Reconfigurable Spatial-Mode Sorter for Super-Resolution Imaging

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Abstract: We build a reconfigurable spatial mode sorter for super resolution imaging using a spatial light modulator (SLM). Our system can easily adapt to sort different, mutually non-orthogonal, spatial mode bases.

High-resolution optical imaging appears in diverse application spaces involving both active (e.g., LIDAR, surface topography) and passive (e.g., fluorescence microscopy, astronomy) sensing needs. Spatial-mode demultiplexing (SPADE), where spatially overlapping component modes of an information-bearing incident field are sorted prior to detection, has recently been identified as a promising tool to enhance quantitative performance in super-resolution imaging [1]. While optical devices that sort a static set of spatial modes (e.g., Hermite-Gauss modes) have been demonstrated for simple imaging tasks [2], more complicated tasks involving relaxed prior information [3] and/or multi-purpose imaging needs will require adaptation of the target mode basis in real time. We demonstrate a reconfigurable mode sorter capable of rapidly switching between multiple spatial mode bases and report progress toward a robust multi-purpose mode-sorting system for super-resolution imaging.

Our system consists of 4 main parts (Fig. 1):

Illumination: We first linearly and uniformly polarize our 532 nm laser source (Edmund Optics 10 mW DPSS). A spatial filter is used to eliminate the higher spatial frequencies of the beam and produce a clean, uniform, Gaussian beam. The filtered beam is then collimated and directed to the SLM.

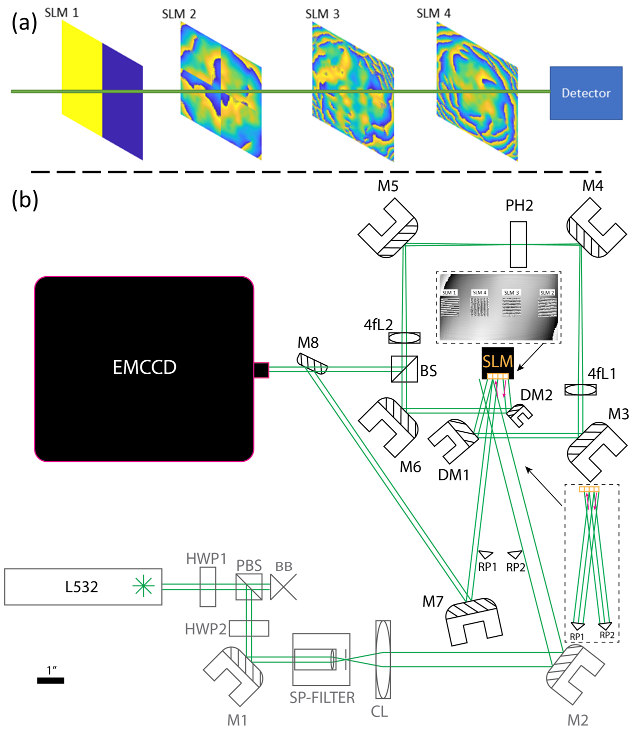

Fig. 1: (a) Illustration of SLM regions used for object encoding and mode sorting. (b) Experimental setup (bottom: illumination, center: SLM, top: 4f system, left: detection).

SLM: Our SLM (Holoeye PLUTO-2.1-VIS-016) has a glass window that is used to protect the refractive elements. If not accounted for, we find that this window can add up to 6 waves of aberration at 532 nm. Because of this the aberrations were measured, and a phase mask is displayed on the whole SLM to cancel these aberrations. On top of the overall phase mask, there are four square regions displayed on the SLM (Fig. 1(a)). The first region is used to encode a phase-modulated object, and the other three are used as phase masks forming the optical transformation that will ideally direct each orthogonal input mode to a respective, pre-set, location on the detector. On each square we applied a blazed grating and use the first diffraction order rather than the noisier zeroth order.

4f system: As can be seen in Fig. 1(b), the light goes through a 4f system right after the object is encoded at the first bounce from the SLM. The 4f system has two main features for our system: (1) The conjugate planes at the beginning and end of the 4f system couple the first and second SLM regions, such that the phase-encoded object is presented to the remaining SLM planes for processing. (2) By placing a pinhole (PH2 in Fig. 1(b)) at the Fourier plane of the 4f system we effectively create a low pass filter. By changing the size of that pinhole, we can change the width of our point spread function (PSF) to perform super-resolution imaging experiments. When no filtering is done, the PSF is basically a delta function.

Detection: As shown in Fig. 1(b), we use a beam splitter (BS) to get both a direct image and the mode-demultiplexed detection from the system. Each of these outputs is detected using an EMCCD camera (Andor iXon 897) for shot-noise-limited detection in a super-resolution imaging context.

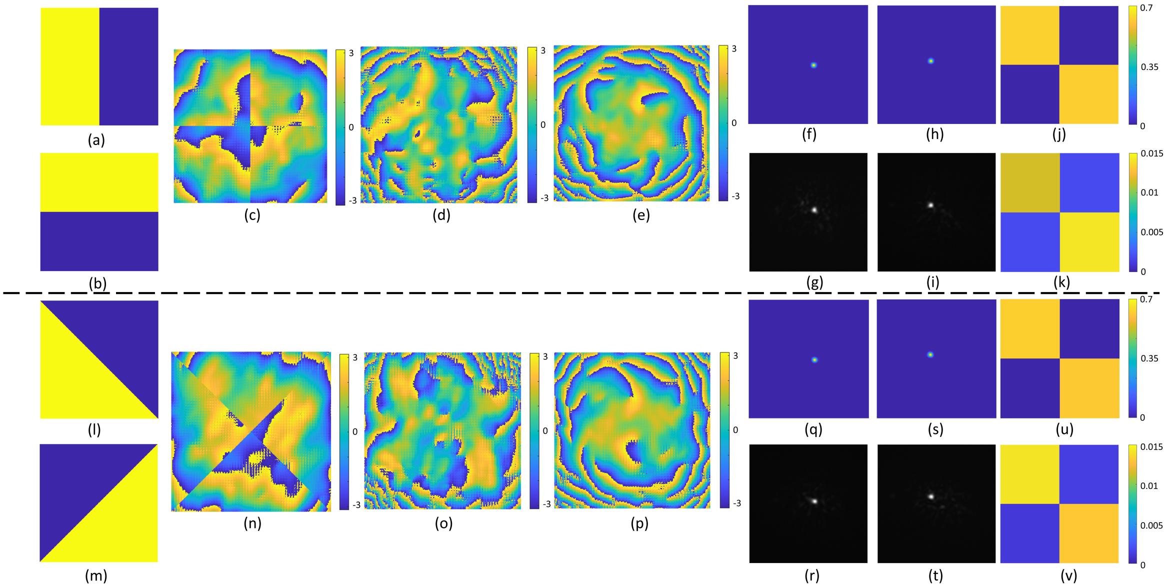

Fig. 2: Mode-sorting results for two spatial mode sets (top and bottom). Each set has two orthogonal binary-phase-encoded Hadamard modes, but the sets are not orthogonal to each other. (a),(b) and (l),(m): Hadamard modes for each mode set. (c)-(e) and (n)-(p): 2nd-4th SLM masks for each mode set. (f),(g): expected and obtained camera output from mode (a) . Similarly, camera outputs (h),(i) correspond to mode (b), outputs (q),(r) correspond to mode (l), and outputs (s),(t) correspond to mode (m). (j),(k): expected and obtained crosstalk matrix for mode set 1. (u),(v): expected and obtained crosstalk matrix for mode set 2.

The transformation from an input spatial mode to a location on the detector depends on the combination of spatially-dependent phase modulation and free-space optical propagation. Having three phase masks allows for a full two periods between these two operations. The phase masks on the final three SLM bounces are generated using an algorithm similar to Ref. [4]. In the algorithm, the wanted output on the detector is back-propagated through the system, while the object (from the first SLM bounce) is propagated forward through the system. In both propagation directions our algorithm accounts for parity changes introduced by the mirrors, prisms, and the 4f system. The algorithm then updates each phase mask to attempt to satisfy a phase matching condition. The phase masks that are used in the final mode sorter are obtained after many iterations converge to a solution.

For the time being, our system can spatially separate two orthogonal binary phase patterns (i.e., Hadamard modes). The novelty of our system, however, comes from its reconfigurability. With the same system we proved that we could go back and forth between sorting two different non-orthogonal mode sets at 1 kHz simply by updating the phase masks displayed on the SLM (Fig. 2(c)-(e) and (n)-(p)). We characterize the crosstalk of our preliminary system with an extinction ratio of approximately 7:1 in each of the two mode sets (Fig. 2(k) and (v)). It is important to note that we did not try to minimize optical losses, and we measure the loss through the system at approximately 98%. To minimize loss, anti-reflection coating on the SLM window would allow to use the zeroth order mode and to not use a blazed grating. Future work will include improving (lowering) the crosstalk, demonstrating spatial separation of more than two modes with high efficiency and low crosstalk, and obtaining the ability to use our system on more complicated spatial structures. Overall, our results show the experimental implementation of a reconfigurable spatial mode sorter with utility for adaptive super-resolution imaging schemes.

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