Near Infrared Waveplate

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ABSTRACT

The waveplate made of Polyvinyl Alcohol (PVA) plastic film has several advantages compared with that of birefringent crystal in visible region, such as its lower cost and insensitivity to temperature and incidence angle. What are the performances when they are used in the near infrared spectral region? In this paper, we provide some experimental results of infrared PVA waveplates. To do this, we make some samples and measure their polarization characteristics at several aspects. Firstly, we measure the performance of these PVA waveplates by precise instruments in laboratory. Secondly, we put the waveplates into a Stokes polarimeter to observe the solar magnetic field at near infrared line FeI1.56μm. By use of this polarimeter mounted on the vertical spectrograph of 2m McMath telescope at Kitt Peak, the two-dimensional Stokes parameters, I, Q, U, and V, of a sunspot were observed. From the results of laboratory and observation, we get the conclusion that PVA waveplate has the fair polarization performance to be used to observe the solar magnetic fields in the near infrared spectral region. By these experiments, we provide a design of an achromatic waveplate in infrared region, which consists of five-element, to illustrate the PVA waveplate is the best choice to it.

Keywords: PVA waveplate, near infrared, retardation, Stokes polarimeter

1. INTRODUCTION

The observation of the solar magnetic fields in the infrared region exhibits unexampled potential because of the following reasons. Firstly, the Zeeman sensitivity of solar spectral line is in proportion to observational wavelength, the spectral lines split completely in the infrared region, and therefore making the observational instrument simple. Secondly, under the same observational circumstance, the seeing and the scattering conditions in infrared are much better than that in visible region. Thirdly, the infrared lines cover from the deepest layers in photosphere to the corona, a large number of Zeeman sensitivity lines with different physical properties are among them. It can be predict confidently that the next leap of solar magnetic fields measurement must occur in the infrared.

As above mention, several infrared solar magnetic fields telescope have being developed in some observatories, such as National Solar Observatory (NSO)/ Advanced Technology Solar Telescope (ATST)[1], Big Bear Solar Observatory/New Solar Telescope (NST)[2] and 1m Infrared Vacuum Solar Telescope (IRST)[3] in China, etc. The main aim of these telescopes is to observe solar magnetic fields in infrared. Waveplates are the indispensable optical elements in any solar magnetic fields telescopes as they play important roles in birefringent filter and polarimeter. In the visible region, the most common type of the waveplate in solar telescope is made of two materials, which are birefringent crystal and PVA plastic film. Comparing with the former, PVA waveplate has several advantages, such as lower cost, large aperture, and insensitivity to temperature and incident angle. But it is seldom used in infrared solar telescope as its optical properties have not been well known. To solve this, we make some samples and measure their optical characteristics at several aspects by precise instrument in laboratory. In the latter time, we happen to have a chance to develop this equipment for IRST, this PVA waveplate was applied in an equipment of polarimetry experiment and make an observation of Stokes parametry of a sunspot. In this paper, we will give the measurement results of the optical performance of waveplate in laboratory at first, and then introduce our polarimeter equipment and the result from observation. At last, we provide a

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design of an achromatic waveplate in infrared region, which consists of five-element, to expand the application of PVA waveplates.

2. PVA PLASTIC FILM

The birefringent crystal, such as mica, quartz, calcite and MgF_2, can be made to be waveplate. But to true zero-order waveplate, any of them will have very less thickness of about several microns. This is impossible in practical production. One of the methods to solve this problem is to make pseudo-zero order waveplate. This kind of waveplate consists of two parts of the same birefringent crystals, which their fast axis is perpendicular to each other. Its retardation depends on the difference of their thickness. It is sensitive to temperature and incident angle. Another method is to select PVA plastic film to be waveplate as the reason in the follows.

Table1 The candidate polymer films for waveplate

Kinds of films	Transmittance	Stiff
Polyethylene	good	worst
Ethylene - acetic	good	worst
Polypropylene（PP）	good	good
Polyvinyl chloride（PVC）	best	best
Polystyrene (PS)	best	best
Polyester（PET）	best	best
Nylon	best	best
Polyvinyl Alcohol	best	best (after level off)
Cellophane	best	best
Poly-Carbonic acid (PC)	best	best
Cellulose acetate	best	best
Poly-Sulphone colophony	best	best
Organic glass	best	best

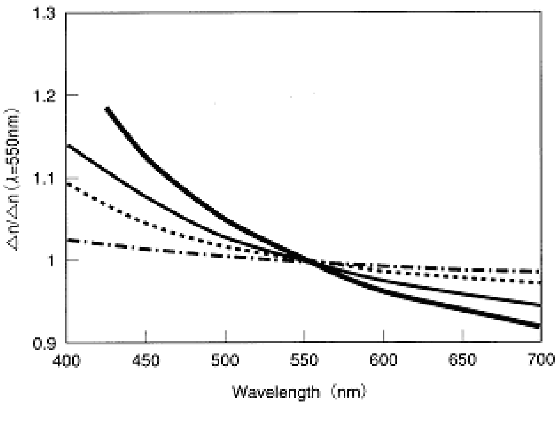


Fig. 1 The chromatic property of the birefringent index of several polymer films
The dashed line indicates Organic glass, the dot-line indicates Polyvinyl alcohol
The thick solid line indicates Poly-Sulphone colophony, the thin solid line indicates Poly-Carbonic acid

It is well know that polymer film has birefringent properties. Table1 lists several kinds of polymer film which can be used to made waveplates. Fig.1 shows some curves of the birefringent index of familiar films varying with wavelength. It is clear that the PVA film is the most insensitive to wavelength among these materials [3]. To make sure that this film can be used in near infrared region, we have measured its transmittance from 200nm to 2000nm (Fig.2). We can conclude from above data that PVA film is the first choice in the polymer films to be waveplate in infrared region.

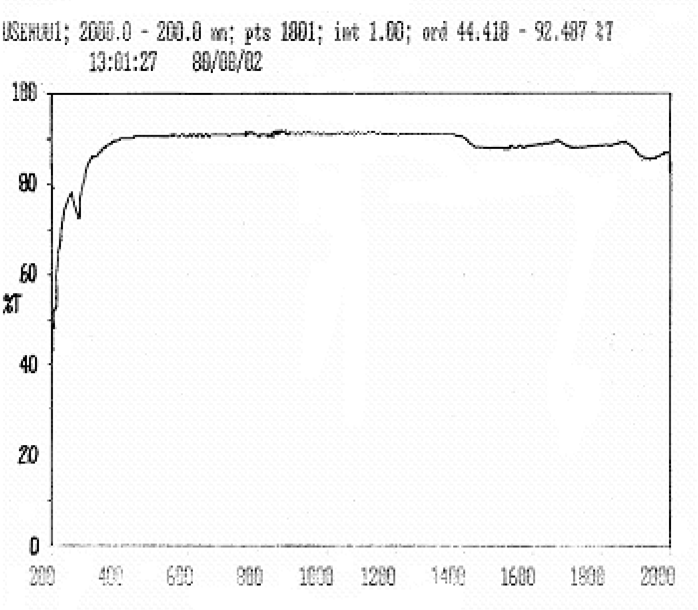


Fig.2 Transmittance of PVA film

3. MANUFACTURE OF PVA WAVEPLATE

The principle of PVA film waveplate is as follows. When PVA film is stretched in one direction, the long molecule chain of the PVA macromolecule compound, which is disorderly and curly, and becomes straight in the rough and parallel to the stretched direction. Because the material electrons bear the different fettering force between the directions parallel to, as well as perpendicular to this long chain, then the birefringent phenomenon appears, and the value of retardation is depended on the stretched length.

Based on the above principle, we designed a stretching machine to make PVA waveplates. By use of this machine, we lengthen and drying the PVA film, and then select the parts by the expected retardation and good uniformity over the aperture. At last, we cut it to the designed size and glue it with K9 glass through infrared optical glue. Thus, The PVA film is protected from deliquescence and spoiled.

4. RESULTS OF MEASUREMENT

4.1 Transmittance

The transmittance of the K9 glass and the PVA waveplates samples is shown in Fig.4 and Fig.5 respectively. For waveplate, the transmittance is about 90% between 400nm to 1300nm, but it reduces to be about 80% when the wavelength is above 1300nm. Comparing Fig.2, Fig.4 and Fig.5, it is clear that this reduction is from the infrared optical glue we customized. In any case, it is the first time to utilize PVA waveplate in infrared region. We are convinced that the PVA waveplate will have the higher transmittance once the commercial glue with good quality is selected.

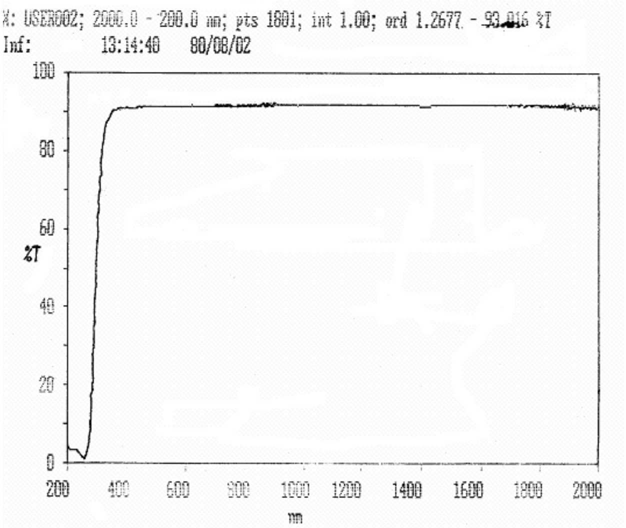


Fig.4 Transmittance of K9 glass

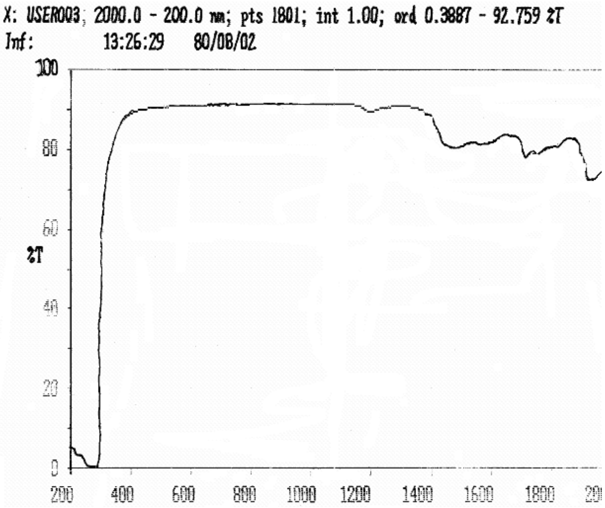


Fig.5 Transmittance of PVA waveplate

4.2 Retardation

Retardation is the key parameter of waveplate. To the precise case, it should be measured in the used wavelength. But we have not got the measuring instrument in infrared region because of the lack of infrared detector and standard light when we made this experiment.

Retardation of birefringent material can be expressed as following formula,

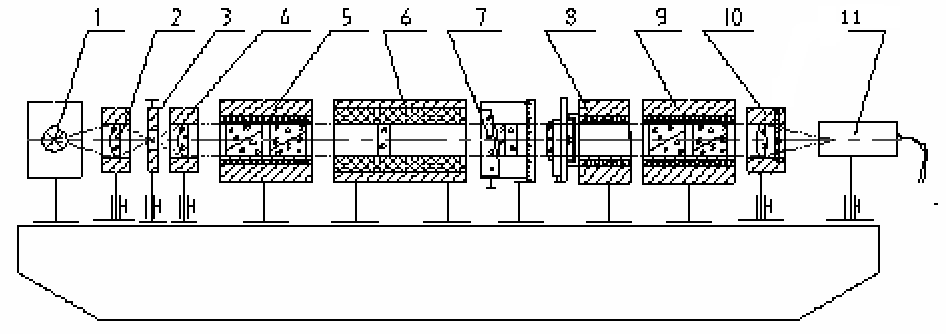
$$\phi = \frac{\mu \cdot \boldsymbol{d}}{\lambda}$$

Where μ is the birefringent index, $\boldsymbol{d}$ is the thickness of birefringent material and λ indicates central wavelength.

From this formula, we can deduce that there is a linear relation between retardation and wavelength when birefringent index and thickness are invariable. The birefringent index of PVA film is insensitive to wavelength as Fig.1 shows, so we can calculate retardation of PVA waveplate in central wavelength from the measuring data in any wavelength.

Fig.6 shows the scheme of the measuring instrument[5]. The tests of waveplates are carried out on it. In the visible region, the prism has the highest polarization resolution. In order to obtain the ideal linear polarized light, two Glan-Tompson prisms are aligned in parallel. The X-Y rotary stage used to place tested optical elements and to move them according to the selected area. Babinet-Soleil compensator is used to measure the retardation of the waveplate. The photomultiplier tube is as detector because of its sensitivity to low light level. All of the rotary parts mounted on a high precise rotary transducer so as to record the rotating angle.

By measuring the PVA waveplates in this instrument, the maximum of retardation errors of PVA waveplate is about 0.3%.



1. homochromous lamp
2. focus lens
3. shutter
4. collimation
5. Glan-Thompson
6. Constant temperature tube
7. compensator
8. X-Y rotatory stage
9. Glan-Thompson
10. image lens
11. block filter
12. PM

Fig.6 Scheme of the measuring instrument for waveplate

4.3 Uniformity

The ideal waveplate should have the same retardation and axis azimuth over the effective aperture, i.e. uniformity. In fact, for waveplates of any material, crystal and polymer, these parameters have a little tolerance among different area of aperture. This lowers its quality. In order to measure the uniformity of our PVA waveplate, we divided the aperture of one waveplate into nine parts, and then measured above parameters on each one respectively. The results of the measurement are given in Table 2.

Table2 Uniformity of PVA waveplates

	(°)	1	2	3	4	5	6	7	8	9	error (PV)
1/2	retardation	182.66	181.24	182.89	182.7	182.10	180.85	182.72	180.92	180.92	0.6%
	azimuth	0.07	0.05	-0.06	-0.04	0.083	0.03	0.03	0.08	0.06	0.143
1/4	retardation	91.36	93.44	92.18	93.2	91.36	90.87	92.05	90.89	91.39	0.7%
	azimuth	-0.06	-0.03	0.05	0.058	-0.04	-0.03	-0.03	-0.08	-0.05	0.138

4.4 Sensitivity to temperature

By use of the instrument which is shown in Fig.5. We put the PVA waveplate into the constant temperature tube, and then adjust its temperature from 20℃ to 100℃ in a step of the data in Table 3. The corresponding retardations measured at each temperature are also given in Table 3. This datum shows that the variety of retardation in per centigrade is a level of 10^{-4} from 20℃ to 65℃. But when the temperature arises over 70℃, this variety increases to be 10^{-3}. Therefore, in order to keep the performance of PVA waveplates, we suggest making them works below 60℃. The curves of retardation varying with temperature are given in Fig.7.

Table3 Sensitivity of PVA waveplates to temperature

Temperature （℃）	20	21	22	23	24	25	26
Retardation （λ）	0.5016	0.5020	0.5022	0.5023	0.5022	0.5022	0.5024
Temperature （℃）	27	28	29	30	31	32	33
Retardation （λ）	0.5023	0.50225	0.50233	0.50237	0.50245	0.50225	0.5023
Temperature （℃）	34	35	36	37	40	45	50
Retardation （λ）	0.5024	0.50233	0.5021	0.5022	0.50179	0.5017	0.50179
Temperature （℃）	53	55	60	65	70	80	100
Retardation （λ）	0.5016	0.5016	0.5015	0.5016	0.5049	0.5067	0.5192

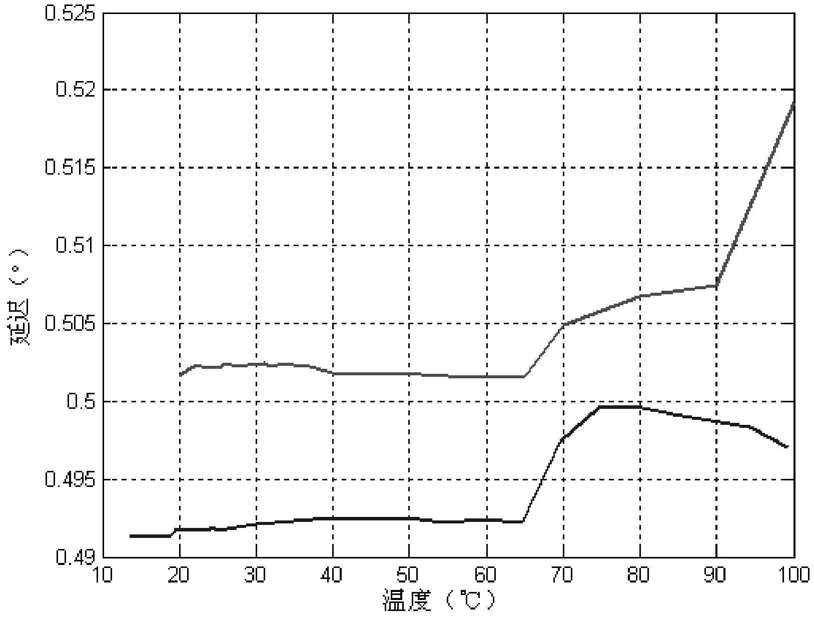


Fig. 7 Sensitivity of PVA waveplates to temperature

4.5 Sensitivity to incident angle

It is clear the Polymer waveplate is insensitive to incident angle compared with that of birefringent crystal from Fig.8. To confirm this, we put these two kinds of material with azimuth of 45° between two perpendicular polarizers in the same time. When the white light passes through this optical system, we can observe phenomenon from analyzer of that the color hyperbola stripe appeared only from the crystal as shown in Fig.9.

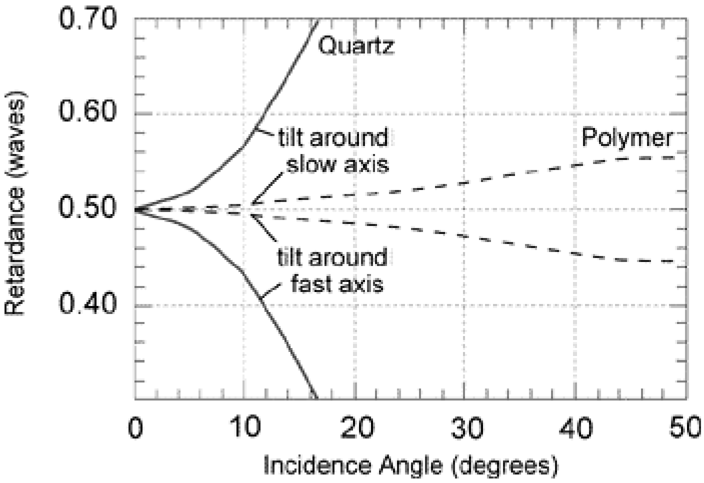
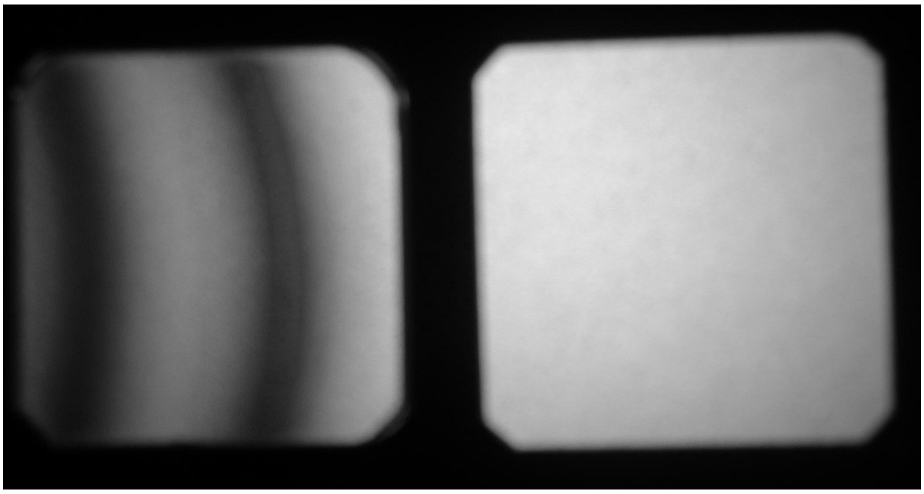


Fig.8 Sensitivity of PVA waveplates to incident angle



Waveplate of birefringent crystal
Waveplate of PVA film

Fig.9 Picture of FOV effect of two kinds of waveplate

5. EXPERIMENT IN INFRARED POLARIMETER

5.1 Design of polarimeter

In China, a project of 1m Infrared Vacuum Solar Telescope (IRST) has been suggested and FeI 1.56um line is selected as the observational spectral line of its polarimeter. According to the requirements of IRST, a primary polarimetry experiment equipment is designed and manufactured [6]. In this polarimeter, it is the first time to utilize the PVA waveplate in infrared region. The optical scheme of this near infrared polarimeter is shown in Fig.10. Where Q_1 and Q_2 are 1/4 waveplate at 1.56um, P is near infrared linear polarizer, and the arrows indicate the direction of the fast axis of these elements. All elements are assemble parallel to each other in surface and can simultaneously be driven to rotate by motors. As the same time, every element can be removed from the optical path by motor flexibly. The mode of modulation of this polarimeter is summarized in Table 4.

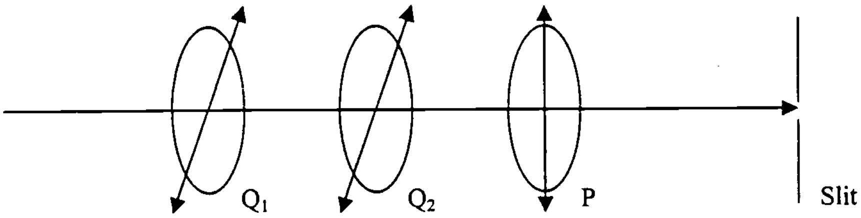


Fig.10 Scheme of optical design for near infrared polarimeter

Table 4 Mode of modulation operation of the polarimeter

MODE	Q_1	Q_2	P	Stokes Polarimeter
1A	45°	0°	45°	(I+Q)/2
1B	45°	0°	-45°	(I-Q)/2
2A	0°	0°	45°	(I+U)/2
2B	0°	0°	-45°	(I-U)/2
3A	0°	NONE	45°	(I+V)/2
3B	0°	NONE	-45°	(I-V)/2

5.2 Observation result

On Sep. 2000, the observation of Stokes parameters of a sunspot was carried out by useing the polarimeter mounted on the vertical spectrograph of the 2m Mcmath-Pierce telescope at Kitt peak. During this day, solar activity is very low. We selected the leading spot of a small sunspot group (NOAA No.9154) to make the Stokes parameters measurement and obtained the profiles of the Stokes I, Q, U, V, at 1.56um. Fig.11 shows the observational results. After these Stokes profiles are fitted with a new method, we can obtain the vector magnetic field information of the leading spot:
$B_{//}$ =2383g, $B_{\perp}$=3665g, γ=56.97°, χ=21.99°. This result is very consistent with the data from the other observatories, so the near infrared waveplate can be used in the high precise Stokes parameters measurement at 1.56um.

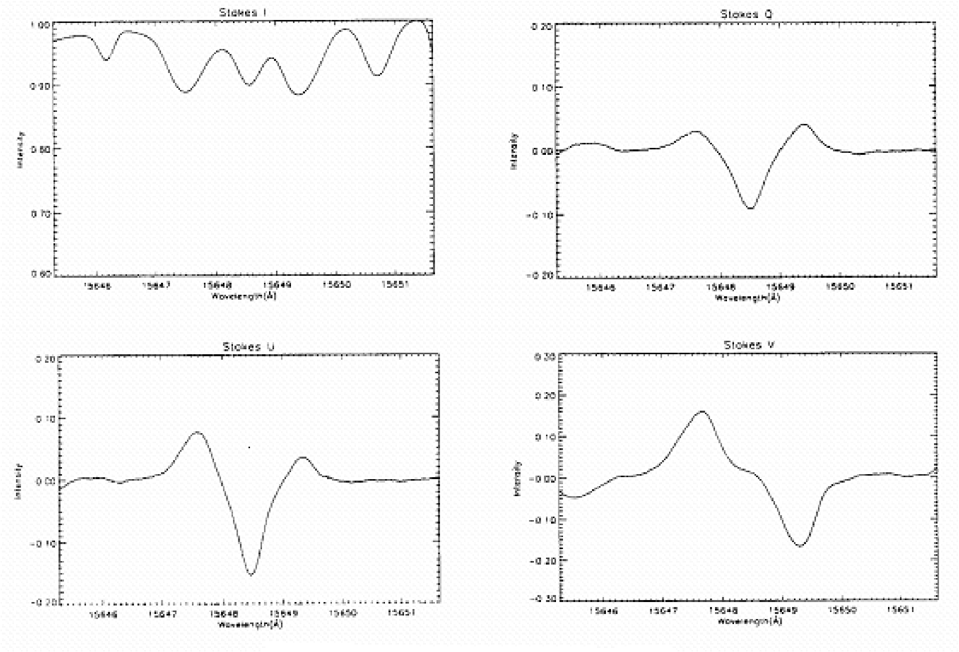


Fig.11 Stokes I, Q, U, V profiles at 1.56um

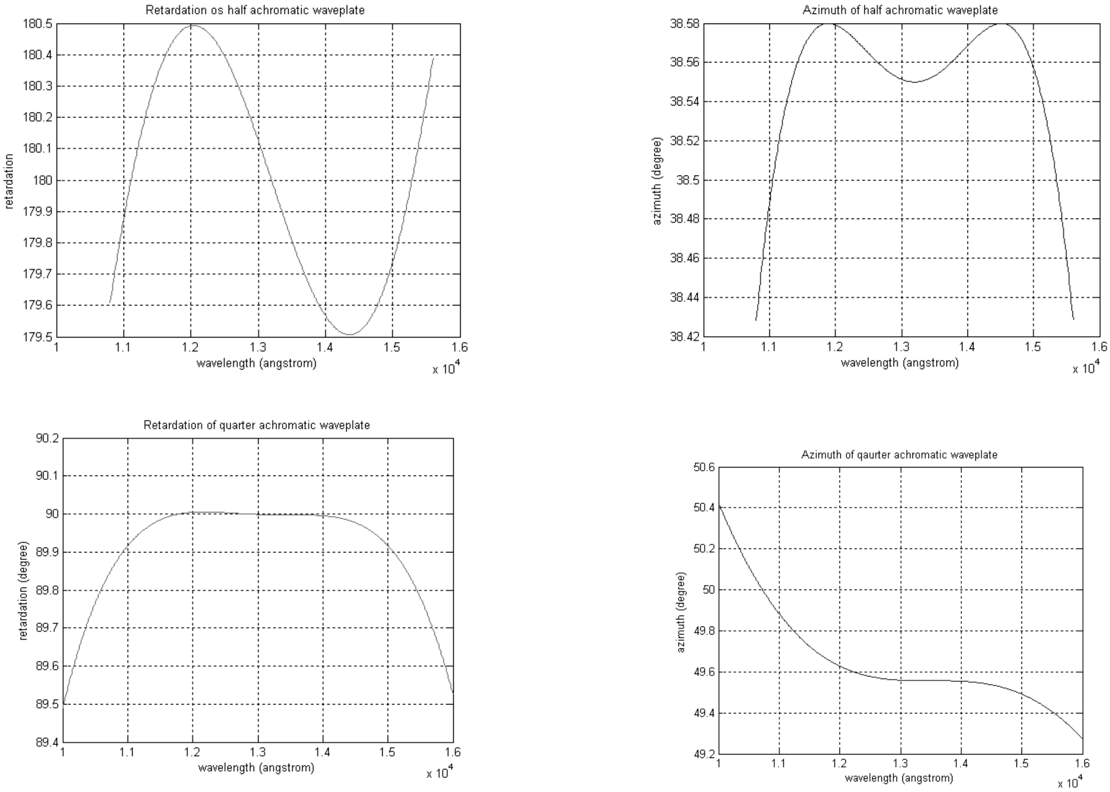


Fig. 12 Design results of achromatic waveplate in near infrared region

6. ACHROMATIC WAVEPLATE IN NEAR INFRARED REGION

The infrared spectral lines locate from the deepest layers in photosphere to the corona, a large number of Zeeman sensitivity lines with different physical properties are among them. So, the astronomers expect to observe infrared lines as more as possible in one solar infrared telescope. In this case, the infrared achromatic waveplates are needed. We provide a design result of an achromatic waveplate in infrared region, which consists of five-element. The advantage of this design is the wide achromatic range comparing with that of the type of two different birefringent crystals (Fig.12). To this achromatic waveplate of multiple plates, the PVA waveplates are the suitable material because of their small thickness.

7. CONCLUSION

From the results of measurements in laboratory and observational experiments, it is confident that PVA plastic film is good material to be made infrared waveplate because of its high transmittance in near infrared region, insensitivity to temperature and incident angle and lower cost. As the same time, comparing with the waveplate of birefringent crystal, it has an absolute advantage of small thickness. Therefore, it is the best choice for the infrared achromatic waveplate, which consists of multiple monochromatic waveplates.

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