The Resurgence of the Linear Optics Interferometer — Recent Advances & Applications

Si-Hui Tan[1,*] and Peter P. Rohde[2,†]
[1]*Singapore University of Technology and Design, 8 Somapah Road, Singapore*
[2]*Centre for Quantum Software & Information (CQSI), Faculty of Engineering & Information Technology, University of Technology Sydney, NSW 2007, Australia*

(Dated: April 14, 2017)

Contents

I. INTRODUCTION

Si-Hui can colour code things she adds like this
And Peter can do it like this

Let's add comments and questions like this

Technical advancements have been made on many fronts. It is possible now to put single-photon sources and linear-optical networks on a silica chip. The advantage of using such integrated photonics over bulk optics is that it is more stable against phase fluctuations, and miniaturized. This increases the scalability of optical implementations of quantum information protocols.

II. MATHEMATICAL BACKGROUND

Mathematical representation for LO networks, and very basic background on quantum optics

A idealized single photon in a quantum interferometer is described by its creation operator $\hat{a}_j^\dagger$, where j is the label of the mode the photon is in within the interferometer. The creation and annihilation operators satisfy the bosonic comutator relationship $[\hat{a}_j, \hat{a}_k^\dagger] = \delta_{j,k}$. A similar commutator relationship can be written up when more degrees of freedom, such as polarization, orbital angular momentum, and time-bins (Tillmann et al., 2015; Bozinovic et al., 2013; Nicolas et al., 2014; Humphreys et al., 2013; Donohue et al., 2013), are present. When multiple photons are present, they experience quantum interference when all quantum labels are the same.

The action of a $2d$-port linear optical interferometer (with an equal number of input and output ports) is expressed as an application of unitary operations on the creation operators,

$$b_i^\dagger = \sum_{j=1}^{d} U_{ij} a_j^\dagger \ , \tag{1}$$

where $a_j^\dagger$ and $b_i^\dagger$ are the creation operators of a single input and output photon in the j-th and i-th modes respectively, and $U \in SU(d)$. All such transformation can be expressed as sequence of beamsplitters and waveplates (Reck et al., 1994). In the case when photons have additional labels, for instance, if they have internal labels on top of spatial labels, it is also possible to derive an analogous decomposition, known as a cosine-sine decomposition (Dhand and Goyal, 2015), that realizes the unitary transformation on the photons into a sequence of

*sihui_tan@sutd.edu.sg
†dr.rohde@gmail.com; URL: http://www.peterrohde.org

beamsplitters and internal transformations. Toolkits using group theory are being developed to deal with partial distinguishabilities among interfering photons (Tan et al., 2013; de Guise et al., 2014, 2016). Others use quantum-to-classical transitions to explain multiparticle interference (Ra et al., 2013). Experimental implementation [Walmsley, Jennewein]

III. OPTICAL ENCODING OF QUANTUM INFORMATION ON SINGLE-PHOTONS

1. Polarisation

2. Dual-rail

3. Time-bins

IV. EFFICIENT CIRCUIT DECOMPOSITIONS OF LINEAR OPTICS NETWORKS

Discuss the Reck et al. decomposition

The task of implementing an arbitrary quantum computation on linear optics comes down to implementing an arbitrary $n \times n$ unitary matrix. If a non-unitary transformation is desired, it can be embedded within a unitary matrix with larger dimensions. An algorithm for expressing an arbitrary unitary matrix *exactly* in terms of a sequence of $\mathcal{O}(n^2)$ beamsplitters and phase-shifters exists (Reck et al., 1994). Alternatively, Mach-Zedner interferometer can also be used as building blocks instead of beamsplitters and phase shifters (Reck et al., 1994; Englert et al., 2001). Later, it has been shown that any nontrivial beam splitter, that does more than swapping modes around or add phases to them, is universal for linear optics (Bouland and Aaronson, 2014). However, they do not provide a construction for arbitrary unitaries.

If the linear optical transformations can be realized on various degrees of freedom of light, then it is possible to realize a $n \times n$ arbitrary unitary transformation, where $n = n_s n_p$ for n_s spatial modes, and n_p internal modes, by a sequence of $\mathcal{O}(n_s^2 n_p)$ beamsplitters and $\mathcal{O}(n_s^2)$ internal transformations (Dhand and Goyal, 2015). Their approach reduces the required number of beamsplitters but increases the total number of optical elements needed increases by a factor of 2.

V. RECONSTRUCTING THE LINEAR OPTICAL NETWORK

Discuss the role of quantum tomography here. Algorithms using O'Brien and Laing, Schaffner and Tillmann–using single-photon, and two-photon inputs to reconstruct the Euler angles of the circuit. Others using coherent-state inputs which has a lower requirement on the state-preparation side.

In many practical situations, the structure of a linear optical device in terms of its constituent beamsplitters and phase shifters is known once it is built. However, owing to manufacturing imperfections, a precise characterization of these devices is still needed post-production. One of the ways, this can be done is via a quantum process tomography (Mitchell et al., 2003; O'Brien et al., 2004; Lobino et al., 2008; Rahimi-Keshari et al., 2011) . However, quantum process tomography is an expensive method in terms of number of measurements required to characterize the network, and it becomes impractical for large optical networks which can be as large as 900 modes (check citations for number of modes).

VI. EXPERIMENTAL IMPLEMENTATION

A. State preparation

Cat state–Schoelkopf group

1. Single-photons

2. Bell pairs

3. Coherent states

4. Squeezed states

B. Linear optics networks

1. Bulk-optics

2. Waveguides

3. Time-bins

Discuss fibre-loop architecture

C. Measurement

1. Photodetection

Discuss number-resolved and bucket detectors, multiplexed detection, APDs, current micropillar detectors

2. Homodyning

VII. APPLICATIONS FOR LINEAR OPTICS INTERFEROMETRY

A. Linear optics quantum computation

B. Boson-sampling

C. Quantum metrology

Discuss NOON states - Heisenberg limited
Discuss MORDOR scheme

D. Encrypted quantum computation

VIII. STATE OF THE ART

Discuss where experiments are at at the moment

IX. CONCLUSION

Acknowledgments

P.P.R. is funded by an ARC Future Fellowship (project FT160100397).

References

M. Tillmann, S.-H. Tan, S. E. Stoeckl, B. C. Sanders, H. de Guise, R. Heilmann, S. Nolte, A. Szameit, and P. Walther, Phys. Rev. X **5**, 041015 (2015), URL http://link.aps.org/doi/10.1103/PhysRevX.5.041015.

N. Bozinovic, Y. Yue, Y. Ren, M. Tur, P. Kristensen, H. Huang, A. Willner, and S. Ramachandran, Science **340**, 1545 (2013).

A. Nicolas, L. Veissier, L. Giner, E. Giacobino, D. Maxein, and J. Laurat, Nat. Photonics **8**, 234 (2014).

P. C. Humphreys, B. J. Metcalf, J. B. Spring, M. Moore, X.-M. Jin, M. Barbieri, W. S. Kolthammer, and I. A. Walmsley, Phys. Rev. Lett. **111**, 150501 (2013), URL http://link.aps.org/doi/10.1103/PhysRevLett.111.150501.

J. M. Donohue, M. Agnew, J. Lavoie, and K. J. Resch, Phys. Rev. Lett. **111**, 153602 (2013), URL http://link.aps.org/doi/10.1103/PhysRevLett.111.153602.

M. Reck, A. Zeilinger, H. J. Bernstein, and P. Bertani, Phys. Rev. Lett. **73**, 58 (1994), URL http://link.aps.org/doi/10.1103/PhysRevLett.73.58.

I. Dhand and S. K. Goyal, Phys. Rev. A **92**, 043813 (2015), URL http://link.aps.org/doi/10.1103/PhysRevA.92.043813.

S.-H. Tan, Y. Y. Gao, H. de Guise, and B. C. Sanders, Phys. Rev. Lett. **110**, 113603 (2013), URL http://link.aps.org/doi/10.1103/PhysRevLett.110.113603.

H. de Guise, S.-H. Tan, I. P. Poulin, and B. C. Sanders, Phys. Rev. A **89**, 063819 (2014), URL http://link.aps.org/doi/10.1103/PhysRevA.89.063819.

H. de Guise, D. Spivak, J. Kulp, and I. Dhand, J. Phys. A:Math. Theor. **49**, 09LT01 (2016).

Y.-S. Ra, M. C. Tichy, H.-T. Lim, O. Kwon, F. Mintert, A. Buchleitner, and Y.-H. Kim, Proceedings of the National Academy of Sciences **110**, 1227 (2013), eprint http://www.pnas.org/content/110/4/1227.full.pdf, URL http://www.pnas.org/content/110/4/1227.abstract.

B.-G. Englert, C. Kurtsiefer, and H. Weinfurter, Phys. Rev. A **63**, 032303 (2001), URL https://link.aps.org/doi/10.1103/PhysRevA.63.032303.

A. Bouland and S. Aaronson, Phys. Rev. A **89**, 062316 (2014), URL https://link.aps.org/doi/10.1103/PhysRevA.89.062316.

M. W. Mitchell, C. W. Ellenor, S. Schneider, and A. M. Steinberg, Phys. Rev. Lett. **91**, 120402 (2003).

J. L. O'Brien, G. J. Pryde, A. Gilchrist, D. F. V. James, N. K. Langford, T. C. Ralph, and A. G. White, Phys. Rev. Lett. **93**, 080502 (2004), URL https://link.aps.org/doi/10.1103/PhysRevLett.93.080502.

M. Lobino, D. Korystov, C. Kupchak, E. Figueroa, B. C. Sanders, and A. I. Lvovsky, Science **322**, 563 (2008), ISSN 0036-8075, eprint http://science.sciencemag.org/content/322/5901/563.full.pdf, URL http://science.sciencemag.org/content/322/5901/563.

S. Rahimi-Keshari, A. Scherer, A. Mann, A. T. Rezakhani, A. I. Lvovsky, and B. C. Sanders, New Journal of Physics **13**, 013006 (2011), URL http://stacks.iop.org/1367-2630/13/i=1/a=013006.