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# A Novel Wavefront Sensor for Solar Adaptive Optics Based on Integrated Photonics

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## ABSTRACT

In this work, a novel kind of wavefront sensor (WFS) for adaptive optics in solar physics based on integrated photonics is proposed. Shack-Hartmann and plenoptic sensors are limited to pupil sampling of approximately 8 cm because they need a solar granulation image with a minimum contrast to be able to compute displacements. To overcome this limitation and effectively use existing deformable mirrors with thousands of actuators, a novel WFS is proposed, which will be able to obtain wavefront phase differences of the beam with higher pupil sampling. The proposed WFS can increase the resolution and speed with respect to the other sensors as the incoming wavefront is obtained by passing the wavefront through optical fibres to the Integrated Photonics - Wavefront Sensor (IP-WFS) and directly measuring the phase differences without the generation of images. In the same way as Shack-Hartmann and plenoptic sensors, the proposed IP-WFS delivers data about the phase differences on the incoming wavefront to subsequently use this information to calculate the deformable mirror actuation. Consequently, the integration of the proposed IP-WFS in the current systems of adaptive optics can be performed without having to make drastic modifications to the existing instruments.

**Keywords:** Solar physics, Adaptive Optics (AO), Photonic Integrated Circuit (PIC), Integrated Photonics - Wavefront Sensor (IP-WFS)

## 1. INTRODUCTION

An adaptive optics system (AOS) is a popular observation technique that recreates and corrects the distorted wavefront caused by inhomogeneities in the atmosphere [1]. Temperature variations generate turbulent movements in the atmosphere. Those variations change atmospheric density and, hence, the refraction index of the atmospheric profile. Therefore, due to the atmosphere, the phase of the observed beam varies until it reaches a ground-based telescope [2]. The AOS technique requires at least three elements [3]: a wavefront sensor (WFS), which measures the perturbations generated as a consequence of the atmospheric turbulence; a wavefront corrector element, e.g. a deformable mirror (DM), to correct the atmospheric aberrations sensed by the WFS; and the control electronic,

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which generates the actuation information from the measured aberrations. These elements are shown in figure 1, which contains a general AOS structure.

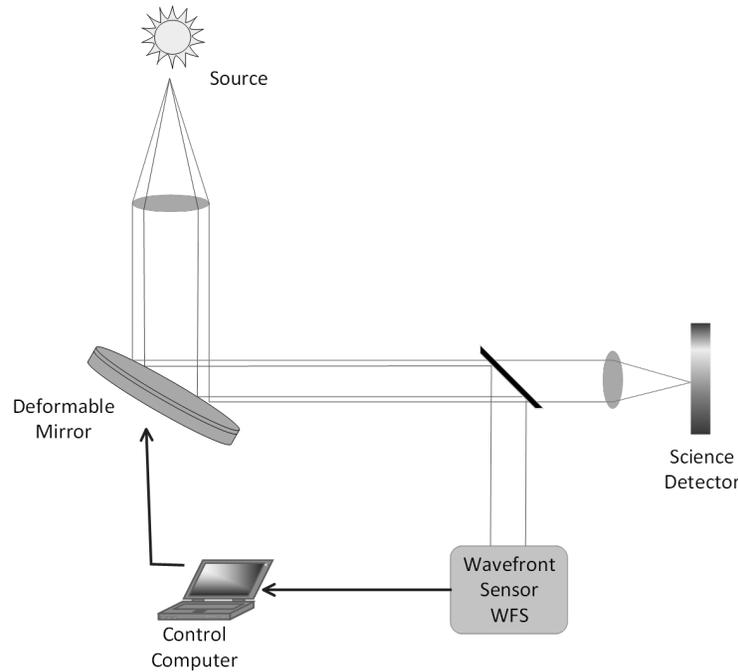


Figure 1. An adaptive optics general system. This diagram shows the principal components of an AOS. Light coming from a distant source is focused by a telescope (not shown) and then colimated to impinge the DM, whose output is split into two light beams; one goes directly to the science sensor, and the second beam goes to the WFS to be measured. Then, a control system calculates the deformable mirror slopes and the corresponding actuator values to change the shape of the mirror in order to compensate the measured wavefront aberrations.

Adaptive optics systems are employed in night- and day-time observations. However, wavefront sensors measure the input signal (the reference wavefront) using different techniques in both cases [4],[5]. Night-time observations use a natural or a laser guide star (LGS) as their reference, whilst in day-time observations for astrophysics, the reference wavefront is a structure of the sun, including granulations, pores or sunspots. In this case, the reference wavefront is an extended and faint structure, instead of a point object. Several considerations should be taken into account in solar observations. For instance, image resolution is affected as a consequence of the extended low contrast object; day-time observations are also greatly affected by ground effects that get worse as the day moves forward (bad seeing) [6],[7], and important science cases related to the sun are found in visible wavelengths.

Wavefront sensors, including pyramid [8], curvature [9],[10] and Shack-Hartmann [11], are very popular in AOS applications. At present, solar telescopes, such as the Daniel K. Inouye Solar Telescope (DKIST), Gregor Telescope [12], New Vacuum Solar Telescope (NVST) [13], Swedish Solar Telescope (SST) [14], and Vacuum Tower Telescope (VTT) [15] use the Shack-Hartmann sensor as their principal WFS. Furthermore, technologies related to plenoptic cameras have been studied as WFS in solar AOS [16],[17]. However, the Shack-Hartmann sensor and plenoptic cameras are limited in the pupil resolution they may achieve for solar observations. These sensors create sub-aperture images to calculate phase differences that require a minimum equivalent pupil size in the range of 8 cm to obtain an acceptable contrast, which is good enough to compute displacements. Furthermore, new optical techniques that imply a large number of sensors to correct vast atmosphere volumes, such as multi-conjugate adaptive optics (MCAO), are nowadays in development. This technique will improve the resolution and sensitivity

of the adaptive optics results, as is the case regarding the future European Solar Telescope (EST). [18].

Nowadays, electronics and photonics integration is used in astrophysical applications [19],[20]. For instance, the Fibred Imager for a Single Telescope (FIRST) is a module belonging to the science instrument SCExAO (Subaru Coronagraphic Extreme Adaptive Optics) installed in the Subaru Telescope. The instrument is an ultra-high angular resolution spectro-imager that combines techniques of the aperture masking and spatial filtering of the wavefront using a single-mode fibre array to calibrate images and measurements beyond the telescope diffraction limit [21],[22] to determinate exoplanet atmospheres. Furthermore, a photonic lantern wavefront sensor (PLWFS) has been proposed as a complementary part in AO systems [23]. This WFS reconstructs the focal plane image using a photonic lantern. This device is composed of a multi-mode waveguide which is then divided to form many individual single-mode waveguides. Then, a neural network learns the relation between the phase (lantern input) and intensity (lantern output) of a beam [24].

The Integrated Photonics - Wavefront Sensor (IP-WFS) presented in this work uses an integrated photonics technology to measure the phase difference of an incoming wavefront in the visible wavelength employing the interference principle. Nowadays, component miniaturisation has led to the development of small-scale amplifiers and interferometer devices. The optical interference basis has been used in practical applications such as wavefront measuring in adaptive optics [1], [25], [26], [27]. Creating an image to obtain phase measurements is no longer necessary; therefore, the identification of an extended structure to estimate slopes, as in a traditional sensor, is not needed. The IP-WFS will measure the phase differences in the pupil after its decomposition in single-mode fibres.

The paper is organised as follows. In section 2, the self-image principle is introduced. Section 3 details the sensor location within the general AOS and the main modules of the IP-WFS. Photonic components such as multimode interferometers, semiconductor amplifiers and phase modulators are detailed. Finally, the phase differences calculation employed by the integrated photonics circuits is explained.

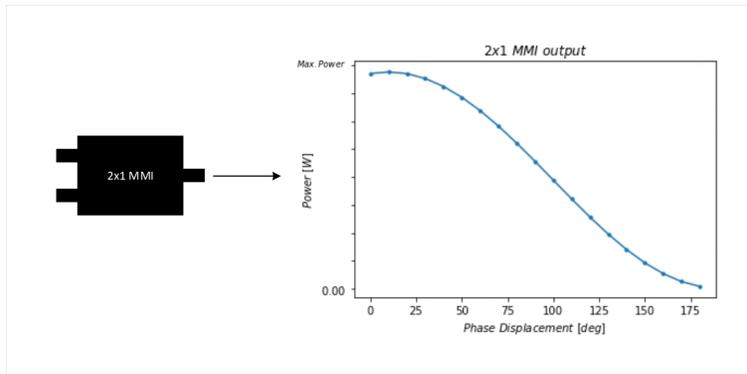


Figure 2. 2x1 MMI output power response. The simulation was done with two lasers in the MMI input, constant amplitude, constant frequency, and variable phase in one laser. The curve shows the coupler behavior after the phase change. Simulation in VPIphotonics software.

## 2. THE SELF-IMAGING PRINCIPLE

The IP-WFS employs the interferometry technique to calculate phase deviations in the beam. Interferometry uses the constructive and destructive addition of radiation to quantify information about a source [28]. The proposed sensor uses a photonic multimode interferometer (MMI) coupler. This component uses the "self-imaging" principle, which states the following [29],[30]: *Self-imaging is a property of multimode waveguides by which an input field profile is reproduced in single or multiple images at periodic intervals along the propagation direction of*

the guide.

The MMI is a multimode waveguide that is excited by a coherent light in the input (a mono-mode input). Due to the "self-imaging" principle, this input is reproduced in single or multiple images in a periodical way along the propagation direction of the guide. These images contain original input properties, and the intensity is distributed proportionally in each image. Figure 2 shows a 2x1 MMI component. The MMI input and output are optical signals, and to obtain an electrical response a photodiode should be used. Figure 2 shows the output response when two laser signals enter the 2x1 MMI. The laser has the same amplitude and frequency, but one laser changes its phase. It is observed that the power output is affected by the change of phase of one of the waves. This means that it is possible to calculate the displacement between the two signals using power measurements.

### 3. THE IP-WFS PROPOSAL

Wavefront sensors of the Shack-Hartmann type are usually placed in an image of the telescope pupil. A micro-lens matrix covers a pupil image associated with a field stop and creates an array of images of the granulation existing in the field; lateral displacements of the images are computed and converted into estimations of the slopes of the wavefront. Though it is not necessary to create an image to obtain phase differences with the proposed IP-WFS, the sensor has to be located along the optical axis where the pupil image is formed. This pupil image is covered by an optical-fibre matrix that corrects a small field, such as in a single conjugate adaptive optics (SCAO) system. The sensor corrects a small field containing the same turbulent distribution at every point. The proposed wavefront sensor measures fibre-by-fibre the light using integrated photonics technology to obtain the phase differences of the incoming beam wavefront. Figure 3 shows the general configuration of an AOS using the new IP-WFS. The beam enters the IP-WFS through a single-mode fibre array. The IP-WFS calculates the phase differences using photonic interferometer devices. Finally, sensor output data are sent to a traditional control unit to adjust the DM.

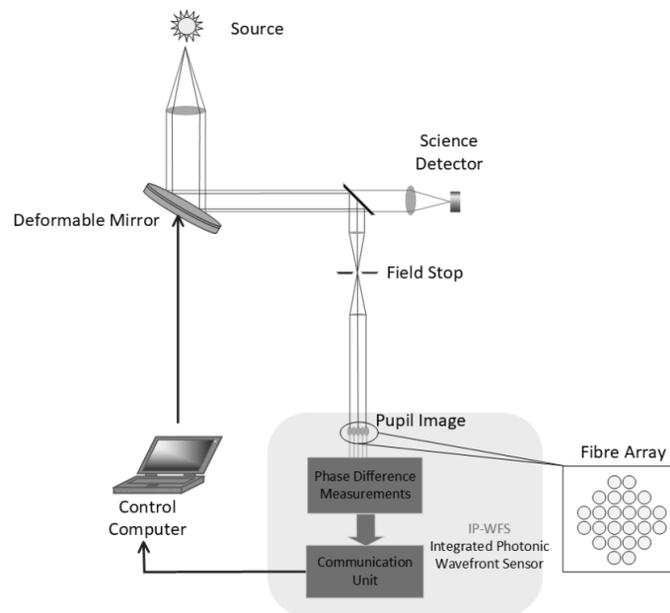


Figure 3. The Integrated Photonics - Wavefront Sensor (IP-WFS) in a general adaptive optics system. Here the beam of light is shown going into the IP-WFS. A collimated beam reaches a single-mode fibre array located in an optical image of the pupil of the telescope. The array carries the light into the integrated photonics chip. Then, using the communication unit, the wavefront data obtained are sent to the general AO control system. Finally, the control system computes the required actuations and commands the deformable mirror.

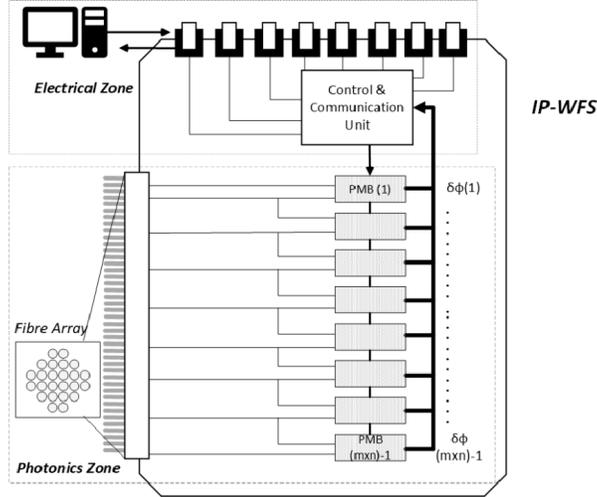


Figure 4. Block diagram of the IP-WFS. The sensor contains two principal modules: A) the photonics zone, composed of the optical-fibre array and the phase measure blocks (PMB) and B) the electrical zone including the control and communication unit.

Figure 4 shows the internal structure of the proposed IP-WFS. Optical signals are captured by a single-mode fibre array. After light crosses the fibre array, each pupil sample enters an individual module called a phase measure block (PMB). Each PMB includes two optical inputs and multiple electrical inputs and outputs to control and read the PMB data, as is shown in figure 6. Electrical outputs are connected to a control and communication unit to calibrate, control and read the PMB modules using software. The sensor should read and deliver data faster than the changes occurring in the atmosphere. Typical values for the Fried parameter  $r_0$  and the wind speed  $\nu$  for the visible wavelength are  $\sim 10$  cm and  $\sim 10$  m/s, respectively; therefore, the period of time over which the aberration changes significantly for visible wavelengths is about  $\sim 10$  ms [11]. The interface between the optics and electronics should work as fast as possible. High-speed photoreceptors should be used to deliver information to the general AO control system. The IP-WFS accepts an input beam and provides a set of phase differences at high speed.

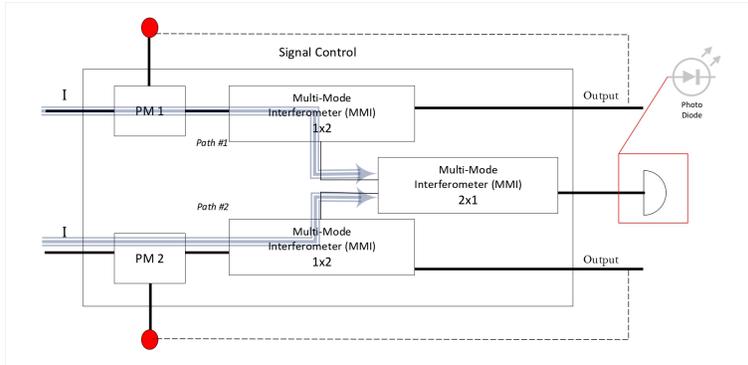


Figure 5. The Phase Measure Block (PMB) during the calibration.

The proposed PMB is configured using MMIs, as is shown in figures 5 and 6. The module contains MMI couplers, phase modulators (PM), semiconductor optical amplifiers (SOA) and high-speed photodiodes. The waveguide material could delay the signals. The PMs are used during the initial calibration to compensate the phase variations produced by the different delays of the waveguides (see figure 5). Then, a constant phase displacement ( $Kn$ ) is set in each PM, as is shown in figure 6. The incoming ray light may have different intensities,

so two  $1 \times 2$  MMI devices and two SOAs are needed to guarantee that both inputs of the  $2 \times 1$  MMI device have the same level of intensity. The self-imaging principle states that the two input intensities of the  $2 \times 1$  MMI will deliver the sum of both the intensities at the output (ideally, if both the inputs are the same, double the intensity). Consequently, Therefore, if the output has double the intensity, both the signals are in phase ( $0^\circ$  displacement). On the other hand, if the output intensity is null or almost zero, the input signals will be in counterphase or destructive interference ( $180^\circ$  displacement).

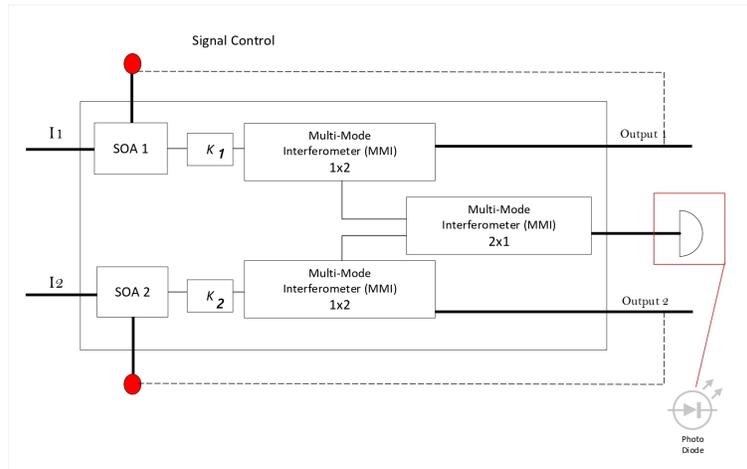


Figure 6. The Phase Measure Block (PMB) after calibration.

#### 4. CONCLUSIONS

A novel zonal WFS for solar AO systems has been presented. The proposed WFS uses photonics technology to obtain phase differences of the wavefront at the pupil image. The self-image principle is used by the multimode interferometer (MMI) component to obtain the desired phase measurement due to interference phenomena. The sensor uses an optical-fibre array to directly introduce the pupil image into the IP-WFS to process the information. Creating and comparing images are not necessary to calculate phase differences with the IP-WFS. For this reason, the phase differences are obtained with high resolution of the pupil plane at high speed. The reconstruction of the slopes is improved and the wavefront reading speed is improved by several orders of magnitude because no camera readout is needed. With the IP-WFS, the resolution and time responses will depend on the DM and control electronics rather than the sensor.

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