Pixel-remapping waveguide addition to an internally sensed optical phased array

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ABSTRACT

The optical phased array (OPA) system with internal phase sensing architecture being developed at the Australian National University has direct applications in tracking and manoeuvring of space debris from a ground-based continuous wave laser. The future effectiveness of this system is dependent on providing a high fill-factor for the emitter array as well as a collimated output in the far field. This is especially important when aiming for high power density incident on space debris and is currently governed by an unmodified single mode fiber to air interface at the final stage of the system.

This research investigates the incorporation of a number of alternative optical head configurations, based on an output remapping waveguide. The waveguide will allow for control over the emitter separation, a key parameter in controlling the beam overlap and increasing the emitter fill factor. A remapping waveguide is designed for development with the 3D laser inscription process for a range of spatial configurations. Consideration is also given to a phase ambiguity issue with the feedback architecture and demonstration of the Gaussian Beam propagation simulations to which the experimental results will be compared is given.

1. INTRODUCTION

The coherent combination of laser beams using an Optical Phased Array (OPA) provides a potential pathway to the power levels required to effectively track and manoeuvre space debris using the photon pressure of continuous wave (CW) lasers.[1] In the past, simulations have been used to assess the feasibility, requirements and potential effectiveness of space debris management through the use of a network of high powered laser sites.[2, 3] The laser power required is on the order of >20kW, with clear advantages to further increasing the power.

An overview of the high power compatible OPA architecture at ANU is given in Fig. 1.[4] The required phase feedback signal is produced from a combination of forward propagating light and light reflected off the final optical head fiber-air interface back into the OPA. The phase measurement is performed with a digital phasemeter and corresponding feedback is applied using phase modulators (in this case electro-optic modulators). The offset between the high power section and the more sensitive feedback instrumentations (in this case electro-optic modulators) presently allows for compatibility with up to 100W per emitter, limited by the current set of asymmetric fiber splitters, rather than a fundamental limit of the architecture. This system has achieved phase stability between emitters of $\lambda/194$, more than sufficient for coherent combination. In addition to being influenced by the phase stability, the output intensity distribution, which would ideally be a low divergence beam with all power in the central peak, is significantly influence by the optical head.

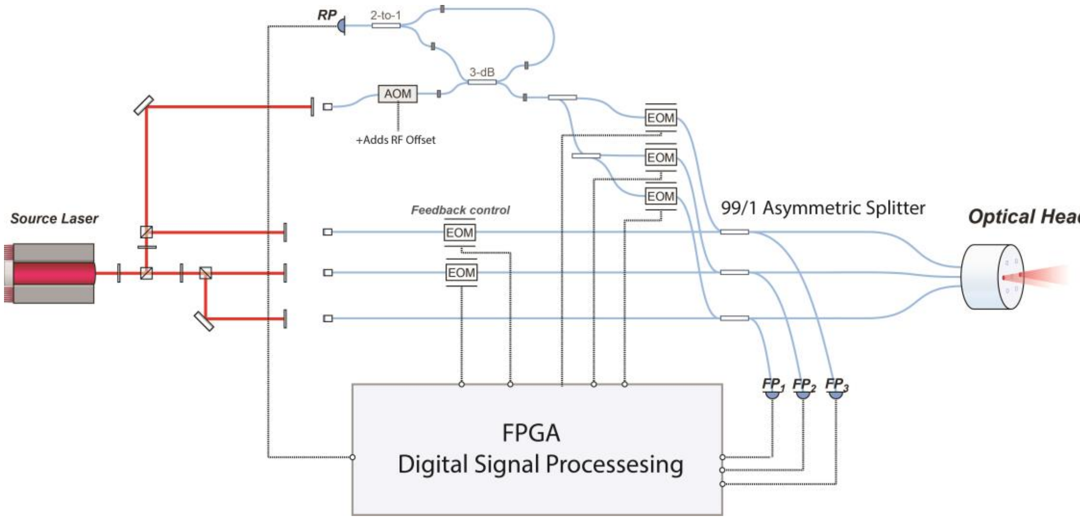

Fig.1. Phase control architecture of the OPA at ANU including temporary free-space section

The fill-factor of the optical head has a significant influence over the far-field intensity distribution, with a higher fill-factor resulting in an increased proportion of the total output power being contained within the central lobe of the output.[5] The fill-factor is given as the ratio of the actively emitting area A_e, to the total emitter aperture area, A_T, which for the seven emitter hexagonal layout seen in Fig. 2, is given by,

$$\textit{Fill-Factor} = \frac{A_e}{A_t} = \frac{r_e^2}{(r_e + d_i)^2}$$

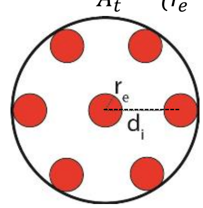

Fig. 2. Definition of spatial dimensions for a seven emitter hexagonal pattern.

Where r_e is the radius of an individual emitter and d_i is the emitter separation between the centers of emitter, also referred to as the emitter pitch, with these properties shown geometrically in Fig. 2. The current optical head consists of cleaved single mode fibers in a hexagonal pattern with a 250μm separation between emitters and an output mode field diameter (MFD) of approximately 6μm.

An increased fill-factor can be practically achieved by reducing the emitter separation or by allowing the beams to expand and collimating individual emitters with a microlens array, effectively increase the emitting area for each. These approaches are shown in Fig. 3.

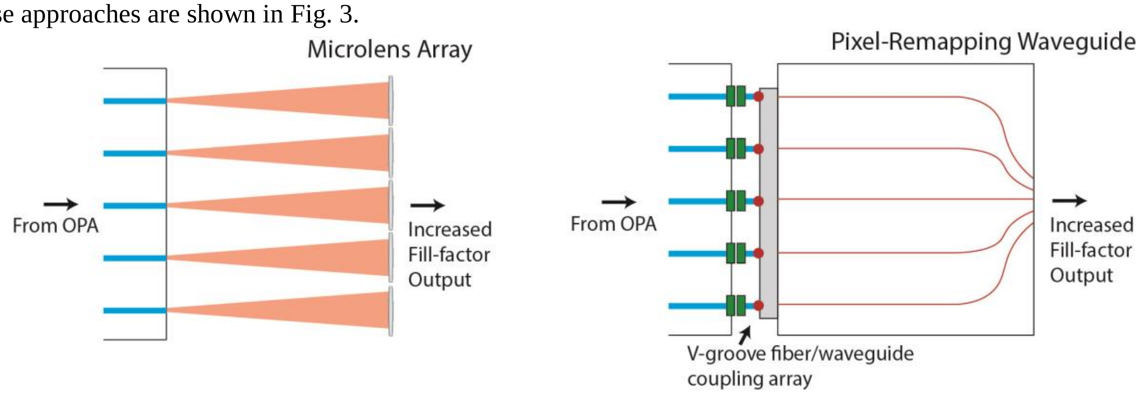

Fig. 3. Approaches for increasing the fill-factor of the fiber array. Left, using a microlens array and right, by remapping the outputs closer.

To effectively use either approach, there are potential complications which should be considered. When using a microlens array, spatial misalignment between the original arrangement and the microlens array can cause slight beam steering of individual emitters. This can however, be mitigated through the manufacture of free-form optics built to the required dimensions. A consideration for the remapping waveguide is that evanescent coupling can result in increasing crosstalk between emitters as their separation is reduced. These approaches are not mutually exclusive, with a microlens array able to be used in conjunction with a remapping waveguide.

The aim of this work is to develop designs to replace the current optical head with a laser inscribed waveguide based optical head in order to control the properties of the optical head, namely the fill-factor. This development will also provide information regarding the capabilities of the laser inscription process relevant to the creation of an optical head. A potential extension of the waveguide optical head is the integration of the phase control aspect of the OPA within a monolithic structure.

2. PIXEL-REMAPPING WAVEGUIDE DESIGN

The precision physical positioning of optical fibers at distances less than 100's of micrometers becomes increasingly challenging. Instead, an array of waveguides can be directly written in a single piece of glass through laser inscription. In this manufacturing method, a femtosecond pulse laser inscribes custom 3D waveguides by inducing a refractive index change at the focal point of the writing laser. The waveguide path is controlled by moving the waveguide material on a 3D translation stage. This technology allows for the prototyping of 3D waveguide devices and has been used for an increasingly large range of applications including photonic lanterns, mode-division multiplexing and pupil remapping.[6]

The waveguide device for the optical head will remap seven OPA fiber channels from a linear array to the hexagonal face pattern seen in Fig. 2, with the specific emitter pitches given in Table. 1. These devices will be aimed at providing an experimental measure of the abilities of laser inscription to remap the pixel positions, but also providing information regarding the influence of crosstalk between waveguides. Measurements of the crosstalk can then be matched to the theoretically expected evanescent coupling and provide information regarding how evanescent coupling might degrade the ability to perform the phase stabilization. The study of the relatively simple designs should also inform future designs incorporating more features.

Table. 1. Emitter pitches and corresponding fill-factor for first iteration of the pixel-remapping waveguide

Separation at output (μm)	6	7.5	10	12.5	15	17.5	20	30	50	100
Fill-factor	78	57	37	26	19	15	12	8	2	0.6

An example of the waveguide paths for the 6μm emitter separation device is given in Fig. 4. The curvature visible in Fig. 4b, is chosen in order to balance bend losses as well as losses due total path length, which has been previously demonstrated.[7]

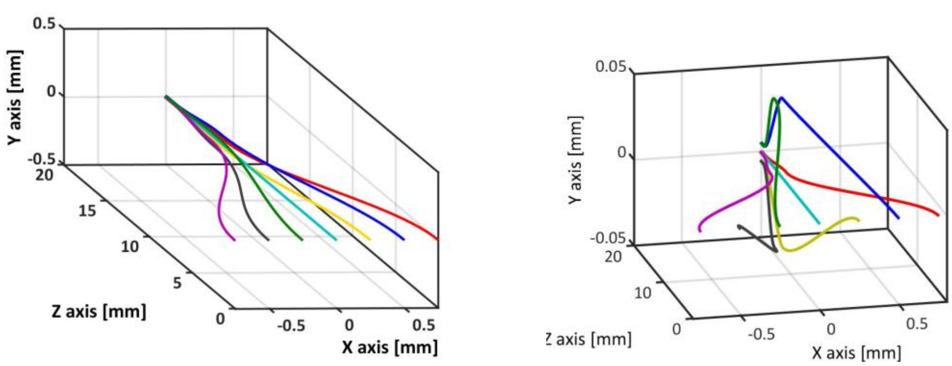

Fig. 4. 3D plot of waveguide paths for the 6μm pitch remapping waveguide a) With equal x and y axis. b) A reduced y-scale to emphasize the increase waveguide bend radius

The intensity distribution at the output of each configuration will be investigated using a CCD imaging camera, in addition the existing high speed photodetector measuring the back reflected signal. A consideration will also be given to the waveguiding properties of the laser written waveguides and the power loss due to the addition.

The ability to electronically steer the output beam of the OPA by manipulating the phase of emitters at the output is one of the technologies most useful features. An experimental demonstration of the steering capability at different emitter pitches and how the power distribution changes will also be considered.

3. GAUSSIAN BEAM PROPAGATION SIMULATION

In conjunction with the experimental measurements of the far-field intensity distribution, the expected intensity, I_c can be simulated through the sum on individual emitter's Gaussian electric fields propagated to given distance, z,

$$I_C = |E_C|^2 = \left| \sum_{i=1}^{N} A_0 \frac{W_0}{W(z)} e^{-\frac{\rho_i^2}{W(z)^2}} e^{-j\left(kz + \frac{k\rho_i^2}{2\,R(z)} - \xi(z) - k\phi_i\right)} \right|^2$$

Where A_0 is the emitter amplitude, W_0 is the emitter Gaussian beam waist, $W(z)$ is the beam width at z, ρ_i is the set of position values for each emitter ($\rho_i = \sqrt{(x-x_i)^2 + (y-y_i)^2}$, with x_i and y_i the central position of the emitter i), $k = \frac{2\pi}{\lambda}$, $R(z)$ is wavefront radius of curvature, $\xi(z)$ is a phase retardation term and ϕ_i is a phase term for each emitter which can be manipulated for beam steering.

An assumption for this simulation is the output of individual emitters having a Gaussian profile, the validity of which can be assessed through a measurement of the individual emitter output mode profile. Its main role is to inform the expected peak positions, sizes and relative power distribution.

An example of the simulated output is given in Fig. 5, showing the beam combination with different cross sections.

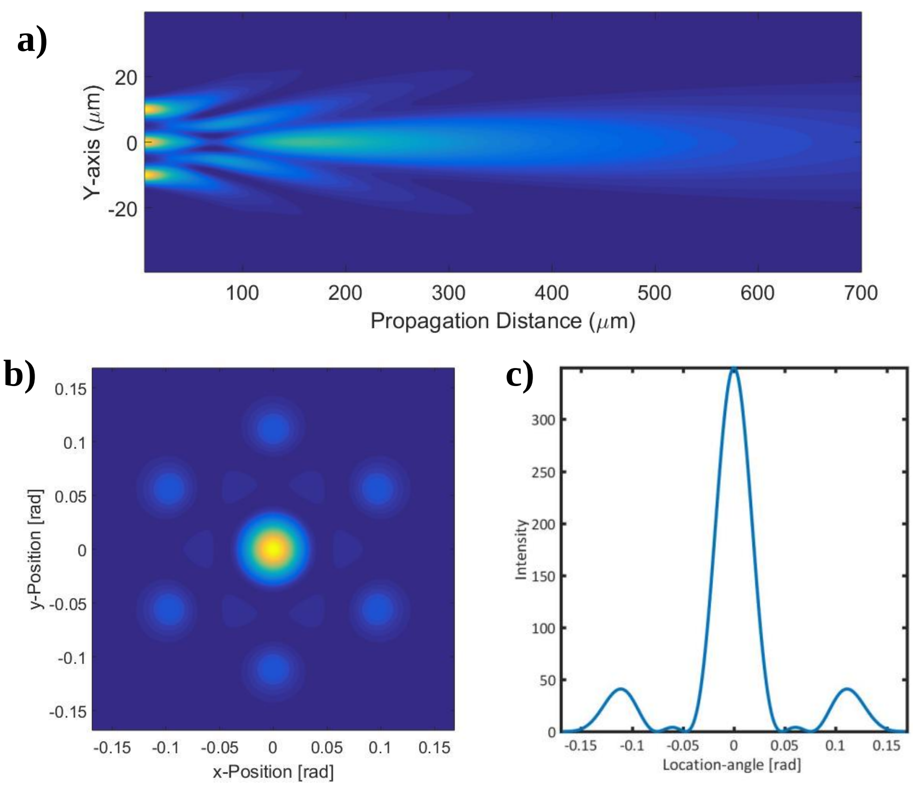

Fig. 5. Simulated Gaussian beam combination for seven emitters in hexagonal configuration, a 10μm emitter pitch and a 6μm Gaussian beam waist. 5.a) gives an intensity map of a cross section of the beam as it travels away from the emitters. 5.b) shows an intensity map of a cross section at 1m from the emitters and 5.c) shows a plot of the intensity along a central vertical slice of 5.b).

4. FUTURE DEVELOPMENT

Beyond the control of the output fill-factor from a remapping waveguide or microlens array, there are several other potential advances and solutions to existing problems which can be incorporated into the optical head. Practically, the internal phase sensing architecture relies on a double passed optical path, which results in the phase being determined from twice the desired path length. When feedback is applied to lock the relative phases in the emitters, there remains an ambiguity of π in the phase measurements, meaning the emitters may be exactly out of phase. A potential solution, which exploits the potential appearance of evanescent coupling between waveguides, is for an inactive waveguide to be introduced between adjacent emitter paths. When the emitters are remapped in close proximity at the end of the waveguide, light from adjacent emitters would couple into the inactive waveguide, and by measuring either the output or back reflection from the inactive waveguide, a coarse measurement of the relative phase of the two emitters would be provided. Potential configurations for the positioning of the inactive waveguides is given in Fig. 6,

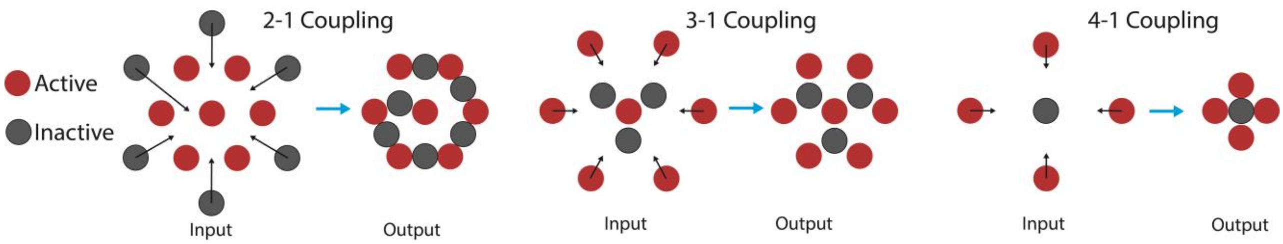

Fig. 6. Configurations for locations of inactive waveguides at the input and output of the optical head for resolving the phase ambiguity.

The insight gained from the initial remapping waveguide tests, should assist informing the positioning and separation of the inactive waveguides. To obtain a useful measurement, the interaction length should be long enough to couple a measurable amount of light from adjacent emitters, but within the phase coherence length for the waveguide and have minimal secondary transfer (to other emitters).

The power handling capabilities are also a remaining challenge. The designs given here incorporate a v-groove array to couple the fiber output of the OPA to the remapping waveguide. This interface will only be capable of handling relatively low powers, on the scale of mWs. Future designs are looking at alternative couple mechanisms to increase the power handling capability.

5. ACKNOWLEDGMENTS

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