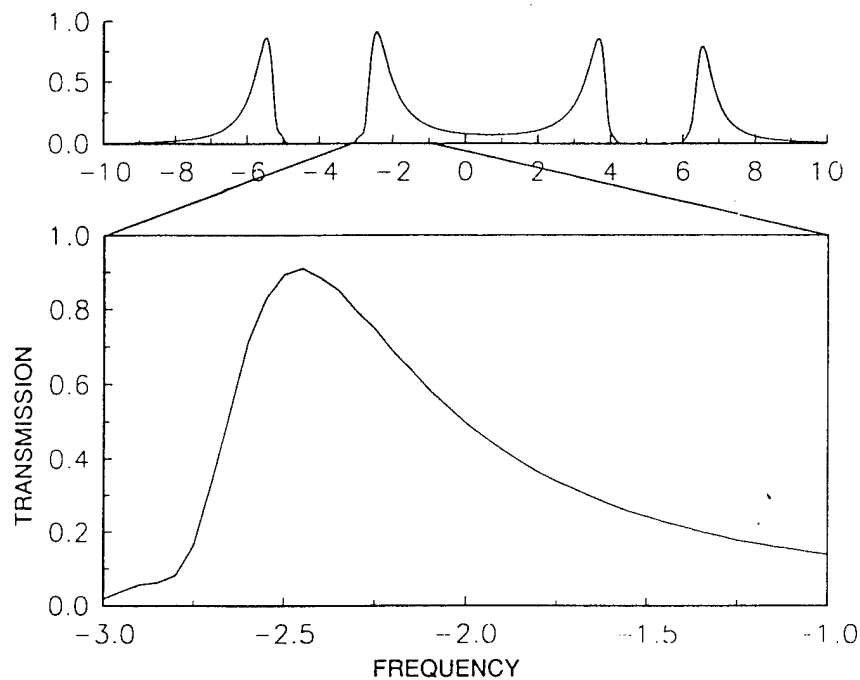
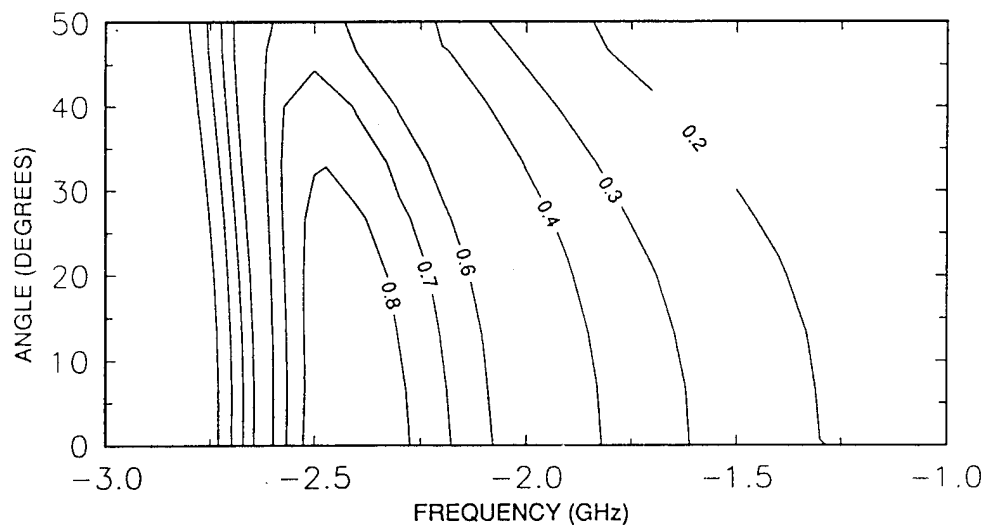Fig. 8. On-axis transmission spectrum peak near 455 nm to be evaluated over the filter of field of view.



Fig. 9. Transmission spectra contours with field angle for $\phi=0$.

waveplate. In analogy to a half wave plate, a 90° rotation of the incident linear polarization is possible when the incident polarization makes an angle of 45° with the principle axes of the "waveplate;" in this case, with the magnetic field. Refering to Fig. 6, a Voigt filter corresponds to setting $\theta = 90°$ and $\phi = 45°$.

We have observed the transmission spectra of Cs Voigt filters at both 852 and 455 nm. An example of a Cs 852 nm Voigt filter transmission spectrum is presented in Fig. 10.

## Conclusion

The blue Cs Faraday filter is suitable for wide field of view, underwater laser receiver applications. As we have demonstrated experimentally, the filter provides a stable, ultra-narrow passband near 455 nm with an integrated transmission as low as 3 GHz

with a near unity peak transmission. We demonstrated that the filter offers a wide field of view as wide as 45° without significant shift in the passband position change in the bandwidth. Our modelling of the filter predicted an intrinsic decrease in transmision of only 15% for a field angle of 45°. Finally, a new type of magneto-optic ultra-narrowband filter, the Voigt filter, may offer significant packaging advantages over the Faraday filter.

<u>Acknowledgements</u>
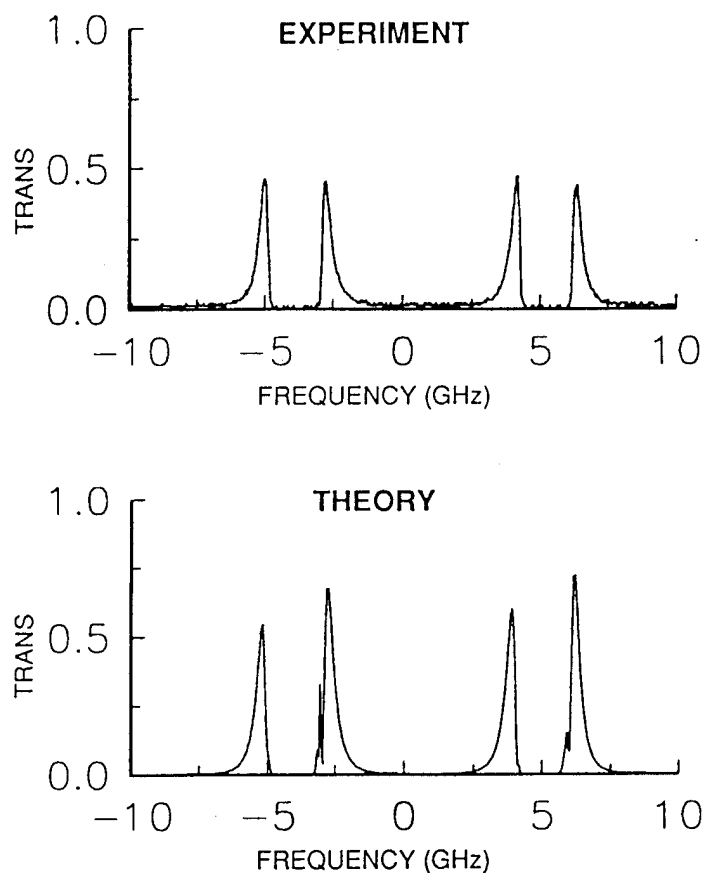
Fig. 10. Measured and calculated Cs 852 nm Voigt filter transmission spectra.

<u>References</u>

1.  Jerry A. Gelbwachs, IEEE J. Quantum Electron. **24** (7), 1266 (1988).
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3.  Taisuke Endo, Tsutomu Yabuzoki, Masao Kitano, Takashi Sato, and Toru Ogawa, IEEE J. Quantum Electron. QE-13 (10), 866 (1977).
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5.  J. Gelbwachs and Y. C. Chen, presented at the International Conference on Lasers '91, San Diego (1991), paper WG 2.
6.  Pochi Yeh, Appl. Opt. **21** (11), 2069 (1982).
7.  D. J. Dick and T. M. Shay, Opt. Lett. **16** (11), 867 (1991). "FADOF" is an acronym for Faraday anomalous dispersion optical filter.
8.  An image preserving ALF was developed by Eric Korevaar et. al., <u>Proceedings of the International Conference on Lasers '89</u>, edited by D. G. Harris and T. M. Shay (STS Press, McLean, VA), pp. 933-939.
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10. F. A. Jenkins and H. E. White, Fundamentals of Optics (McGraw-Hill Book Co., New York, 1957), pp. 599-601.

*Bill Scharpf*

# TTC Thermo Electron Technologies Corporation

# Ultra-Narrow Linefiltering Using a Cs Faraday Filter at 455 nm

J. Menders, P. Searcy, K. Roff, S. Bloom, E. Korevaar

**Thermo Electron Technologies Corporation**
9550 Distribution Avenue
San Diego, CA 92121-2305
(619) 578-5885

**Lasers '91, San Diego**
Blue - Green Technology II
10 December 1991

19950802 016

# TTC

## AN ALTERNATIVE TO THE ALF

- Background limited laser receivers require ultra narrow linewidth filters to reach quantum limited operation

  - submarine laser communication
  - free space communication
  - remote sensing

- The conventional approach is the atomic line filter (ALF)

  - operate at discrete atomic absorption lines

- The Faraday filter is an alternative to the ALF for most applications

  - very high peak transmission
  - variable bandwidth, ~ 1-5 GHz
  - tunable over ~ 5 GHz
  - imaging filter, wide field of view
  - instantaneous response

# TTC

## TOPICS

- Principles of Faraday filter operation

- Previous filter development at 852 nm

- On-axis transmission spectrum measurements and modelling at 455 nm

- The Voigt filter: a new ultra-narrowband filter

- Model extension to three dimensions

- Off axis transmission measurements and predictions at 852 nm

- Off axis transmission measurements and predictions at 455 nm

2331-V

# PRINCIPLES OF FARADAY FILTER OPERATION

**TTC**

- The Cs vapor exhibits resonant Faraday rotation near strong absorption lines (e.g. 455, 459, 852, 894 nm)

MAGNETIC FIELD COIL

ATOMIC VAPOR CELL

HORIZONTAL POLARIZER

VERTICAL POLARIZER

HORIZONTAL POLARIZER

PLANE POLARIZED

SIGNAL

FREQUENCY

HOT VAPOR CELL IN AN AXIAL MAGNETIC FIELD

UNPOLARIZED LIGHT

VERTICAL POLARIZER

SIGNAL

NOISE

FREQUENCY

91-13284b
Ref. 90-12367b
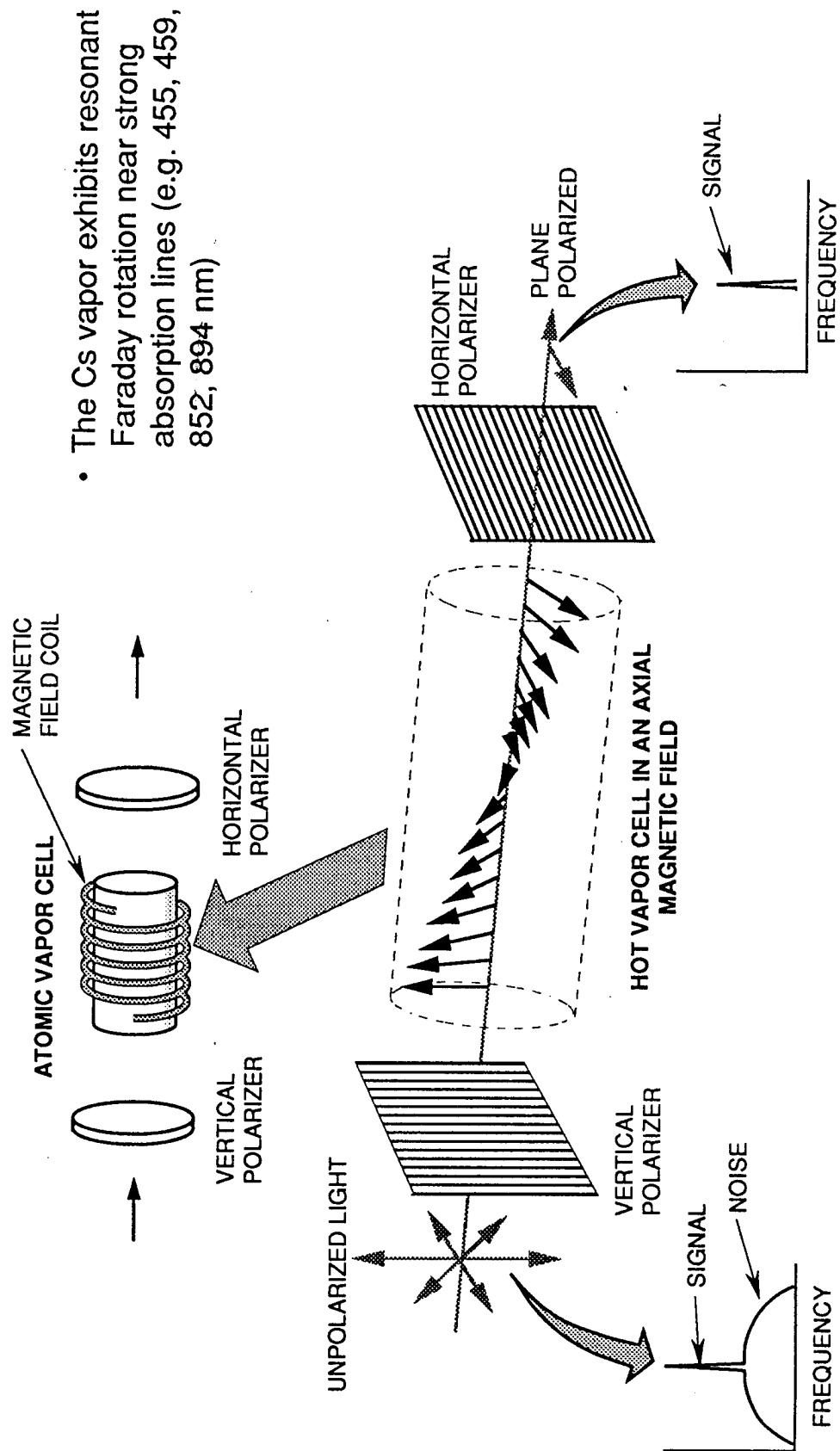
# TTC MODEL FOR THE Cs 852 RESONANT FARADAY EFFECT
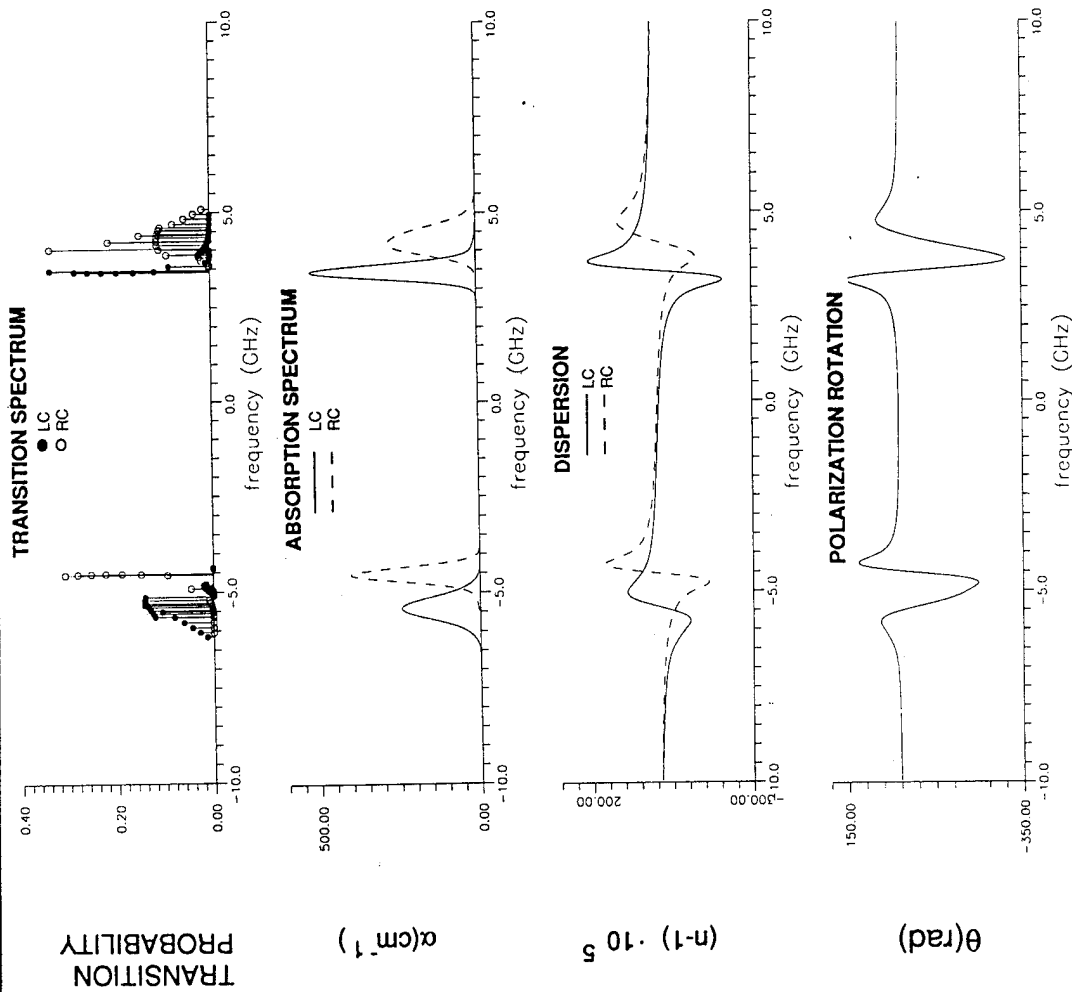
- B = 200 G, T = 120° C

- OVER-ALL HF SPLIT COMMON TO ALL Cs FFs.

- HF AND ZEEMAN INCL

- VAPOR DENSITY, NAT AND DOPPLER BROADENING

- USING THE KRAMERS-KRONIG RELATION

- SLOWLY VARYING BIREF RESULTS IN A PLATEAU IN THE ROTATION

- TENS OF ROTATIONS ARE MADE APPROACHING THE RESONANCE

- MODULATION BANDWIDTHS DEPEND ON THE SLOPE

TRANSITION SPECTRUM
- LC
- RC

frequency (GHz)

TRANSITION PROBABILITY

ABSORPTION SPECTRUM
LC
RC

frequency (GHz)

$\alpha(\text{cm}^{-1})$

DISPERSION
LC
RC

frequency (GHz)

$(n-1) \cdot 10^5$

POLARIZATION ROTATION

frequency (GHz)

$\theta(\text{rad})$

4

90-13066

# FARADAY FILTER EQUATIONS

Transition Probability:

$$P_{nk}^{(i)} \propto |\langle n|\sigma_i|k\rangle|^2 \; ; \; \sum_{nk} P_{nk}^{(i)} = 1$$

Absorption:

$$\alpha_{12}(\Delta) = \frac{n\lambda^2}{8\pi} \cdot \frac{g_1}{g_2} \cdot A_{21} \cdot N \cdot g(\Delta)$$

Index of Refraction:

$$n(\Delta) - 1 = \frac{n\lambda^3}{32\pi^2} \cdot \frac{g_1}{g_2} \cdot A_{21} \cdot N \cdot \frac{\Delta}{\Delta_{HW}} g(\Delta)$$

Doppler Broadening:

$$\alpha_{12}(\nu) = \int_{-\infty}^{\infty} \alpha_i(0) \cdot g\left(\nu - \nu_o \frac{\nu}{c} \nu_o\right) \cdot N \cdot f(v_z) \cdot dv_z$$

$$n_i(\nu) - 1 = \int_{-\infty}^{\infty} [n_i(0) - 1] \cdot g\left(\nu - \nu_o \frac{\nu}{c} \nu_o\right) \cdot N \cdot f(v_z) \cdot dv_z$$

Transmission (on axis):

$$T(\nu) = \frac{1}{4}\left[t_+(\nu) - 2\sqrt{t_+(\nu)} \cdot t_-(\nu) \cdot \cos(2\delta) + t_-(\nu)\right]$$

$$t_{\pm}(\nu) = \exp[-\alpha_{\pm}(\nu) \cdot z]$$

$$\delta(\nu) = \frac{\pi\nu z}{c}[n_+(\nu) - n_-(\nu)]$$

- The absorption and the index of refraction are summed over the transition with the appropriate $\nu_o$ and weighting by $P_{nk}$

2331-V

# Cs $6s_{1/2}$ - $7p_{3/2}$

## HYPERFINE AND ZEEMAN SPLITTING
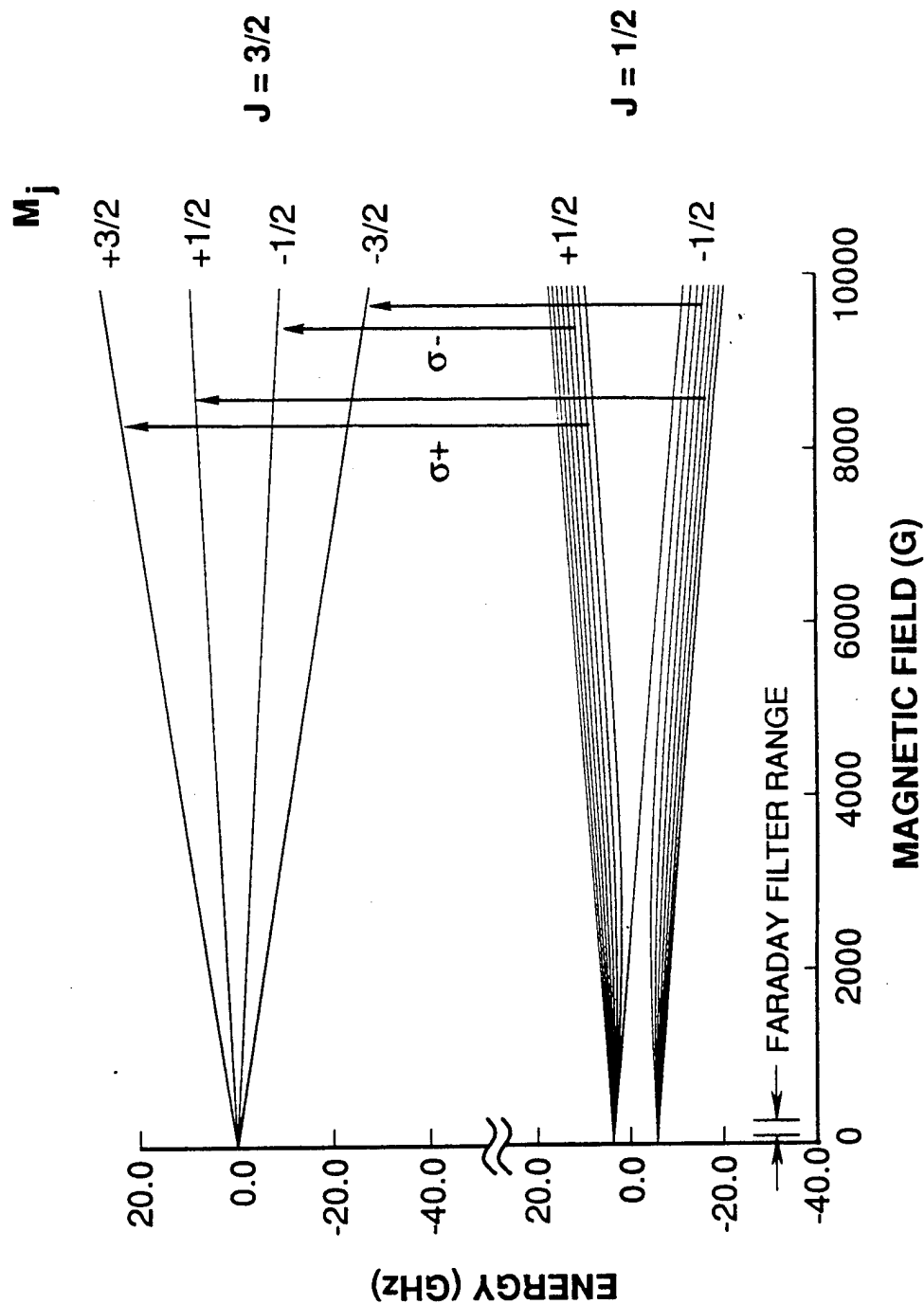
**TTC**

$M_j$

$J = 3/2$

+3/2
+1/2
-1/2
-3/2

$\sigma-$

$\sigma+$

$J = 1/2$

+1/2
-1/2

FARADAY FILTER RANGE

ENERGY (GHz)

20.0  0.0  -20.0  -40.0  20.0  0.0  -20.0  -40.0

0  2000  4000  6000  8000  10000

MAGNETIC FIELD (G)

91-14104

# TTC — FILTER DEVELOPMENT STATUS PRIOR TO 1991

- Transmission spectrum measurements at 852 nm
- Measurements anchored theory of transmission spectra at 852 nm
- Predicted filter performance at 455 nm

## OUR CALCULATIONS AND MEASUREMENTS ARE IN EXCELLENT AGREEMENT

EXPT

THEORY

200 G   120° C

frequency (GHz)
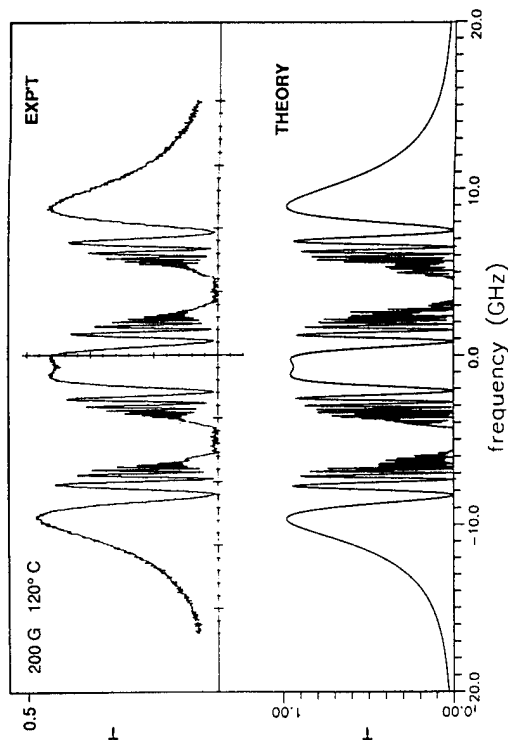
90-13067

B = 200 G
T = 120° C

- "Cold cell" transmission of 0.54 due to Fresnel losses accounts for scaling between theory and experiment
  - Spectra agree in detail

## WE PREDICT A HIGH TRANSMISSION, NARROW PASSBAND AT 455 nm

455 nm

82%

0.7 GHz

200 G   140° C

459 nm

transmission

frequency (GHz)
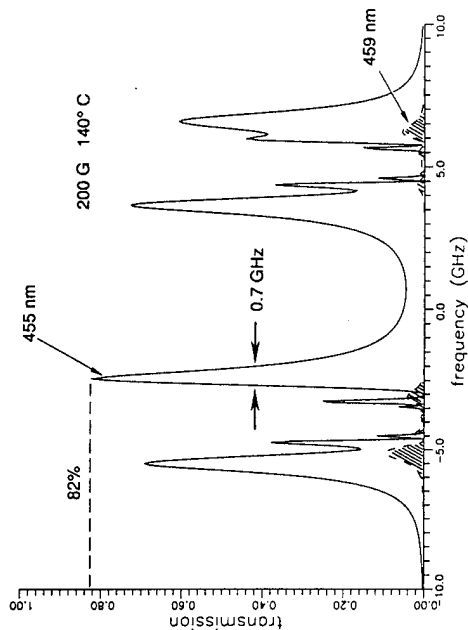
- Unwanted transmission at 459 nm is small at this operating point

90-13068

- Measurements at 455 had not yet been made

7

91-14469

# TTC

## BLUE FARADAY FILTER TRANSMISSION MEASUREMENTS

SPECTROMETER

DET

Cs ABSORPTION CELL

911 nm + 455 nm

Cs FARADAY FILTER

IR BLOCKING FILTER

DET

KNbO$_3$ DOUBLER (IN OVEN)

FARADAY ISOLATOR

50 mW LASER DIODE

911 nm FREQUENCY RAMPED

8

91-14097

# *TTC*
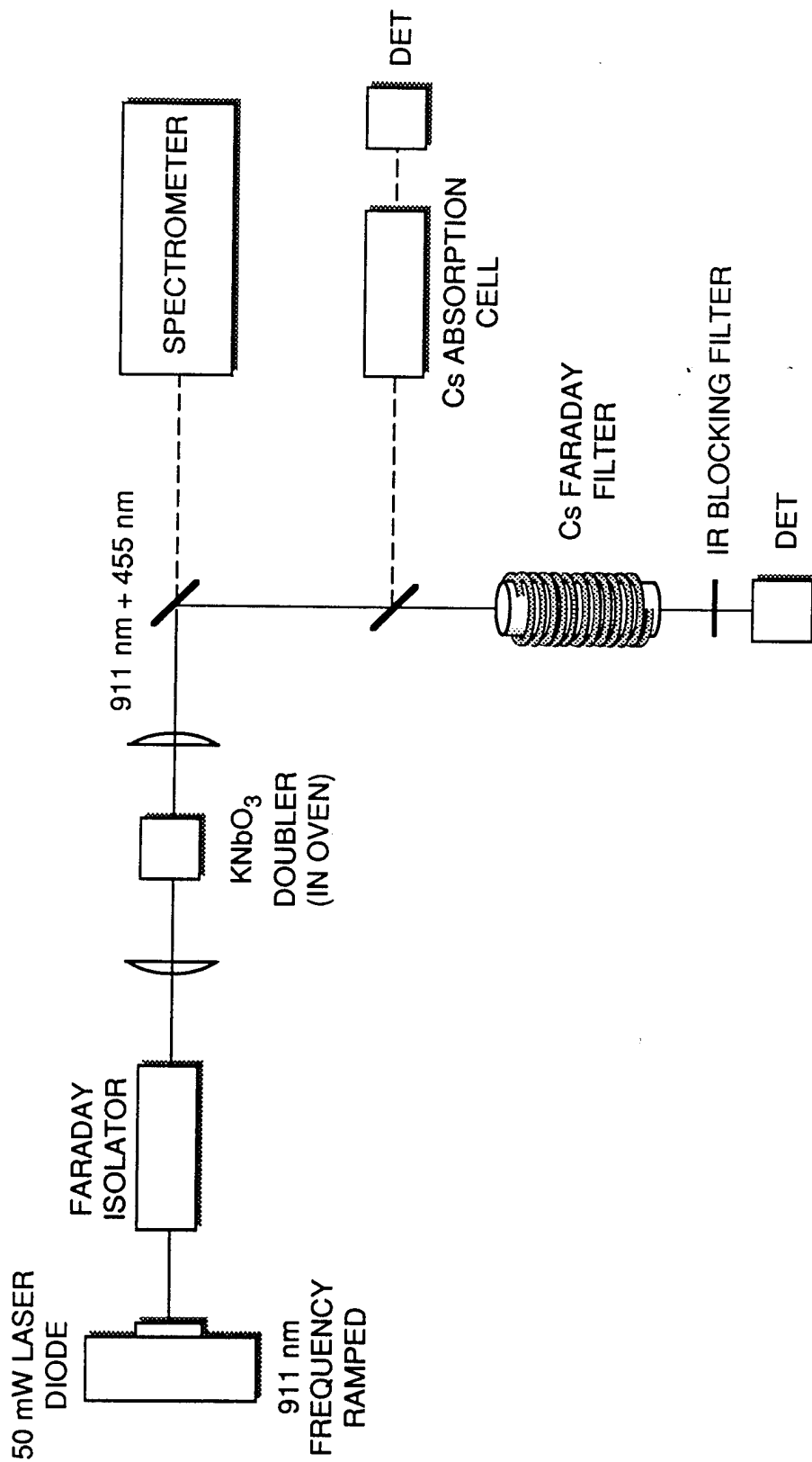
## BLUE FARADAY FILTER TRANSMISSION SPECTRUM AT 200 G, 140° C

91-14102
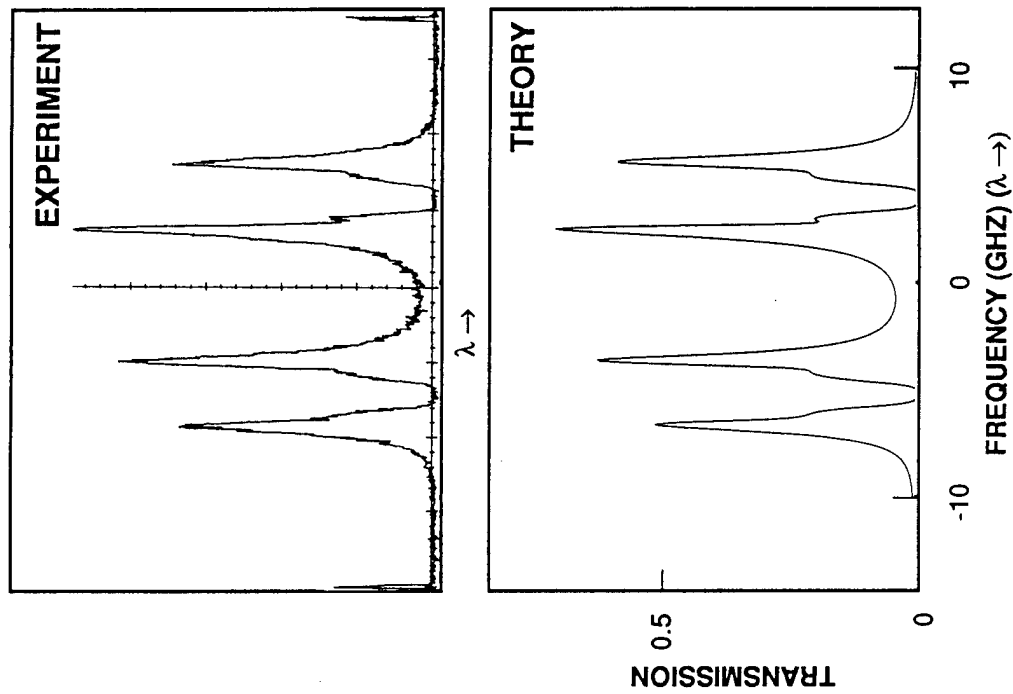
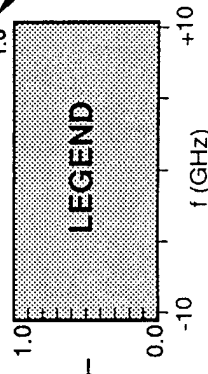# BLUE FARADAY FILTER TRANSMISSION SPECTRUM AT 200 G, 200° C

**TTC**

EXPERIMENT

$\lambda \rightarrow$

THEORY

TRANSMISSION

1.0

0.5

0

-10        0        10

FREQUENCY (GHZ) ($\lambda \rightarrow$)

10

91-14103
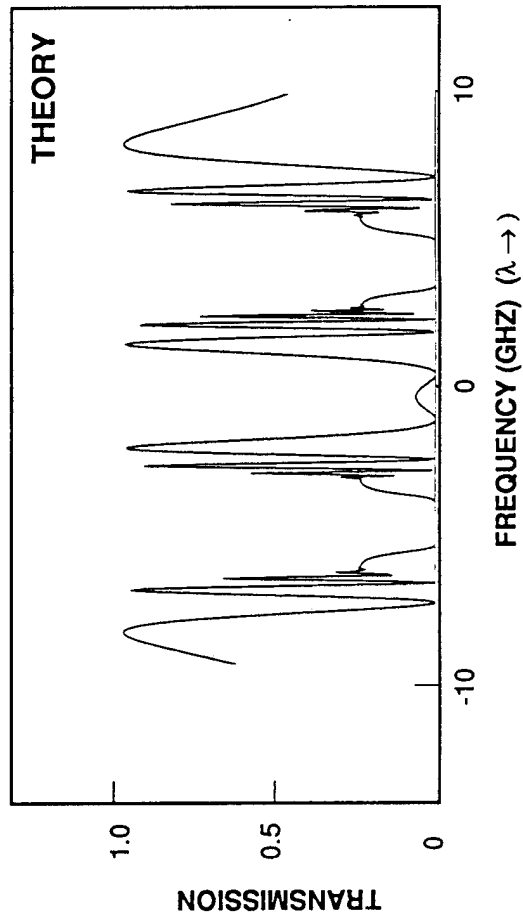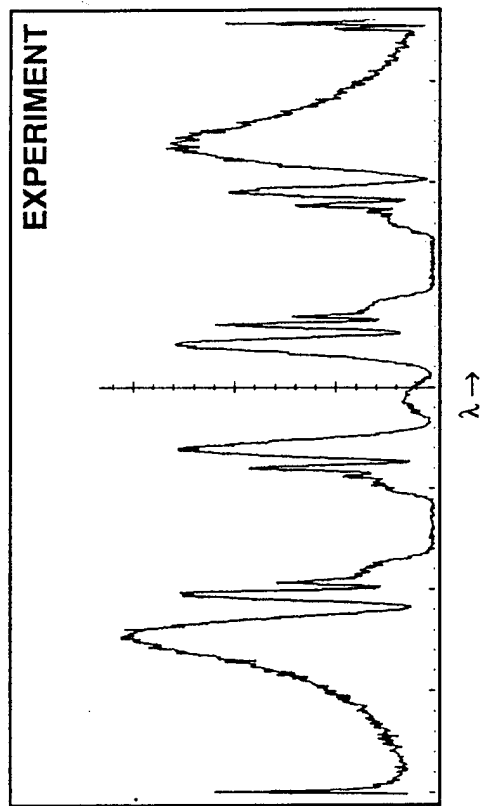
# TTC CALCULATED 455 SPECTRAL VARIATION WITH B, T
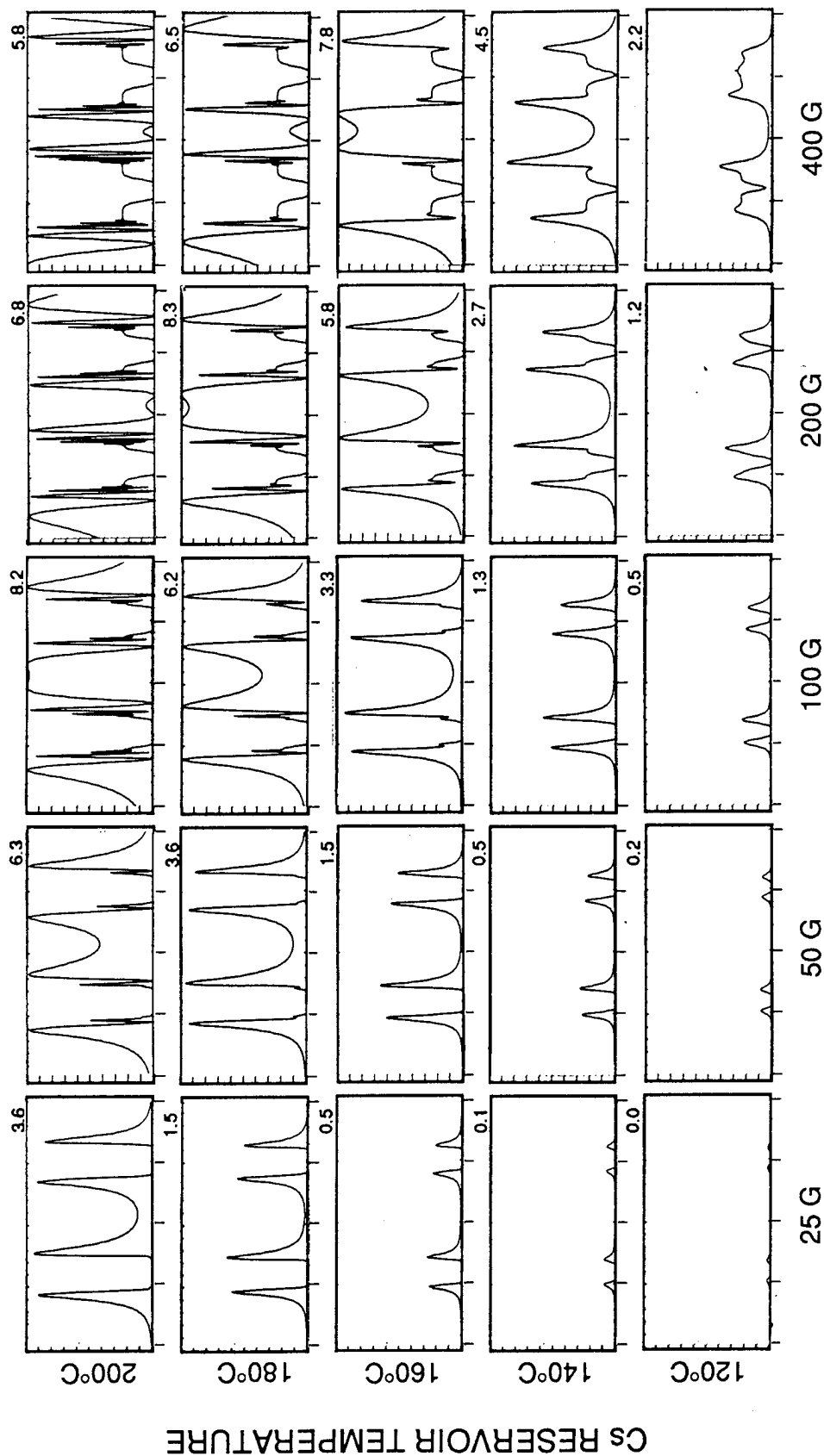


MAGNETIC FIELD

$\dfrac{\int T dz}{GHz}$

6.9 mÅ = 0.6 pm = 1 GHz

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91-14099

# TTC

## CALCULATED 459 SPECTRAL VARIATION WITH B, T
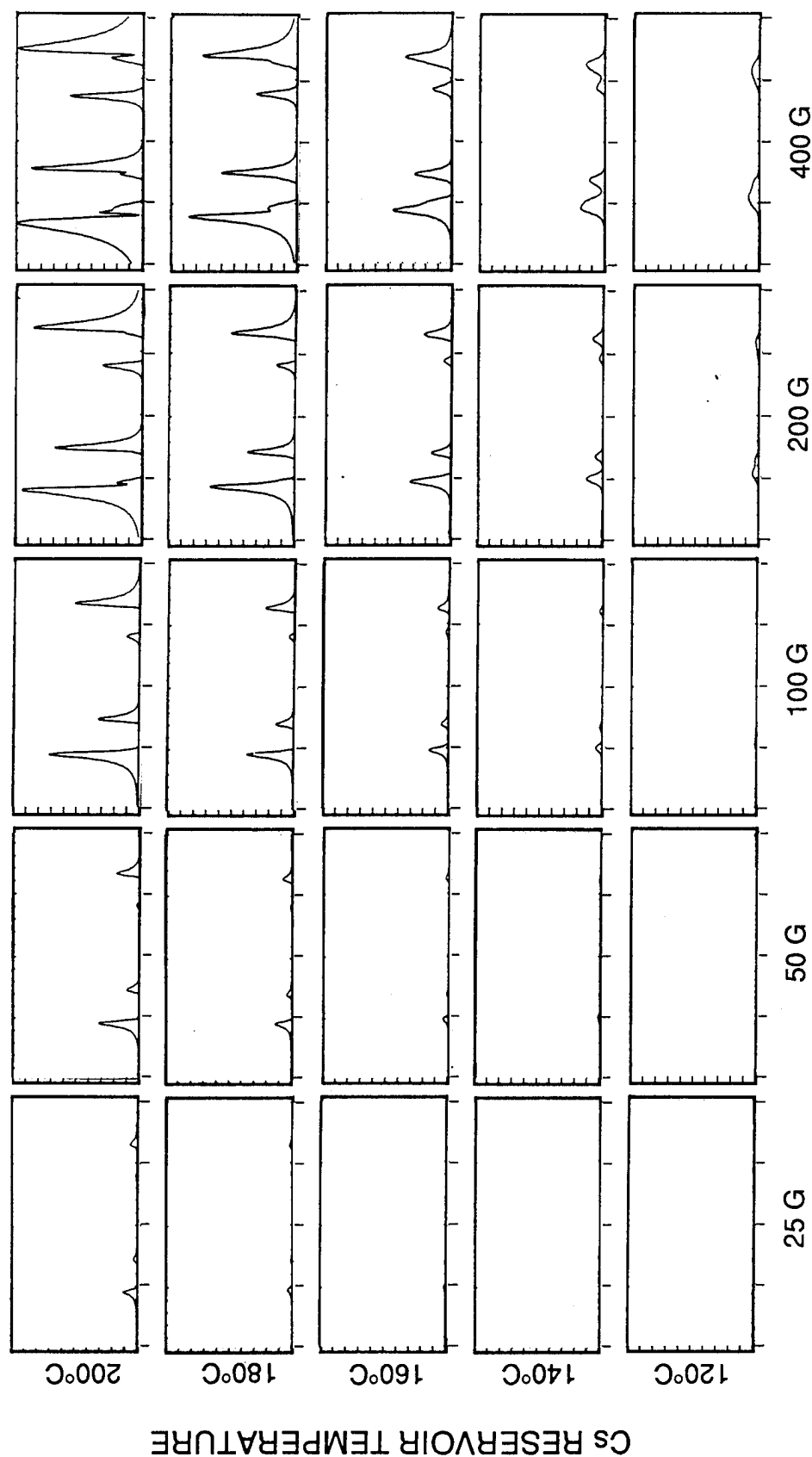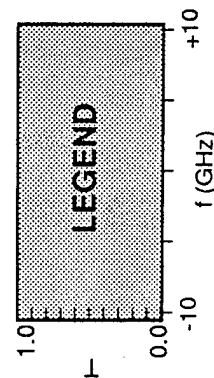


MAGNETIC FIELD

25 G — 50 G — 100 G — 200 G — 400 G

Cs RESERVOIR TEMPERATURE

200°C — 180°C — 160°C — 140°C — 120°C

LEGEND

f (GHz)

-10 — 0.0 — +10

1.0

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91-14100

# MODEL EXTENSION TO 3-D

*TTC*

- In general, $\vec{E}$ components along $\vec{B}$ couple to $\Delta m = 0$, or $\pi$ transitions at distinct frequencies
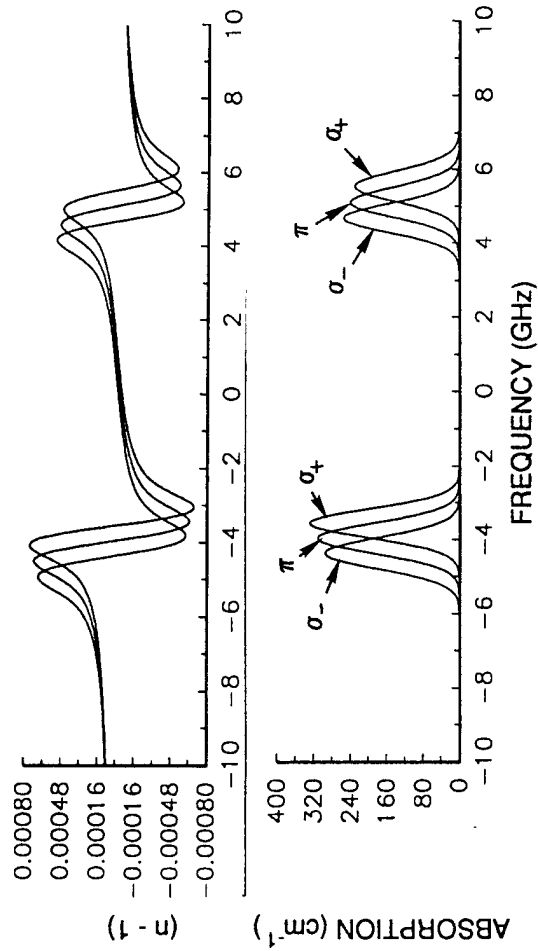
Cs, 455 nm

T = 200° C

B = 200 G

L = 1 in.
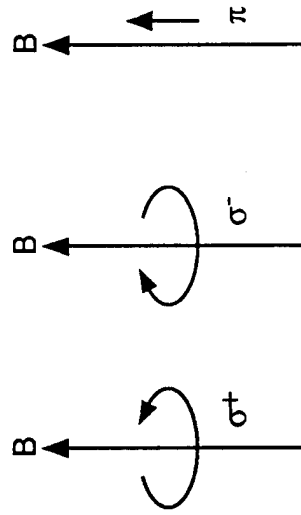
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# TTC

## THE LEFT- AND RIGHT CIRCULAR POLARIZATION ANALYSIS IS SPECIFIC TO PROPAGATION ALONG $\vec{B}$

- In general, other directions have varying eigen-polarizations and -indices

- The dielectric tensor can be generalized to include the Faraday effect of a field along z

$$\varepsilon = \begin{bmatrix} \varepsilon_0 & -i \cdot \varepsilon_B & 0 \\ +i \cdot \varepsilon_B & \varepsilon_0 & 0 \\ 0 & 0 & \varepsilon_0 \end{bmatrix}$$

where $\varepsilon$ is the isotropic dielectric coefficient and $\varepsilon_B = n_r^2 - n_l^2$

- Maxwell's equations lead to a matrix form of the wave equation

$$\left( \underbrace{\varepsilon_i \cdot \begin{bmatrix} -s_y^2 - s_z^2 & s_x \cdot s_y & s_x \cdot s_z \\ s_x \cdot s_y & -s_z^2 - s_x^2 & s_y \cdot s_z \\ s_x \cdot s_z & s_y \cdot s_z & -s_x^2 - s_y^2 \end{bmatrix} + [\varepsilon]}_{[\varepsilon]} \right) \vec{E} = 0. \quad \vec{k} = |\vec{k}| \hat{s}$$

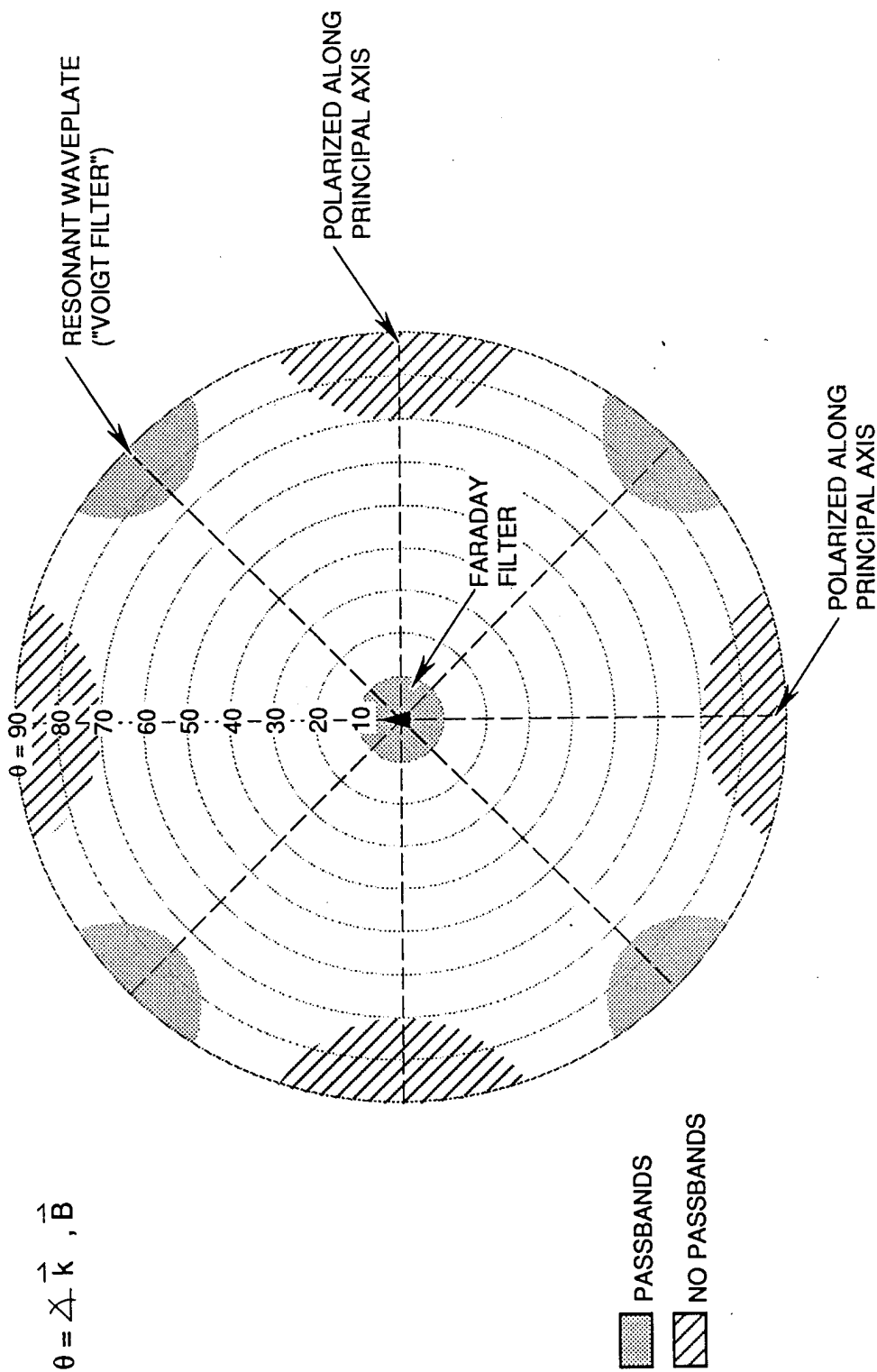- Eigen - indices $n_i^2 = \varepsilon_i$ are determined from $|\langle \ldots \rangle| = 0.$

2331-V

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## TWO PROPAGATION DIRECTIONS YIELD SIMPLE EIGEN INDICES AND POLARIZATIONS

$\vec{1}$B

$\otimes$    $\otimes$

$\otimes$    $\otimes$    $\otimes$    $\otimes$
$\hat{R}$    $\otimes$    $\hat{L}$

$\otimes$    $\otimes$

$\hat{y}$    $\hat{z}$    $\vec{1}$B = B$\hat{z}$

$\otimes$

- Propagation along $\vec{B}$ (Faraday Effect)

  – Circular polarizations $\hat{R}$, $\hat{L}$

  – Circular indices $n_R$, $n_L$

- Propagation perpendicular to $\vec{1}$B (Voigt effect)

  – Linear polarizations $\hat{y}$, $\hat{z}$

  – $n_y = \dfrac{1}{2}(n_R + n_L)$; $n_z = n_\pi$
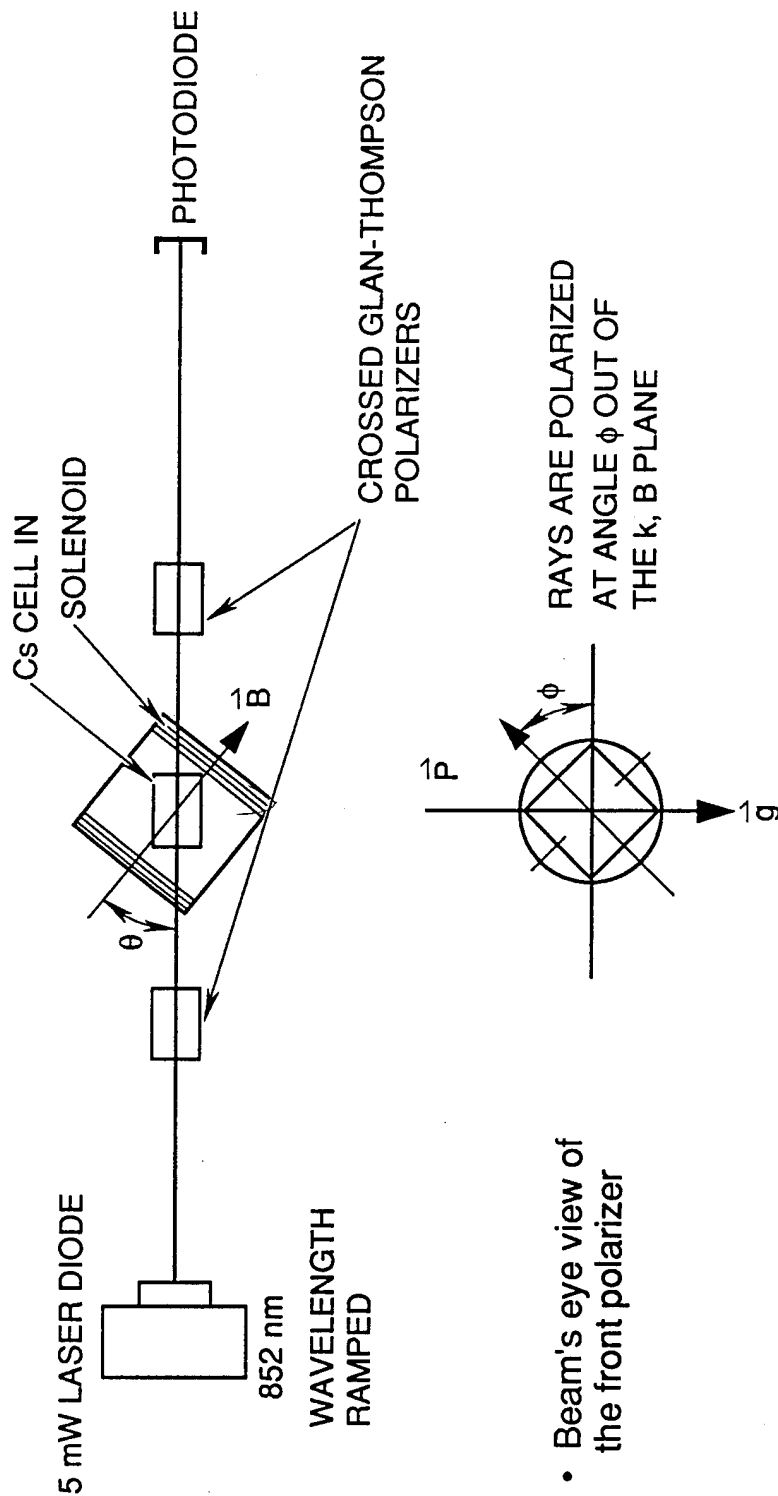
  – Similar to birefringence

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# TTC
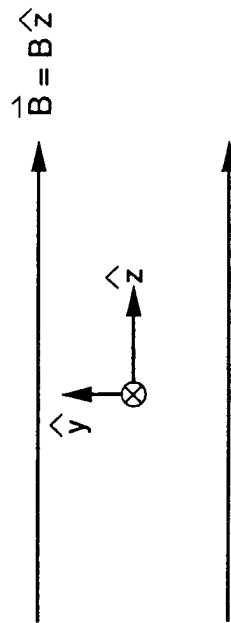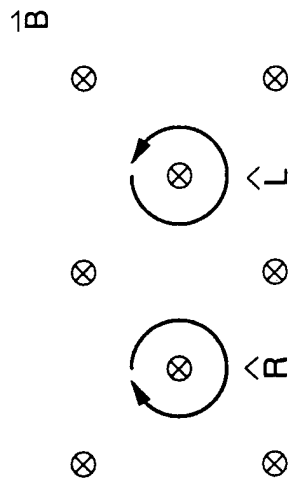
## EXPECTED BEHAVIOR OF THE TRANSMISSION SPECTRUM OVER THE FIELD OF VIEW

### INPUT POLARIZER VERTICAL OR HORIZONTAL

$$\theta = \measuredangle \hat{k}, \vec{B}$$



RESONANT WAVEPLATE ("VOIGT FILTER")

POLARIZED ALONG PRINCIPAL AXIS

FARADAY FILTER

POLARIZED ALONG PRINCIPAL AXIS

$\theta = 90$  80  70  60  50  40  30  20  10

▨ PASSBANDS

▨ NO PASSBANDS

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# TTC

## OFF-AXIS TRANSMISSION EXPERIMENTS

PHOTODIODE

CROSSED GLAN-THOMPSON POLARIZERS

Cs CELL IN SOLENOID

1B

θ

5 mW LASER DIODE

852 nm

WAVELENGTH RAMPED

RAYS ARE POLARIZED AT ANGLE φ OUT OF THE k, B PLANE

1P

φ

1g

- Beam's eye view of the front polarizer

- This cell and field arrangement avoids the complication of variations in Fresnel losses

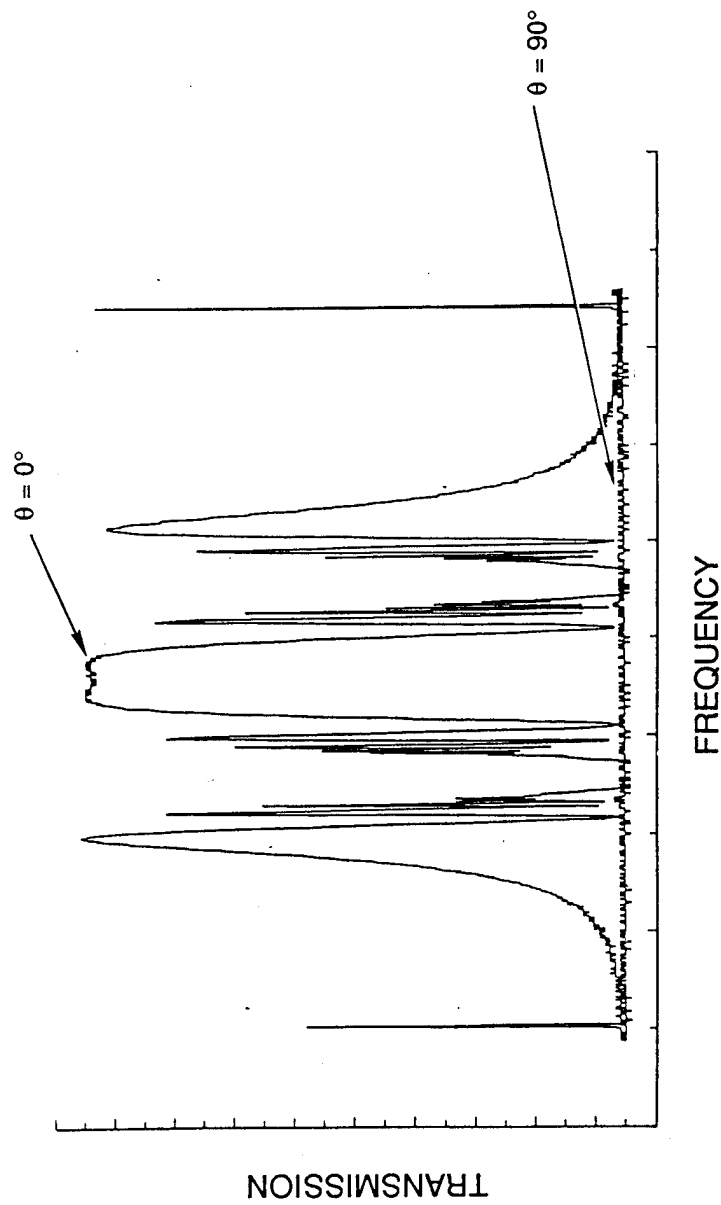- Transmission spectra do not reflect pathlength increases with θ

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# TTC

## FILTER TRANSMISSION MEASUREMENT SET-UP
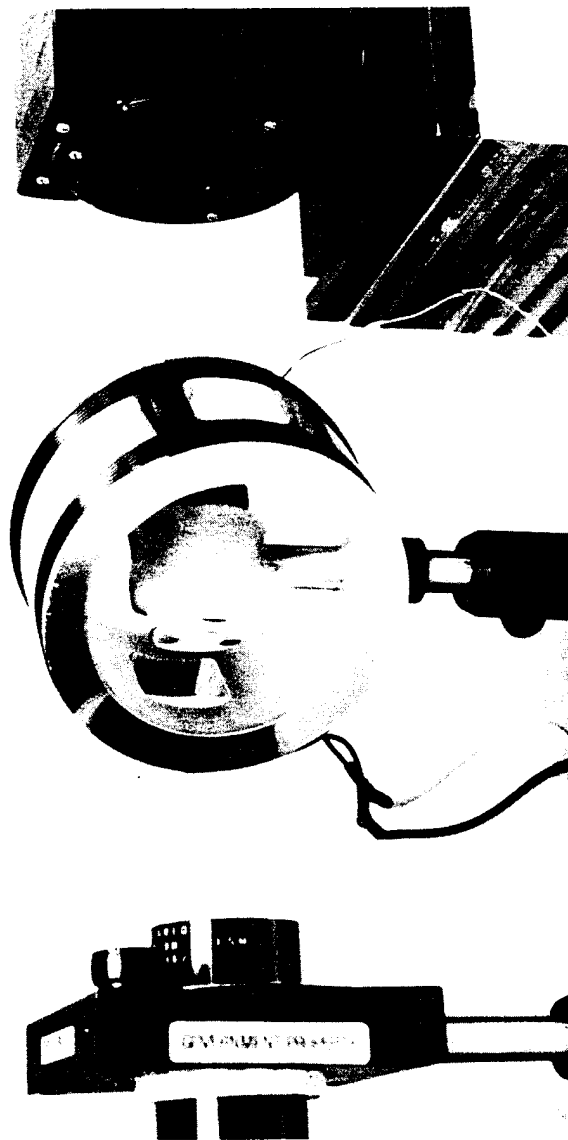


- The beam and the cell remain fixed
- The solenoid rotates to set $\theta$
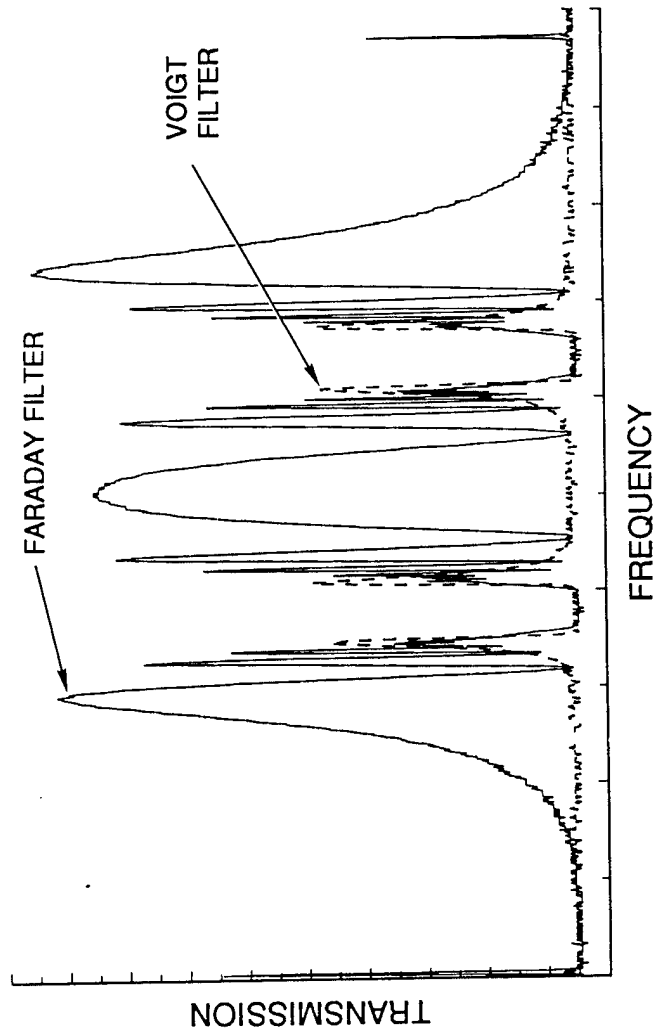- Crossed polarizers "roll" to set $\emptyset$

91-14483

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# HORIZONTAL FAN SPECTRA (VERTICALLY POLARIZED INPUT)



θ = 0°

θ = 90°

TRANSMISSION

FREQUENCY

- Rays in the horizontal fan see:
  - A Faraday filter on axis
  - Crossed polarizers for θ = 90°

- Similarly for the vertical fan

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91-14472

# TTC DIAGONAL FAN SPECTRA (VERTICALLY POLARIZED INPUT)

FARADAY FILTER

VOIGT FILTER

TRANSMISSION

FREQUENCY

- Rays in a diagonal fan see:
  - A Faraday filter on axis
  - A Voigt filter at $\theta = 90°$

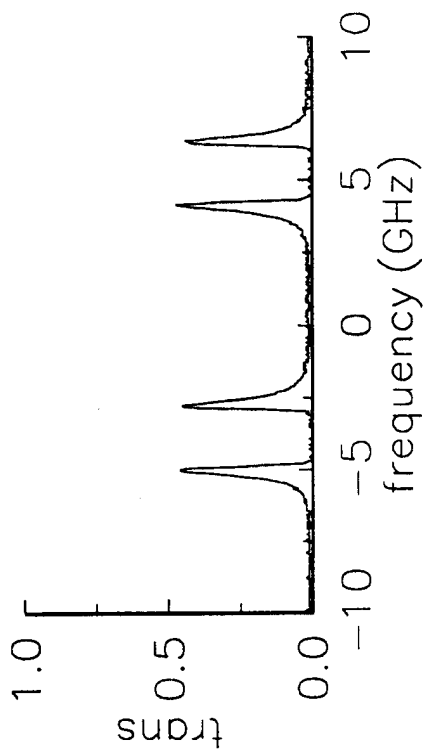- As $\theta$ increased, the transmission band shifted and narrowed

20

91-14473

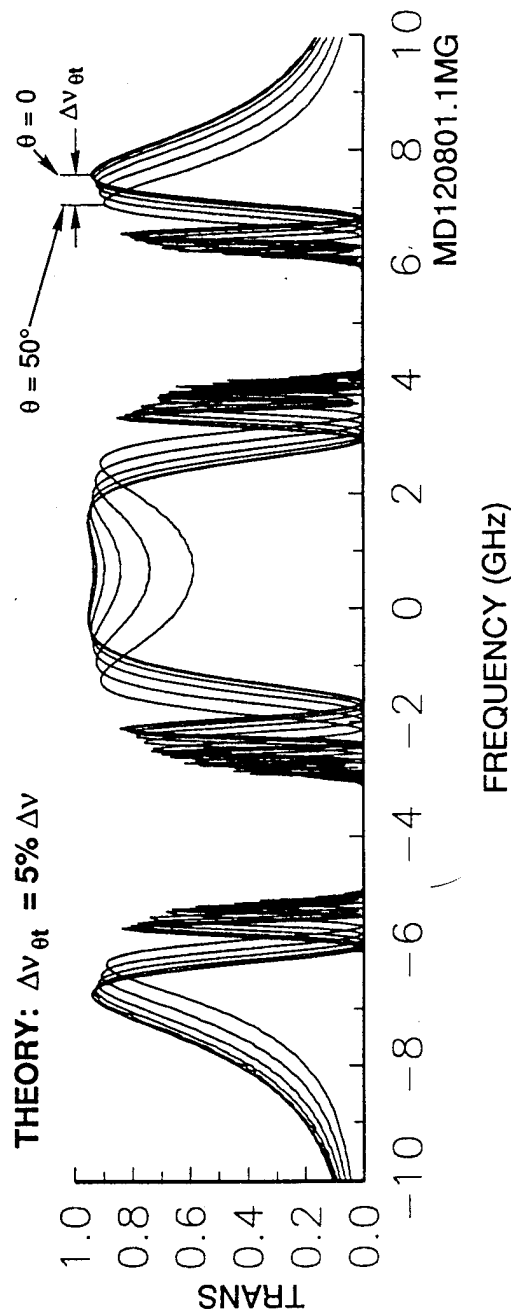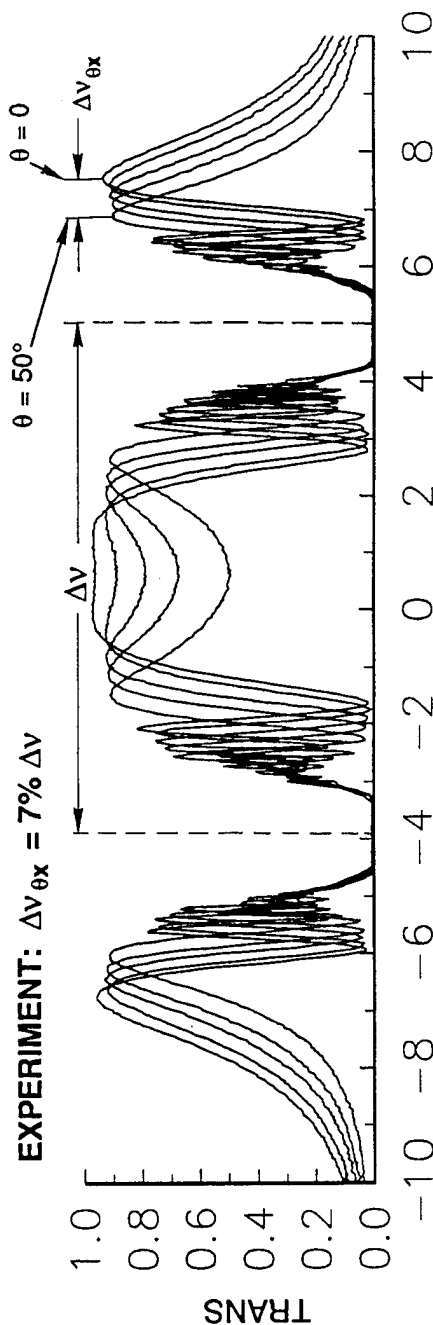# THE VOIGT FILTER CAN ALSO PROVIDE ULTRA-NARROWBAND FILTERING

**TTC**
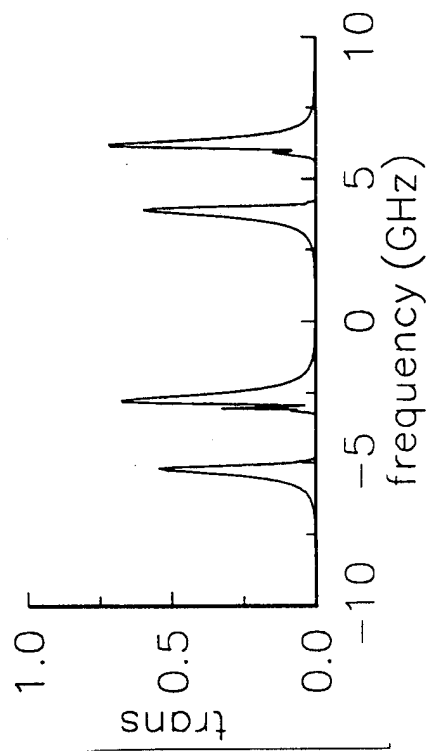
THEORY

EXPERIMENT

Cs, 852 nm, B = 100 G, T = 105° C, L = 2.54 cm

91-14689

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# TTC

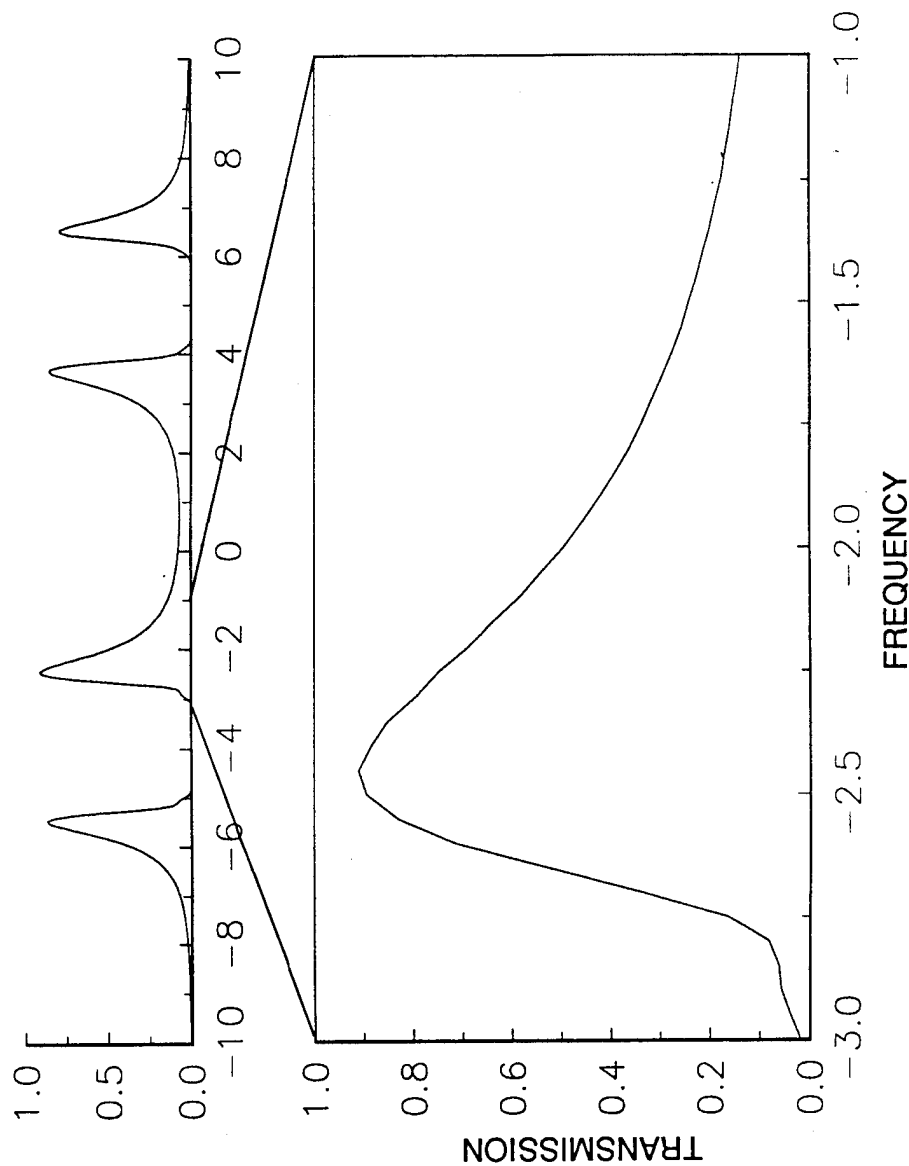## THE OBSERVED SHIFT IN PASSBAND POSITION (FIXED PATHLENGTH) IS A GIVEN BY THE THEORY



EXPERIMENT: $\Delta\nu_{\theta x} = 7\%\ \Delta\nu$

THEORY: $\Delta\nu_{\theta t} = 5\%\ \Delta\nu$

FREQUENCY (GHz)

MD120801.1MG

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91-14686

**TTC**

## WE HAVE ANALYZED THE SENSITIVITY OF A TYPICAL BLUE PASSBAND IN DETAIL

Cs @ 180° C    50 G

L = 1 cm/cos θ    φ = 0°

TRANSMISSION

FREQUENCY

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# TTC

## TRANSMISSION SPECTRA CONTOURS OVER FIELD
## ANGLE FOR A PASSBAND NEAR 455 nm

Cs @ 180° C  50 G

L = 1 cm/cos θ   φ = 0
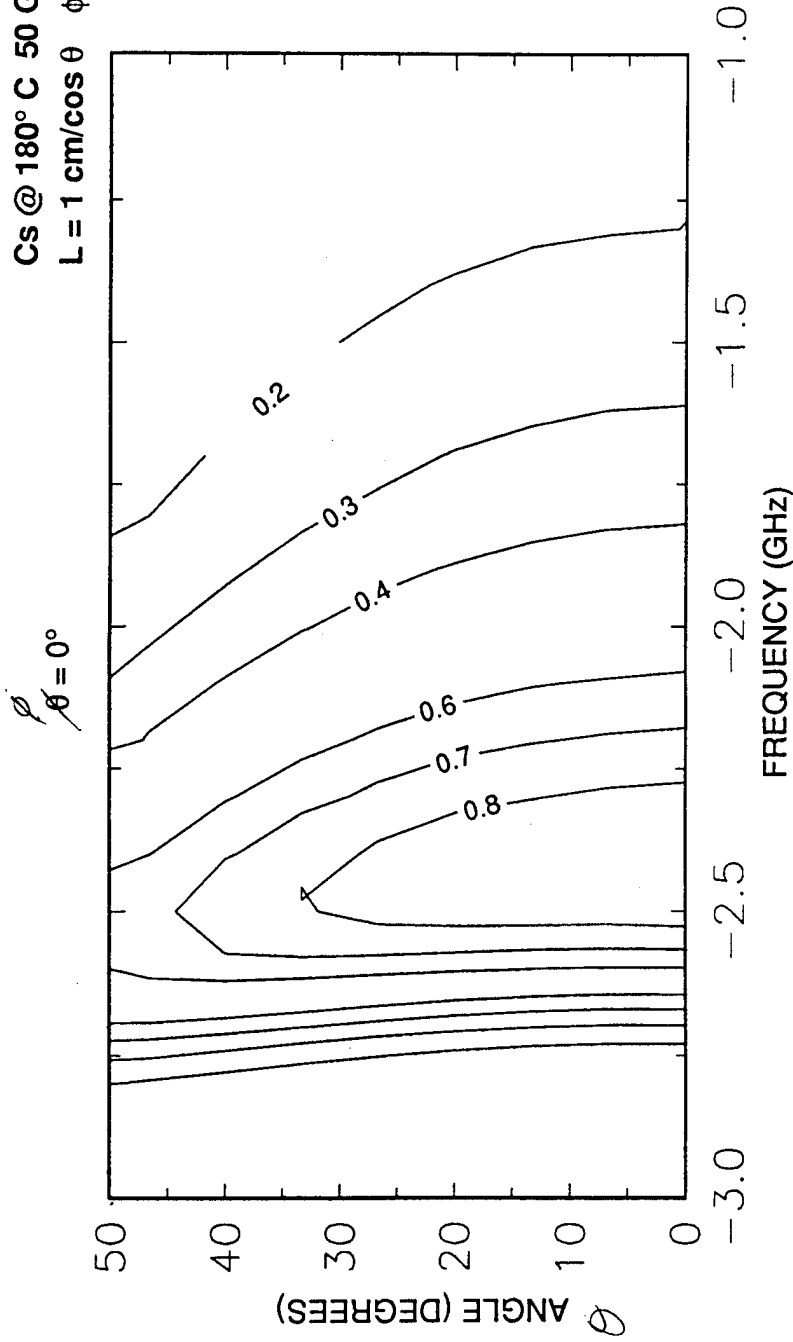


- Horizontal slices give spectra at fixed angle
  — Passband position is independent of angle
- Vertical slices give T vs. θ
  — Peak transmission decreases by 10% for θ = 35°

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91-14688

# TTC

## PERFORMANCE COMPARISON:
## FARADAY FILTER vs. PASSIVE Cs FILTER

| | Passive Cs ALF | Cs Faraday Filter | Comment |
|---|---|---|---|
| Throughput | 10%? (at best) | 40%/polarization | • ALF: 1% typical<br>• two FFs can provide 80% throughput |
| Field-of-View (full angle) | ~ 90° | 90° | • FF: assuming no polarizer limiting |
| Bandwidth | 1 GHz | 0.6 - 9.0 GHz | • ALF bandwidth is usually broadened by buffer gas |
| Noise Bandwidth | 2 passbands @ 455 nm<br>2 passbands @ 459 nm | 4 passbands @ 455 nm<br>(~ 3 GHz) | |
| Tunability | 0 | 5 GHz | • FF can provide Doppler compensation |
| Aperture | 6" - 10" | 1: - ≥ 4" | |
| Complexity | complicated optical coatings and thermal structure | simple | |

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# *TTC*

## CONCLUSIONS

- Ultra-narrowband blue faraday filter spectra have been observed
  - Spectra agree with our predictions
  - Near unity transmission
  - ~ 1 GHz passbands
  - 3 GHz integrated transmission

- We predicted and observed a new type of ultra-narrowband filter - the "Voigt filter"

  - Transverse magnet geometries may lead to higher packing densities

- A typical blue Faraday filter passband is insensitive to field angles up to 35°

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