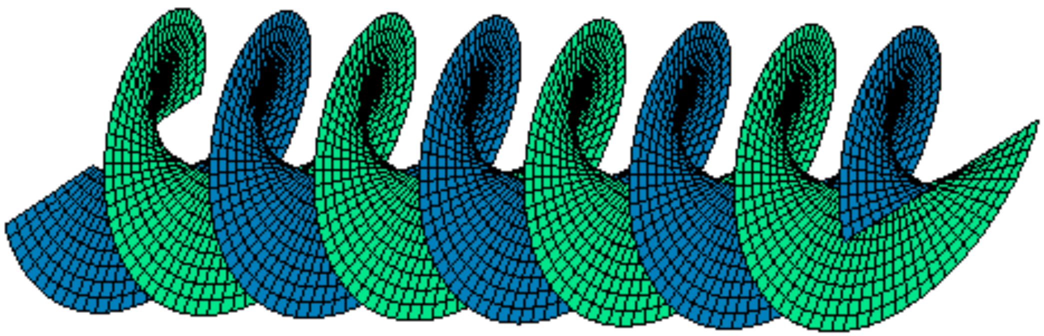
The Abdus Salam
International Centre for Theoretical Physics

Workshop on Singular Optics and its Applications to Modern Physics



Spin-to-orbital conversion of the angular momentum of light

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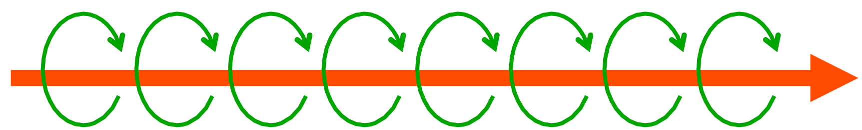
Outline:

- ❑ Introduction: spin and orbital angular momentum of light
- ❑ Spin–orbital angular momentum conversion
- ❑ q-plate: the concept
- ❑ q-plates: the current technology
- ❑ Concept generalization: Pancharatnam-Berry phase optical elements (PBOE) for arbitrary wavefront shaping

Introduction: spin and orbital angular momentum of light

Spin and orbital angular momentum of light (SAM & OAM)

That is, different ways for a light "ray" to "rotate upon itself" while it propagates



Standard expression of field angular momentum: $\boldsymbol{J} = \varepsilon_0 \int \mathrm{d}\boldsymbol{r}\, \boldsymbol{r} \times [\boldsymbol{E} \times \boldsymbol{B}]$

An equivalent expression (from Noether theorem): $\boldsymbol{J}_{\mathrm{rad}} = \boldsymbol{L}_{\mathrm{rad}} + \boldsymbol{S}_{\mathrm{rad}}$

SAM $\boldsymbol{S}_{\mathrm{rad}} = \varepsilon_0 \int \mathrm{d}\boldsymbol{r}\, \boldsymbol{E}_{\perp} \times \boldsymbol{A}_{\perp}$

OAM $\boldsymbol{L}_{\mathrm{rad}} = \varepsilon_0 \sum_l \int \mathrm{d}\boldsymbol{r}\, E_l^{\perp} (\boldsymbol{r} \times \nabla) A_l^{\perp}$

Only radiative terms (transverse fields)

Equivalent up to a surface term

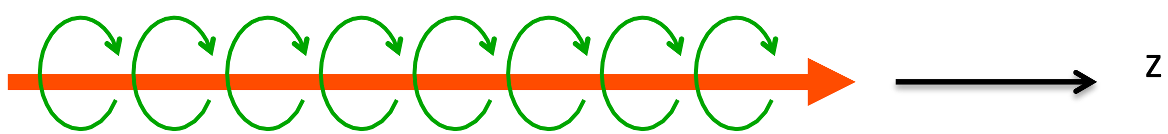
[S. J. van Enk & G. Nienhuis, J. Mod. Opt. **41**, 963 (1994)]

Spin and orbital angular momentum of light (SAM & OAM)

Some old-standing problems with SAM and OAM definitions:

- ❑ Other definitions are also possible (particularly for the SAM and OAM density and/or fluxes): Is there a "most correct" one? What criteria should we use?
- ❑ Gauge invariance (but problem solved if we restrict to radiative transverse fields)
- ❑ Actual physical meaning of SAM and OAM terms (Independent measurability? Are they true angular momenta, i.e. generators of rotations with proper commutation rules? Etc.)
- ❑ Coupling with matter: local density or flux coupling? SAM and OAM coupling with different degrees of freedom of matter?

However, most problems go away in the paraxial limit (for the "z" component)



[S. J. van Enk & G. Nienhuis, J. Mod. Opt. **41**, 963 (1994); T. A. Nieminen et al., J. Opt. A: Pure Appl. Opt **10**, 115005 (2008)]

Spin and orbital angular momentum of light (SAM & OAM)

SAM and OAM in the paraxial limit (monochromatic wave):

SAM: fully intrinsic, related with circular polarizations

$$\mathbf{S} = \frac{\varepsilon_0}{2i\omega}\int d\mathbf{r}\, \mathbf{E}^* \times \mathbf{E} \approx \frac{\varepsilon_0 \hat{\mathbf{z}}}{2\omega}\int d\mathbf{r}\, S_3$$

OAM: further splits into

External OAM, related with beam axis position and total momentum

$$\mathbf{L}_{ext} = \mathbf{r}_{cm} \times \mathbf{P}$$

Depends on the choice of origin of coordinate system

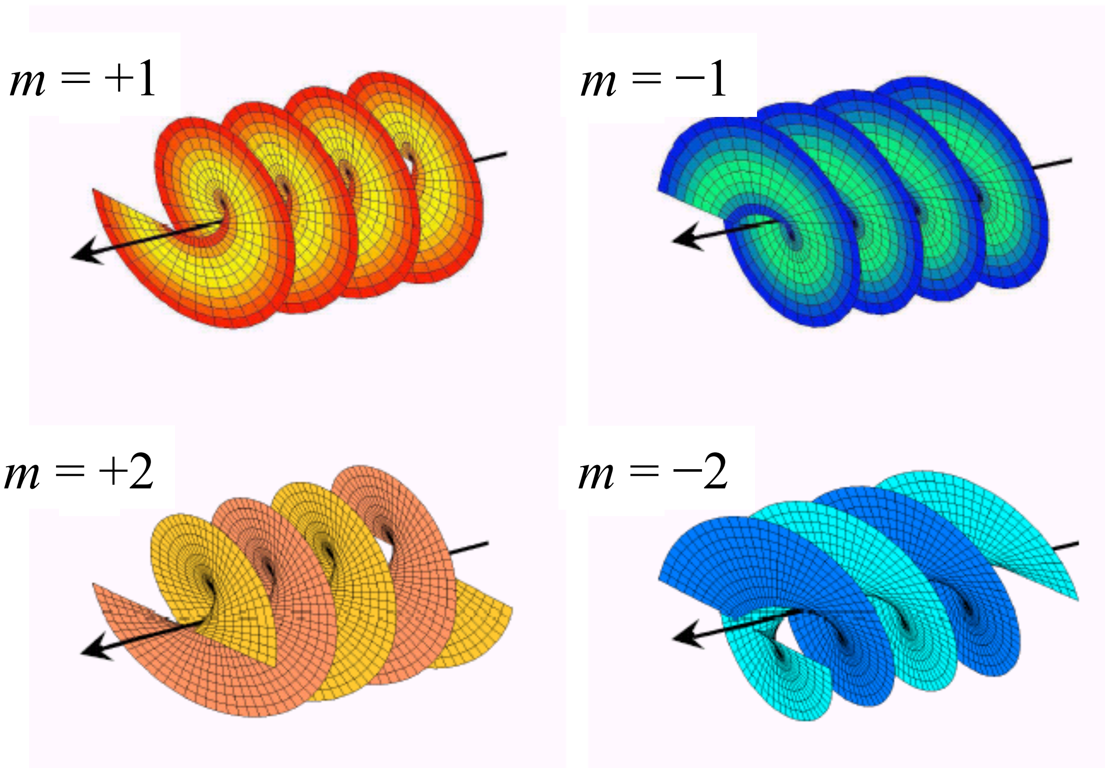
Internal OAM, related with helical wavefront

$$\mathbf{L}_{\text{int}} = \frac{\varepsilon_0}{2i\omega}\int d\mathbf{r} \sum_{h=x,y,z} E_h^* \mathbf{r} \times \nabla E_h \approx \frac{\varepsilon_0 \hat{\mathbf{z}}}{2i\omega}\int d\mathbf{r} \sum_{h=x,y,z} E_h^* \frac{\partial}{\partial \varphi} E_h$$

Spin and orbital angular momentum of light (SAM & OAM)

Helical modes: (using cylindrical coordinates r, φ, z)

$$\mathbf{E}(\mathbf{r},t) = \mathbf{E}_0(r,z)e^{im\varphi}e^{i(kz-\omega t)}$$



helical phase factor:

$$e^{im\varphi}$$

$$m = 0, \pm 1, \pm 2, \pm 3 \ldots$$

Angular momentum (OAM):

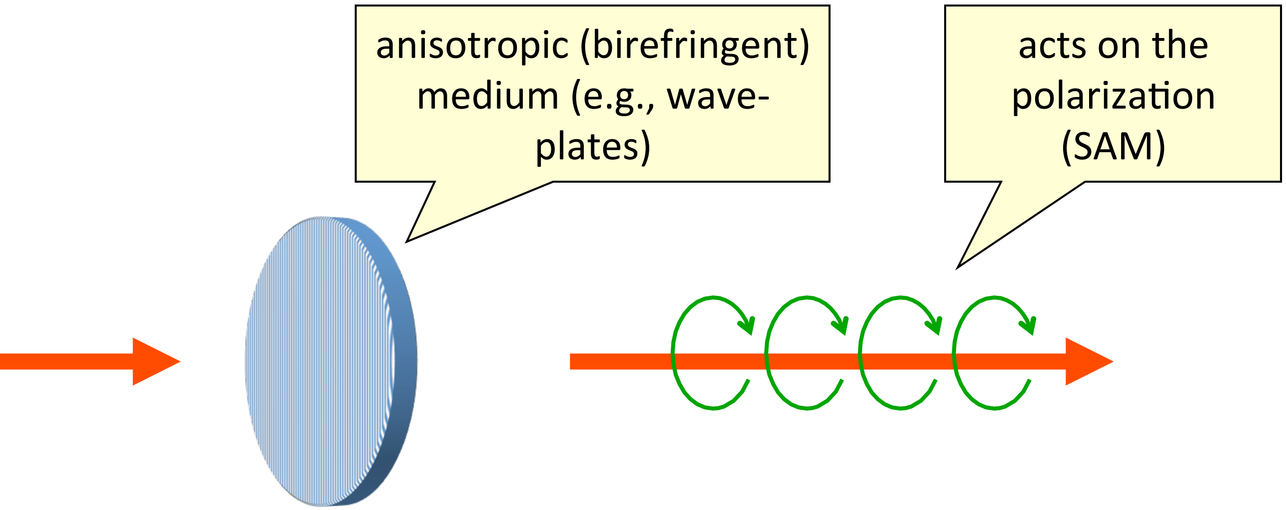
$$L_z = m\hbar \quad \text{per photon}$$

[L. Allen, M.W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman, *Phys. Rev. A* **45**, 8185 (1992)]

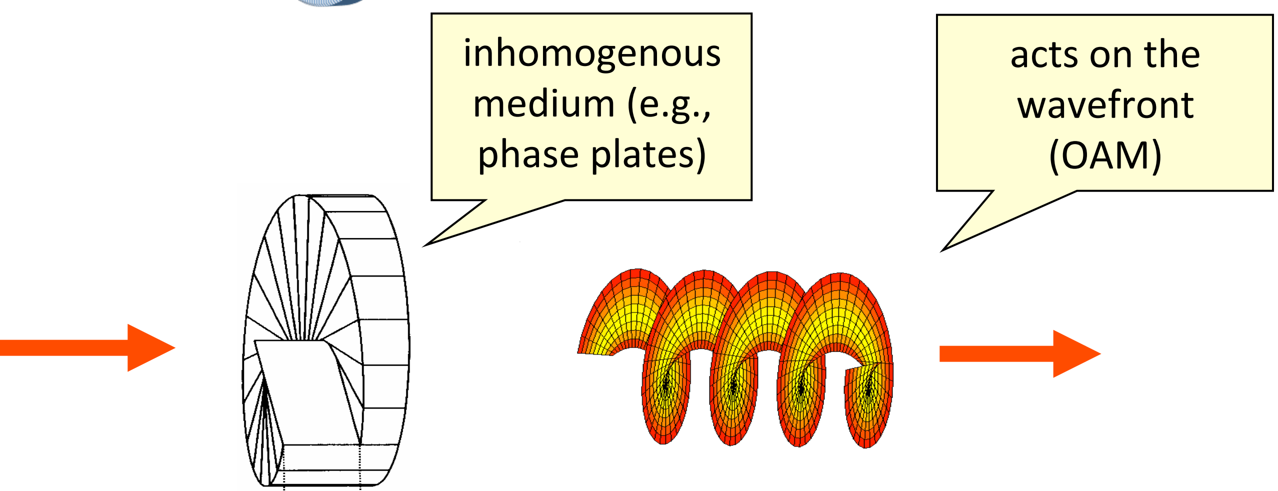
SAM and OAM interaction with matter

SAM and OAM are separately conserved during propagation in vacuum and in **isotropic homogeneous transparent** media. What about other media?

Effect of **medium anisotropy**:



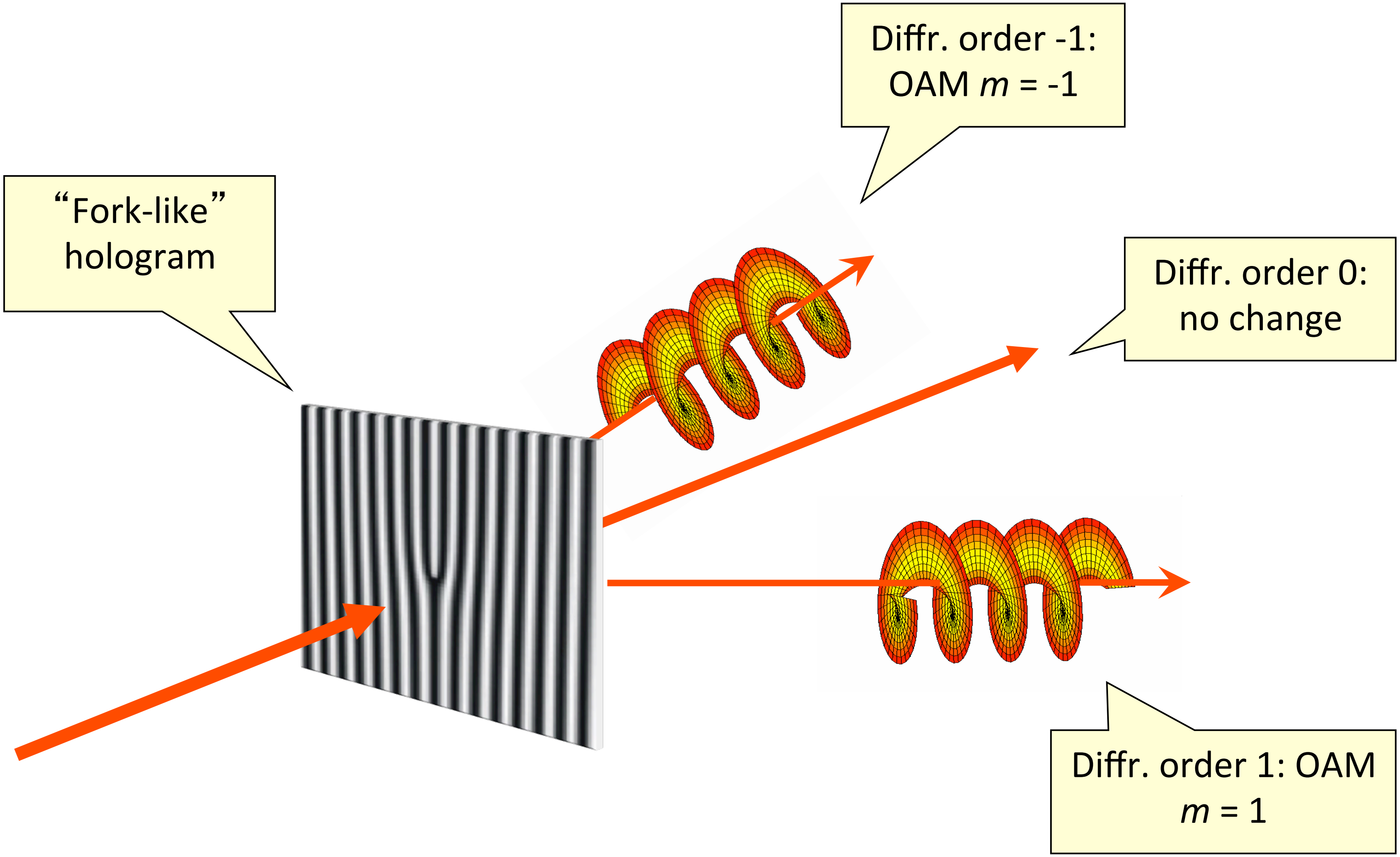
Effect of **medium inhomogeneity**:



[M.W. Beijersbergen et al., Opt. Commun. **112**, 321 (1994); M. Berry, in Singular Optics, SPIE 3487 (1998)]

SAM and OAM interaction with matter

Holograms can be considered as a special case of (strongly) inhomogeneous media:



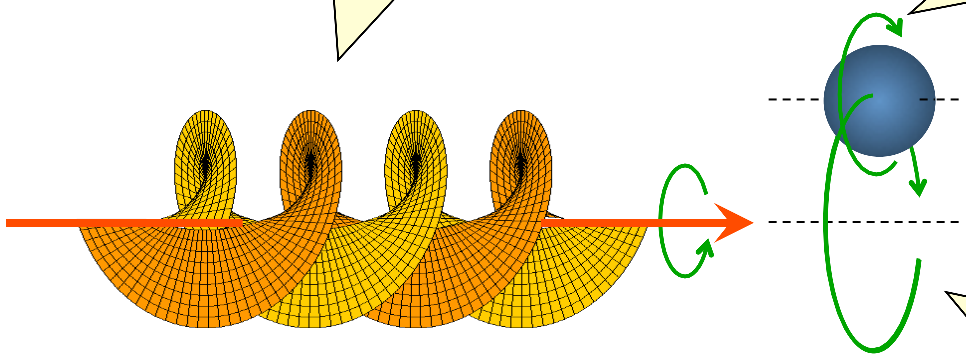
[V. Y. Bazhenov, M. V. Vasnetsov, M. S. Soskin, *Sov. Phys.—JETP Lett.* **52**, 429 (1990)]

SAM and OAM interaction with matter

Absorbing media couple both with SAM and OAM, although not exactly in the same way:

Circular-polarized and/or helical beam of light

Spin angular momentum of light makes an **absorbing particle spin around its own axis** (internal angular momentum)



Orbital angular momentum of light makes the **particle rotate around the beam axis** (external angular momentum)

However, absorption allows only transfer of angular momentum from light to matter, not vice versa

[H. He et al., PRL **75**, 826 (1995); N. B. Simpson et al., Opt. Lett. **22**, 52–54 (1997); A. T. O’Neil et al., PRL **88**, 053601 (2002)]

Spin–orbital angular momentum conversion

SAM – OAM conversion (optical spin-orbit effects)

"SAM – OAM conversion" is here defined as an optical process in which SAM and OAM both vary during propagation but the total angular momentum is conserved, ***whatever the input state of light***

More generally, optical spin-orbit coupling effects take place whenever SAM and OAM affect each other during propagation. SAM – OAM conversion is a special case of spin-orbit coupling effect

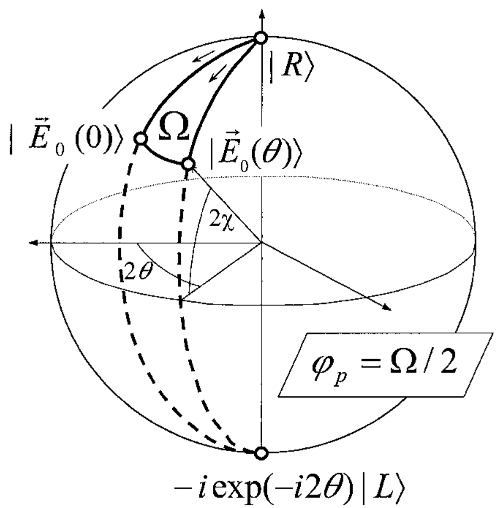
Question:
Under what conditions does SAM – OAM conversion take place?

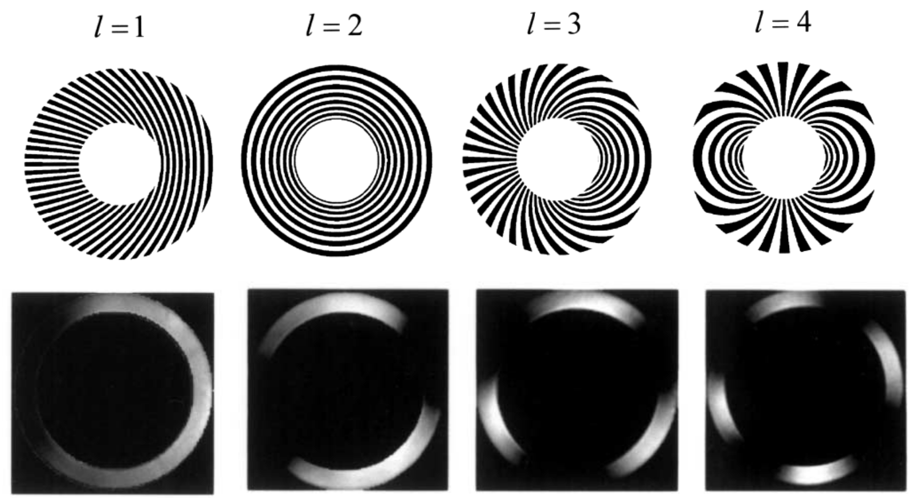
Before attempting an answer, let us **review the main findings reported so far**, following a chronological order (probably an incomplete list)

Notice: from 1992 (when the OAM research field actually started) to 2002, there was no prediction or observation of SAM – OAM conversion (except for external OAM effects)

2002: Space-variant sub-wavelength gratings

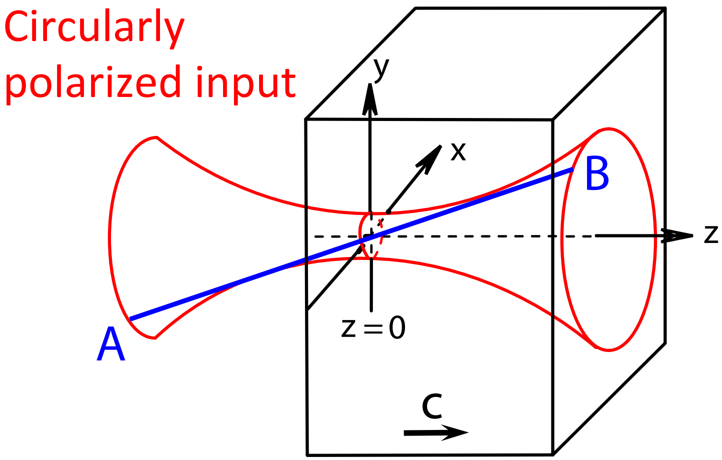
Hasman's group (after an idea of Rajendra Bhandari) demonstrates wavefront reshaping by exploiting the Pancharatnam-Berry phase arising in space-variant polarization manipulations. Among other examples, they demonstrate generation of helical modes (hence nonzero OAM) [Z. Bomzon et al., OL **27**, 1141 (2002); G. Biener et al., OL **27**, 1875 (2002)]





- this is actually the first reported observation of SAM – OAM conversion involving internal OAM (for mid-infrared light, $\lambda \approx 10$ μm)
- however, the authors **do not explicitly discuss the angular momentum of light** in the process
- the experiment was carried out only for a fixed input polarization and could not distinguish the output OAM sign (not a full test of SAM – OAM conversion)

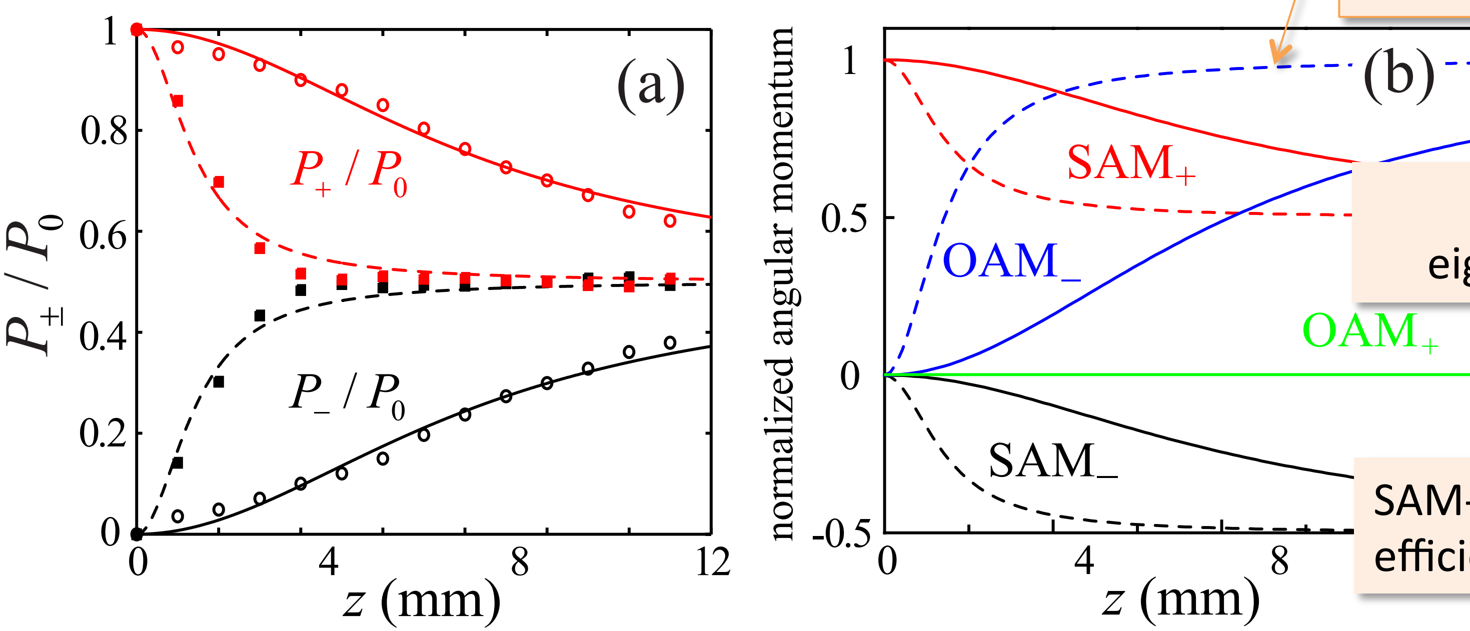
2003: Propagation in uniaxial birefringent crystals



Ciattoni et al. predict theoretically that a gaussian beam travelling along the optical axis of a **uniaxial birefringent crystal** undergoes SAM – OAM conversion (although they do not use this expression)
[JOSA A **20**, 163 and PRE **67**, 036618 (2003)]

First observed by Brasselet et al. in 2009
[Opt. Lett. **34**, 1021 (2009)]

Average output OAM = input SAM = ± ħ



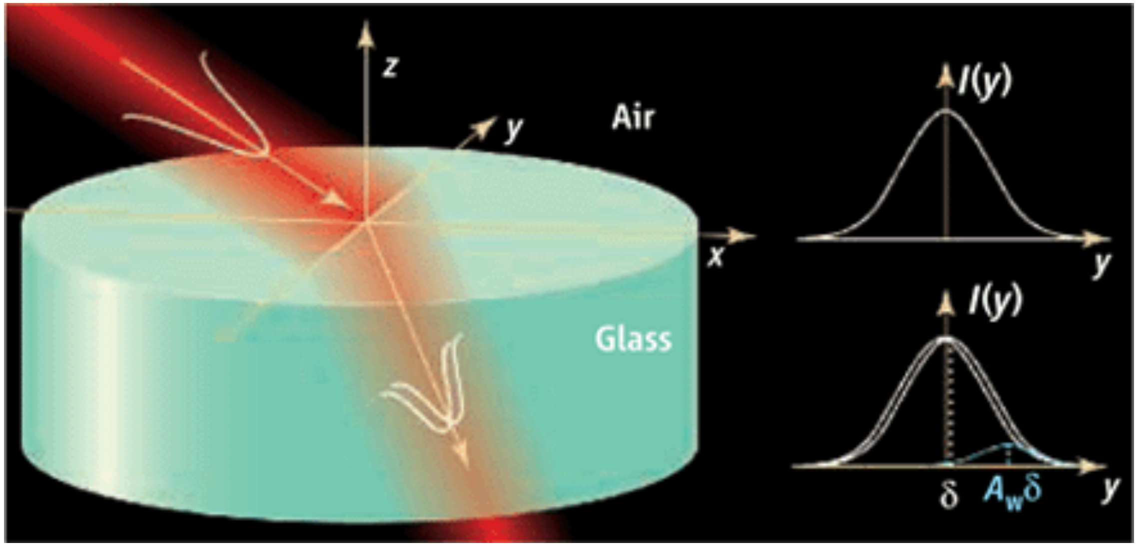
Output OAM eigenvalues = ± 2ħ

SAM-OAM conversion efficiency ≤ 50%

2004: Propagation in inhomogeneous media: spin Hall effect of light

M. Onoda et al. predict the occurrence of a “spin Hall effect of light”, a transverse shift of circularly polarized optical beams crossing gradients of dielectric properties, and explain it in terms of Berry phases (similar to Imbert-Fedorov shift of total internal reflection) [PRL **93**, 083901 (2004)]

A similar prediction is made also by Kostantin Yu Bliokh et al. [Phys. Lett. A **333**, 181 (2004)]. Later, he also extends this theory to a “OAM Hall effect” [K. Yu. Bliokh, PRL **97**, 0403901 (2006)]

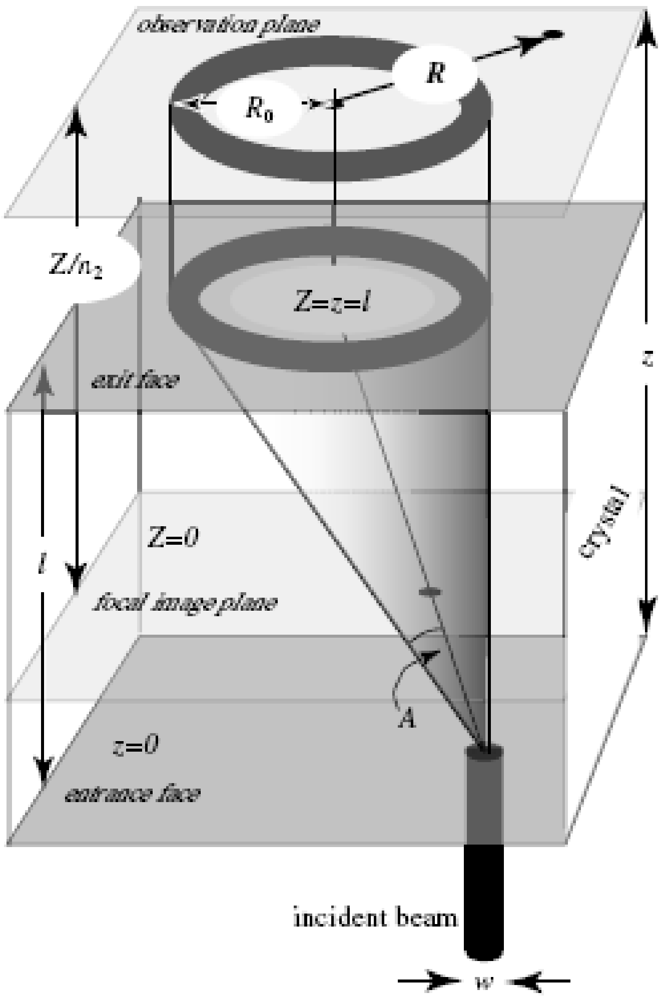


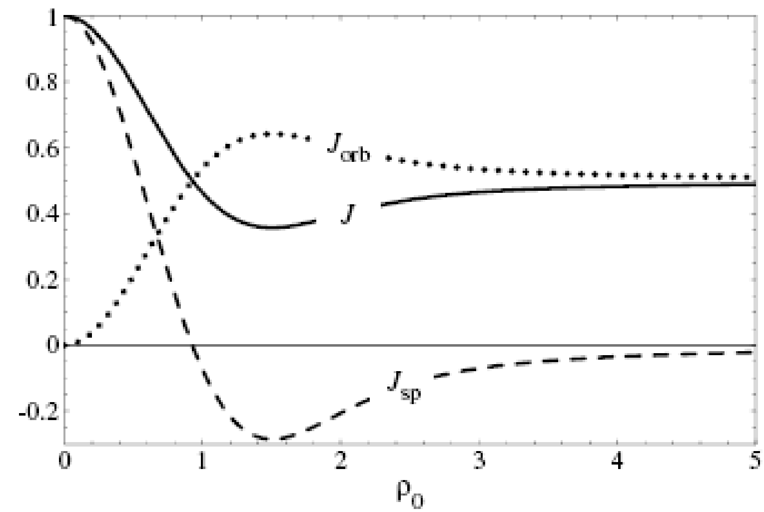
First observed in 2008 by Onur Ostein and Paul Kwiat [Science **319**, 787 (2008)]

This effect (as well as the old Imbert-Fedorov shift) provide examples of **conversion of SAM into <u>external OAM</u>**

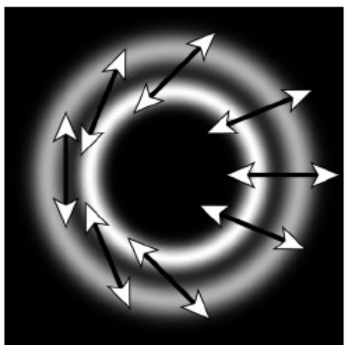
2005: Conical diffraction in biaxial birefringent crystals

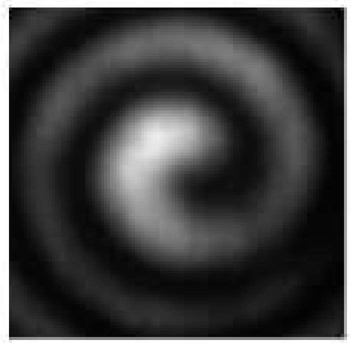
Michael V. Berry et al. discuss a form of SAM-OAM conversion for light entering biaxial birefringent crystals [J. Opt. A: Pure Appl. Opt. **7**, 685 (2005)]





Output OAM eigenvalues = ± ħ

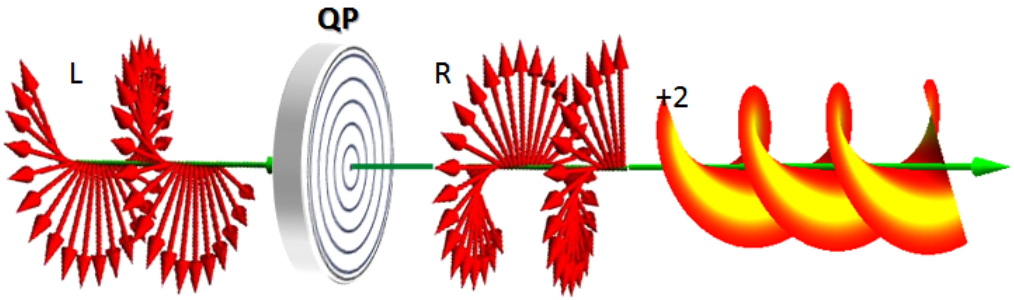




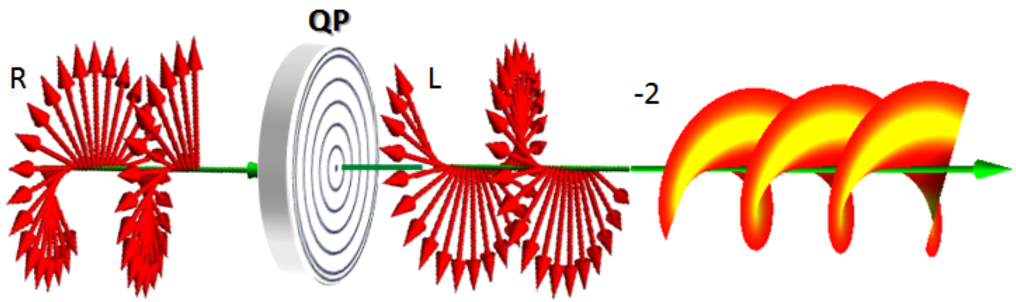
Confirmed experimentally by D. P. O'Dwyer et al. in 2010 [Opt. Express **18**, 16480 (2010)]

2006: Propagation in inhomogeneous anisotropic media

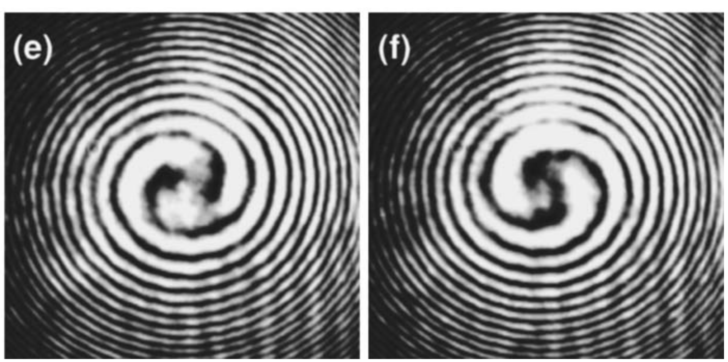
Marrucci et al. predict and observe SAM – OAM conversion in liquid crystal cells having a singular pattern with topological charge: the “**q-plates**” [PRL **96**, 163905 (2006); APL **88**, 221102 (2006)]



Output OAM eigenvalues = ± 2ħ, (but other values are also possible)



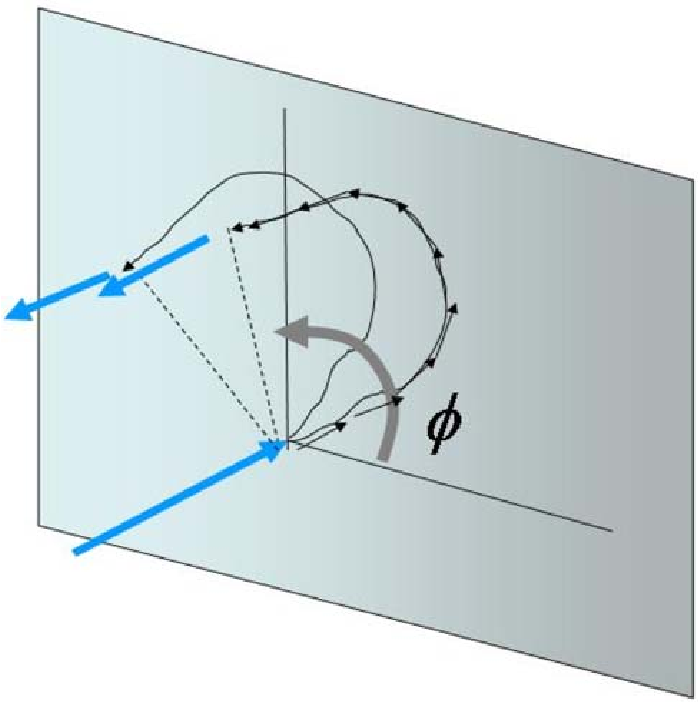
SAM-OAM conversion efficiency up to ≈ 100%

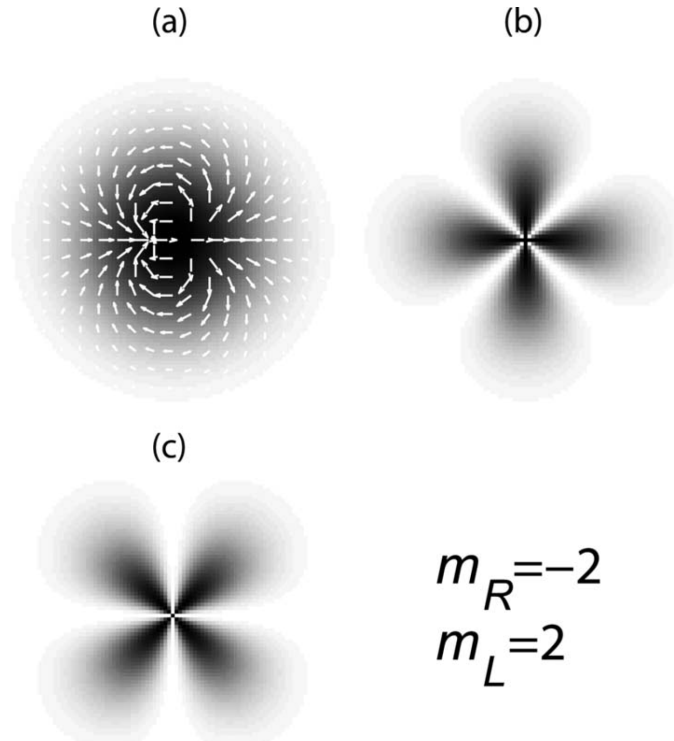


This is the first paper explicitly reporting and fully demonstrating experimental optical SAM – OAM conversion!

2006: Backscattering from disordered media

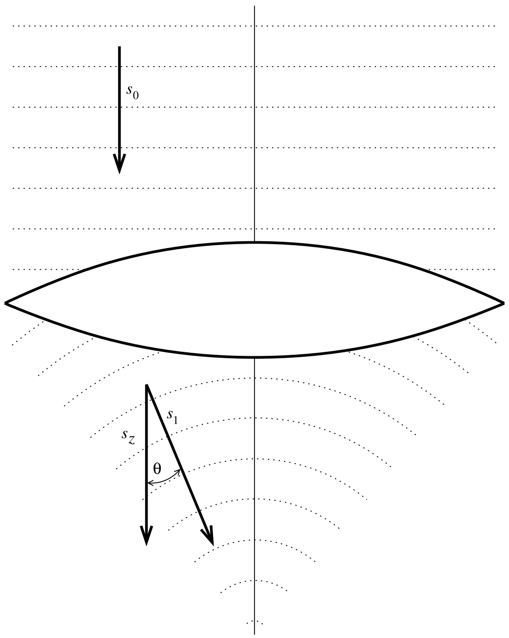
C. Schwartz explains the previously observed patterns of back-scattered light from disordered media in terms of Berry phases and SAM – OAM conversion [OL **31**, 1121 (2006)]

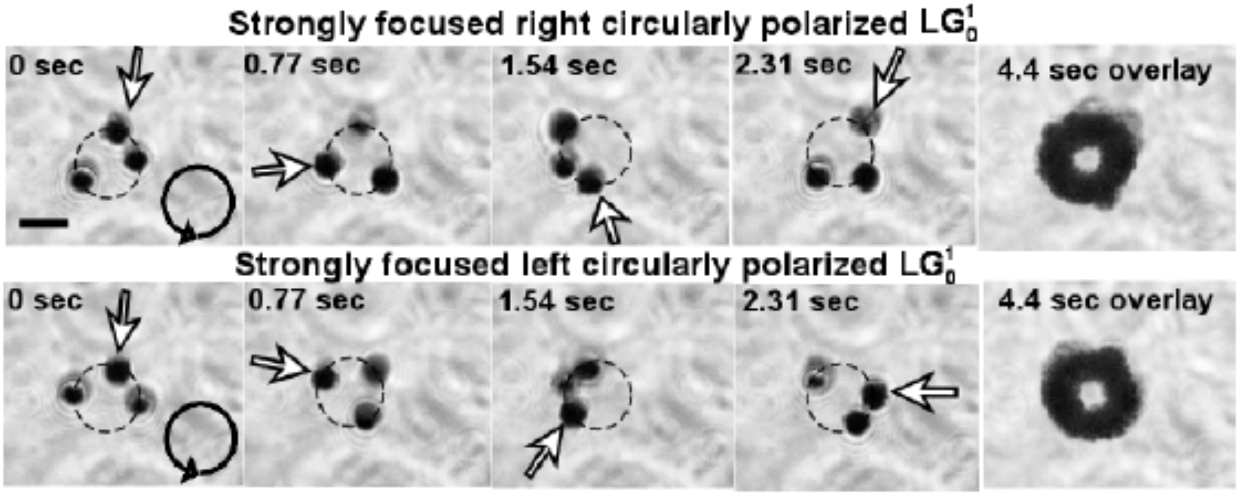




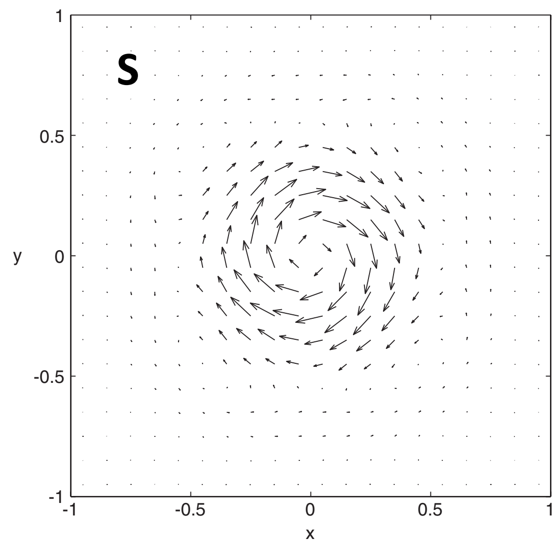
2007: Strong focusing of circularly polarized light

Y. Zhao et al. [PRL **99**, 073901 (2007)] and H. Adachi et al. [PRA **75**, 063409 (2007)] report the experimental demonstration of a nonzero OAM content in strongly focused circularly polarized beams





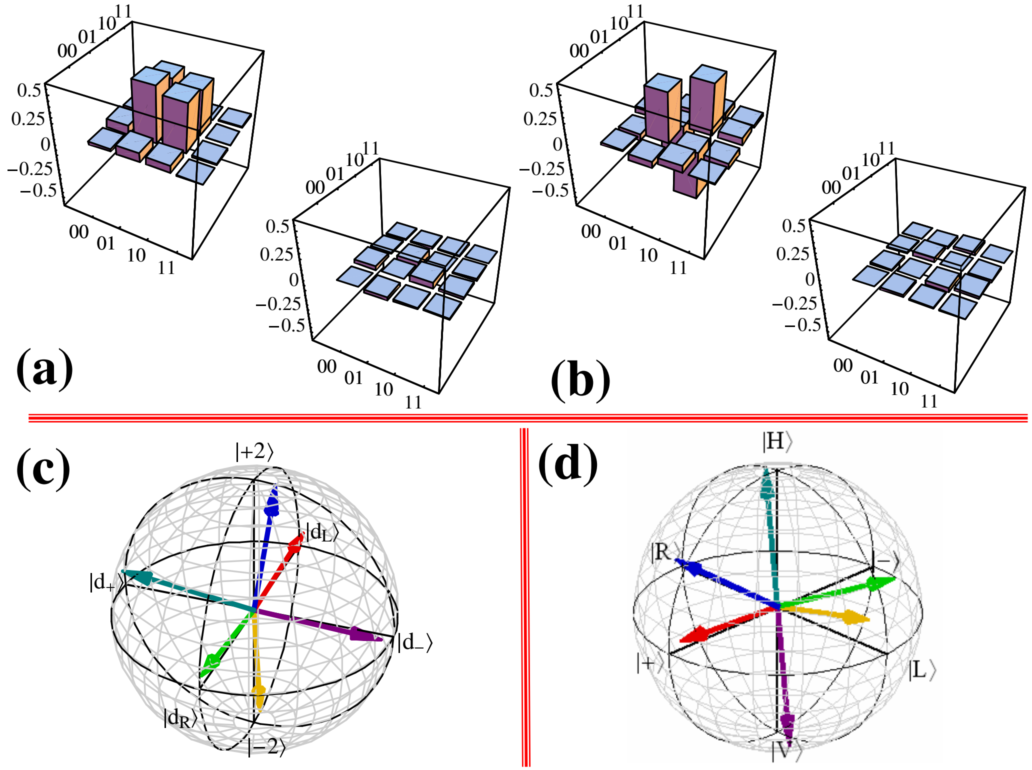
A first prediction of this effect was actually given by T. A. Nieminen et al. [Arxiv 2004; J. Opt. A **10**, 115005 (2008)]



(however, this OAM appears only in strongly non-paraxial regime, where the definition of SAM and OAM as distinct angular momenta is not so clear)

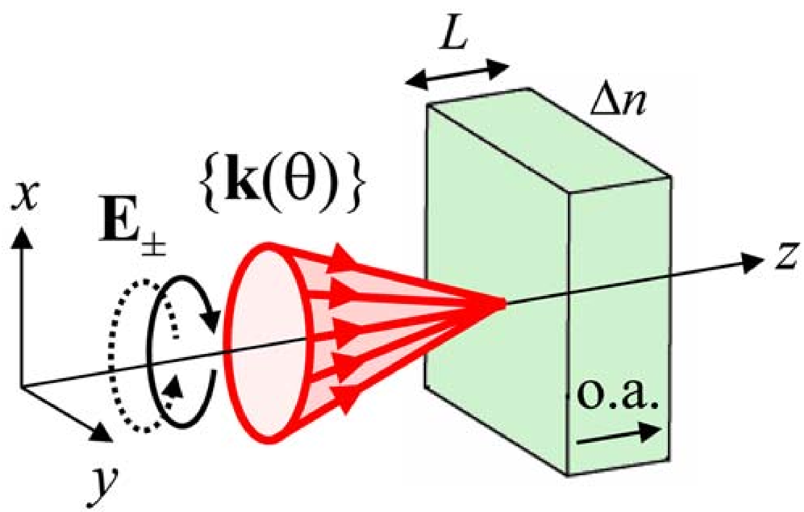
2009: SAM – OAM conversion for single photons (in q-plates)

E. Nagali et al. report the first experimental demonstration of SAM – OAM conversion in single photons and in correlated photon pairs [PRL **103**, 013601 (2009)]



2010: Conical beams in uniaxial birefringent crystals

Fadeyeva et al. [JOSA A **27**, 381 (2010), Opt. Express **18**, 10848 (2010)] and Loussert et al. [Loussert et al., Opt. Lett. **35**, 7 (2010)] demonstrate high efficiency SAM – OAM conversion of conical (Bessel) beams propagating through a uniaxial birefringent crystal



Output OAM = ±2ħ

Conversion efficiency can reach ≈100%

2011: Propagation in curved space-time

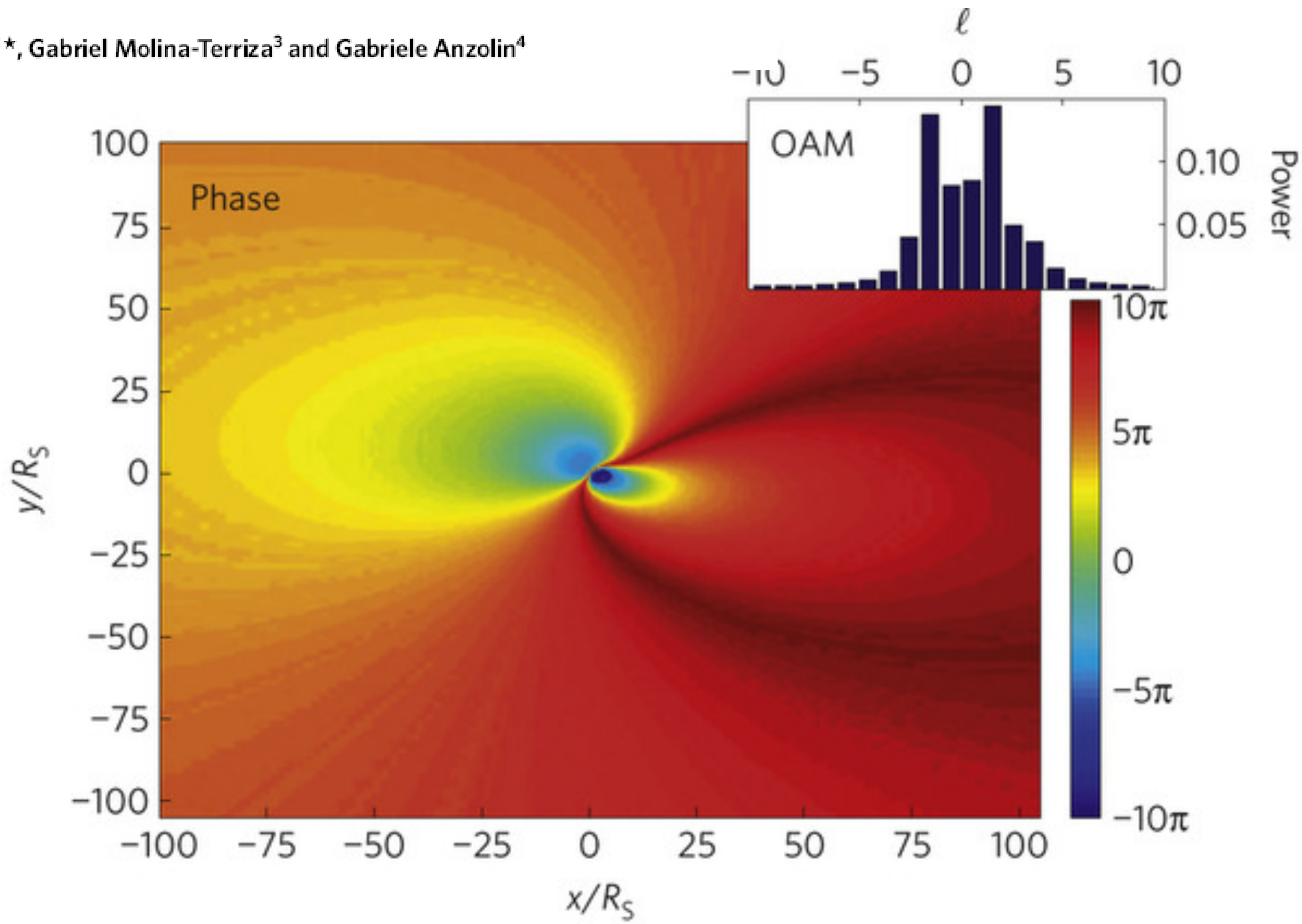
nature physics

LETTERS

PUBLISHED ONLINE: 13 FEBRUARY 2011 | DOI: 10.1038/NPHYS1907

Twisting of light around rotating black holes

Fabrizio Tamburini[1], Bo Thidé[2]*, Gabriel Molina-Terriza[3] and Gabriele Anzolin[4]



SAM – OAM conversion: conditions for occurrence

Categories of SAM – OAM processes identified so far:

- ❑ Propagation in **homogeneous anisotropic media** + **deviation from full paraxiality** (uniaxial crystals, conical diffraction)
- ❑ Propagation in **inhomogeneous isotropic media** + **large variation of propagation direction** (spin Hall effect, strong focusing, back-scattering)
- ❑ Propagation in **inhomogeneous anisotropic media** (patterned liquid crystals, e.g. q-plates, sub-wavelength gratings, curved space-time)

In all cases, a **global rotational symmetry of medium** around the z-axis ensures exact conservation of the total angular momentum z-component: $J_z = L_z + S_z$

Otherwise some exchange of angular momentum with the medium is involved (e.g., general q-plates, conical diffraction in biaxial crystals)

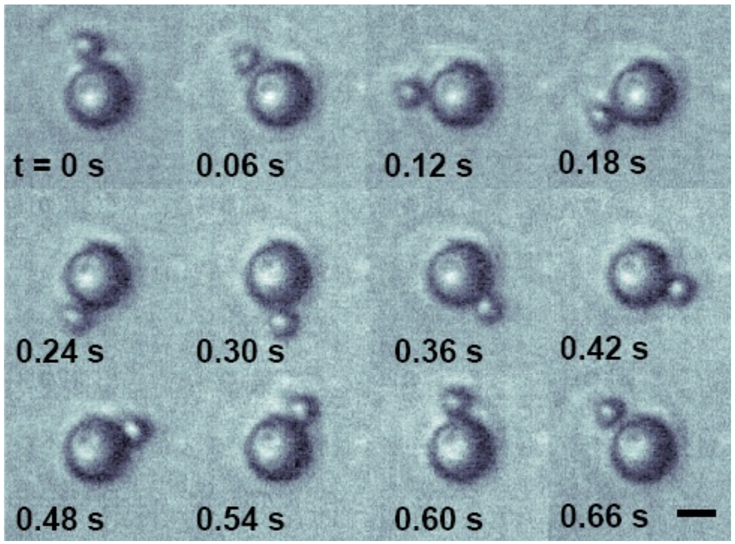
Notice: only the last case allows SAM – OAM conversion of undeflected fully paraxial beams

q-plate: the concept

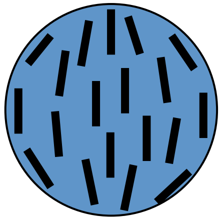
[L. Marrucci, C. Manzo, D. Paparo, PRL **96**, 163905 (2006); APL **88**, 221102 (2006)]

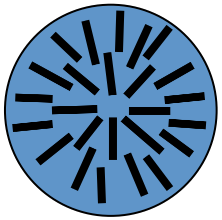
q-plate: origin of the idea (2005)

Experiment on spinning liquid crystal droplets by circularly polarized light:
[C. Manzo, D. Paparo, L. Marrucci, I. Jánossy, *Phys. Rev. E* **73**, 051707 (2006)]



However, we found two kinds of droplets:





Bipolar droplets: Almost homogeneous birefringence. **They can be spun by light.**

Radial droplets: Inhomogeneous birefringence. **They do not spin!**

But **radial droplets** anyway modify the light polarization and therefore should **exchange (spin) angular momentum with light** [*Istvan Jánossy, private discussion*]

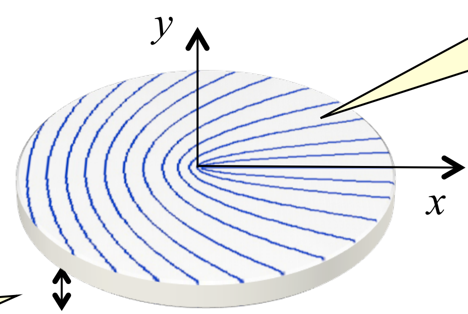
So, why don't they rotate?

The simple answer we found: SAM goes into OAM!

q-plate idea!!

q-plate structure: patterned half-wave plates

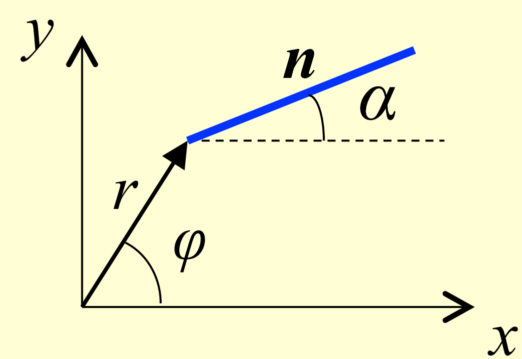
The optical axis orientation in the plate is **patterned**



Cell thickness and birefringence chosen so as to have uniform **half-wave retardation**

$$\alpha(x,y)=\alpha(r,\varphi)$$

α = angle between the local optical axis ***n*** and a reference axis



q-plate structure: patterned half-wave plates

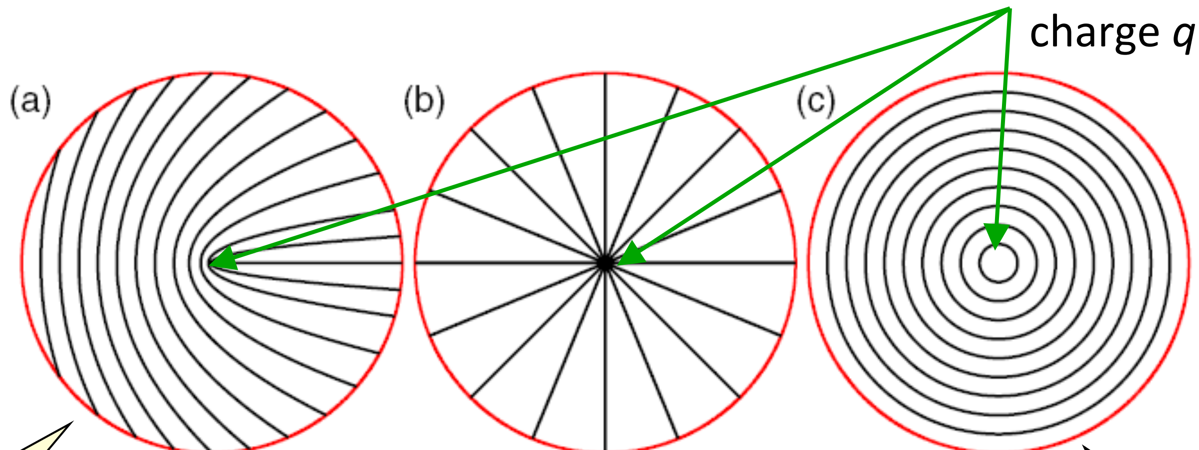
General pattern:

$$\alpha(x,y) = \alpha(r,\varphi) = q\varphi + \alpha_0$$

with q integer or half-integer

Three examples:

Topological defect of charge *q* in the center



$q = ½$ ($\alpha_0 = 0$)

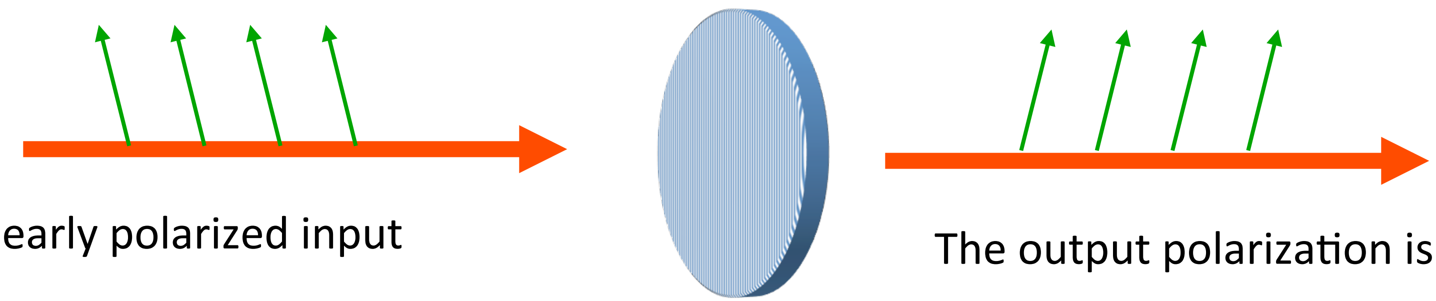
$q = 1$ ($\alpha_0 = 0$)

$q = 1$ ($\alpha_0 = \pi/2$)

Notice: *q* = 1 yields rotational-symmetric patterns (such as the radial droplets)

q-plate optical effect

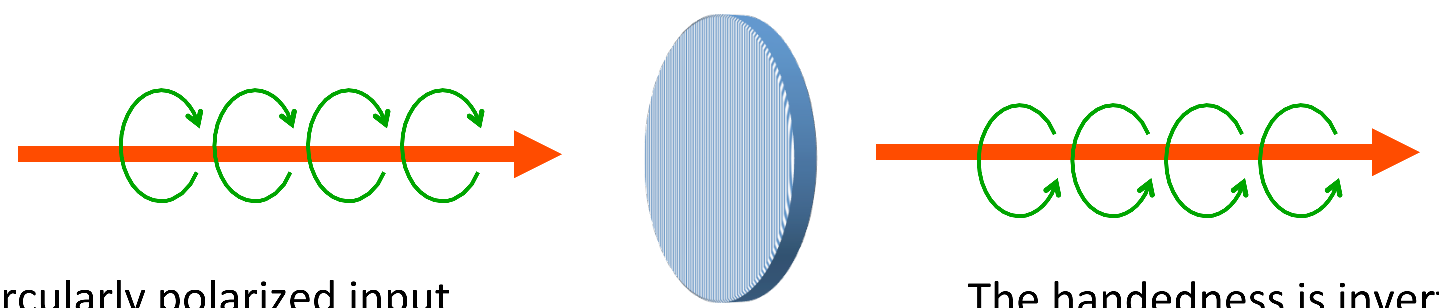
Consider first a <u>normal (uniform)</u> half-wave plate



For linearly polarized input

The output polarization is rotated

The extent of the polarization rotation depends on the optical axis orientation



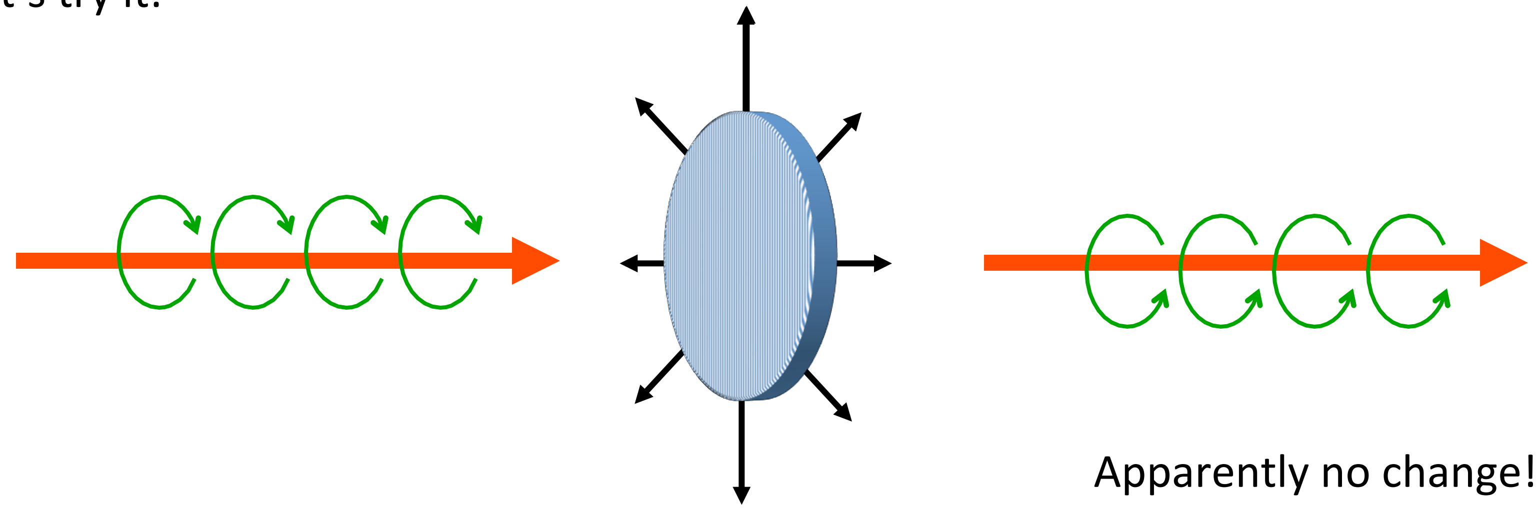
For circularly polarized input

The handedness is inverted

But what is the effect of rotating the optical axis in this case?

q-plate optical effect

Let's try it:



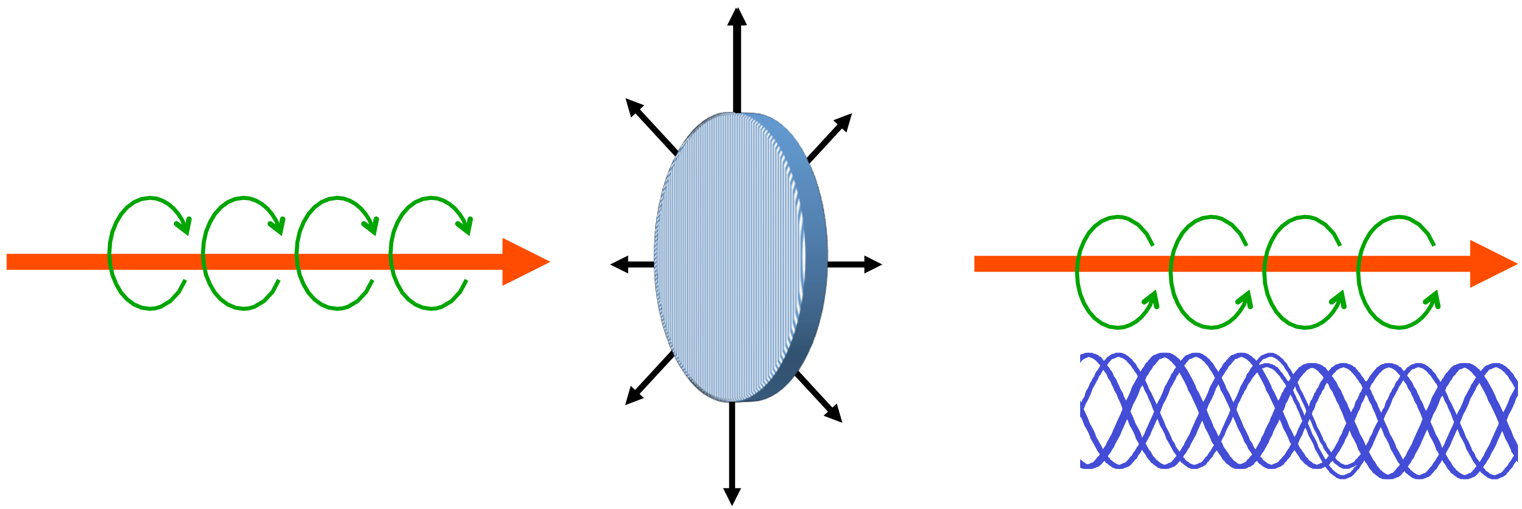
Apparently no change!

No change in the output polarization and optical intensity

But let us check also the optical phase

q-plate optical effect

Phase-shift induced by rotated half-wave plate on circular-polarized light:



Phase-shift versus half-wave axis rotation: $\Delta\Phi = \pm 2\alpha$

The ± sign is determined by the input polarization handedness

q-plate optical effect: Jones calculus

Jones matrix of an *α*-oriented half-wave plate: $\mathbf{M} = \begin{bmatrix} \cos 2\alpha & \sin 2\alpha \\ \sin 2\alpha & -\cos 2\alpha \end{bmatrix}$

Let us apply it to an **input left-circular** polarized plane wave:

$$\mathbf{M} \times \begin{bmatrix} 1 \\ i \end{bmatrix} E_0 = \begin{bmatrix} \cos 2\alpha + i \sin 2\alpha \\ -i \cos 2\alpha + \sin 2\alpha \end{bmatrix} E_0 = \begin{bmatrix} 1 \\ -i \end{bmatrix} e^{i2\alpha} E_0$$

The output polarization is **uniform right-handed circular**

The wave has acquired a **phase retardation**

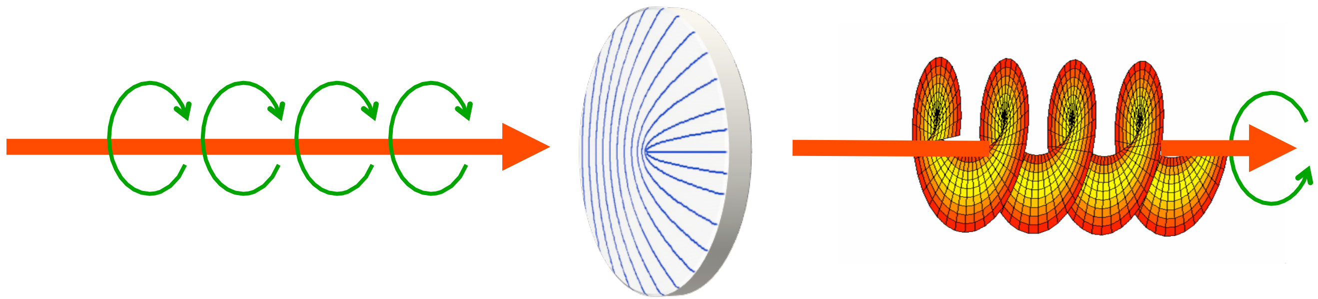
$$\Delta\Phi = 2\alpha$$

Pancharatnam-Berry geometrical phase

(unrelated with optical path length)

q-plate optical effect

Now consider again a non-uniform half-wave plate:



The wavefront gets reshaped!

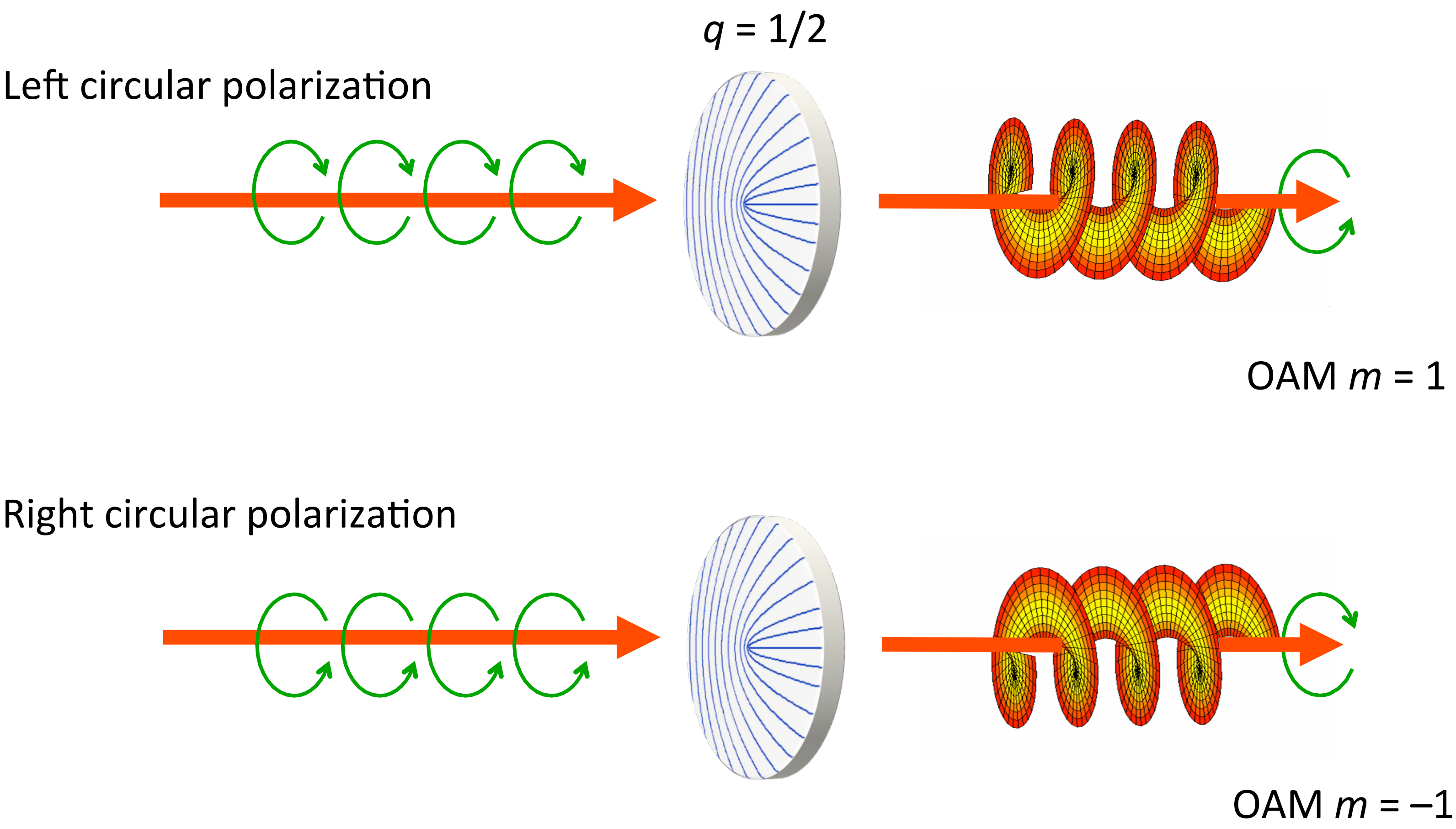
For the specific q-plate pattern: $\alpha(r,\varphi) = q\varphi + \alpha_0$

$$\Delta\Phi(x,y) = \pm 2\alpha = \pm 2q\varphi + \left(\pm 2\alpha_0\right) = m\varphi + \text{cost.}$$

Helical phase with $m = \pm 2q$ **!**

q-plate optical effect

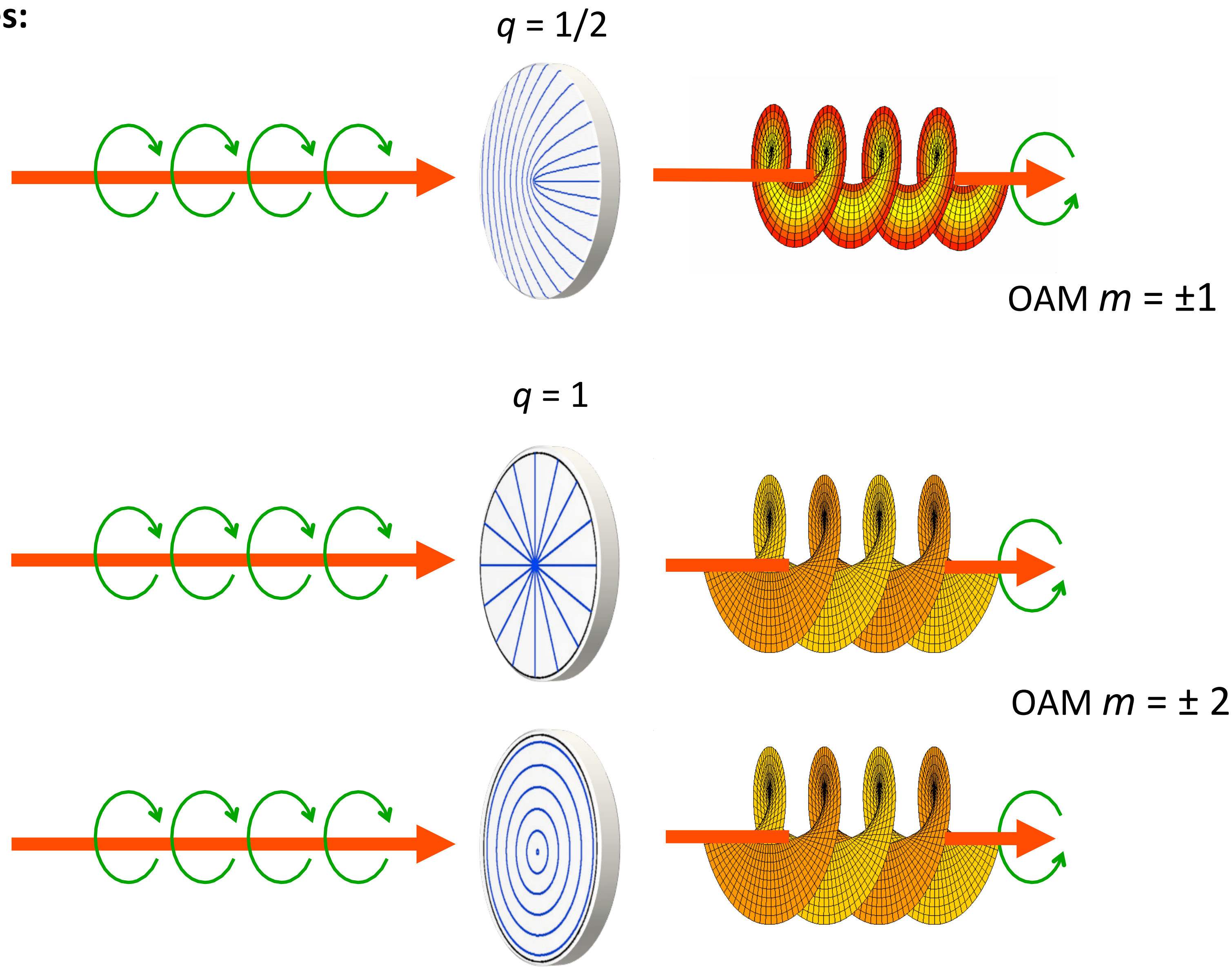
Examples:



Polarization controlled OAM handedness!

q-plate optical effect

Examples:



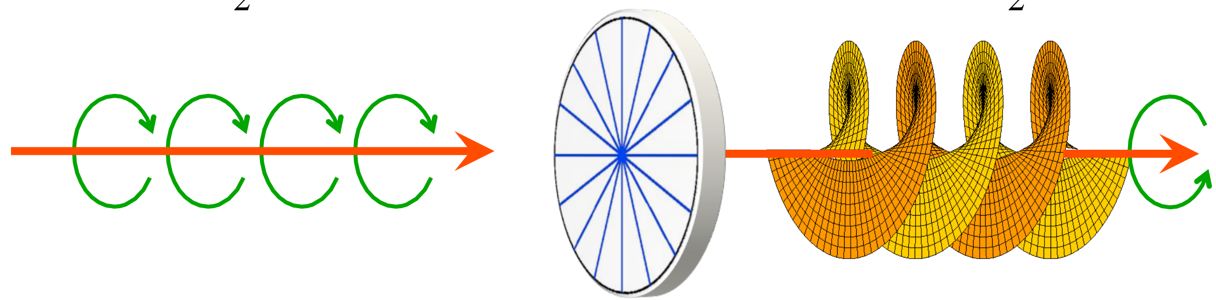
Photon angular momentum balance: case $q = 1$

Left-circular input:

Spin: $S_z = +\hbar$
Orbital: $L_z = 0$
Total: $J_z = +\hbar$

q-plate

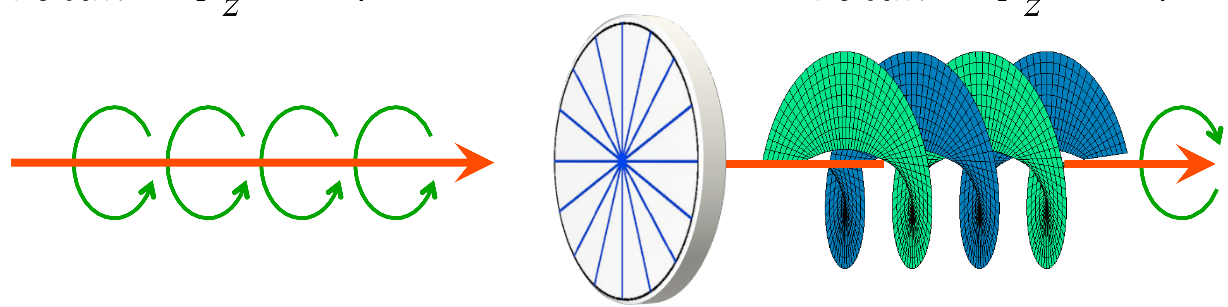
Spin: $S_z = -\hbar$
Orbital: $L_z = +2\hbar$
Total: $J_z = +\hbar$



Right-circular input:

Spin: $S_z = -\hbar$
Orbital: $L_z = 0$
Total: $J_z = -\hbar$

Spin: $S_z = +\hbar$
Orbital: $L_z = -2\hbar$
Total: $J_z = -\hbar$

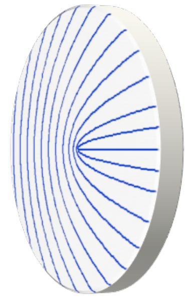


Spin-to-orbital conversion of optical angular momentum

Photon angular momentum balance: general case

Spin: $S_z = \pm\hbar$
Orbital: $L_z = m\hbar$

Total: $J_z = (m \pm 1)\hbar$



Spin: $S_z = \mp\hbar$
Orbital: $L_z = m\hbar \pm 2q\hbar$

Total: $J_z = [m \pm (2q-1)]\hbar$

For $q \neq 1$, $\Delta J_z = \pm 2(q-1)\hbar \neq 0$ → **Torque on the *q*-plate**

For $q = 1$, $\Delta J_z = 0$ → **No torque on the medium**
(medium is only a “coupler” between spin and orbital angular momentum of light)

This is why radial droplets don’t rotate!

But, what happens if the plate birefringent retardation is not just half-wave?

q-plate optical effect: general birefringence retardation

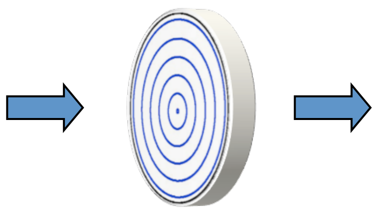
We use a quantum notation:

Input photon $|\text{spin,orbital}\rangle$

Birefringent retardation δ

Output photon: coherent superposition of "converted" and "unconverted" states

$$|\pm 1, m\rangle$$



$$|\psi\rangle = a|\pm 1, m\rangle + b|\mp 1, m \pm 2q\rangle$$

Notice: we call $\delta = \pi$ the "optimal tuning" condition for the q-plate

Superposition coefficients: $$\begin{cases} a = \cos\frac{\delta}{2} \\ b = i\sin\frac{\delta}{2} e^{i\alpha_0} \end{cases}$$

The output photon state is **not an eigenstate of spin and orbital** angular momenta

Notice: in the $q = 1$ case, still **all-optical conversion** (no torque on the medium)

q-plates:
the current technology

[L. Marrucci, C. Manzo, D. Paparo, PRL **96**, 163905 (2006); APL **88**, 221102 (2006)]

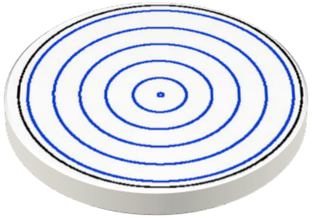
[E. Karimi, B. Piccirillo, E. Nagali, L. Marrucci, E. Santamato, APL **94**, 231124 (2009)]

[B. Piccirillo, V. D'Ambrosio, S. Slussarenko, L. Marrucci, E. Santamato, APL **97**, 241104 (2010)]

[S. Slussarenko, A. Murauski, T. Du, V. Chigrinov, L. Marrucci, E. Santamato, Opt. Express **19**, 4085-4090 (2011)]

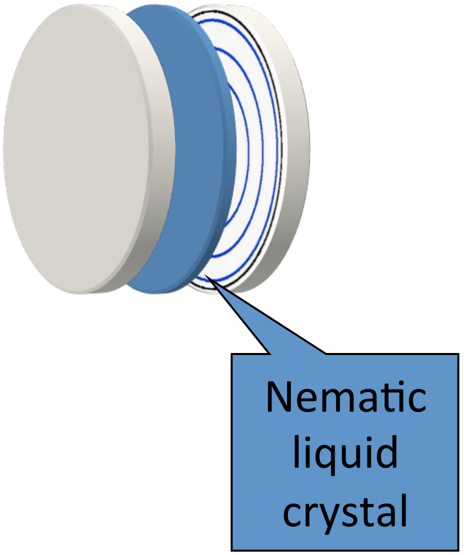
Making a liquid crystal q-plate: the first method

1) **Circular rubbing** of one substrate (with **planar anchoring**)

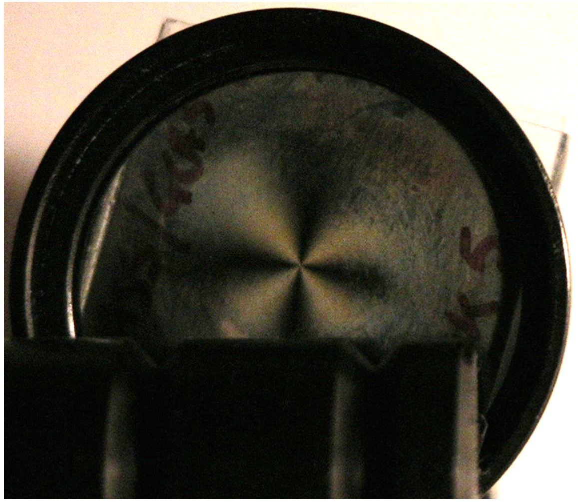


$q = 1$ geometry

2) Assemble the cell with **thickness chosen** for having **half-wave retardation** (only approximate)



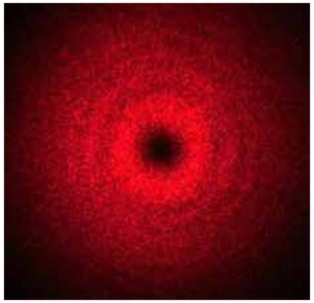
The cell between crossed polarizers:



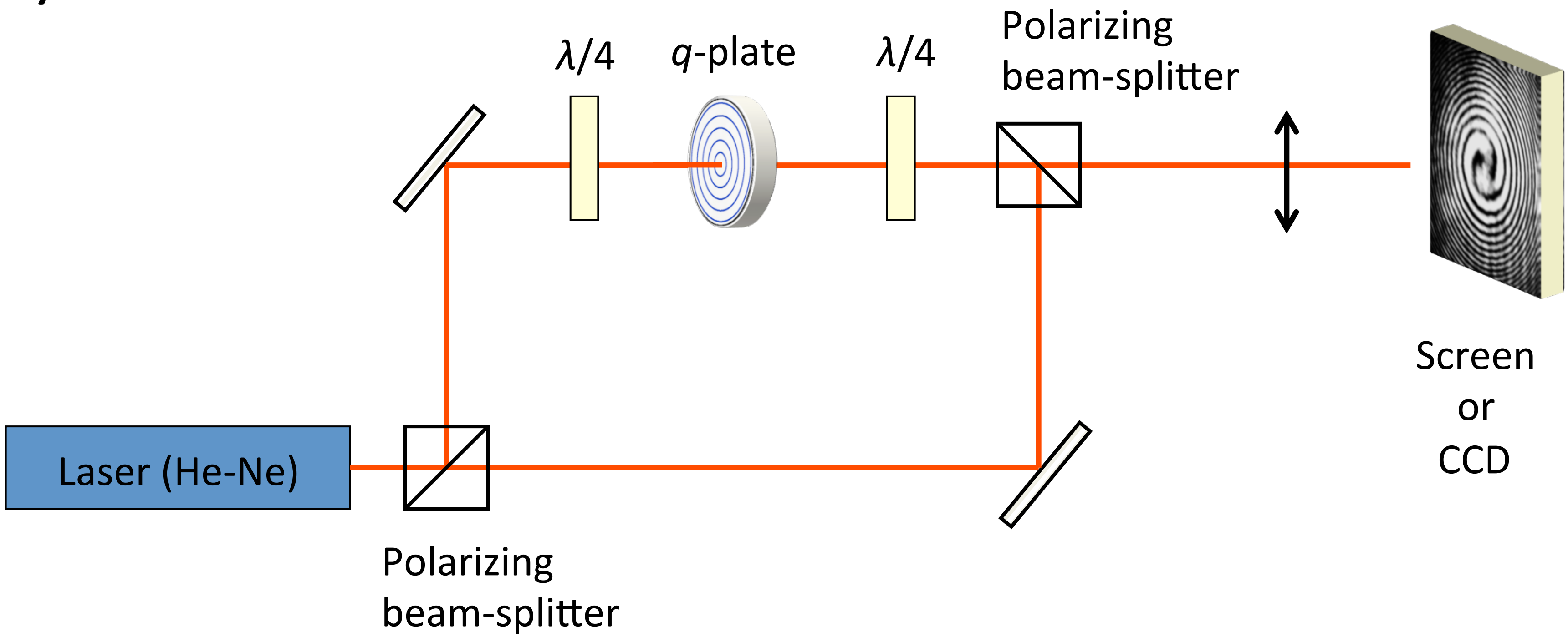
[L. Marrucci, C. Manzo, D. Paparo, PRL **96**, 163905 (2006); APL **88**, 221102 (2006)]

Liquid crystal q-plate: testing the optical effect

As a first step, we check that a vortex appears in the outgoing beam:

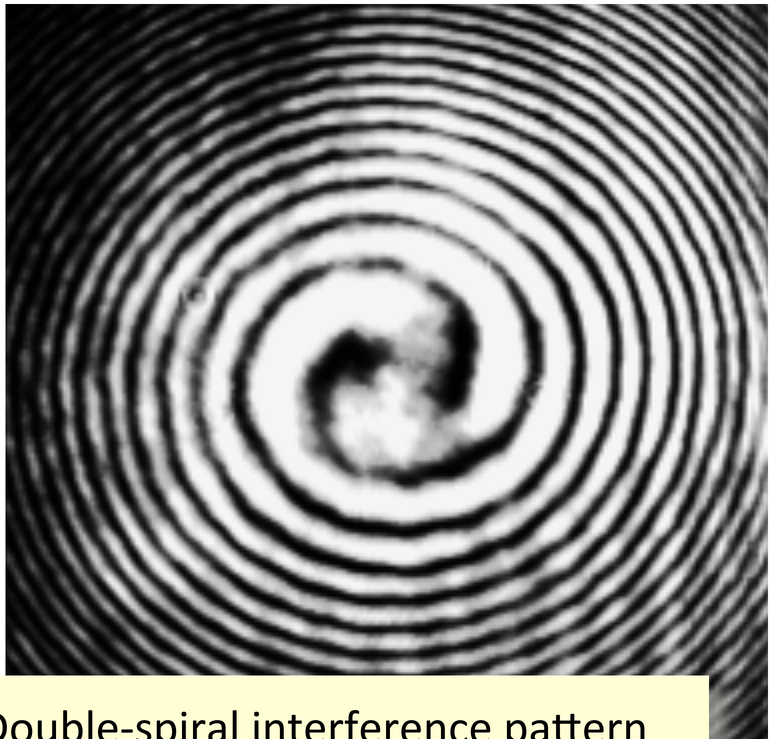


Wavefront measurement by interference:



Liquid crystal q-plate: testing the optical effect

Left-circular input



Right-circular input

Double-spiral interference pattern

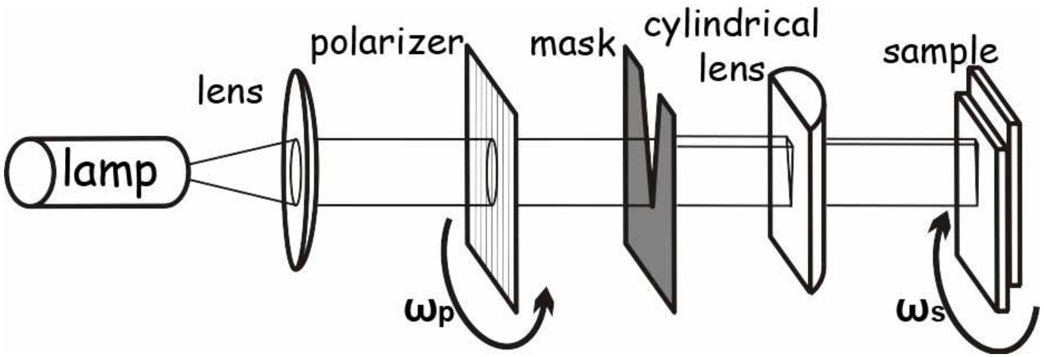
➔ Helical wavefront with $m = \pm 2$

Spiral handedness switches sign with input polarization!

These simple observations confirm the occurrence of SAM – OAM conversion

Making a liquid crystal q-plate

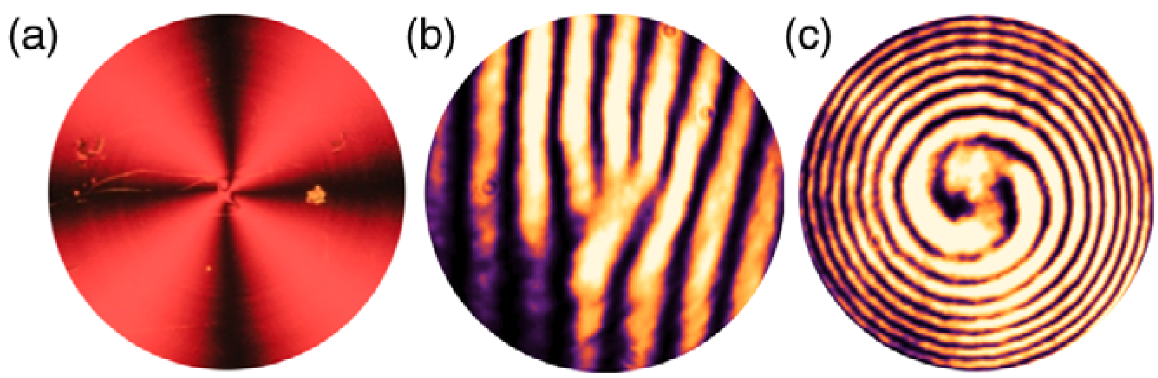
A better method: optical writing of the liquid crystal pattern



Photosensitive surface layers (e.g., azo-polymers)

Resulting q-plates have better optical quality:

$q = 1$



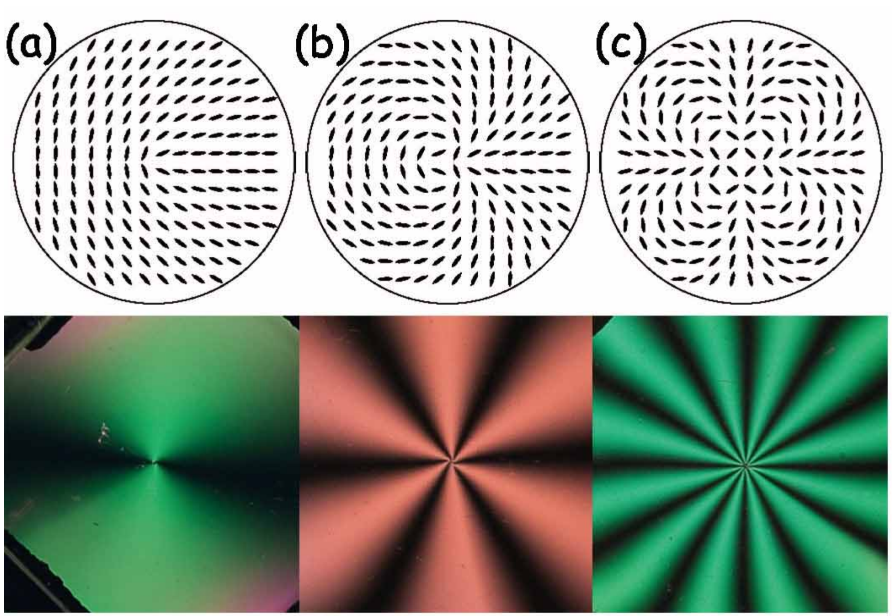
Moreover, by rotating both the polarizer and the sample…

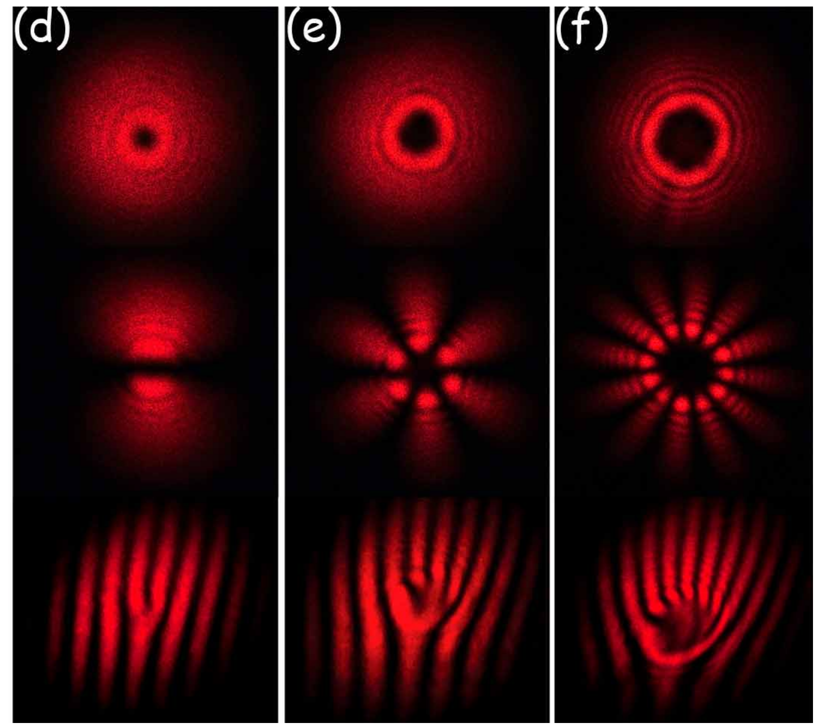
[S. Slussarenko, A. Murauski, T. Du, V. Chigrinov, L. Marrucci, E. Santamato, Opt. Express **19**, 4085-4090 (2011)]

Making a liquid crystal q-plate

We can make q-plates with arbitrary q!

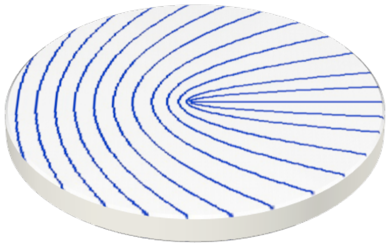
$q = 1/2$ $q = 3/2$ $q = 3$ $q = 1/2$ $q = 3/2$ $q = 3$





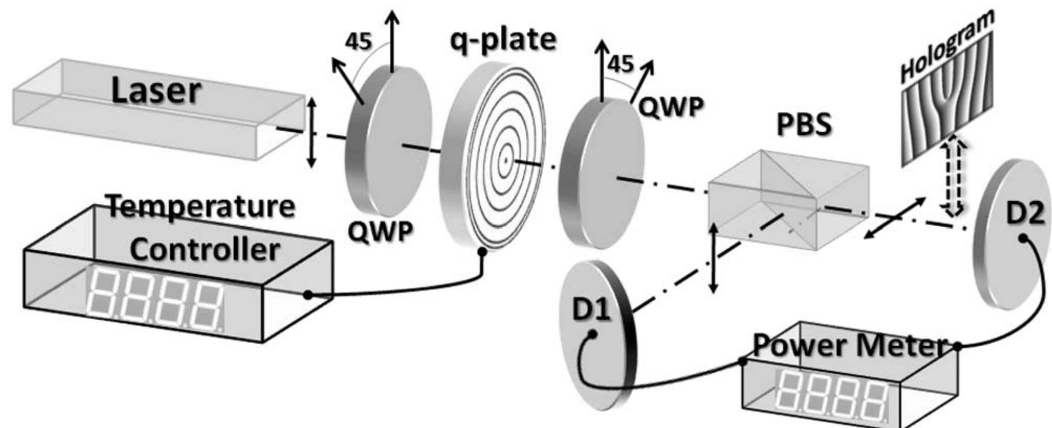
[S. Slussarenko, A. Murauski, T. Du, V. Chigrinov, L. Marrucci, E. Santamato, Opt. Express **19**, 4085-4090 (2011)]

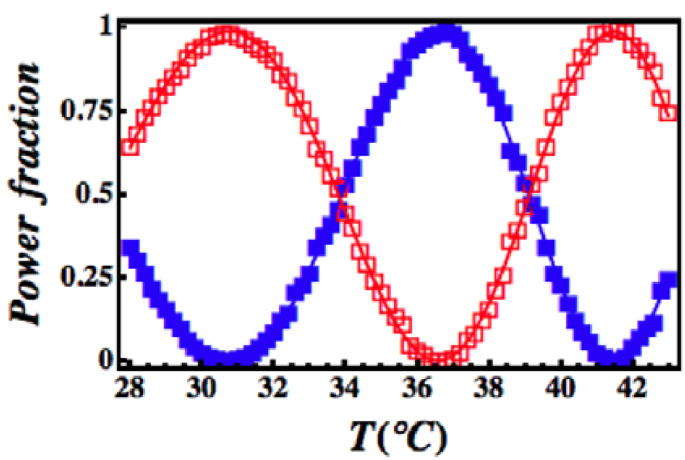
"Tuning" a liquid crystal q-plate



We need a method for controlling and adjusting the birefringence retardation δ of the q-plate

Our first demonstrated method was thermal: exploiting the material Δn(T)





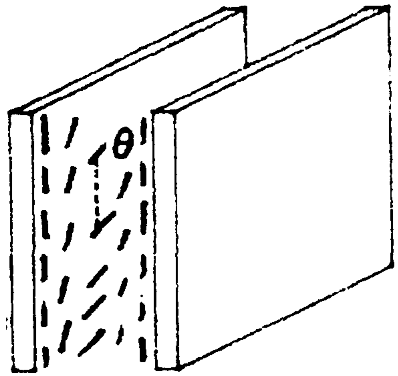
By changing δ, the converted and unconverted components of the output wave oscillate

[E. Karimi, B. Piccirillo, E. Nagali, L. Marrucci, E. Santamato, APL **94**, 231124 (2009)]

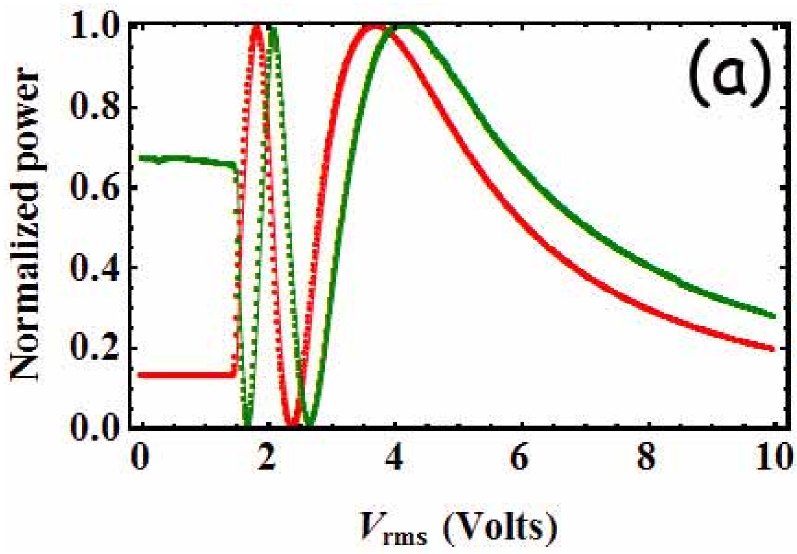
“Tuning” a liquid crystal q-plate

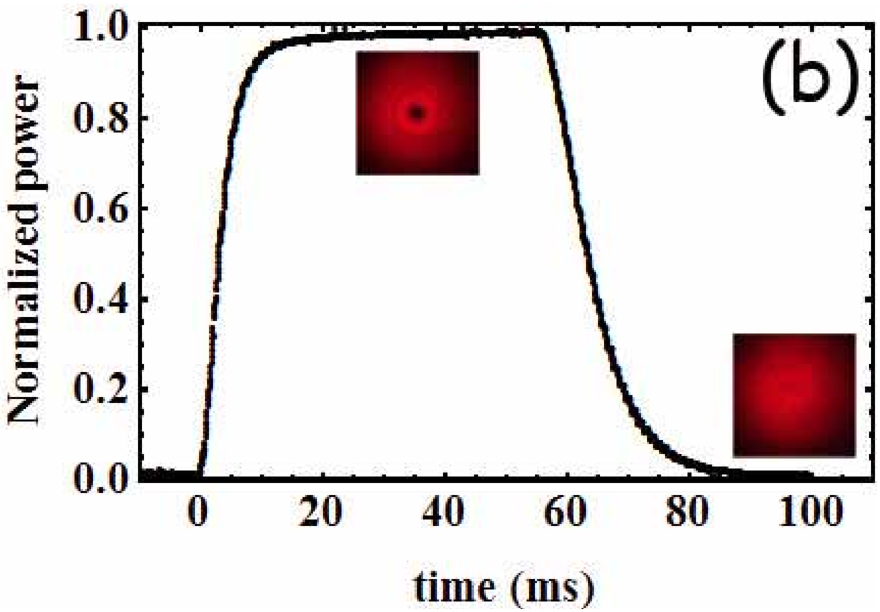
A more convenient approach:
electric tuning

The working principle is the electric-field induced reorientation of the liquid crystal molecular orientation



Electric q-plate: conversion efficiency and time response:

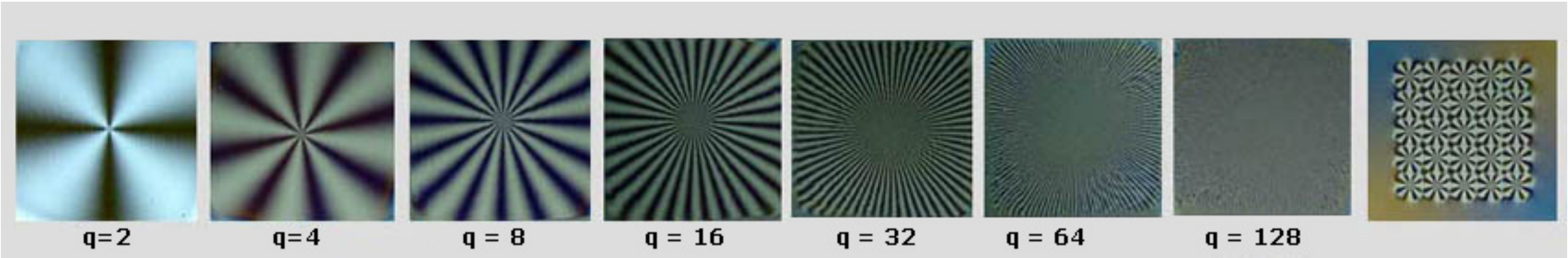




[B. Piccirillo, V. D'Ambrosio, S. Slussarenko, L. Marrucci, E. Santamato, APL **97**, 241104 (2010)]

q-plates: not only us

Liquid-crystal-polymer q-plates (diffractive waveplates) by Beam Co. (FL, USA):
[Nelson V. Tabiryan et al.]



A drawback of this polymer-only technology: not easily tunable

Concept generalization:

Pancharatnam-Berry phase optical elements (PBOE) for arbitrary wavefront shaping

[R. Bhandari, *Phys. Rep*. **281**, 1–64 (1997)]

[Z. Bomzon, G. Biener, V. Kleiner, and E. Hasman, *Opt. Lett*. **27**, 1141 (2002)]

[L. Marrucci, C. Manzo, D. Paparo, *Appl. Phys. Lett***. 88**, 221102 (2006)]

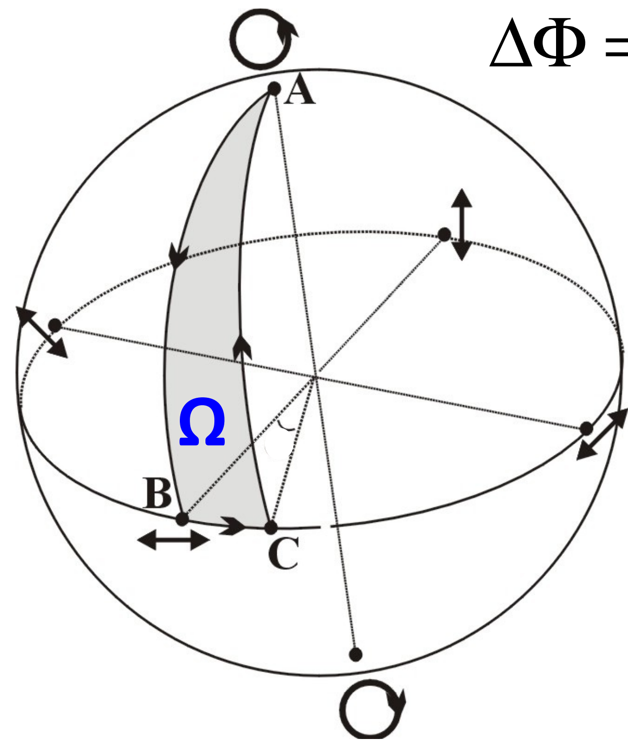
Pancharatnam-Berry geometrical phase

It is **an optical phase shift ΔΦ** that arises due to a **sequence of polarization transformations, independent of the optical path length**

ΔΦ is fixed by the geometry of the "path" in the polarization space (Poincaré sphere)

$$\Delta\Phi = \frac{\Omega}{2}$$

For a closed path, ΔΦ = **Ω / 2**, where **Ω** is the solid angle subtended by the enclosed area in the Poincaré sphere



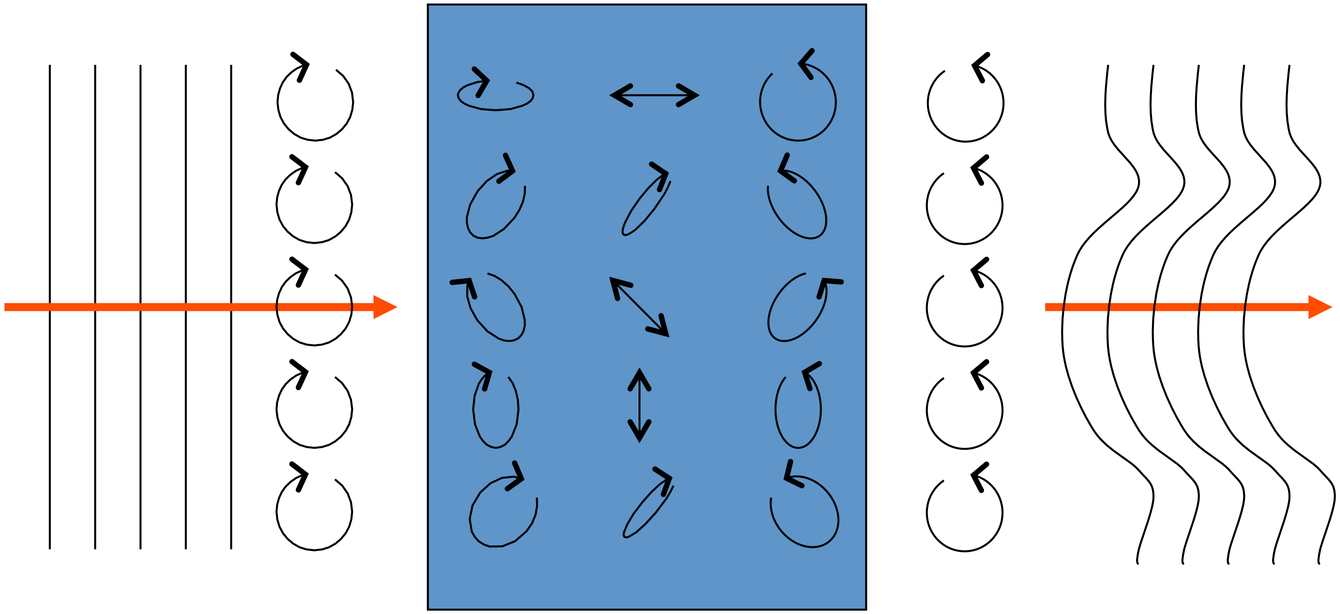
For **two different open paths sharing the same initial and final states**, ΔΦ = **Ω / 2** gives the **difference** in the acquired optical phase in the two transformations

Using Pancharatnam-Berry phase for wavefront shaping

Input wavefront (with uniform initial polarization)

Optical system inducing non-uniform polarization transformations but a uniform final polarization

Reshaped output wavefront



What kind of optical systems can be used?

Patterned half-wave plates (like "*q*-plates")

Jones matrix: $$\mathbf{M}(x,y)=\begin{bmatrix}\cos 2\alpha(x,y) & \sin 2\alpha(x,y)\\ \sin 2\alpha(x,y) & -\cos 2\alpha(x,y)\end{bmatrix}$$

Apply it to an **input left-circular** polarized plane wave:

$$\mathbf{M}(x,y)\times\begin{bmatrix}1\\ i\end{bmatrix}E_0(r,z)=\begin{bmatrix}\cos 2\alpha+i\sin 2\alpha\\ -i\cos 2\alpha+\sin 2\alpha\end{bmatrix}E_0(r,z)=\begin{bmatrix}1\\ -i\end{bmatrix}e^{i2\alpha(x,y)}E_0(r,z)$$

Wavefront acquires a **position-dependent phase retardation**

$$\Delta\Phi(x,y)=2\alpha(x,y)$$

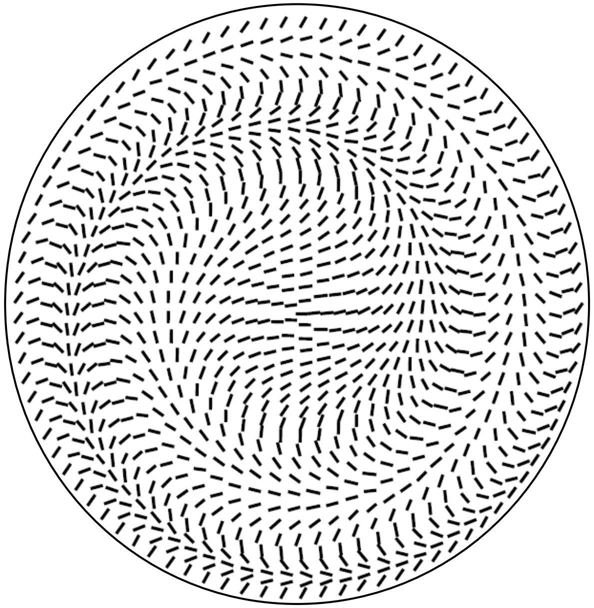
Pancharatnam-Berry geometrical phase

With suitable patterning of the plate, we may generate wavefronts of any prescribed shape

Example: a PBOE lens

Optical axis pattern:

$$\left[\alpha(r,\varphi) = cr^2 \right]$$

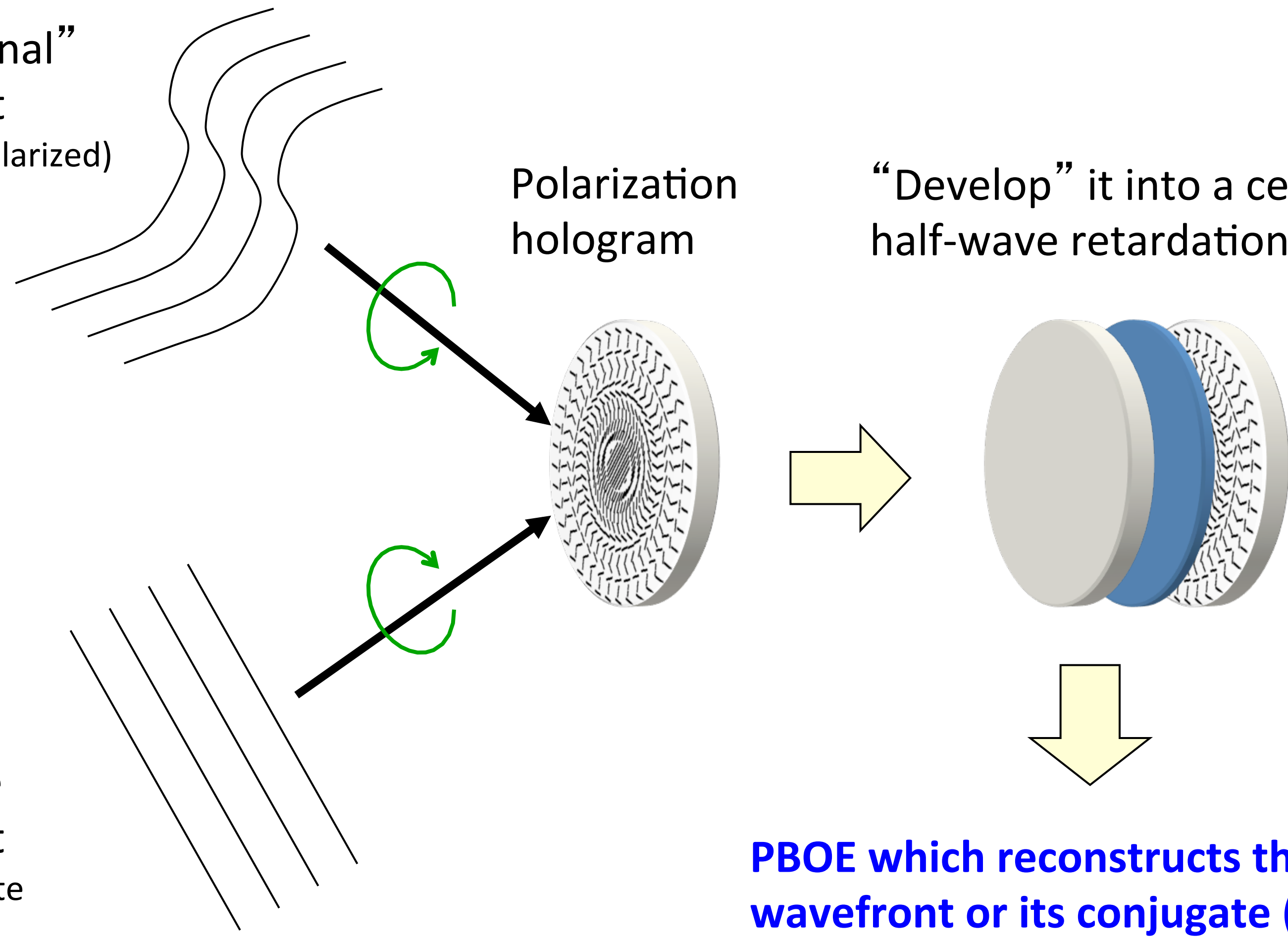


This pattern could be made with computer-controlled micro-rubbing or photo-alignment

This lens will be focusing or defocusing depending on the input circular polarization handedness: **fast polarization multiplexing**

The lens **thickness will be uniform and very thin** (few microns). Similar to Fresnel lens, but without optical discontinuities

PBOE and polarization holography

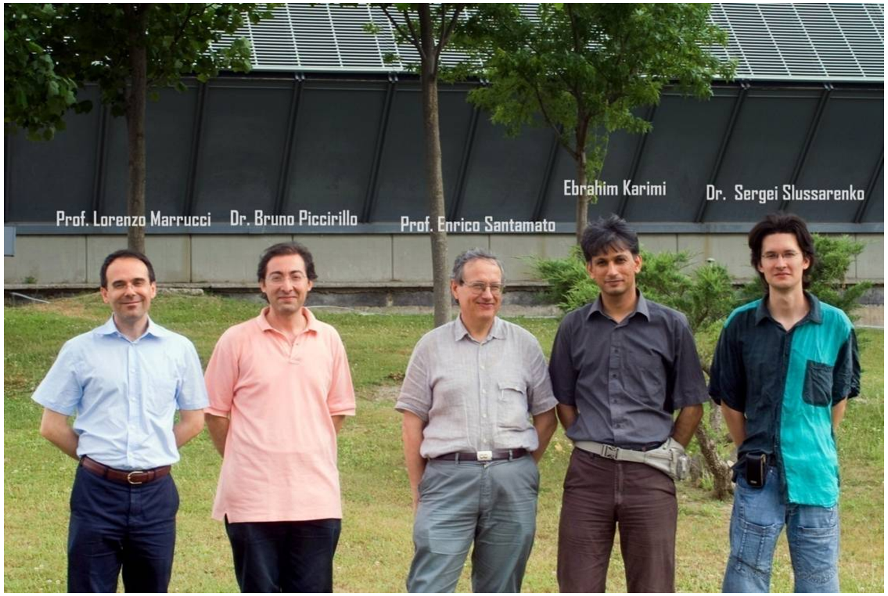


PBOE which reconstructs the signal wavefront or its conjugate (with 100% efficiency, single order output)

Acknowledgments

Coworkers of first works on SAM-OAM conversion:

Current coworkers:



Current sponsor:

SEVENTH FRAMEWORK PROGRAMME

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