Contemporary Physics, 2000, volume 41, number 5, pages 275–285

Light with a twist in its tail

MILES PADGETT and L. ALLEN

Polarized light is a phenomenon familiar to anyone with a pair of polaroid sunglasses. Optical components that change the nature of the polarization from linear to circular are common in any undergraduate laboratory. Probably only physicists know that circularly polarized light carries with it an angular momentum that results from the spin of individual photons. Few physicists realize, however, that a light beam can also carry orbital angular momentum associated not with photon spin but with helical wavefronts. Beams of this type have been studied only over the last decade. In many instances orbital angular momentum behaves in a similar way to spin. But this is not always so: orbital angular momentum has its own distinctive properties and its own distinctive optical components. This article outlines the general behaviour of such beams; how they can be used to rotate microscopic particles; how they interact with nonlinear materials; the role they play in atom–light interactions and how the rotation of such beams results in a measurable frequency shift.

1. Introduction

A light beam consists of a stream of photons. Each photon has an energy $\hbar\omega$ and a linear momentum of $\hbar k$ which is directed along the beam axis perpendicular to the wavefronts. Independent of the frequency, each photon has a spin angular momentum of $\hbar$ aligned parallel or antiparallel to the direction of propagation. Alignment of all the photon spins gives rise to a circularly polarized light beam.

Few physicists realize that light beams can also carry an orbital angular momentum which does not depend upon polarization and so is not related to the photon spin. This article will explain the difference between spin and orbital angular momentum; how light beams with orbital angular momentum are generated and how they behave. Specifically it will show how these beams can form an optical spanner, interact within nonlinear materials, play new roles in atom–light interactions and can lead to rotational Doppler shifts.

2. Orbital angular momentum and Laguerre–Gaussian modes

Lasers are widely used in optical experiments as the source of *well-behaved* light beams of a defined frequency. The energy flux in any light beam is given by the Poynting vector which may be calculated from the vector product of the electric and magnetic fields. In vacuum, or any isotropic material, the Poynting vector is parallel to the wavevector and perpendicular to the wavefront of the beam. In normal laser light, the wavefronts are planar; the wavevector, and the linear momentum of the photons, is directed along the beam axis in the z direction. The field distributions of such beams are paraxial solutions to Maxwell's wave equation but, although these simple beams are the most common, other possibilities exist. For example, beams that have l intertwined helical wavefronts are also solutions of the wave equation. The structure of these complicated beams is difficult to visualize, but their form is familiar to us all in the guise of the '$l = 3$' fusilli pasta. Most importantly, the helical wavefronts have a Poynting vector and a wavevector that spiral around the beam axis. This means that the momentum of the each photon has an azimuthal component (figure 1). A detailed calculation of the momentum, involves all the electric and magnetic fields present, particularly those in the direction of propagation. For all points in the beam, the ratio between the azimuthal and z components of the momentum is found to be l/kr. The linear momentum of each photon is given by $\hbar k$, so if we take the cross-product of its azimuthal component with the radius vector, r, we get an *orbital* angular momentum per photon of $l\hbar$. Note also that the azimuthal component of the wavevector is l/r, independent of the wavelength.

Authors' address: Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK.

Contemporary Physics ISSN 0010-7514 print/ISSN 1366-5812 online
http://www.tandf.co.uk/journals

Surprisingly, it was not until 1992 that this deceptively simple result was identified for beams with helical wavefronts [1].

Although we have explained the importance of helical wavefronts, we have said nothing as to what these beams look like. Ordinary laser beams, with planar wavefronts are usually characterized in terms of Hermite–Gaussian modes [2]. These modes have rectangular symmetry and are described in terms of two mode indices m and n, which give the number of nodes in the x and y directions respectively; the modes are labelled HG_{mn}. In contrast, beams with helical wavefronts are best characterized in terms of Laguerre–Gaussian modes described by the indices l, the number of intertwined helices, and p, the number of radial nodes. We should note, for $l \neq 0$, the phase singularity on the beam axis results in a zero on axis intensity (figure 2).

When a beam with helical wavefronts is also circularly polarized, then the angular momentum has both orbital and spin components and the total angular momentum of the light beam is $(l \pm 1)\hbar$ per photon [3].

2.1. *The Poynting vector interpretation of orbital and spin angular momentum*

A careful calculation of the Poynting vector for Laguerre–Gaussian models leads to a physically understandable interpretation of orbital angular momentum. It arises

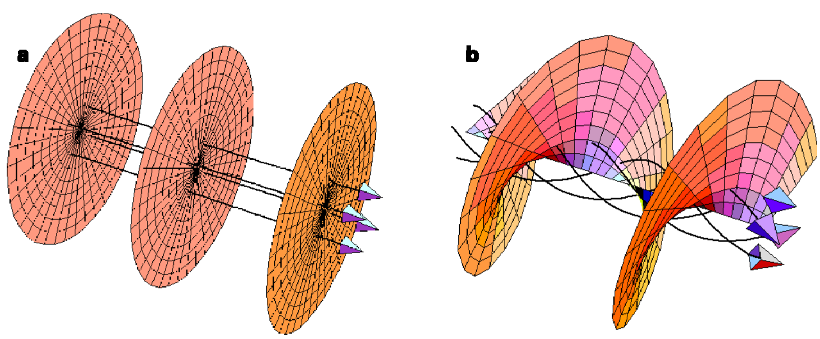


Figure 1. Laser beams usually have planar wavefronts with wavevectors parallel to the beam axis. Beams with helical wavefronts have wavevectors which spiral around the beam axis and give rise to an orbital angular momentum.

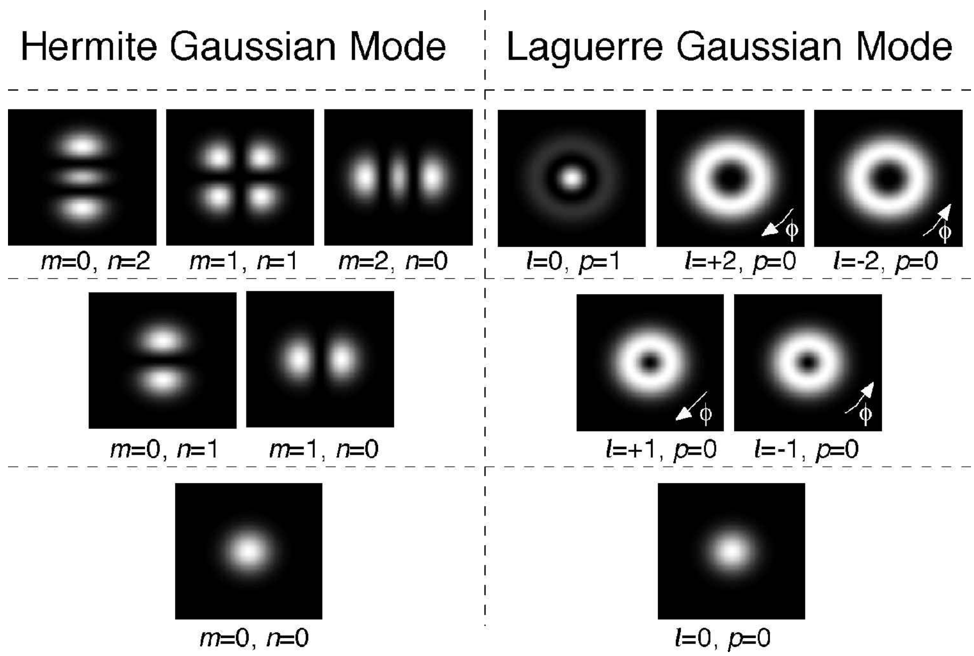


Figure 2. The transverse profile of most laser beams can be described in terms of either Hermite–Gaussian or Laguerre–Gaussian modes.

because there is an azimuthal component of the Poynting vector at each point on the wavefront and non-zero resultant when integrated over the beam cross-section.

The spin angular momentum of circularly polarized light may be interpreted in a similar way. A beam with a circularly polarized planar wavefront, even though it has no orbital angular momentum, has an azimuthal component of the Poynting vector proportional to the radial intensity gradient. This again integrates over the cross-section to a finite value. We note that when the light is linearly polarized there is no azimuthal component to the Poynting vector and so no spin angular momentum.

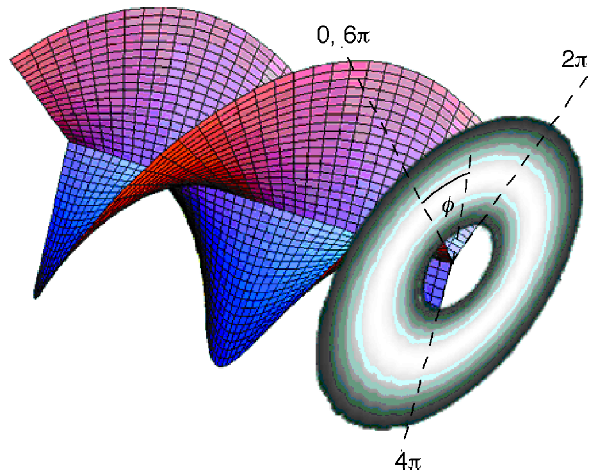


Figure 4. A beam with helical wavefronts has an azimuthal phase dependence of exp (i$l\phi$). The l= 3 example shown here has phase change of 6π around the beam axis.

3. Generation of beams possessing orbital angular momentum

But how can such beams be generated? Most commercial lasers emit a HG_{00} mode with a planar wavefront and a transverse intensity described by a Gaussian function.

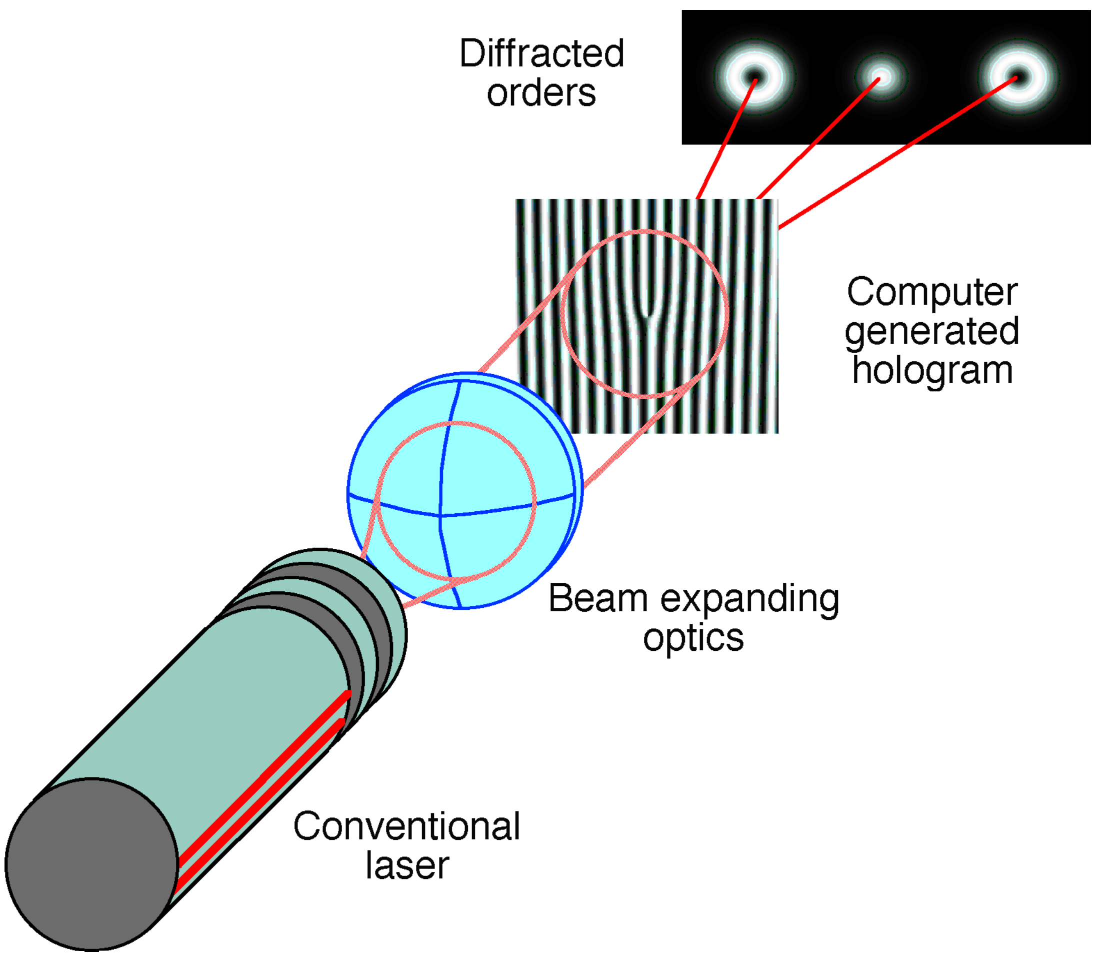


Figure 3. A computer generated hologram resembles a distorted diffraction grating and when placed in the beam of a conventional laser produces a first-order diffracted spot of the desired form.

Although a number of different methods have been used to successfully transform a HG_{00} Hermite–Gaussian mode into a Laguerre–Gaussian mode, the simplest to understand is perhaps the use of a computer generated hologram [4]. Although the term 'hologram' is correct, it is more informative to describe it as a computer-generated diffraction pattern which gives diffracted beams of the desired form. In its simplest form, a computer-generated hologram is produced from the calculated interference pattern that results when the desired beam intersects the beam of a conventional laser at a small angle. The calculated pattern is transferred to high-resolution holographic film. When the developed hologram is placed in the original laser beam a diffraction pattern results, the first order of which has the desired amplitude and phase distribution (figure 3).

There are various levels of sophistication in hologram design. Holograms that comprise only black and white areas with no grey scale, are referred to as binary holograms. In these, the relative intensities of the two interfering beams play no role and the transmission of the hologram is set to be zero for a calculated phase difference between 0 and π, or unity for a phase difference between π and 2π. A limitation of binary holograms is that very little of the incident power ends up in the first order diffracted spot, although this can be partly overcome by blazing the grating [5]. When mode purity is of particular importance, it is also possible to create rather more sophisticated holograms where the contrast of the pattern is varied as a function of radius such that the diffracted beam has the required radial profile [6].

But how do physicists know when they have actually got a Laguerre–Gaussian mode? This is more tricky than it might appear because an annular intensity profile does not necessarily imply helical wavefronts. Nor have we discussed how the rotational sense of the wavefronts may be deduced. The key to identification of a Laguerre–Gaussian mode lies in the previous section, namely the distinctive interference pattern it creates when interfered with a plane wave.

Two beams with plane wavefronts, interfere to give a straight-line fringe with a spacing that depends on both the wavelength and the intersection angle. However, if one of the beams has helical wavefronts the pattern is more complicated. The l intertwined wavefronts mean that for all cross-sections through the beam, there is an azimuthal phase term of exp $(il\phi)$ (figure 4). If such a beam is interfered with a co-linear plane wave then the interference pattern would comprise of l dark spokes. If the intersection angle is increased then these spokes are combined with the straight-line fringes to give distorted fringes with a l-fold dislocation on the beam axis.

Rather than interfere a helical beam with a plane wave it is often easier to interfere it with its own mirror image. The mirror image of the beam has the opposite sense of rotation, hence, exp $(il\phi)$ transforms to exp $(-il\phi)$ and the phase difference is exp $(i2l\phi)$. This results in $2l$ dark spokes, or fringe dislocations, in the interference pattern (figure 5). This allows the l value of any Laguerre–Gaussian mode to be measured unambiguously.

4. Orbital angular momentum in nonlinear optics

Second harmonic generation is a technique widely employed to convert the output of an infrared laser into the visible. For example, the 1064 *nm* emissions from Nd:YAG laser are routinely converted to 532 *nm* by passage through the nonlinear material KTP.

Second harmonic generation may be envisaged as the destruction of two photons of low frequency and the creation of one photon of twice the frequency. As the energy of each photon is given by $\hbar\omega$ we see that this condition is consistent with the conservation of energy,

$$\hbar\omega + \hbar\omega \rightarrow \hbar 2\omega.$$

However, conservation of energy alone is not enough to ensure efficient second harmonic generation; the conservation of linear momentum is also important. The momentum conservation is complicated by the fact that the nonlinear

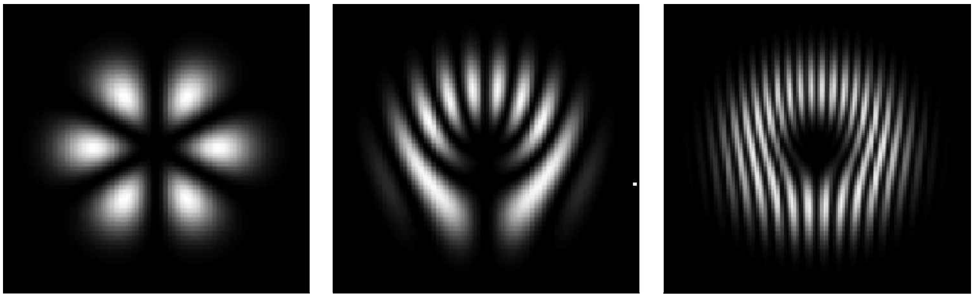


Figure 5. Interference between an l= 3 Laguerre–Gaussian mode and its own mirror image produces 6 dark radial fringes (left). As the angle between the beams is increased straight-line fringes are introduced and the azimuthal phase terms result in fringe dislocations on the beam axis.

interaction takes place in a crystal which exhibits a frequency dependent refractive index. The process of balancing the refractive index for the low frequency and doubled frequency light is known as 'phase-matching' and usually requires the careful control of the angle of the nonlinear crystal and its temperature to a fraction of a degree and a few Kelvin respectively.

It seems reasonable to expect that what is true for the linear momentum must be true also for the angular momentum. Conservation of angular momentum implies that in second harmonic generation, two photons with orbital angular momentum $l\hbar$ per photon should combine to form a single photon with an orbital angular momentum of $2l\hbar$. This is indeed the case (figure 6); examination of the interference pattern of a Laguerre–Gaussian mode with its own mirror image both before and after second harmonic generation shows the number of fringe dislocations to double (figure 7).

Although the conservation of orbital angular momentum is not unexpected, it is important to recognize that the same is not true for spin angular momentum as no single photon can carry more than $\pm\hbar$!

5. Transfer of the orbital angular momentum from light to matter

In 1936, Beth used a quarter-wave plate, suspended from a quartz fibre to transform circularly polarized light to a linear polarization [7]. In this process the spin angular momentum of $\hbar$ per photon was removed from the light beam and transferred to the wave plate, giving a measurable torque. After the realization that light beams with orbital angular momentum could be generated, the obvious challenge was to transfer the angular momentum to matter. The difficulty was how to do so. An absorbing particle will also absorb linear momentum from the beam. Consequently, any slight misalignment of the beam axis to the rotation axis of the particle would result in unwanted motion from which the rotation arising for the orbital angular momentum could not be distinguished. The solution lay in the use of optical tweezers.

Optical tweezers rely on the force experienced by a dielectric material when placed in an electric field gradient. A tightly focused laser beam has an extremely large electric field gradient, resulting in a force on a small transparent particle directed towards the beam focus. In 1987, after many years of related research, Ashkin and co-workers used a tightly focused beam of laser light to trap a micron-sized glass sphere in three dimensions [8].

In 1994, we suggested [9] that optical tweezers could be used to ensure the alignment of the light beam and the rotation axis of the particle, thereby eliminating any unwanted motion (figure 8). The first demonstration of this angular momentum transfer was reported in 1995 by He and

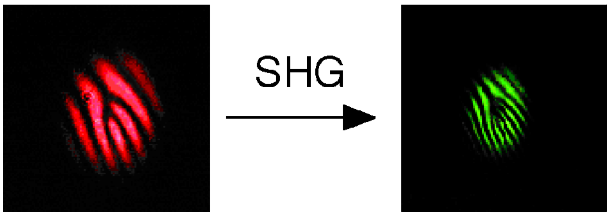


Figure 7. For second harmonic generation, interference patterns reveal that the orbital angular momentum per photon doubles.

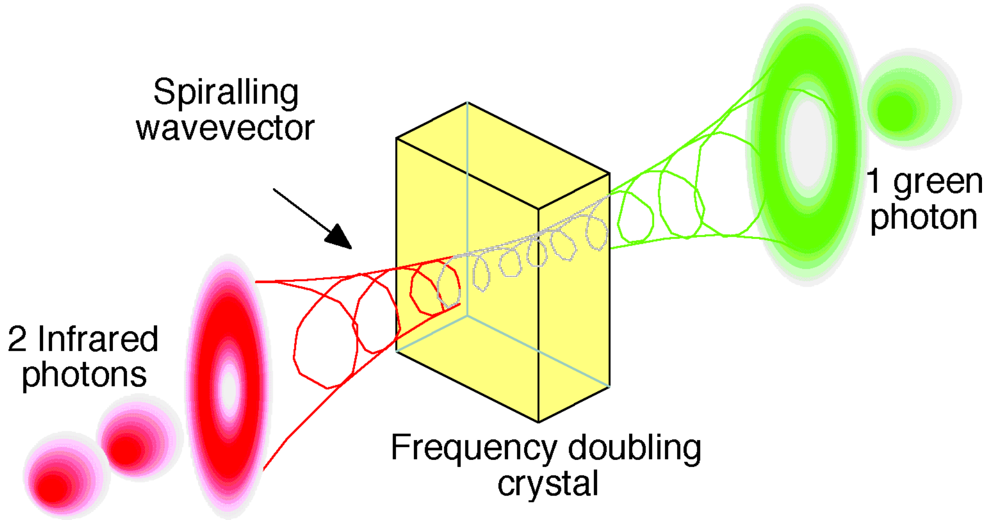
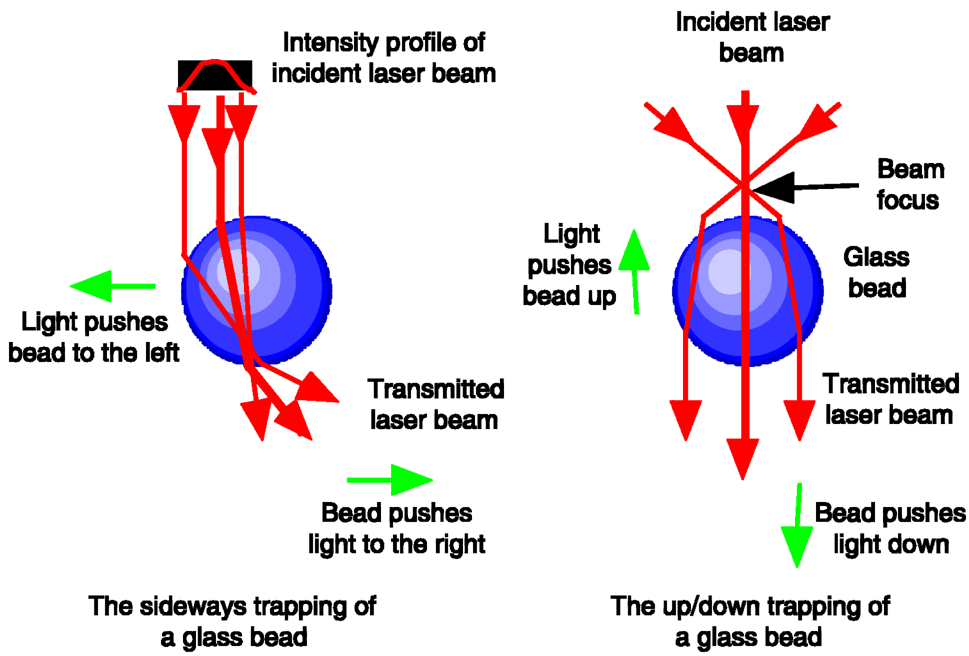


Figure 6. In second harmonic generation two photons combine to form one photon with twice the energy, that is double the frequency, and twice the orbital angular momentum.

A ray optics explanation of optical tweezers

Although correctly described in terms of the gradient force, a useful insight into optical tweezers can be obtained from a ray optical picture.

A light ray passing through a transparent bead will be refracted such that, even in the absence of absorption, there will be a reaction force on the object. If the beam is tightly focused then this force will have both lateral and axial components leading to trapping in three dimensions. Optical tweezers are now widely used in bio-physics for the manipulation of living cells.



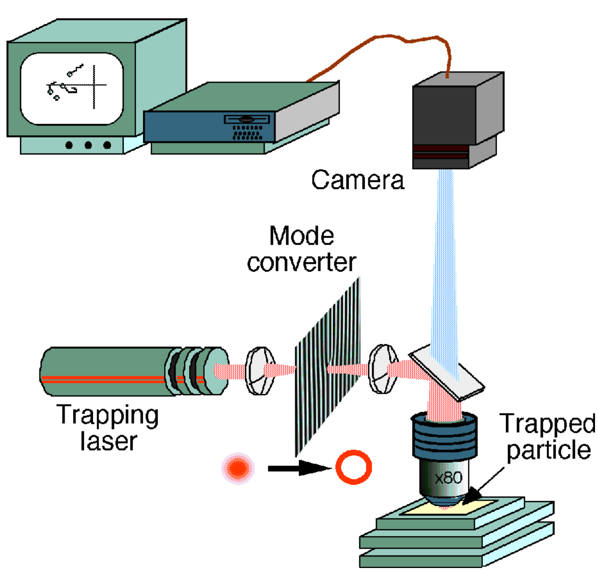


Figure 8. An optical spanner is formed by using a Laguerre–Gaussian laser beam to trap and rotate a trapped particle in optical tweezers.

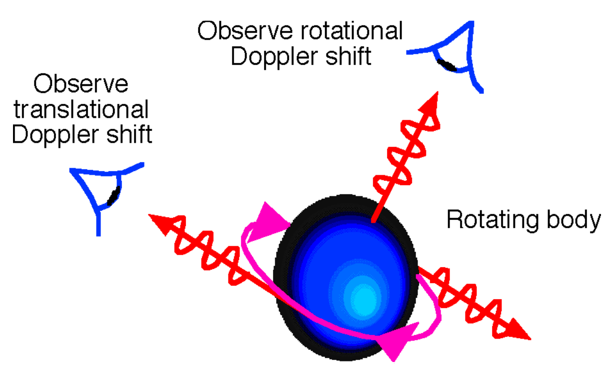


Figure 9. The rotational Doppler shift is observed along the normal to the plane of rotation where the translational Doppler shift is zero.

co-workers [10]. The micron-sized particles were of a highly absorbing ceramic powder and could, consequently not be trapped in the conventional way. Absorption of the linear momentum from the beam meant that the particle could only be confined in two-dimensions near the intensity null on the beam axis. Restraint in the axial dimension was provided by the microscope cover-slip. When trapped with a Laguerre–Gaussian mode of azimuthal mode index $l = 3$, rotation of the particle was observed attributable to the transfer of orbital angular momentum from the beam. However, the inherent experimental uncertainty meant that it was impossible to relate accurately the rotation speed to the torque, the amount of absorbed light and the angular momentum per photon.

In a refined experiment, we were able to overcome this problem by comparing the transfer of both spin and orbital angular momentum in the same beam to partially absorbing teflon particles, suspended in alcohol. Because the particles were now largely transmitting, the gradient force was sufficient to trap in three dimensions and hence isolate it from the sample cell walls [11]. Power levels of a few tens of milliWatts gave measurable rotation speeds of a few Hertz. When the handedness of a $l = 1$, circularly polarized Laguerre–Gaussian mode with an orbital angular momentum $\hbar$, the total angular momentum was changed from $\hbar - \hbar = 0$ to $\hbar + \hbar = 2\hbar$ per photon. The resulting 'stop–start' rotation of the particle confirmed the magnitude of the orbital angular momentum as equal to that of the spin, $\pm\hbar$. It also showed that the orbital and spin angular momentum components of a light beam are transferred in an equivalent fashion.

6. The rotational Doppler shift

The first-order translational Doppler shift is a well-known phenomenon. The relative velocity between an optical source and the observer gives rise to a frequency shift,

$$\Delta\omega = \frac{v}{c}\omega = kv = \frac{p}{\hbar}v,$$

where v is the relative linear velocity and p the linear momentum per photon.

Much less well known is that there is a rotational equivalent to the effect, where the frequency shift depends on the angular momentum per photon. It is important to recognize that this is distinct from the effect where the rotation of a large body, such as a galaxy, gives rise to a linear component of velocity between the source and observer. The rotational Doppler shift, also known as the rotational frequency shift, is observed in the direction of the angular velocity vector where the normal translational Doppler shift is zero (figure 9).

The magnitude of the electric field at any point in a linearly polarized light beam oscillates at the optical frequency. For a circularly polarized light beam, the magnitude of the electric field remains the same but it rotates around the optical axis at the optical frequency. In 1980, Garetz showed that when a circularly polarized light beam is rotated about its own axis, a frequency shift equal to the rotation frequency of the beam is introduced [12]. Geometrically, this effect is simple to understand; it is equivalent to the second hand of a watch appearing to rotate more quickly if placed on a rotating turntable. More recently, similar frequency shifts have been predicted for atomic systems subject to a rotating potential [13] and for beams containing orbital angular momentum after passing through rotating cylindrical lenses [14].

To rotate a light source or a detector about a beam axis, presents a number of experimental challenges. Any translational motion may result in additional frequency shifts due to the linear Doppler shift. An elegant solution to these difficulties is to insert a rotating half-wave plate into the light beam. A half-wave plate rotates the linear polarization of a light beam. If the half-wave plate is itself rotated with angular velocity Ω, then the polarization is rotated with an angular velocity 2Ω without the possibility of any lateral motion.

As the spin angular momentum introduces a frequency shift to a rotating beam, the next question is does orbital do the same? An insight into the how such beams will behave may be gained by examining the direction of the electric field at different points in the cross-section of the Laguerre–Gaussian mode. As before, if the beam is circularly polarized then the magnitude of the electric field remains constant and its direction depends on the phase of the beam. Laguerre–Gaussian beams have a phase which changes with azimuthal position. An advance in phase results in a clockwise or anticlockwise rotation of the electric field depending on whether the circular polarization is right or left handed. The resulting field distributions have a rotational symmetry of $l \pm 1$, depending on the relative sense of the helical wavefronts and the polarization (figure 10). We note that $(l \pm 1)\hbar$ is the total angular momentum per photon, that is spin plus orbital. When one of these beams is rotated, the electric field is advanced, or retarded, by $l \pm 1$ cycles which will be observed as a frequency shift of

$$\Delta\omega = (l \pm 1)\Omega.$$

We see that this rotational Doppler shift is equal to the total angular momentum per photon multiplied by the angular velocity and may be compared with the translational Doppler shift which is the linear momentum per photon multiplied by the linear velocity.

We recently measured this frequency shift using a millimetre-wave source oscillating at 96 GHz and high quality frequency meters which can count the shift directly [15]. As circularly polarized Laguerre–Gaussian modes form a complete set from which any arbitrary monochromatic beam can be described, this rotational Doppler shift effect is entirely general for all light beams.

7. Interaction of Laguerre–Gaussian beams with atoms

When a laser beam is tuned near the absorption frequency of an atom, forces are exerted on the centre of mass [16] of the atom. There is a dissipative force due to the momentum of the absorbed light and a dipole force that arises from the intensity gradient of the light field acting on the atomic dipole. The latter force, which is responsible for operation of optical tweezers is discussed in section 5.

As the dissipative force depends upon the momentum of the light, its detailed nature will be modified by the orbital angular momentum in the beam. Consider an atom

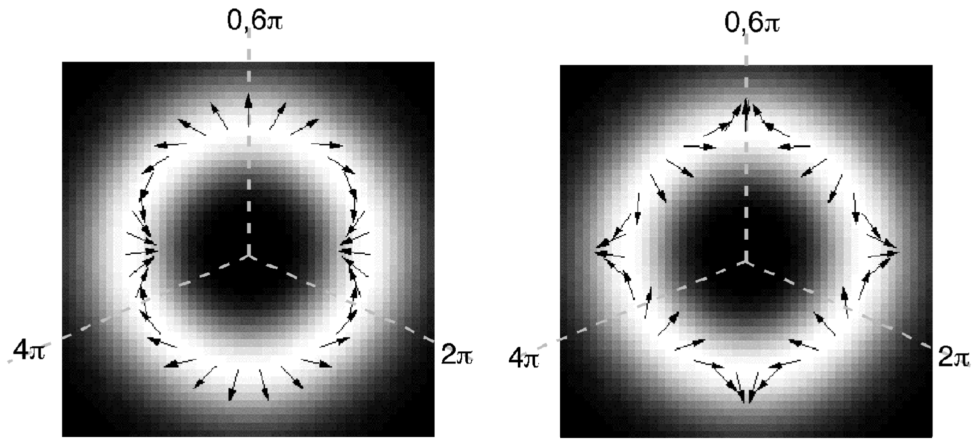


Figure 10. An $l = 3$ Laguerre–Gaussian mode has an azimuthal phase variation of 6π. However, when circularly polarized, a 2-fold or 4-fold rotational symmetry is revealed, depending on the relative sense of the helical wavefronts and the polarization.

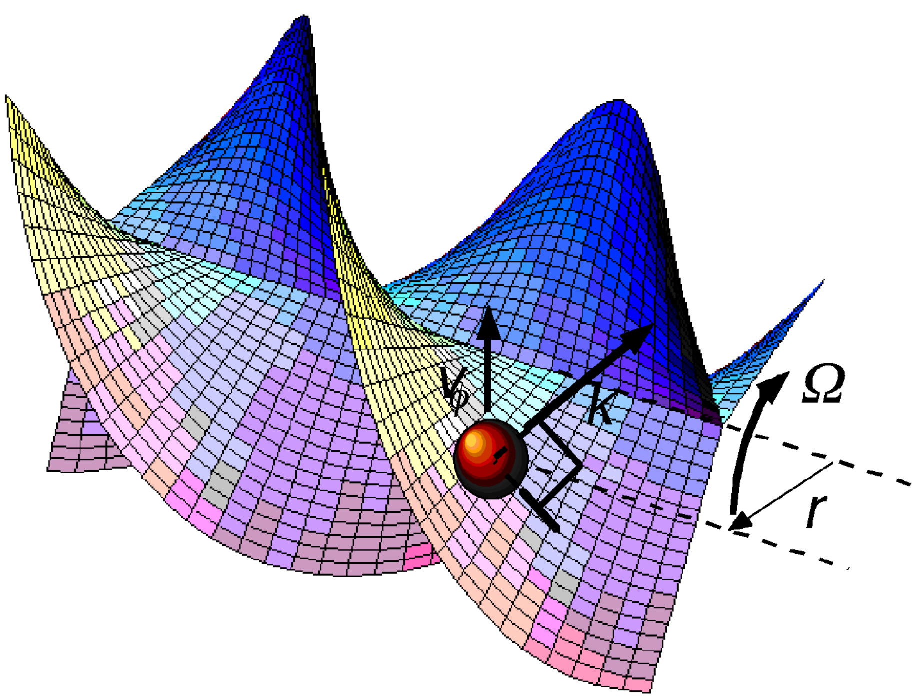


Figure 11. An atom in a Laguerre–Gaussian beam will experience an azimuthal Doppler shift proportional both to its rotational velocity and the orbital angular momentum per photon.

rotating with an angular velocity Ω a distance r away from the axis of a Laguerre–Gaussian beam (figure 11). As stated in the previous section, the translational Doppler shift of the transition frequency is given by the scalar product of the atom velocity and the wavevector of the light, $\Delta\omega = \bar{k}\ \bar{v}$. Here, the atom has a velocity in the azimuthal direction of Ωr and the azimuthal component of the Laguerre–Gaussian wavevector is l/r, resulting in a frequency shift [17],

$$\Delta\omega = \bar{k}\ \bar{v} = k_\phi v_\phi = \frac{l}{r}\Omega r = l\Omega.$$

We note that this is the same result as for the rotational Doppler shift and interestingly shows there is indeed a link between the translational and rotational shifts. A good deal of other theoretical work on the cooling and trapping of atoms has been done for beams with orbital angular momentum [18].

8. Representation of beams with spin and orbital angular momentum

We have so far shown several similarities between the spin and orbital angular momentum properties of a light beam. Indeed in many cases it seems that they are essentially interchangeable. Consideration of how the polarization of a light beam may be represented might be expected to give us further insight into the properties of light beams with orbital angular momentum.

Light polarized at 45° can be generated from two orthogonal linear polarizations added together. The introduction of a $\pi/2$ phase difference between them transforms linear polarization at 45° to a circular polarization state; introducing an additional π phase delay reverses the handedness of the polarization state (figure 12). Such phase delays are usually introduced by use of birefringent plates which must be carefully adjusted in thickness so that the difference in the speed of light of the two orthogonal polarization states results in the desired phase delay.

It transpires that Hermite–Gaussian and Laguerre–Gaussian modes behave in a similar way. For example a HG_{10} oriented at 45° can be generated from orthogonal HG_{10} and HG_{01}. Introducing a $\pi/2$ phase difference between these states transforms the HG_{10} at 45° to a $LG^1{}_0$. Introducing an additional π phase delay reverses the handedness of the $LG^1{}_0$, that is l is changed from + 1 to -1 or vice versa (figure 13). Rather than using birefringent waveplates, phase delays between orthogonal Hermite–Gaussian modes are introduced by combinations cylindrical lenses [19] which create a Gouy phase shift between the modes. Such devices are known as mode converters. A π phase delay is effectively introduced by any optical component that transforms an optical beam into its mirror image. A Dove prism is such an optical component; it inverts any image and therefore changes right hand helically phased light into left hand helically phased light or vice versa (figure 14).

The similarity in the representation of light beams containing spin and orbital angular momentum does not stop here. The polarization state of a light beam can be represented as a point on the Poincaré sphere as the superposition of orthogonal states and a similar sphere exists for Laguerre–Gaussian and Hermite–Gaussian modes [20]. The Jones polarization matrices also have a matrix equivalent for Laguerre–Gaussian and Hermite–Gaussian modes. The matrix representation can in fact be

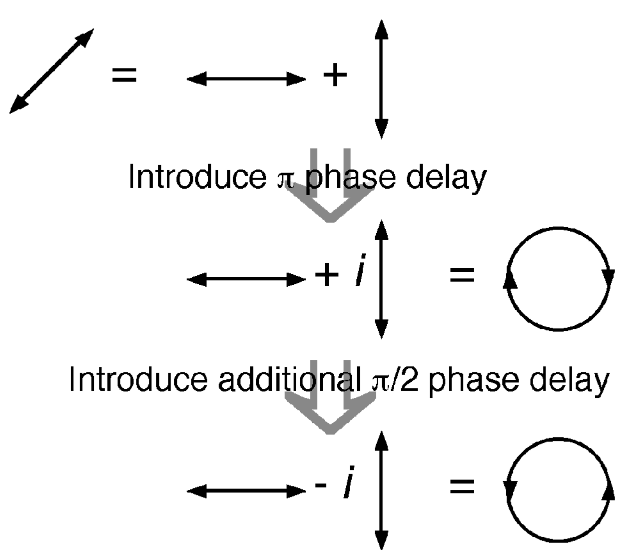


Figure 12. Two orthogonal linear polarization states can be added to give light polarized at 45° or added with a phase delay to give circularly polarized light.

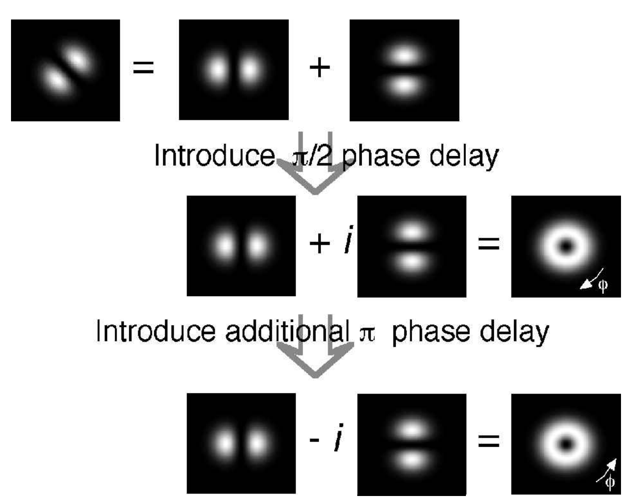


Figure 13. Two orthogonal Hermite–Gaussian modes can be added to give a Hermite–Gaussian mode at 45° or added with a phase delay to give a Laguerre–Gaussian mode.

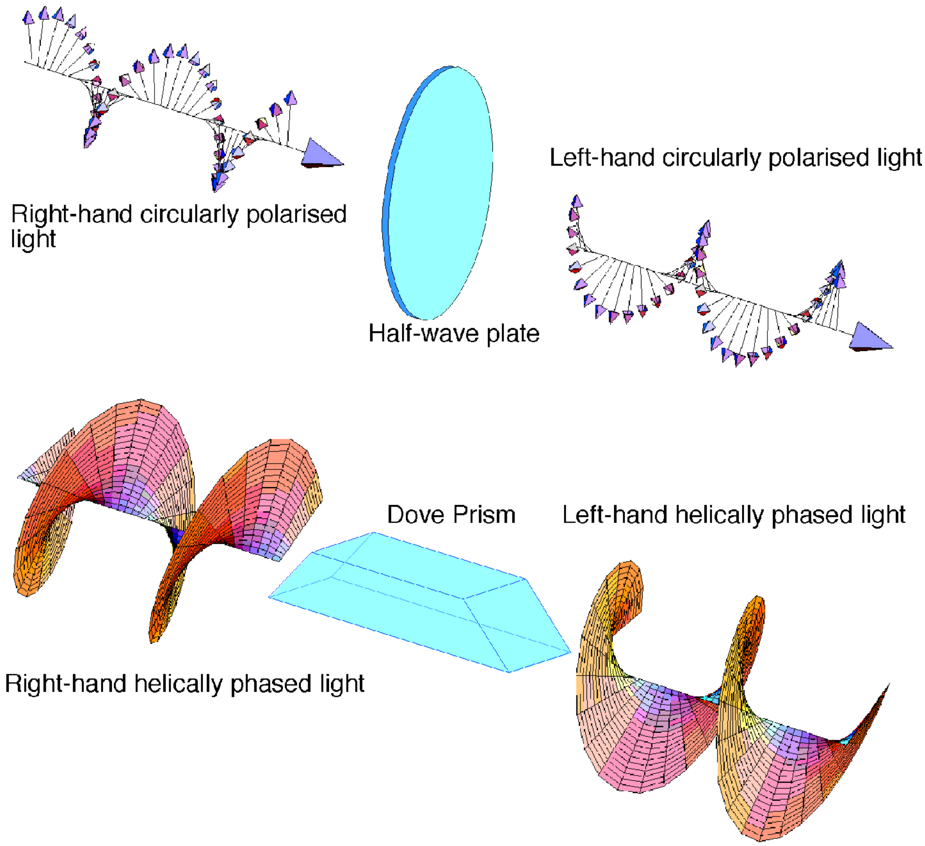


Figure 14. A half-wave plate and a Dove prism act as equivalent optical components for spin and orbital angular momentum respectively.

extended to encompass beams with both orbital and spin angular momentum simultaneously [21]. Such analogies have led to the conclusion that the rotational Doppler shift due to orbital angular momentum, as with circular polarization, is an example of a dynamically evolving Berry phase.

9. Future directions

When attempting to identify the future direction of any area of physics one can only be sure of one thing—you are going to be wrong! The study of orbital angular momentum is, no doubt, no exception, however, there are a few avenues that seem to be of particular interest.

Although the role of orbital angular momentum in second harmonic generation is now well understood, the same is not true for the reverse process of parametric down conversion. In degenerate down conversion, a single input photon becomes two photons of half the frequency. It is tempting to think that the orbital angular momentum will be divided in the same fashion. However, we have already shown [22] that when averaged over many photons, the orbital angular momentum of both the down converted beams is ill-defined. This can be seen from the fact that the down converted beams are spatially incoherent and therefore cannot have helical wavefronts or associated orbital angular momentum. Nevertheless, work by Mair and Zeilinger has demonstrated that at the single photon level, orbital angular momentum is conserved in down-converted pairs [23]. One exciting possibility is that this work can be extended to explore quantum entanglement of the orbital angular momentum quantum number of the two emitted beams of photons. Previous experiments of this kind have considered only the entanglement of the spin angular momentum.

Another obvious question that has still not been fully addressed is whether orbital and spin angular momentum can act in an equivalent fashion in relation to the selection rules for atomic transitions. For example, when placed in a magnetic field atomic emission/absorption lines are split into components, some of which only interact with circularly polarized light. Are there situations where a linearly polarized light beam containing orbital angular momentum could play the role of circularly polarized light? Our feeling is not, but then again . . . . It seems certain, however, that higher order multipole processes will depend on l and this is currently under investigation. It has already been shown that the orbital angular momentum can be absorbed in a system of cold caesium atoms and subsequently emitted on a different transition [24].

The field of orbital angular momentum in light beams is less than a decade old, no doubt many more exciting experiments remain to be performed, new theory developed and further insight into the properties of light beams achieved.

Acknowledgments

Miles Padgett and L. Allen thank the Royal Society and the Leverhulme Trust respectively for support. The authors would also like to thank Jochen Arlt, Johannes Courtial, Kishan Dholakia, Duncan Robertson, Neil Simpson and also Mohamed Babiker, William Power and Wei Lai for their contributions on the projects that make up much of the work covered in this article.

References

[1] Allen, L., Beijersbergen, M. W., Spreeuw, R. J. C., and Woerdman, J. P., 1992, *Phys. Rev. A*, **45,** 8185.
[2] Siegman, A. E., 1986, *Lasers*, Mill Valley, CA: University Science books.
[3] Barnett, S. M., and Allen, L., 1994, *Optics Commun.*, **110,** 670.
[4] Heckenberg, N. R., McDuff, R., Smith, C. P., and White, A. G., 1992, *Optics. Lett.*, **17,** 221.
[5] Heckenberg, N. R., McDuff, R., Smith, C. P., Rubinsztein-Dunlop, H., and Wegener, M.J., 1992, *Optics Quant. Elec.*, **24,** S951.
[6] Arlt, J., and Padgett, M. J., 2000, *Optics Lett.*, **25,** 192.
[7] Beth, R. A., 1936, *Phys. Rev.*, **50,** 115.
[8] Ashkin, A., Dziedzic, J. M., Bjorkholm, J. E., and Chu, S., 1986, *Optics Lett.*, **11,** 288.
[9] Padgett, M. J., and Allen, L., 1995, *Meas. Sci. Technol.*, **6,** 248.
[10] He, H., Friese, M. E. J., Heckenberg, N. R., and Rubinsztein-Dunlop, H., 1995, *Phys. Rev. Lett.*, **75,** 826.
[11] Simpson, N. B., Dholakia, K., Allen, L., and Padgett, M. J., 1997, *Optics Lett.*, **22,** 52.
[12] Garetz, B. A., and Arnold, S., 1979, *Optics Commun.*, **31,** 1.
[13] Bialynicki-Birula, I., and Bialynicka-Birula, Z., 1997, *Phys. Rev. Lett.*, **78,** 2539.
[14] Nienhuis, G., 1996, *Optics Commun.*, **132,** 8.
[15] Courtial, J., Robertson, D. A., Dholakia, K., Allen, L., and Padgett, M. J., 1998, *Phys. Rev. Lett.*, **81,** 4828.
[16] Letokhov, V. S., Minogin, V. G., 1987, *Laser Light Pressure on Atoms*, New York: Gordon and Breach.
[17] Allen, L., Babiker, M., and Power, W. L., 1994, *Optics Commun.*, **112,** 141.
[18] Allen, L., Babiker, M., Lai, W. K., and Lembessis, V. E., 1996, *Phys. Rev. A*, **54,** 4259.
[19] Beijersbergen, M. W., Allen, L., van der Veen, H. E. L. O., and Woerdman, J. P., 1993, *Optics Commun.*, **96,** 123.
[20] Padgett, M.J., and Courtial, J., 1999, *Optics Lett.*, **24,** 430.
[21] Allen, L., Courtial, J., and Padgett, M. J., 1999, *Phys. Rev. E*, **60,** 7497.
[22] Arlt, J., Dholakia, K., Allen, L., and Padgett, M. J., 1999, *Phys. Rev. A*, **59,** 3950.
[23] Mair, A., and Zeilinger, A., 1999, *Epistemological and Experimental perspectives on Quantum Physics*, edited by D. Greenberger (Netherlands: Kluwer Academic Publishers, pp. 249 – 252.
[24] Tabosa, J. W. R., and Petrov, D. V., 1999, *Phys. Rev. Lett.*, **83,** 4967.

Miles Padgett is a Royal Society University Research Fellow in the Department of Physics and Astronomy at the University of Glasgow. After a PhD in laser spectroscopy he briefly escaped academia to work as a management consultant only to return to a series of Research Fellowships. His interest in orbital angular momentum began over dinner when he made the mistake of asking the co-author of this paper ‘what are your research interests?’. He now balances this area of research with active programmes in optical instrumentation, specifically pollution monitoring and medical imaging.

L. Allen became a laser physicist in 1961 and made a ruby laser in 1962, since when he has published four books on lasers and quantum optics and a large number of papers. In 1991, after five years in senior academic administration he became peripatetic, working in Leiden; Utrecht; JILA, Colorado and as a Visiting Professor at Essex and St Andrews. He is currently a Leverhulme Emeritus Fellow with a Visiting position at Glasgow. His great mistake appears to have been answering questions over dinner.