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Citation: [Review of Scientific Instruments](#) **79**, 10E704 (2008); doi: 10.1063/1.2969421

View online: <http://dx.doi.org/10.1063/1.2969421>

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Imaging interferometers for analysis of Thomson scattered spectra^{a)}

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(Presented 13 May 2008; received 12 May 2008; accepted 22 July 2008;
published online 31 October 2008)

Polarization interferometers have some potential efficiency advantages for imaging Thomson scattering spectral analysis. In this article we present a number of designs for high-efficiency imaging polarization interferometers for Thomson scattering spectral analysis. The use of high-efficiency crystal polarizing beamsplitters (both displacement and angle) results in low-loss complementary passbands (no edge losses), simple imaging systems, and wide field of view. The efficiency and relative merits of both multiple-filter and dispersive-type configurations are being assessed before installation on the JT-60U ruby-laser Thomson scattering system. Light is transferred from the viewing port via a linear array of optical fiber bundles which will be imaged through the interferometer onto the photocathode of an intensified charge coupled device camera. Because of the broadband nature of the Thomson light, the optical delays required to Fourier analyze the spectrum are quite small. This leads to compact multicolor or dispersive systems based on combinations of Wollaston and Savart splitters and traditional waveplates. © 2008 American Institute of Physics. [DOI: 10.1063/1.2969421]

I. INTRODUCTION

An efficient multicolor detection system for measuring the scattered spectrum is a key component of pulsed laser Thomson scattering systems. Multichannel color filter spectrometers are almost exclusively used for infrared yttrium aluminum garnet laser systems,^{1,2} while both filter and grating spectrometer systems are used for ruby-laser systems.^{3–5} Recently, a folded four-color imaging spectrometer has been described for edge Thomson measurements on RFX-Mod.⁶ Most color filter spectrometers require multiple field lenses and focusing lenses and suffer reflection and transmission losses at the interference filters. It is therefore worthwhile to assess the utility of simple and compound birefringent filter spectrometers which may have some potential advantages in terms of light efficiency and compactness,⁷ especially in multichannel imaging systems.

A simple single element polarization interferometer based on a polarizer-waveplate-polarizer combination has been used as a two channel ratio spectrometer for estimating temperature on the reversed field pinch TPE-RX.⁸ The detected intensities at the output ports of the final polarizer can be regarded as antiphase measurements of the optical interferogram at an optical delay fixed by the waveplate. Alternatively, in the optical frequency domain, the interferometer can be regarded as a dual passband filter having complementary sinewave transmission functions (ignoring birefringence dispersion). This device is inefficient in the sense that half of the input radiation is lost at the first beamsplitter. Moreover,

the sinusoidal passband is not optimum while the use of only two channels restricts the useful temperature dynamic range.

In this article we propose alternative multichannel imaging and dispersive filter systems that largely overcome these drawbacks. In Sec. II, we indicate how both input polarization states can be angularly multiplexed through the optical chain to produce two pairs (or more) of complementary, independent color filters. In addition, some additional advantage can be obtained by replacing the simple delay waveplates with compound “Solc” waveplates⁹ that give rise to sharper transmission bands and temperature resolution comparable to the performance of ideal square passband filters. Assuming lossless components, in Sec. III we numerically compare the utility of simple and compound waveplate polarization interferometers with interference filter spectrometers having ideal rectangular passbands.

II. SINGLE AND MULTIPLE DELAY IMAGING FILTERS

A simple two-color birefringent filter configuration is shown in Fig. 1. Half the radiation is lost at the first polarizer. The waveplate combined with the Wollaston prism gives rise to a wavelength-dependent transmissivity which

FIG. 1. (Color online) Simple two-color polarization filter.

^{a)} Contributed paper, published as part of the Proceedings of the 17th Topical Conference on High-Temperature Plasma Diagnostics, Albuquerque, New Mexico, May 2008.

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FIG. 2. (Color online) Optical layout (elevation and plan views) for producing four independent color filters. See text for discussion.

depends on the optical delay introduced by the waveplate $\phi = 2\pi LB(\lambda)/\lambda$ where L is the plate thickness, $B(\lambda)$ is the wavelength-dependent birefringence, and λ is the wavelength. The orthogonally polarized images occupy exactly complementary (no loss) passbands with filter response $(1 \pm \cos \phi)/2$.

To improve both efficiency and spectral resolution, it is straightforward to use polarizing beamsplitters to direct both polarization states through independent waveplates to generate the four-color filter imaging system shown in Fig. 2. The primary advantage is that all of the incident light is transmitted with high efficiency using a small number of high transparency, wide field-of-view components.

An alternative approach is to use a Wollaston prism in place of the first polarizer, thereby angularly multiplexing both polarization components through the optical chain. The final Wollaston is crossed with the first to give rise to two pairs of nominally identical passbands. A field-widened Savart plate¹⁰ oriented with its optical axis in the same plane as the Wollaston splitting plane produces a netzero-delay, approximately linear phase shear. Tilting the plate as shown in Fig. 3 gives rise to an asymmetry in the amplitude of the phase shift for the upper and lower beams. For appropriate fixed waveplate delay and shear plate parameters, the split at the final Wollaston gives rise to two pairs of independent, complementary passbands that can be arranged to span the Thomson spectrum. The optical system is shown in Fig. 3. Though the Savart plate is in the collimated portion of the

FIG. 3. (Color online) Optical layout for producing four angularly multiplexed, independent color images. The tilted Savart plate introduces an asymmetric phase shift that relatively shifts the upper and lower color bands.

FIG. 4. (Color online) (a) Arrangement of waveplates required to produce an approximately rectangular passband Solc filter. (b) Angular dependence of transmitted passband for a LiTaO₃ Solc filter having a unit thickness of 0.43 mm. The three curves are for 0° and $\pm 5^\circ$ angles of incidence. The field of view of birefringent polarization interferometers can be expanded using field-widening techniques.

input beam, the spread of ray angles about the first Wollaston split angles will introduce a small angle-dependent distortion in the transmitted passband. This can be corrected via a suitable calibration procedure.

Variants of this system using one or more additional Wollaston prisms can be used to generate eight or more independent color birefringent filters.

A. Solc waveplates

A Solc filter⁹ is a multiwaveplate polarization interferometer whose passband can be tailored according to the number of plates and their respective thicknesses and orientations. It is possible to produce an approximate flattop response using three waveplates whose thicknesses are in the ratio $(d, 2d, 2d)$ and whose orientations relative to the polarizer are $(45^\circ, -15^\circ, 10^\circ)$.¹¹ The Solc filter waveplate arrangement is shown in Fig. 4(a). The composite component can be used in place of the waveplates shown in Figs. 1 and 3. For high temperature plasmas, typical quartz waveplate thicknesses of order $d=0.5$ mm give rise to a composite optic with high transparency and wide acceptance angles. A typical response is shown in Fig. 4(b).

III. COMPARATIVE PERFORMANCE

Model Thomson spectra for electron temperatures in the range of 2–30 keV as well as the overall JT-60U ruby-laser scattering system spectral response are shown in Fig. 5(a). The corresponding interferograms, representing the power transmitted through a simple polarization interferometer as a function of the thickness of a magnesium fluoride waveplate,

FIG. 5. (Color online) (a) The Thomson spectra for temperatures between 2 and 30 keV. The solid curve represents the overall system spectral response (including the camera intensifier). (b) The calculated interferograms of the received spectra vs the thickness of a magnesium fluoride waveplate for temperatures in the range of 2–30 keV.

FIG. 6. (Color online) Passbands and collected number of photons for simple MgF₂-based waveplate, Solc filter, and idealized rectangular bandpass filter for nett waveplate thickness $d=55$ micrometers (1.3 waves delay at 500 nm) (left) and $d=95$ micrometers (right).

are shown in Fig. 5(b). It can be seen that waveplates introducing a delay between one and two waves will be sensitive to temperature changes.

Optimal filter design is a trade-off between the number of channels and spectrometer optical efficiency. Following the procedure described by Naito *et al.*,¹² we can assess the relative temperature sensitivity of simple, Solc, and square passband filters. For the purposes of the comparison, we assume the following parameters relevant for the JT-60U system: laser energy of 8 J, collection solid angle of 0.005 sr, spatial resolution of 0.02 m, filter efficiency of 50% (two polarizations), system spectral response as in Fig. 5(a), collection efficiency of 20%, electron density of $1 \times 10^{19} \text{ m}^{-3}$. For simplicity, the plasma light component is ignored. Figure 6 shows the passbands for simple, Solc, and square passband filters and the calculated number of detected photons versus temperature. The waveplate thicknesses $d=55 \mu\text{m}$ and $d=95 \mu\text{m}$ have been selected so as to maximize sensitivity to temperature changes in the range of 1–20 keV. Very wide bandwidths are necessary for estimating high temperatures. Using the analysis of Naito *et al.*, we have calculated the expected electron temperature resolution versus electron temperature for all three passband types (see Fig. 7). The performance of the Solc waveplates compares favorably

with the ideal rectangular passbands, and as expected, is substantially better than that of simple waveplates. For properly optimized passbands, this suggests that high-efficiency birefringent filters could be an attractive alternative to the use of multiple, noncomplementary interference filters.

ACKNOWLEDGMENTS

This work is supported in part by the Grant-in-Aid for Scientific Research in Priority Area “Advanced diagnostics for burning plasma” from the Japanese Ministry of Education, Culture, Sports, Science and Technology (No. 18035016).

FIG. 7. (Color online) Comparison of the temperature-dependent T_e resolution for simple (red curve) and Solc (green curve) waveplates and ideal square passband filters (blue curve).

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