Wide-field One-shot Optical Polarimeter: HOWPol

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ABSTRACT

For prompt optical polarimetry of gamma-ray burst (GRB) afterglow, we require wide-field imaging polarimeter which can produce both Stokes Q and U parameters from only a single exposure, as well as quickly-moving telescope and enclosure system. HOWPol is an optical imaging polarimeter which provides four linearly polarized images at position angles of 0°, 45°, 90° and 135°, i.e., Stokes I, Q, U, simultaneously. The key device is the wedged double Wollaston prism described by Oliva (1997)[1] and Pernechele et al. (2003).[2] The images are focused on two 2k×4k fully-depleted CCDs. We report the design and development of the optical devices of HOWPol, which will be mounted to the 1.5-m Kanata telescope at Hiroshima University and stand by the GRB alert.

Keywords: imaging, instrumentation, polarimetry, spectroscopy, gamma-ray burst

1. INTRODUCTION

A gamma-ray burst (GRB) is the most energetic explosions in the universe. It is considered as a result of relativistic outflows launched during the core-collapse of massive stars (producing supernovae) or the mergers of compact objects.[3–5] A commonly-accepted model implies dissipation of bulk kinetic energy via collisionless shocks, in which magnetic fields are generated in the shock process and highly relativistic electrons are accelerated in a power-law distribution of energies. In these conditions, radiation is emitted through the synchrotron process. Synchrotron radiation from a coherent magnetic field should be intrinsically polarized. So far observational and theoretical efforts were produced to understand the emission mechanism in the various phases of GRB process, e.g., the prompt emission and the afterglow.[6] However, the observational material of GRB polarization is still much poor.

Polarimetric observation generally needs large amount of photons and therefore needs a larger telescope than typical imaging, because the required accuracy is mostly of ~ 0.1 % order. However, afterglow emission of GRB quickly decays as $\propto\sim t^{-1}$ after the burst as shown in Figure 1. To obtain polarimetric data of early afterglow of

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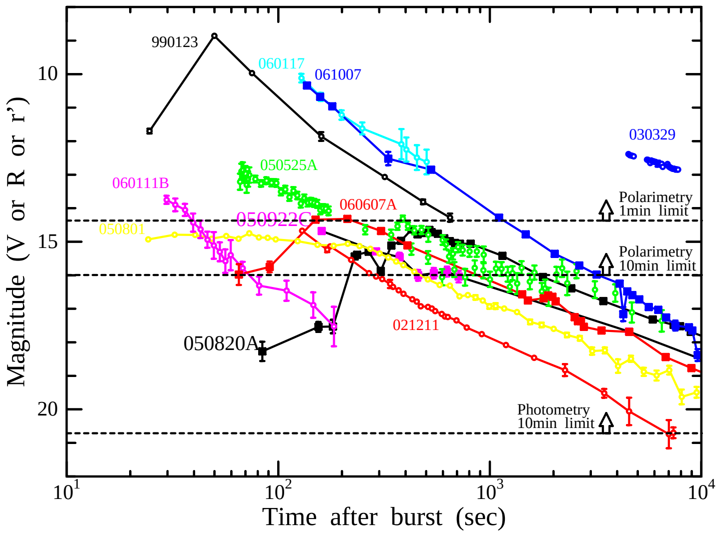


Figure 1. Sample of lightcurves for bright optical afterglow of GRBs. We aim polarimetry at brighter phase ($t < 10^3$ sec).

GRBs, we should have a polarimeter of which the field of view is larger than the initial position error of GRBs ($\sim 3'$) as well as a quickly-moving larger telescope and its enclosure system. Since the early emission of GRBs changes rapidly, the polarimeter should also have a function to produce both the Stokes parameters for linear polarization (i.e., Q/I and U/I) within a short timescale.

In this paper we describe the development of our new imaging polarimeter, HOWPol (Hiroshima One-shot Wide-field Polarimeter; Fig. 2) and its current status.

1.1 1.5-m Kanata telescope

Hiroshima Astrophysical Science Center of Hiroshima University finished construction of a 1.5-m diameter telescope named "Kanata" (Kanata means a far away in Japanese) in 2006 May (Fig. 2). This telescope stands in Higashi-Hiroshima Observatory at 503-m above sea-level, situated 7 km to the southeast of Higashi-Hiroshima campus of the university. The natural seeing size at the observatory is $\simeq 1.1$–$1.2''$ in avarage (FWHM in R-band) . The telescope was originally constructed as the IR simulator in Mitaka campus (Tokyo, Japan) of National Astronomical Observatory of Japan (NAOJ) in 1994, and had been used for instrumentation and many experiments for 8.2-m Subaru telescope. At the movement from Mitaka to Hiroshima, the telescope underwent a whole replacement of the control system. Now the telescope can move with a speed of $5° \text{ sec}^{-1}$ in azimuth, which is five times faster than the previous control system. This speed is remarkably high for one-meter size telescopes. The enclosure of the telescope (a hemisphere-type dome) can also rotate with the same speed. The telescope has three foci, Cassegrain and two Nasmyth ones (every focus has the focal ratio of 12.01/12.2), and it takes only 30 seconds to switch the focus. Thus, Kanata telescope has an advantage for quick-response observations of GRB afterglow. An automatic observation system responding to the GRB alert has already been developed for this telescope with a simultaneous optical and near-IR (NIR) versatile instrument, TRISPEC.[7] We have reported some earliest ground-based optical and NIR observations of GRBs to GCN (GRB Coordination Network) to date.[8,9] Althogh TRISPEC has a capability of imaging polarimetry, a prompt polarimetry for GRBs is practically unavailable because of the limits provided by the optical configuration and the control system.

2. OVERVIEW OF OPTICAL DESIGN

The main purpose in the development of HOWPol is a construction of wide-field ($> 6'\phi$) imager with a polarimetric capability, which will be always attached to Nasmyth focus of the Kanata telescope and ready for observation. Since the Nasmyth focus uses the tertiary mirror, it is subject to significant instrumental polarization and has

Figure 2. (Left) HOWPol and its auto-guider attached to the Nasmyth focus of Kanata telescope, (middle) Overview of Kanata telescope, (right) Higashi-Hiroshima Observatory

been commonly avoided for use of polarimetry. However, the Cassegrain focus (at axial symmetry) of Kanata telescope is usually used by other instruments (e.g., TRISPEC) and it is difficult to occupy the Cassegrain focus by a single instrument. In order to perform quick-response observation for transient objects, we should keep HOWPol ready for observation. Therefore, we decided that HOWPol is attached to the Nasmyth focus. The instrumental polarization is expected to be derived by the polarization data of many field stars and/or the calibrating observation performed after the target observation.

Figure 3 shows a schematic view of HOWPol and Figure 4 represents the components of the optical train. The overall design of the body is similar to that of Wide Field Grism Spectrograph 2 (WFGS2).[10] At the telescope focal plane, we have an aperture mask exchanger. The collimator and the camera lens systems were designed and manufactured by Lens-Ya!, Inc. and Hayashi Lens, Inc., respectively. The composite focal ratio (including telescope optics) is 6.9 and the focal length of the camera is 148 mm. The collimated beam section is 266 mm in length. The magnification factor of the camera to the collimator is 0.57. The surfaces of the lenses are single-layer anti-reflection coated: the total transmittance is $\geq$ 50 % at 5000–11000 Å . The 80 % encircled energy diameter of the point-spread-function for white light (4500–11000 Å) is $0''.6$ arcsec (= 30 μm = 2.0 pixels at the CCD surface) over the field of view (FOV) of $15'\phi$ in a typical imaging mode. This optical train produces achromatic pupil image of $\phi = 23.9$ mm in collimated beam section. 80 % encircled energy diameter of the pupil image is less than 52 μm at 4500–11000 Å (32 μm at 6000–11000 Å). This feature is important to use the double wedged Wollaston (WeDoWo) prism. The concept using this prism is described in §3.

In this collimated beam section, we have an X-stage of polarimetric calibration unit, a filter exchanger and a prism exchanger. A mechanical shutter (Melles Griot) is placed between the pupil mask and the prism exchanger. A CCD dewer is mounted to a Z-stage for a focus adjustment. Stepping motors are used for movement of the stages and the exchangers, which are controlled from a PC through RS232C interface.

It is noted that an autoguider box is placed between HOWPol and the Nasmyth rotator flange. It has a CCD detector (Bitran BS-41L) mounted on an X-Y stage and a wavelength calibration lamp (Hg-Ne) mounted on a θ stage. They are controlled by a single PC connected with the telescope control PC and the HOWPol master PC via socket communication.

3. WEDGED DOUBLE WOLLASTON (WEDOWO) PRISM

For high-production-rate ($\Delta t \sim 10$ sec) wide-field linear polarimetry, we adopt a WeDoWo prism as the polarimetric analyzer. The design and application of the WeDoWo prism are described by Oliva (1997) and Pernechele et al. (2003).[1,2] Figure 5 is a sketch of the prism. The prism consists of two pieces of Wollaston prisms. The optical axis of one half prism is at 0° an that of the other one is at 45°. The incident surface of each piece has a wedge angle to avoid the cross-talk between the output beams of the two prisms. When the WeDoWo prism is located at the pupil image position, we have four linearly polarized images at different positions on the CCD. Thus, the prism enables us to obtain polarized images at position angle of 0°, 45°, 90°, 135° with only a single exposure of CCD measurement. We can derive the Stokes parameters I, Q/I and U/I of the incident beam

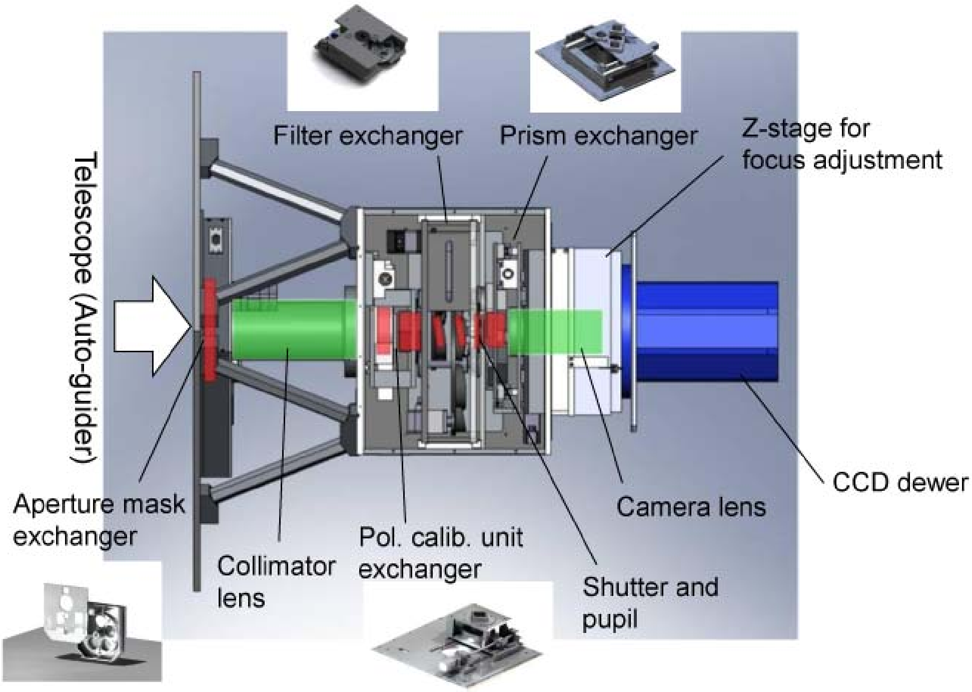


Figure 3. Schematic view of HOWPol

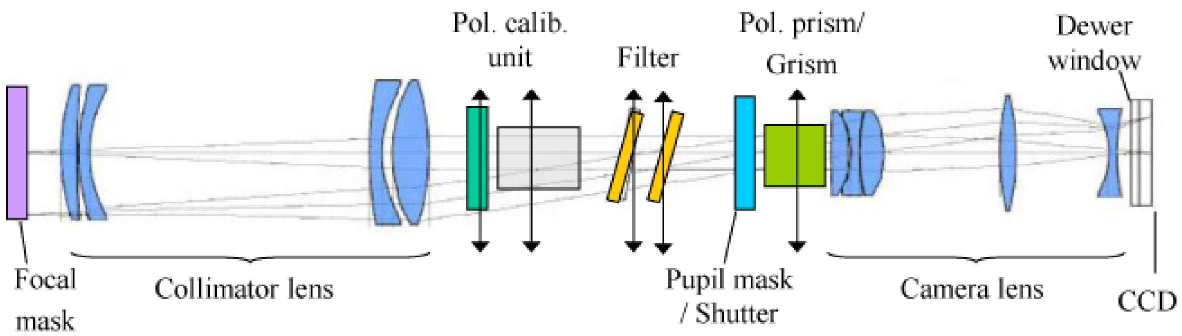


Figure 4. Optical train of HOWPol. The total length between the focal mask and the CCD is 748.63 mm. The WeDoWo prisms are inserted just after the pupil mask.

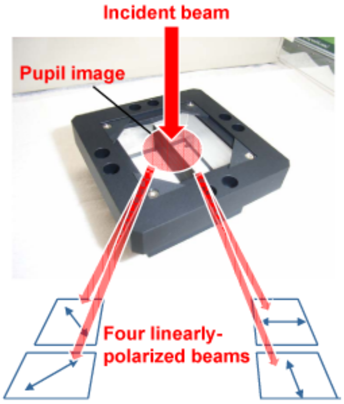


Figure 5. A sketch of the WeDoWo prism and its beam separation. It consists of two pieces of Wollaston prisms. The optical axis of one half prism is at 0° an that of the other one is at 45°. The incident surface of each piece has a wedge angle to avoid the cross-talk between the output beams of the two prisms. The WeDoWo prism is located at the pupil image position in the collimated beam section and produces four linearly polarized beams at different deviation angles.

according to following equations,

$$\begin{aligned} I &= i(0^\circ) + i(90^\circ) = i(45^\circ) + i(135^\circ), \\ \frac{Q}{I} &= \frac{i(0^\circ) - i(90^\circ)}{i(0^\circ) + i(90^\circ)}, \\ \frac{U}{I} &= \frac{i(45^\circ) - i(135^\circ)}{i(45^\circ) + i(135^\circ)}, \end{aligned} \tag{1}$$

where $i(\psi)$ is the intensity of each output beam polarized in the direction of ψ. In an actual measurement, $i(\psi)$ should be replaced by $k(\psi)i(\psi)$ where k is efficiency of each beam. The k and its ratio (e.g., $k(0^\circ)/k(90)^\circ$) can be derived from proper calibration data, such as unpolarized standard and photometric standard stars, and then corrected for.

We have manufactured two types of the prisms. One is a wide-field type and the other is a narrow-field type. The structure of each prism, the image layout on the detector, and results of the lay trace are shown in Figures 6–8. We describe each prism in the following subsections.

3.1 Wide-field type WeDoWo prism

This prism is designed to have 7×7 arcmin^2 FOV covering a typical error $\sim 3'$ of the BAT (Burst Alert Telescope) onboard positioning in the gamma-ray burst explorer, Swift. Since the FOV is a square, the image format is necessarily 2×2 as shown in Figure 7. To produce such a large image separation, we need to use a material having a large birefringence, $|n_e - n_o| > 0.15$. In optical wavelengths, calcite ($CaCO_3$) and rutile (TiO_2) can be a candidate for such a device.[11]

We have developed our first wide-field type WeDoWo prism of calcite, which was fabricated by Nitto Optical, Co., Ltd. * The total dimension is $40\times40\times28.8$ (height) mm. A half piece of the prism consists of three calcite blocks as in Figure 6 to reduce the image distortion. The image format on the detector is shown in Figure 7. We have four linearly-polarized $7' \times 7'$ images without vignetting.

A Wollaston prism with a large separation angle suffers from severe lateral chromatism. As shown in Figure 8, the point source image between 8000 Å and 10000 Å is elongated by ~ 250 μm ($= 5''$) at the CCD surface. Thus, we obtain 2D spectral images with very-low dispersion ($\lambda/\Delta\lambda \simeq 20$–$40$) for any objects. Therefore, this type of WeDoWo prism will be used only for a point-like source with a large positional error ($\simeq 0.3'$–$3'$) such as GRB afterglow.

*We are planning to develop a more durable rutile prism in the future.

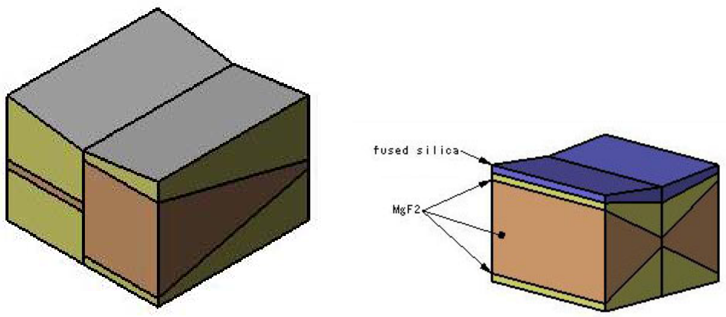


Figure 6. (Left) Schematic view of the wide-field type WeDoWo prism made of calcite blocks, (right) Narrow-field type made of MgF_2 crystals together with achromatising fused silica wedges.

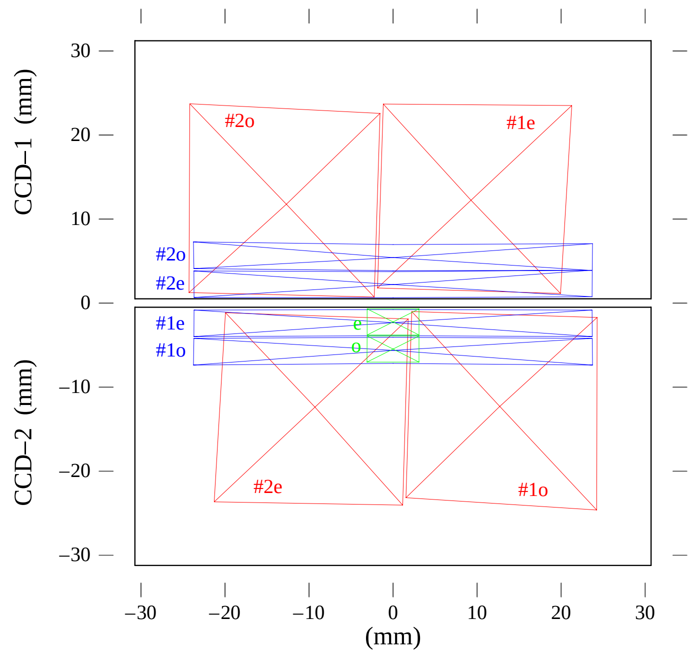


Figure 7. Image format of four polarization images (1o, 1e, 2o, and 2e) on the two 2k-4k CCDs with the wide-field polarimetry mode (four $7' \times 7'$ images arranged in 2×2) and the narrow-field one (four $14.5' \times 1'$ from top to bottom).

3.2 Narrow-field type WeDoWo prism

Although the main target of this instrument is the early afterglow of GRBs, the frequency of GRB observations is expected to be about once a month. For most occasions, HOWPol will be used in observations for well-positioned astronomical targets.

For these purposes, we adopted a narrow-field type WeDoWo prism made of MgF_2 crystal, which shows very low chromatism below 1 μm.[11] To minimize the lateral chromatism, we introduce a wedge of fused silica at the incident surface of the device.[1] It was fabricated by Kogakugiken, Corp. The total dimension is 42×42×30.8 (height) mm. A half piece of the prism consists of three MgF_2 blocks and one fused silica wedge as shown in Figure 6. With a single $14.5' \times 1'$ slot of a focal mask, we obtain four linearly-polarized images as shown in Figure 7. The lateral chromatism (Fig. 8) is negligible in observations with a typical wide-field filter. This WeDoWo prism can be used even for diffuse objects, e.g., reflection nebulae and comets.

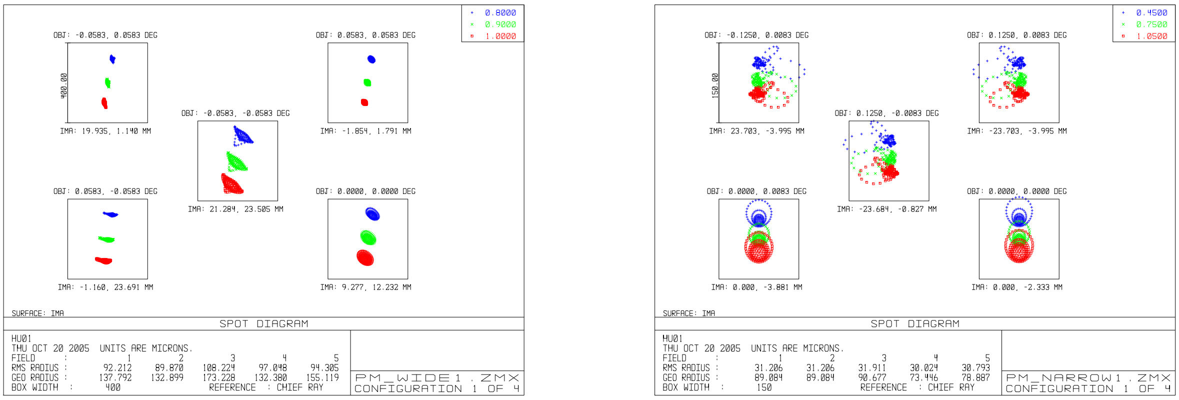


Figure 8. Results of ray-trace in wide-field polarimetry (left) and narrow-field one (right). These images show the spot diagrams of ordinary ray produced by a half prism (i.e., #1o ray in Fig. 6) at five positions within the field of view. For the wide-field type, the spots at 8000, 9000 and 10000 Å are shown. The box size is 400×400 μm. For the narrow-field one, 4500, 7500 and 10500 Å are shown. The box size is 150×150 μm. The wide-field type suffers from severe lateral chromatism.

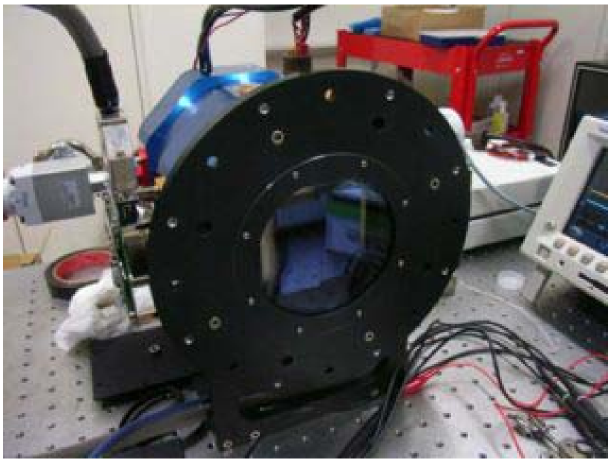
Figure 9. (Left) Pictures of focal masks for wide-field and narrow-field imaging polarimetry, (right) central images obtained by the CCDs with the narrow-field mask illuminated by an artificial light. The left and right images are before and after inserting the narrow-field type WeDoWo prism, respectively.

4. OTHER OPTICAL COMPONENTS

Besides the imaging polarimetry mode, HOWPol has, of course, imaging mode of $15'\phi$ FOV. In the near future, spectroscopy and spectropolarimetry will be also available. In this section, we describe some optical components introduced in HOWPol.

In the aperture mask changer, five types of focal masks can be set at a time in a turret. The turret is rotated by a stepping motor and rack-and-pinion drive. The gear is preloaded near the each mask position to achieve good reproducibility in the orientation of the turret. Currently we put a circular aperture of $15'\phi$ for imaging, a rectangular aperture of $7' \times 7'$ for wide-field imaging polarimetry, a series of rectangular aperture of $14.5' \times 1'$ and $6.3' \times 1'$ for narrow-field imaging polarimetry, a series of $2.3'' \times 1'$ slitlets for spectropolarimetry, and 5×5 pinholes at every 15 mm intervals for checking image distortion. The picture of the masks for imaging polarimetry is shown in the left side of Figure 9. The masks for spectropolarimetry is made of poreless ceramics (fluorine mica) to avoid a harmful effect on polarimetry with conductive material,[12] and others are made of metals (aluminum or phosphor bronze).

The X-stage of the polarimetric calibration unit has a superachromatic half-wave plate manufactured by Astropribor (mounted on a smaller θ-stage) and a normal-type Wollaston prism. They are used for detailed polarimetric calibration with the WeDoWo prisms or the spectropolarimetry mode.



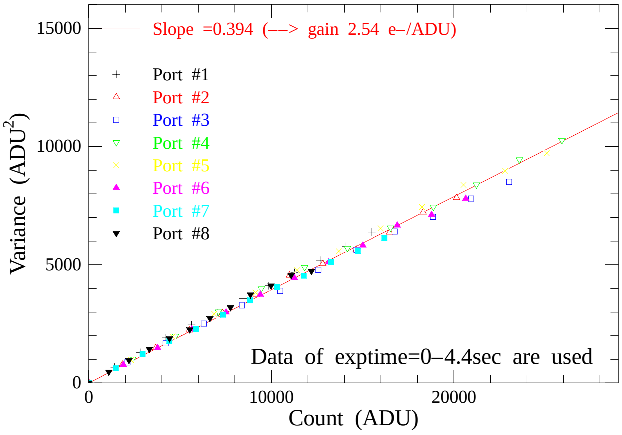


Figure 10. (Left) Two 2k×4k HPK CCDs inside the dewer of HOWPol, (right) results of count-variance relation test with the CCDs suggesting a conversion factor of 2.5 ADU per electron.

The filter exchanger consists of two filter turrets. Each turret is rotated by a stepping motor and rack-and-pinion drive. There are six positions for filter holders on each turret and we can set up to 10 filters and/or corresponding components at a time. Each filter has a diameter of 60 mm. Currently, we put Johnson-Cousins *BVRI* and SDSS *z'* filters (Asahi Spectra Co., Ltd.) on the changer. To suppress ghost images produced by reflections among the optical surfaces, every filter is tilted by 10 degrees. We also set two polarizing filters (for optical and near-IR wavelength, respectively) and masks for Hartmann tests. In the near future, we will add some order-cut filters and narrow band filters.

At the end of the collimated beam section, we have a prism exchanger consisting of an X-Y stage moved by stepping motors and ball screws. The positional reproducibility is expected to be 20 μm, which is sufficiently less than the aberration of the pupil image of HOWPol optics. This exchanger takes two WeDoWo prisms and a lens for checking the pupil image. In the near future, two grisms using volume phase holographic (VPH) gratings will be introduced. The low-dispersion grism ($\lambda/\Delta\lambda \simeq 600$) will be a 474 mm^{-1} VPH grating sandwiched between two BK7 prisms (apex angle is 20°). The medium-dispersion one ($\lambda/\Delta\lambda \simeq 2300$) will be a 1579 mm^{-1} VPH grating sandwiched between two ZnSe prisms (apex angle is 20°).

5. DETECTOR

The detector of HOWPol consists of a pair of fully-depleted back-illuminated CCDs developed in collaboration with NAOJ and Hamamatsu Photonics K. K..[13,14] The 200 μm-thick depletion layer greatly enhanced the quantum efficiency at longer wavelengths (≃9000–11000 Å) compared with those of normal CCDs. Each CCD chip has 2048×4096 pixels with 15 μm-square pixels. The CCDs cover the entire 15′ diameter FOV at the Nasmyth foci of Kanata telescope with a pixel scale of 0.30″ pixel^{-1}. They yield good sampling of a stellar image in a typical seeing condition (∼ 1.2″ FWHM in *R*-band) at the Higashi-Hiroshima Observatory. The CCDs are mounted on an invar mother-plate, which is cooled to −100°C with the CryoTiger refrigerator with PT-13 gas (IGC-APD Cryogenics). The CCD mother-plate and the cold head of the refrigerator are placed in a dewer (Fig. 10), which is mounted to HOWPol body through a Z-stage (a motorized vertical stage with a central aperture; Sigma Koki Co., Ltd.) for focusing.

We use the array control system called 'Messia V'[15] and 'MFront2' Front-End electronics for CCD control and data acquisition. Each CCD chip has four readout ports and all eight ports are simultaneously read out. Under the current setting, it takes about 20 sec to read all the effective pixels in the 1×1 binning mode. The conversion factor of the CCD is about 2.5 e^- ADU^{-1} (Fig. 10) and the read out noise is about 4 e^- r.m.s. in average. We are now improving this CCD control system for our observational use.

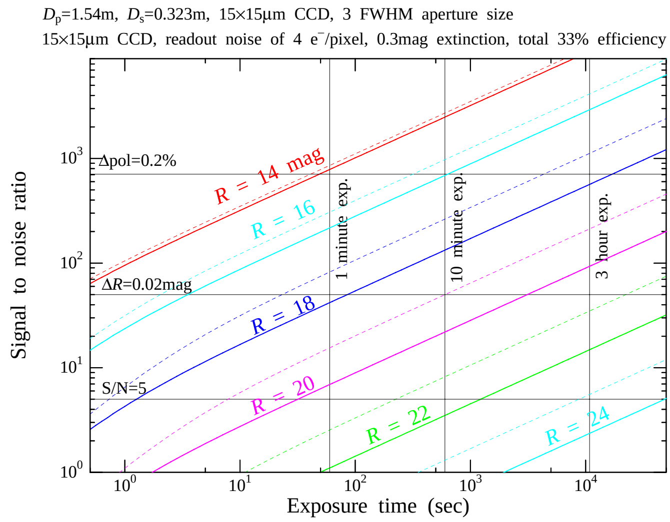


Figure 11. Signal-to-noise ratio for several brightness objects with HOWPol with Kanata telescope plotted versus exposure time. Solid and dashed lines denote the S/N under a typical condition and superior one, respectively (see Table 1).

6. CONCLUDING REMARKS

As shown in Figure 2, the setup of the hardware and its optical components for imaging polarimetry has been almost completed. After finishing improvements of control system on the CCD and optical components, we will start observation. In a prompt mode, we will be able to begin wide-field imaging polarimetry less than ~ 90 sec after the burst (~ 70 sec after receiving the alert) with HOWPol and Kanata telescope.

The signal-to-noise ratio in R-band is calculated as shown in Figure 11 and the limiting magnitude is estimated as in Table 1. In a typical observing condition, we can perform R-band polarimetry down to 16.0 mag at 10 min exposure (14.2 mag at 1 min exp.). Recently, Akerlof and Swan (2008) reported that 40 % Swift GRBs (total 108 samples) showed optical afterglow and 4.6 % (0.9 %) showed optical afterglow brighter than 16 mag (14 mag) at 1000 sec after the burst.[16] Assuming that 100 GRBs are discovered per a year and 5 % out of them are observable, we can expect to obtain polarimetric data of one bright afterglow sample (16 mag at 1000 sec after the outburst) in four year monitoring.

Table 1. Estimated limiting magnitude in R-band of HOWPol and 1.5-m Kanata telescope

Condition	Typical[a]	Worse[b]	Superior[c]
Photometry[d]	19.2	18.0	20.0
Detection[e]	22.4	21.3	23.3
Imaging polarimetry[f]	16.0	15.1	16.5

[a] 1.3″ seeing, 18.5 mag arcsec^{-2} sky brightness.
[b] 1.8″ seeing, 17.0 mag arcsec^{-2} sky brightness.
[c] 1.1″ seeing, 20.0 mag arcsec^{-2} sky brightness.
[d] ΔR=0.02 mag at 10 min exposure.
[e] S/N= 10 at 3 hr exposure.
[e] Δp=0.2% at 10 min exposure.

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