Shaping up High-dimensional Quantum Information*

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ABSTRACT

Polarisation is a two dimensional attribute of photons. However other properties of photons, such as transverse spatial mode can serve as higher-dimensional carriers of quantum information called qudits. The quantum properties of the transverse spatial mode, or shape, were first demonstrated in 2001, adding shape to the repertoire of quantum information carriers. Qudits have advantages for quantum communication including higher information capacity, improved security against eavesdroppers and better resilience to noise.

INTRODUCTION

Information is physical. At the level of my computer hardware, the act of writing this article is a stream of bits represented as high and low voltages in the various parts of my computer. Quantum bits, or "qubits", are fundamentally different in that they follow different physical rules. For example, qubits can be in a superposition of two states. Only when the qubit is measured does it assume a definite value, which could be any of the two states in the superposition. Quantum information – theory, experiment, and technological efforts – deal mostly with qubits. The first demonstrations of entanglement in photons were based on measurements of polarisation; in terms of number of levels or dimensionality, polarisation is two-dimensional. Photons are endowed with properties that are not limited to two dimensions, such as wavelength and transverse spatial mode. Any of these properties can serve as higher-dimensional carriers of quantum information, called "qudits".

There is (so far) no perceived advantage in using qudits for quantum computation [1]. Not surprisingly, quantum computation is based mainly on qubits (e.g. the superconducting qubits of IBM and Google). However, quantum systems are naturally high-dimensional so even if there is no advantage, I do not dismiss qudit quantum computation. The advantages of qudits for quantum communication are more apparent. These include higher quantum information capacity, improved information security against eavesdroppers, better resilience to noise and imperfect randomness, simplified quantum logic, and more efficient quantum computation for some very specific tasks [2]. Despite these advantages qudit quantum information lags behind qubit quantum information, because it is naturally more difficult to generate, manipulate, and measure qudits. It is in this last aspect, particularly in measuring qudits encoded in the transverse spatial mode of light, that I and colleagues have made significant progress in recent years.

SHAPE OF SINGLE PHOTONS

The first demonstration of the quantum properties of the transverse spatial mode, or shape, of single photons was achieved in 2001 by Anton Zeilinger's group at the University of Vienna [3]. They showed quantum correlations in the orbital angular momentum (OAM) of single photons produced from spontaneous parametric down-conversion (a nonlinear process in which two daughter photons are produced from a higher energy pump pho-

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ton). The OAM of light, manifested in beams with helical phasefronts like the Laguerre-Gaussian (LG) beams, are routinely generated for micromanipulation experiments but has not been measured in single photons previously. This work [3] added shape to the repertoire of quantum information carriers. For example, Figure 1 shows how we used the shape of light to encode a 2-dit string [4]. In [3], the authors used computer-generated fixed holograms – a device already widely used for transforming light in the fundamental Gaussian mode into different shapes that can then be used for purposes like micromanipulation, imaging, and microscopy. In hindsight, the use of these holograms to measure the shape of single photons is rather intuitive: optics also works in reverse. Single-photon detectors are usually coupled to single-mode fibres that accept only the fundamental Gaussian mode. One can then use the same hologram for measurement, to transform an incoming beam into the fundamental Gaussian mode that can then be coupled to the fibre connected to the single-photon detector (see Figure 2). However, using fixed holograms is not practical, especially when a greater number of states need to be measured – a new hologram needs to be created and the experiment re-aligned for every measurement.

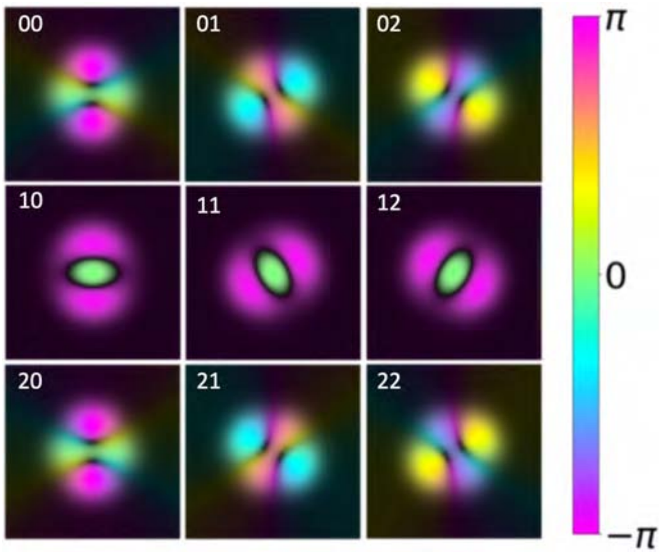

Fig. 1: A string y_0y_1, where y_0 and y_1 can take on any of 3 values, e.g. {0,1,2}; this can be represented by 9 different shapes of light. These shapes can also be measured in single photons. (Figure after [4])

MAKING SHAPE ACCESSIBLE

It is in this problem of making the shape of single photons a practically accessible degree of freedom that I, together with colleagues at the University of Glasgow, made my contribution.

But first, some background about me: When I was 15, I heard my physics teacher say that he hates quantum physics. I was curious and quickly googled what quantum physics is – I have been hooked ever since! However, the beginning of my research career was definitely not in quantum physics. At the University of the Philippines, I joined an Optics group as part of my degrees. For my Master's, I learnt how to tailor beams by using spatial light modulators (SLMs), for use in microscopy and microfabrication. The SLMs are like liquid crystal displays that impart a programmable phase to an incoming beam. For example, they can impart a helical phase like those needed for beams carrying OAM. These SLMs are a powerful device that can generate beams of different shapes. My aspiration to work in the field of quantum physics has grown over time, and it is with the SLMs that I saw an opportunity to enter the quantum physics field.

Fortuitously, in 2007 I read a paper from University of Glasgow's Optics Group, which at that time was known for optical tweezers, a technique heavily reliant on SLMs. They re-created the 2001 results of Zeilinger's group using SLMs [5]. I was greatly excited by this and I quickly contacted the group. Prof Miles Padgett, one of the authors of the paper, eventually became my PhD supervisor. In 2008, I moved to Scotland and spent the next seven years in Glasgow measuring the shape of single photons. My research made this tedious task significantly easier by employing programmable holograms encoded in SLMs. This simple technological step of replacing a fixed hologram with an SLM has made arbitrary projective measurements of shape in single photons more versatile. With this technique, we have demonstrated differences between classical and quantum physics via Bell inequalities [6], Leggett inequalities [7] and the Einstein-Podolsky-Rosen paradox [8]. Other groups have also shown qudit quantum key distribution and quantum imaging [2].

Towards the end of my PhD, I visited Zeilinger's group at the University of Vienna: it was almost surreal to see a technique that I dreamt of as a Master's student being used by the group that (in my mind) started the field. The number of groups pursuing qudit quantum information using the shape of light has also grown over the years and I am very proud that my work has enabled these developments.

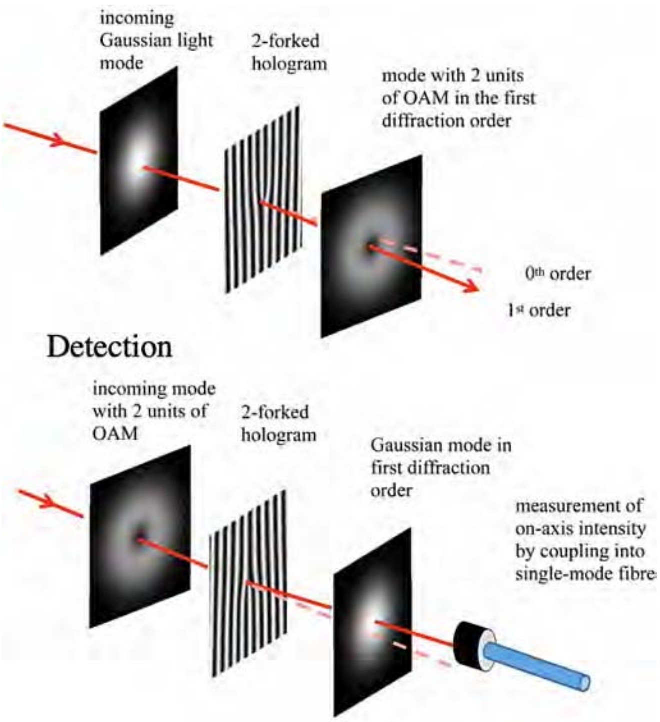

Fig. 2: A shaped beam, like one with 2 units of OAM can be generated by a forked hologram. The first order beam will be doughnut-shaped, as shown. For detection, the same hologram be used to transform an incoming doughnut-shaped beam into a fundamental Gaussian mode that can be coupled to a single-mode fibre connected to a single-photon detector.

A RICH PLAYGROUND

More than ten years since I started working in this field, I still find qudit quantum information a rich playground, from both foundational and technological perspectives. Two-dimensional and higher-dimensional Hilbert spaces are mathematically different; how the differences manifest in experiments, and how that translates in terms of advantage for quantum information tasks are questions that excite me. Applications related to communication are also promising, possibly providing provably secure, high-capacity options for transmitting information. Historically the field has benefitted from simple technological progress that enabled more dialog between experimentalists and theorists. The way forward will entail nothing less and I certainly hope I will contribute towards extending our present capabilities!

References

[1] M. A. Nielsen and I. Chuang, C.K. Jones, Quantum Computation and Quantum Information, Cambridge University Press, 2010.
[2] M. Erhard, R. Fickler, M. Krenn, and A. Zeilinger, "Twisted photons: new perspectives in high dimensions", Light: Science and Applications., 7, 17146 (2018).
[3] A. Mair, A. Vaziri, G. Weihs, and A. Zeilinger, "Entanglement of the orbital angular momentum states of photons", Nature, 412, 313 (2001).
[4] M. Kewming, S. Shrapnel, A. G. White, and J. Romero, "The advantages of ignorance", arXiv:1903.09487 (2019).
[5] E. Yao, S. Franke-Arnold, J. Courtial, M. J. Padgett and S. M. Barnett, "Observation of quantum entanglement using spatial light modulators", Optics Express, 14, 13089 (2006).
[6] J. Romero, J. Leach, B. Jack, M. R. Dennis, S. Franke-Arnold, S. M Barnett, and M. J. Padgett, "Entangled optical vortex links", Physical Review Letters, 108, 100407 (2011).
[7] J. Romero, J. Leach, B. Jack, S. M. Barnett, M. J. Padgett, and S. Franke-Arnold, "Violation of Leggett inequalities in orbital angular momentum spaces", New Journal of Physics, 12, 123007 (2010).
[8] J. Leach, B. Jack, J. Romero, A. K. Jha, A. M. Yao, S. Franke-Arnold, D. G. Ireland, R. W. Boyd, S. M. Barnett, and M. J. Padgett, "Quantum correlations in optical angle--orbital angular momentum variables", Science, 329, 662 (2010).

Dr **Jacquiline Romero** was born in Manila. She holds BS Applied Physics magna cum laude and MS Physics degrees from the University of the Philippines. She finished her PhD at the University of Glasgow, where she was a researcher for seven years. In 2015, she moved to Brisbane to join the Quantum Technology Group at the University of Queensland (UQ). In 2016 she took up an Australian Research Council Discovery Early Career Researcher Award with the same group. She is currently a Senior Lecturer and Westpac Bicentennial Foundation Research Fellow at UQ, and continues her mission to extend quantum information using the transverse shape of light. Dr Romero was awarded the 2018 Ruby-Payne Scott Medal by the Australian Institute of Physics in recognition of her outstanding work as an early career researcher "For her outstanding contribution to the fields of optics and quantum physics, in particular for establishing the shape of light as a degree of freedom for encoding quantum information."