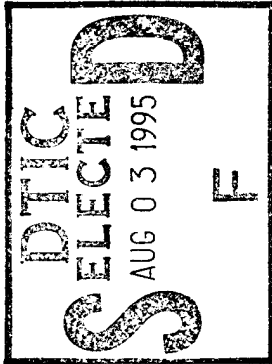




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Blue Cesium Faraday and Voigt Filters

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ULTRA-NARROW MAGNETO-OPTIC ATOMIC LINE FILTERS FOR LASER RECEIVERS

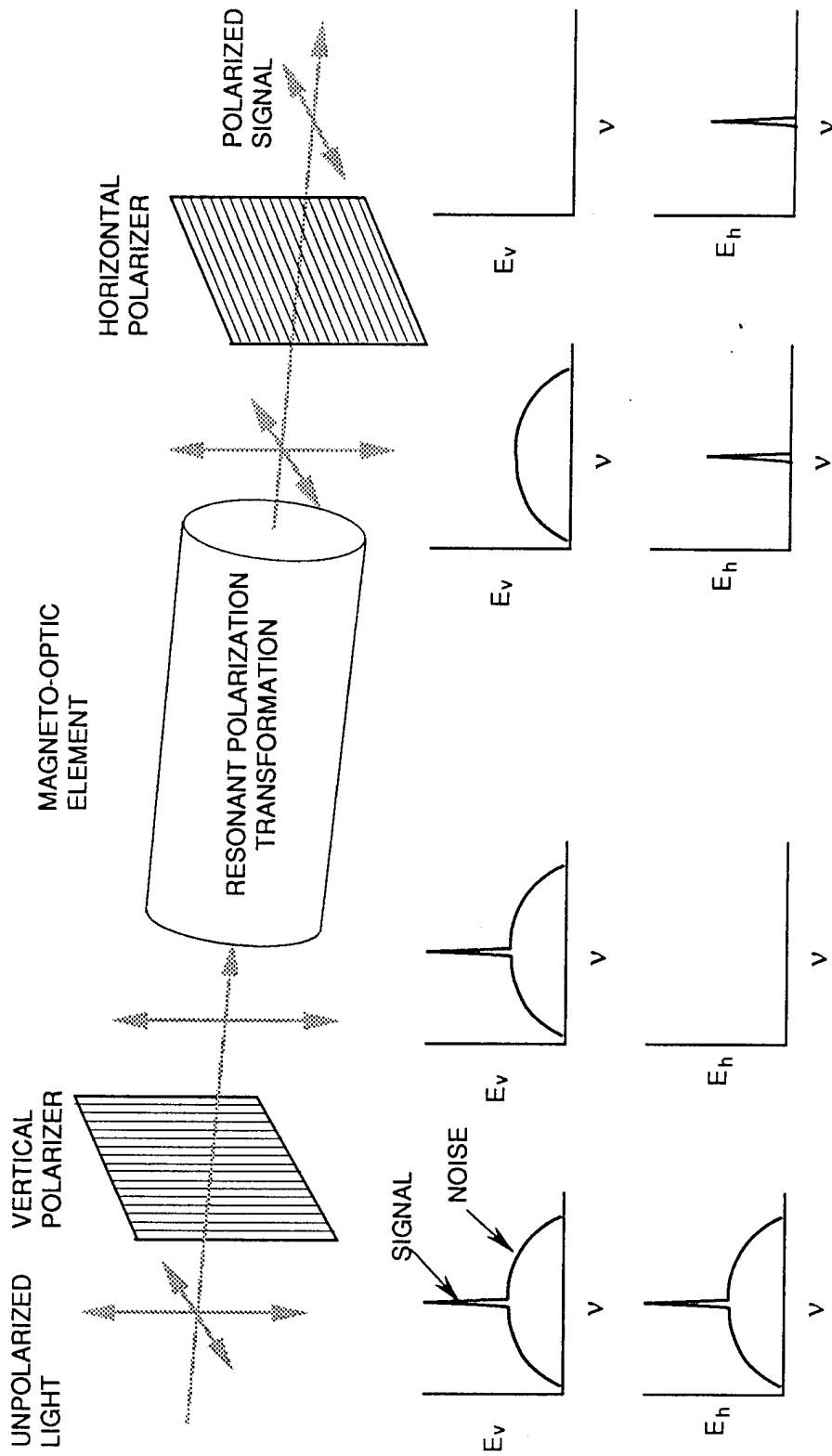
- Background limited laser receivers require ultra-narrow linewidth filters to reach quantum limited operation
 - submarine laser communication
 - free space communication
 - remote sensing
- Like the conventional absorptive/re-emissive atomic line filters (ALF), the M-0 ALFs
 - operate at discrete atomic absorption lines
 - have Doppler limited passbands
- However, M-0 ALFs are imaging filters with
 - very high peak transmission
 - wide field-of-view
 - instantaneous response

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- Principles of resonant magneto-optic filter operation
- Modelling approach to magneto-optic filters
- The Faraday and Voigt filters
- Setup for spectrum measurements
- Faraday filter spectra - measured and calculated
- Voigt filter spectra - measured and calculated
- Off axis transmission measurements and predictions at 455 nm
- The Faraday filter field-of-view



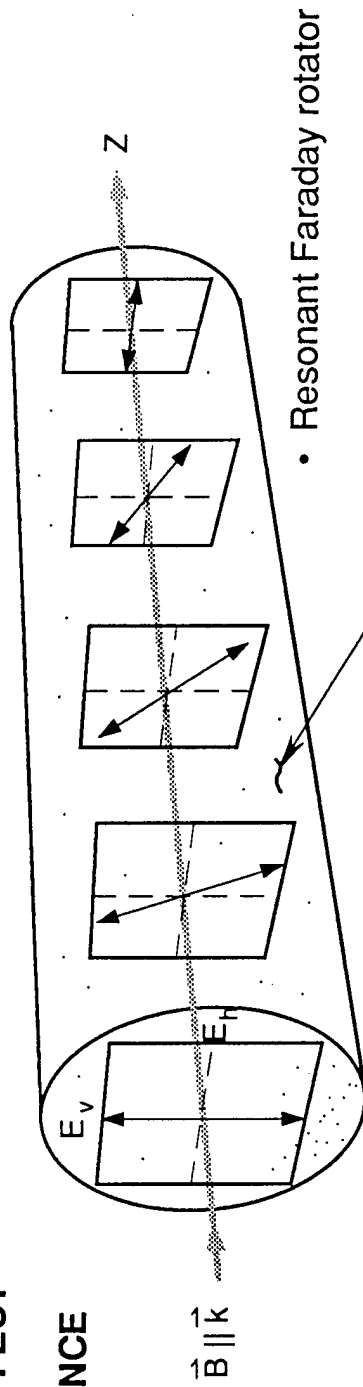
PRINCIPLES OF RESONANT MAGNETO-OPTIC FILTER OPERATION



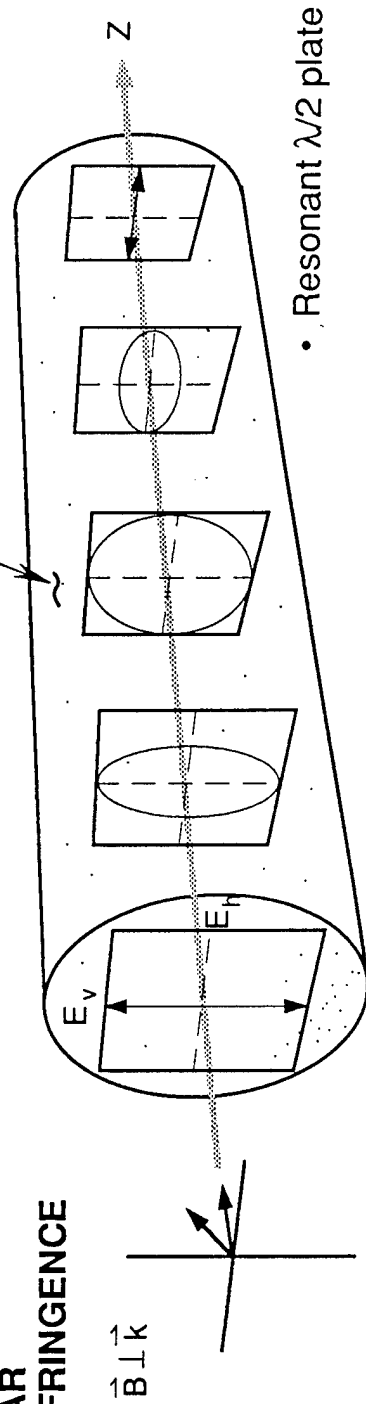
- The magneto-optic element transforms vertical into horizontal polarization over a narrow spectral band
- In-band light is transmitted; out-of-band light is blocked

**FARADAY AND VOIGT EFFECTS IN ATOMIC VAPORS
PROVIDE RESONANT MAGNETO-OPTIC ELEMENTS**

**FARADAY EFFECT -
CIRCULAR
BIREFRINGENCE**



**VOIGT EFFECT -
LINEAR
BIREFRINGENCE**



Atoms in a Magnetic Field

- Cs, $6^2S_{1/2} \rightarrow 7^2P_{3/2}$, $\lambda = 455 \text{ nm}$
- $H' = (\text{hyperfine } \vec{I} \cdot \vec{J}) + (\text{Zeeman } \sim \vec{B} \cdot \vec{J})$
- $E_{\text{FMF}}(B)$, $|FM_F\rangle$
- $P_{ij}(\sigma_+)$, $P_{ij}(\sigma_-)$, $P_{ij}(\pi)$

Vapor Optical Coefficients

- $N(T)$, $g_D(\nu)$
- $\alpha(\sigma_+)$, $\alpha(\sigma_-)$, $\alpha(\pi)$
- $\alpha(\sigma_+)$, $\alpha(\sigma_-)$, $\alpha(\pi)$

Propagation Eigen Modes

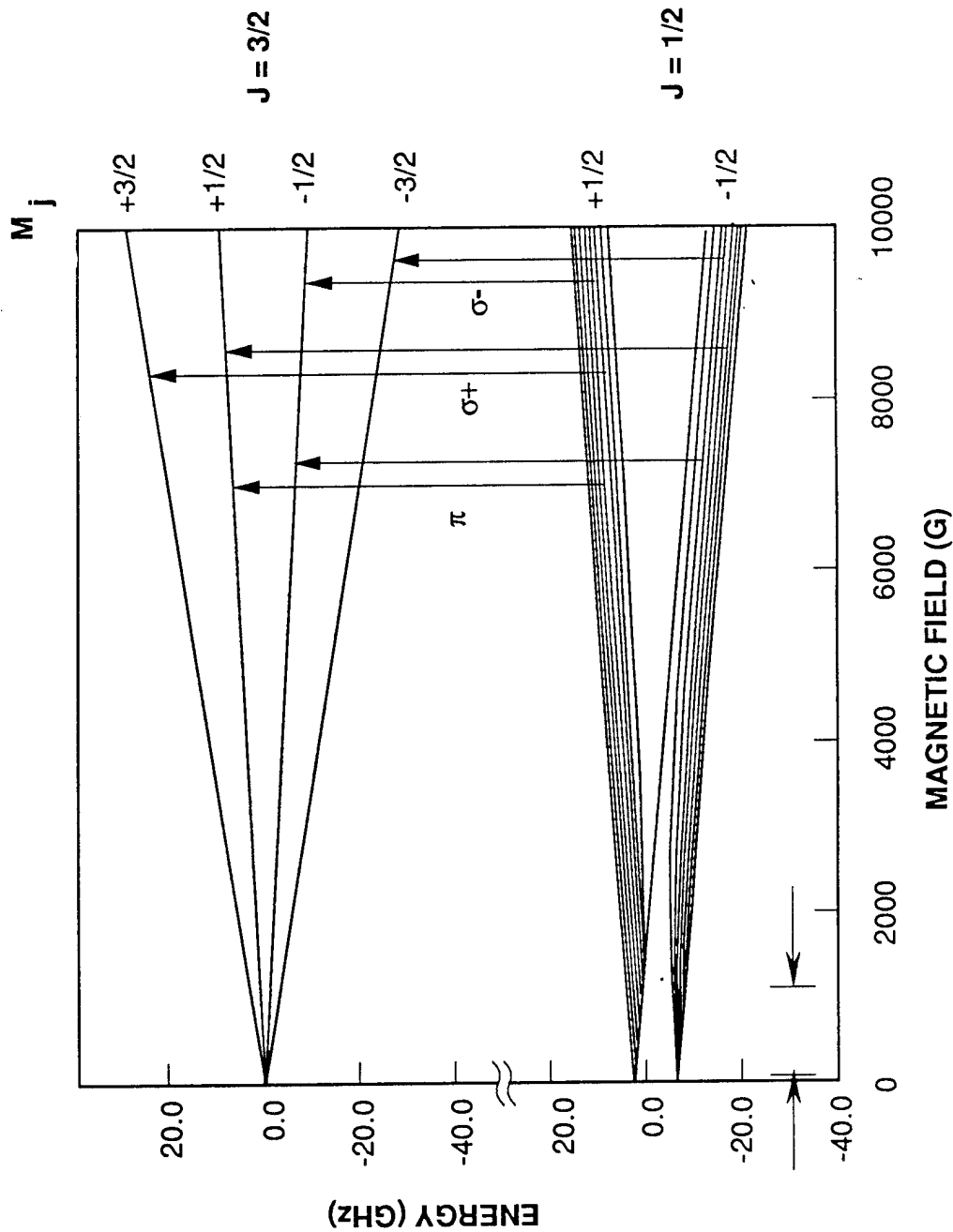
- $n_i(\vec{k})$, $\vec{\epsilon}_i(\vec{k})$

Transmission Spectrum

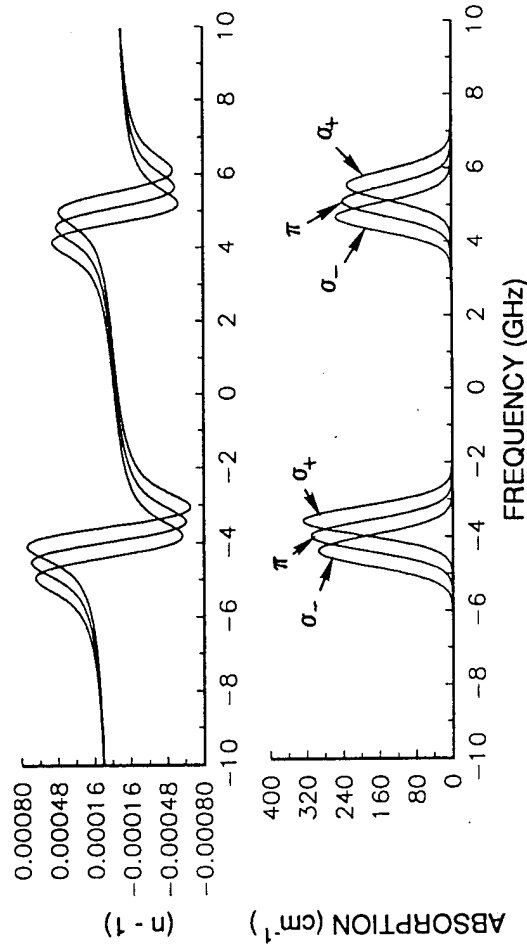
- $\vec{E}(z) \sim \hat{\epsilon}_1 E_1(o) e^{i(n_1 k_0 z)} + \hat{\epsilon}_2 E_2(o) e^{i(n_2 k_0 z)}$



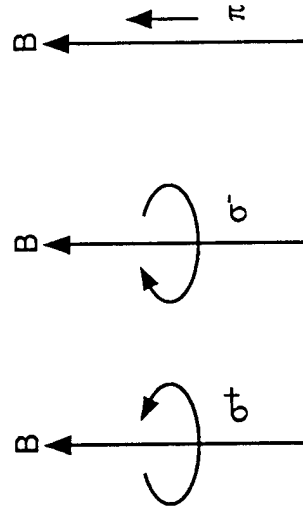
Cs $6s_{1/2} - 7p_{3/2}$ (455 nm)
HYPERFINE AND ZEEMAN SPLITTING



REFRACTIVE INDICES AND ABSORPTION



Cs, 455 nm
T = 200°C
B = 200 G
L = 1 in.



THE LEFT- AND RIGHT CIRCULAR POLARIZATION ANALYSIS IS SPECIFIC TO PROPAGATION ALONG B

- In general, other directions have varying eigen-polarizations and -indices
- A simple dielectric tensor w.r.t. the \hat{R}, \hat{L}, z basis describes the Faraday effect for a field along z

$$\epsilon = \begin{bmatrix} \epsilon_0 & -i \cdot \epsilon_B & 0 \\ +i \cdot \epsilon_B & \epsilon_0 & 0 \\ 0 & 0 & \epsilon_0 \end{bmatrix}$$

where $\epsilon_0 = n_z^2$ and $\epsilon_B = n_F^2 n_z^2$

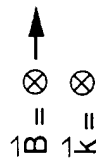
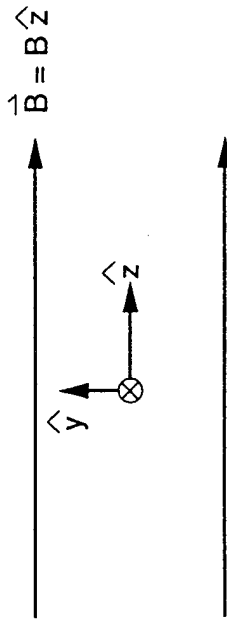
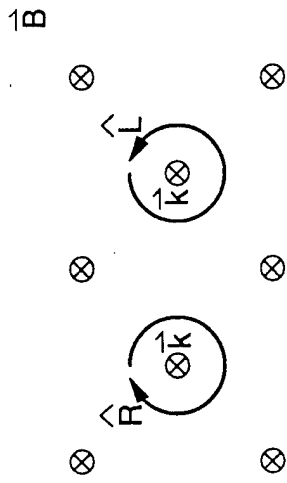
- Maxwell's equations lead to a matrix form of the wave equation

$$\left\{ \begin{array}{l} \epsilon_i \cdot \begin{bmatrix} -s_y^2 - s_z^2 & s_x \cdot s_y & s_x \cdot s_z \\ s_x \cdot s_y & -s_x^2 - s_z^2 & s_y \cdot s_z \\ s_x \cdot s_z & s_y \cdot s_z & -s_x^2 - s_y^2 \end{bmatrix} + [\epsilon] \end{array} \right\} \vec{E} = 0. \quad \vec{k} = k \hat{s}$$

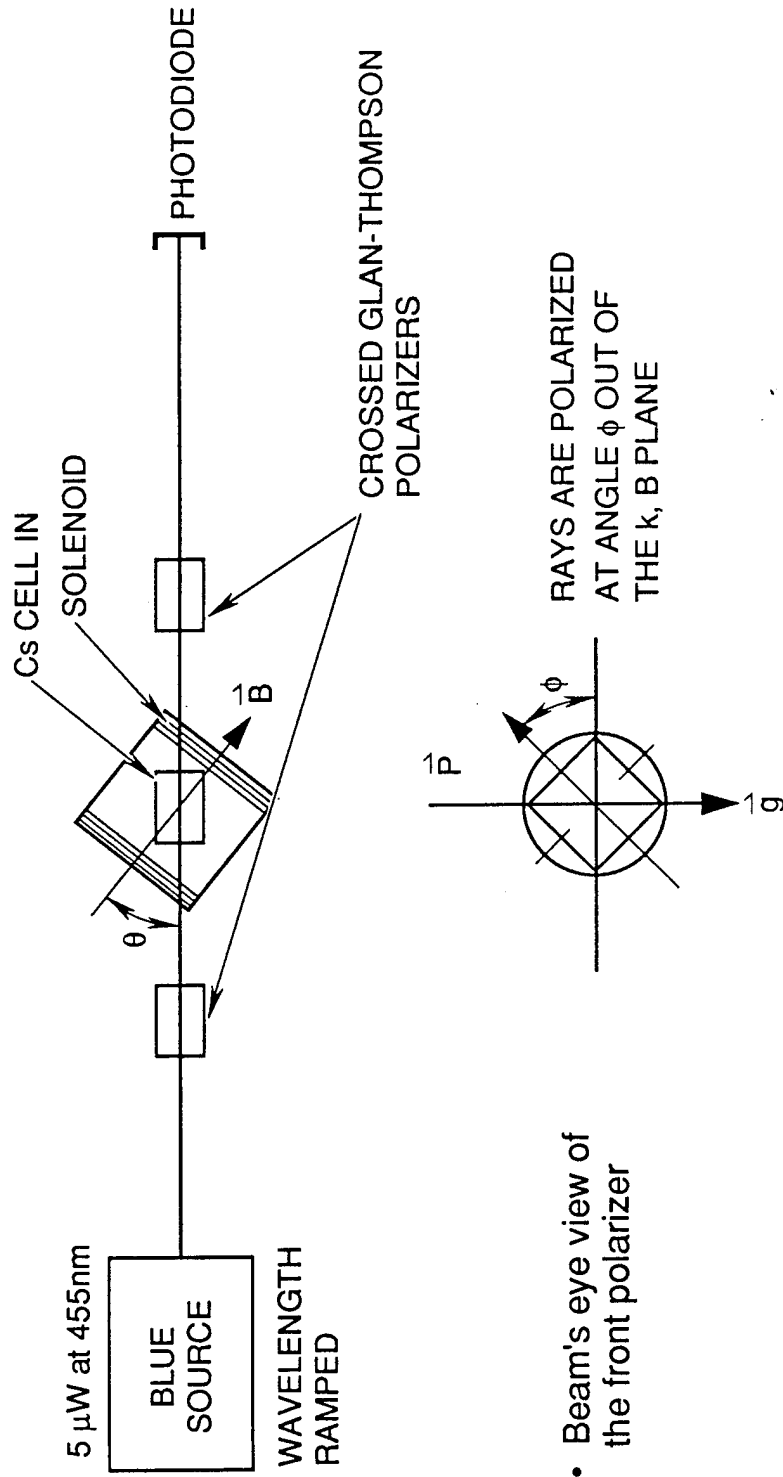
- Eigen - indices $n_i^2 = \epsilon_i$ are determined from $|\{\dots\}| = 0$.

TWO PROPAGATION DIRECTIONS YIELD SIMPLE EIGEN INDICES AND POLARIZATIONS

- Propagation along \hat{B} (Faraday Effect)
 - Circular polarizations \hat{R}, \hat{L}
 - Circular indices n_R, n_L
- Propagation perpendicular to \hat{B} (Voigt effect)
 - Linear polarizations \hat{y}, \hat{z}
 - $n_y = \frac{1}{2}(n_R + n_L)$; $n_z = n_\pi$
 - Similar to birefringence

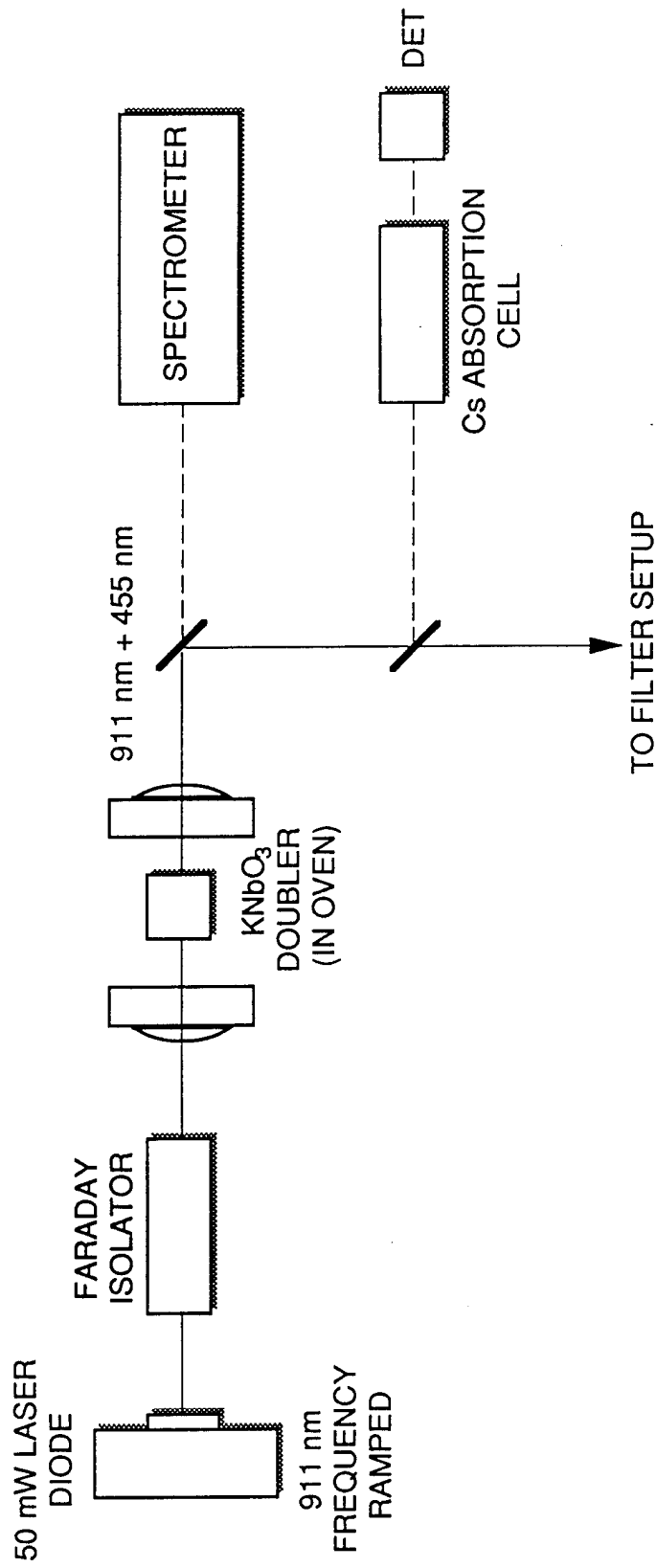


OFF-AXIS TRANSMISSION EXPERIMENTS



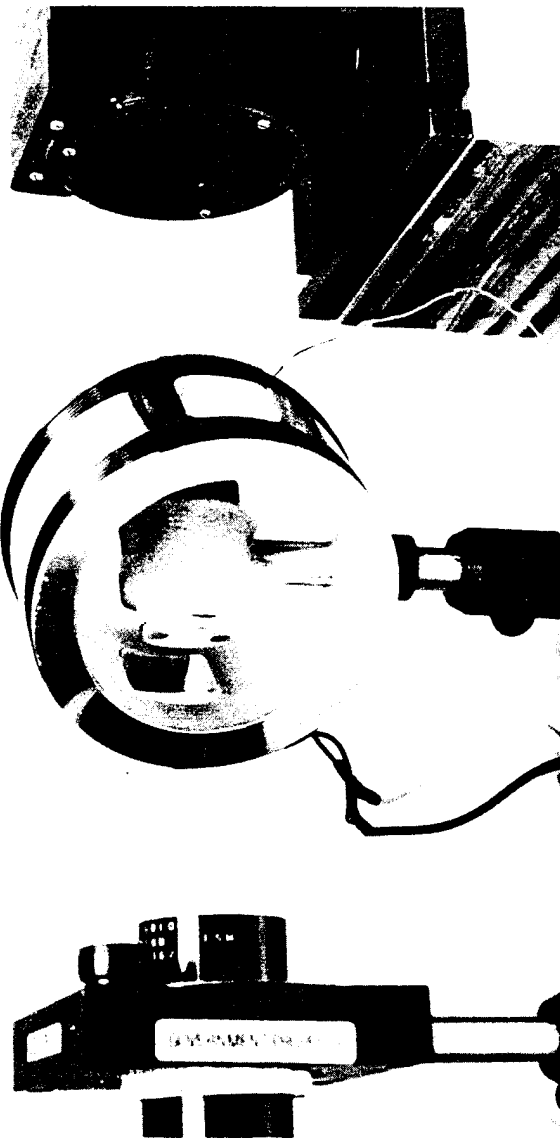
- Beam's eye view of the front polarizer
- RAYS ARE POLARIZED AT ANGLE ϕ OUT OF THE k, B PLANE
- This cell and field arrangement avoids the complication of variations in Fresnel losses
- Transmission spectra do not reflect pathlength increases with θ

BLUE SOURCE



TTC

FILTER TRANSMISSION MEASUREMENT SET-UP

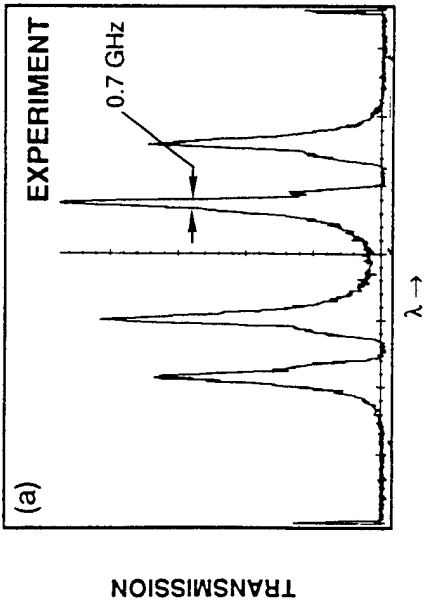


- The beam and the cell remain fixed
- The solenoid rotates to set θ
- Crossed polarizers "roll" to set \emptyset

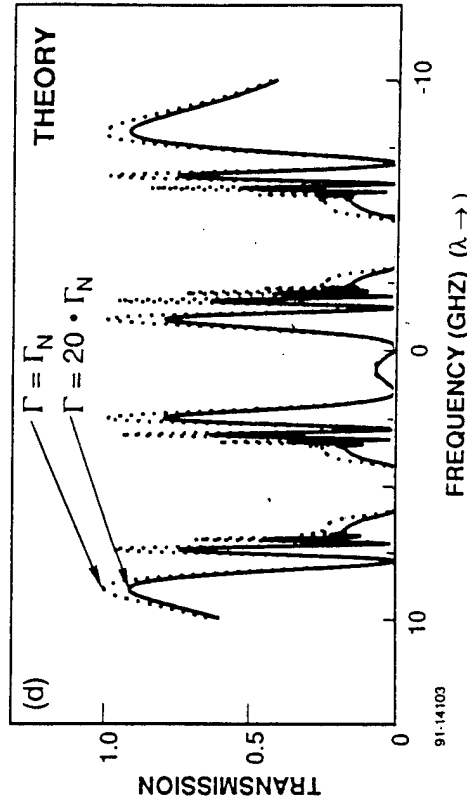
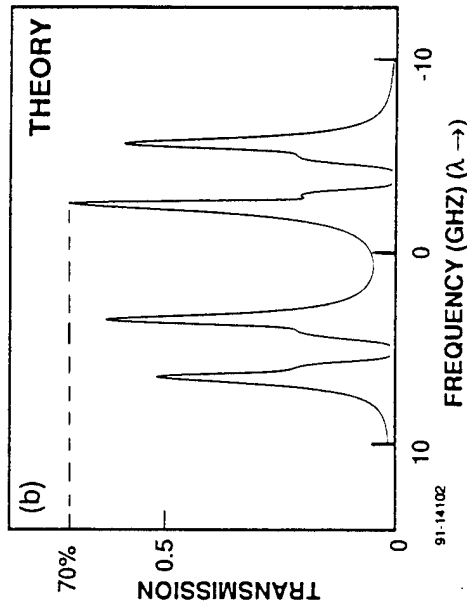
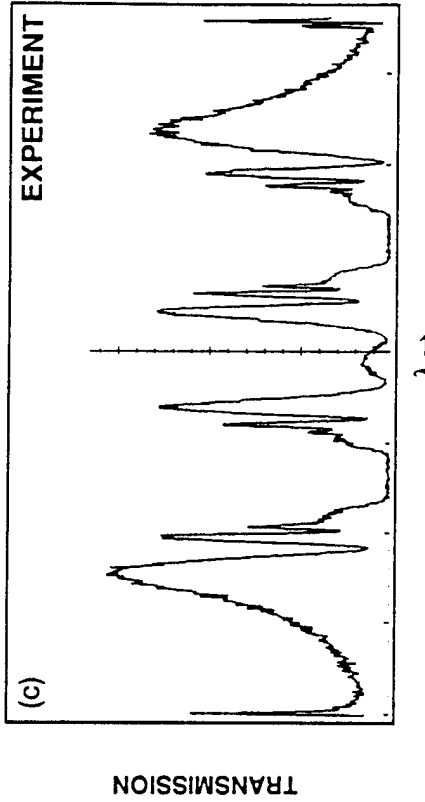


BLUE FARADAY FILTER ($\vec{k} \parallel \vec{B}$) SPECTRA ARE WELL PREDICTED

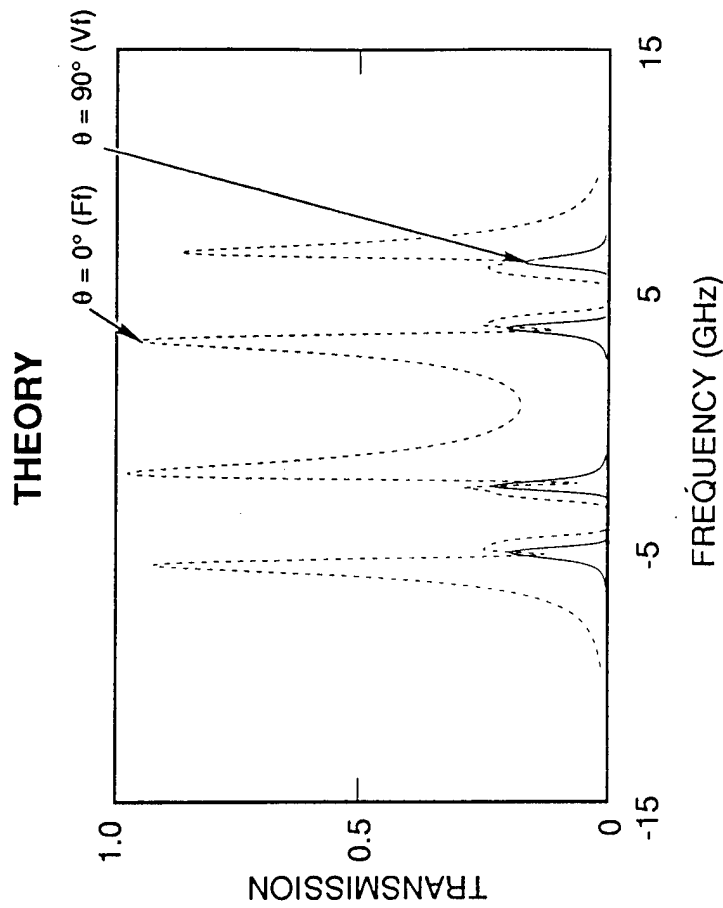
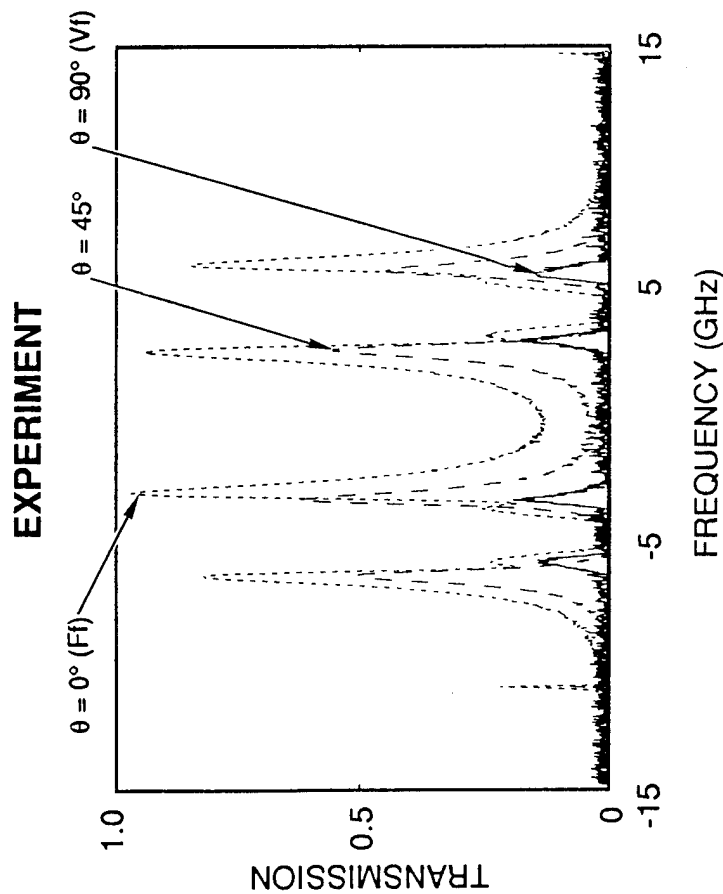
140° C, 200 G, 1 in.



200° C, 200 G, 1 in.

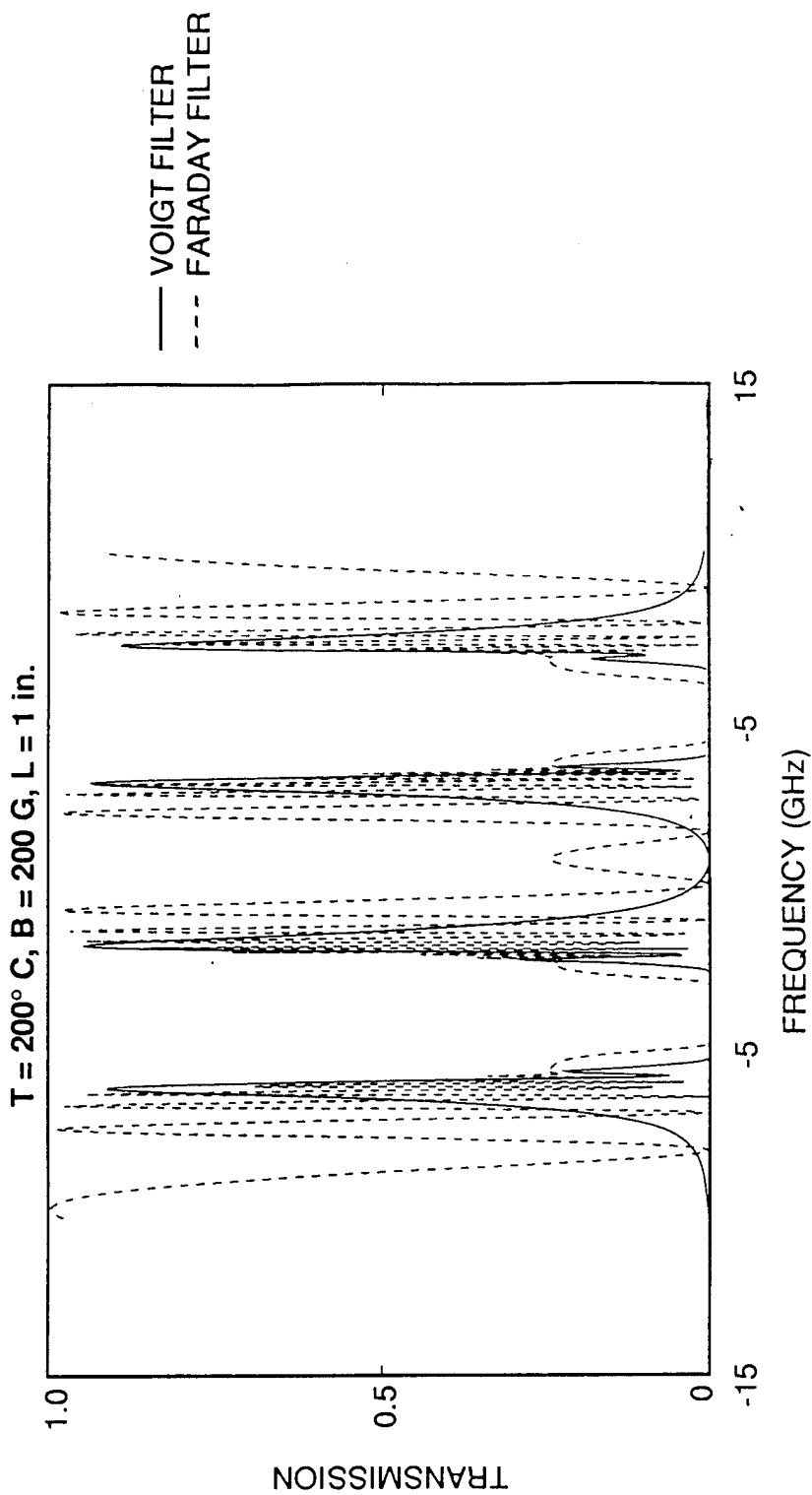


- Optimum conditions minimize bandwidth and maximize transmission
- Additional broadening becomes apparent at temperature $T \geq 200^\circ \text{C}$

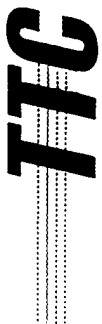
BLUE FILTER TRANSMISSION vs. θ AT $\phi = 45^\circ$ 

Cs, 455 nm with $T = 140^\circ C$, $B = 200 G$, $L = 1$ in.

OPTIMIZED VOIGT FILTER CALCULATION



- High transmission (15%) and narrow bandwidth (0.6 GHz)
- The optimum Voigt filter transmission spectrum occurs at a higher temperature than the optimum Faraday filter spectrum

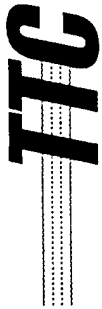


BLUE FARADAY FILTER FIELD-OF-VIEW ASSESSMENT

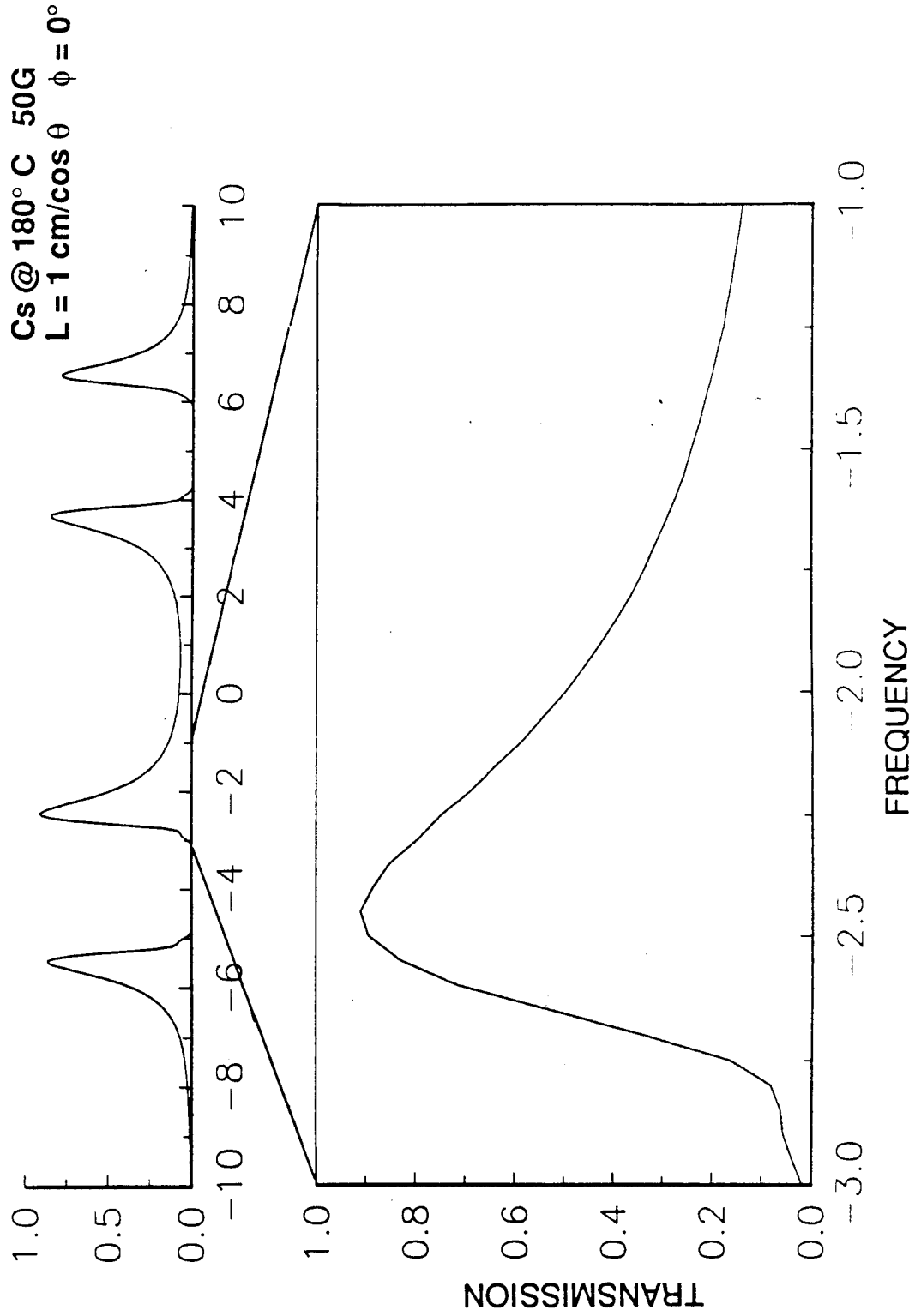
- A heuristic argument led to wide FOV expectations:

$$\text{since } Z = \frac{L}{\cos \theta} \text{ and } \Delta n_{\infty} \vec{B} \cdot \vec{k} = B k \cos \theta, \text{ we expect } z \Delta n \sim \text{const}$$

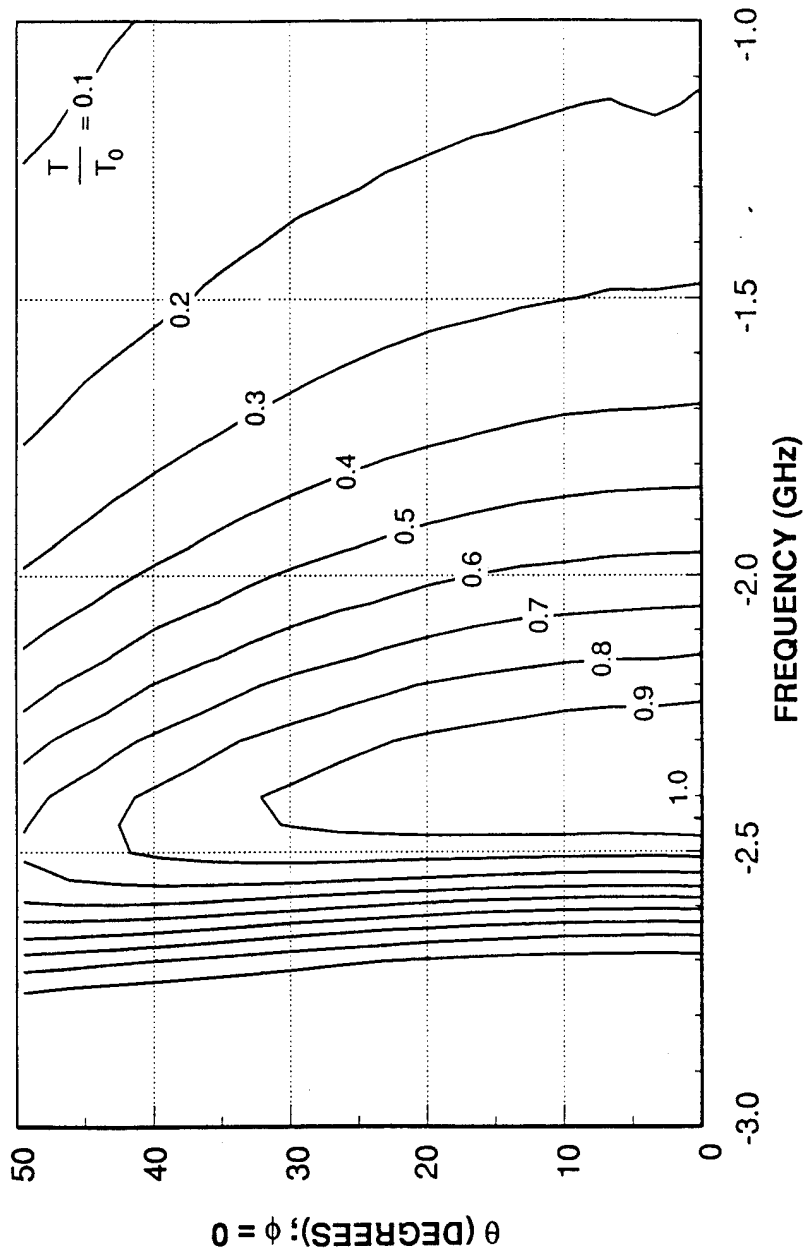
- Approach to FOV assessment
 - Anchor off-axis modelling to experiments
 - z fixed in experiments
 - Calculate FOV ($z = L/\cos \theta$)



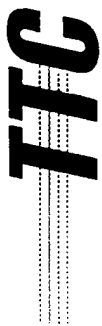
**WE HAVE ANALYZED THE SENSITIVITY OF A TYPICAL
BLUE PASSBAND IN DETAIL**



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



- Faraday filter operated at 180° C, 50 G, 1 cm
- 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 $\theta = 31^\circ$



CONCLUSIONS

- Ultra-narrowband blue Faraday and Voigt 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°