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
• 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

\[ \vec{B} \parallel \vec{k} \]

- Resonant Faraday rotator

VOIGT EFFECT – LINEAR BIREFRINGENCE

\[ \vec{B} \perp \vec{k} \]

- Resonant \( \lambda/2 \) plate
FILTER TRANSMISSION SPECTRUM CALCULATION

Atoms in a Magnetic Field
- Cs, $^6 \text{Sr} \, 5_{1/2} \rightarrow 7^2 \, ^2 \text{p}_{3/2}, \lambda = 455 \ \text{nm}$
- $H' = (\text{hyperfine } \vec{I} \cdot \vec{J}) + (\text{Zeeman } \vec{B} \cdot \vec{J})$
- $E_{\text{FM}} (B), \ | \text{FM}_F >$
- $P_{ij} (\sigma_+), \ P_{ij} (\sigma_-), \ P_{ij} (\pi)$

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

Propagation Eigen Modes
- $n_i (k), \ \varepsilon_i (k)$

Transmission Spectrum
- $\hat{E}(z) \sim \hat{\varepsilon}_1 E_1 (o) e^{i(n_i k_o z)} + \hat{\varepsilon}_2 E_2 (o) e^{i(n_2 k_o z)}$
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 $\mathbf{B}$

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

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

where $\varepsilon_0 = n_\mathbf{z}^2$ and $\varepsilon_B = n_\mathbf{z} n_\mathbf{r}$

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

$$
\begin{bmatrix}
-S_y^2 - S_z^2 & \mathbf{s}_x \cdot \mathbf{s}_y & \mathbf{s}_x \cdot \mathbf{s}_z \\
\mathbf{s}_x \cdot \mathbf{s}_y & -S_x^2 - S_z^2 & \mathbf{s}_y \cdot \mathbf{s}_z \\
\mathbf{s}_x \cdot \mathbf{s}_z & \mathbf{s}_y \cdot \mathbf{s}_z & -S_x^2 - S_y^2
\end{bmatrix}
\begin{bmatrix}
\varepsilon_i \\
\mathbf{s}_x \cdot \mathbf{s}_y \\
\mathbf{s}_x \cdot \mathbf{s}_z
\end{bmatrix}
+ [\varepsilon] \mathbf{E} = 0.
$$

$\mathbf{k} = |k| \hat{\mathbf{k}}$

- Eigen-indices $n_\mathbf{r}^2 = \varepsilon_i$ are determined from $|\{\ldots\}| = 0$. 

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
- This cell and field arrangement avoids the complication of variations in Fresnel losses
- Transmission spectra do not reflect pathlength increases with $\theta$
FILTER TRANSMISSION MEASUREMENT
SET-UP

- The beam and the cell remain fixed
- The solenoid rotates to set θ
- Crossed polarizers "roll" to set Ø
BLUE FARADAY FILTER (k || \hat{B}) SPECTRA ARE WELL PREDICTED

140° C, 200 G, 1 in.

(a) EXPERIMENT

TRANSMISSION

\lambda \rightarrow

0.7 GHz

(b) THEORY

TRANSMISSION

0 0.5 1.0

FREQUENCY (GHz) (\lambda \rightarrow)

70%

200° C, 200 G, 1 in.

(c) EXPERIMENT

TRANSMISSION

\lambda \rightarrow

(d) THEORY

TRANSMISSION

\Gamma = \Gamma_N

\Gamma = 20 \cdot \Gamma_N

\Gamma = \Gamma_N

FREQUENCY (GHz) (\lambda \rightarrow)

- Optimum conditions minimize bandwidth and maximize transmission
- Additional broadening becomes apparent at temperature T \geq 200° C
BLUE FILTER TRANSMISSION vs. $\theta$ AT $\phi = 45^\circ$

EXPERIMENT

THEORY

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

T = 200° C, B = 200 G, L = 1 in.

- 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
• A heuristic argument led to wide FOV expectations:

\[ Z = \frac{1}{\cos \theta} \quad \text{and} \quad \Delta n \propto \vec{B} \cdot \vec{k} = B k \cos \theta, \text{ we expect } z \Delta n \sim \text{const} \]

• 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 θ = 31°
CONCLUSIONS

- Ultra-narrowband blue Faraday and Voigt filter spectra have been observed
  - Spectra agree with our predictions
  - Near unity transmission
  - $\sim 1$ 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°