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Optics Group, School of Physics & Astronomy, University of Glasgow
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(last updated January 2012)

Project titles

1 Optical Atomic Force Microscopy 2

2 Challenges in Orbital Angular Momentum 2

3 Multi-object, high-throughput, spectro-microscopy 3

4 Full-field Coherent Quantum Imaging 4

5 Optical Tweezers at Long Range and High Pressure 6

6 Security in the vortex 7

7 Holographic flow measurement 7

8 Ray-optics beyond wave optics 9

9 Complex-position optics 11

10 Transformation optics for optical angular momentum 11

11 Phase-dependent atom optics 11

12 Quantum interface for atoms and light with orbital angular momentum 13

1 Optical Atomic Force Microscopy

Project partner(s):
Glasgow supervisor(s): Miles Padgett
Reference number: OAFM

Atomic force microscopy (AFM) is a state-of-the-art imagining technique that uses a sharp probe to scan backwards and forwards over the surface of an object. The probe tip can have atomic dimensions, meaning that AFM can image the surface of an object at near-atomic resolution. However, the limitation of these systems is that, just like with a record player, the needle has to be held by a mechanical arm or cantilever. This restricts the access to the sample and prevents the probing of deep channels or indeed any surface that isn't predominantly horizontal.

Our idea is to hold the tip of an AFM in an optical beam, without any mechanical constraint. Optical tweezers use the momentum of light beams to trap and move individual spheres, here we will use them to hold and control the AFM tip — without need for any mechanical fixing.

We have shown the use of data-projector technology to shape light beams to hold many objects, and that this can give control over a simple probe. We have also shown that high-speed cameras can measure the force acting on the probe with 100 times greater sensitivity than most AFMs. Finally we have shown that the interface of optical tweezers can be made intuitive, e.g. controlled by iPhone or force-feedback joystick!

In this project we will develop our use of video game graphics cards for high-speed control and force-feedback to give the user a tactile interface, perhaps utilising the professional equivalent of a Wii motion controller. We will automate a fully-3D scanning system so that complete surface images will be obtained. We will create new probe types, functionalised to give various contrast enhancements. Initially our images will be of standard AFM test samples, but beyond this benchmarking we have budgeted for visits by leading biophysical researchers to test our new approach in their real applications. These range from cell-to-cell interactions to the differentiation of single stem cells.

The project is ambitious, breaking new ground in optical tweezers, AFM and imaging technologies, but the track records of the collaborating teams lend credence to the success of this project.

2 Challenges in Orbital Angular Momentum

Project partner(s): University of Strathclyde & "critical friends"
Glasgow supervisor(s): Miles Padgett
Reference number: OAM

Stand in the way of a light beam and it could both knock you over and send you in a twirl. Over 100 years ago Maxwell worked out the fundamental equations describing how light propagates through space. Embedded within these equations is that light carries both energy and momentum, but although its energy is apparent in our everyday lives, its momentum is not. However, shine light down a microscope and its momentum can be seen to move, or trap, microscopic objects. Circularly polarized light also carries a Spin Angular Momentum causing the microscopic object to spin.

Although the study of light has been central to the development of modern physics, it was not until the 1990's that it was realized that a whole new class of light beam could be created simply in the laboratory. Inserting a modified diffraction grating in the beam from a laser pointer is all that is required to create a light beam carrying Orbital Angular Momentum. The effect of OAM can be 100's time greater than that given by the spin alone - allowing our previous demonstration of the optical rotation of microscopic objects: an optical spanner! Beyond microscopic rotations, Orbital Angular Momentum (OAM) opens new opportunities across optical science.

We wish to unlock the potential of OAM in both classical and quantum science. However, fundamental questions remain pertaining both to the underlying physics and technological limitations. This research programme will address these limitations, each a scientific achievement in their own right but together paving the route to:

- OAM to enable an improved form of microscopy.
- OAM as a secure basis on which to build a fast cryptographic network.
- OAM at the heart of new types of optical sensors.

We benefit from "critical friends" and will form an international steering panel to meet annually with the team. We have the agreement of two of the world's leading scientists to serve on this panel. To maximise our wider impact, the panel will also include an industrialist from Scottish Enterprise and be convened by the chair of the Glasgow University KT committee. The panel will agree with the PIs, quantitative targets for high-impact journal publications, invited talks at both academic and industrial events and, most importantly, targets for exploitation (patents, license, consultancy).

3 Multi-object, high-throughput, spectro-microscopy

Project partner(s): University of Strathclyde, Heriot-Watt University, Durham University
Glasgow supervisor(s): Miles Padgett
Reference number: MOHTSM

Microscopy is a pervasive technology with applications from biology to material and nanoscience. At their heart, microscopes are predominately based on high numerical aperture, short focal length objective lenses producing images that can be seen by eye and/or electronically recorded, typically with 3-colour CCD cameras or a selection of coloured filters, but leaving the full spectral details unknown.

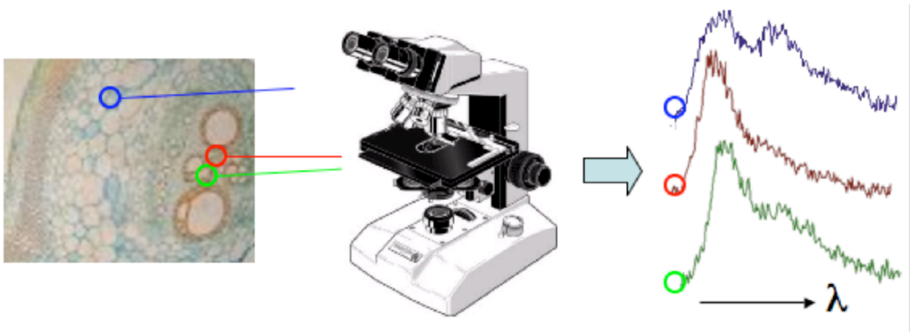

Figure 1: (See project 3.)

We plan to revolutionise the field of spectroscopic microscopy by developing a technology that will provide full colour spectrum, simultaneously from many points within a sample. To record high resolution (spatially and spectral) spectra across an extended field of view with a conventional microscope one currently employs a time-sequential recording technique: either a spectrally dispersed image of a single point or a line is scanned across the scene, or an extended image is recorded through a spectrally scanned filter, both methods being comparatively slow. We propose to develop a novel approach combining all the advantages of the existing methods into a single unit: i.e. a system with both high spatial, spectral, and temporal resolution. Although real-time, high-resolution spectral imaging has been a goal for many years no existing approach comes close to this combination of features. Of those techniques that record spectral and image data simultaneously, the Computed Tomographic Imaging Spectrometer (CTIS) is of most interest. However our technique is superior because it can view the whole field indiscriminately, rather than specific regions, it is has a superior signal to noise ratio, and, most importantly, it has 1000 spectral channels as opposed to 50. This project will develop a demonstrator and benchmark it against challenging problems in bio microscopy, spectroscopy and security, including multipoint SERS and Raman microscopy, and spectroscopically contrasted imaging in a range of biological samples.

4 Full-field Coherent Quantum Imaging

Project partner(s): University of Strathclyde
Glasgow supervisor(s): Miles Padgett
Reference number: FFCQI

Quantum entanglement is the invisible non-classical link that can exist between objects separated from each other. Although disputed by Einstein, entanglement is now accepted as a fundamental property of the universe. Light sources exist where photons are emitted as entangled pairs, each photon is ill-

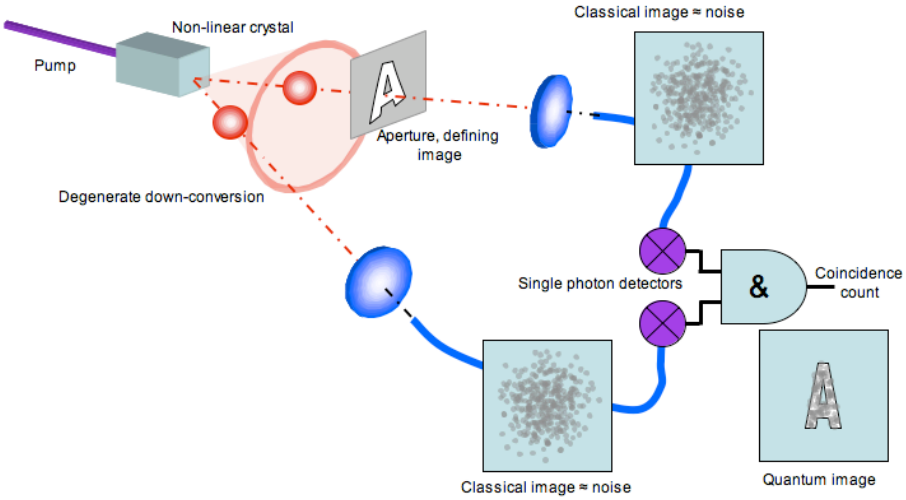

Figure 2: Principle of quantum imaging. (See project 4.)

defined in direction and energy, but measurement of either gives knowledge of both. If one of the beams of photons is used to illuminate an object, then the image is imprinted onto the other / enabling detection by a remote camera. This is called Quantum or Ghost Imaging, an object placed in one location and be imaged at another! This is all thanks to the coherence of quantum mechanics.

Making Ghost Imaging work is a technological challenge, one needs to detect the position of individual photons and distinguish these from any and all sources of noise. To date this has only been possible by raster-scanning single detectors backwards and forwards over the image plane / meaning any Ghost image takes a long time to record. In this work we will develop a real-time Ghost Camera giving live Ghost Images.

The system will allow us to explore still disputed questions in the interpretation of Quantum Mechanics including the correct angular form of Heisenberg's uncertainty principle; the pioneering of ghost spectroscopy and explore potential applications in covert imaging, surveillance and sensing.

To succeed we will develop a new way of using state of the art photon detectors, computer controlled holograms and short pulse laser sources, while verifying the quantum aspects of our work will require a careful theoretical analysis.

5 Optical Tweezers at Long Range and High Pressure

Project partner(s):
Glasgow supervisor(s): Miles Padgett
Reference number: OTLRHP

Optical tweezers move microscopic objects around using nothing more than the gentle touch of light itself. For over 20 years scientists have used optical tweezers to explore the small forces in nature - to watch and measure the motion of individual cells, bacteria and biomotors on a piconewton/nanometre scale.

One problem with tweezers is that they require very powerful lenses meaning that the optical trap is usually less than a millimetre from the lens itself. This short range of the optical tweezers limits their application and it is this limitation we seek to overcome.

Jointly with some of our international collaborators we will build a portable technology demonstrator where the trapping point can be a few mm above a simple mirror and 10mm away from the lens. We have just shown that these mirror traps can be electronically enhanced to give similar performance to a traditional tweezers.

Again with our collaborators we wish to illustrate how such a system can allow science that is beyond the "range" of traditional systems. For example we will show optical trapping within an ultra-high pressure cell, which typically have diamond windows too thick for traditional systems. We will trap at pressure up to 1GigaPascal exploring the strange changes in resulting viscosity and, for example, look at whether bacteria can still swim. We will use the increased optical access to measure optical forces from first principles — addressing the age old dilemma of how much force a light beam really produces.

6 Security in the vortex

Project partner(s): University of Bristol
Glasgow supervisor(s): Miles Padgett
Reference number: GLAPHOT002

We will develop a new approach to creating non-copyable physical keys. These keys will be simple glass discs 10-20mm in diameter. Under illumination by laser light, each glass disc produces a unique signature speckle pattern. Although familiar as the mottled 2D pattern obtained by scattering a laser beam from a wall or screen, speckle is truly a 3D phenomenon. The waves interfereing over the full volume of space, the wall or screen simply being a single cross section.

In the scattered volume of light, the bright regions are threaded by a tangle of lines of darkness. This network of optical vortices is unique to the scattering object, critically dependent on its nanoscale structure. Back calculating from any speckle pattern to deduce the shape of the original glass is virtually impossible and the extreme sensitivity of the speckle pattern / and particularly the dark vortices / to the form of the glass means that no technique exists where the disc can be replicated with sufficient precision to produce the same 3D pattern, i.e. the key is non-copyable.

The complexity of the vortex network is such that any sub set of it carries sufficient information to verify the key. Any section, or sections, through this network will be readable by a compact optical system. Verification that the key is the original could be obtained by a non-secure, web-based interrogation of a central (secure) database. Two-way authentication between key holder and legitimate authenticator will be established by the database providing a sub-set of further information about the vortex signature, which could subsequently confirmed by the key holder.

The underpinning science extends beyond optical speckle to include all physical phenomena which are described in terms of waves. Out findings will impact upon fields as diverse as superfluids, cosmic strings and reaction-diffusion waves in heart tissue.

7 Holographic flow measurement

Project partner(s): School of Electronics and Electrical Engineering
Glasgow supervisor(s): Miles Padgett
Reference number: GLAPHOT004

Ever been caught by a speed camera? Most work by taking two images in quick succession the speed of your car being calculated from the separation of

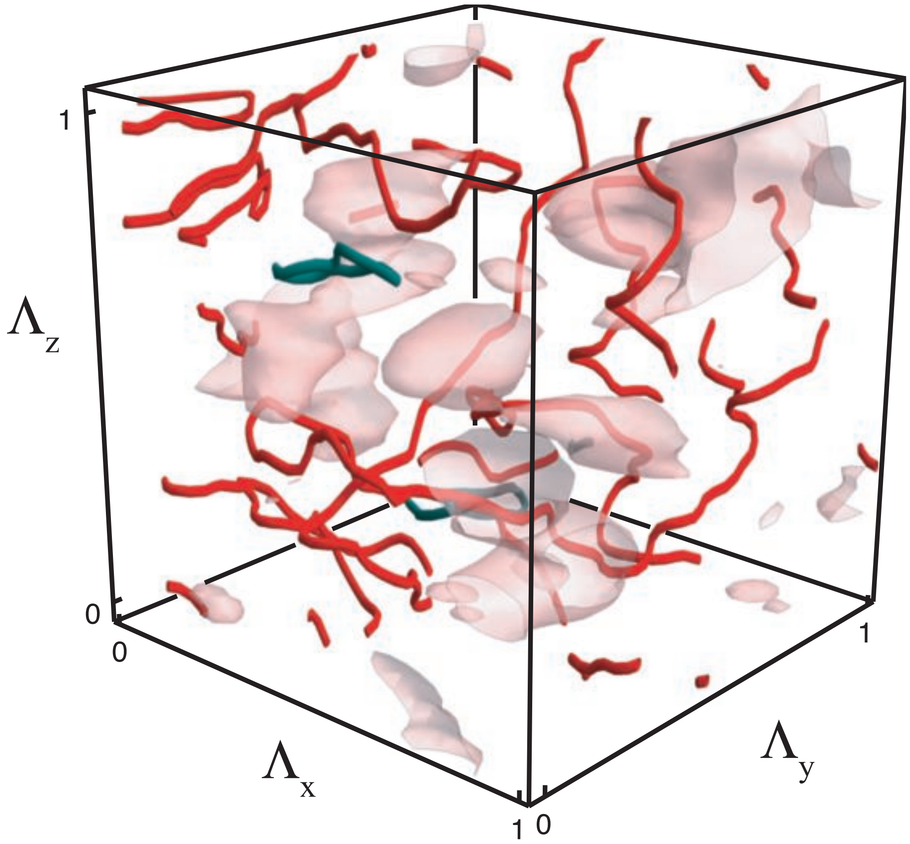

Figure 3: 3D complexity of laser speckle. (See project 6.)

its images. We have invented a similar technique for measuring the speed of micron-sized objects moving within a fluid.

Our technique relies on optical tweezers, tightly focussed beam of light to trap and hold micro-sized test particles in the fluid. Pulsing the tweezers repeated releases the objects into the fluid flow and the speed camera records their velocity, before the particles are re trapped. The result of many measurements is averaged to give the velocity of the fluid flow to an accuracy of one micron per second.

One area where we will apply our technique is micro-fluidics, micron-sized networks of fluid channels allowing the transfer and mixing of chemical reagents, probes or bio-objects. Such systems are the basis of "lab on chip" technology, cheaper, more compact and faster than their full sized lab equivalents. The small scale of lab chips means that fluid behaviour is non-intuitive, water flow being more like concrete, hence the ability to measure the fluid is both elegant and instructive.

Beyond gaining an understanding of micro-fluidic flow, our aim is to apply the technique to various bio-applications. Fluid flow around a cell creates mechanical stress, modifying the cell response with a parameter that is not understood; motile cells can swim in a fluid, but again the interplay between the creation and sensing of fluid flow is poorly understood. We believe that our ability to measure the fluid flow with both spatial and temporal resolution combined with our proven expertise in other imaging and sensing technologies will allow us to address these and many other interesting issues.

8 Ray-optics beyond wave optics

Project partner(s): Masaryk University (Brno, Czech Republic), University of Rochester (USA), École Polytechnique Fédérale de Lausanne (EPFL, Switzerland)
Glasgow supervisor(s): Johannes Courtial
Reference number: ROBWO

Microscopes and telescopes — in fact just about any optical instrument that creates images — relies on the fact that light rays change direction when they encounter a surface or interface. In the case of the mirror, this is described by the law of reflection, and for the interface between different refractive indices it's Snell's law. If the media involved are isotropic, then (together with the direction change on passage through a phase wedge) these are all the light-ray-direction changes that preserve the continuity of light rays, i.e. that ensure that light rays do not jump sideways at the interface. In crystals, light-ray-direction changes can be slightly more general.

Our group is pioneering novel materials that change the direction of light rays in unprecedented ways. In many ways, this is analogous to what optical metamaterials — periodic structures of sub-wavelength-size resonant electronic circuits — do to light waves. We believe these materials will open up many new possibilities, for example for solar concentrators or range finders.

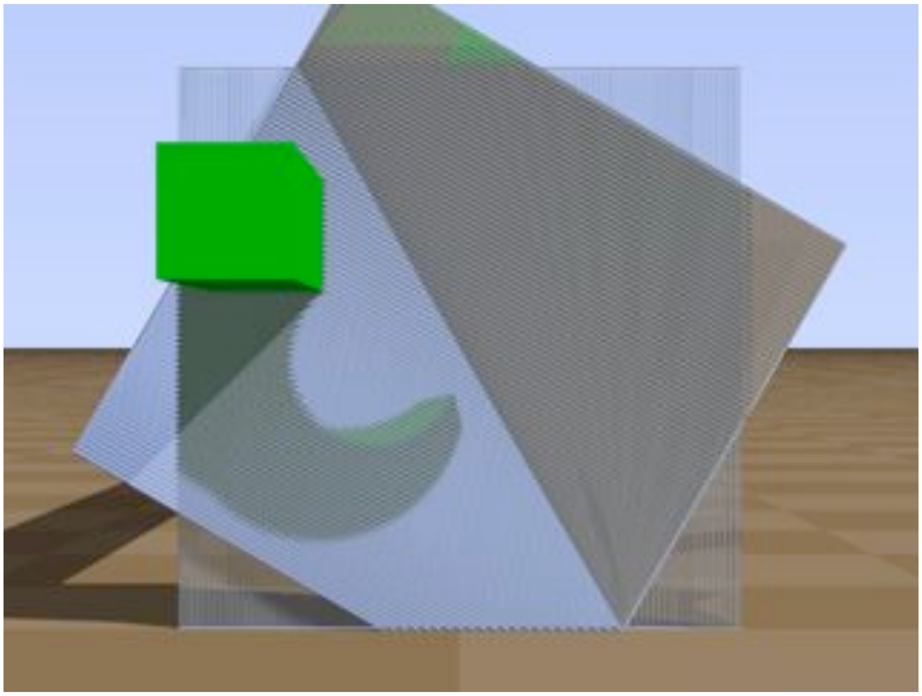

Figure 4: View through a ray-direction-changing material that is “impossible” wave-optically. (See project 8.)

9 Complex-position optics

Project partner(s): University of Rochester (USA), École Polytechnique Fédérale de Lausanne (EPFL, Switzerland)
Glasgow supervisor(s): Johannes Courtial
Reference number: CPO

A window that rotates all light rays by a fixed angle around the window normal can be formally described as a refracting interface between different complex refractive indices [1]. (In this formalism, complex refractive index does not imply absorption.) We intend to investigate the effect of this complex refractive index on (quantum) imaging.

The application to imaging follows naturally from insertion of complex refractive index into the lens-makers equation, resulting in a complex focal length. This in turn can be inserted into the thin-lens equation, resulting in complex image positions. The image of a point light source is then a spread out, twisted, ray bundle. There are several links with other fields which we intend to investigate; for example, twisted ray bundles have orbital angular momentum, and they are closely related to the rays in Gaussian beams, which can be formally described as originating from a complex source position.

10 Transformation optics for optical angular momentum

Project partner(s): Masaryk University (Brno, Czech Republic)
Glasgow supervisor(s): Johannes Courtial
Reference number: TOFOAM

Inhomogeneous materials bend light-ray trajectories. How can this be utilized? Imagine we want to bend light-ray trajectories in some way. If we can find a coordinate system ("electromagnetic space") in which the desired light-ray trajectories are straight lines, then transformation optics provides a recipe for finding continuously-varying material properties that bend light rays along the desired trajectories [2, 3]. These material properties can be realized in the form of metamaterial structures.

We apply transformation optics to the field of orbital angular momentum (OAM) of light. OAM is due to the spatial structure of light fields, and transforming this structure changes OAM. For example, by transforming a light beam, OAM can be converted into transverse momentum [4]; this can be done with holograms, but in principle it can be done much better with transformation optics.

11 Phase-dependent atom optics

Project partner(s): University of Strathclyde
Glasgow supervisor(s): Sonja Franke-Arnold

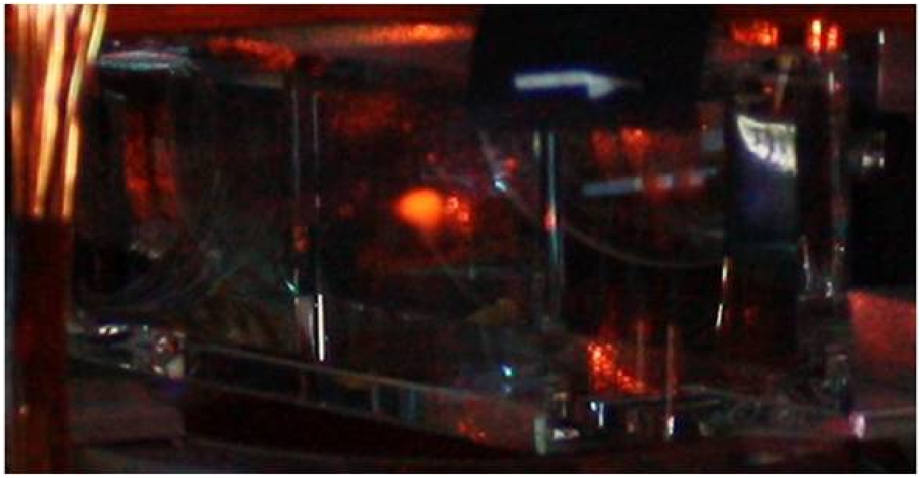

Figure 5: (See project 11.)

Reference number: GLAPHOT010

Laser cooling atoms to milli-Kelvin degrees and beyond has become common practice. In the extreme, the atoms are so cold that their de-Broglie wavelength exceeds their separation, and a Bose Einstein condensate is formed. However, many quantum coherent effects can be studied on simpler systems such as cold atoms or even atomic vapours, and in this project we focus on cold Rubidium atoms. This project will be based on a fully operational standard magneto-optical trap (MOT) for Rb87 atoms, in which we routinely hold 5×10^8 atoms at temperatures in the range of some 100 micro Kelvin.

It has been predicted that, if more than one light beam is interacting with atoms, the different excitation amplitudes compete with each other. The atoms then display electro-magnetically induced transparency (EIT), where a powerful laser beam makes a gas transparent. Furthermore, if light beams couple several atomic levels in a closed loop configuration, coherences are formed due to interference in the atomic excitations, rendering the system sensitive to the phase of the light, such that it can be switched from opaque to semi-transparent. This may offer new perspectives in control techniques in quantum electronics although very few experiments have investigated these effects.

This project aims to use spatial light modulators to sculpt the phase profile of a light beam, and then to imprint this spatial phase pattern onto the population of the atomic sample. One phase pattern could be the azimuthal phase dependence of orbital angular momentum carrying Laguerre Gauss light beams. The subsequent interaction of such light with atoms will clarify the transfer of orbital angular momentum between light and matter and reveal the disputed nature of light's optical angular momentum within a dielectric.

12 Quantum interface for atoms and light with orbital angular momentum

Project partner(s): University of Strathclyde
Glasgow supervisor(s): Sonja Franke-Arnold
Reference number: GLAPHOT012

The long-term vision of quantum computation is to establish a quantum information network: a set of quantum processors linked by transmission lines interspersed by quantum buffers. A quantum computer that works not only in a two-dimensional basis of qubits but instead uses quantum images has additional advantages, allowing a larger bandwidth and intrinsically secure quantum protocols. The orbital angular momentum (OAM) of light offers a convenient — and intriguing — state basis for quantum images. The infinite-dimensional basis of OAM states enables a single photon to carry high dimensional quantum information described as qudits.

While it is perfectly feasible to generate and detect all required OAM modes, there is to date no system that efficiently processes or stores OAM quantum information. The full exploration of the high dimensionality poses both experimental and theoretical challenges. While OAM information can conveniently be carried by photons, its storage and processing requires the interaction of OAM carrying photons with media, be it atomic vapours, single atoms or ions, Bose condensates or nonlinear crystals. This project will develop experiments and theory that enable the transfer of OAM between photons and atomic media, and the interaction of OAM within the medium itself.

In a first preliminary experiment we have observed the parametric transfer of OAM light from two pump lasers at 780nm and 776nm to light at 420nm and an unobserved infrared transition. More generally, this project aims to study OAM conservation in 4 wave mixing processes in an atomic vapour or a sample of cold atoms and to investigate the effect of mode-matching over propagation on the generation of different combinations of OAM modes in the two generated coherent light beams.

References

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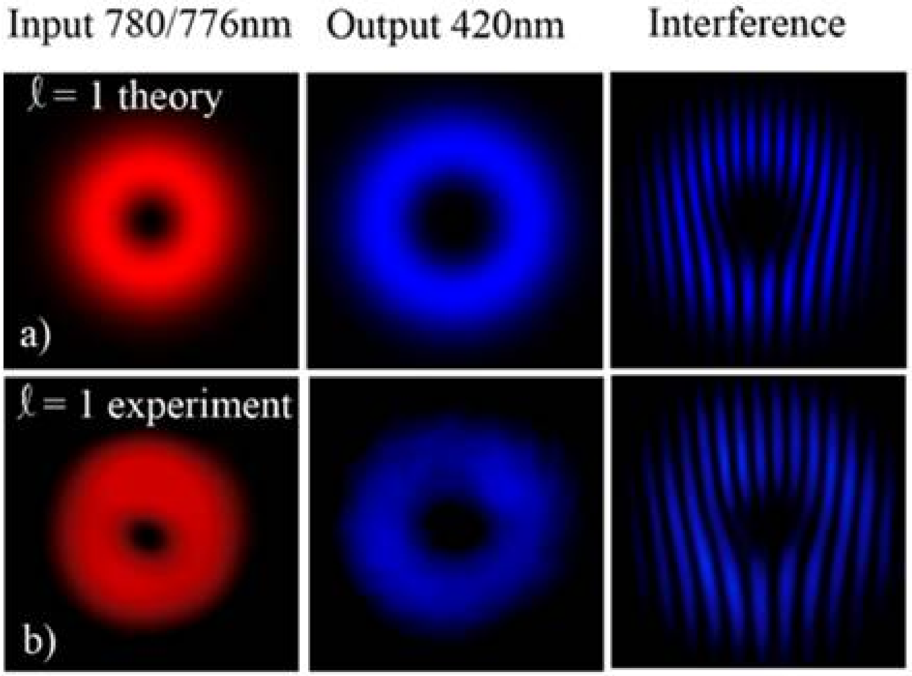

Figure 6: (See project 12.)

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