Coherent control of light through laser written photonic lanterns

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Abstract: We demonstrate coherent control of light through bespoke laser written photonic lanterns. This enables imaging in a variety of new situations, with potential applications to micro-endoscopy, chip-based LIDAR, and microfluidic imaging.

Introduction

Photonic lanterns reformat adiabatically couple light from an array of single mode optical waveguides to a single multimode waveguide, or vice versa [1]. Conventionally, they find applications in situations where light propagating in a multimode optical waveguide requires processing in a spatial mode independent way. By efficiently reformatting the light into an array of single mode waveguides, tasks such as spectral filtering or optical switching can take place in a single mode environment, eliminating mode dependent effects. For example, photonic lanterns have been used to spectrally filter astronomical signals collected from telescopes, and as splitters and combiners in telecoms applications. Recently, some of the authors demonstrated the potential of photonic lanterns as components in a flexible high-resolution micro-endoscopic imaging system [2], and the present work develops this theme. Here, we demonstrate the use of a high-speed digital micro-mirror device to measure the Transmission Matrix (TM) of a laser inscribed photonic lantern. Inversion of this TM enables calculation of the relative amplitudes and phases with which to excite the single mode waveguide array, to coherently control the field at the multimode output facet of the photonic lantern. This technique offers a route towards the creation of scanning imaging systems using photonic lanterns in a variety of new situations, with potential applications to micro-endoscopy, chip-based LIDAR, and microfluidic imaging.

Experimental and Results

The photonic lantern

Here we chose to work with an *integrated* chip-based photonic lantern rather than a multicore fibre photonic lantern used in [2]. This device was fabricated using ultrafast laser inscription, similar to the device reported in [3]. The device was inscribed in Eagle 2000 glass using a 500 kHz train of circularly polarized, ~350 fs, 84 nJ pulses at a wavelength of ~1 μm, which were focused into the substrate using a 0.4 NA lens. One end of the device terminated in a 5 × 5 array of individual minimally coupled waveguides, with an inter-waveguide separation of 30 μm in both axes. Each waveguide was fabricated using the multiscan technique [4] and was therefore constructed from 18 scans of the material through the laser focus, with an inter-scan separation of 200 nm and a translation speed of 4 $mm.s^{-1}$. Over a transition of ~15 mm, these discrete waveguides were brought together slowly to produce a single multimode waveguide with dimensions ~18 μm × 18 μm. The individual waveguides were designed and observed to be single mode at around 785 nm, and so were few-moded at the 633 nm wavelength used in the following section.

Transmission matrix measurement and inversion

The transmission matrix (TM) [5, 6] of the photonic lantern was measured using an optical set-up similar to that described in [7]. In brief, the photonic lantern is placed in one arm of a Mach-Zhender interferometer. Before the photonic lantern, laser light (1 mW at a wavelength of 633 nm) propagating in this arm of the interferometer first reflects from a digital micro-mirror device (DMD – Vialux V-7001 XGA). Light diffracts from the binary amplitude patterns that can be displayed on the DMD. These binary patterns can be designed to diffract a target complex field into the first diffraction order. By blocking the light around this order, the DMD can be used as a complex beam shaping device, capable of creating arbitrary amplitude and phase patterns, limited only by the spatial bandwidth of the DMD chip. In this way the DMD is used to raster-scan a focused beam across the input waveguide array of the photonic lantern. The light transmitted through the lantern at each input focal position is re-imaged onto a camera, along with a reference beam that was propagated around the photonic lantern through the second arm of the interferometer. Phase stepping holography is used to reconstruct the complex field across the multimode output facet of the photonic lantern corresponding to each input focal spot position. An example of these complex fields is shown in Fig. 1(b,d,f). This information is used to reconstruct the TM of the photonic lantern, which can then be inverted to retrieve the input field required to create a foci at target positions at the multimode output facet. The DMD is then used to generate the required input fields (intensity only shown in Fig. 1(g,i,k)), which are modulated to raster scan the focus at the output of the photonic lantern as shown at several target locations in Fig. 1(h,j,l).

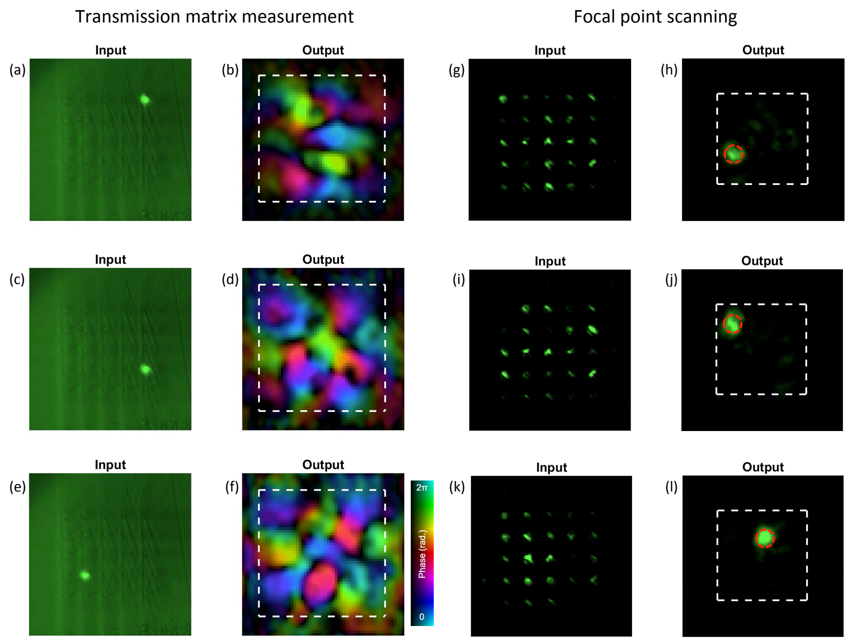

Fig. 1: (Left two columns) TM measurements (Right two columns) Coherent light control of light to generate and scan a focus at the multimode output of the photonic lantern (boundary shown with white box).

3. Conclusions and future work

We have demonstrated that the optical field at the multimode output port of a photonic lantern can be shaped by controlling the excitation field at the input waveguide array. Here we have shown the formation and scanning of a near-diffraction limited focused spot, which has potential application as scanning imaging system. These preliminary results can be further improved by implementing polarization control into the beam shaping system [8], which would increase the contrast of the foci by a factor of two. Using a higher mode capacity photonic lantern would enable the creation of more tightly focused and regularly shaped spots. This approach can also be translated to multi-core fibre photonic lanterns. Our simulations also indicate that multicore fibre photonic lanterns provide a route to interrogate the relative phases of the multimode basis states at the distal end with access only to the proximal fibre array end of the lantern. Therefore we believe that multicore fibre photonic lanterns offer a robust route to ultra-high resolution micro-endoscopy. We also highlight that coherent control of light through integrated photonic lanterns could find potential applications in areas such as chip-based LIDAR and microfluidic imaging.

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