Light in a Twist: Orbital Angular Momentum

Miles Padgett
Kelvin Chair of Natural Philosophy
The talk today

- Orbital Angular Momentum, what is it?
- What has been done with OAM
- A couple of example of what we have done and doing!
• 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.
• 1992, Allen, Beijersbergen, Spreeuw and Woerdman

• 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, $2\pi \geq \phi \geq 0$

\[
\begin{align*}
\ell &= 0, \text{ plane wave} \\
\ell &= 1, \text{ helical wave} \\
\ell &= 2, \text{ double helix} \\
\ell &= 3, \text{ pasta fusilli etc.}
\end{align*}
\]

\[
\ell = \text{vortex charge}
\]

Interference $+/-$
Orbital angular momentum from Skew rays

Poynting vector
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)

Making OR measuring phasefronts with holograms

Make interactive by using SLM

Switching time ≈5-20mSec
Efficiency ≈50%

Light source OR detector

Generate

Measure
Richard Bowman

A gift for all the family.....
And the point of shaping the spot is......
A double-start helix ($\ell=2$)

Chambord castle (chateaux de la Loire)
OAM in optical manipulation

He et al. PRL 1995

Entanglement of the orbital angular momentum states of photons

Mair et al. Nature 2001
Spiral interferometry

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


Astronomical demonstration of an optical vortex coronagraph

Grover A. Swartzlander, Jr,1,2 Erin L. Ford,1 Rukiah S. Abdul-Malik,1 Laird M. Close,2 Mary Anne Peters,2 David M. Palacios,3 and Daniel W. Wilson1

OAM in communication

**New Journal of Physics**

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

Fabrizio Tamburini\(^1\), Elettra Mari\(^1\), Anna Sponselli\(^1\),
Bo Thidé\(^4,5\), Antonio Bianchini\(^1\) and Filippo Romanato\(^6,7\)


**Nature Photonics**

Terabit free-space data transmission employing orbital angular momentum multiplexing

Jian Wang\(^1\,\ast\), Jing-Yuan Yang\(^1\), Ifan M. Fazli\(^1\), Nisar Ahmed\(^1\), Yan Yan\(^1\), Hao Huang\(^1\), Yongzong Ren\(^1\),
Yang Yue\(^1\), Samuel Dulin\(^3\), Moshe Tur\(^4\) and Alan E. Willner\(^\ast\)

Wang et al. Nature Photon 2012
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
Miles Padgett’s corkscrew laser beam creates a ring of light with a dark centre.
Optical Vortices before Angular Momentum

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

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
• Either numerically or experimentally, one can map the vortex positions in different planes.
The tangled web of speckle
Entanglement of OAM states

Entanglement of the orbital angular momentum states of photons

Alois Mair, Alipasha Vaziri, Gregor Weihs & Anton Zeilinger

PHYSICAL REVIEW LETTERS

Measuring Entangled Qutrits and Their Use for Quantum Bit Commitment

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)
• Poynting vector “cork screws”, azimuthal skew angle is
  \[ \theta = \ell/kr \]
• Does this upset a co-linear phase match? - No
• Frequency & \( \ell \)-index both double
• “Path” of Poynting vector stays the same
  \[ \ell = \ell_0 \]
• phase matching maintained

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

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

Near perfect (anti) Correlations in angular momentum

![Diagram of angular momentum measurements and correlation plot]
Correlations in angle

Near perfect Correlations in angle

\[ \phi_i + \pi \]

\[ \phi_s - \pi \]

\[ \phi_i + \pi \]

\[ \Delta \phi \]

\[ -\pi \]

\[ \phi_s - \phi_i \]

\[ +\pi \]
Angular EPR

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

\[
\left[ \Delta(\ell_s | \ell_i) \Delta(\ell_i) \right]^2 \left[ \Delta(\phi_s | \phi_i) \Delta(\phi_i) \right]^2 = 0.00475 \hbar^2 \ll 0.25 \hbar^2
\]
Entanglement of OAM states

*Printed in Great Britain*

Rotary ‘aether drag’

By R. V. Jones, F.R.S.
Department of Natural Philosophy, University of Aberdeen, Scotland
Optical Activity /Faraday effect for OAM

Sonja Franke-Arnold
Graham Gibson
Emma Wisniewski-Barker

Bob Boyd
Poincaré-sphere equivalent for light beams containing orbital angular momentum

M. J. Padgett and J. Courtial
The (Magnetic) Faraday Effect

- Rotation of plane polarised light
  \[ \Delta \theta_{pol} = BLV \]
  - \( V \) Verdet constant
- OR treat as phase delay of circularly polarised light
  \[ \Delta \phi = \sigma BLV \]

\[ \Delta \theta = \Delta \phi_{+\sigma,-\sigma} / \Delta \sigma \]

But the magnetic Faraday effect does NOT rotate an Image
• Photon drag, gives Polarisation rotation

\[ \Delta \theta = \frac{\Omega L}{c} \left( n_g - 1/n_\phi \right) \]

\[ \Delta \phi = \frac{\sigma \Omega L}{c} \left( n_g - 1/n_\phi \right) \]

• Mechanical Faraday Effect
- SAM -> Polarisation rotation
- OAM-> Image rotation
- Look through a Faraday isolator ($\Delta \theta \approx 45^\circ$), is the “world” rotated - NO
  - SAM and OAM are not equivalent in the Magnetic Faraday effect
  - SAM and OAM are not equivalent in the optical activity
Enhancing the effect:...

- Plug in “sensible numbers” and get a micro-radian rotation...
- Increase the group index to enhance the effect

\[ \Delta \theta_{image} = \frac{\Omega L}{c} \left( n_g - \frac{1}{n_\phi} \right) \]
• Shine an elliptical laser beam (≈LG, Δℓ=2) @ 532nm through a spinning Ruby bar.
$\approx 25\text{Hz}$ clockwise $\leftrightarrow$ anticlockwise
A beam splitter for OAM

Martin Lavery

Gregorius Berkhout (Leiden)

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

$\ell = 0$ $\ell = 1$ $\ell = 2$ $\ell = 3$ etc

$\sigma = +1$ $\sigma = -1$
Measuring spin AM

- Polarising beam splitter give the “perfect” separation of orthogonal (linear) states
  - Use quarter waveplate to separate circular states
  - Works for classical beams AND single photons
Measuring Orbital AM

- OAM beam splitter give the “perfect” separation of orthogonal states
  - But how?
It works for plane waves

- A “plane-wave” is focused by a lens
- A phase ramp of $2\pi$ displaces the spot
• Image transformation
  - $\phi \rightarrow x$ and $r \rightarrow y$
  - i.e. $L_z \rightarrow p_x$
Replacing the SLMs

- The principle works
- But the SLMs are inefficient (≈50% x 2)
- Use bespoke optical elements (plastic)
  - Prof. David J Robertson
  - Prof. Gordon Love

reformater

phase corrector
• The principle works
• But the SLMs are inefficient (≈50% x 2)
• Use bespoke optical elements (glass/plastic)
  – Prof. David J Robertson
  – Prof. Gordon Love
Evolution in time c.f. translation and rotation

\[ \Phi = f(kz + \omega t) \quad \Phi = f(kz + \omega t + \ell \theta) \]

\( \ell = 0 \)  time c.f. translation  \( \ell > 0 \)  time c.f. rotation
Linear vs. Rotational Doppler shifts

- Light source
- Beam of light
- Light source
- Rotation symbol $\Omega$

Left: Linear Doppler shift with speed $v$
Right: Rotational Doppler shift
Doppler shift from a translating surface

\[ \Delta \omega = \omega_0 \cos \theta \frac{v}{c} \]

But for rotation and OAM

\[ v = \Omega r \quad \text{and} \quad \theta = \frac{\ell}{kr} \]

[Diagram showing Doppler shift with vectors for \( v \) and \( \theta \) and equations for \( \Delta \omega \)]
Rotational Frequency shifts

Scattered Light

Observe frequency shift between +/- $\lambda$ components

Detector

Illuminate
Rotational Doppler shift in scattered light

\[ \Delta \omega = 2 \ell \Omega \]

c.f. Speckle velocimetry? Albeit, in this case, angular
Thank you to you and my Group

More talks in 238
If you would like a copy of this talk please ask me

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