



south AFRICAN INSTITUTE OF PHYSICS 59th Annual Conference 7-11 July 2014 UNIVERSITY OF JOHANNESBURG

Light in a Twist: Orbital Angular Momentum

Miles Padgett FRS

Kelvin Chair of Natural Philosophy

EPSR

SEO YEAR

THE ROYAL SOCIET

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The Angular Momentum of (circularly polarised) Light

The Wave Motion of a Revolving Shaft, and a Suggestion as to the Angular Momentum in a Beam of Circularly Polarised Light.

By J. H. POYNTING, Sc.D., F.R.S.

(Received June 2,-Read June 24, 1909.)

When a shaft of circular section is revolving uniformly, and is transmitting power uniformly, a row of particles originally in a line parallel to the axis will lie in a spiral of constant pitch, and the position of the shaft at any instant may be described by the position of this spiral.



(spin) Angular Momentum



The talk today

- Orbital (i.e. not spin!) Angular Momentum, what is it?
- What has been done with OAM
- A couple of example of what we have done





A question

- A photon carries a spin angular momentum of \hbar
- So how does a multi-pole transition (ΔJ > ħ) conserve angular momentum?



Linear momentum at a radius exerts a torque

ħk



$\hbar k \times r$ -> multipole transition

PROCEEDINGS THE ROYAL A

Notes on the Theory of Radiation

C. G. Darwin

Proc. R. Soc. Lond. A 1932 136, 36-52

Providing the lever is long enough, a fixed linear momentum can exert an arbitrary high torque



Getting started on Orbital Angular Momentum of Light

• 1992, Allen, Beijersbergen, Spreeuw and Woerdman

PHYSICAL REVIEW A

VOLUME 45, NUMBER 11

I JUNE 1992

Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes

L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman Huygens Laboratory, Leiden University, P.O. Box 9504, 2300 RA Leiden, The Netherlands (Received 6 January 1992)

• 1994, Les meets Miles at dinner.....





Orbital Angular Momentum from helical phase fronts





Angular momentum in terms of photons

- Spin angular momentum
 - Circular polarisation
 - $\sigma\hbar$ per photon
- Orbital angular momentum
 - Helical phasefronts
 - $\ell\hbar$ per photon







Optical vortices, Helical phasefronts, Angular momentum

- Intensity, $I \ge 0$
- Phase, $2\pi \ge \phi \ge 0$
 - ℓ = 0, plane wave
 - ℓ = 1, helical wave
 - ℓ = 2, double helix ℓ = 3, pasta fusilli etc.



 ℓ = vortex charge



Orbital angular momentum from Skew rays





Making helical phasefronts with holograms

Screw dislocations in light wavefronts

V. YU. BAZHENOV, M. S. SOSKIN and M. V. VASNETSOV Institute of Physics, Academy of Sciences of Ukraine, 252650 Kiev, Prospect Nauki 46, Ukraine

(Received 14 June 1991; revision received 8 January 1992)

JOURNAL OF MODERN OPTICS, 1992, VOL. 39, NO. 5, 985-990





Making OR measuring phasefronts with holograms





Richard Bowman

A gift for all the family.....

App Store > Education > Richard Bowman



iHologram

Description

Screenshots

iHologram creates beautiful patterns by rendering the Fraunhofer holograms used in Holographic Optical Tweezers iPhone/IPad graphics chip. Use it to learn about diffraction and holography, or just to make pretty pictures?

Richard Bowman Web Site > iHologram Support >



CThis app is designed for both Phone and Pad

Category: Education Released: 14 October 2010 Version: 1.0 1.0 0.2 MB Language: English Developer: Richard Bowman © Richard Bowman

Rated 4+

Requirements.Compatible with Phone 3GS, Phone 4, Pod touch (3rd generation), Pod touch (4th generation) and Pad. Requires IOS 3.2 or later.





A double-start helix (ℓ =2)



Chambord castle (chateaux de la Loire)





And the point of shaping the spot is.....









OAM in optical manipulation

VOLUME 75, NUMBER 5

PHYSICAL REVIEW LETTERS

31 JULY 1995

Direct Observation of Transfer of Angular Momentum to Absorptive Particles from a Laser Beam with a Phase Singularity

H. He, M. E. J. Friese, N. R. Heckenberg, and H. Rubinsztein-Dunlop Department of Physics, The University of Queensland, Brisbane, Queensland, Australia Q4072 (Received 28 November 1994; revised manuscript received 4 April 1995)

He et al. PRL 1995







15 June 2002

OPTICS COMMUNICATIONS

Optics Communications 207 (2002) 169-175

www.distviet.com/locate/optcom

Dynamic holographic optical tweezers Jennifer E. Curtis, Brian A. Koss, David G. Grier*

Curtis et al. Opt Commun. 2002



OAM in quantum optics

Entanglement of the orbital angular momentum states of photons

Alois Mair", Alipasha Vaairt, Gregor Welhs & Anton Zeillinger

Sustan für Experimentalplysik, Universitär Wien, Bultzmanngatur 5, 1090 Wien, Austria

Entangled quantum states are not separable, regardless of the spatial separation of their components. This is a manifestation of an aspect of quantum mechanics known as quantum nonlocality¹³. An important consequence of this is that the measurement of the state of one particle in a two-particle entangled state defines the state of the second particle instantaneously, whereas neither particle possesses its own well-defined state before the



Mair et al. Nature 2001





OAM in imaging

Spiral interferometry

Severin Fürhapter, Alexander Jesacher, Stefan Bernet, and Monika Ritsch-Marte Division of Biomedical Physics, Innsbruck Medical University, Müllerstrasse 44, A-6020 Innsbruck, Austria

Fürhapter et al. Opt. Lett. 2005





Astronomical demonstration of an optical vortex coronagraph

Grover A. Swartzlander, Jr.,^{1,*} Erin L. Ford,¹ Rukiah S. Abdul-Malik,¹ Laird M. Close,³ Mary Anne Peters,² David M. Palacios,³ and Daniel W. Wilson³

Swartzlander et al. Opt. Express 2008



OAM in communication

New Journal of Physics

Encoding many channels on the same frequency through radio vorticity: first experimental test

Fabrizio Tamburini^{1,2,8}, Elettra Mari³, Anna Sponselli¹, Bo Thidé^{4,5}, Antonio Bianchini¹ and Filippo Romanato^{6,7}

Tamburini et al. New J Phys. 2012







Terabit free-space data transmission employing orbital angular momentum multiplexing

Jian Wang^{1,2}*, Jeng-Yuan Yang¹, Irfan M. Fazal¹, Nisar Ahmed², Yan Yan¹, Hao Huang¹, Yongxiong Ren¹, Yang Yue¹, Samuel Dolinar³, Moshe Tur⁴ and Alan E. Willner¹*

Wang et al. Nature Photon 2012



OAM in Lasers



ARTICLE Received 30 May 2013 | Accepted 10 Jul 2013 | Published 2 Aug 2013 | DOb: 10.1038/ncomme3289 A digital laser for on-demand laser modes Sandile Ngcobo^{1,2}, Igor Litvin², Liesl Burger² & Andrew Forbes^{1,2}

Ngcobo et al. Nature Commun. 2013







OAM in not just light

PRL 100, 024302 (2008)

PHYSICAL REVIEW LETTERS

week ending 18 JANUARY 2008

Transfer of Angular Momentum to Matter from Acoustical Vortices in Free Space

Karen Volke-Sepúlveda,1 Arturo O. Santillán,2.* and Ricardo R. Boullosa2

Volke-Sepulveda et al. PRL 2008





Vol 467 16 September 2010 dok:10.1038/nature09366

nature

LETTERS

Production and application of electron vortex beams

J. Verbeeck¹, H. Tian¹ & P. Schattschneider²

Verbeeck et al. Nature 2010



Graham Gibson, Johannes Courtial, Miles J. Padgett Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, Scotland 1 November 2004 / Vol. 12, No. 22 / OPTICS EXPRESS 5448

The OAM communicator

University of Glasgow





Miles Padgett's corkscrew laser beam creates a ring of light with a dark centre





Optical Vortices before Angular Momentum

Proc. R. Soc. Lond. A. 336, 165–190 (1974) Printed in Great Britain

Dislocations in wave trains

BY J. F. NYE AND M. V. BERRY H. H. Wills Physics Laboratory, University of Bristol

Quantised Singularities in the Electromagnetic Field



P. A. M. Dirac

Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character, Vol. 133, No. 821. (Sep. 1, 1931), pp. 60-72.





Fractality and Topology of Light's darkness

Kevin O'Holleran Florian Flossmann



Mark Dennis (Bristol)





Vortices are ubiquitous in nature

- Whenever *three* (or more) plane waves interfere optical vortices are formed
 - Charge one vortices occur wherever there is diffraction or scattering







Map out the vortex position in different planes

 Either numerically or experimentally one can map the vortex positions in different planes



PRL 100, 053902 (2008)

PHYSICAL REVIEW LETTERS

week ending 8 FEBRUARY 2008

Fractality of Light's Darkness

Kevin O'Holleran,^{1,*} Mark R. Dennis,² Florian Flossmann,¹ and Miles J. Padgett¹

The tangled web of speckle

Jniversity fGlasgow





Quantum entanglement with spatial light modulators

Jonathan Leach Barry Jack Sonja Franke-Arnold (Glasgow)









Steve Barnett and Alison Yao (Strathclyde)

Bob Boyd Anand Jha (Rochester)







PHYSICAL REVIEW A

VOLUME 56, NUMBER 5

NOVEMBER 1997

Second-harmonic generation and the conservation of orbital angular momentum with high-order Laguerre-Gaussian modes

J. Courtial, K. Dholakia, L. Allen, and M. J. Padgett

OAM in second harmonic generation

 Poynting vector "cork screws", azimuthal skew angle is

 $- \theta = \ell/kr$

iversity

- Does this upset a co-linear phase match? -No
- Frequency & *l*-index both double
- "Path" of Poynting vector stays the same
 - phase matching maintained





Correlations in angular momentum





Correlations in angle





Quantum Correlations in Optical Angle–Orbital Angular Momentum Variables

6 AUGUST 2010 VOL 329 SCIENCE

Jonathan Leach,¹ Barry Jack,¹ Jacqui Romero,¹ Anand K. Jha,² Alison M. Yao,³ Sonja Franke-Arnold,¹ David G. Ireland,¹ Robert W. Boyd,² Stephen M. Barnett,³ Miles J. Padgett¹*

Angular EPR



Correlations in complimentary basis sets -> demonstrates EPR for Angle and Angular momentum

$$\left[\Delta \left(\ell_{\rm s} \left|\ell_{\rm i}\right\rangle \hbar\right]^2 \left[\Delta \left(\phi_{\rm s} \left|\phi_{\rm i}\right\rangle\right)^2 = 0.00475\hbar^2 << 0.25\hbar^2$$



Rotational Doppler Shifts

Martin Lavery



Steve Barnett and Fiona Speirits







Doing work on a light beam changes its energy and hence shifts it's frequency





Doppler shift from a SPINNING surface

Ω



sinα≈ℓ/kr & v=Ωr



 $\Delta \omega_{\ell,-\ell} = 2\Omega \ \ell$



Martin Lavery

The Rotational Frequency shift of Scattered Light





Making/Measuring OAM

Diffraction grating (hologram) to make/ measure $\ell=3$





Diffraction grating (hologram) to make/ measure $\ell = -3$



Diffraction grating (hologram) to make/ measure $\ell = \pm -3$



Detection of a Spinning Object Using Light's Orbital Angular Momentum

Martin P. J. Lavery,^{1*} Fiona C. Speirits,² Stephen M. Barnett,² Miles J. Padgett¹ SCIENCE VOL 341 2 AUGUST 2013

Illuminate with OAM at +/- ℓ and measure $\Delta \omega$



С





Thank you to you and my Group





If you would like a copy of this talk please ask me

www.gla.ac.uk/schools/physics/research/groups/optics/

