Novel Direct Vision Prism and Wollaston Prism Assembly for Diffraction Limit Applications

Noboru Ebizuka [a, b, c], Hideo Yokota [c], Fumiyoshi Kajino [a], Koji S. Kawabata [d], Masanori Iye [e], Shuji Sato [b]

[a] Dept. of Phys., Konan Univ. Higashi-nada, Kobe, Hyogo, 658-8501, Japan;
[b] Dept. of Astrophys., Nagoya Univ., Chigusa, Nagoya, Aichi, 464-8602, Japan;
[c] RIKEN (Inst. Phys. and Chemi.), Wako, Saitama, 351-0198, Japan;
[d] Astroph. Sci. Center, Hiroshima Univ., Higashi-Hiroshima, Hiroshima, 739-8526, Japan;
[e] Nation's Astron. Obs. of Japan, Mitaka, Tokyo, 181-8588, Japan.

ABSTRACT

We propose two types of novel prisms; 1) a direct vision prism with approximately linear angular dispersion as a function of wavelength (Liner dispersion prism: LDP) suitable for a wide range spectrometer, and 2) a novel Wollaston prism assembly (WPA) suitable for a polarizing imager and spectro-polarimeter with a wide wavelength coverage. LDP composes several kinds of glasses or plastics or crystals. Angular dispersion of LDP is enlarged by employment of with some kind of plastic. LDPs, which are employed polycarbonate and Cytop (Amorphous fluorocarbon resin), provide approximately linear angular dispersion in ultraviolet and visible wavelength, respectively. WPA is composed of two or three kinds of Wollaston prism with different birefringent crystals. WPA provides an achromatic angular separation or an angular separation with linear dispersion. These prisms will enable us to achieve a diffraction-limited capability on next generation telescopes of both ground-based and space-borne.

Keywords: spectroscopy, linear dispersion, polarimetry, FTS, interferometer, MCFTS

1. INTRODUCTION

Although spectroscopic observations with wide wavelength coverage have been basic and important methods for astrophysical studies, even today higher performance is required for a spectrograph with wide wavelength coverage [1, 2]. Diffraction gratings are commonly used for astronomical observations since a grating has large and linear angular dispersion as a function of wavelength. However a grating has disadvantages for wide range observations that diffraction efficiency of the grating decreases on both sides of a blazed wavelength, and the grating uses a narrow wavelength range within an octave since higher order diffractions overlap onto the first order spectrum [3]. Fourier transform spectrometers (FTS) and prism spectrographs are generally used for spectroscopic measurements with wide wavelength coverage. However FTS has disadvantages for astronomical observations because scintillation caused by air turbulence becomes fatal noise for FTS, and the throughput advantage (Jacquinot's advantage) of FTS becomes extinct for a point source like a star [1]. In this reason, prism spectrographs have been used for astronomical observations with wide wavelength coverage [2].

A prism has disadvantages of small angular dispersion and poor linearity against wavelength compared with diffraction gratings. Nevertheless the prism is a useful dispersion device especially for the diffraction limit applications such as a space telescope or ground based telescope with adaptive optics (AO) since the prisms have high efficiency and it is easy to achieve fine wave front precision [4, 5]. The poor linearity demerit of a prism is remedied by combination of prisms with several materials. We propose two types of novel prisms; 1) a direct vision prism with approximately linear angular dispersion as a function of wavelength (Liner dispersion prism: LDP) useful for a wide range spectrometer, and 2) a novel Wollaston prism assembly (WPA) suitable for a polarizing imager and spectro-polarimeter with a wide wavelength coverage.

2. DIRECT VISION PRISM WITH LINEAR DISPERSION

A direct vision prism, which is combined several kinds of prisms with different refractive indices dispersion such as a dispersion prism of Amici's spectrometer (Fig.1), is commonly used for survey observations since this prism is easily

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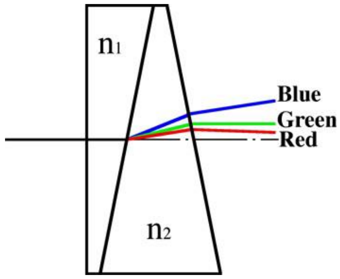

Fig. 1. Schematic representation of conventional direct vision prism.

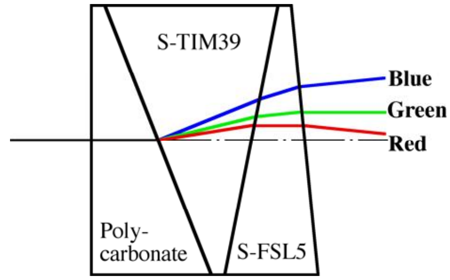

Fig. 2. Schematic representation of novel direct vision prism.

installed into imaging instruments. Measurement efficiency of a conventional dispersion prism is poor since the prism has non-linear angular dispersion against wavelength.

By combination of prisms with various refractive indices, we are able to design a direct vision prism with the approximately linear angular dispersion against wavelength (LDP, Fig. 2). We would explain about essence of the design method for LDP. Refractive index n (λ) of a dielectric is given by power series,

$$n(\lambda)=A_0+A_1\lambda^{2}+A_2\lambda^{-2}+A_3\lambda^{-4}+A_4\lambda^{-6}+A_5\lambda^{-8}\ldots, \quad (1)$$

where λ is wavelength, A_0, A_1, A_2, A_3, A_4 and A_5 are constants. n (λ) is practically described as,

$$n(\lambda) = A_0+ A_2\lambda^{-2}+ A_3\lambda^{-4}. \quad (2)$$

Figure 3 shows refractive indices of S-TIM39 and S-FSL5 of optical glasses (Ohara co. Ltd.) and polycarbonate (PC) normalized at 500 nm, and ines of refractive indices in figure 3 are fitted by equation 2.

LDP with approximately linear angular dispersion as a function of wavelength can be produced by coordination of prisms with various ratios of A_2 and A_3 so that an angular dispersion function of LDP approximates to the first power of wavelength i.e., proportional to wavelength λ. LDP is able to provide lager angular dispersion if a couple of prism materials of the LDP are close to their absorbing wavelength since refractive index dispersion becomes lager toward absorbing wavelength. Moreover LDP provides larger angular dispersion by using some kind of a plastic since prastics of some kind have smaller absolute value of A_2 and A_3 ratio than that of glasses or crystals.

Dispersion equations of refractive indices normalized at 500 nm for S-TIM39, S-FSL5 and PC between 400 and 1,000 nm can be expressed as,

$$n(\lambda) = 0.965 + 0.00543\lambda^{-2}+ 0.000143\lambda^{-4}, \quad (3)$$

$$n(\lambda) = 0.985 + 0.00303\lambda^{-2}- 0.0000765\lambda^{-4}, \quad (4)$$

$$n(\lambda) = 0.968 + 0.00289\lambda^{-2}+ 0.000482\lambda^{-4}, \quad (5)$$

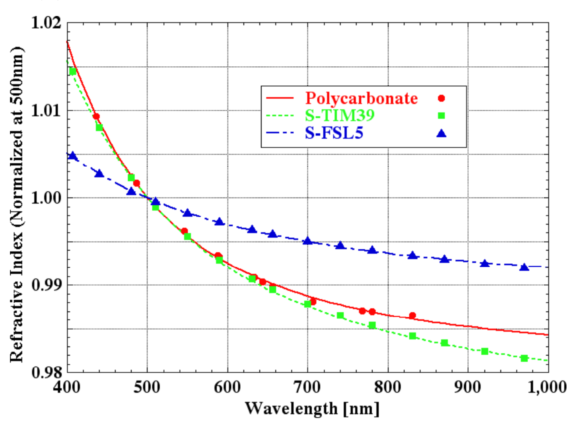

Fig. 3. Refractive index dispersion of polycarbonate, S-TIM39 and S-FSL5. Lines are expressed by Eqs. 3-5, markers of glasses are given by Sellmeier's equation, and markers of polycarbonate indicate measured values.

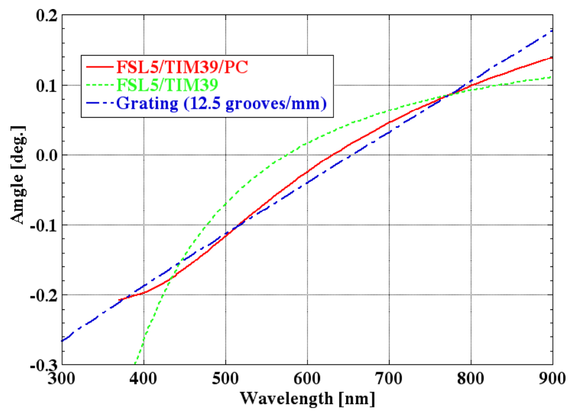

Fig. 4. Angular dispersion of LDP and conventional direct vision prism for visible wavelength, and transmission grating. The solid line represents the curve of LDP combined with PC prism of 22.71 degree in vertex angle, S-TIM39 prism of -27.28 degree and S-FSL5 prism of 7.75 degree, the broken line represents the curve of a conventional direct vision prism combined with S-TIM39 prism of -10.69 degree and S-FSL5 prism of 12.0 degree, and the dash-dotted line represents the curve of a transmission grating with a groove period of 80 μm (12.5 grooves/mm).

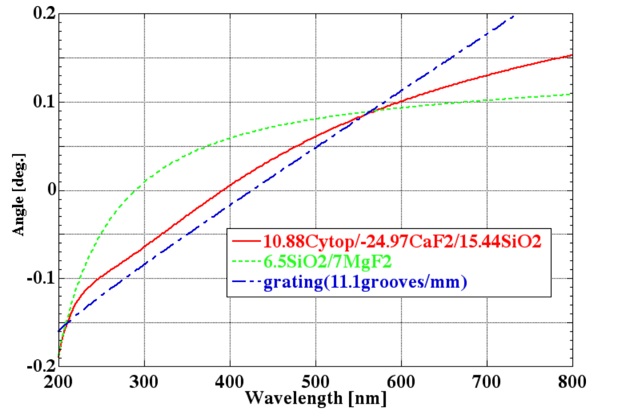

Fig. 5. Angular dispersion of LDP and conventional direct vision prism for ultraviolet, and transmission grating. The solid line represents angular dispersion curve of LDP combined with Cytop prism of 10.88 degree in vertex angle, calcium fluoride prism of -24.97 degree and silica prism of 15.44 degree, the broken line represents a conventional direct vision prism combined with calcium fluoride prism of -7 degree and silica prism of 6.5 degree, and the dash-dotted line represents a transmission grating with a groove period of 90 μm (11.1 grooves/mm).

respectively, where λ is wavelength in micron. The A_2 and A_3 ratio are 6:1, 38:1, 40: -1 for PC, S-TIM39 and S-FSL5, respectively, namely, PC has small A_2 and A_3 ratio.

As shown in figure 4, LDP of the solid line composed of S-TIM39, S-FSL5 and PC provides approximately linear dispersion between 380 and 850 nm. Note S-TIM39 and PC have absorption below 400nm. As shown in figure 3, the dispersion of normalized refractive indices of S-TIM39 and PC are similar, but the refractive index of PC is larger than that of S-TIM39 at a shorter wavelength, and smaller at a longer wavelength. This difference produces the linear dispersion characteristics for the LDP, and a S-FSL5 prism compensates the linearity on a shorter wavelength.

A dispersion characteristic similar to the LDP with PC is realized even if LDP is composed of all glass prisms, but the all glass LPD is two times thicker than the LDP with PC because absolute values of A_2 and A_3 ratio of glasses are 6 times larger than that of PC. On the other hand, angular dispersion of LPD is enlarged by combination of a material with smaller A_2 and A_3 ratio. We found that angular dispersion of LDP enlarges as 1.5 times by the use of a synthetic (imaginative) material with A_2 value of 0 instead of PC, that is,

$$n(\lambda) = 0.984 + 0\,\lambda^{-2} + 0.001\,\lambda^{-4}. \quad (6)$$

Linear dispersion of LDP can be extended to ultraviolet by combination of silica (SiO_2), calcium fluoride (CaF_2) and Cytop (Amorphous fluorocarbon resin, Asahi glass Co. Ltd. [6]). As shown in figure 5, the LDP of the solid line achieves approximately linear dispersion between 220 and 600 nm. A_2 and A_3 ratio obtained from refractive indices between 200 and 1,000 nm are 112:1, 125:1 and 50:-1 for silica, calcium fluoride and Cytop, respectively.

2. WOLLASTON PRISM ASSEMBLY

Wollaston prisms (WP), which provide a data set of P and S polarizations simultaneously (Fig. 6), are used in many astronomical instruments [7-10]. Small dispersion of a separation angle would be desirable for imaging polarimetry, while substantial and large and linear dispersion of a separation angle against wavelength would be usable for spectro-polarimetry. Although they are used in imaging polarimetry, the WP has disadvantages of chromatic aberration because birefringent crystals with small refractive index dispersion have difficulties, BBO (BaB_2O_4) with a large size crystal is difficult to obtain, and YLF ($LiYF_4$) has a small angular separation for example (Fig. 7). On the other hand, dispersion of a separation angle of the WP for spectro-polarimetry is very small compared with an angular separation even though a birefringent crystal with large refractive index dispersion. Moreover, as shown in figure 7, dispersion of a separation angle of almost all WPs tend to decrease with increasingly wavelength between ultraviolet and visible wavelength.

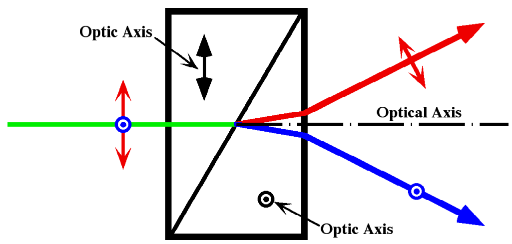

Fig. 6. Schematic representation of Wollaston prism.

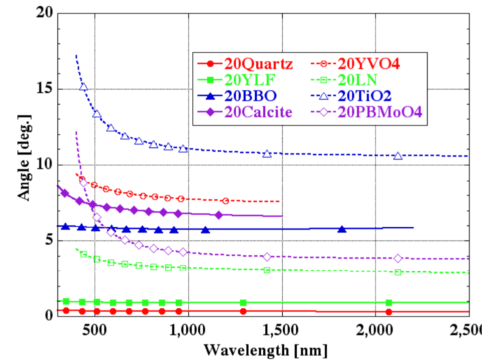

Fig. 7. Dispersion of separation angle of Wollaston prisms.

As shown in figure 8 left, a Wollaston prism assembly (WPA) combines two or three kinds of WPs with different birefringent crystals. WPA is able to design desirable characteristics of an angular separation so that vertex angle of each WP is appropriately given, and WPs are aligned so as to subtract the angular separation of the second and/or third WP from that of the fist WP. WPA with lithium niobate ($LiNbO_3$: LN) and calcite ($CaCO_3$) of the bold solid lines in figure 8 right has large dispersion of a separation angle in visible wavelength so it is useful for spectro-polarimetry, and WPA of the bold dash-dotted lines has the very small dispersion ranging from 400 to 2,000 nm so it is suitable for imaging polarimetry.

WPA composed of LN and YVO_4 WPs (Fig. 9 left) provides an angular separation with linear dispersion against wavelength from 800 to 3,000 nm (Fig. 9 right). Addition of a TiO_2 WP to the WPA of LN and YVO_4 extends the linear dispersion toward a shorter wavelength. The WPA composed of LN, YVO_4 and TiO_2 WPs (Fig. 10 left) provides the linear dispersion from 450 to 3,000 nm (Fig. 10 right). These WPAs are suitable for wide range spectro-polarimetry. We checked up characteristics of each WP, LN WP has the dispersion characteristic similar to YVO_4 and TiO_2 WP below 1,000 nm, but an angular separation of LN WP decrease rather steeply with increasingly wavelength above 1,000nm. Note, LN and YVO_4 have absorption below 400nm, and TiO_2 have absorption below 450 nm.

More over these WPA are available for polarizing interferometer of a multi-channel Fourier transform spectrograph (MCFTS) [11]. MCFTS provides an approximately constant spectral resolution ($\Delta\lambda$) between 400 and 1,000 nm by using WPA of the solid broken line in figure 8 right. And MCFTS provides an approximately constant spectral resolution from 500 to 3,000 nm by using WPA composed of LN, YVO_4 and TiO_2 WPs in figure 10.

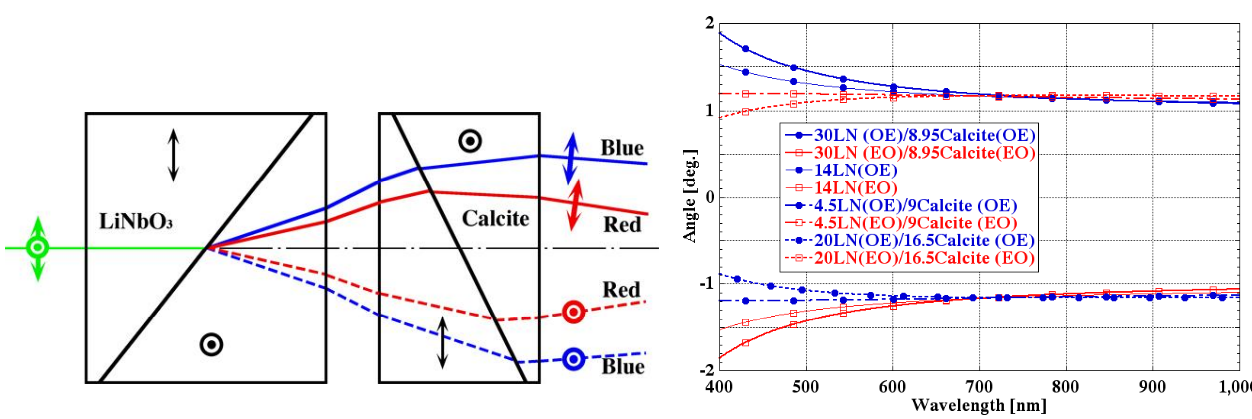

Fig. 8. Schematic representation (left) and dispersion of separation angle (right) of Wollaston prism assembly with $LiNbO_3$ (LN) and calcite ($CaCO_3$). Tiny solid lines represent the dispersion curves of a LN Wollaston prism (WP) with vertex angle of 14 degree. The bold solid lines represent the dispersion curve of a LN WP of 30 degree in vertex angle and calcite WP of -8.95 degree, the bold dash-dotted lines represent a LN WP of 4.5 degree and calcite WP of -9 degree, the bold broken lines represent a LN WP of 20 degree and calcite WP of -16.5 degree.

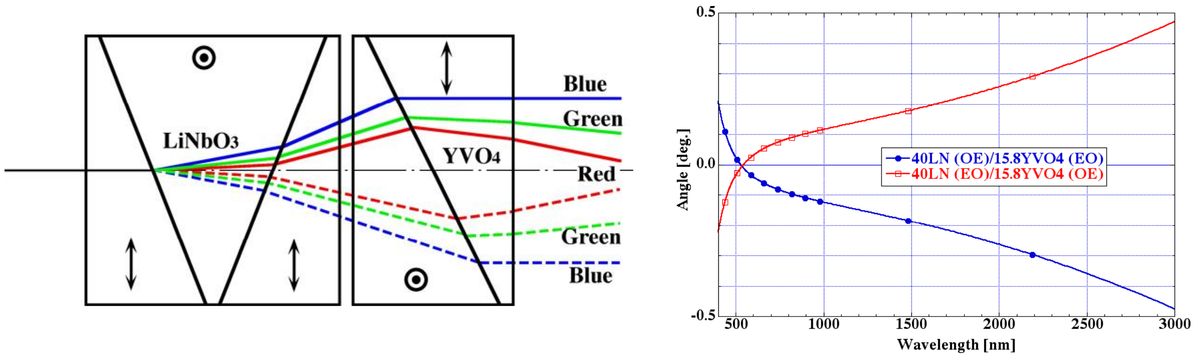

Fig. 9. Schematic representation (left) and dispersion of separation angle (right) of WPA with LN WP of 40 degree in vertex angle and YVO_4 WP of -15.8 degree

3. APPLICATIONS FOR DIFFRACTION LIMIT

Owing to AO techniques, the resolving power (λ/Δλ) is much remedied by employing the narrow slits at the entrance of a spectrometer. Because the diffraction limit of a 10 m telescope is 0.0126" at 0.5 μm, we expect that improvement of a resolving power is as large as 40 times for a point source compared with that of 0.5" seeing. However an optical device used for diffraction limit requires wave front with fine precision such as ~1/20 wave. A diffraction grating is difficult to achieve such a strict wave front precision. On the other hand a prism is a useful dispersion device for the diffraction limit applications since it is easy to achieve fine wave front precision.

LDP and WPA are available for large diameter optics so as to align long prism pieces precisely if each prism achieves fine wave front precision. Moreover, stacking of the prisms provides a larger angular dispersion or separation since these prisms have small losses for incident light. In this way, LDP and WPA are able to realize large angular dispersion and separation respectively for diffraction limit applications.

CONCLUSION

Angular dispersion of LDP is enlarged by the use of a plastic prism. LDP composed of S-TIM39, S-FSL5 and PC provides approximately linear dispersion between 380 and 850 nm and LDP composed of silica, calcium fluoride and Cytop provides approximately linear dispersion between 220 and 600 nm. LDP is an ideal dispersion device for wide range spectroscopy at the diffraction limit, which overcomes disadvantages of a diffraction grating and conventional direct vision prism. LDP is also available for a cross disperser of an echelle spectrograph.

WPA composed of LN and calcite provides an achromatic angular separation ranging from 400 to 2,000 nm, and WPA composed of $LiNbO_3$, YVO_4 and TiO_2 has linear dispersion of separation angle ranging from 450 to 3,000 nm for example. WPA is a versatile polarizing prism for an imaging and spectro-polarimetry with wide wavelength coverage. WPA is available for a polarizing interferometer of MCFTS.

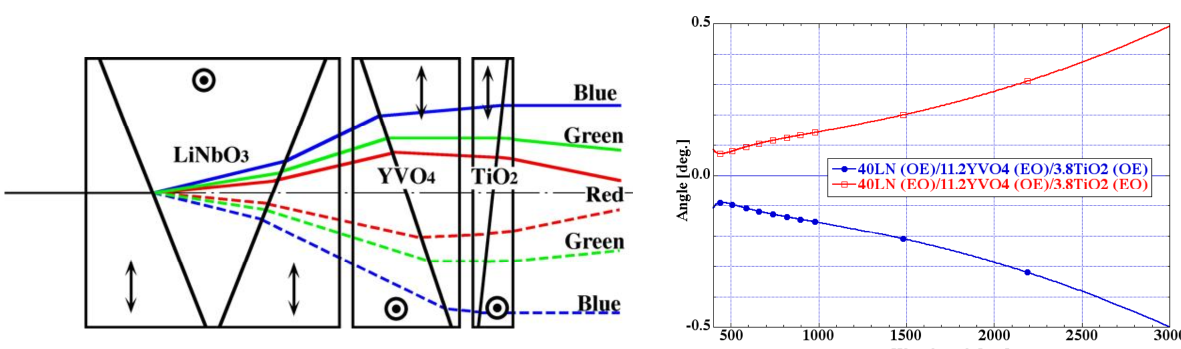

Fig. 10. Schematic representation (left) and dispersion of separation angle (right) of WPA with $LiNbO_3$ WP of 40 degree in vertex angle, YVO_4 WP of -11.2 degree and a TiO_2 WP of -3.8 degree.

We have mainly explained about LDP and WPA with liner angular dispersion as a function of wavelength. However these prisms are able to provide the liner dispersion as a function of wave number or constant for resolving power over a wide wavelength range.

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