A stable and narrow-linewidth external-cavity diode laser at 1083nm

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The advent of external cavity diode lasers (ECDLs) has greatly facilitated atomic physics and ultra-cold atom research by providing significantly cheaper lasers with increasingly narrower linewidths at wavelengths ranging from 400 nm to 2 μm [1]. However, for atomic transitions such as 2S→P in metastable helium (He*), no commercially available diode laser exists with adequate power and narrow linewidth for laser cooling and manipulation [2]. Thus, fibre lasers are reluctantly the expensive workhorse of choice for many ultra-cold He* atom labs around the world.

We have developed and characterised a stable and narrow linewidth ECDL at 1083 nm, tunable over 150 nm, for laser cooling of He* atoms. Following the design principles from Bennetts, et. al. [3], the laser incorporates a fibre-coupled gain-chip as its gain medium and a mechanically rigid design of the external cavity.

From the heterodyne beat note signal of two similarly constructed ECDLs we determined the free-running linewidths of each laser to be 12 kHz (Fig. 1), while the long term free running wavelength stability of the laser is measured to be ~ 30MHz/day.

In the future, we plan to utilise the ECDL to cool and trap He* atoms with which we will perform high-precision measurements of metastable helium’s tune-out wavelengths for a precision test of quantum electrodynamics [4].

References


Pixel-remapping waveguide and microlens array for an optical phased array

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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 [1]. The future effectiveness of this system is dependent on increasing the emitter surface fill-factor at the output of the array, which increases the power contained within the central interference peak of the array [2]. This is especially important when aiming for maximum optical intensity incident on space debris. The output optical head of the OPA is currently governed by an unmodified single mode fibre-to-air interface at the final stage of the system.

This research investigates the incorporation of a number of alternative optical head configurations generated using 3D femtosecond pulse laser inscription, with the aim of remapping the input of the waveguide from a linear array into a hexagonal pattern with specific spatial dimensions. The optical head configurations have different emitter separation at the output, with centre-to-centre distances between the minimum structurally stable size of ~5-6μm to the existing fibre based optical head at 250μm. Additional microlens arrays with a pitch of 30μm and 250μm are also used for the collimation of individual emitter outputs, avoiding the degradation in beam collimation by misaligned outputs which would occur if a single collimation lens or mirror is used.

The influence of each optical head configuration is investigated in regards to the output beam intensity distribution, steering range (from changing the individual emitter phases), power loss through the waveguide and potential generation of waveguide crosstalk. A particular focus is given to crosstalk between emitter paths occurring as a result of evanescent coupling between the waveguides. The ability of the waveguide to allow the transmission of the Fresnel reflection from each emitter, used in the phase sensing, as a result of the addition of the optical head is also monitored.

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References

Metasurfaces as phase-sensitive, angle-selective spatial frequency filters
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Metasurfaces can be created from ensembles of nanoparticles in a periodic two dimensional array. These nanoparticles act as resonators and support localized surface plasmon resonances (LSPRs); collective oscillations of conduction electrons in metallic nanoparticles which scatter light. Distinct resonant modes can be excited at different frequencies by tuning the geometry, metal, the surrounding optical environment and the illumination conditions. These modes can be divided into two general categories: bright (or dipole) modes, have a broad resonance and can be easily excited with a normal incidence plane wave and dark (or subradiant) modes with zero net dipole moment which are more difficult to excite. The latter require tailored excitation schemes such as spatial phase shaping, evanescent field excitation, off-normal incidence or non-uniformly polarized light [1]. Interest in dark modes originates in their longer lifetimes, spectrally narrower resonances as well as their sensitivity to phase gradients in an incident field [2].

Recently metasurfaces have demonstrated their potential to replace conventional optical components such as lenses, beam splitters and holograms. Here we introduce a metasurface where each unit cell contains three silver nanorods arranged radially at 120° to each other (a radial trimer) as shown in Fig 1(a). Fig 1(b) shows an SEM of structures fabricated in silver using electron beam lithography. The specific geometry under consideration had rod lengths of 100 nm, widths and heights of 40 nm and the nanorods had centre-to-centre distances of 70 nm. The array periodicity is 300 nm and surrounding refractive index is 1.5. Figure 2 shows the reflection of p polarized light through the metasurface as a function of wavelength for different angles of incidence. Values obtained computationally using the Finite Element Method (FEM) implemented in COMSOL Multiphysics compared with those obtained experimentally using illumination through an objective lens. In the FEM results obtained at normal incidence, only the dipole mode at 755 nm can be seen, but as the angle of incidence increases, a peak at 640 nm appears. The surface charge distribution obtained using the FEM confirms that the mode with resonance centered on 640 nm has a radial charge separation. The dependence on angle of incidence indicates that these modes are sensitive to phase gradients whereas the dipole mode is strongly excited for all angles of incidence.

The electromagnetic response to linearly polarized light of the radial trimer in k-space was obtained at fixed wavelengths associated with the excitation of different modes using Electrostatic Eigenmode Model [3] (shown in Fig 3 (calculated) and Fig 4 (experimental)). The EEM assumes the electrostatic approximation but provides a useful adjunct to rigorous full-field solvers such as FEM. As subradiant modes are excited at higher incidence-angles (larger spatial frequencies), a particular range of high spatial frequencies are strongly scattered depending on the incident polarization of the light. It is apparent that at the wavelength associated with dark mode excitation, the scattered field has been filtered in spatial frequency and, hence, that a metasurface can be designed to act as an ultracompact spatial filter. Such sensitivity to phase gradients also has applications in wavefront sensing and image processing.

Here we will present FEM, EEM and experimental results showing the electromagnetic response of various metasurfaces.

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References
Optical force characterization of CHO cells

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Optical tweezers are a widely-used tool in microbiology for the measurement of forces produced by systems such as molecular motors [1] and cell adhesion. Recently, there have been significant developments into characterisation of optical forces in complicated or messy environments such as living cells or the local environment near a wall or other structure. Other dielectric/absorbing objects and optical aberrations complicate the measurement of optical forces in situ. Here we use computer simulation and an experimental force estimation method to characterize the optical force required to arrest motion on objects such as chromosomes moving along the mitotic spindles in Chinese Hamster Ovarian (CHO) cell division. We also investigate how beam shaping methods can be used to improve trap stiffness and measurement sensitivity under similar conditions.

There are huge disagreements as to the force acting on chromosomes in cell division ranging from 0.1-700pN [2, 3]. Latest results show that the force must be bounded by 10pN due to the maximum optical force which could be exerted on a chromosome [2]. In this work the movement and trapping inside optical tweezers on isolated chromosomes was performed along with simulation to demonstrate the trapping dynamics. The trapped cylinder calculations quantitatively match the experimental observations and show that the escape force method creates an undesirable escape trajectory due to forces perpendicular to the drive force. As a result, relative calibration methods are difficult to perform, except near the equilibrium.

A force estimation technique using the deflection of light to estimate the momentum transfer to the optical system was implemented. This method offers advantages in that only a single calibration of the system is necessary under ideal conditions, but it does not fully escape the limitations of other methods as some of the light can be lost leading to under- or over-estimates of trapping force. We have investigated this phenomenon and show an example in figure 1 which gives the result on a 6um long cylinder proxy, refractive index 1.36 and 1um diameter. Even with such a low contrast some light is lost leading to about 10% variation near the peak forces.

The cell itself presents other challenges as the surface, structure and organelles within it distort the light. Figure 2 shows the application of the force estimation method applied over the entire surface of the CHO cell. Isolated CHO cells are about 14um in diameter when spread out. Only within 2um of the edge of the cell does the surface significantly bias any force measurement. If the cell moves, which is the case with uncoated glass slides, the measurement of intra-cellular material can easily be changed by the variation of scattering from the cell surface. Beam shaping also has a role to play in trapping organelles and chromosomes. The shape greatly affects the ‘useful’ region of the trap, a cylindrical object such as a chromosome has a region of optical response to displacement. By reconfiguring to a dual beam configuration or specially shaped beam will produce strong linear traps. As the experimental force estimation method used is insensitive to the particular distribution of light as long as the imaging system is correctly aligned such a method can be employed to obtain accurate and highly localised measurement of the cellular environment.

We have non-invasively penetrated the cellular environment with optical probes and have obtained quantitative measurement of the optical force which can be applied to particular organelles and structures such as chromosomes.

References


Laser manufacturing technologies have become more prevalent in recent years, and one field in which they are seeing significant growth is use in microfabrication. These techniques have been shown to reliably produce structures on microscopic scales, with multiphoton lithography achieving feature sizes as small as 65 nm [1], as well as various other additive techniques such as stereolithography, selective laser sintering and selective laser melting and reductive techniques like laser ablation and drilling. One method being explored to deposit metal atoms, particularly the noble metals, onto semiconducting metal oxide substrates is a technique called laser photodeposition. By exposing the semiconducting substrate to above bandgap light, conduction band electrons are generated which reduce a metal salt at the interface between solution and substrate [2]. This effectively ‘writes’ the metal ions on to the substrate where the laser illuminates.

In this paper we report fast selective laser solution photodeposition of gold onto zinc oxide films using a focused 325 nm continuous wave laser. A two step process is used [2], first 3 ml of 0.1375 mM HAuCl$_4$ in ethanol is exposed to a 3 W 380nm UV LED for 6 minutes in a cuvette to decompose the HAuCl$_4$ to a metastable AuCl$_2$$^-$.- The zinc oxide film is then immersed in this solution and exposed to the laser. The laser excites electrons from the valence band to the conduction band in the ZnO film which can then reduce the metastable AuCl$_2$$^-$ to metallic AuO. A pattern is written by translating the zinc oxide film about the laser beam path using a micro-positioning stage.

We report on the effect that different laser parameters (such as intensity and exposure time) have on the resulting gold structures and how they can be tuned to control the photodeposition process. Under continuous wave laser exposure we have observed that even modest intensities of the order of 1 mW are capable of locally depleting gold ions from the solution near the exposure site. Repeated runs of the pattern, or slower translation speeds are required to deposit more significant amounts of gold onto the ZnO. Figure 1 is an SEM image of a simple square pattern of gold deposited onto the substrate, it can be seen that the corners appear brighter due to the stage momentarily stopping to change direction, slightly increasing the exposure time.

Patterns are written through physical translation of the sample. A number of different scan patterns have been programmed to observe a number of different effects such as the depletion rate of gold from the solution and how the write speed influences the amount of gold deposited. To date a number of these simple patterns have been written that prove the feasibility of using this technique to print microscopic structures to perform desired functions.

Future work will investigate how parameters such as polarisation and intensity distribution influence the photodeposition process. One interesting area to be explored is in the use of specially shaped laser beams instead of the conventional gaus-
Optimizing phase to enhance optical trap stiffness

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Precise wavefront engineering can greatly expand the capabilities of optical tweezers, allowing new forces such as pushing or pulling tractor beams [1]. Recently, we demonstrated that this also allows order-of-magnitude improvements in trap stiffness [2]. One key obstacle to potential applications is the lack of an efficient algorithm to compute an optimized phase profile, with the enhanced trapping experiments in Ref. [2] relying on a steepest descent algorithm that could take up to a week to converge. Here we introduce an algorithm that reduces the wait from days to minutes, and which can locate superior phase-only profiles to the previous algorithm.

Using this we characterize the increase in trap stiffness achievable with phase-only control, and its dependence on particle size, refractive index, and optical polarization. Consistent with our previous findings, we find that order-of-magnitude increases in trap stiffness are possible for silica spheres in water larger than 4μm diameter, and that the resulting trap exhibits qualitatively different characteristics than is typical in optical tweezers. Surprisingly, optical vortices appear consistently in the optimized phase profiles and appear to be important to the performance of the optimized trap. The method in Ref. [2] calculated a continuous phase surface which precludes vortices; consequently, this method can locate superior solutions which in some cases can achieve up to three times higher trap stiffness.

These results are compared to the Eigenmode method [3] which locates the globally optimal wavefront for full wavefront control (see Fig. 1a,b). While full wavefront control can always outperform phase-only control, it is much more difficult to implement. Phase-only control is already incorporated in every holographic optical tweezers experiment, while amplitude or polarization control are only used in highly specialized experiments. We find that phase-only control can achieve almost all of the enhancement possible with full wavefront shaping; for instance, phase control allows 62 times higher trap stiffness for 10μm silica spheres in water, while amplitude control and non-trivial polarization further increase this by 1.26 and 1.01 respectively.

By efficiently calculating optimal phase profiles, this algorithm allowed us to systematically characterize the capabilities of a phase-enhanced trap, and it opens the way for future applications of enhanced trapping. Further, it is also applicable to many other problems in linear optics, and it could see important applications in wavefront optimization more generally.

Figure 1: (b) Achievable trap stiffness vs. diameter for a silica sphere in water for 5 separate cases: Gaussian trap, phase-optimized (our algorithm), the optimal wavefront from Eigenmode method, application of the phase of the Eigenmode wavefront, and optimal polarization-amp-phase control. (b) The relative enhancement in trap stiffness that can be achieved using phase engineering, amplitude, and polarization. The inset shows this on a logarithmic scale. The enhancement achievable with phase-only control rises sharply, while for particles larger than 1μm amplitude control offers a near-fixed enhancement of 1.35±0.10. Polarization control offers minimal benefit, with a maximum enhancement of 1.09 at 1μm, dropping to 1.010±0.003 above 5μm. (c) Heat-map of the trap stiffness achievable with phase-only control at different particle diameters and refractive indices; with (d) showing the relative enhancement this offers over a diffraction limited Gaussian trap.

References

A single-detector stereo-SCIDAR (SCIInitiation Detection And Ranging) system will be used to profile atmospheric turbulence above Mount Stromlo Observatory (MSO) and provide information to enhance the design of adaptive optics (AO) systems tasked with acquiring and tracking space debris.

A catastrophic collision between a fragment of debris and a satellite has the potential to create even more debris: as the amount of debris increases, so too does the probability of a collision [1]. In future this may result in a series of runaway cascading collisions which make the orbital environment extremely hazardous and near impossible to enter from Earth. Due to the relatively small size of space debris fragments they can be very difficult to acquire and track. AO systems will be used to reduce the difficulty of acquiring and tracking small objects by improving the resolution of ground-based telescopes to provide near diffraction-limited operation.

A SCIDAR system is being developed by the Research School of Astronomy and Astrophysics (RSAA) in conjunction with the Space Environment Research Centre (SERC) to characterise turbulence above the Australian National University’s MSO just outside Canberra. The EOS Space Systems’ 1.8m debris-ranging telescope at MSO will be used in future to track space debris to improve space situational awareness.

The SCIDAR system will record valuable data including refractive index structure constant, \(C_n^2\), turbulence above Mount Stromlo Observatory, and wind speed profiles. Of particular interest are the Fried parameter, \(r_0\), and the turbulence temporal coherence time, \(\tau_0\), which will be used to optimise the AO systems’ deformable mirror’s actuator pitch and operational correction rate.

SCIDAR operates on the principle of observing two stars separated by a known angular separation, \(\theta\), using a telescope (Fig. 1a). Aberrations induced by atmospheric turbulence inhabit different positions in each star’s measured scintillation pattern. Post-processed short exposures of these scintillation patterns are then auto-correlated or cross-correlated when used in two different modes: generalised SCIDAR mode or stereo-SCIDAR mode, respectively (Fig. 1b left and Fig. 1b right). The correlations contain peaks which refer to the turbulent layer height at which the aberrations were induced. The amplitude of these peaks is proportional to the strength of the turbulent layer being measured.

Generalised SCIDAR mode will overlap the scintillation pattern pupil images of double stars on a detector. The stereo-SCIDAR mode will utilise a compound roof prism to separate the pupil images and record them on a single detector, whereas a previous stereo-SCIDAR system separated the pupil images onto their own dedicated detectors [2].

Generalised SCIDAR—the capability to conjugate to different altitudes in the atmosphere—necessitates a moveable analysis plane. The moveable analysis plane provides the advantage of sensitivity to ground layer turbulence. However, a trade-off needs to be made between ground layer sensitivity and altitude resolution due to the increase in propagation distance, Eq. 1:

\[
\delta h(z) = 0.78 \sqrt{\frac{\lambda z}{\theta}}
\]

Where \(z\) is the propagation distance to the turbulent layer and \(z = |h - h_{\text{conj}}|\), \(\lambda\) is the wavelength, \(h\) is the altitude of the turbulent layer and \(h_{\text{conj}}\) is the detector conjugate altitude.

Optical design of the generalised SCIDAR mode has been completed and components have arrived. Design of the compound roof prism for the stereo-SCIDAR mode is ongoing. Lab integration will begin after custom components have been fabricated. A generalised SCIDAR observation campaign is planned to begin January 2017 and run for approximately two months. Once the pupil-separating prism has been fabricated the system will be upgraded to stereo-SCIDAR and an observation campaign will run from March 2017 until the end of the year. The system will measure the scintillation patterns of double stars separated by 10 to 25 arcseconds up to an altitude of approximately 15 km.

![Figure 1: a) Generalised SCIDAR concept. Two stars separated by \(\theta\), different turbulent layers, ground layer and conjugate distance below ground are shown. b) Left: Generalised SCIDAR mode overlaps the scintillation pattern pupil images. Right: Stereo-SCIDAR separates the pupil images using a compound roof prism. L1, L2 and L3 signify system lenses. The blue dashed double arrow implies the moveable analysis plane.

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References