Multi-plane light conversion based mode multiplexers

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Abstract *In this paper we will discuss some recent advances in multi-plane light conversion. Optical systems that use a cascade of phase planes to implement arbitrary spatial transformations.*

Introduction

Multi-plane light conversion (MPLC) consists of a cascade of phase planes separated by a unitary transformation, typically free-space propagation or a Fourier transform [1], [2]. In a manner broadly similar to transforming polarisation bases by introducing polarisation dependent phase shifts between components using two waveplates, MPLC uses phase planes to introduce phase shifts between spatial components to transform spatial bases. For an input spatial basis consisting of *N* spatial modes, it is possible to transform to an arbitrary output spatial basis of *N* modes using of order *N* phase planes. This is a powerful technique for implementing many new optical systems and transforms. In this paper we discuss some recent applications.

Laguerre-Gaussian mode sorter

As mentioned above, in the general case, transforming a spatial basis of *N* modes, will in general require on the order of *N* phase masks. However there are important instances whereby a spatial basis transformation can be performed using substantially less. A lens is a good example, a single phase plane, which performs a spatial Fourier transform, converting from the position basis, to the k-space basis. As it turns out, a Hermite-Gaussian decomposition is another transformation requiring only a small number of planes. Specifically, a Cartesian grid (x,y) of diffraction limited spots can be transformed into the Hermite-Gaussian basis (m,n) relatively easily. But only if the input and output basis is arranged such that the Cartesian position of the spot in the array, maps to the Cartesian index of the Hermite-Gaussian mode. When the transformation is arranged in this way, it is possible to decompose a large number of modes, with very few planes. Examples have been demonstrated using 7 planes to decompose 210 or 325 HG/LG modes [2].

Fig. 1 illustrates a schematic of how this transformation is performed. Each spot starts at a particularly position (x,y) on a Cartesian grid. Each of these spots propagates through 7 phase planes by reflecting between a spatial light modulator (SLM) and a mirror. Through this transformation, each spot is mapped onto a specific Hermite-Gaussian mode (m,n), and then further transformed into the Laguerre-Gaussian basis through the use of two cylindrical lenses.

This new transformation, and it's relatively straightforward optical implementation provides access in optics to a new type of spatial transformation. Many optical systems make use of the fact that a Fourier transform can be easily performed using a lens. This new Laguerre-Gaussian mode sorter allows optical systems to exploit the Laguerre-Gaussian transformation, which is particularly appropriate for applications in fibre optics and beam optics [3], [4] where the LG and HG modes are a convenient basis choice.

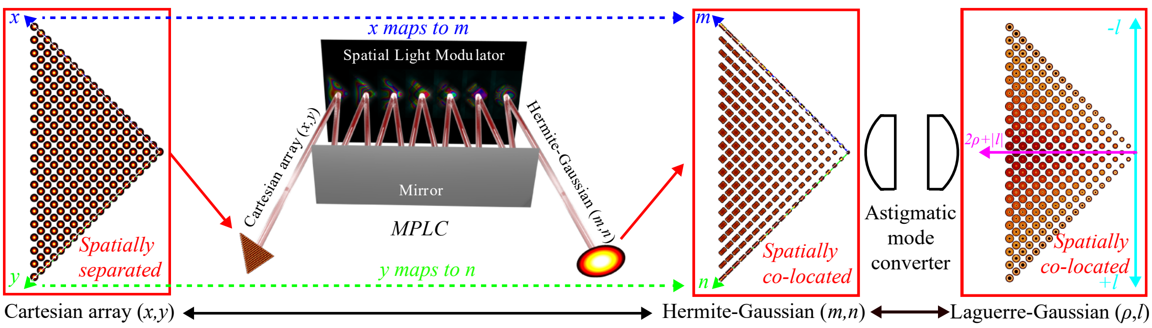

Fig. 1 : Schematic of Laguerre-Gaussian mode sorter

Time Reversal of Optical Waves

A recent application of the Hermite-Gaussian mode sorter [5] is as part of a spatially resolved spectral pulse shaper [6]. A device which allows the spectral/temporal response of each HG mode in each polarisation to be controlled independently. That is, a device which is able to create a completely arbitrary vector spatiotemporal optical field. Which in turn can be used to generate a time reversed optical wave. When light propagates through a complex media such as an optical fibre, white paint or biological tissue, it becomes scattered amongst many spatial and polarisation modes, which arrive at many different times. Although the input to the medium may start at a single point in space and time, at the output, after propagation, it becomes this complicated optical field that is completely arbitrary in space, time and polarisation. The creation of a time-reversed version of this field, could back-propagate through the medium to recreate the original source, but in order to create such a field, full control is required over all lights degrees of freedom independently and simultaneously. The ability of the HG mode sorter to transform the 2D spatial HG spatial basis, into a 1D array of spots [5] enables three dimensions of a beam (2 space, 1 time) to be controlled using a single 2D surface of a standard spatial light modulator.

The schematic for the arbitrary spatiotemporal beam shaper system is illustrated in Fig. 2. The source beam enters as a spatiotemporal focus polarised at 45 degrees with respect to the spatial light modulator. This input beam is dispersed across the SLM in much the same way as a traditional polarised-resolved spectral pulse shaper or wavelength-selective switch. There are spatially separated beams on the left and right of the SLM for the horizontal and vertically polarised components respectively. Each beam is spectrally dispersed, meaning applying a phase tilt left/right along the SLM introduces a wavelength-dependent phase-shift (delay), whilst apply the phase tilt up/down with vertically shift the position of the output spot in the Fourier plane of the SLM where a HG mode sorter is located. The HG mode sorter maps these 1D output spatial positions to 2D HG modes. Effectively acting as a lookup table, whereby the SLM can selected 2D modes from a 1D list. Creating complicated phase masks on the SLM redistributes light in both the left/right and up/down directions in the Fourier plane, which in turn redistributes the light in time and space respectively. Allowing for the creation of arbitrary vector spatiotemporal beams. For every addressable wavelength, it's own combination of spatial and polarisation modes can be assigned, which equivalently means the ability to create arbitrary spatial and polarisation wavefronts at arbitrary delays in time.

Such a system is the first capable of generating completely non-separable space-time beams, where all the linear properties of light can be controlled arbitrarily and simultaneously. It can be thought of as a kind of ultrafast wavefront spacer, whereby a set of approximately 90 completely independently wavefronts can be created at a rate limited by the supported optical bandwidth of the system. In this case, 4.4 THz. Examples have been demonstrated of rapidly rastering focal points, complicated spatial fields such as smiley faces delivered to specific points in time through a multimode fibre, as well as 3D light sculptures of well-known objects like the Eiffel tower. When collimated, this equates to an 3D volumetric light field in the shape of the Eiffel tower, flying through space at the speed of light.

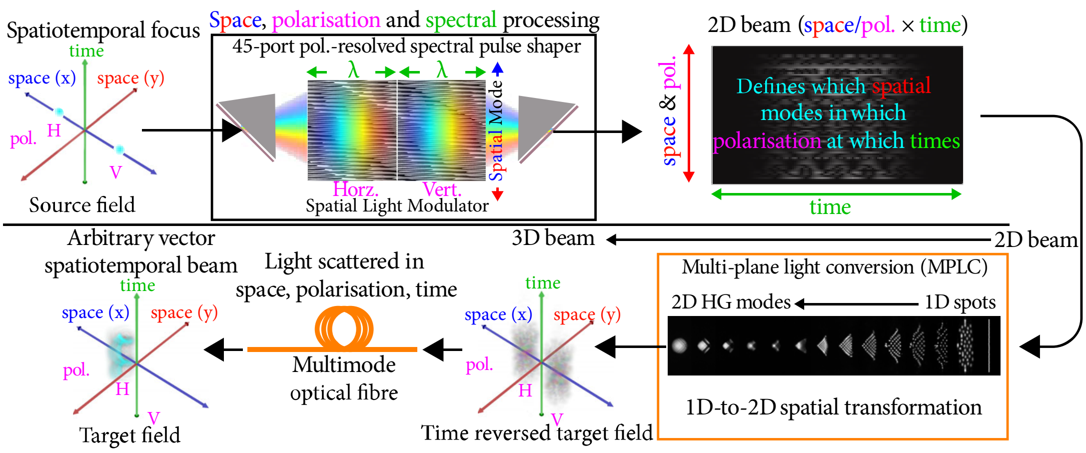

Fig. 2 Schematic of an arbitrary vector spatiotemporal beam shaping system. A type of spatially and polarisation resolved spectral pulse shaper.

Other Applications

Other potential applications make use of the ability of MPLC to perform new spatial basis transformations, in a way which has traditionally not been feasible. One example is their use to implement optical gates for quantum information [7][8], or to implement generalisations of Stokes polarimetry for spatial state tomography [9]. The ability to easily perform a Laguerre-Gaussian spatial decomposition, could also open opportunities in more unexpected areas such as astronomical instrumentation, where the spatial filtering capabilities of and LG mode sorter could be used as a coronagraph for the detection of exoplanets [10].

References

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