High-Capacity, Free-Space Quantum Key Distribution Based on Spatial and Polarization Encoding

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

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PAPER

High-dimensional quantum cryptography with twisted light

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Simulating thick atmospheric turbulence in the lab with application to orbital angular momentum communication

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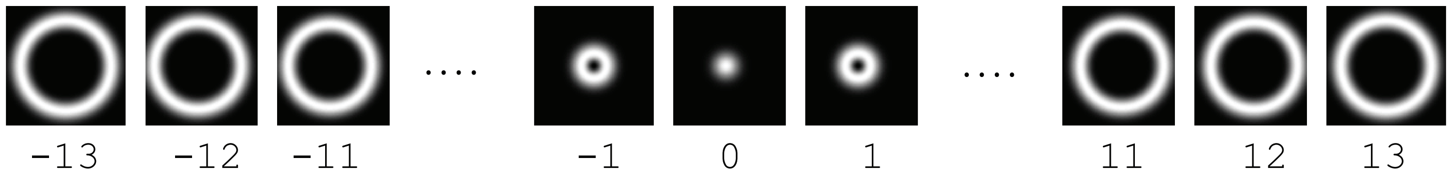
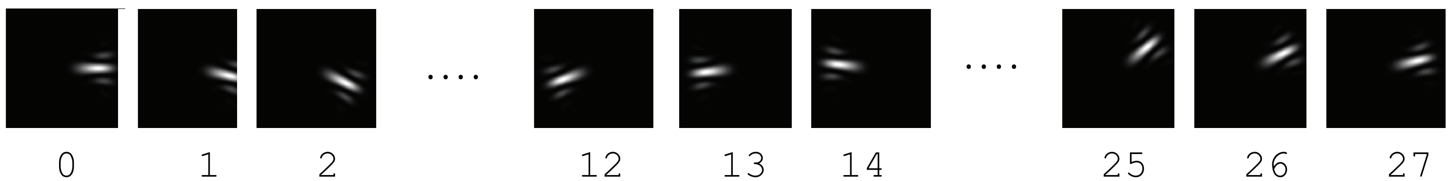
The OAM-QKD Concept

- We encode randomly in one of two mutually unbiased bases

Laguerre-Gaussian Basis

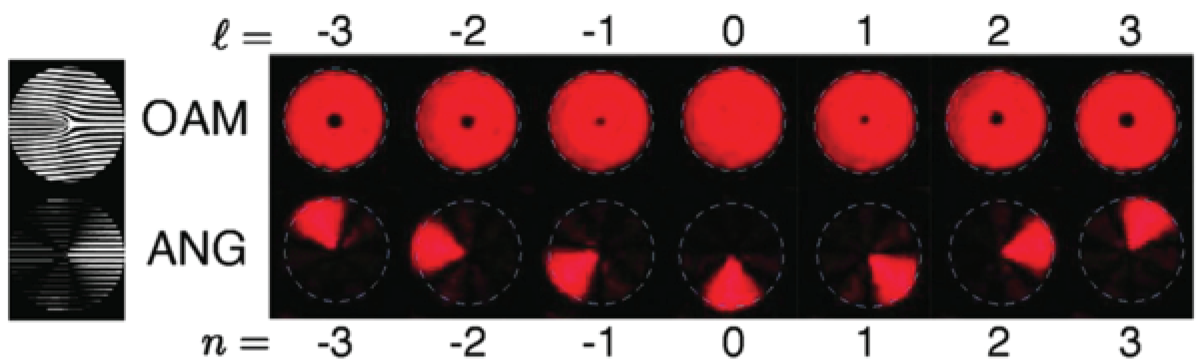


"Angular" Basis: linear combination of LG states (mutually unbiased with respect to LG)



$$\Psi_{\mathrm{AB}}^{N} = \frac{1}{\sqrt{27}} \sum_{l=-13}^{13} \mathrm{LG}_{l,0} \exp\left(i2\pi N l/27\right)$$

- Our actual implementation (N=7)

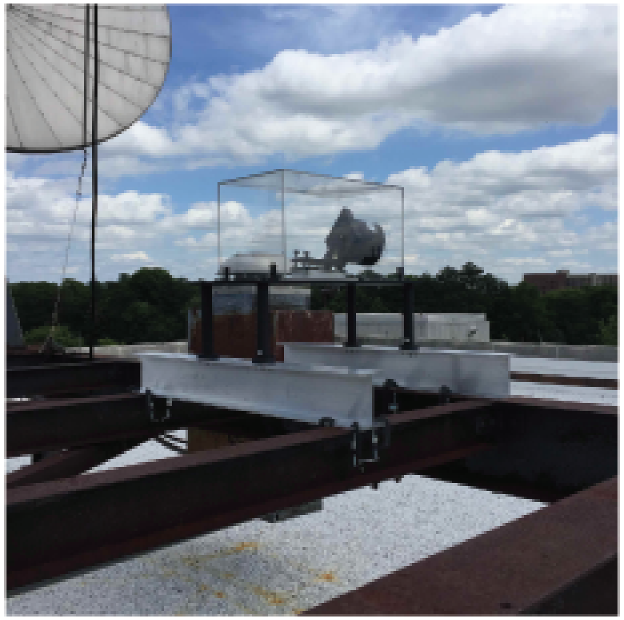


New Journal of Physics 17, 033033 (2015)

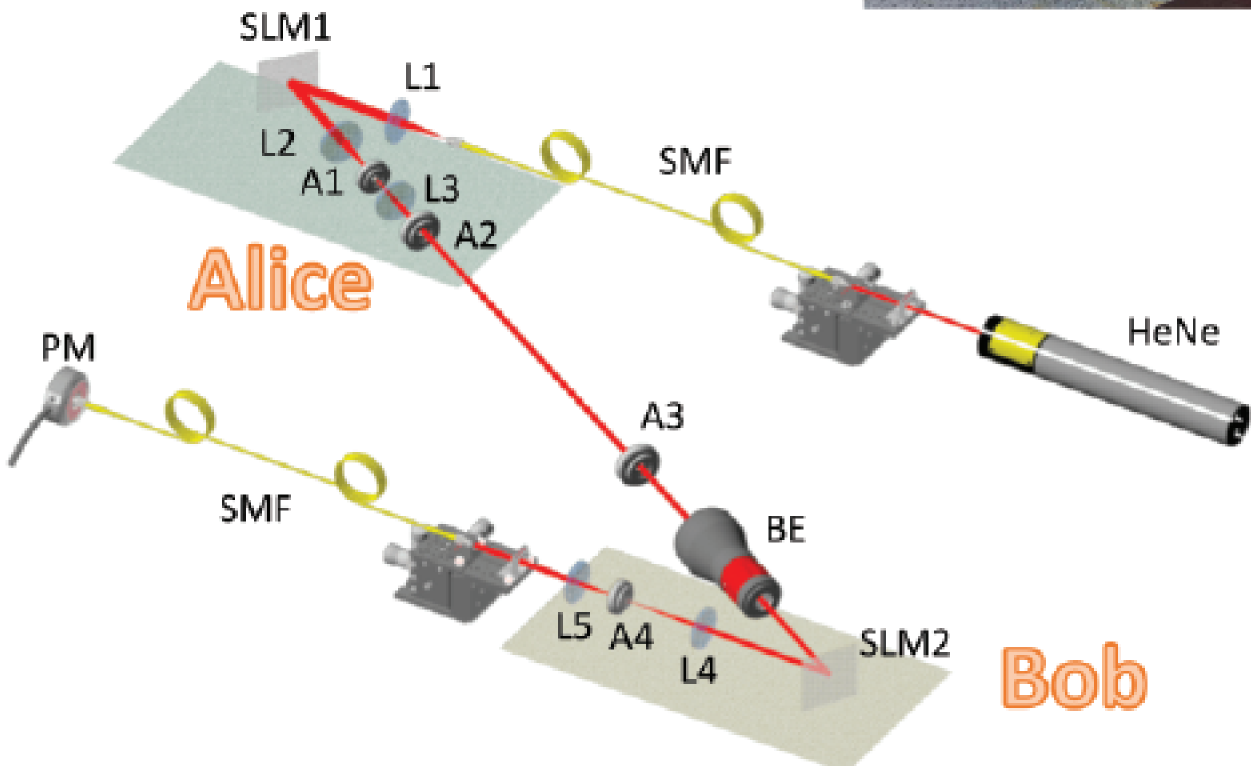
We Have Constructed Two Free-Space Links in Rochester

- Outdoor, between the Optics and Physics Buildings
  Total propagation distance ~ 350 meters
  Diameter of the sending aperture: 7.62 cm
  Diameter of the receiving aperture: 1.81 cm
  Fresnel Number : 4.89

- Indoor, inside the Optics Building
  Propagation distance = 3.1 meters
  Diameter of the sending aperture: 0.3 cm
  Diameter of the receiving aperture: 0.3 cm
  Fresnel number: 3.96



$$N_F = \frac{\pi D_1 D_2}{4L\lambda}$$

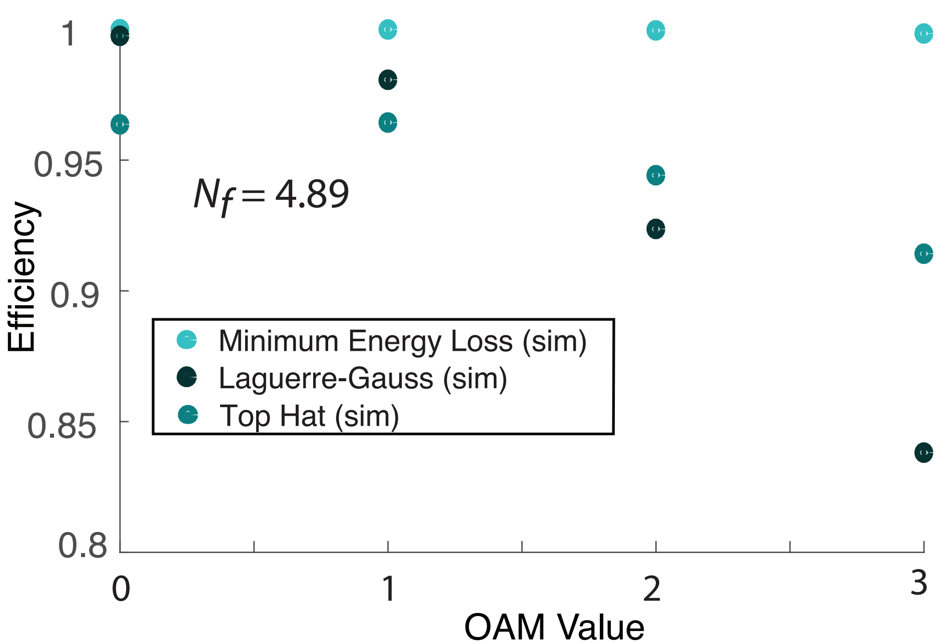


Transmission Efficiency

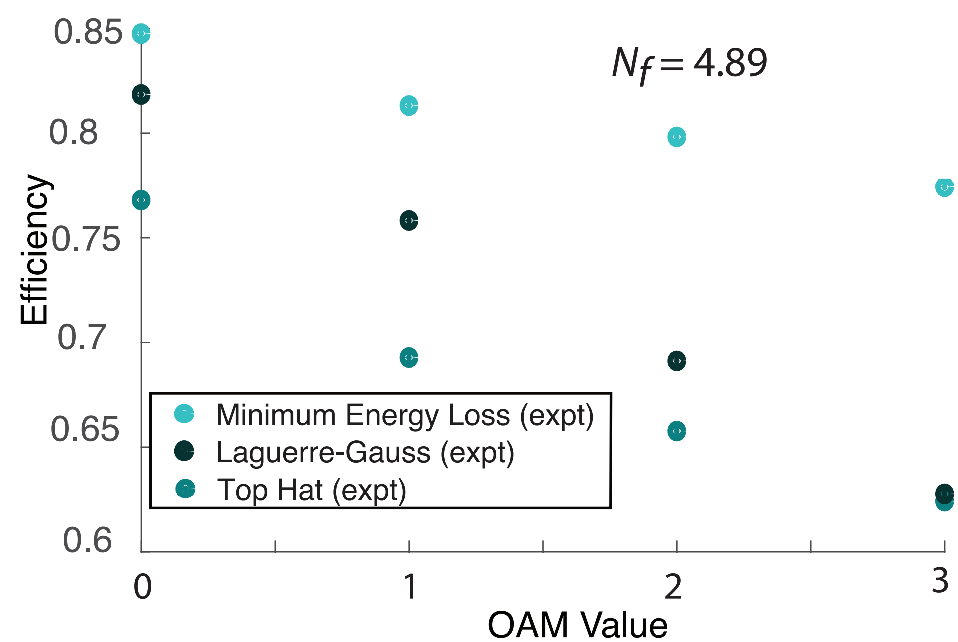
- Define efficiency as the fraction of the launched power that is received
- Different OAM modes diffract at different rates
- Minimum-energy-loss modes maximize the efficiency by using the optimum R(*r*)

> Minimum energy loss (MEL) modes satisfy the eigenvalue relation of the propagation operator H:
>
> $$H|N_f, \ell\rangle = \varepsilon_{N_f,\ell}|N_f, \ell\rangle \tag{1}$$
>
> where N_f is the Fresnel number of the system and $\varepsilon_{N_f,\ell}$ is the eigenvalue representing the efficiency associated with the mode $|N_f, \ell\rangle$.

- Simulation: No turbulence



- Measured: Outdoor link



Security Issues and OAM QKD

- Under many conditions, different OAM modes show different amounts of "loss."
- Specifically, they diffract at different rates; the received power depends on OAM value.
- Two sets of modes that are mutually unbiased at the transmitter may not remain unbiased at all propagation distances z.
- This unbiasedness comprises a security risk.
- We are studying ways to prevent this loss of unbiasedness

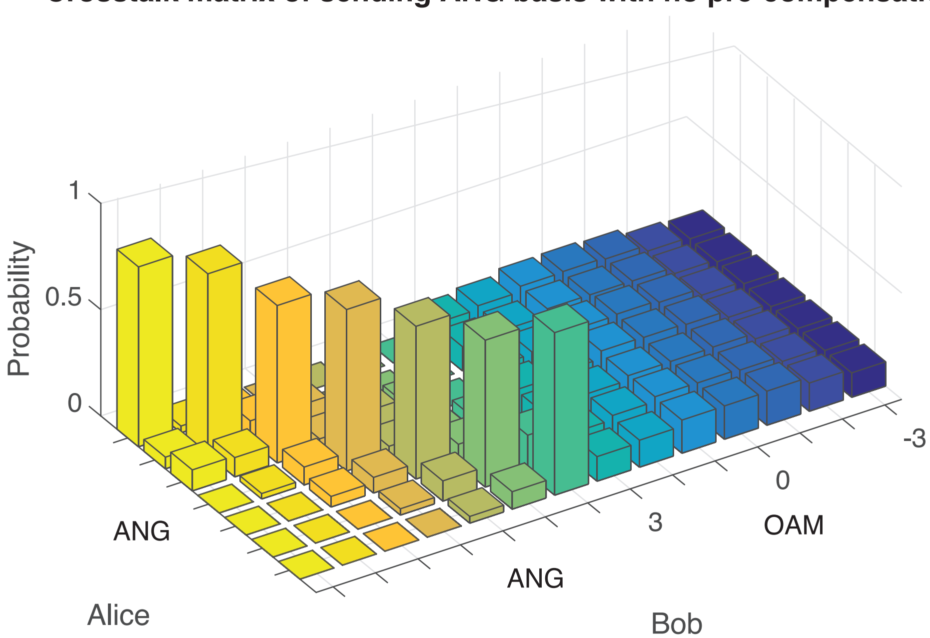
Pre-Compensation to Decrease Mode Cross Talk and Biasedness

- Instead of transmitting minimum-energy-loss modes, we transmit pre-compensated modes
- Pre-Compensation Scheme
  - Vary the beam-waist parameter w_0 for each OAM so that each mode has the same efficiency
  - Use these modes in OAM basis and to form the ANG basis

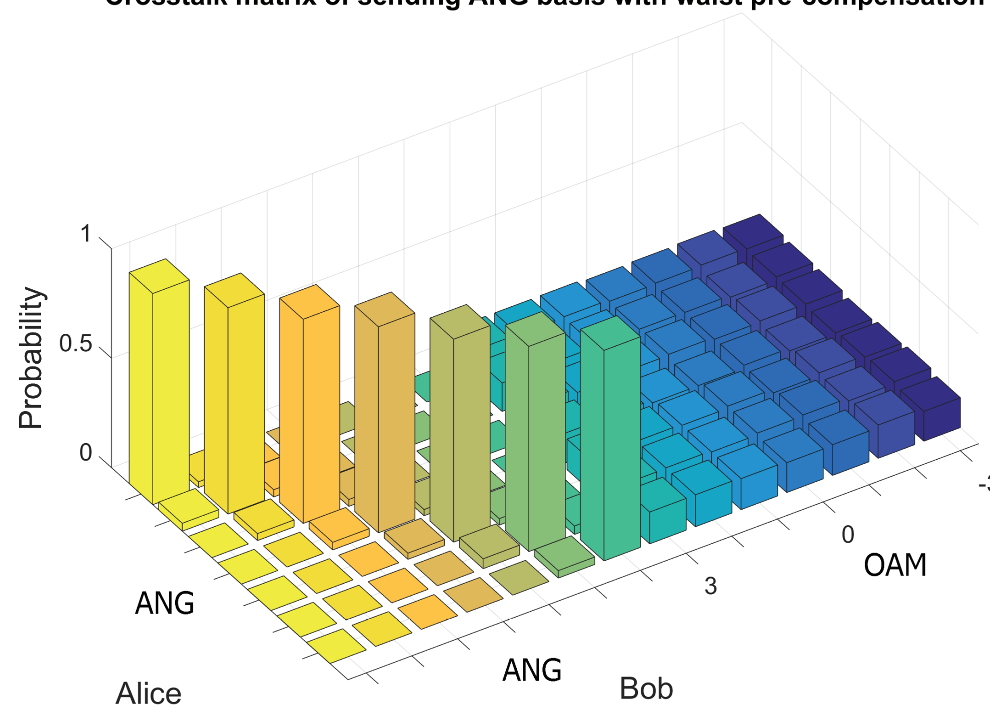
$$|j\rangle = \frac{1}{\sqrt{d}} \sum_{\ell=-L}^{L} |N_f, \ell, w_{|\ell|}\rangle e^{i2\pi j\ell/d}|$$

- Experimental results for our indoor free-space link

Crosstalk matrix of sending ANG basis with no pre-compensation



Crosstalk matrix of sending ANG basis with waist pre-compensation



Two Recent Publications

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PAPER

Orbital angular momentum modes do not increase the channel capacity in communication links

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Capacity limits of spatially multiplexed free-space communication

Ningbo Zhao[1], Xiaoying Li[1], Guifang Li[1,2*] and Joseph M. Kahn[3*]

Increasing the information capacity per unit bandwidth has been a perennial goal of scientists and engineers[1]. Multiplexing of independent degrees of freedom, such as wavelength, polarization and more recently space, has been a preferred method to increase capacity[2,3] in both radiofrequency and optical communication. Orbital angular momentum, a physical property of electromagnetic waves discovered recently[4], has been proposed as a new degree of freedom for multiplexing to achieve capacity beyond conventional multiplexing techniques[5–9], and has generated widespread and significant interest in the scientific community[10–14]. However, the capacity of orbital angular momentum multiplexing has not been established or compared to other multiplexing techniques. Here, we show that orbital angular momentum multiplexing is not an optimal technique for realizing the capacity limits of a free-space communication channel[15–17] and is outperformed by both conventional line-of-sight multi-input multi-output transmission and spatial-mode multiplexing.

between the capacity of OAM multiplexing and that of systems using conventional LOS MIMO or spatial-mode multiplexing (SMM).

To provide a framework for a fair comparison, we first define a canonical LOS system, as shown in Fig. 1a. This comprises a transmitter aperture, and a free-space transmission channel including a single thin positive lens and a receiver aperture, all circular and aligned along a common central axis. To simplify the analysis, we assume that the aperture sizes and numerical apertures (or equivalently, the antenna gains) on the transmitter and receiver sides are identical. The canonical system is low-pass in terms of transverse spatial frequencies, with maximum input angle Θ or numerical aperture NA = sinΘ and thus maximum transverse spatial frequency $k_0 \times$ NA, where $k_0 = 2\pi/\lambda$ and λ is the wavelength. The transmitter and receiver planes are confined to circles of finite radius R_0. We can therefore conveniently describe the physical resources of the LOS wireless channel by a dimensionless space–bandwidth product (SBP) $2R_0 \times 2\mathrm{NA}/\lambda$. As shown in Supplementary Section 1, this canonical single-lens system, with

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Sorting quantum systems efficiently

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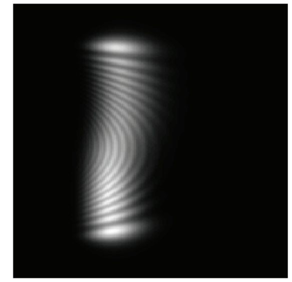
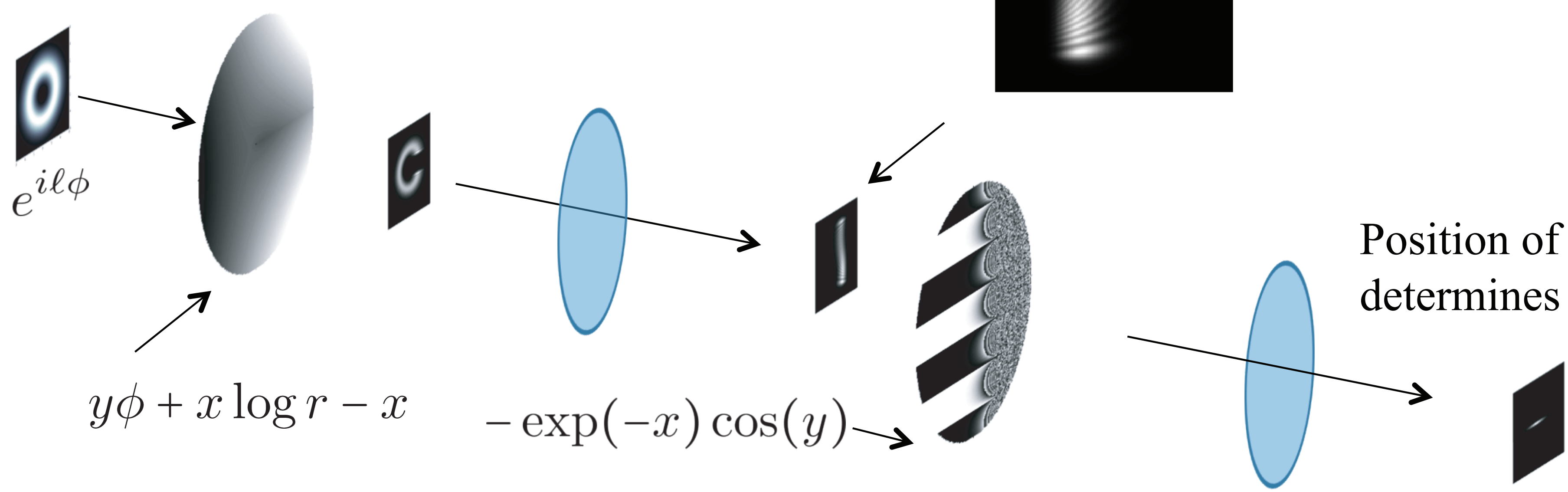
Measuring the state of a quantum system is a fundamental process in quantum mechanics and plays an essential role in quantum information and quantum technologies. One method to measure a quantum observable is to sort the system in different spatial modes according to the measured value, followed by single-particle detectors on each mode. Examples of quantum sorters are polarizing beam-splitters (PBS) – which direct photons according to their polarization – and Stern-Gerlach devices. Here we propose a general scheme to sort a quantum system according to the value of any *d*-dimensional degree of freedom, such as spin, orbital angular momentum (OAM), wavelength etc. Our scheme is universal, works at the single-particle level and has a theoretical efficiency of 100%. As an application we design an efficient OAM sorter consisting of a single multi-path interferometer which is suitable for a photonic chip implementation.

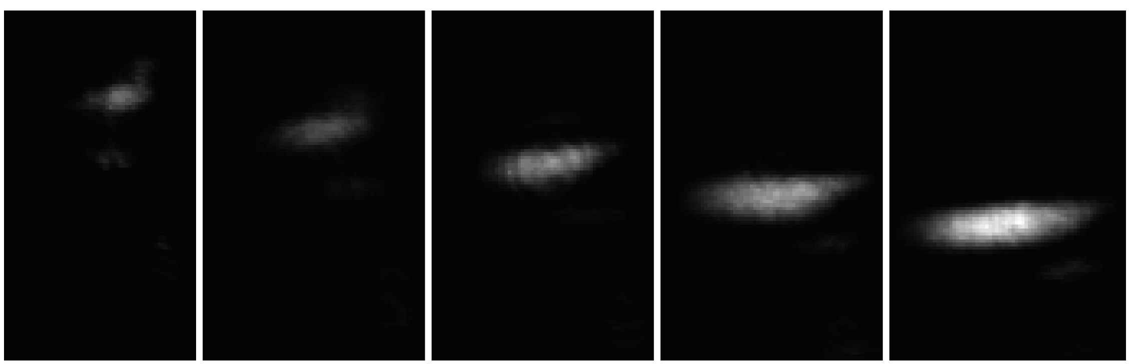
The Glasgow (Padgett) Orbital Anguar Momentum (OAM) Sorter

Optically implement the transformation $\phi \to x$





Experimental Results (CCD images in output plane)



$\ell = 1$ $\ell = 2$ $\ell = 3$ $\ell = 4$ $\ell = 5$

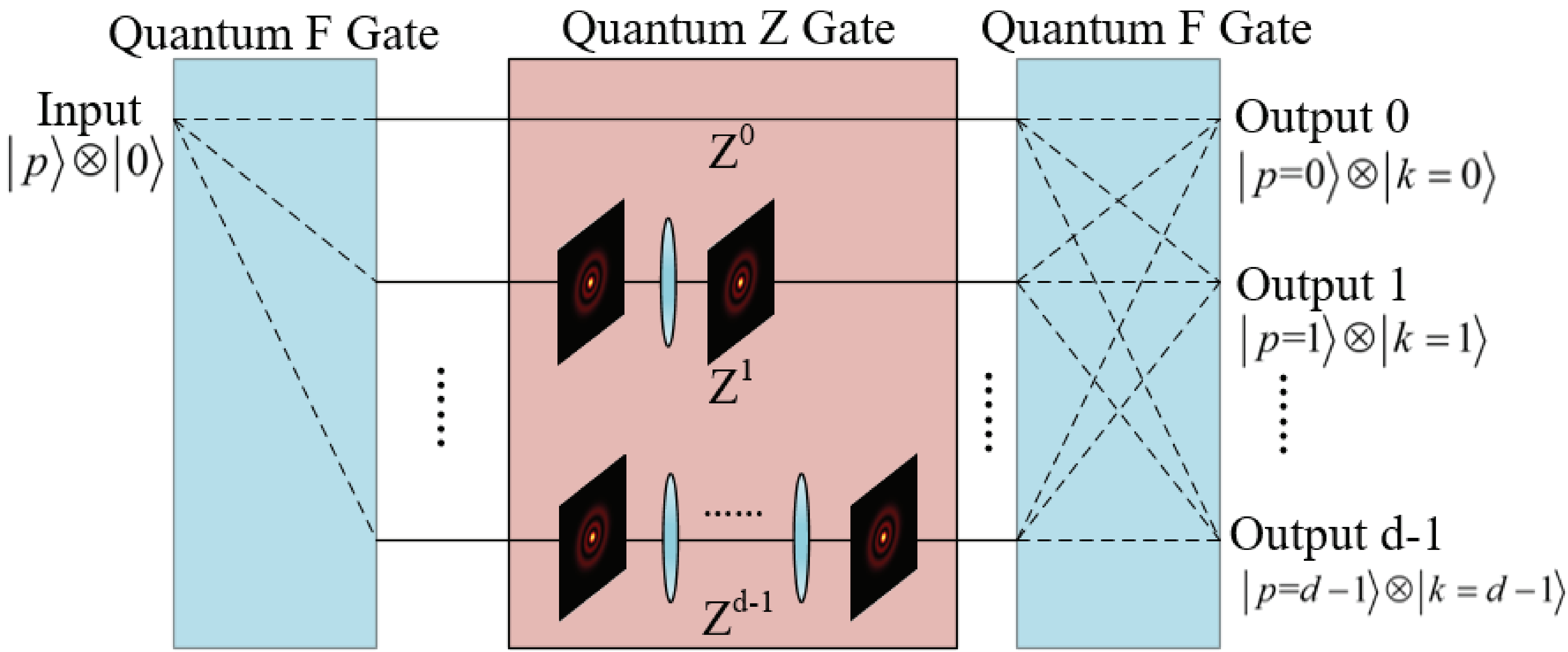
-Can also sort angular position states.

-Limited by the overlap of neighboring states.

*Berkhout *et al.* *PRL* **105,** 153601 (2010).
O. Bryngdahl, *J. Opt. Soc. Am.* **64**, 1092 (1974).

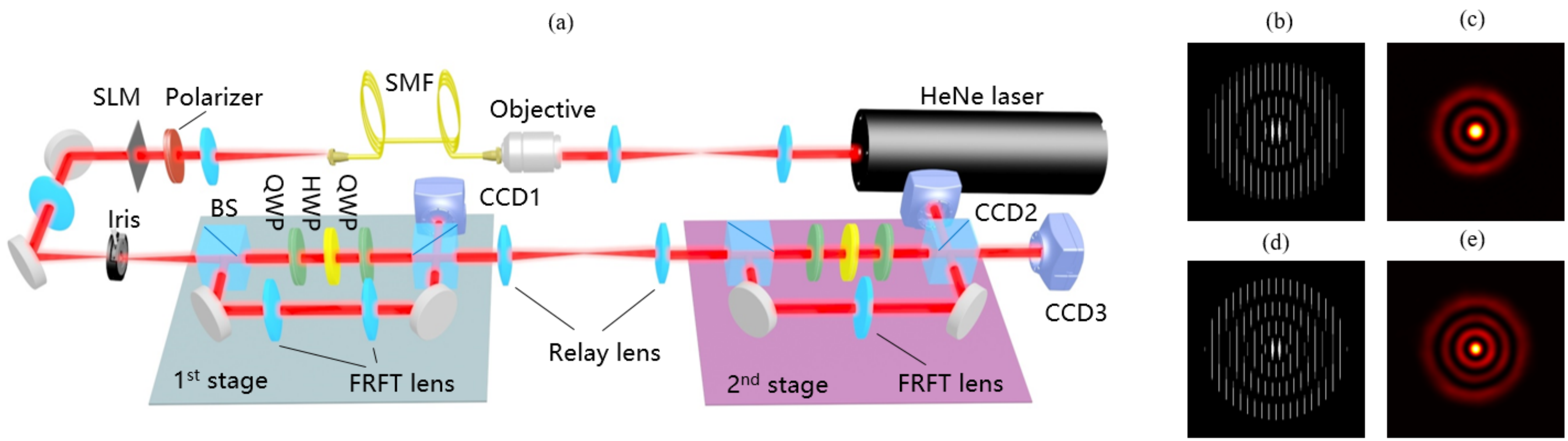
Sorting LG modes Using Fractional Fourier Transforms (FRFTs)

- Conceptual quantum circuit analog of the radial mode sorter.
- It can redirect the incident mode to corresponding output port according to the radial index p



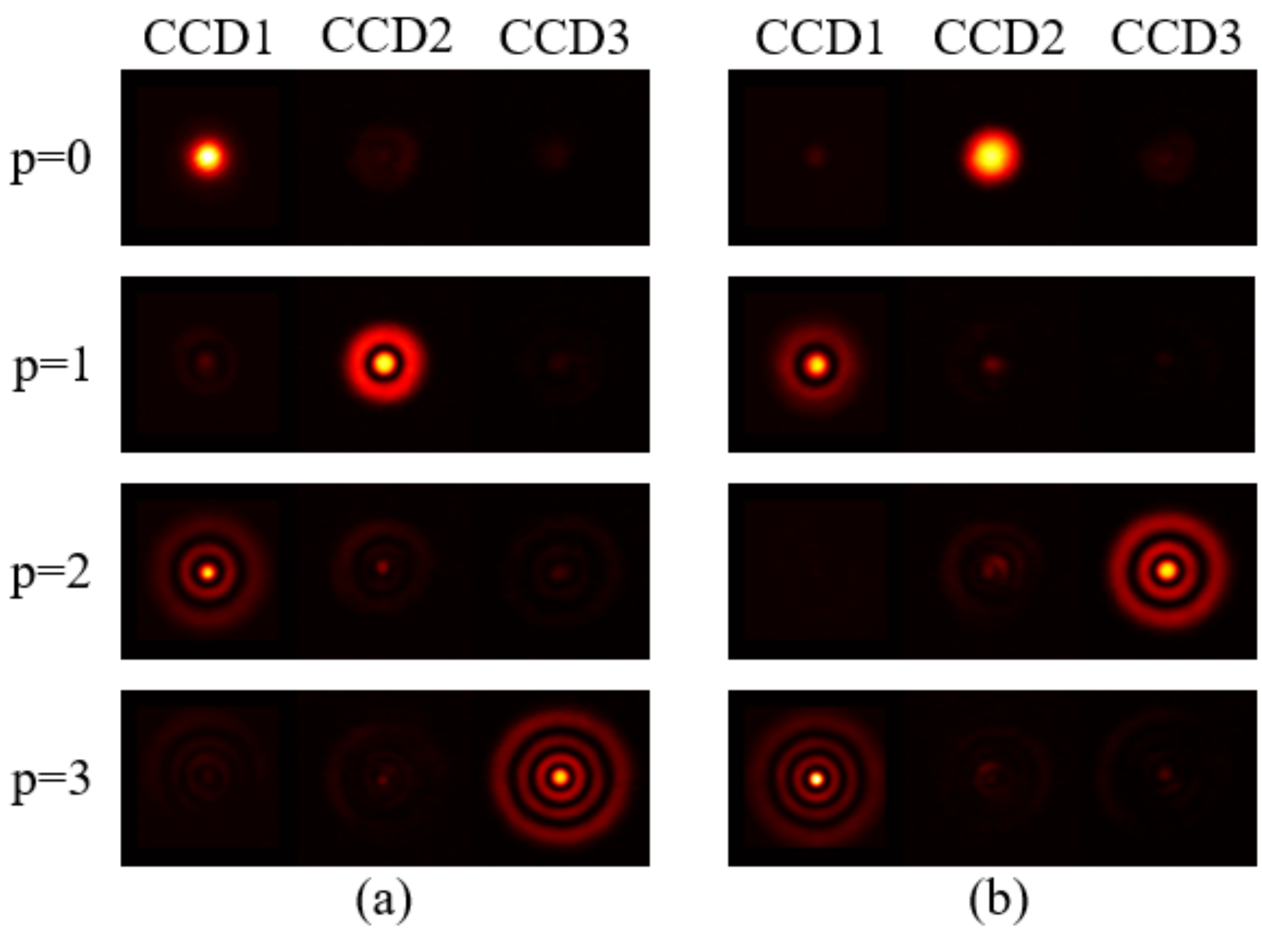
Experimental Setup

- (a) Experimental setup.
- (b) and (d) are computer generated hologram for p=2 and p=3 mode, respectively.
- (c) and (e) are experimental record of the generated p=2 and p=3 radial mode, respectively.



Sorting LG modes using FRFT

- (a) odd order modes are sorted to CCD2 and CCD3, respectively.
- (b) even order modes are sorted to CCD2 and CCD3, respectively.
- This is achieved by adjusting the phase shift in the sorter.



Sorting LG modes using FRFT

(a) Experimental results for various superposition states.
(b) the result for sorting different OAM modes.
(c) the measured crosstalk matrix.