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Enhancing polarisation imaging through novel approaches to polarimetry and adaptive optics

Chao He[a] & **Martin J. Booth**[a]

[a]*Department of Engineering Science, University of Oxford, Parks Road, Oxford, OX1 3PJ, UK*
chao.he@eng.ox.ac.uk; martin.booth@eng.ox.ac.uk

ABSTRACT

Precise polarisation imaging requires two key aspects – imaging resolution and vector information correctness. Errors in the state of polarisation (SOP) can disrupt these two aspects hence leading to imperfect interference at the focus, and incorrect vector states in the illumination or detection. Those issues will therefore lead to detrimental problems for high resolution polarisation sensitive optical systems, such as Stokes/Mueller confocal microscopes. The SOP errors can be introduced in different ways, which include pre-measurement processes, such as denoising, optimisation, and calibration, which are built on matrix calculation processes which would introduce an error amplification; or, other errors sources in optical systems such as focusing through stressed optical elements, due to Fresnel's effects, or induced via polarising effects in materials or biological tissues.

Here we put forward two techniques to deal with those errors, including next generation polarimetry and next generation adaptive optics techniques. We first show a new polarimetry method that has the ability to map all polarisation analyser states into a single vectorially structured light field, hence all vector components are analysed in a single-shot. We extract the vectorial state through inference from a physical model of the resulting image, providing a single-step sensing procedure. These methods in effect circumvent these method-related error amplification, accumulation and complex preprocessing steps. We then show a new adaptive optics technology that can correct both phase and polarisation aberrations within the optical systems. We validate improvements in both vector field state and the focal quality of an optical system, through correction for commonplace vectorial aberration sources.

Keywords: Polarimetry, microscopy, adaptive optics

1. NOVEL POLARIMETRY

Optical polarimetry plays important role in lots of research fields, such as remote sensing, material characterizing, or biomedical diagnosis [1-15]. The precision and accuracy of such methods are of paramount importance. Numerous techniques for polarimetry have been put forward in the past decades. But if we summarise their commonality, they 1) directly or indirectly use matrix calculation to calculate the vector components of the light; 2) require the processes of denoising, optimization, and calibration to take place before the measurement. Those properties limit the sensing ability via the accumulation of various errors [1] (such as the widely-appreciated minimum error propagation amplification induced by the matrix calculation process, which will always exist).

Here, we put forward a new measurement paradigm based on a novel physical concept to circumvent such limits, hence a notable departure from previous methods that rely upon matrix based calculations: rather than solving for the vector polarisation components in the conventional cumbersome way, we convert this complex task into an intuitive problem that is equivalent to searching for the maximum intensity point in an image. This is achieved through the use of a single, vectorially structured, light field (known as a Full Poincaré Beam (FPB) [16, 17]).

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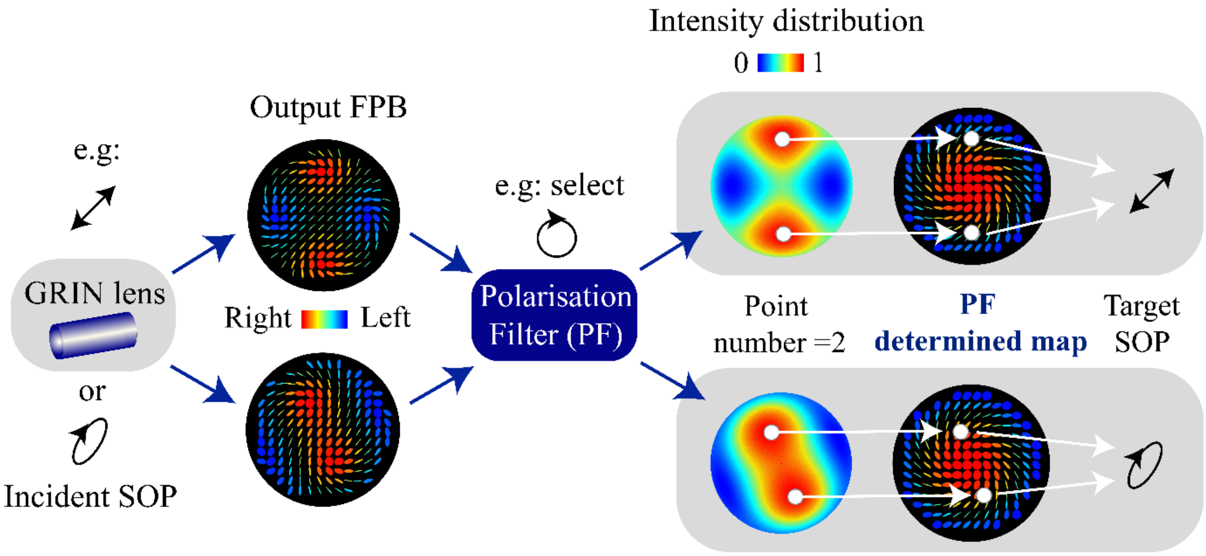

Figure 1: Concepts and mechanisms of the new sensing paradigm. Adapted from Ref [17].

Figure 1 illustrates how our new paradigm works, utilizing a simple GRIN lens system as an example. As we can see in Fig. 1, a FPB is generated after this passes through the GRIN lens. The output vector field is then filtered via a polarisation filter assembly leading to a non-uniform intensity distribution that can be recorded by the detector. Intuitively, one can understand that the brightest points within the intensity distribution must correspond to the eigenstate of the filter, and the positions of these points depend upon the input state. Hence, a link between incident Stokes vector and the recorded brightest point locations can be made, which also can be harnessed to enable new polarisation sensing method. The method presents new prospects for sensing that is more directly linked to the vector state, rather than indirect estimation via a matrix calculation.

2. VECTORIAL ADAPTIVE OPTICS

Adaptive optics (AO) is widely used to perform feedback correction of phase aberrations in a range of applications, from the inter-galactic scale of astronomical telescopes to the molecular level in super-resolution microscopy [18-30]. However, in polarisation imaging, the effects of polarisation distortion are also of importance for imaging quality. Here, we also put forward a new AO method – named vectorial adaptive optics (V-AO) – to correct the polarisation aberration as well as its associated phase aberration. Figure 2 illustrates this new approach. Central to this method is a versatile vectorial field compensation system consisting of two liquid crystal spatial light modulators to fully control the output state of polarisation (SOP) and a deformable mirror to compensate for phase.

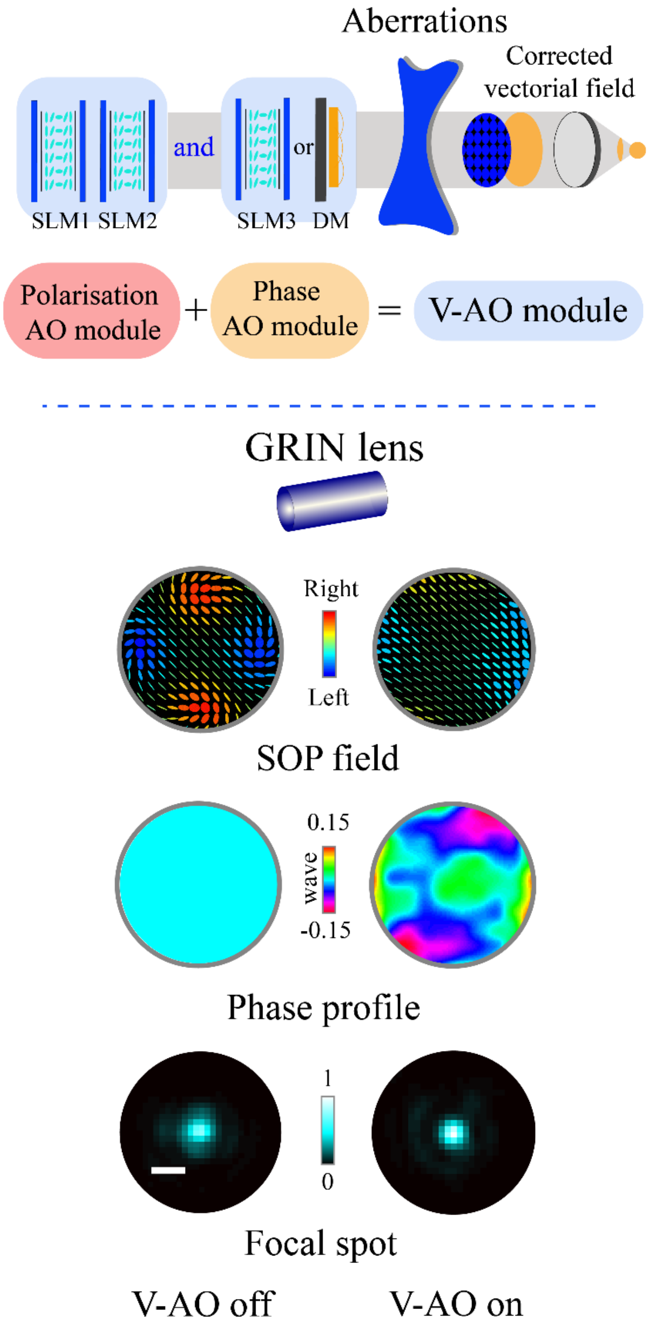

Figure 2: V-AO setup and aberration correction of GRIN lens. SLM: spatial light modulator. DM: deformable mirror. Adapted from Ref [21].

We also show experimental results in Fig. 2, which indicate the mitigation (via V-AO) of the effects of polarisation aberration of a GRIN lens. GRIN lenses are widely used for compact imaging systems and microscopy; applications span across connectors for quantum chips to biopsy probes for clinical diagnosis. GRIN lenses suffer from a rotationally symmetric birefringence variation that is concomitant with their symmetrical graded index profile. This property is considered as a nuisance as it introduces a vectorial perturbation that disrupts GRIN lens based imaging systems; these perturbations cannot be compensated via traditional phase AO. Therefore, widespread adoption of GRIN optics in sensitive systems is hindered. Similar experiments were conducted following the same process in Fig. 2. The figure shows results comparing before and after correction. The vector fields, the correction patterns on the deformable mirror, as well as focal spot comparisons are given. These demonstrations show that the feedback sensor-based V-AO method can improve the performance of an optical system both in terms of uniformity of the SOP in the pupil and distortions at the focus.

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