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Vectorial adaptive optics – correcting both polarization and phase

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ABSTRACT

Adaptive optics (AO) normally concerns the feedback correction of phase aberrations. Such correction has been of benefit in various optical systems, with applications ranging in scale from astronomical telescopes to super-resolution microscopes. Here we extend this powerful tool into the vectorial domain, encompassing feedback correction of both polarisation and phase. This technique is termed vectorial adaptive optics (V-AO). We show that V-AO can be implemented using sensor feedback, where an imaging polarimeter is used as the analog to the wavefront sensor used in phase AO. Alternatively, correction can be performed indirectly using so-called "sensorless" AO, which for phase AO does not employ a wavefront sensor but uses indirect optimization of the optical performance. Sensorless V-AO takes a similar approach optimizing the vectorial state through indirect optimization in the focal plane. An intermediate quasi-sensorless V-AO method is also shown. We validate improvements in both vector field state and the focal quality of an optical system, through correction for commonplace vectorial aberration sources, ranging from objective lenses to biological samples. This technique pushes the boundaries of traditional scalar beam shaping with feedback by providing control of extra vectorial degrees of freedom, which also paves the way for next generation AO functionality by manipulating the complex vectorial field.

Keywords: Adaptive optics, vectorial field, polarisation

1. INTRODUCTION

Adaptive optics (AO) normally concerns the feedback correction of phase aberrations [1, 2]. However, the performance of certain optical systems is also sensitive to polarization errors. These errors lead to extra phase and polarisation distortion that can be introduced, for example, when focusing through stressed optical elements, due to Fresnel's effects or induced via polarising effects in materials or biomedical tissues [3-6]. These effects directly alter the state of polarisation (SOP) of the light field and the focal quality, hence degrading vectorial information analysis and the resolution of optical systems that compound the effects caused by phase aberrations. Incorrect vector states in the illumination or detection beams are greatly detrimental for polarisation sensitive microscopes, including Stokes/Mueller confocal microscopes, second/third harmonic generation microscopes and super-resolution fluorescence polarisation microscopy [6, 7, 8]. Such effects are vital, e.g., in label-free cancer detection using Stokes/Mueller microscopes, for which the correctness of the vectorial state is essential. On the other hand, incorrect polarisation disrupts the interference at the focus and hence affects the efficiency and resolution of super-resolution microscopes, for example [9-14], in the creation of the zero-intensity center of the ring-shaped STED microscopy or MINFLUX beams; in the interference light fields of the SIM or 4pi microscopes; and even the performance of general wide-field microscopes. Such effects would become more problematic which imaging deeper in samples. We present the concept of vectorial adaptive optics (V-AO) [15] to extend AO compensation techniques into the vectorial beam domain by including polarization. Full polarization and phase correction are implemented using sensor-based methods and "sensorless" approaches. We demonstrate that V-AO can improve the vector field and focus spot quality of optical systems that suffer from combined phase and polarization aberrations.

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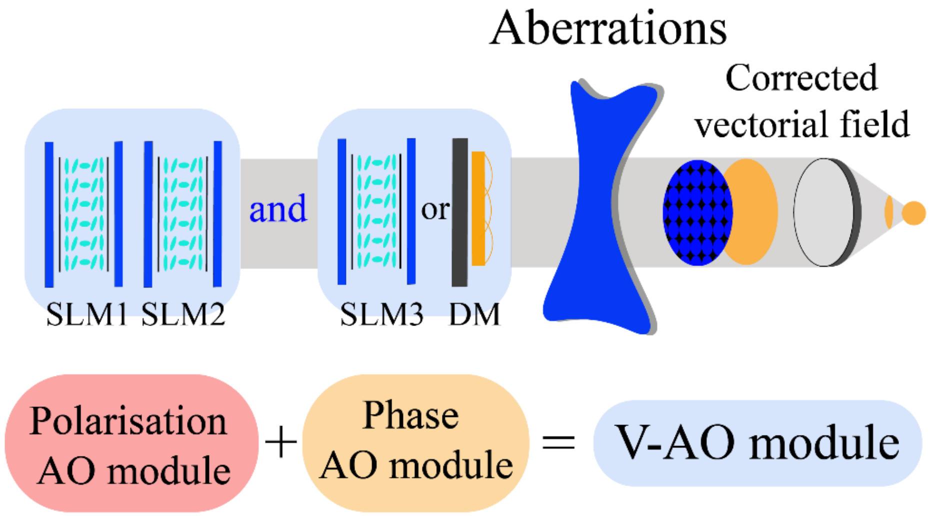

Figure 1: Schematic of V-AO concept. A combination of spatial light modulators (and possible a deformable mirror or other phase corrector) is used to provide full control over the polarization and phase state of light. The output from this system is set so that the desired, corrected vectorial state is obtained after propagation through the aberrating object. Adapted from Ref [15].

2. PRINCIPLES OF VECTORIAL ADAPTIVE OPTICS

Conventional phase AO requires a method of phase measurement to determine the input aberration and a method of phase compensation, which is set to provide correction that has the conjugate phase to the input. Phase measurement can be performed using a wavefront sensor or through indirect optimisation methods, which are termed wavefront-sensorless methods. Phase compensation is usually performed using an adaptive element, such as a deformable mirror (DM) or a liquid crystal spatial light modulator (SLM) [16-20]. The schematic of the setup can be found in Fig.1. V-AO correction is implemented experimentally through three methods: sensor-based, quasi-sensorless, modal-sensorless.

For the sensor-based method, we used an imaging MM polarimeter, which was able to extract the full polarisation properties across the profile of a beam or an object. A complete MM polarimeter consists of a polarisation state generator (PSG) and a polarisation state analyser (PSA). Following the MM measurement of the object using the PSG and PSA, the SLMs were set such that the output SOP after propagation through the object is spatially uniform. This was achieved by setting the patterns displayed by precisely calibrated SLMs, so that the SLMs introduced a pre-compensation aberration, leading to uniform output SOP. Phase aberration can also be introduced by the object, while additionally further phase variations are introduced by the SLMs themselves. Full correction was achieved by first correcting the SOP aberration using the SLMs and then applying phase only correction via conventional sensorless AO.

For the quasi-sensorless method, a polarizer is placed near the pupil (in a conjugated plane) before an additional camera. For each point in the pupil, there is hence an input Stokes vector that maximises the detected intensity and any other state will result in a reduced intensity. This intensity can be mapped onto the surface of the Poincaré sphere. The point with maximum intensity corresponds to the eigenvector of the analyser and hence indicates the optimal state pre-correction that must be applied with the V-AO module. This process can also be carried out in parallel for each single point in the pupil.

For the sensorless method, V-AO correction is achieved with no additional hardware through focal plane measurement alone, taking advantage of prior knowledge of the nature of the vectorial aberration. There are various scenarios where assumptions can reasonably be made about the eigenmode axes of a polarising object. For example, this may occur in stressed optics, such as an endoscopic lens, which exhibits azimuthally or radially distributed birefringence axes, as determined by the intrinsic stress direction; alternatively, in biological samples such as muscle tissue, where the axes follows the stress direction or the alignment direction of the intrinsic fibres [3, 21-24]. While such prior knowledge about symmetry is useful, the value of retardance is often still unknown, such as due to variation from different manufacturing processes for the lens, or the state of the biological tissue so adaptive vectorial correction is needed.

We explain in detail the three methods and their properties respectively in our following work in Ref [15], with demonstrations of the improvement of both vector field and focal spot after correction of commonplace vectorial aberrations.

3. DEMONSTRATIONS

Gradient index (GRIN) lenses focus light through a radially symmetric refractive index profile. Their manufacture involves an ion-exchange process that creates the lens's refractive index profile, but it also causes a radially symmetric birefringence variation [25-28]. Such birefringence effects would introduce polarisation errors to GRIN lens based applications. Hence, here we chose a GRIN lens for demonstration of a real vectorial aberration correction. Fig. 2 shows results comparing before and after V-AO correction. The vector fields, the correction patterns on the DM, as well as focal spot comparisons are given. Those demonstrations validate that the feedback V-AO method can improve the performance of an optical system both in terms of uniformity of the state of polarization (SOP) in the pupil and distortions at the focus.

We validated the experimental feasibility of the quasi-sensorless method sensorless method using a titled waveplate array and a birefringence calibration target as the aberrating object. The formal waveplate array is widely used to generate vector vortex beams, such as for the depletion focus in a STED microscope. We have shown the state before and after correction including the SOP fields, the phase on the DM, the focal spots. The improvement in performance has also been exemplified through comparison of focal spot intensity profiles. Further demonstrations showed compensation of the deleterious vectorial effects of a series of protected silver mirrors, as well as a thin biological specimen.

More details of the mechanisms, as well as further experimental results, can be found in Ref [15].

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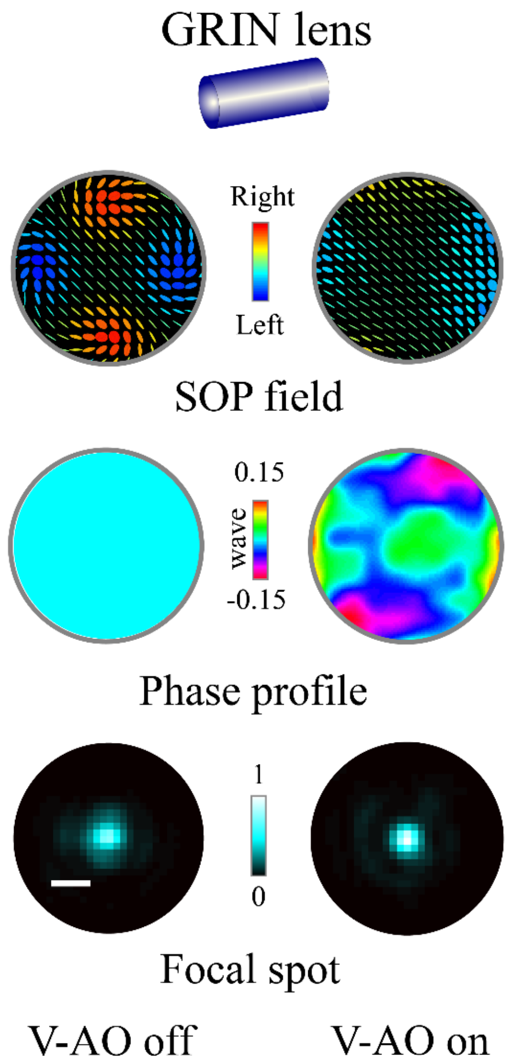

Figure 2: V-AO correction of vectorial aberrations of GRIN lens. The complex vector beam produced after propagation through the GRIN lens is shown in the top left. Following the vectorial AO process, the polarization state becomes more uniform. Correction of the polarization state using the multiple SLM system introduced phase aberrations that were compensated using the deformable mirror. The combined effect of these two steps is to create a uniform state with flattened phase. Observation of the focus shows that the vectorial compensation leads to a diffraction limited spot. Adapted from Ref [15].

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