Novel infrared polarimeter for the ESO CRIRES+ instrument

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ABSTRACT

The CRIRES infrared spectrograph at the European Southern Observatory (ESO) Very Large Telescope (VLT) facility will soon receive an upgrade. This upgrade will include the addition of a module for performing high-resolution spectropolarimetry. The polarimetry module will incorporate a novel infrared beamsplitter based on polarization gratings (PGs). The beamsplitter produces a pair of infrared output beams, with opposite circular polarizations, which are then fed into the spectrograph. Visible light passes through the module virtually unaltered and is then available for use by the CRIRES adaptive optics system. We present the design of the polarimetry module and measurements of PG behavior in the 1 to 2.7 μm wavelength range.

Keywords: infrared, spectropolarimetry, polarization grating, CRIRES, ESO, VLT

1. CRIRES+

CRIRES (the CRyogenic high-resolution InfraRed Echelle Spectrograph),[1] currently installed on the 8.2m Antu telescope at the European Southern Observatory (ESO) Very Large Telescope (VLT) facility, will receive an upgrade between 2014 and 2017. The upgraded instrument, CRIRES+, will have updated detectors, an updated data-reduction pipeline, support for cross-dispersed observing, and a polarimetry module which will allow simultaneous spectroscopy and polarimetry.

Here we describe the polarimetry module and the laboratory testing that has been performed so far to validate its design.

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2. POLARIMETRY MODULE DESIGN

The CRIRES+ polarimetry module consists of two independent circularly-polarizing beamsplitters. These are mounted side-by-side on a linear stage (shared with a set of gas cells for wavelength calibration) at the beginning of the CRIRES+ optical chain, with one or the other being moved into the beam based on the wavelength range to be observed. This position allows the polarimeter direct access to the telescope output beam. As there are no birefringent optics or coatings upstream of the polarimeter, measurements of circular polarization with CRIRES+ will have the advantage of being largely free of instrumental polarization effects.

Each beamsplitter consists of a parallel, air-spaced pair of identical polarization gratings (PGs, described in Section 3). The PGs do not rotate with respect to one another, but are able to rotate together to allow beam-switching. The first (upstream) PG splits the slowly-converging incoming telescope beam into two polarized beams which deviate slightly from the axis of the telescope beam. The second (downstream) PG removes this deviation, producing a pair of polarized beams which are parallel and separated by a short distance. These beams focus 1 mm beyond the nominal telescope focal plane, well within the 4 mm that the AO system can accommodate. A ZEMAX rendering of typical beam paths is shown in Figure 1.

The separation of the polarized beams at the focal plane in the Y/J band is approximately 1 mm per 11 mm of PG separation. The beam separation also increases with wavelength. To reduce the variation in beam separation across the working wavelength range of the polarimetry module, the two independent beamsplitters have different PG spacings. The position of the upstream PG is the same in both beamsplitters. Only the position of the downstream PG differs. The PG spacing is 31.9 mm for the Y/J-band beamsplitter and 18 mm for the H/K-band beamsplitter. The beam separation is approximately 2.9 mm (corresponding to 5 arcsec on the sky) at the center of each beamsplitter's wavelength range.

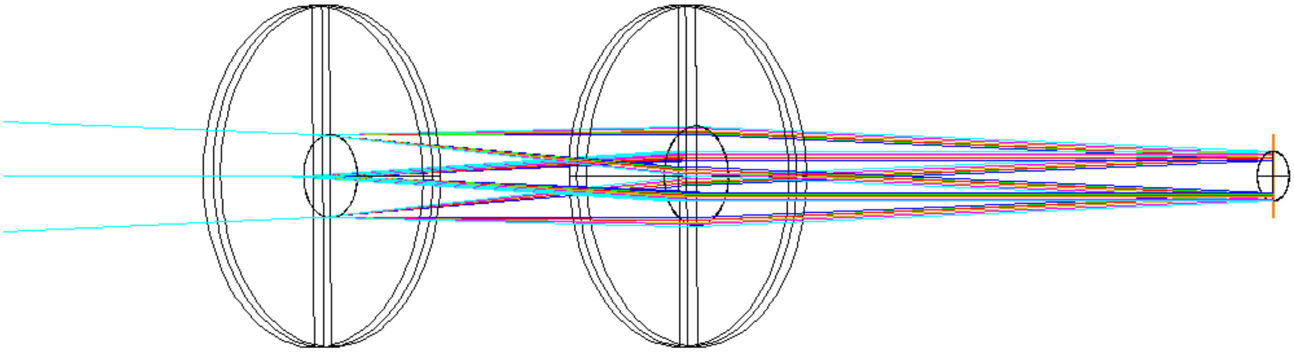

Figure 1. A ZEMAX rendering of a beamsplitter based on two PGs. The telescope beam approaches from the left. The crosshair on the right represents the telescope focal plane.

3. POLARIZATION GRATINGS

3.1 Description

The North Carolina State University (NCSU) Opto-electronics and Lightwave Engineering Group (OLEG) manufactures PGs.[2] A grating pattern (configured for a specific application) is produced in a thin liquid crystal layer on a glass substrate. The liquid crystal layer is then polymerized to make the pattern permanent. Additional liquid crystal layers may be added using the same process, allowing the creation of PGs with complex optical behavior. The PG is then covered with a second layer of glass for mechanical protection.

A PG splits an incoming beam into a pair of beams (representing the first diffraction order of the grating) with opposite circular polarizations. The two beams leave the PG at a shallow angle to the incoming beam path. This angle grows with wavelength. Through the use of multiple liquid crystal layers with carefully-chosen properties, PGs can be manufactured to provide high first-order throughput over a wide wavelength range while providing high zeroth-order throughput over another wavelength range and while directing very little light into higher orders in either wavelength range. This capability allows the CRIRES+ polarimetry module to produce two (first-order) circularly-polarized infrared beams for use by the spectrograph and to transmit one (zeroth-order) unpolarized visible-light beam for use by the adaptive optics (AO) system, all with high throughput.

3.2 Optical properties of CRIRES+ PGs

3.2.1 Throughput

The *throughput* of an optical assembly is the intensity of a particular output beam (or beams) divided by the intensity of the input beam.

Between 1.0 and 2.7 μm the PGs incorporated into the CRIRES+ polarimetry module will have high (~80%) throughput into the first order and low ($\leq$10%) throughput into the (unpolarized) zeroth order. With an unpolarized source, each of the first-order beams will contain about 40% of the incoming light in this wavelength range.

Between 0.4 and 0.8 μm the PGs will have the opposite behavior – low throughput into the first order and high throughput into the zeroth order. This will allow the CRIRES+ AO system, which operates at visible wavelengths, to see a single image of the light source rather than two or three.

Between 0.8 and 1.0 μm the PGs will undergo a transition between these two behaviors.

The results of laboratory testing of a prototype PG with this configuration are described in Section 4.

3.2.2 Extinction

Extinction, in the context of the CRIRES+ polarimetry module, can be defined as the ratio of the throughput of light of one polarization into a given first-order beam to the throughput of light of the opposite polarization into the same beam.

The CRIRES+ project requirements state that the polarimetry module must provide an extinction ratio of at least 1:33 (3%), with a goal of 1:100 (1%). The PG manufacturer has stated that the PGs delivered for CRIRES+ will provide an extinction ratio of 1:200 (0.5%).

4. LABORATORY TESTING OF PROTOTYPE PGS

Two prototype PGs of 25 mm diameter were obtained in late 2013 to allow the Uppsala team to become familiar with PG behavior, independently confirm the throughput performance data provided by NCSU, and refine the design of the PGs which will become part of the CRIRES+ polarimetry module. One of the prototypes is pictured in Figure 2.

Laboratory tests were conducted to determine the throughput (into the various orders) of one of the prototype PGs and the uniformity of this throughput across the PG surface. The test "star" was generated by (wavelength-appropriate) lamps shining through a monochromator with a 600 line/mm grating. Three detectors were used: a Starlight Xpress SXVR-H9 between 0.4 and 1.1 μm, a Xenics XS-1.7-320 between 0.94 and 1.65 μm, and a CEDIP Infrared Systems (FLIR) Titanium between 1.75 and 2.7 μm. A wavelength-appropriate objective lens was mounted to each detector.

4.1 Throughput testing

4.1.1 Methods

Throughput was tested as follows:

1. The monochromator slit was imaged by the detector/lens combination.
2. At each of a set of monochromator wavelengths spanning the sensitivity range of the detector, a series of frames was recorded with a PG in the beam between the monochromator and detector. This configuration produces three spots, corresponding to orders -1, 0, and $+1$. Immediately before or after each series of frames, an accompanying series of dark frames was recorded with the light source blocked.

Figure 2. Bare 25 mm prototype PG.

3. At each of the same set of monochromator wavelengths, a series of frames was recorded without a PG in the beam. This configuration produces one spot. Immediately before or after each series of frames, an accompanying series of dark frames was recorded with the light source blocked.
4. The process above was repeated for each detector.

A single median-combined image was generated from each series of frames. Dark images were subtracted from the corresponding light images to remove background (including stray light, detector dark current, and any thermal emission from the test apparatus). Box photometry was performed on the spots. At each wavelength, spot intensities with the PG in the beam were divided by spot intensities with the PG out of the beam to determine throughput into the three orders.

4.1.2 Results

Zeroth-order and first-order throughput were measured between 0.4 and 1.65 μm. Due to the particular combination of objective lens and detector size available, only the zeroth-order throughput was measured between 1.8 and 2.7 μm. Results are shown in Figures 3 and 4.

4.2 Uniformity testing

Variation in the positioning of the PGs, including errors in the positioning of the linear stage which holds the calibration gas cells and the polarimetry module, will inevitably cause some variation in the set of illuminated locations on the PGs. For this reason, the behavior of the PGs must be as uniform as possible across their surfaces.

4.2.1 Methods

A simple test of the throughput uniformity of a prototype PG across its surface was performed as follows using the Xenics XS-1.7-320 detector:

1. The monochromator slit was imaged by the detector/lens combination.

2. A PG was mounted on a vertically-oriented X/Y stage and placed in the beam between the monochromator and detector. This allowed control of the location at which the incoming beam struck the PG.

3. A series of frames was recorded with the incoming beam passing through each of nine positions arranged in a 3×3 grid on the PG. This process was performed with the monochromator set to each of two wavelengths: 1.3 and 1.65 μm. Immediately before or after each series of frames, an accompanying series of dark frames was recorded with the light source blocked.

4. A series of frames was recorded without a PG in the beam and with the monochromator set to each of two wavelengths: 1.3 and 1.65 μm. Immediately before or after each series of frames, an accompanying series of dark frames was recorded with the light source blocked.

Median combination and background subtraction were performed as in Section 4.1.1. Box photometry was performed on the spots. At each wavelength and grid position, spot intensities with the PG in the beam were divided by spot intensities with the PG out of the beam at that wavelength to determine throughput into the three orders. The horizontal and vertical positions of the grid points, expressed in mm from the center point, were as follows:

-3, -3	0, -3	+3, -3
-3, 0	0, 0	+3, 0
-3, +2	0, +2	+3, +2

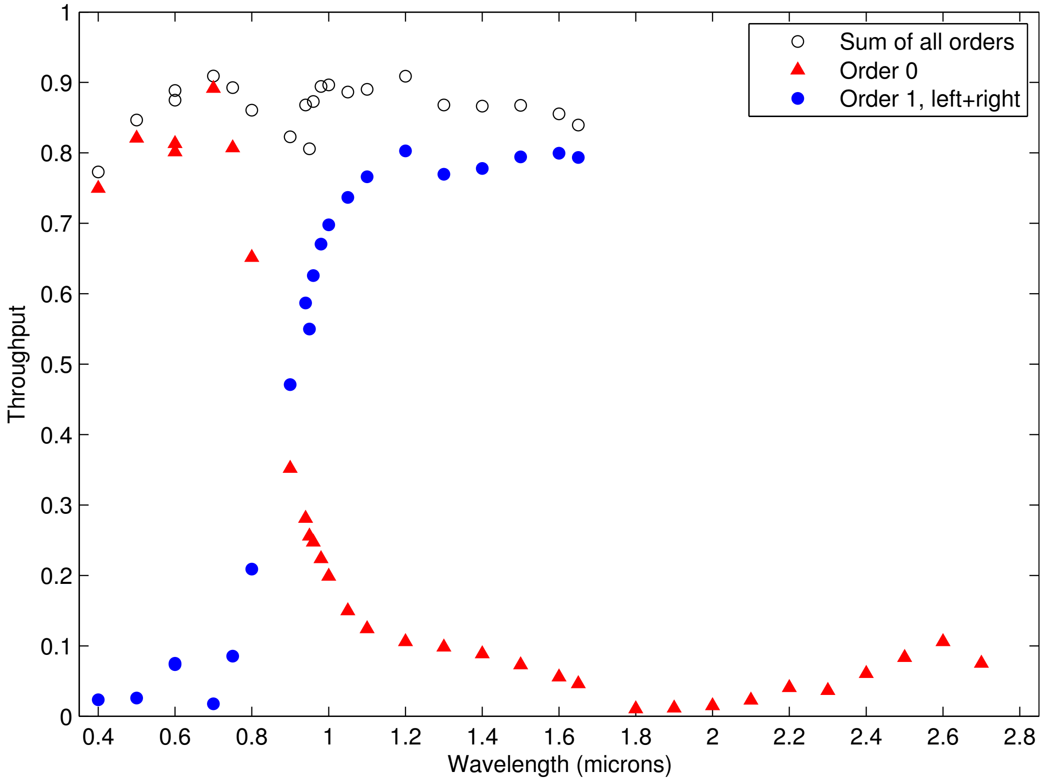

Figure 3. Measured throughput of a single prototype PG. Note the transition in behavior near 0.9 μm. Note that first-order data are not available longward of 1.65 μm.

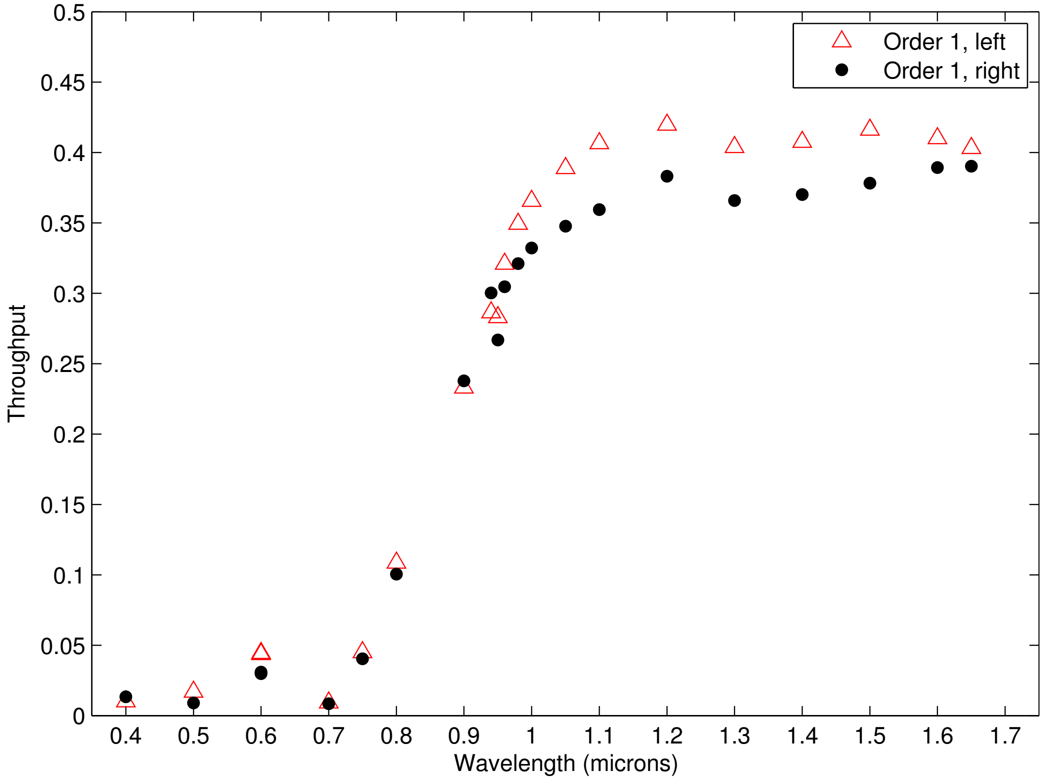

Figure 4. Measured first-order throughput of a single prototype PG.

4.2.2 Results

A 3×3 grid of throughput values was determined for each wavelength and order, with each value being normalized to the value in the center of its grid.

The values for 1.3 μm are:

Order 1, left			Order 0			Order 1, right		
1.028	1.038	1.010	0.788	0.919	1.050	1.030	1.037	1.009
1.039	1	1.006	0.895	1	1.124	1.044	1	1.000
1.041	1.027	1.009	0.888	0.968	1.105	1.047	1.015	1.016

The values for 1.65 μm are:

Order 1, left			Order 0			Order 1, right		
1.039	1.001	1.010	0.724	0.959	1.054	1.015	1.027	0.971
1.023	1	1.011	0.713	1	1.070	1.016	1	0.994
1.007	1.036	0.999	0.660	0.872	1.180	0.998	1.002	0.983

The variation in throughput within each grid of values is:

Wavelength	% Variation Order 1, left	% Variation Order 0	% Variation Order 1, right
1.3 μm	4.1	33.7	4.7
1.65 μm	4.0	52.0	5.7

4.2.3 Analysis

The diameter of the telescope beam at the upstream PG will be approximately 6 mm. If the beam were to shift laterally by, for example, 3 mm, the ratio of the left beam intensity to the right beam intensity could change by as much as 1.2%. In practice, the shift is expected to be smaller than 0.1 mm. PG uniformity is nevertheless critical for good performance. The 10 mm diameter circle at the center of the PGs will need to be uniform to within 0.4% for Stokes V to be measurable to a precision of 10^{-3}.

5. CONCLUSION

The PG-based circularly-polarizing beamsplitter design described in Section 2 provides the following:

1. two parallel, circularly-polarized beams using only two optical elements
2. a telescope focus shift small enough for compatibility with the AO system
3. a single star for use by the AO system
4. acceptable visible-light throughput for use by the AO system
5. acceptable extinction
6. high infrared throughput.

The authors look forward to demonstrating its performance on the sky at the VLT in 2017.

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REFERENCES

[1] Käufl, H.-U., Ballester, P., Biereichel, P., Delabre, B., Donaldson, R., Dorn, R., Fedrigo, E., Finger, G., Fischer, G., Franza, F., Gojak, D., Huster, G., Jung, Y., Lizon, J.-L., Mehrgan, L., Meyer, M., Moorwood, A., Pirard, J.-F., Paufique, J., Pozna, E., Siebenmorgen, R., Silber, A., Stegmeier, J., and Wegerer, S., "CRIRES: a high-resolution infrared spectrograph for ESO's VLT," in [*Ground-based Instrumentation for Astronomy*], Moorwood, A. F. M. and Iye, M., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **5492**, 1218–1227 (Sept. 2004).

[2] Packham, C., Escuti, M., Ginn, J., Oh, C., Quijano, I., and Boreman, G., "Polarization Gratings: A Novel Polarimetric Component for Astronomical Instruments," *Publications of the Astronomical Society of the Pacific* **122**, 1471–1482 (Dec. 2010).