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A near infrared polarimeter for astrophysical studies

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Abstract. A state-of-the-art near infrared photo polarimeter was designed and developed at Physical Research Laboratory, Ahmedabad, India to undertake the study of star forming regions, symbiotic stars and, AGB stars etc. The instrument is fully computer controlled and provides on line results. The instrument operates in the wavelength region 1 - 2.5 μm for polarization measurements. Recently, the instrument was tested on the 1.2m telescope at Mt.Abu, India. Observations were taken in *J,H,K* bands on some standard stars and some program stars. Zero polarization and some standard polarization stars were observed. The performance of the instrument has been tested for 100% polarization and the results are found to be quite satisfactory.

1. Introduction

Astronomical polarimetry at visible wavelengths began as a new field about four decades ago with Hall's and Hiltener's discovery of the interstellar polarization (Hall 1949; Hiltener 1949) and has contributed to our understanding of the astronomical phenomena through many discoveries. High precision polarimetric measurements in the optical and UV regions are possible at the present time because of the high sensitivity of PMTs. The precision is limited due to the photon statistical noise. A good account of the development of optical polarimeters is given by Serkowski (1974). At Physical Research Laboratory a precision optical polarimeter was built and is operational since 1984 (Deshpande et al. 1985). Encouraged by the success of the optical polarimeter, we undertook the program to develop an IR photopolarimeter in the wavelength region from 1 to 2.5 μm in the first stage which will be augumented to the upper limit of 5 μm in the future. The optical layout of our IR polarimeter is similar to that of the Hatfield polarimeter (Bailey and Hough 1982) used at the Anglo-Australian Observatory. The present paper describes an instrument fabricated after modifications on the existing design and gives some results of the field tests.

The growth of the polarimetry in the infrared spectral region has been rather slow internationally, due to :

i) the low sensitivity of the IR detectors relative to the PMTs. Measuring a 1% polarization in stellar objects of interests is equivalent to measuring the flux of an object which is 5 magnitude fainter than the program star, and

ii) the problem of non availability of suitable optical components needed in IR bands. High quality super achromatic λ/2 and λ/4 wave plates, polaroid sheets, dichroic prism etc. for IR wavelength are becoming available only recently.

The sensitivity of IR polarimeters has increased dramatically during the last twenty years (Kobayashi et al. 1980; Jones and Klebe 1988; Dyck and Jones 1978; Bailey and Hough 1982; Kemp et al. 1978; McLean et al. 1986). An improvement by an order of magnitude has been achieved at 5 μm through the modification of the telescope by minimizing thermal background received by the detectors. Even more progress has been made in the 1-5 μm region through the application of InSb photo voltaic detectors. Recently, the 1.2m IR telescope of Physical Research Laboratory has become operational. The telescope has a vibrating secondary mirror facility which is expected to further improve the performance in IR polarimetry.

The scientific objectives are to make polarization studies of astronomical objects in the infrared window lying within 1-5 μm. A wide range of astronomical problems can be studied through IR polarimetry. Of particular interest for polarimetry in the 1 - 5 μm region are Bok globules, T Tauri stars, late type stars, symbiotic stars, AGB stars, cataclysmic variables etc. Study of dust shells around protostars, grain's characteristics and magnetic field geometry in Bok globules, and star formation regions are possible with near IR photometry. Star formation studies in Bok globules, young clusters and the study of bright galaxies are our main objectives. Most of the observations are planned on PRL's 1.2 m telescope at Gurushikhar, Mt. Abu and we expect to get a host of new exciting results.

The aim in studying the Bok globules is to understand the role of dust grains and magnetic field in the formation of the stars in globules. Dark globules contain dust grains which generally are non-spherical and may be aligned by the ambient magnetic field. When radiation from the background stars passes through the globule, it gets attenuated and polarized due to the aligned grains. We have attempted this problem in the optical region and polarization measurements were made in UBVRI bands for the stars in the outer regions of globules. (vide: Joshi et al. 1985; Joshi et al. 1987; Kulkarni et al. 1986). As we go towards the center of the globule the attenuation increases and becomes very high in the visual wave bands (in some cases more than 30 mag or even more near the center). However, in infrared this attenuation is much smaller compared to the visual region. (e.g. in K-band (2.2 μm) attenuation is 100 times less than for the V-band (0.05 μm)). Therefore, we plan to conduct the polarimetric measurements in near IR bands for the back ground stars which lie near the central region of a globule. These measurements are important to understand the role of magnetic field and dust grains in the formation and evolution of globules and subsequent formation of stars.

2. Instrumental details

The optical lay out of the instrument is given in Figure 1. For polarization measurements the instrument operates in the wavelength region 1-2.5 μm. The incoming light signal is modulated by a rotating super achromatic Pancharatanam half-wave retarder. The rotation of the half-wave retarder is performed in high precision steps and having 96 steps in one rotation. The modulated signal passes through the analyzer (Foster prism). After passing through the Foster prism the light beam gets divided in two perpendicular beams. The direct beam after hitting a vibrating tertiary mirror falls on the InSb detector. An aperture plate, filter wheel and a Fabry lens are mounted inside the dewar in it's cold environment. The second beam is used for the monitoring purpose.

The detailed block diagram of the polarimeter is shown in Figure 2. Most of the blocks are self explanatory. InSb detector mounted inside a liquid nitrogen dewar was acquired from M/S Infra Red Laboratories Inc., USA. The filters *J,H,K,L,M* and various apertutres are mounted inside the dewar. A blackened baffle is mounted on the detector mounting to prevent the scattered light from reaching the detector.

The IR polarimeter can be operated in two modes:
a) for point sources, and
b) for extended sources.

In mode (a), a tertiary mirror chopping between sky & (sky+object) is used at 20 Hz in square wave fashion. The stay time to the total period is better than 80% at 20 Hz. The retarder plate is rotated in step mode at a rate of 2 steps per second derived from the above 20 Hz. Each rotation of the retarder plate is performed in 96 steps. Sampling of data is done for each step. The vibrating mirror continuously chops (chopping frequency 20 Hz) the light signal between the sky and (sky+object) to eliminate the high background. The signal is fed to a Lock-in-amplifier which corrects the signal for the sky background. The output from the Lock-in-amplifier is digitized with a 16 bit A/D converter and the digitized data are stored in a computer for further processing. In this case we get the degree of polarization and the polarization angle along with the intensity of the object.

In mode (b), tertiary chopping is not practical as the maximum throw angle in the present case is 60 arcseconds. In this case sampling on the source and sky is done independently. The retarder plate is rotated at 6 RPS giving a modulation frequency of 24 Hz for the polarized light. In this case, $\lambda/2$ plate rotation itself acts as a chopper for the polarized light. In this mode, signal is passed through a band-pass filter and a low-pass filter (with a time constant of 1 sec) to separate modulated and unmodulated signals. The modulated signal, after passing through narrow bandpass filter is amplified by a factor n (in present case typical value is 128). In this process errors in measuring percent polarized light get reduced. The pre-amplification increases the sensitivity to detect even a very small(0.1%) polarized light signal for bright sources. This way the instrument is able to utilize the full dynamic range of the detector system for the small modulated polarized light signal against the large unpolarized light signal.

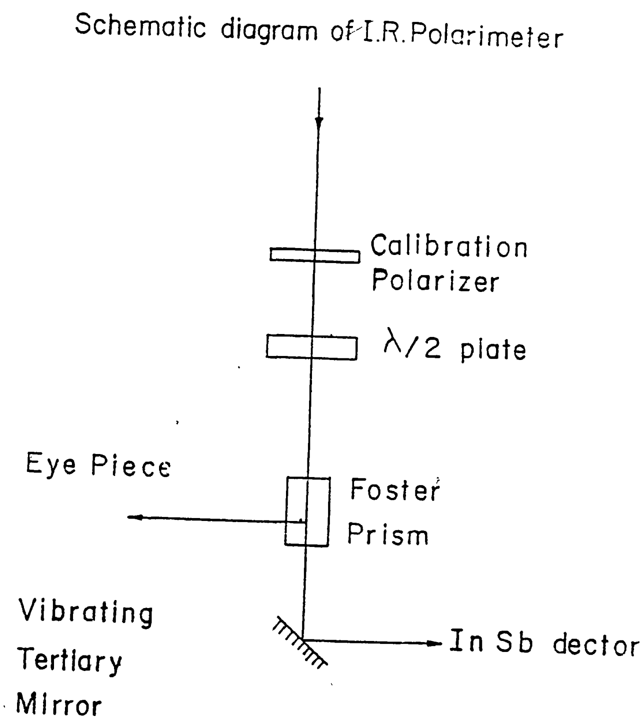

Figure 1. Optical layout of IR polarimeter.

For calibrating and checking the performance of the instrument in both the modes at any time during the observing run, there is a provision to insert a Glan Prisma; a Glan Prism in the beam produces 100% polarized light from unpolarized light. The instrument, in a perfect working condition, should be able to detect 100% polarization.

3. Working principle

Let the incoming light be represented by Stokes' vector *(I, Q, U, V)*. The intensity I^{1} of the light falling on the dector after passing through a rotating achromatic half-wave plate and a Foster prism is represented as:

$$I^{1} = 1/2(I + Q\cos(4\theta) + U\sin(4\theta)) \quad (1)$$

where θ is the angle between the polarization vector and the optical axis of the half-wave retarder.

The signal gets modulated with a frequency which is four times the mechanical rotation frequency of the half-wave plate. One rotation of the half-wave plate is performed in 96 steps. As one sine curve is completed in 24 steps, the data in first 24 steps is folded with the next 24 steps and so on and several cycles are folded to achieve high *S/N* ratio. Finally the above equation is fitted to the data using least square fit to get the Stokes parameters. Degree of polarization and position angle are then calculated as follows:

$$p = \sqrt{(Q^2+U^2)}; \text{ and } \tan(2\theta) = U/Q \quad (2)$$

Error in the degree of polarization is estimated from the least square fit.

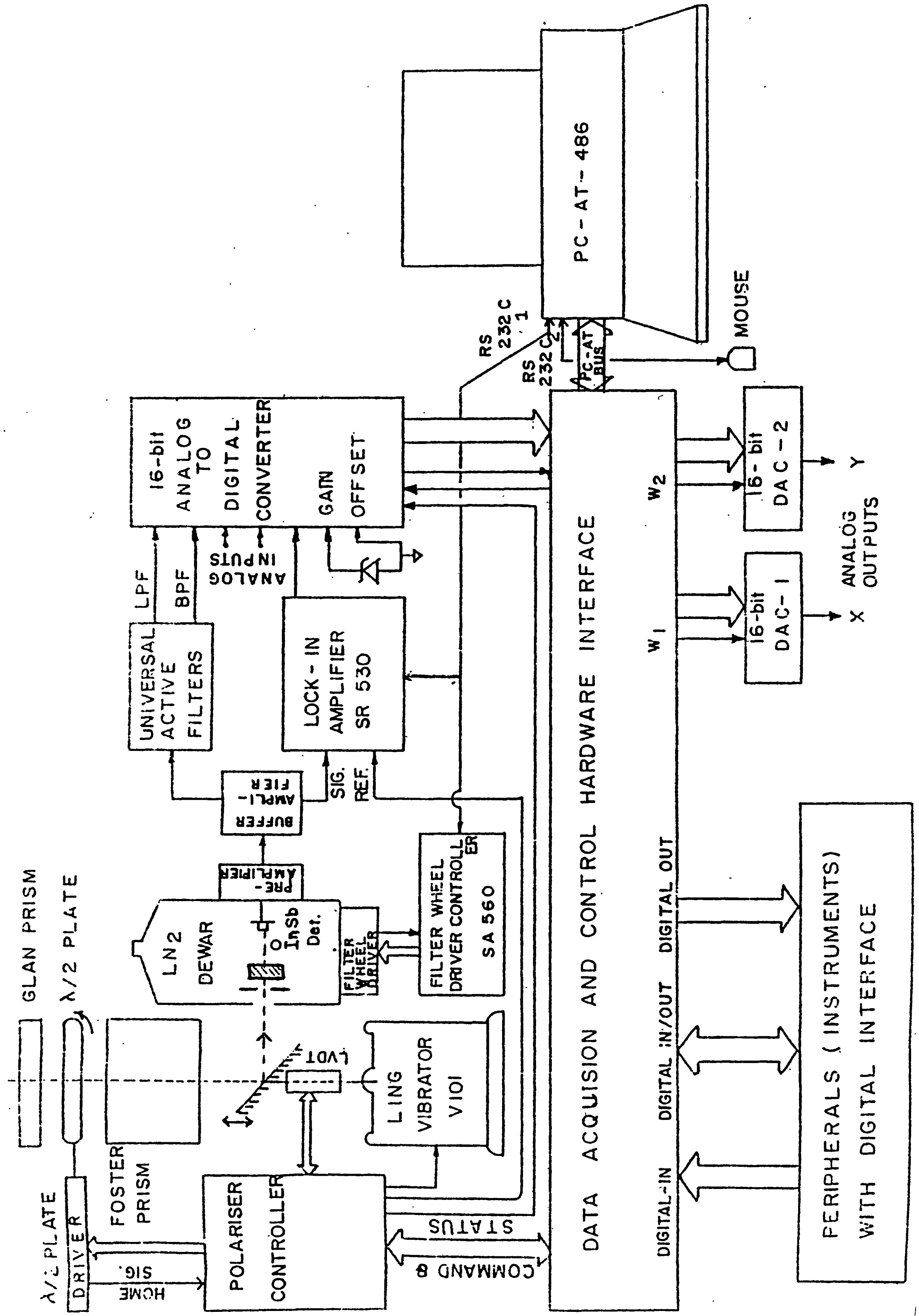

Figure 2. detailed block Diagram of IR polarimeter.

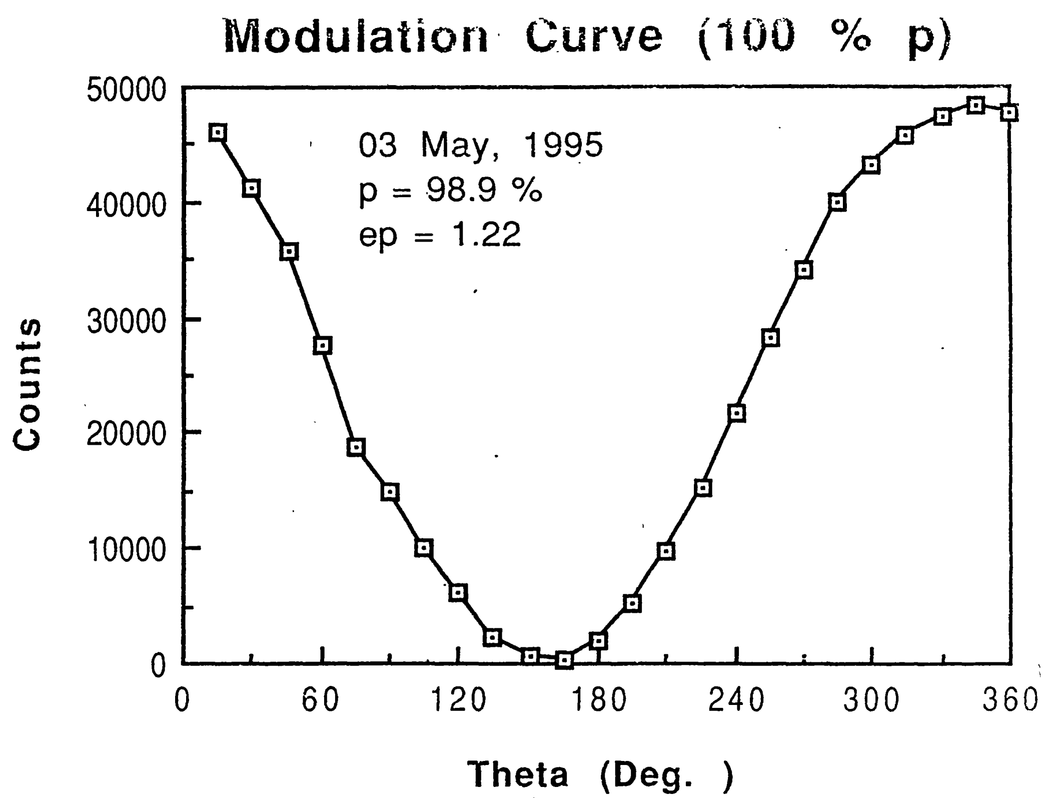

Figure 3. Modulation curve for 100% polarization.

4. Results

The instrument has been tested on the 1.2m telescope at Mt.Abu, India. Observations were made in *J,H,* and *K* bands on some standard stars and some program stars. Zero polarization and some known polarization stars were observed. Some of the test results are cited in Table la and lb. The performance of the instrument was tested for 100% polarization by inserting a Glan prism in the beam; the star α Boo being used as the source. Results based on observations taken at three different times show the consistent performance of the instrument. The same star was also used to test the performance for zero polarization. In this case, we remove the Glan prism from the path and directly measure the polarization of the star light. α Boo is expected to be an unpolarised star in near-IR bands. The values obtained at three different times are also shown in Table la. Within observational errors, the instrumental polarization is close to zero. Typical integration time for each set was 48 seconds. In Table lb, the polarization values obtained for two stars with known polarization are compared with those available in the literature. Within the errors of observations, the polarization values match. The modulated signal is shown for 100% polarized light in Figure 3. The fit is excellent. The least square fitted values of % p and error in polarization (ep) are noted on the figure. More observations are planned in the near future.

Table la. Performance of IR polarimeter for 100% and 0% polarization in K band.

Source	Glan in (for 100% polarization)	for 0%polarization
α Boo	98.8 ± 0.8	0.31 ± 0.26
	98.8 ± 0.32	0.297 ± 0.27
	99.8 ± 0.625	0.45 ± 0.27

Table lb. Observed polarization in J,H,K of stars with known polarization.

Star	Degree polarization (%P)			Source
	J	H	K	
δVir	0.235±0.2	0.683 ± 0.2	0.426 ± 0.4	present
	0.4	0.05 ± 0.6	0.08 ± 0.00	Dyck et al., 1991
VY CMa	-	-	4.3 ± 0.57	present
	-	-	2.8 ± 0.2	Dyck et al., 1991

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