INTEGRATED OPTIC SEGMENT PISTON SENSOR FOR
THE GMT

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Abstract. Integrated Optic Piston Sensor (IOPS) for the Giant Magellan Telescope (GMT)[1] uses single mode laser written waveguides to measure segment piston of the GMT primary mirrors. Light in the H-band (from 1.5 to 1.6 µm) incident on each segment originating from an off-axis guide star is coupled into separate laser written single mode waveguides in a fused silica substrate. Light from neighbouring segments is interfered in several coupling regions where waveguides are in spatial proximity allowing coupling, in order to produce an interference signal at the output. The output signal intensity is directly related to the phase difference at the waveguide input, originating from the segment piston.

IOPS is located in the on-instrument wavefront sensor of the GMT, which includes a deformable mirror for low order aberration correction. IOPS is designed to work with the Laser Tomography Adaptive Optics (LTAO)[2] system. Small residual tip-tilt modes caused by atmospheric dispersion at the IOPS input will reduce performance significantly as these modes are seen by IOPS as segment piston. This aliasing effect also exists for higher order modes, but with a reduced magnitude. The input of IOPS is dithered by a small amount with a steering mirror in order to measure and minimise residual tip-tilt. Segment piston sensitivity of less than 35 nm RMS is achieved with Strehl at the IOPS input greater than 15% with a detector integration time of 7.5 seconds and dithered input.

1 Introduction

The extremely large telescopes (ELTs) currently in design have such overwhelmingly large primary mirrors as to necessitate the use of segmented mirrors. The simplicity of producing many like segments to complete a large primary mirror outweighs the drawbacks of not having a single optical surface. One of the biggest challenges with a segmented primary mirror is phasing the segments to produce a single optical surface and achieve a diffraction limited image. In this paper we propose a phasing system for the Giant Magellan Telescope (GMT) which utilises an integrated optic phasing sensor to measure segment piston.

Integrated optics have been in development for photonic applications[3] such as all optical routing and integrated components. Integrated optics contain optical elements within a substrate material which perform operations on optical signals presented to the device. The properties of light is used in elements such as waveguides and Bragg gratings to control how light moves through the integrated optic. Optical signals can be spectrally, spatially, or temporally filtered, amplified or attenuated, split and combined in a single integrated optic device. As an integrated optic device IOPS is made up of waveguides within a single substrate.

1.1 Laser written waveguides

Waveguides are regions of a material in which light of a certain wavelength is well contained. Light will follow a waveguide along a path for significant distance without great attenuation.

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Typical waveguides consist of a cylindrical region of higher refractive index in a substrate. The refractive index contrast between the waveguide and surrounding material is typically on the order of $10^{-3}$. This contrast can be achieved in several ways, such as with chemical dopants introduced locally (such as a fibre optic cable), or by permanently altering the material with nonlinear interaction (such as laser written waveguides).

Laser written waveguides are a recent technology allowing for the production of high quality waveguides with three dimensional structure in a substrate. They are typically produced in fused silica with high power femtosecond laser pulses in the infrared. The high intensity laser light produces a permanent local defect in the substrate, resulting in a refractive index contrast of around $10^{-3}$. Waveguides are produced by translating the substrate on a high precision stage, allowing for any structure of waveguides to be produced in 3D within a substrate. This allows for the development of sophisticated optical circuits, in which coupling between waveguides can be utilised to measure any phase difference between primary mirror segments with IOPS. Laser written integrated optics offer an exciting new way of providing integrated optic components in astronomy[4][5], as the waveguides can be written in 3D allowing for near-arbitrary waveguide layout. Integrated optics in astronomy have been demonstrated as pupil remapping for the Dragonfly project[6].

1.2 Coupled waveguides

Light propagating along an optical waveguide is contained within that waveguide in the form of an optical mode. The mode shape is the intensity profile along the cross section of the waveguide. These modes extend evanescently beyond the waveguide due to the electromagnetic properties of light. If another waveguide is brought in proximity to this evanescent field, it can be captured within that waveguide. Fig. 1 shows two waveguides in profile at different propagation lengths $z$. A mode is first ($z = 0$) in the right waveguide with the mode profile extending evanescently into the left waveguide. Proximity of the two waveguides for sufficient propagation length (typically a few millimetres to centimetres) can result in all of the light being transferred from the waveguide in which it is first coupled into the waveguide in proximity.

One coupling length ($L_c$) is the propagation length required for light to transfer from one waveguide to its neighbour. In Fig. 1 an initial mode within one waveguide ($z = 0$) is evenly split between the two waveguides after propagating half the coupling length ($z = L_c/2$), before the entire mode is transferred to the left waveguide after one coupling length ($z = L_c$).

Fig. 1. Light is contained in the right waveguide at propagation point $z = 0$, with an evanescent field overlapping another waveguide. At half the coupling length ($z = L_c/2$) the light is equally distributed between both waveguides. At the coupling length ($z = L_c$) the light has been completely transferred to the left waveguide.
The coupling ratio (the relative amount of light coupled from one waveguide to another) is determined by the rate of coupling and the coupling length (the length of waveguide which is in proximity to a coupled neighbour). For a particular waveguide design and wavelength, the coupling ratio is controlled with the coupling length and waveguide proximity to achieve the desired ratio.

If two coupled waveguides each contain an optical signal, the output will contain mixture of both signals. The intensity of the outputs will depend on the phase difference between the two signals. This is caused by constructive and destructive interference between the two signals in the coupling region, where the phase of each signal is added.

1.3 IOPS waveguide design

The waveguides are written along the length of the fused silica substrate, following a path which performs the coupling required in IOPS. The propagation length of each waveguide before the couplers must be equal in order to maintain the same relative phase between the waveguides. Waveguides at the input and output should be orthogonal to the face of the substrate, in order to ensure efficient input and output coupling.

The IOPS design requires two coupling ratios, 50:50 and 67:33 to ensure equal distribution of light between all outputs. A waveguide diameter of 10 µm with circular geometry and numeric aperture of 0.13 allows for single mode operation and high transmission (< 0.1 dB cm⁻¹) over the wavelength range of 1500-1600 nm in H-band. This numeric aperture in fused silica (refractive index n = 1.46) requires an index contrast of 5.8×10⁻³.

The coupling between waveguides is achieved with proximity of another waveguide. Fig. 2 shows a 2D schematic of the waveguides and location of coupling regions. The couplers each work in the same way, though their function can be quite different. This arrangement of waveguides will be folded and modified to fit within the substrate to match the input and output waveguide positions.

The first coupling region has a coupling ratio of 67:33. The smaller component is next utilised at coupler 3, while the larger component is split at coupler 2.

The second coupling region splits the larger ratio component from coupler 1 with a ratio of 50:50. One component of this ratio is used as a reference for normalisation of the outputs. The
reference waveguide does not have an input, and so does not need to begin before this coupling region. The length of this waveguide has no impact on its function. The other component of this coupler travels to coupler 3.

The final coupling region combines the signals from two neighbouring segments. This coupler is functionally different from the previous two in that its function is not to split the signal, rather to interfere two signals. Each waveguide at the input to this coupling region contains light from corresponding neighbouring segments. Light couples between the two waveguides to produce a combined and complimentary signal in each output waveguide. The intensity of light in each waveguide at the output of the coupler depends on the phase difference at the input to this coupler. All waveguides leading to this coupler must be the same length in order to preserve the phase difference between signals. After this coupler the length of the waveguides may be different by any amount. The final waveguide design will be calculated to maintain phase difference between waveguides before this coupler in the upcoming design cycle, along with final waveguide parameters and prototypes.

2 IOPS Performance

The performance of IOPS is measured in a simulation as the difference between the actual segment piston of that simulation, and the segment piston as measured by IOPS. This IOPS segment piston error is influenced by several factors including the magnitude of the star, the residual wavefront error incident on IOPS, low order Zernike modes aliasing, and detector noise. Any differential tip-tilt between IOPS and the tip-tilt sensor arising from atmospheric dispersion also induces some error into the measured segment piston. Each source of IOPS error is looked at individually and the accumulated error presented in Section 2.6. Low order Zernike modes and tip-tilt modes at the input of IOPS are of greatest concern as these modes will appear to IOPS to be segment piston (aliasing).

2.1 Segment piston arising from low order Zernike modes

Static or quasi-static low order Zernike modes (including tip-tilt) at the input of IOPS will arise from component misalignment, non-common path aberrations between IOPS and the truth wavefront sensor, and anisoplanatism arising from the off-axis angular distance of the tip-tilt guide star. Aliasing occurs through IOPS because each input takes light from one entire segment, effectively averaging the phase over that segment. Low order Zernike modes are highly asymmetric with regard to the GMT pupil, resulting in some modes with significant average phase difference between two neighbouring segments. Other segment piston sensors which only use light from the closest edge of two neighbouring

Fig. 3. Left: A coma mode with peak to valley of 100 nm on the GMT pupil in nm. Right: Segment piston for this coma mode as seen by IOPS in nm (the average phase over each segment).
segments avoid this aliasing because the phase between the regions of each segment captured does not vary greatly. By taking light from the entire segment, we are able to use fainter stars and increase the sky coverage.

Fig. 3 shows a coma Zernike mode with peak to valley of 100 nm on the GMT pupil, and the segment piston IOPS detects as a result of this mode. This mode is not symmetric to the GMT pupil, and IOPS will measure a segment piston for each segment except the central segment. The magnitude of the error is less for higher order modes because the average phase over a single segment is reduced. The truth and dynamic calibration sensor in the OIWFS will measure these modes, and they will be corrected in closed loop with the DM in the OIWFS. The residual low order modes after this correction and the LTAO system[2] depend on the off-axis distance of the guide star. 30 and 60 arc second off-axis guide star results in IOPS segment piston error of 16 and 39 nm RMS respectively.

2.2 Dithering the IOPS input to measure and correct tip-tilt

There may be some residual (< 10 mas) tip-tilt on IOPS due to atmospheric dispersion between the K-band used for tip-tilt, and the H-band used for IOPS. Any tip-tilt on IOPS will be measured as significant segment piston and will reduce coupling efficiency of light into the IOPS waveguides due to the shift in spot position.

IOPS can measure tip-tilt with a dithered input by measuring the coupling efficiency of all the segments. The coupling efficiency of a segment is measured with the reference output. Taking the average signal from all reference outputs it is possible to calibrate and then calculate the tip-tilt incident in IOPS. A larger tip-tilt will reduce the coupling efficiency as the spot at the input moves off the centre of the waveguides, lowering the coupling efficiency.

While the magnitude of tip-tilt on the input is simple to calculate using the reference outputs, the direction of the tip-tilt mode can only be measured by dithering the input to IOPS by a small amount. This is because tip-tilt in any direction will reduce the coupling efficiency by the same amount, due to the circular symmetry of the waveguides and input spot. By dithering the input it is possible to correlate the dither direction with the coupling efficiency and derive the tip-tilt magnitude and direction. A closed loop with a steering mirror for the IOPS input can then be used to correct any residual tip-tilt on IOPS. The dither is performed by tilting the steering mirror in front of IOPS in four directions of equal separation and magnitude. The mirror remains in one of these positions for the one integration period of the detector, with a complete dither taking four detector integration periods.

![Fig. 4. IOPS segment piston error as a function of residual wavefront error from the GMT LTAO system.](image)
2.3 IOPS performance with wavefront aberrations

Fig. 4 shows the IOPS segment piston error for several residual wavefront error incident on IOPS. The IOPS segment piston error increases with the wavefront error, a dramatic increase in error is seen above 400 nm RMS residual wavefront. This is due to the degradation of the spot at IOPS input, with multiple lobes and speckle appearing in the image. The lobes and speckle in the image are caused by phase discontinuities which perturb the phase at the input enough such that it can no longer always give an accurate representation of the input phase[7].

2.4 Limiting magnitude and detector noise

The detector performance and total throughput of IOPS will determine the limiting magnitude of the guide star which can be used for segment piston measurements with IOPS.

Fig. 5 shows the IOPS segment piston error as a function of guide star magnitude. A flat wavefront with some segment piston was presented to the IOPS simulation. The detector integration time and guide star magnitude are varied and segment piston error calculated with an estimated throughput of 50%[7]. The simulation also includes photon noise and sky background with a bandwidth of 100 nm in the H-band of 349 photons per second per segment at IOPS input, with a 10 mas field stop. The signal to noise ratio is optimised by taking the higher flux signal of two related outputs.

2.5 IOPS Bandwidth

IOPS will operate with a bandwidth of 100 nm, from 1500 nm to 1600 nm. While the integrated optic is designed to work over this bandwidth, the coupling region which interferes light from neighbouring segments is optimised for a narrowband signal. The bandwidth will add a small error to the IOPS segment piston measurement because the coupling coefficient (which determines how much light is coupled between waveguides) depends on the wavelength. A simulation was conducted to assess the impact of this bandwidth on IOPS performance. A flat wavefront of 1500 and 1600 nm were propagated separately through IOPS. Segment piston was calculated using the average of these two outputs and the segment piston error arising from these wavelengths was found to be 6 nm RMS.
2.6 Total IOPS error

Each source of IOPS segment piston error has been simulated in isolation to reduce simulation development time and complexity. It is possible to add the error from each source in quadrature to arrive at a total IOPS segment piston error, assuming the errors are independent.

The largest contributors to the IOPS segment piston error are from residual wavefront error and static low order Zernike modes. The residual tip-tilt, detector noise and bandwidth each contribute around 5 nm of error to the system. Table 1 shows a summary of the segment piston error for a tip-tilt guide star 30 and 60 arc seconds off-axis, with 10 mas residual tip-tilt corrected in closed loop to 5 nm, with a magnitude $m_H = 17$ guide star using part of the H-band with 100 nm bandwidth (from 1500 nm to 1600 nm), and detector with readout noise of 20 e⁻ (Fig. 5). IOPS exceeds the requirement of 35 nm RMS segment piston sensitivity with a guide star 30 arc seconds off-axis, but does not meet the requirement at 60 arc seconds off-axis due to large low order Zernike mode contribution from anisoplanatism.

Table 1. IOPS segment piston error sources and total. Residual WFE: 270 nm (30''), 370 nm (60'') with 0 nm static segment piston, low order Zernike modes excluding piston, tip-tilt and focus, 10 mas residual tip-tilt corrected in closed loop for 60 s, $m_H = 17$ magnitude guide star, detector with readout noise of 20 e⁻, 100 nm bandwidth.

<table>
<thead>
<tr>
<th>Error source</th>
<th>30'' (nm RMS)</th>
<th>60'' (nm RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low order Zernike modes</td>
<td>16</td>
<td>39</td>
</tr>
<tr>
<td>Residual wavefront</td>
<td>5</td>
<td>26</td>
</tr>
<tr>
<td>Residual tip-tilt</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Detector noise</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>18.60</strong></td>
<td><strong>47.56</strong></td>
</tr>
</tbody>
</table>

3 Mechanical and optical design

3.1 IOPS Detector

The IOPS detector collects light from each output over a specified integration time. The detector consists of a linear array of Indium Gallium Arsenide (InGaAs) photodiodes, each collecting a single IOPS output. An InGaAs detector is used for its high sensitivity around the H-band and low dark current at cryogenic temperatures.

A Hamamatsu InAgAs G9203-256D linear photodiode array is chosen as the detector for IOPS, as it provides high sensitivity over the wavelength range 1500 to 1600 nm. The pixels are arranged in a linear array with 50×500 µm size, with a pitch of 50 µm. The total length of the active area is 12.8 mm.

3.2 Optical Design

IOPS receives a pupil image in H-band, positioned by the dichroic steering mirror in the OI-WFS. The OIFWFS does not provide pupil derotation, resulting in a requirement for IOPS to rotate with the pupil to maintain segment stability on the lenslet array. The pupil size on the lenslet array is 1.5 mm, with each segment having a diameter of 0.5 mm. A pupil mask sits in
front of the lenslet array to increase IOPS tolerance to rotation error. The pupil mask increases the tolerance of IOPS to rotation error by preventing light from neighbouring segments hitting a lenslet. The pupil mask is defined with a segment pupil radius 5\% less than the segment pupil image radius. Small rotation errors will be blocked by the increased gap between segments caused by the mask. Additionally any defects in the lenslet array at the lenslet boundaries will be blocked by the mask, reducing the risk of scattered light entering the waveguide substrate.

The lenslet array consists of hexagonally arranged lenslets. Each lenslet collects light from a single segment and focuses it on one IOPS input waveguide. Each subaperture is 0.5 mm in size, aspherical in design, has a numeric aperture of 0.13 and focal length of 1.923 mm. This numeric aperture matches well with the waveguides of IOPS, resulting in good coupling into each waveguide. The spot position of each lenslet will be measured on the manufactured lenslet array, and used as the starting coordinates for each input waveguide.

IOPS has 21 outputs, three coming from each input. A single detector collects light from each output over an integration period. The maximum divergence at the output of each waveguide is governed by the numeric aperture. The divergence angle is given by the formula $\theta = \sin(N.A.)$. For a numeric aperture of 0.13 the divergence angle is 7.5\(^\circ\). The detector active area is < 0.4 mm from the output of IOPS, giving a spot size diameter of approximately 50 \(\mu\)m.

3.3 Mechanical Design

Fig. 6 shows a cutaway mechanical design of IOPS. The detector, waveguide substrate, and lenslet array are rigidly mounted together and rotate with a stepper motor. A flex circuit connects the detector throughout rotation.

References