Review Vol. 25, No. 10 | 15 May 2017 | OPTICS EXPRESS 11265

Optics EXPRESS

Orbital angular momentum 25 years on [Invited]

MILES J. PADGETT[*]

School of Physics and Astronomy, University of Glasgow, Glasgow, Scotland, UK
[*]*Miles.Padgett@glasgow.ac.uk*

Abstract: Twenty-five years ago Allen, Beijersbergen, Spreeuw, and Woerdman published their seminal paper establishing that light beams with helical phase-fronts carried an orbital angular momentum. Previously orbital angular momentum had been associated only with high-order atomic/molecular transitions and hence considered to be a rare occurrence. The realization that every photon in a laser beam could carry an orbital angular momentum that was in excess of the angular momentum associated with photon spin has led both to new understandings of optical effects and various applications. These applications range from optical manipulation, imaging and quantum optics, to optical communications. This brief review will examine some of the research in the field to date and consider what future directions might hold.

OCIS codes: (050.4865) Optical vortices; (260.6042) Singular optics; (230.6120) Spatial light modulators; (140.3300) Laser beam shaping; (090.1970) Diffractive optics; (350.4855) Optical tweezers or optical manipulation.

References and links

1. J. H. Poynting, "The wave motion of a revolving shaft, and a suggestion as to the angular momentum in a beam of circularly polarised light," Proc. R. Soc. Lond., A Contain. Pap. Math. Phys. Character **82**(557), 560–567 (1909).
2. C. G. Darwin, "Notes on the theory of radiation," Proc. R. Soc. Lond., A Contain. Pap. Math. Phys. Character **136**(829), 36–52 (1932).
3. L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman, "Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes," Phys. Rev. A **45**(11), 8185–8189 (1992).
4. J. Courtial, K. Dholakia, L. Allen, and M. J. Padgett, "Gaussian beams with very high orbital angular momentum," Opt. Commun. **144**(4-6), 210–213 (1997).
5. A. M. Yao and M. J. Padgett, "Orbital angular momentum: origins, behavior and applications," Adv. Opt. Photonics **3**(2), 161–204 (2011).
6. M. Padgett, "Light's twist," Proc. Math. Phys. Eng. Sci. **470**(2172), 20140633 (2014).
7. C. Tamm, "Frequency locking of two transverse optical modes of a laser," Phys. Rev. A Gen. Phys. **38**(11), 5960–5963 (1988).
8. P. Coullet, G. Gil, and F. Rocca, "Optical vortices," Opt. Commun. **73**(5), 403–408 (1989).
9. J. F. Nye and M. V. Berry, "Dislocations in wave trains," Proc. R. Soc. Lond. A Math. Phys. Sci. **336**(1605), 165–190 (1974).
10. M. V. Berry, J. F. Nye, and F. Wright, "The elliptic umbilic diffraction catastrophe," Philos. Trans. R. Soc. Lond. A **291**(1382), 453–484 (1979).
11. M. W. Beijersbergen, L. Allen, H. E. L. O. van der Veen, and J. P. Woerdman, "Astigmatic laser mode converters and transfer of orbital angular momentum," Opt. Commun. **96**(1-3), 123–132 (1993).
12. M. W. Beijersbergen, R. P. C. Coerwinkel, M. Kristensen, and J. P. Woerdman, "Helical-wavefront laser beams produced with a spiral phaseplate," Opt. Commun. **112**(5-6), 321–327 (1994).
13. V. Y. Bazhenov, M. V. Vasnetsov, and M. S. Soskin, "Laser-beams with screw dislocations in their wave-fronts," JETP Lett. **52**, 429–431 (1990).
14. A. Jesacher, A. Schwaighofer, S. Fürhapter, C. Maurer, S. Bernet, and M. Ritsch-Marte, "Wavefront correction of spatial light modulators using an optical vortex image," Opt. Express **15**(9), 5801–5808 (2007).
15. M. Mirhosseini, O. S. Magaña-Loaiza, C. Chen, B. Rodenburg, M. Malik, and R. W. Boyd, "Rapid generation of light beams carrying orbital angular momentum," Opt. Express **21**(25), 30196–30203 (2013).
16. J. Leach and M. J. Padgett, "Observation of chromatic effects near a white-light vortex," New J. Phys. **5**, 154 (2003).
17. H. I. Sztul, V. Kartazayev, and R. R. Alfano, "Laguerre-Gaussian supercontinuum," Opt. Lett. **31**(18), 2725–2727 (2006).

#291298 https://doi.org/10.1364/OE.25.011265
Journal © 2017 Received 23 Mar 2017; revised 29 Apr 2017; accepted 30 Apr 2017; published 4 May 2017

18. N. Radwell, R. D. Hawley, J. B. Götte, and S. Franke-Arnold, “Achromatic vector vortex beams from a glass cone,” Nat. Commun. **7**, 10564 (2016).
19. C. Maurer, A. Jesacher, S. Fürhapter, S. Bernet, and M. Ritsch-Marte, “Tailoring of arbitrary optical vector beams,” New J. Phys. **9**(3), 78 (2007).
20. K. J. Mitchell, S. Turtaev, M. J. Padgett, T. Čižmár, and D. B. Phillips, “High-speed spatial control of the intensity, phase and polarisation of vector beams using a digital micro-mirror device,” Opt. Express **24**(25), 29269–29282 (2016).
21. L. Marrucci, C. Manzo, and D. Paparo, “Optical spin-to-orbital angular momentum conversion in inhomogeneous anisotropic media,” Phys. Rev. Lett. **96**(16), 163905 (2006).
22. G. Biener, A. Niv, V. Kleiner, and E. Hasman, “Formation of helical beams by use of Pancharatnam-Berry phase optical elements,” Opt. Lett. **27**(21), 1875–1877 (2002).
23. X. Cai, J. Wang, M. J. Strain, B. Johnson-Morris, J. Zhu, M. Sorel, J. L. O’Brien, M. G. Thompson, and S. Yu, “Integrated compact optical vortex beam emitters,” Science **338**(6105), 363–366 (2012).
24. H. He, M. E. J. Friese, N. R. Heckenberg, and H. Rubinsztein-Dunlop, “Direct observation of transfer of angular momentum to absorptive particles from a laser beam with a phase singularity,” Phys. Rev. Lett. **75**(5), 826–829 (1995).
25. A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and S. Chu, “Observation of a single-beam gradient force optical trap for dielectric particles,” Opt. Lett. **11**(5), 288–290 (1986).
26. K. C. Neuman and S. M. Block, “Optical trapping,” Rev. Sci. Instrum. **75**(9), 2787–2809 (2004).
27. N. B. Simpson, K. Dholakia, L. Allen, and M. J. Padgett, “Mechanical equivalence of spin and orbital angular momentum of light: an optical spanner,” Opt. Lett. **22**(1), 52–54 (1997).
28. R. A. Beth, “Mechanical detection and measurement of the angular momentum of light,” Phys. Rev. **50**(2), 115–125 (1936).
29. M. E. J. Friese, T. A. Nieminen, N. R. Heckenberg, and H. Rubinsztein-Dunlop, “Optical alignment and spinning of laser-trapped microscopic particles,” Nature **394**(6691), 348–350 (1998).
30. A. T. O’Neil, I. MacVicar, L. Allen, and M. J. Padgett, “Intrinsic and extrinsic nature of the orbital angular momentum of a light beam,” Phys. Rev. Lett. **88**(5), 053601 (2002).
31. V. Garcés-Chávez, D. McGloin, M. J. Padgett, W. Dultz, H. Schmitzer, and K. Dholakia, “Observation of the transfer of the local angular momentum density of a multiringed light beam to an optically trapped particle,” Phys. Rev. Lett. **91**(9), 093602 (2003).
32. J. E. Curtis, B. A. Koss, and D. G. Grier, “Dynamic holographic optical tweezers,” Opt. Commun. **207**(1-6), 169–175 (2002).
33. M. Padgett and R. Bowman, “Tweezers with a twist,” Nat. Photonics **5**(6), 343–348 (2011).
34. S. Ngcobo, I. Litvin, L. Burger, and A. Forbes, “A digital laser for on-demand laser modes,” Nat. Commun. **4**, 2289 (2013).
35. K. Ladavac and D. Grier, “Microoptomechanical pumps assembled and driven by holographic optical vortex arrays,” Opt. Express **12**(6), 1144–1149 (2004).
36. J. Leach, H. Mushfique, R. di Leonardo, M. Padgett, and J. Cooper, “An optically driven pump for microfluidics,” Lab Chip **6**(6), 735–739 (2006).
37. Y. Arita, M. Mazilu, and K. Dholakia, “Laser-induced rotation and cooling of a trapped microgyroscope in vacuum,” Nat. Commun. **4**, 2374 (2013).
38. P. A. M. Dirac, “Quantised singularities in the electromagnetic field,” Proc. R. Soc. Lond., A Contain. Pap. Math. Phys. Character **133**(821), 60–72 (1931).
39. K. O’Holleran, M. J. Padgett, and M. R. Dennis, “Topology of optical vortex lines formed by the interference of three, four, and five plane waves,” Opt. Express **14**(7), 3039–3044 (2006).
40. K. O’Holleran, M. R. Dennis, F. Flossmann, and M. J. Padgett, “Fractality of light’s darkness,” Phys. Rev. Lett. **100**(5), 053902 (2008).
41. K. O’Holleran, M. R. Dennis, and M. J. Padgett, “Topology of light’s darkness,” Phys. Rev. Lett. **102**(14), 143902 (2009).
42. M. R. Dennis, A. C. Hamilton, and J. Courtial, “Superoscillation in speckle patterns,” Opt. Lett. **33**(24), 2976–2978 (2008).
43. M. Uchida and A. Tonomura, “Generation of electron beams carrying orbital angular momentum,” Nature **464**(7289), 737–739 (2010).
44. J. Verbeeck, H. Tian, and P. Schattschneider, “Production and application of electron vortex beams,” Nature **467**(7313), 301–304 (2010).
45. B. J. McMorran, A. Agrawal, I. M. Anderson, A. A. Herzing, H. J. Lezec, J. J. McClelland, and J. Unguris, “Electron vortex beams with high quanta of orbital angular momentum,” Science **331**(6014), 192–195 (2011).
46. J. Harris, V. Grillo, E. Mafakheri, G. C. Gazzadi, S. Frabboni, R. W. Boyd, and E. Karimi, “Structured quantum waves,” Nat. Phys. **11**(8), 629–634 (2015).
47. C. Greenshields, R. L. Stamps, and S. Franke-Arnold, “Vacuum Faraday effect for electrons,” New J. Phys. **14**(10), 103040 (2012).
48. K. Volke-Sepúlveda, A. O. Santillán, and R. R. Boullosa, “Transfer of angular momentum to matter from acoustical vortices in free space,” Phys. Rev. Lett. **100**(2), 024302 (2008).
49. K. D. Skeldon, C. Wilson, M. Edgar, and M. J. Padgett, “An acoustic spanner and its associated rotational Doppler shift,” New J. Phys. **10**(1), 013018 (2008).

50. S. Gspan, A. Meyer, S. Bernet, and M. Ritsch-Marte, “Optoacoustic generation of a helicoidal ultrasonic beam,” J. Acoust. Soc. Am. **115**(3), 1142–1146 (2004).
51. C. E. Demore, Z. Yang, A. Volovick, S. Cochran, M. P. MacDonald, and G. C. Spalding, “Mechanical evidence of the orbital angular momentum to energy ratio of vortex beams,” Phys. Rev. Lett. **108**(19), 194301 (2012).
52. B. A. Garetz, “Angular Dopper effect,” J. Opt. Soc. Am. **71**(5), 609–611 (1981).
53. I. Bialynicki-Birula and Z. Bialynicka-Birula, “Rotational frequency shift,” Phys. Rev. Lett. **78**(13), 2539–2542 (1997).
54. J. Courtial, D. A. Robertson, K. Dholakia, L. Allen, and M. J. Padgett, “Rotational frequency shift of a light beam,” Phys. Rev. Lett. **81**(22), 4828–4830 (1998).
55. M. P. J. Lavery, S. M. Barnett, F. C. Speirits, and M. J. Padgett, “Observation of the rotational Doppler shift of a white-light, orbital-angular-momentum-carrying beam backscattered from a rotating body,” Optica **1**(1), 1–4 (2014).
56. S. Franke-Arnold, S. M. Barnett, E. Yao, J. Leach, J. Courtial, and M. Padgett, “Uncertainty principle for angular position and angular momentum,” New J. Phys. **6**, 103 (2004).
57. A. Mair, A. Vaziri, G. Weihs, and A. Zeilinger, “Entanglement of the orbital angular momentum states of photons,” Nature **412**(6844), 313–316 (2001).
58. K. Dholakia, N. B. Simpson, M. J. Padgett, and L. Allen, “Second-harmonic generation and the orbital angular momentum of light,” Phys. Rev. A **54**(5), R3742–R3745 (1996).
59. S. S. R. Oemrawsingh, X. Ma, D. Voigt, A. Aiello, E. R. Eliel, G. W. ’t Hooft, and J. P. Woerdman, “Experimental demonstration of fractional orbital angular momentum entanglement of two photons,” Phys. Rev. Lett. **95**(24), 240501 (2005).
60. A. Vaziri, J. W. Pan, T. Jennewein, G. Weihs, and A. Zeilinger, “Concentration of higher dimensional entanglement: qutrits of photon orbital angular momentum,” Phys. Rev. Lett. **91**(22), 227902 (2003).
61. J. Leach, B. Jack, J. Romero, A. K. Jha, A. M. Yao, S. Franke-Arnold, D. G. Ireland, R. W. Boyd, S. M. Barnett, and M. J. Padgett, “Quantum correlations in optical angle-orbital angular momentum variables,” Science **329**(5992), 662–665 (2010).
62. J. Leach, B. Jack, J. Romero, M. Ritsch-Marte, R. W. Boyd, A. K. Jha, S. M. Barnett, S. Franke-Arnold, and M. J. Padgett, “Violation of a Bell inequality in two-dimensional orbital angular momentum state-spaces,” Opt. Express **17**(10), 8287–8293 (2009).
63. R. Fickler, R. Lapkiewicz, W. N. Plick, M. Krenn, C. Schaeff, S. Ramelow, and A. Zeilinger, “Quantum entanglement of high angular momenta,” Science **338**(6107), 640–643 (2012).
64. X.-L. Wang, X.-D. Cai, Z.-E. Su, M.-C. Chen, D. Wu, L. Li, N. L. Liu, C. Y. Lu, and J. W. Pan, “Quantum teleportation of multiple degrees of freedom of a single photon,” Nature **518**(7540), 516–519 (2015).
65. M. Malik, M. Erhard, M. Huber, M. Krenn, R. Fickler, and A. Zeilinger, “Multi-photon entanglement in high dimensions,” Nat. Photonics **10**(4), 248–252 (2016).
66. M. Babiker, W. L. Power, and L. Allen, “Light-induced torque on moving atoms,” Phys. Rev. Lett. **73**(9), 1239–1242 (1994).
67. N. Yu, P. Genevet, M. A. Kats, F. Aieta, J.-P. Tetienne, F. Capasso, and Z. Gaburro, “Light propagation with phase discontinuities: generalized laws of reflection and refraction,” Science **334**(6054), 333–337 (2011).
68. P. Genevet, J. Lin, M. A. Kats, and F. Capasso, “Holographic detection of the orbital angular momentum of light with plasmonic photodiodes,” Nat. Commun. **3**, 1278 (2012).
69. Z. Yan and N. F. Scherer, “Optical vortex induced rotation of silver nanowires,” J. Phys. Chem. Lett. **4**(17), 2937–2942 (2013).
70. N. M. Litchinitser, “Applied physics. Structured light meets structured matter,” Science **337**(6098), 1054–1055 (2012).
71. S. W. Hell and J. Wichmann, “Breaking the diffraction resolution limit by stimulated emission: stimulated-emission-depletion fluorescence microscopy,” Opt. Lett. **19**(11), 780–782 (1994).
72. C. Maurer, A. Jesacher, S. Bernet, and M. Ritsch-Marte, “What spatial light modulators can do for optical microscopy,” Laser Photonics Rev. **5**(1), 81–101 (2010).
73. G. A. Swartzlander, “Peering into darkness with a vortex spatial filter,” Opt. Lett. **26**(8), 497–499 (2001).
74. G. A. Swartzlander, Jr., E. L. Ford, R. S. Abdul-Malik, L. M. Close, M. A. Peters, D. M. Palacios, and D. W. Wilson, “Astronomical demonstration of an optical vortex coronagraph,” Opt. Express **16**(14), 10200–10207 (2008).
75. S. Fürhapter, A. Jesacher, S. Bernet, and M. Ritsch-Marte, “Spiral interferometry,” Opt. Lett. **30**(15), 1953–1955 (2005).
76. S. Fürhapter, A. Jesacher, S. Bernet, and M. Ritsch-Marte, “Spiral phase contrast imaging in microscopy,” Opt. Express **13**(3), 689–694 (2005).
77. R. Steiger, S. Bernet, and M. Ritsch-Marte, “SLM-based off-axis Fourier filtering in microscopy with white light illumination,” Opt. Express **20**(14), 15377–15384 (2012).
78. M. P. Lee, G. M. Gibson, R. Bowman, S. Bernet, M. Ritsch-Marte, D. B. Phillips, and M. J. Padgett, “A multi-modal stereo microscope based on a spatial light modulator,” Opt. Express **21**(14), 16541–16551 (2013).
79. L. Torner, J. Torres, and S. Carrasco, “Digital spiral imaging,” Opt. Express **13**(3), 873–881 (2005).
80. S. R. P. Pavani and R. Piestun, “Three dimensional tracking of fluorescent microparticles using a photon-limited double-helix response system,” Opt. Express **16**(26), 22048–22057 (2008).
81. A. Jesacher, M. Ritsch-Marte, and R. Piestun, “Three-dimensional information from two-dimensional scans: a

scanning microscope with post acquisition refocusing capability," Optica **2**(3), 210–214 (2015).
82. G. Gibson, J. Courtial, M. Padgett, M. Vasnetsov, V. Pas'ko, S. Barnett, and S. Franke-Arnold, "Free-space information transfer using light beams carrying orbital angular momentum," Opt. Express **12**(22), 5448–5456 (2004).
83. F. Tamburini, E. Mari, A. Sponselli, B. Thidé, A. Bianchini, and F. Romanato, "Encoding many channels on the same frequency through radio vorticity: first experimental test," New J. Phys. **14**(3), 033001 (2012).
84. J. Wang, J.-Y. Yang, I. M. Fazal, N. Ahmed, Y. Yan, H. Huang, Y. Ren, Y. Yue, S. Dolinar, M. Tur, and A. E. Willner, "Terabit free-space data transmission employing orbital angular momentum multiplexing," Nat. Photonics **6**(7), 488–496 (2012).
85. A. E. Willner, H. Huang, Y. Yan, Y. Ren, N. Ahmed, G. Xie, C. Bao, L. Li, Y. Cao, Z. Zhao, J. Wang, M. P. J. Lavery, M. Tur, S. Ramachandran, A. F. Molisch, N. Ashrafi, and S. Ashrafi, "Optical communications using orbital angular momentum beams," Adv. Opt. Photonics **7**(1), 66 (2015).
86. M. Tamagnone, C. Craeye, and J. Perruisseau-Carrier, "Comment on 'Encoding many channels on the same frequency through radio vorticity: first experimental test," New J. Phys. **14**(11), 118001 (2012).
87. N. Zhao, X. Li, G. Li, and J. M. Kahn, "Capacity limits of spatially multiplexed free-space communication," Nat. Photonics **9**(12), 822–826 (2015).
88. M. J. Padgett and L. Allen, "The Poynting vector in Laguerre-Gaussian laser modes," Opt. Commun. **121**(1-3), 36–40 (1995).
89. M. J. Padgett, F. M. Miatto, M. P. J. Lavery, A. Zeilinger, and R. W. Boyd, "Divergence of an orbital-angular-momentum-carrying beam upon propagation," New J. Phys. **17**(2), 023011 (2015).
90. V. D'Ambrosio, E. Nagali, S. P. Walborn, L. Aolita, S. Slussarenko, L. Marrucci, and F. Sciarrino, "Complete experimental toolbox for alignment-free quantum communication," Nat. Commun. **3**, 961 (2012).
91. G. C. G. Berkhout, M. P. J. Lavery, J. Courtial, M. W. Beijersbergen, and M. J. Padgett, "Measuring orbital angular momentum superpositions of light by mode transformation," Phys. Rev. Lett. **105**, 153601 (2010).
92. S. Restuccia, D. Giovannini, G. Gibson, and M. Padgett, "Comparing the information capacity of Laguerre-Gaussian and Hermite-Gaussian modal sets in a finite-aperture system," Opt. Express **24**(24), 27127–27136 (2016).
93. C. Paterson, "Atmospheric turbulence and orbital angular momentum of single photons for optical communication," Phys. Rev. Lett. **94**(15), 153901 (2005).
94. B. Rodenburg, M. P. J. Lavery, M. Malik, M. N. O'Sullivan, M. Mirhosseini, D. J. Robertson, M. Padgett, and R. W. Boyd, "Influence of atmospheric turbulence on states of light carrying orbital angular momentum," Opt. Lett. **37**(17), 3735–3737 (2012).
95. A. Trichili, A. B. Salem, A. Dudley, M. Zghal, and A. Forbes, "Encoding information using Laguerre Gaussian modes over free space turbulence media," Opt. Lett. **41**(13), 3086–3089 (2016).
96. N. Bozinovic, Y. Yue, Y. Ren, M. Tur, P. Kristensen, H. Huang, A. E. Willner, and S. Ramachandran, "Terabit-scale orbital angular momentum mode division multiplexing in fibers," Science **340**(6140), 1545–1548 (2013).
97. A. Wang, L. Zhu, S. Chen, C. Du, Q. Mo, and J. Wang, "Characterization of LDPC-coded orbital angular momentum modes transmission and multiplexing over a 50-km fiber," Opt. Express **24**(11), 11716–11726 (2016).
98. M. Krenn, J. Handsteiner, M. Fink, R. Fickler, and A. Zeilinger, "Twisted photon entanglement through turbulent air across Vienna," Proc. Natl. Acad. Sci. U.S.A. **112**(46), 14197–14201 (2015).
99. Y. Yan, G. Xie, M. P. J. Lavery, H. Huang, N. Ahmed, C. Bao, Y. Ren, Y. Cao, L. Li, Z. Zhao, A. F. Molisch, M. Tur, M. J. Padgett, and A. E. Willner, "High-capacity millimetre-wave communications with orbital angular momentum multiplexing," Nat. Commun. **5**, 4876 (2014).
100. G. Xie, Y. Ren, Y. Yan, H. Huang, N. Ahmed, L. Li, Z. Zhao, C. Bao, M. Tur, S. Ashrafi, and A. E. Willner, "Experimental demonstration of a 200-Gbit/s free-space optical link by multiplexing Laguerre-Gaussian beams with different radial indices," Opt. Lett. **41**(15), 3447–3450 (2016).
101. M. Mafu, A. Dudley, S. Goyal, D. Giovannini, M. McLaren, M. J. Padgett, T. Konrad, F. Petruccione, N. Lutkenhaus, and A. Forbes, "Higher-dimensional orbital-angular-momentum-based quantum key distribution with mutually unbiased bases," Phys. Rev. A **88**(3), 032305 (2013).
102. M. Mirhosseini, O. S. Magaña-Loaiza, M. N. O'Sullivan, B. Rodenburg, M. Malik, M. P. J. Lavery, M. J. Padgett, D. J. Gauthier, and R. W. Boyd, "High-dimensional quantum cryptography with twisted light," New J. Phys. **17**(3), 033033 (2015).
103. M. Krenn, J. Handsteiner, M. Fink, R. Fickler, R. Ursin, M. Malik, and A. Zeilinger, "Twisted light transmission over 143 km," Proc. Natl. Acad. Sci. U.S.A. **113**(48), 13648–13653 (2016).

1. Introduction

As long ago as the 1600s, Kepler reasoned that light must carry a linear momentum, his logic being that the tails of comets always pointed away from the sun. Although all of light's momentum and energy properties are encapsulated in Maxwell's equations, it wasn't until 1909 that Poynting used a mechanical analogy to articulate that a circularly polarized light beam contained an angular momentum that we would now attribute to the $\hbar$ spin of individual photons [1]. Moving beyond this spin angular momentum Darwin (grandson of the famous naturalist) pointed out that the conservation of angular momentum during higher-order atomic/molecular transitions required an optical angular momentum of multiple units of $\hbar$ per photon [2]. This additional angular momentum is called “orbital angular momentum” (OAM) and can be thought to arise simply from the effect of light’s linear momentum acting off-axis with respect to the center of the optical beam or center of mass of the interacting object. For many decades it was implicitly assumed that this orbital angular momentum was a rare event, just as high-order transitions are themselves rare (they have low absorption cross-sections). In 1992 this assumption was overturned when Allen, Woerdman and associates established that light beams with helical phase-fronts, described by a transverse phase structure of $\exp(-i\ell\phi)$, carry an orbital angular momentum equivalent to $\ell\hbar$ per photon, i.e. potentially an angular momentum many times greater than the spin of the photon [3]. An important feature of all beams with helical phase-fronts is that the beam axis marks a singularity in the optical phase, akin to the time at the north pole! This phase singularity is manifested as a perfect zero in the optical intensity, meaning that OAM-carrying beams typically have annular intensity cross-sections. (Beams with other profiles can also carry OAM, e.g [4].).

In the 25 years since the ‘92 paper, orbital angular momentum has established itself as one of the most interesting of optical modes, with relevance to optical manipulation, imaging, quantum optics, optical communications and elsewhere. More broadly, OAM has given rise to studies of phase-structured light beams with unique that properties arise from their phase structure, not their intensity [5,6].

2. Helical beams pre –92 and post –92

Central to the Allen et al. paper [3] is the link it establishes between beams with helical phase-fronts and orbital angular momentum (OAM). However, these helically-phased beams had themselves been generated and studied earlier, not least as the examples of the transverse modes produced from suitably configured laser cavities [7], or as resulting from optical vortices [8]. The study of optical vortices (or their acoustic counterpart) with phase singularities at their center had been also been extensive from the 1970s onwards [9,10]. However, in none of these earlier works had any link been made between these features and the possibility of angular momentum in the beam.

The early work on OAM itself proposed and then implemented the use of cylindrical lenses to transform the high-order Hermite-Gaussian modes emitted by a conventional laser into helically-phased Laugerre-Gaussian modes [11]. In addition, the same research group demonstrated perhaps the most obvious production method for OAM, namely the insertion into a normal laser beam of a phaseplate with a thickness that increased with azimuthal angle, such that the transmitted beam acquired a transverse phase cross section of $\exp(-i\ell\phi)$ [12].

Perhaps the most significant work immediately prior to ‘92 relevant to future experiments involving OAM was the generation of helically-phased beams using a diffraction grating containing an ℓ-pronged fork dislocation in the ruled lines. As shown by Soskin and associates, an incident plane-waved beam aligned co-axially with this dislocation results in a first-order diffracted beam with helical phase-fronts described again by $\exp(-i\ell\phi)$ [13]. It is this use of diffractive optical elements that has been central to many subsequent studies of phase-structured beam formation and is now common to the vast majority of modern experiments using OAM. This diffractive-optic approach is made all the more applicable by the commercial availability of computer addressable, pixelated, spatial light modulators that can be controlled to act as reconfigurable diffractive optical elements. Furthermore various algorithms exist for implementing aberration correction of the SLM devices such that the beams produced are of high optical fidelity e.g [14].

The majority of SLMs used for studies of OAM are based on the thin films of liquid crystal whose refractive index can be locally switched by applying an electric field and hence, if the films are laid over a pixelated electronic array, can be controlled to give a spatially dependent phase variation to the reflected light. A number of commercial devices are available capable of diffracting well in excess of 50% of the incident energy into a desired beam type. It is also possible to use intensity modulators based on digital micro-mirrors to create diffractive optical components. Although the diffraction efficiency of these digital micro-mirror devices (DMD) is much lower than an SLM, their low-cost and much higher-speed performance offer capabilities that the liquid crystal devices cannot match [15].

Strictly speaking the design of a diffractive optical element is only correct for one operating wavelength, so if a broad-band or a white-light beam is desired, a different technique is required. However, diffractive elements remain a possibility providing that an additional element is incorporated to compensate for their angular dispersion, such elements can be a compensation prism [16] or an additional grating [17]. Alternatively bespoke optical elements can use Fresnel reflections, or similar, to introduce a spatially dependent phase shift, allowing the generation of white-light vortex beams [18].

Beyond phase structuring alone, it is possible to use combinations of SLMs and waveplates to overlap two orthogonally polarized beams to create generalized vector vortex beams. This was first achieved with liquid crystal SLMs [19] and more recently with DMDs [20].

Various other methods also exist for generating vortex beams using structured materials. Some of these methods rely upon a spatial dependent geometrical phase delay that is created using liquid crystal films, carefully oriented using structured surfaces (so called “q-plates”) [21] or rely on the structured surface itself [22]. Finally the desire to use OAM on-chip has led to the development of chip-scale sources relying on the vertical emission from ring waveguides with small slots introduced to act as scattering centers with a defined and controllable phase relationship [23].

3. OAM in optical manipulation

Following the initial recognition of OAM in laser beams, the question was how might these beams be used? Rubinsztein-Dunlop and associates published one dramatic example in 1995 [24] when they combined OAM with optical tweezers. The use of optical beams to manipulate microscopic particles had been pioneered throughout the 70s and 80s by Ashkin leading to the single-beam gradient force trap, which are now known as optical tweezers [25]. Somewhat counter intuitively, a single tightly-focused, laser beam is all that is required to trap a microscopic particle in three-dimensions. Key to this technique is that a tightly-focused laser beam creates a large gradient in the modulus of the electric field, with the field modulus decreasing in all directions as one moves away from the beam focus. Any dielectric particle falling within this gradient region experiences a force directed toward the position of highest optical intensity, and if the focus is tight enough this gradient-force is sufficient even to overcome the linear momentum of the light, which acts to push the particle in the axial direction. Following their initial demonstration, optical tweezers have found ever increasing use in biological sciences [26].

Rubinsztein-Dunlop and associates used a diffractive optical element to produce an $\ell = 3$, OAM-carrying beam and then coupled this beam into an optical tweezers to trap an absorbing particle. The linear momentum of the light beam pushed the absorbing particle to a cover slip and the angular momentum in the beam set the particle spinning about its own axis. This work was the first demonstration of an orbital angular momentum transfer from light to a microscopic object. In a similar experiment, others used a semi-transparent particle which could be trapped in 3 dimensions and combined the orbital angular momentum of a $\ell = 1$, beam with the spin angular momentum of circularly polarized light. By controlling the relative handedness of the two beams the total angular momentum $(\ell \pm \sigma)$, could be switched from zero to $2\hbar$ per photon causing the spinning of the particle to stop and start [27]. However, this stop/start behavior caused by the total of the orbital and spin angular momentum applies only when the focused beam is smaller than the particle and the particle is confined to the optical axis of the beam. In an alternative configuration, where the annular beam is larger than the particle size and the particle is confined off-axis with respect to the beam, the behavior is different. With respect to the spin angular momentum any birefringent object that falls into a circularly polarized beam is set into rotation about its own axis, as first observed in the 1930s [28], and then spectacularly repeated within an optical tweezers in the late 90s [29]. Therefore for the off-axis particle, the spin angular momentum causes the particle to spin about its own axis. By contrast, the helical phase-fronts of the OAM exert an azimuthal scattering force acting on the particle causing it to orbit around the beam axis. Taking the spin and orbital angular momentum together creates something akin to a microscopic, optically-driven, orary [30,31].

The use of OAM in optical tweezers and arguably the use of OAM more widely was given a significant boost in 2002 when Grier and associates used a programmable spatial light modulator to switch between different beam types and steer multiple beams independently of each other, their so called "holographic optical tweezers" [32]. Since that time, the use of structured beams within optical tweezers has become common place and spatial light modulators have been widely adopted for beam shaping more generally, either as a component in an optical system [33] or as an active beam shaper as part of a laser cavity [34]. The spin angular momentum too has played an important role in optical tweezers leading to optically driven pumps [35,36] and most recently in the ultra high-speed rotation of particles trapped in vacuum [37].

4. OAM a wave-like property

In the 25 years since the recognition of OAM as an optical degree of freedom, OAM has enabled insights into various wave phenomenon. Although OAM was originally espoused in terms of optical fields, the related field of phase singularities within wave-fields has a prehistory which include considerations as to the singularities that might arise in electron wavefunctions [38] and, as discussed above, to studies of singularities that arise in acoustic fields [9]. More generally phase singularities occur whenever three, or more, plane-waves interfere [39], an extreme example of which is optical speckle. In optical speckle each black speck is indeed a phase singularity around which the phase advances (clockwise or anti-clockwise) by 2π. In 3-dimensions, these phase singularities trace out lines of perfect darkness, fractal in nature, that percolate all of space [40], creating topological features comprising loops and even (rarely) knots [41]. However, this intricate 3D structure should not be directly linked to OAM since the fields in the vicinity of these singularities are super oscillatory [42], and therefore the associated energy lies in the space between the singularities and the total angular momentum of a random speckle pattern averages to zero as the lateral expanse of the speckle increases.

Although the earlier work on electron and acoustic vortices was not motivated by OAM, OAM can be present in both electron and acoustic fields. Beyond optics, helical phasefronts can be created with electrons which therefore also carry OAM [43–45]. Unlike an optical beam, the charge on the electrons means that the azimuthal component of the Poynting vector gives rise to a significant and constant magnetic field in the axial direction, creating interesting opportunities for new modalities of electron microscopy [46] and also producing a Faraday-like effect in vacuum [47].

The acoustic realization of OAM has unique properties too. In a gaseous or liquid medium, sound is exclusively a longitudinal wave; the absence of any transverse restoring force means that transverse waves are impossible and hence there can be no circular polarization and consequently no spin angular momentum. But a spatially extended acoustic wave can still be created to have an $\exp(-i\ell\phi)$ phase dependence and hence a corresponding orbital angular momentum. Perhaps the most obvious approach to the creation of an OAM carrying acoustic wave is to use a circular array of loudspeakers, each driven at the same frequency but with a relative phase dependent upon the speakers angular position. Using such an approach it is possible to create an acoustic beam with sufficient angular momentum to set a suspended macroscopic object into rotation [48,49]. The acoustic regime also extends to ultrasonics [50], and multi-element transducers play the role of the spatial light modulator and such arrangements have allowed precise measurements to be made of the energy, linear momentum and angular momentum [51].

In various manifestations OAM has highlighted wave phenomena not previously studied but that become more noticeable/understandable in cylindrical co-ordinates. Perhaps the first of these phenomena was the rotational, or angular, Doppler shift. Just as, when placed on a rotating turntable, the hands of a watch appear to speed up or slow down, the rotation of the electric field vector of a circularly polarized light beam can sped up or slowed down by the rotation of the light beam about its own propagation axis [52]. A similar effect applies to orbital angular momentum too, where the frequency shift that arises from a rotation of the source or of the observer at an angular velocity Ω is given by $\Delta\omega = \ell\Omega$ [53,54]. This rotational frequency shift effect is also observable in the light that is back-scattered from a rotating rough surface even in geometries where the linear Doppler shift is zero [55].

Another a phenomenon that becomes more apparent in polar co-ordinates is the angular form of the uncertainty relationship. In the linear case, the uncertainty relationship between position and momentum $\Delta x \Delta p \geq \hbar / 2$ is one of the most striking relationships of modern physics. Much less well known is the rotational equivalent relating the uncertainties in angular position and angular momentum, which for small uncertainty in angular position is given as $\Delta\phi\Delta\ell \geq 1/2$ [56].

5. OAM in quantum and nano optics

Although the necessity for OAM was originally reasoned with respect to angular momentum conservation in quantized high-order transitions, the majority of the early post-92 research focused on macroscopic interactions. The first single-photon based experiments involving OAM were those of Zeilinger and associates who examined the quantum entanglement of two photons both carrying OAM [57]. Following ‘92 it had been shown that a laser beam carrying OAM could be frequency doubled using a non-linear crystal and subject to the same phase-matching conditions as a fundamental mode. However, in the case of OAM, in addition to doubling the frequency of the light the ℓ-value doubled too [58]. This doubling of the OAM, while halving of the photon number, corresponds to a conservation of OAM within the optical field. It should be noted that this conservation of angular momentum within the optical fields alone does not necessarily apply to the spin angular momentum, which can be exchanged with the non-linear (often birefringent) crystal itself. In addition to frequency doubling, another second-order, non-linear effect is parametric down-conversion. In down-conversion, an incident pump photon gives rise to signal and idler photons with frequencies set by the boundary conditions of conversion of energy and momentum. The conservation of momentum is vectorial in nature and hence applies to the transverse directions as well as the axial. This transverse conservation of linear momentum ensures a conservation of OAM, meaning that the OAM of the signal and idler photons must sum to that of the pump. In addition to applying to integer values of OAM these conservations apply to both fractional OAM values [59] and superpositions of OAM states [60].

Subsequent work in the OAM state-space has shown EPR-type [61] and Bell-type [62] entanglement for OAM even for ℓ-values over 100 [63]. Recent work in the OAM state-space has included multi-variable teleportation [64] and both multi-photon and combined multi-state entanglement [65].

The interactions of OAM and matter have been studied in depth but whereas early work considered mainly atomic interactions e.g [66]. more recent studies have consider the interactions with nanostructured materials. A key demonstration in this regard was the use of a nano antenna whose resonances impart controllable phase delays to the re-emitted light, seemingly bringing modifications to Snell's law in a similar way to that which a diffractive optical element does but in this case with less optical thickness [67]. Nano patterning of the surface can lead to selective coupling to a detector element [68] or, as discussed above, OAM emission [23]. Vortex beams too have been used to manipulate nanowires within optical tweezers [69]. Indeed the whole overlap between structured light and structured matter seems likely to be a key area of future research [70].

6. OAM in imaging

Another area where OAM has led to new approaches has been within imaging. Leaving aside the important use of beams with annular intensity distributions and their application in STED microscopy [71], OAM and phase-structured light beam leads to new modalities [72]. If a spiral phase plate, or its diffractive equivalent, is placed into the Fourier-plane of an imaging system then the system's point spread function acquires an $\exp(-i\ell\phi)$ phase term and correspondingly an annular intensity cross section. Within an imaging system this gives the potential to null any bright points of light which might otherwise overwhelm the remaining image [73]. Such an approach had been implemented by Swartzlander and associates within a telescope when attempting to suppress light from a bright star to observe neighboring objects [74].

OAM is relevant to microscopy too. Ritsch-Marte and associates developed a new form of interferometric imaging using a helically-phased beam as the reference wave [75]. In normal interferometry it can be difficult to distinguish whether a particular feature is an elevation or depression from the surrounding surface, both of which give rise to closed loop fringes. To overcome this problem, it is standard practice to acquire sequential phase-stepped images from which to distinguish the two cases. However, when the reference wave is helically-phased, the closed fringes become a single spiral fringe with a handedness that allows an elevation to be distinguished from a depression using a single interferogram.

Beyond the application to interferometry, the inclusion of a spiral phase plate into the image train of a microscope modifies the point spread function of the imaging system, as discussed above. When imaging a phase object, this point spread function gives a omni-directional edge enhancement of the image [76], and the implementation using an SLM allows various phase filters and resulting modalities to be applied sequentially [77] or simultaneously [78]. More generally images can be analysed in terms of their spiral spectrum for identifying gradients and dislocations [79], and more sophisticated OAM based filters can give depth information [80] and even the ability to reconstruct fully 3D images from a single scan of the sample [81].

7. OAM in communications

Perhaps the most active, and arguably most contentious, of OAM sub-field of recent years has been the application of OAM to optical communication. The key motivation being that whereas the spin angular momentum of light has only two orthogonal states, the OAM has potentially an unlimited number of states. An early explicit use of OAM for free-space communication was in 2004 by Padgett and associates who used OAM in a telescope-to-telescope optical link over a range of a few meters [82]. That original system used SLMs to both make and then measure one of 8 different OAM states, albeit with an inherent optical measurement efficiency of 1/8. Subsequently, a long path-length demonstration was made in the radio-wave regime using two co-propagating yet distinguishable OAM channels [83]. Despite these early demonstrations it was not until Willner and associates combined OAM with their existing expertise in practical communications systems that the possible potential of OAM for expanding the range of multiplexing options became truly appreciated [84,85].

Although OAM offers an interesting potential for multiplexing one should acknowledge that certain fundamental limits still apply; a debate that has been contentious e.g [86,87]. At longer ranges, the aperture of the transmitting and receiving telescopes sets the efficiency of transmission. As was recognized from the early studies, for a fixed Rayleigh range, the radius of maximum intensity of a helically-phased beam increase with the OAM value (for a single-ringed, $p = 0$, Laguerre-Gaussian mode, the radius of maximum intensity scales linearly with $\sqrt{\ell}$ [88]). This $\sqrt{\ell}$ scaling also applies to the divergence of OAM-carrying beams. Consequently for a low-loss system supporting various modes with the same beam waist, the aperture of both the transmission and receiving optics must be increased as the OAM gets larger, the product of transmission and receiving apertures scaling linearly with ℓ [89]. More generally, the number of orthogonal modes that can be coupled, with low loss, through any optical system is given by the Fresnel number of the system, a limit that applies to all possible modal sets. The choice therefore as to which modal set to adopt in any one system is simply one of taking advantage of the available component technologies, while respecting the known boundary conditions and likely aberrations and/or misalignments. Modal sets based upon OAM have the potential advantage of being circular, and hence match the typical telescope aperture, are rotationally invariant with respect to detection [90], have components available for efficient mode separation [91], and in some situations maintain their orthogonal properties of the modal set even when subject to aperture restrictions [92]. A particular concern in the use of spatial modes has been the impact of time-varying atmospheric aberrations and how they might result in cross-talk between the modes [93–95].

However, whatever limitations might be present, the performance of communications systems based upon OAM are quite impressive, ranging from implementation in fibre [96] [97], over-city links [98], mm-wave operation [99] and have reached 200Tbit data rates in free-space [100]. Systems based on OAM have also been used by Boyd and associates and other groups for high dimensional quantum key distribution [101,102]. Most recently OAM transmission has been reported in free-space over 143km [103]. Whether such systems will prove to offer long-term technical advantage for communication systems in the commercial sphere, only time will tell.

8. Conclusions

In the 25 years since OAM was articulated by Allen et al. an extensive and supportive community has been established across the globe. Beyond the field of OAM, the realisation that the Poynting vector can be engineered over the beam cross-section has triggered research into many beam types, and light-matter interactions in both the classical and quantum regimes. Hopefully, the OAM community will continue to thrive and continue to use OAM and structured light to both inform new fundamental questions about light and optics and enable new applications in imaging, sensing and communications.

Funding

Engineering and Physical Sciences Research Council (EP/M01326X/1).