THE MAGNETO-OPTICAL FILTER

I: Preliminary Observations in Na D Lines

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Abstract. Transmission curves and theoretical calculations of the magneto-optical filter, designed and built by the authors, are shown together with some observed transmission spectra. At present the filter has a total halfwidth of ~ 80 mA; and the maximum transmission is 25%. From the analysis of the theoretical curves and from the observed spectra, we deduced the possibility of making up a filter with a very narrow passband (less than 30 mA) and a very high transmission (up to nearly 100% apart from losses arising from the glass cell, lenses and polarizers).

The article concludes with a selection and discussion of photographs obtained with the filter.

1. Introduction

The working principle of the filter, depending on magneto-optical effects, has already been introduced in previous, so far only theoretical, publications (Cacciani, 1967; Cacciani et al., 1968; Beckers, 1970; Cacciani et al., 1970, 1971). It consists of Na vapours in a magnetic field $H$ between two crossed polarizers. The latter cut off all of the spectrum except for those wave-lengths for which the vapours, due to magneto-optical effects, change the polarization (see Figure 1b).

The actual construction of the apparatus (see Figure 1a) has required the solution of a number of technical problems, which we will discuss elsewhere in a paper devoted exclusively to them.

In order to get the transmission profile of the filter, the relevant equations were numerically evaluated. In Figures 2a and 3a, Section 2, the results are shown for selected values of the parameter $\tau_0$, i.e. the optical depth passed through by the light beam. A Voigt profile with a Doppler width $\Delta \lambda_D = 8.5$ mA was used. The hyperfine structure of the sodium D lines was also considered. Such a structure in fact broadens each Zeeman component considerably ($\approx 16$ mA totally): so this effect has to be taken into account. In comparison, the inhomogeneity of the magnetic field (at present $\Delta H/H \approx 5\%$) has a negligible effect.

The magneto-optical filter, we discovered, has a passband $HW \approx 80$ mA; and the theoretical maximum transmission is 25%. By varying the vapour Na density and the strength of the magnetic field, it is possible to have higher transmissions – up to nearly 100% – and a slightly larger passband (see Figure 4). Moreover, better performances of the filter can be obtained by utilizing mainly the Faraday rotation instead of the Righi contribution to the transmission profile (See Section 2).
2. Theoretical Analysis

The optics of the magneto-optical filter (polarizers and vapours in a longitudinal magnetic field, see Figure 1b), can be mathematically expressed by the Jones' matricial calculus (Shurcliff, 1962). It leads to the following expression:

\[
\begin{bmatrix}
1 & 1 & 0 \\
2 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\cos \delta/2 - \sin \delta/2 \\
\sin \delta/2 & \cos \delta/2
\end{bmatrix}
\begin{bmatrix}
\exp(-\tau_{\sigma}^R) i \\
\exp(-\tau_{\sigma}^V) i
\end{bmatrix}
\left\{ \begin{array}{c}
e -\tau_{\sigma}^R i \\
1
\end{array} \quad \begin{array}{c}
e -\tau_{\sigma}^V i \\
1
\end{array} \right\},
\]

in which \{\ldots\} is the state vector representing the linearly polarized light \(L\). In order to facilitate the calculus of our particular problem we designate such a vector as the interference (addition in the Jones’ calculus) of two other vectors \( \begin{bmatrix} i & -i \end{bmatrix} \), that is lefthanded and righthanded circular polarizations. The coefficients \( \exp(-\tau_{\sigma}^{R,V}) \) take into account the absorptions in the Zeeman effect. \( \tau_{\sigma}^{R,V} \) are the optical depths for the red and violet \( \sigma \) components. The matrix \( \begin{bmatrix} \cos \delta/2 - \sin \delta/2 \\
\sin \delta/2 & \cos \delta/2
\end{bmatrix} \) is the operator describing the Macaluso-Corbino effect, i.e. the Faraday rotation in the wings of the spectral line (Born, 1965). Because of this effect, the Na vapour, in a longitudinal magnetic field acts like a circular retarder which determines the phase-delay \( \delta \) between the two vectors \( \begin{bmatrix} i \\
1
\end{bmatrix} \) and \( \begin{bmatrix} -i \\
1
\end{bmatrix} \). The matrix \( \begin{bmatrix} 10 \\
00
\end{bmatrix} \) is the operator related to the exit polarizer \( P_2 \).

Finally the coefficient \( \frac{1}{2} \) is the normalization factor for intensity of the linearly polarized light \( L \).

Following Jones’ calculus the transmitted light is obtained by making the square modulus of the expression (1)

\[
I_{TR} = \frac{1}{4} \left[ \exp(-2\tau_{\sigma}^R) + \exp(-2\tau_{\sigma}^V) - 2\exp(-\tau) \right] + \exp(-\tau) \sin^2 \delta/2,
\]

where \( \tau = \tau_{\sigma}^R + \tau_{\sigma}^V \).

In Equation (2) the transmitted light consists of two terms. The first one \( \frac{1}{4} \left[ \exp(-2\tau_{\sigma}^R) + \exp(-2\tau_{\sigma}^V) - 2\exp(-\tau) \right] \) results from the so-called Righi effect. It is related to the Zeeman effect in that the \( \sigma \) components can only absorb circular polarized light, transmitting the other circular polarized component. The exit polarizer \( P_2 \) transmits half of this residual circular polarized light. The transmission due to the Righi effect can be as much as 25% if either \( \tau_{\sigma}^R \) or \( \tau_{\sigma}^V \) are very large (see flat regions in Figures 2a, 3a and 4). If, on the other hand, both \( \tau_{\sigma}^R \) and \( \tau_{\sigma}^V \) are large at the same time, the Righi effect transmission will be small (see central depression in Figure 3a).

The second term of Equation (2) results from the so-called Macaluso-Corbino effect, with amplitude smoothed by a factor \( \exp(-\tau) \). It is related to the refractive behavior of the Zeeman effect: For the wings of very strong lines \( \delta \) can be large even where \( \tau \) is small; so that the Equation (2) can approach \( I_{TR} = 100\% \). This situation occurs in the very narrow region between the \( \sigma \) components shown in Figure 4.

The transmitted intensity \( I_{TR} \) was computed by using a Voigt profile with a Doppler width \( \Delta \lambda_D = 8.5 \) mÅ and the hyperfine structure of the Na D lines. The Voigt profile