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Solar and Stellar Polarimetry with Liquid Crystal Retarders

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Abstract. We present some preliminary result of a study for the application of Liquid Crystals Variable Retarder (LCVR) plates in achromatic imaging Stokes polarimeters. The use of LCVR plates allows to replace mechanically rotating retarders of a polarimeter with electrically controlled devices, without having moving parts. Broad band instruments in the visible spectrum are required when observing photon flux limited astronomical sources. These observations are favoured by using polarimeters achromatic over a consistent portion of the visible band. We propose to develope an achromatic polarimeter based on electro-optically modulating liquid crystals for ground and space-based instrumentation.

Key words. Polarimetry – Solar Corona

1. Introduction

Scattering polarization in the visible wavelenght band is a physical process common to many astrophysical situations, as in the case of Thomson scattering by free electrons, Rayleigh and Raman scattering by atoms and molecules. Thomson scattering of the solar photospheric continuum off coronal electrons of the extended corona is responsible for the emission of polarized visible light, with no wavelength dependence, indicated as *K-corona.* Polarization measurements of the K-corona yeld the coronal electron density, one of the fundamental physical parameters of the solar corona. For pre-main sequence stars important structures source of polarized scattered radiation are the circumstellar clouds, accretion discs, and protoplanetary dust discs. Early-type main sequence and evolved stars often show mass loss, disc structures and non-radial pulsations, while interacting binary systems are the site of irradiation and reflection effects, all of them expected to present measurable scattering polarization. Moreover, we expect that the presence of an extrasolar planet around a solar type star, could be revealed by detecting a polarized signal of Rayleigh scattered radiation, modulated with the orbital period.

Diagnostic techniques requiring high-precision polarimetry (with a precision of about 10^{-5}) are limited by low photon flux when working with spectral resolutions of the order of $R = \lambda/\Delta\lambda \approx 100000$. Broad band observations in the visible spectrum are greatly favoured by using polarimeters achromatic over a consistent portion of

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the visible light band, with a spectral resolution of about $R = \lambda/\Delta\lambda \approx 10$. In the visible, polarization analysis of images is traditionally carried out by modulating the signal via mechanical rotation of polarizing optical elements (e.g., waveplates, linear polarizers). The disadvantage for ground-based application is the slow operation of mechanical modulation relative, for instance to photometric variation due to atmospheric seeing. The disadvantage of this approach for space application is the use of mechanisms and, as a consequence, large weight, size and power consumption. Therefore, the challenge for broadband visible-light polarization from ground and space is the development of achromatic optics that do not require moving mechanisms, and achieve miniaturization through drastic reduction of size, weight, and power consumption. We propose to meet this challenge by developing a achromatic polarimeter based on electro-optically modulating liquid crystals for ground and space-based instrumentation.
Achromatic retarders based on electro-optically driven liquid crystals would allow high frequency polarization modulation (< 100 Hz). This would increase the polarimetric sensitivity of ground-based astronomical telescopes. The broader wavelength band would increase the signal. The high frequency polarization modulation would reduce the noise introduced by the atmospheric seeing in the accurate photometry required for high sensitivity polarimetry. Ground-based coronagraph (Elmore et al., 2002), and remote sensing instrumentation from space (Fleck, Domingo, and Poland, 1995) for the observation of the faint, visible-light solar corona would also benefit from high-cadence broadband polarization imaging in the visible (i.e., $400 - 600$ nm). Electro-optically driven liquid crystals require low-voltage, and have no moving parts. This would reduce size, weight, and power consumption in space payloads.

2. Polarimeter based on Achromatic Liquid Crystals

Fixed-retardance achromatic waveplates are assembled from at least two layers of different birifrangent materials with their retardance fast-axes oriented at an angle from each other (Pancharatnam, 1955). The birifrangent materials classically used for assembling these achromatic retarders are crystalline plates, such as quartz-Mg2F. Multiple layers of nematic liquid crystals have been used as birifrangent materials in alternative to crystalline plates to assemble achromatic waveplates with fixed retardance (Kohns, et al.,1996).
Our purpose is to develop an achromatic waveplate assembled from birifrangent liquid crystal layers and whose retardance can be varied electro-optically by appliying a varying bias voltage. This achromatic liquid crystal variable retarder (ALCVR) will be the key element of a broadband ($400 - 600$ nm) imaging polarimeter for ground and space based astronomical telescopes, such as that for the HERSCHEL/UVCI space-borne coronagrap (He Resonant Scattering in Corona and Heliosphere / Uv and Visible-light Coronagraphic Imager; Gardiol et al. 2003), that will be developed in the Optics Laboratory of the Astronomical Observatory of Torino.
The instrument concept is based on the following optical design: two ALCVR are aligned in series along the polarimeter optical axis. The fast axis of one retarder is oriented at 45° to the slow axis of the second. They are followed by a linear polarizer acting as the analyzer. This system is very compact and it can be integrated directly in front of a CCD camera, resulting in a very light-weight, miniaturized, broadband Stokes-polarimeter. The fast demodulation of the polarization signal will accomplished with a scheme based on differential imaging using CCD detectors with on-chip charge storage (Stokman, 1982).

3. Preliminary Laboratory Tests

The project description and laboratory activity for the development of an imaging Stokes polarimeter based on LCVR, including the LCVR retardance vs. wavelength characterization and the Mueller matrix determination of the polarimeter, have been presented by Zangrilli et al. (2003).

As a preliminary analysis, we tested a LCVR plate assembled in a rotator configuration, and measured, as a function of the wavelength, the differential rotation of the polarization plane of an input radiation. The purpose was to estimate the extension of the achromaticity interval, i.e. the region about the LCVR operation wavelength (~ 530 nm) where its retardance can be assumed as constant.

A LCVR rotator continuously rotates a monochromatic, linearly polarized input radiation. The assembly design consists of a LCVR combined with a quarter-wave retarder, with the fast axis of one retarder oriented at 45° to the slow axis of the second. A linear polarizer is put in front of the LCVR plate, with its transmission axis parallel to the slow axis of the quarter-wave retarder, in order to have a linearly polarized input. The quarter-wave plate converts elliptical polarization (formed by the LCVR) to linear polarization. Polarization rotation is achieved by electrically controlling the LCVR retardance. The rotation angle is equal to one-half the retardance change from the LCVR. A linear polarizer acts as analyzer of the outcoming radiation from the rotator.

In principle, removing the linear polarizer put in front of the above described assembly, this rotator configuration can be used as a polarimeter to measure the Q and U components of the Stokes vector, for example that of the K-corona radiation. The polarization plane orientation of the incoming radiation is electrically controlled and the analyzer transmission axis is kept fixed. An optical bandpass filter, centered on the wavelength of operation of the LCVR, is put in front of the rotator, in order to restrict the observations in a proper wavelength interval where the LCVR can be assumed achromatic.

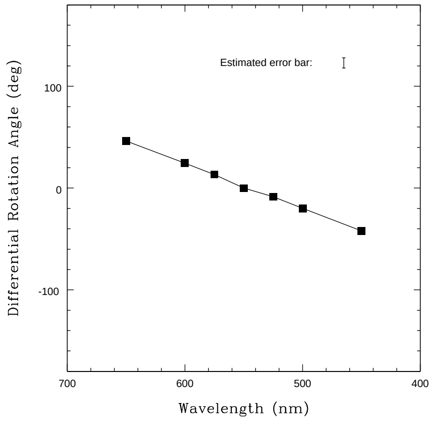

Fig. 1. Differential rotation angle as a function the input radiation wavelegth, from a LCVR rotator.

For fixed wavelength and voltage, we measured the radiation intensity at different angles of the analizer transmission axis, and found the maxima of the modulation curve. The variation of the rotation angle as a function of the wavelength has been determined by assuming as a reference the rotation for a 550 nm beam of radiation. The resulting profile is shown in Fig. 1. The estimated error of the measured differential rotation angles is about $\pm 5°$. From Fig.1 we see that the rotation linearly varies of $\pm 45°$ over the wavelength range of the measures ($450 - 650$ nm). Moreover, we have the indication that polarization measurements with the precision of about 1 % (corresponding to a 1° uncertainty on the rotation), would require a passing band of about 20 Å, reducing, in the case of K-corona observations, the photon flux of two order of magnitude.

4. Conclusions

Our first laboratory analysis indicates that a single LCVR plate cannot be used as the component of a broad band achromatic polarimeter over the $450 - 600$ nm band. In the case of K-corona measurements, the restriction to a wavelength interval where the rotation from the LCVR rotator assembly is measured with an uncertainty of about 1°, would imply the loss of about two order of magnitude of the incoming radiation intensity. Future laboratory tests will be dedicated to the study of the achromaticity properties of LCVR plates combinations, in order to enlarge the operating band width of a LCVR based polarimeter.

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