Light in a Twist: Orbital Angular Momentum

Miles Padgett FRS
Kelvin Chair of Natural Philosophy
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.

\[
\frac{\text{Angular Momentum Carried}}{\text{Energy Carried}} = \frac{1}{\omega} = \frac{\hbar}{\hbar \omega}
\]

(spinn) Angular Momentum per photon

Energy per photon

Angular frequency
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 photon carries a spin angular momentum of $\hbar$

So how does a multi-pole transition ($\Delta J > \hbar$) conserve angular momentum?
Linear momentum at a radius exerts a torque

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

**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
Huysgens 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

\[ p_\theta = 0 \]

\[ p_\theta \neq 0 \]
Angular momentum in terms of photons

- Spin angular momentum
  - Circular polarisation
  - $\sigma \hbar$ per photon

- Orbital angular momentum
  - Helical phasefronts
  - $\ell \hbar$ per photon

$\sigma = +1$

$\sigma = -1$

$\ell = 0$

$\ell = 1$

$\ell = 2$

$\ell = 3$

etc
Optical vortices, Helical phasefronts, Angular momentum

- Intensity, \( I \geq 0 \)
- Phase, \( 2\pi \geq \phi \geq 0 \)
  - \( \ell = 0 \), plane wave
  - \( \ell = 1 \), helical wave
  - \( \ell = 2 \), double helix
  - \( \ell = 3 \), pasta fusilli etc.

\( \ell \) = vortex charge
Orbital angular momentum from Skew rays

Poynting vector
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)

Making OR measuring phasefronts with holograms

Make interactive by using SLM

Switching time 
≈5-20mSec
Efficiency ≈50%

Generate

Light source
OR detector

Measure
A gift for all the family.....
A double-start helix ($\ell=2$)

Chambord castle (chateaux de la Loire)
And the point of shaping the spot is......
OAM in optical manipulation

He et al. PRL 1995

Entanglement of the orbital angular momentum states of photons

Aless Mair, Alpasha Vaziri, Gregor Weihs & Anton Zeilinger
Institut für Experimentalphysik, Universität Wien, Boltzmanngasse 3, 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 non-locality\(^2\). 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
Spiral interferometry

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


Astronomical demonstration of an optical vortex coronagraph

Grover A. Swartzlander, Jr., Erin L. Ford, Rukiah S. Abdul-Malik, Laird M. Close, Mary Anne Peters, David M. Palacios, and Daniel W. Wilson

OAM in communication

**New Journal of Physics**

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

Fabrizio Tamburini, Eleonora Mari, Anna Sponselli, Bo Thidé, Antonio Bianchini and Filippo Romanato


**ARTICLES**

*Terabit free-space data transmission employing orbital angular momentum multiplexing*

Jian Wang, Jeng-Yuan Yang, Irfan M. Fazal, Nisar Ahmed, Yan Yan, Hao Huang, Yongxiong Ren, Yang Yue, Samuel Dulinar, Moshe Tur and Alan E. Willner

Wang et al. Nature Photon 2012
OAM in Lasers

A digital laser for on-demand laser modes

Sandle Ngcobo1,2, Igor Litvin1, Liesl Burger1,2 & Andrew Forbes1,2

OAM in not just light

Transfer of Angular Momentum to Matter from Acoustical Vortices in Free Space
Karen Volke-Sepulveda, Arturo O. Santillán, and Ricardo R. Boallosa

Volke-Sepulveda et al. PRL 2008

Production and application of electron vortex beams
J. Verbeeck, H. Tian, and P. Schattschneider

Verbeeck et al. Nature 2010
The OAM communicator
Miles Padgett's corkscrew laser beam creates a ring of light with a dark centre.
Optical Vortices before Angular Momentum

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

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
The tangled web of speckle
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)
OAM in second harmonic generation

- Poynting vector “cork screws”, azimuthal skew angle is
  \[ \theta = \frac{\ell}{kr} \]
- Does this upset a co-linear phase match? - No
- Frequency & \( \ell \)-index both double
- “Path” of Poynting vector stays the same
  - phase matching maintained

1 green photon
\[ \ell = 2\ell_0 \]

“cork screwing” Poynting vector

2 infra red photons
\[ \ell = \ell_0 \]
Correlations in angular momentum

Near perfect (anti) Correlations in angular momentum
Correlations in angle

Near perfect Correlations in angle

\[ \phi_s \pm \pi \]
\[ \phi_i \pm \pi \]

\[ \Delta \phi \]

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

\[
\left[ \Delta(\ell_s | \ell_i) \hbar \right]^2 \left[ \Delta(\phi_s | \phi_i) \right]^2 = 0.00475 \hbar^2 \ll 0.25 \hbar^2
\]
Rotational Doppler Shifts

Martin Lavery

Steve Barnett
and Fiona Speirits
Linear vs. Rotational Doppler shifts

Light source
- exerts force = $P/c$

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

Light source
- exerts torque = $\ell P/\omega$
Orbital angular momentum -> Skew rays, $\alpha \neq 0$

$$\alpha = \frac{\ell}{kr}$$
Doppler shift from a SPINNING surface

\[ \Delta \omega = \Delta \omega_\ell = \Omega \ell \]

\[ \Delta \omega_{\ell, -\ell} = 2\Omega \ell \]

c.f. \( \Delta \omega = \sin \alpha \omega_0 v/c \)

\[ \sin \alpha \approx \ell/kr \quad & \quad v = \Omega r \]
The Rotational Frequency shift of Scattered Light

Scattered Light

Observe frequency shift between +/- $\ell$ components
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 $\ell=\pm 3$
Illuminate with OAM at $\pm \ell$ and measure $\Delta \omega$.

**Detection of a Spinning Object Using Light’s Orbital Angular Momentum**

Martin P. J. Lavery, Fiona C. Speirits, Stephen M. Barnett, Miles J. Padgett

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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/