The resurgence of the linear optics interferometer — recent advances & applications

Si-Hui Tan[a,b], Peter P. Rohde[c,*]

[a]*Singapore University of Technology and Design, Singapore University of Technology and Design, 8 Somapah Rd, Singapore 487372*
[b]*Centre for Quantum Technologies, National University of Singapore, Block S15, 3 Science Drive 2, Singapore 117543, Singapore*
[c]*Centre for Quantum Software & Information (CQSI), Faculty of Engineering & Information Technology, University of Technology Sydney, NSW 2007, Australia*

ARTICLE INFO

ABSTRACT

Linear optics has seen a resurgence for applications in quantum information processing owing to its miniaturisation on-chip, and increase in production efficiency and quality of single photons. Time-bin encodings have also become feasible owing to architectural breakthroughs, and new processing capabilities. Theoretical efforts have found new ways to implement universal quantum computations with linear optics requiring less resources, and to demonstrate the capabilities of linear optics without requiring a universal optical quantum computer.

1. Introduction

Linear optics play a prominent role in quantum information processing. Photons make fantastic 'flying' qubits, and are readily used for quantum communication [1] and quantum key distribution [2]. In 2001, Knill, Laflamme and Milburn (KLM) showed that efficient quantum computing is possible using only linear optical components, that is single photons, beamsplitters, phase shifters and photon counting [3]. Furthermore, an optical implementation of quantum protocols can potentially piggyback on existing communication infrastructure. Combined with the relative ease of transporting quantum states of light, as compared to say trapped ions or superconducting qubits, linear optics forms a powerful platform for quantum information processing.

The promises offered by linear optics have spearheaded many technical advancements. One of the major successes for linear optics is the paradigm shift from bulk optics to integrated photonics [4]. The advantage of using such integrated photonics over bulk optics is that it is more stable against phase fluctuations, and miniaturized. This has increased the scalability of optical implementations of quantum information protocols. Furthermore, it is now possible to have single-photon sources and detectors together with linear-optical networks on a silica chip [5, 6]. Having all components on chip reduces coupling losses which would be crucial for fault-tolerance [7].

---

*sihui_tan@sutd.edu.sg

In the last decade, single photons have been produced mainly through a nonlinear optical process know as spontaneous parametric down-conversion (SPDC), a nonlinear optical process. SPDC produces single photons in correlated pairs that has been a staple source of entanglement. Through developments in production, the number of high quality indistinguishable photons that can be simultaneously produced have increased steadily over the years. Single-photon pairs, once a novelty, are now run-of-the-mill business for quantum optical labs, and three or four photons have become commonplace [8, 9, 10, 11]. Experiments using up to ten photons have been demonstrated [12, 13]. We have also seen the meteoric rise of quantum dots in the role for producing single photons [14, 15, 16]. They are a scalable source of single photons which are highly indistinguishable, and are produced on demand–a significant advantage over SPDC which is an inherently probabilistic process.

Another approach to linear optics is to pack more features known as degrees of freedom onto a single photon, and to increase the degree of control over them. It is possible to manipulate degrees of freedom like polarization, time-of- arrival, and orbital angular momentum [17, 18, 19, 20, 21]. Since KLM, new proposals for linear optical quantum computations (LOQC) have surfaced [22, 23, 24, 25]. Some of them support new functionalities like secure delegated quantum computations [26, 27]. Others do not promise universality in their processing, but still performs tasks such as sampling [28], encrypted quantum walks [29], and secure quantum computations [30] that might be hard or impossible with a classical system. Such methods open up new ways to engineer quantum states and quantum operations, and expand the toolbox of baseline resources we have for implementing quantum computations, which could prove crucial in the race to achieve quantum supremacy.

We begin in Section 2 with an overview of the mathematical treatment of linear optical transformation on single photons, and in Section 3 with a description of some commonly used qubit encodings. Any unitary transformation acting on the spatial label of single photons can be efficiently decomposed into a network of beamsplitters and phase-shifters. We discuss this, and an extension to handle additional internal states, in Section 4. For applying any linear optical circuit, one needs an accurate description of its unitary representation. A full quantum tomography is costly and time-consuming. Some practical methods have been devised to do this reconstruction without resorting to tomography, and these are described in Section 5. In Section 7, we recap the experimental breakthroughs in state preparation of single photons, and some entangled quantum states. This is followed by advances in time-bin based architecture for linear optical networks, and photodectors in Sections 8 and 9 respectively. Last, but not least, we review applications for linear optical interferometry in LOQC, BOSONSAMPLING, and quantum metrology.

2. Mathematical background

A single photon in a quantum interferometer is described by its creation and annihilation operators, $\hat{a}_j^\dagger$ and $\hat{a}_j$ respectively, where j is the mode label of the interferometer. These operators satisfy the bosonic comutation relationship $[\hat{a}_j, \hat{a}_k^\dagger] = \delta_{j,k}$. The action of a $2d$-port linear optical interferometer that has 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 transformations can be expressed as sequences of beamsplitters and phase-shifters [31] (see Section 4). By convention, the interferometer is assumed to act only on the spatial mode of the input state.

Additional quantum labels are added to the creation and annihilation operators when other degrees of freedom, such as polarization, orbital angular momentum, and time-bins, are present. In this case, their commutator relation is

$$[\hat{a}_{j,\alpha}, \hat{a}_{k,\beta}^\dagger] = \delta_{j,k} \delta_{\alpha,\beta} \, , \tag{2}$$

where α and β represent these other degrees of freedom. As a consequence, quantum interference between multiple photons only occur when all quantum labels are the same. It is also possible to derive an analogous decomposition to that of Reck *et al.* that realizes the unitary transformation on such photons as a sequence of beamsplitters and internal transformations.

Control of indistinguishability of these photons may enable future applications. Mathematical methods have been developed to deal with partial distinguishabilities among interfering photons, including those using group theory

[32, 33, 34], and quantum-to-classical transitions [35]. Recently, by controlling multiple degrees of freedom of single photons, genuine three-photon interference that has no independent entanglement between any two subpairs of photons was demonstrated [36, 37].

3. Optical encoding of quantum information on single-photons

Using quantum states of light, there are a multitude of approaches to encoding quantum information. Beginning with a logical qubit,

$$|\psi\rangle_L = \alpha|0\rangle_L + \beta|1\rangle_L, \tag{3}$$

we now discuss the most prominent such encodings, which have been widely employed. We will specifically focus on single-photon encodings, as opposed to, for example, continuous variable encodings.

These encodings are all isomorphic to one another, but nonetheless, because they are represented using entirely different physical systems, they each exhibit their own unique advantages and disadvantages, and methods by which to implement operations upon them.

3.1. Polarisation

In polarisation encoding, the polarisation of a single photon in a single spatial mode encodes a logical qubit. Specifically, we represent the logical qubit as,

$$|\psi\rangle_L = \alpha|H\rangle + \beta|V\rangle, \tag{4}$$

where H (V) denotes a horizontally (vertically) polarised single photon.

Polarisation encoding has the elegance that the most common optical error mechanisms, such as loss or path-length mismatch, affect the two logical basis states equally. Furthermore, single-qubit operations may be directly implemented using wave-plates, which implement a rotation in polarisation space. Relevant to the preparation of large entangled states, such as cluster states, polarising beamsplitters can be employed to perform non-deterministic Bell state projections.

When physically constructing protocols based on polarisation-encoding, for obvious reasons it is extremely important that optical components be polarisation-preserving. Not doing so would obviously corrupt the logical state. Some waveguide technologies, for example, exhibit different refractive indices for the two polarisations.

3.2. Dual-rail

In dual-rail encoding, a single photon encodes a logical qubit as a superposition across two spatial modes,

$$|\psi\rangle_L = \alpha|1, 0\rangle + \beta|0, 1\rangle, \tag{5}$$

where $|i, j\rangle$ is a two-mode state with i (j) photons in the first (second) spatial mode. Using this encoding, phase-shifters and beamsplitters between the two spatial modes implement arbitrary single-qubit operations. Converting between polarisation- and dual-rail-encoding is trivial using polarising beamsplitters, which separate horizontal and vertical components into distinct spatial modes, or vice-versa.

Unfortunately, because the two basis states evolve via independent paths, our dual-rail qubits are susceptible to path-length-mismatch, a problem that does not affect polarisation encoding. Nonetheless, there are certain advantages to using two paths as opposed to one as is the case in single-rail encoding where the presence or absence of a photon denotes the logical bit. The loss of a photon in a dual-rail qubit is easily noted by its absence, whereas in a single-rail encoding, it would have been confused for one of the states. Moreover, a no-go result precludes universal quantum computation using just linear optics without the use of measurements in a single-rail encoding [38], thus making dual-rail encoding a more attractive alternative.

3.3. Time-bins

Time-bin qubits encode quantum information into the time-of-arrival of single photons, which have fixed polarisation and reside in a single spatial mode. Effectively, we discretise the direction of propagation of photons into discrete bins, which are treated as orthogonal basis states. Specifically, we are employing the encoding,

$$|\psi\rangle_L = \alpha|1\rangle_t|0\rangle_{t+\tau} + \beta|0\rangle_t|1\rangle_{t+\tau}, \tag{6}$$

where $|0\rangle_t$ ($|1\rangle_t$) denotes the vacuum (single-photon) state with arrival time t. Here τ is the time-bin separation, which must be sufficiently large that the temporal envelopes of neighbouring photons do not overlap, thereby ensuring orthogonality of the logical basis states.

This encoding is particularly resource-savvy, since a single spatial mode (e.g length of optical fibre) can encapsulate many time-bin qubits as a 'time-bin-train'. The amount of quantum information that can be encoded into the train is limited only by its physical length.

Unlike polarisation or dual-rail encoding, time-bin encoding does not lend itself to 'native' single-qubit operations. Rather, fast switching can be used to spatially separate neighbouring time-bins, implement a beamsplitter operation between them, before converting back to time-bin encoding. An experiment has built on this idea to implement a two-qubit gate by fast switching to a polarization basis [20]. Another promising advance is an ultrafast measurement technique for time bins based on converting into frequency bins [21]. Scalable networks using time-bin encoding are also possible using a loop-based architecture [39]. This is discussed in more detail in Section 8.

4. Efficient circuit decompositions of linear optics networks

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 beamsplitters and phase-shifters was described by Reck *et al.* [31]. This decomposition requires $O(n^2)$ linear optical elements, and the algorithm for finding the decomposition has polynomial runtime. Thus, such decompositions can always be determined and implemented efficiently. The layout for the original Reck *et al.* decomposition is shown in Fig. 1. However, since then a multitude of alternate decompositions have been found. A notable downside of the original decomposition is that different photons experience different circuit depth, i.e pass through different numbers of optical elements, resulting in asymmetry in losses and the accumulation of errors.
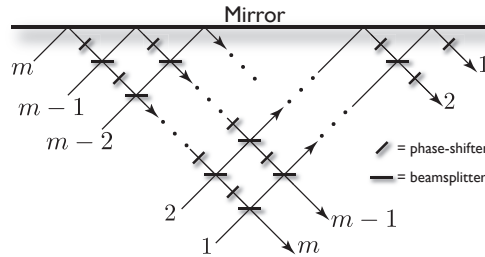

Fig. 1: Efficient decomposition of arbitrary linear optics networks into a sequence of beamsplitters and phase-shifters.

Alternatively, Mach-Zedner interferometers can also be employed as building blocks instead of beamsplitters and phase-shifters [40]. Later, it was shown that any nontrivial beamsplitter, that does more than permuting modes or adding phases to them, is universal for linear optics [41]. However, they do not provide an explicit construction for arbitrary unitaries.

If the linear optical transformations is to 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 $O(n_s^2 n_p)$ beamsplitters and $O(n_s^2)$ internal transformations [42]. This approach reduces the required number of beamsplitters but increases the total number of optical elements needed by a factor of 2.

5. Reconstructing linear optics networks

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 may still be needed post-production. One approach for achieving this is via quantum process tomography, discussed in the next section.

However, quantum process tomography is an expensive approach in terms of the number of measurements required to characterise the network, with exponential overhead, becoming impractical for large optical networks which can contain hundreds of modes using present-day technology [43]. To mitigate this problem, alternative characterisation protocols have been developed.

Generally, the unitary matrices of $d \times d$ linear optical devices are complex $U_{ij} = r_{ij}e^{i\theta_{ij}}$, where $0 \leq r_{ij} \leq 1$, and $0 \leq \theta_{ij} \leq 2\pi$. To characterise these numbers, one can do so by injecting one- and two-photon states into the network with correlated photon detection [44]. With some mathematical simplifications, the parameters can be solved for using the one-photon transmissions, and the visibility of two-photon inputs. An increased accuracy in the characterization is possible by estimating and correcting systematic errors that arise due to mode mismatch [45]. Others have used numerical methods to find the closest parameters that yield the observed visibilities [46, 47].

An alternative method to process tomography is feeding coherent states to probe the interferometer [48, 49] instead of Fock states. Such states are produced by a standard laser source, thus reducing experimental resources. The r_{jk} terms can be calculated from the ratios of output intensities at the kth port to the input intensity at the jth port. The remaining phases θ_{ij} are found by the interference pattern given by a two-mode coherent state $|\alpha\rangle|\alpha e^{\phi}\rangle$. When the states are injected into ports 1, and j respectively, the output intensity at the kth port is

$$I_k = I(r_{1k}^2 + r_{jk}^2 + 2r_{1k}r_{kj}\cos(\phi + \theta_{jk})), \tag{7}$$

where $\theta_{jk} = 0$ for $k = 1$, and I is the intensity of the input coherent states. By scanning the phase shift ϕ and locating the maximum value of I_k for $j = 2, \ldots, m$, all unknown phases can be found via $\theta_{jk} = 2\pi - \phi$. An elegant modification of this scheme removes the need for precise control of the phase-shift ϕ by suggesting instead to plot the output intensity I_k with respect to the input intensity I [49]. In time, the natural drift in the laser source will cause this plot to trace out an ellipse, known as a Lissajous figure, whose orientation and direction of evolution will give the phase θ_{jk} and its sign respectively.

While the input-to-output amplitudes of a linear optics network may be efficiently determined (in terms of number of measurements), it does not characterise the full quantum process it implements, which may contain errors in other degrees of freedom.

6. Quantum state and process tomography

When demonstrating quantum protocols experimentally it is generally absolutely critical to characterise the device prior to actual protocol execution. Tomography can be used to reconstruct the full density operator of an output state, and quantum process tomography to reconstruct the full process matrix implemented by a device. While various other measurement schemes can partially reconstruct quantum states or processes, or simply reconstruct certain parameters quantifying them, tomography is complete – fully and uniquely reconstructing state and process matrices, from which any other measure can be determined. Importantly, state and process tomography require no interference or multiqubit gates – just separable single-qubit measurements in different bases. But unfortunately they require a number of measurements growing exponentially with the size of the system.

State tomography is achieved by measuring expectation values in a complete basis for the state Hilbert space. For one qubit, for example, a complete basis is the Pauli basis, which wields the completeness relation,

$$\hat{\rho} = \text{tr}(\hat{\rho}) + \text{tr}(\hat{X}\hat{\rho})\hat{X} + \text{tr}(\hat{Y}\hat{\rho})\hat{Y} + \text{tr}(\hat{Z}\hat{\rho})\hat{Z}. \tag{8}$$

These traces correspond exactly to the expectation values in the respective bases, which are easily determined using separable measurements. Process tomography employs state tomography as a primitive, applying an equivalent completeness relation, but across the space of quantum processes, which may be decomposed into a basis input to output states. For a single qubit process this may be represented as,

$$\mathcal{E}(\hat{\rho}) = \sum_{i,j=1}^{4} \chi_{i,j}\hat{\sigma}_i\hat{\rho}\,\hat{\sigma}_j^{\dagger}. \tag{9}$$

which generalises to an arbitrary number of qubits. Here χ is the process matrix in the Pauli basis.

7. State preparation

The photonic states that are most commonly employed in linear optics protocols can be divided into Fock states (e.g single-photon), and entangled states, such as EPR, GHZ and cluster states. We will consider advances in each of these.

7.1. Fock states

Sources of single photons for applications in quantum information processing can be separated into two main categories: those produced by spontaneous parametric down-conversion (SPDC), and those by solid-state emitters in a cavity. To-date, SPDC has been able to produce up to ten entangled photons [12, 13] that can in turn be converted into indistinguishable photons, and a quantum dot emitter in a microcavity has produced five photons [15].

In SPDC, a nonlinear crystal with a large $\chi^{(2)}$ non-linearity is pumped with a laser source and with a small probability, the pump beam is absorbed by the crystal to produce two beams of lower energy known as the signal and idler. Owing to conservation of energy and momentum, the two beams have spatio-temporal correlations that can be engineered to produce twin-beam states with perfect photon number correlation, of the form

$$|\psi\rangle_{\text{SPDC}} = \sqrt{1 - \chi^2} \sum_{n=0}^{\infty} \chi^n |n, n\rangle, \tag{10}$$

where χ is the squeezing parameter. If a single photon were to be detected in one of the modes, it is certain that the other mode would similarly contain a single photon.

Solid-state single photon sources are versatile and efficient sources of single photons, however, the photons they produce have suffered from the lack of indistinguishability that is necessary for typical quantum information processing applications. Recent developments using resonant excitation of quantum dots were able to overcome these limitations. Laser pulses are used to excite the electronic resonance of the quantum dots and trigger the emission of high quality single photons [15]

7.2. Einstein-Podolsky-Rosen (EPR) pairs

An EPR pair, or Bell pair, is one of the four states,

$$|0\rangle_A |0\rangle_B \pm |1\rangle_A |1\rangle_B, \text{ and } |1\rangle_A |0\rangle_B \pm |0\rangle_A |1\rangle_B , \tag{11}$$

which are all maximally entangled and locally equivalent to one another. These are the simplest examples of entangled states, and their preparation via SPDC has been the mainstay of entangled state preparation for quantum optical processing [50]. In some applications, it may be desired to have the EPR pairs conditionally prepared, *i.e.* successfully prepared only under certain measurement outcomes of auxiliary modes. Because the EPR qubits are not measured directly, they can be used subsequently. Several theoretical approaches have been proposed for this purpose [51, 52, 53], and demonstrated [54, 55].

7.3. Greenberger-Horne-Zeilinger (GHZ) states

GHZ states form a class of entangled quantum states on multiple subsystems with at least three parties [56]. For qubit encodings with n subsystems, a GHZ state is of the form

$$|\Psi_n^{(\text{GHZ})}\rangle = \frac{|0\rangle^{\otimes n} + |1\rangle^{\otimes n}}{\sqrt{2}} . \tag{12}$$

These states are also non-local, and have been used extensively in experimental test for non-locality [57, 58]. This has been a subject matter covered in detail by another review [59]. To date, six- [60, 58], eight- [61, 62], and ten-photons [12, 13] GHZ states have been produced.

The GHZ state is also known as the NOON state, because it is written as

$$|\psi_n^{(\text{NOON})}\rangle = \frac{1}{\sqrt{2}}(|n, 0\rangle + |0, n\rangle) , \tag{13}$$

in the second quantization representation. This notation is commonly used in quantum metrological applications.
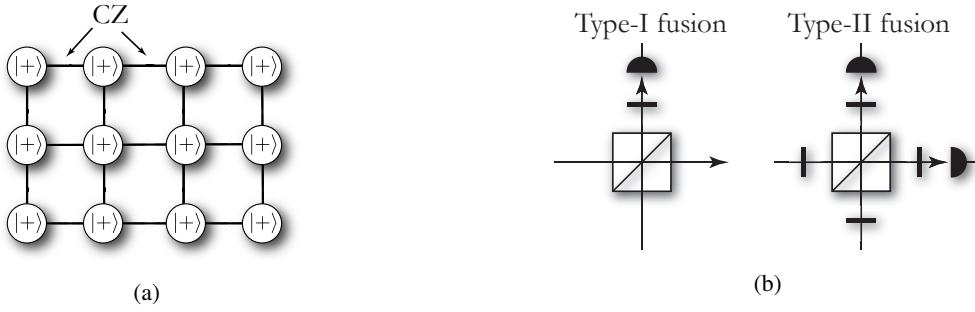
(a)

(b)

Fig. 2: (a) The representation of cluster states as a graph. Vertices represent qubits initialised into the $|+\rangle$ state, while edges represent the application on CPHASE gates, the ordering of which is irrelevant. (b) Fusion gates for joining smaller cluster states into larger ones. Both require only a single polarising beamsplitter, and waveplates. The type-I and -II fusion gates consume 1 or 2 qubits (photons) respectively, creating an edge between the remaining graphs. The type-I gate consumes one fewer photon, but requires number-resolved detection on the detected mode. The type-II gate requires only on/off photodetection, but consumes an additional photon. Thus, the type-I gate can be employed to fuse two Bell pairs into a 3-qubit cluster state, whereas the type-II gate will only grow clusters when beginning with at least 3 qubits per cluster.

7.4. Cluster states

Cluster states form another class of multiparty entangled states, and were conceived in the context of arrays of qubits with an Ising-type interaction [63]. These states can be represented as a graph, in which vertices are qubits initialized into the superposition state $|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$, with CPHASE operation applied between edges, as shown in Fig. 2a. For this reason, such states are also referred to as graph states. The CPHASE operations generate entanglement between the qubits, and because they commute, are independent of ordering.

Cluster states are a resource state for a model of quantum computation known as measurement-based quantum computation (MBQC). Here, having such a state as a resource enables universal quantum computation using only single-qubit measurements [64]. In fact, only (X,Y)-plane measurements are needed [65]. Therefore, the preparation of such states is highly valuable, generating much interest in their efficient preparation.

Unfortunately, implementing CPHASE gates using linear optics is complicated and highly non-deterministic. A major improvement upon this is to use fusion gates-rotated polarising beamsplitters, which implement projections onto the Bell states. These operations fuse smaller cluster states, represented using polarisation encoding, into larger ones, consuming one (type-I fusion) or two (type-II fusion) photons in the process. These operations are shown in Fig. 2b. Although these operations are non-deterministic with a success probability of 1/2, they require only a single beamsplitter, already a major improvement over directly implementing CPHASE gates. Furthermore, unlike CPHASE gates, fusion operations require only high Hong-Ou-Mandel visibility, rather than the Mach-Zehnder stability required within existing CPHASE gate implementations, a major experimental simplification.

Although these gates are non-deterministic and consume qubits, strategies have been described for efficiently preparing arbitrarily large cluster states of arbitrary topology, and using far fewer optical elements than by directly employing CPHASE gates [22, 23, 24, 25]. Experimentally, small photonic cluster states have been demonstrated using both SPDC [66, 60, 67, 68] and quantum dot sources [69]. To this end, continuous variable cluster states have fared better as large cluster states containing more than 10,000 entangled modes are possible [70], with the caveat that it is difficult to address modes individually for processing.

8. Time-bin loop-based architecture for linear optical networks

Using time-bin encoding of optical qubits, the obvious question is how to perform operations upon them. In [39], a dual-loop architecture was presented for implementing arbitrary passive linear-optics on photonic pulse-trains with time-bin separation τ, shown in Fig. 3a. The inner loop has length exactly τ, while the outer one has length $> n\tau$ (n is the number of optical modes). The architecture is controlled via three dynamically controlled beamsplitters. The first and last need only be on/off switches, whose sole purpose is to couple in the prepared pulse-train, keep it within the outer loop for the required duration, and then couple out of the outer loop, yielding the transformed pulse-train. The central beamsplitter must be able to implement arbitrary classically-controlled beamsplitter operations.

The architecture is frugal in its use of optical components, requiring only three dynamic beamsplitters, and several lengths of fibre. The beauty of this architecture is that the experimental requirements do not increase with the number
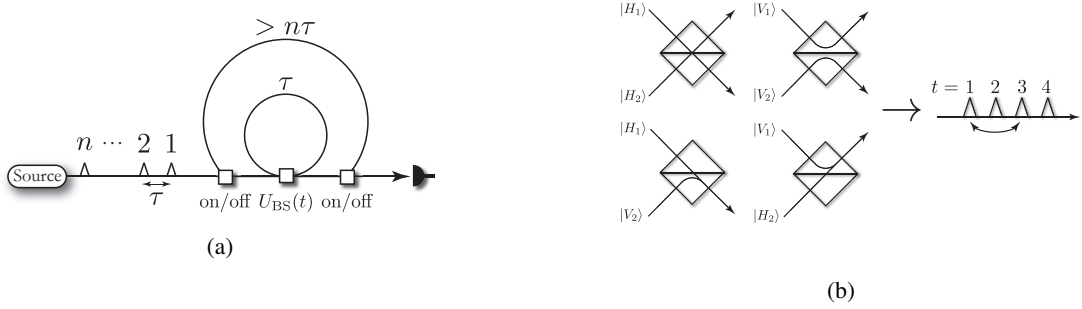
(a)

(b)

Fig. 3: (a) A fibre-loop architecture for implementing arbitrary linear optics operations upon a time-bin-encoded pulse-train. (b) Mapping between two polarisation-encoded qubits undergoing a polarising beamsplitter (PBS) operation, and its equivalent representation using 4 time-bins in a pulse-train. The PBS completely reflects (transmits) the vertical (horizontal) polarisations. The evolution of the four logical basis states, and their respective outputs, are shown explicitly. Writing out this PBS transformation in matrix form yields a permutation. Taking this permutation and relabelling the modes, we obtain the time-bin transformation shown underneath – a simple swap of two of the four time-bins.

of optical modes. The only parameter that scales with the number of optical modes is the outer loop, which must be at least long enough to house the entire time-bin-encoded pulse-train. Note, however, that the central beamsplitter must be controllable at sub-τ time-scales, so as to enable each temporal mode to be addressed individually, which is technically challenging.

The workings of the scheme can be thought of as follows: the inner loop allows arbitrary beamsplitter operations between neighbouring time-bins; the outer loop does nothing interferometric, but rather enables the pulse-train to undergo as many applications of the inner loops as necessary. It then follows that this scheme is universal for linear optics, as a sufficient number of beamsplitter operations between neighbouring modes enables universal decompositions, using for example, the Reck *et al.* decomposition described in Section 4.

As a simple example of how such time-bin encoding maps to other encodings, in Fig. 3b we show the isomorphism between the polarising beamsplitter operation and a pairwise temporal beamsplitter operation. This implies a direct mapping for implementing cluster state preparation within the time-bin scheme.

The above description applies to passive linear optics, which is sufficient for protocols such as BosonSampling, but insufficient for universal optical quantum computation, which requires the addition of ancillary states, and measurement with fast-feedforward. To address this, it was shown in [71] that by dynamically preparing ancillary pulse-trains (from the already-existing source), classically controlled by time-resolved measurements at the output, and changing the switching sequence, we can effectively couple in and out arbitrary subsets of the optical modes, enabling partial measurements to be implemented.

9. Photodetection

Broadly speaking, there are two main classes of photodetectors: non-photon-number-resolving (also referred to as bucket, or on/off) detectors, and photon-number-resolving (PNR) detectors. As the names suggest, non-PNR detectors only detect the presence or absence of photons in an incident beam, while PNR detectors are able to measure its number of photons. The outcomes of a PNR detector are described by the measurement projectors,

$$\hat{\Pi}_n = |n\rangle\langle n|, \; n = 0, 1, \dots , \tag{14}$$

while those of the non-photon-number-resolving detectors are given by

$$\hat{\Pi}_{\text{off}} = \hat{\Pi}_0, \; \text{and} \; \hat{\Pi}_{\text{on}} = \hat{I} - \hat{\Pi}_{\text{on}} . \tag{15}$$

Detailed reviews have been written about these detectors [72, 73], so we shall only outline a few important examples.

A common example of a non-PNR detector is the avalanche photodiode (APD). These devices are made up of semiconductor material, usually silicon, which generate an electron that quickly generates a cascade of electrons. This avalanche of electrons generate a current that can be measured. APDs are affordable, offer low dark count rates with reasonable efficiency, and can be made to operate in a broad spectrum of wavelengths. Superconducting nanowire

single-photon detector (SNSPD) is another type of non-PNR detector. This detector operates in its superconducting phase just below the critical density, and it phase changes back to normal when a photon is absorbed. This causes a spike in current around it, which, when detected, would indicate the absorption of the photon.

PNR detectors are a wonderful addition to the linear optical toolbox. A notable example is the superconducting transition edge sensor (TES) which has an extremely high quantum efficiency. The principle it operates on is very similar to the SNSPD, but with a much higher sensitivity that allows it to detect the energy of single photons. The visible light photon counter (VLPC) is another kind of PNR detector. The way VLPC works is in principle very similar to the APD, but with an additional layer of silicon that is lightly doped with arsenic (As). Owing to the presence of the As, a single photon absorption event always create an electrical signal that is always of the same magnitude. Thus, the output electrical signal is just proportional to the number of detected photons. Last, PNR detectors can be created by connecting many non-PNR detectors in parallel to one another, and summing the signals at the output. For instance, like in the theoretical proposal of [74]. Such an approach has been successfully demonstrated with SNSPD [75], and APDs [76, 77**?**].

10. Applications for linear optics interferometry

10.1. Linear optical quantum computation (LOQC)

The advancements in linear optics have opened up avenues for implementation. One of the key requirements is nonlinear couplings between the different optical modes. Photons do not naturally interact with one another so some careful engineering is needed to achieve this coupling. Methods used include measurements and feedforwarding [3], and photon-atom interactions [78]. The former requires non-deterministic operations, which succeed only part of the time and have to be repeated. This can be challenging given the limited resources to begin with. Comprehensive reviews have been written previously to cover this topic [59, 79], hence we will focus on recent advances.

Integrated photonic circuits has greatly improved the feasibility of LOQC. Their small size and interferometric stability enable the requisite quantum interference to happen in certain LOQC settings. Programmable circuits that are reusable have also emerged [80, 81]. This saves resources and lead time for producing new circuits. Combining these chips with existing higher-efficiency sources and detectors will expand their capabilities. Loss can be mitigated by moving all components, *i.e.* sources and detectors, onto the same chip as the linear optical circuit [5, 6]. What remains is to have fast feedforward also on chip. This might pose the greatest challenge yet for universal LOQC. The bottleneck is in the speed of modulation in the feedforward circuitry; only a handful of experiments have been able to implement adaptive feedforward for the purposes of LOQC [67, 82, 83, 84].

Better single-photon sources (see Section 7.1) are part of the solution. Improvement in control of their degrees of freedom have also led to more efficient designs of circuits [85, 86] that enabled the optical implementation of quantum teleportation of the state of a single photon [87]. In this way, three-qubit [86, 88, 89] and four-qubit [90] gates have also been implemented using LOQC.

Cross-Kerr nonlinearity is a type of nonlinearity implemented through atom-photon interactions. It has been thought for some time that fundamental noise limits in atom-photon interactions will prevent any help for LOQC [91, 92, 93]. However, this belief has been countered by the construction of a cphase gate using photons that undergo cross-Kerr interaction [78]. Regardless of who is right in this debate, stronger Kerr nonlinearities have been achieved in the last five years [94, 95, 96, 97], and this avenue remains a tantalizing possibility for deterministic quantum gates.

Although there has been tremendous progress in linear optics, it seems likely that an efficient, and fault-tolerant universal quantum computer will require a hybrid system. Nonetheless, linear optics remains fascinating platform for applications and foundation work.

10.2. Boson-sampling

The difficulty in producing nonlinear operations required for universal LOQC led researchers to seek out alternative ways for demonstrating its power in the near term. BosonSampling is the result of such an effort. It is a restricted model of non-universal quantum computation [28] that constitutes sampling the photocounts from the probability distribution of identical bosons scattered by a passive linear optical interferometer. While not universal, the boson-sampling scheme is strongly believed to implement a classically hard task. Consider such a circuit of m input (and output) modes that is injected with n indistinguishable single photons such that $m \sim O(n^2)$. Then, the boson-sampling

task consists of generating a sample from the probability distribution of single-photon measurements at the output of the circuit. The probability of detecting s_j photons at the jth output mode is

$$p(s_1, \ldots, s_m) = \frac{|\mathrm{Per}(U_S)|^2}{s_1! \ldots s_n!} \, , \qquad (16)$$

where Per() denotes the permanent of a matrix, $S = \{s_1, \ldots, s_m\}$ denotes an output photon-number configuration, and U_S is obtained from the interferometer unitary U by keeping its first n columns and repeating its jth row s_j times. The appearance of the permanent, which is #P-hard in general (a complexity class even harder than NP-hard), in this statistics contributes to the hardness of the boson-sampling problem. Note that the number of configurations $|S| = \binom{n+m-1}{n}$ in the output superposition scales exponentially with m. For this reason, the boson sampler does not let us *calculate* matrix permanents, as this would require knowing individual amplitudes with high precision, which would require an exponential number of samples. Rather, the boson sampler samples across a distribution of permanents without actually revealing any of them to the experimenter. Nonetheless, this is a classically intractable problem. It is also known that boson-sampling is as hard as stimulating the short time evolution of a certain Hamiltonian[98].

where **P**er() denotes the permanent of a matrix, $S = \{s_1, \ldots, s_m\}$ denotes an output photon-number configuration, and U_S is obtained from the interferometer unitary U by keeping its first n columns and repeating its jth row s_j times. The appearance of the permanent, which is #P-hard in general (a complexity class even harder than NP-hard), in this statistics contributes to the hardness of the boson sampling problem. Note that the number of configurations $|S| = \binom{n+m-1}{n}$ in the output superposition scales exponentially with m. For this reason, the boson sampler does not let us *calculate* matrix permanents, as this would require knowing individual amplitudes with high precision, which would require an exponential number of samples. Rather, the boson sampler samples across a distribution of permanents without actually revealing any of them to the experimenter. Nonetheless, this is a classically intractable problem. It is also known that boson sampling is as hard as stimulating the short time evolution of a certain Hamiltonian[98].
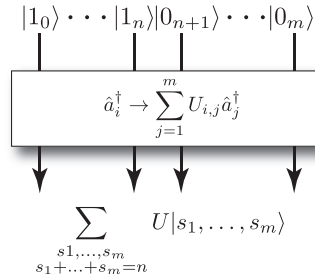
$$|1_0\rangle \cdots |1_n\rangle |0_{n+1}\rangle \cdots |0_m\rangle$$

$$\hat{a}_i^\dagger \to \sum_{j=1}^m U_{i,j} \hat{a}_j^\dagger$$

$$\sum_{\substack{s_1, \ldots, s_m \\ s_1 + \ldots + s_m = n}} U|s_1, \ldots, s_m\rangle$$

Fig. 4: The Boson-Sampling model. A string of n single photons is prepared in m optical modes. They are evolved via a passive interferometer U. Finally the photon-statistics are sampled from the distribution $p(s_1, \ldots, s_m)$.

Owing to the simplicity of BosonSampling and its overarching implications for computer science, multiple experiments were reported shortly after its theoretical conception [9, 10, 11, 99]. A recent experiment showed a bosonsampling machine beating an early computer [15]. BosonSampling has piqued so much interest, that a complete discussion would make up its own review, so we shall only outline some main developments here. One variant, known as scatter-shot bosonsampling, proposes using pumped SPDC heralded photon sources to increase the rate of generating input photons [100, 101], by inputting an SPDC source into *every* mode rather than just the first n, thereby boosting the probability of preparing the desired n photons. Others varied the source input to cat-states [102] and thermal states [103] . An exciting modification allows the determination of molecular vibronic spectra [104], a task that goes beyond demonstrating a computationally hard task.

Certifying that a bosonsampling task has been correctly performed is non-trivial. Some efforts look into discriminating between a valid bosonsampling and a uniform distributions [105, 106]. Another shows how to discriminate data arising from either indistinguishable or distinguishable photons [107, 108]. More general benchmark standards have also been instituted [109]. Another approach to verify that the interferometer is behaving as expected is to make use of suppression laws [110] together with fully reconfigurable optical circuits. When the circuits are tuned to implement certain unitary matrices, specific input and output combinations are suppressed [111]. Last but not least, a bound for

the transition amplitudes for BOSONSAMPLING indicates that an approximation algorithm for the permanent is possible [112]. Such an algorithm can help with verifying the sampling distribution, but their proof does not construct the algorithm needed for this to happen.

As experimental imperfections threaten the scalability of BOSONSAMPLING, there have been efforts to look into its error tolerance [113], fault-tolerance [114], and experimental artefacts [115, 116]. Some works have resulted in interesting connections to exotic mathematical entities like immanants [32, 33] and the multi-dimensional permanent [117]. A time-bin implementation of BOSONSAMPLING [39] seems particularly attractive in terms of robustness [118].

10.3. Other sampling problems – hard & easy

Numerous other sampling problems have since been described, using, for example,

1. Cat states (superpositions of coherent states)
2. Photon-added coherent states .
3. Photon-added or -subtracted squeezed vacuum states.
4. Two-mode squeezed vacuum states (SPDC states).
5. Gaussian states.
6. Positive P-function states.

Of these, 1-4 have been shown to yield hard sampling problems under photodetection, assuming certain reasonable complexity assumptions. And 5-6 have been shown to implement polynomial-time classical algorithms, under Gaussian measurements.

10.4. Quantum simulations

Quantum simulations is about simulating a quantum system by quantum mechanical means [119], and there are generally two approaches to achieving this. The first approach is known as digital quantum simulation and achieved by building a quantum computer from unitary gate components that are generated by a Hamiltonians of quantum processes. Progress using this approach has already been discussed in Section 10.1. The second approach is known as analog quantum simulation and involves building simpler analog devices that mimic other, perhaps less accessible, quantum systems. We focus on discussing analog quantum simulation in this section. Further discussions can be found in reviews written on quantum simulations [120, 119], including one specifically for optical quantum simulations [121].

Quantum interferometers have been proposed and in some cases implemented as quantum simulators. In quantum chemistry, the energy spectrum of the hydrogen molecule has been calculated using a quantum simulator comprising of a pair of entangled photons in a polarization-dependent interferometer [122]. With two entangled photon pairs, valence-bond states have been simulated and a fiber-based tunable directional coupler gives analogue control over superpositions of different valence-bond states [123]. The model of BOSONSAMPLING, when coupled with two-level systems that are coupled to the ports of the quantum interferometer, simulates a general spin XY Hamiltonian [124]. Quantum interferometers can also be used to simulate quantum walks which in turn can be used to simulate topological phases [125], transitions between fermionic and bosonic behavior [126, 127, 128, 129], fractional statistics of anyons [130, 131, 132], and excitation transfer in biological systems [133, 134].

10.5. Quantum metrology

An archetypal task for quantum metrology is the following: Given a Mach-Zedner interferometer, with an unknown phase shift of magnitude φ inserted in one of the two paths (see Fig. 5a), can one deduce φ via a judicious use of quantum states and measurements with a higher sensitivity than that of a completely classical interferometer? Indeed, one can, and the standard deviation, $\Delta\varphi$, after N trials using quantum estimation is $\Delta\varphi = 1/N$, which gets a factor of $\sqrt{N}$ improvement over classical phase estimation. As this sensitivity is also a fundamental limit arising from Heisenberg's uncertainty principle, *i.e.* we cannot measure definitively the phase, it is known as the Heisenberg limit. Most famously, NOON states achieve this limit using N photons in a single trial. Many reviews have been written for quantum metrology and Heisenberg-limited quantum phase estimation [135, 136, 137] so we will not dwell on the history of this application. Instead, we will discuss new paradigms for quantum metrology that have been made possible by the aforementioned advancements in linear optics.

As discussed in Section 10.2, the resources needed for Boson-sampling are readily available, but executes a task that is believed to be hard classically. Surprisingly, an entanglement between a large number of path labels is possible
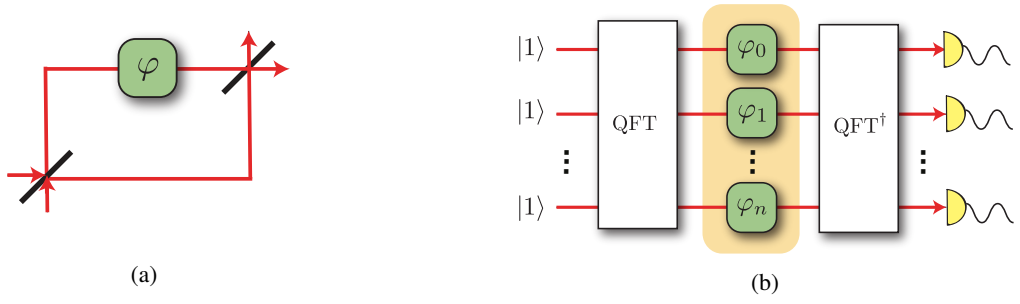
(a)

(b)

Fig. 5: (a) A schematic diagram of the Mach-Zehnder interferometer comprising of two 50/50 beamsplitters with a phase shift φ in one of its two paths. (b) Architecture of the quantum Fourier transform interferometer for metrology using single-photon states. QFT: Quantum Fourier transform circuit, and $\varphi_k = (k-1)\varphi$. Single photons are injected into the input modes on the left-hand-side, and a N-fold coincidence measurement is conducted at the output on the right-hand-side.

with single photons in a passive linear optical device. Motes *et al.* harnessed this so-called number-path entanglement for quantum metrology without the use of entangled states [?]. Here, the phase shift to be estimated, φ, manifests itself as a linear phase gradient across N modes (See Fig. 5b). By straddling these modes among a quantum Fourier transform and its conjugate operation, it is possible to achieve $\Delta\varphi = O(N^{-3/2})$ using a coincidence measurement with just a string of N single photons, for up to at least $N = 25$ modes.

Quantum multi-parameter estimation is the extension of quantum phase estimation to sense multiple phases in a multi-arm interferometer [138]. Theoretical work has shown that it is favorable to probe all phases simultaneously rather than individually [139, 140], and it remains to realize existing proposals for implementation [8]. Nonetheless, for a Heisenberg-limited sensitivity, entangled states and joint measurements across modes are likely to be required.

11. Optical switching

Some of the protocols thus far require switching between different optical modes. This is achieved experimentally via a Mach-Zehnder interferometer with a dynamic, classically-controlled phase-shift in one path. The variable phase may be implemented in a number of ways using various types of phase modulators, such as electro-optic or acousto-optic modulators. With this construction setting the phase to $\phi = 0$ performs the identity operation, whereas for $\phi = \pi$ it performs a swap gate. This is shown in Fig. 6.
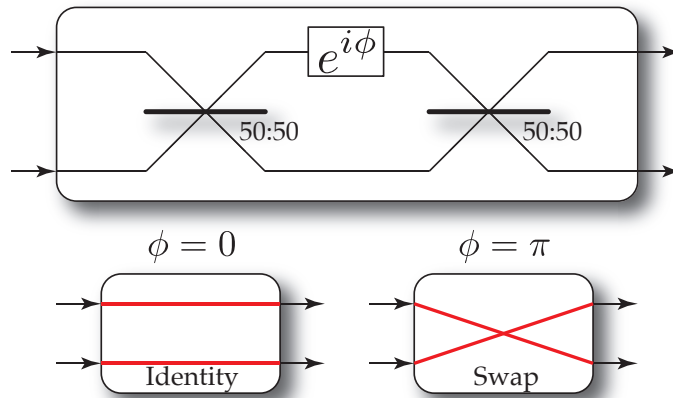

Fig. 6

This concept for switching is widely used in current labs, however it is very slow using present-day technology. For the purposes of fast-feedforward – required for universal optical quantum computing for example – we would require switching times on the order of nanoseconds, which requires the switching time to be faster than the time to the destination of the light it needs to switch. Presently this remains a daunting challenge, requiring much further research, with quantum memories being a candidate for loosening the switching time limitations.

12. Conclusion

Linear optical interferometry has become a leading contender for the implementation of quantum information processing protocols. The preparation, manipulation and measurement of photonic quantum information has become mainstream and widely employed, with impressive experimental accuracies.

We have discussed the various ways in which quantum information can be represented in photonics, how they can be manipulated and detected, and some of their leading applications.

Although there are countless physical architectures for the implementation of quantum information processing, and it is far from certain which will win 'the quantum race for supremacy, optics will always find a home as the only contender for applications involving quantum communication. For this reason, the future of linear optics interferometry is a bright one, which will find inevitable applicability in the future quantum world.

Acknowledgments

References

[1] T. E. Northup, R. Blatt, Quantum information transfer using photons, Nat Photon 8 (5) (2014) 356—363.
    URL http://dx.doi.org/10.1038/nphoton.2014.53
[2] H.-K. Lo, M. Curty, K. Tamaki, Secure quantum key distribution, Nat Photon 8 (8) (2014) 595–604.
    URL http://dx.doi.org/10.1038/nphoton.2014.149
[3] E. Knill, R. Laflamme, G. Milburn, A scheme for efficient quantum computation with linear optics, Nature (London) 409 (2001) 46.
[4] T. Meany, M. Grä fe, R. Heilmann, A. Perez-Leija, S. Gross, M. J. Steel, M. J. Withford, A. Szameit, Laser written circuits for quantum photonics, Laser & Photonics Reviewsdoi:10.1002/lpor.201500061.
    URL http://dx.doi.org/10.1002/lpor.201500061
[5] J. P. Sprengers, A. Gaggero, D. Sahin, S. Jahanmirinejad, G. Frucci, F. Mattioli, R. Leoni, J. Beetz, M. Lermer, M. Kamp, S. Hfling, R. Sanjines, A. Fiore, Waveguide superconducting single-photon detectors for integrated quantum photonic circuits, Applied Physics Letters 99 (18) (2011) 181110. doi:10.1063/1.3657518.
    URL http://dx.doi.org/10.1063/1.3657518
[6] J. W. Silverstone, D. Bonneau, K. Ohira, N. Suzuki, H. Yoshida, N. Iizuka, M. Ezaki, C. M. Natarajan, M. G. Tanner, R. H. Hadfield, V. Zwiller, G. D. Marshall, J. G. Rarity, J. L. O'Brien, M. G. Thompson, On-chip quantum interference between silicon photon-pair sources, Nat Photon 8 (2) (2014) 104–108.
    URL http://dx.doi.org/10.1038/nphoton.2013.339
[7] Y. Li, P. C. Humphreys, G. J. Mendoza, S. C. Benjamin, Resource costs for fault-tolerant linear optical quantum computing, Phys. Rev. Xdoi:10.1103/PhysRevX.5.041007.
    URL https://link.aps.org/doi/10.1103/PhysRevX.5.041007
[8] N. Spagnolo, L. Aparo, C. Vitelli, A. Crespi, R. Ramponi, R. Osellame, P. Mataloni, F. Sciarrino, Quantum interferometry with three-dimensional geometry, Scientific Reports 2 (2012) 862 EP –.
    URL http://dx.doi.org/10.1038/srep00862
[9] M. Tillmann, B. Dakic, R. Heilmann, S. Nolte, A. Szameit, P. Walther, Experimental boson sampling, Nat Photon 7 (7) (2013) 540–544.
    URL http://dx.doi.org/10.1038/nphoton.2013.102
[10] J. B. Spring, B. J. Metcalf, P. C. Humphreys, W. S. Kolthammer, X.-M. Jin, M. Barbieri, A. Datta, N. Thomas-Peter, N. K. Langford, D. Kundys, J. C. Gates, B. J. Smith, P. G. R. Smith, I. A. Walmsley, Boson sampling on a photonic chip, Science 339 (6121) (2013) 798–801. doi:10.1126/science.1231692.
    URL http://science.sciencemag.org/content/339/6121/798
[11] M. A. Broome, A. Fedrizzi, S. Rahimi-Keshari, J. Dove, S. Aaronson, T. C. Ralph, A. G. White, Photonic boson sampling in a tunable circuit, Science 339 (6121) (2013) 794–798. doi:10.1126/science.1231440.
    URL http://science.sciencemag.org/content/339/6121/794
[12] X.-L. Wang, L.-K. Chen, W. Li, H.-L. Huang, C. Liu, C. Chen, Y.-H. Luo, Z.-E. Su, D. Wu, Z.-D. Li, H. Lu, Y. Hu, X. Jiang, C.-Z. Peng, L. Li, N.-L. Liu, Y.-A. Chen, C.-Y. Lu, J.-W. Pan, Experimental ten-photon entanglement, Phys. Rev. Lett.doi:10.1103/PhysRevLett.117.210502.
    URL https://link.aps.org/doi/10.1103/PhysRevLett.117.210502
[13] L.-K. Chen, Z.-D. Li, X.-C. Yao, M. Huang, W. Li, H. Lu, X. Yuan, Y.-B. Zhang, X. Jiang, C.-Z. Peng, L. Li, N.-L. Liu, X. Ma, C.-Y. Lu, Y.-A. Chen, J.-W. Pan, Observation of ten-photon entanglement using thin bib3o6 crystals, Opticadoi:10.1364/OPTICA.4.000077.
    URL http://www.osapublishing.org/optica/abstract.cfm?URI=optica-4-1-77
[14] X. Ding, Y. He, Z.-C. Duan, N. Gregersen, M.-C. Chen, S. Unsleber, S. Maier, C. Schneider, M. Kamp, S. Höfling, C.-Y. Lu, J.-W. Pan, On-demand single photons with high extraction efficiency and near-unity indistinguishability from a resonantly driven quantum dot in a micropillar, Phys. Rev. Lett.doi:10.1103/PhysRevLett.116.020401.
    URL https://link.aps.org/doi/10.1103/PhysRevLett.116.020401

[15] H. Wang, Y. He, Y.-H. Li, Z.-E. Su, B. Li, H.-L. Huang, X. Ding, M.-C. Chen, C. Liu, J. Qin, J.-P. Li, Y.-M. He, C. Schneider, M. Kamp, C.-Z. Peng, S. Hoefling, C.-Y. Lu, J.-W. Pan, Multi-photon boson-sampling machines beating early classical computersarXiv:quant-ph:1612.06956.

[16] H. Wang, Z.-C. Duan, Y.-H. Li, S. Chen, J.-P. Li, Y.-M. He, M.-C. Chen, Y. He, X. Ding, C.-Z. Peng, C. Schneider, M. Kamp, S. Höfling, C.-Y. Lu, J.-W. Pan, Near-transform-limited single photons from an efficient solid-state quantum emitter, Phys. Rev. Lett.doi:10.1103/PhysRevLett.116.213601.
URL https://link.aps.org/doi/10.1103/PhysRevLett.116.213601

[17] M. Tillmann, S.-H. Tan, S. E. Stoeckl, B. C. Sanders, H. de Guise, R. Heilmann, S. Nolte, A. Szameit, P. Walther, Generalized multiphoton quantum interference, Phys. Rev. Xdoi:10.1103/PhysRevX.5.041015.
URL http://link.aps.org/doi/10.1103/PhysRevX.5.041015

[18] N. Bozinovic, Y. Yue, Y. Ren, M. Tur, P. Kristensen, H. Huang, A. Willner, S. Ramachandran, Terabit-scale orbital angular momentum mode division multiplexing in fibers, Science 340 (2013) 1545–1548.

[19] A. Nicolas, L. Veissier, L. Giner, E. Giacobino, D. Maxein, J. Laurat, A quantum memory for orbital angular momentum photonic qubits, Nat. Photonics 8 (2014) 234–238.

[20] P. C. Humphreys, B. J. Metcalf, J. B. Spring, M. Moore, X.-M. Jin, M. Barbieri, W. S. Kolthammer, I. A. Walmsley, Linear optical quantum computing in a single spatial mode, Phys. Rev. Lett.doi:10.1103/PhysRevLett.111.150501.
URL http://link.aps.org/doi/10.1103/PhysRevLett.111.150501

[21] J. M. Donohue, M. Agnew, J. Lavoie, K. J. Resch, Coherent ultrafast measurement of time-bin encoded photons, Phys. Rev. Lett.doi:10.1103/PhysRevLett.111.153602.
URL http://link.aps.org/doi/10.1103/PhysRevLett.111.153602

[22] M. A. Nielsen, Optical quantum computation using cluster states, Phys. Rev. Lett. 93 (2004) 040503.

[23] D. E. Browne, T. Rudolph, Resource-efficient linear optics quantum computation, Phys. Rev. Lett. 95 (2005) 010501.

[24] M. Gimeno-Segovia, P. Shadbolt, D. E. Browne, T. Rudolph, From three-photon greenberger-horne-zeilinger states to ballistic universal quantum computation, Phys. Rev. Lett.doi:10.1103/PhysRevLett.115.020502.
URL https://link.aps.org/doi/10.1103/PhysRevLett.115.020502

[25] M. Pant, D. Towsley, D. Englund, S. Guha, Percolation thresholds for photonic quantum computing, arXiv:1701.03775.

[26] S. Barz, E. Kashefi, A. Broadbent, J. F. Fitzsimons, A. Zeilinger, P. Walther, Demonstration of blind quantum computing, Science 335 (6066) (2012) 303–308. doi:10.1126/science.1214707.
URL http://science.sciencemag.org/content/335/6066/303

[27] K. A. G. Fisher, A. Broadbent, L. K. Shalm, Z. Yan, J. Lavoie, R. Prevedel, T. Jennewein, K. J. Resch, Quantum computing on encrypted data, Nature Communications 5 (2014) 3074 EP –.
URL http://dx.doi.org/10.1038/ncomms4074

[28] S. Aaronson, A. Arkhipov, The computational complexity of linear optics, in: Proceedings of the Forty-third Annual ACM Symposium on Theory of Computing, STOC '11, ACM, New York, NY, USA, 2011, doi:10.1145/1993636.1993682.
URL http://doi.acm.org/10.1145/1993636.1993682

[29] P. P. Rohde, J. F. Fitzsimons, A. Gilchrist, Quantum walks with encrypted data, Phys. Rev. Lett.doi:10.1103/PhysRevLett.109.150501.
URL https://link.aps.org/doi/10.1103/PhysRevLett.109.150501

[30] S.-H. Tan, J. A. Kettlewell, Y. Ouyang, L. Chen, J. F. Fitzsimons, A quantum approach to homomorphic encryption, Scientific Reports 6 (2016) 33467 EP –.
URL http://dx.doi.org/10.1038/srep33467

[31] M. Reck, A. Zeilinger, H. J. Bernstein, P. Bertani, Experimental realization of any discrete unitary operator, Phys. Rev. Lett.doi:10.1103/PhysRevLett.73.58.
URL http://link.aps.org/doi/10.1103/PhysRevLett.73.58

[32] S.-H. Tan, Y. Y. Gao, H. de Guise, B. C. Sanders, Su(3) quantum interferometry with single-photon input pulses, Phys. Rev. Lett.doi:10.1103/PhysRevLett.110.113603.
URL http://link.aps.org/doi/10.1103/PhysRevLett.110.113603

[33] H. de Guise, S.-H. Tan, I. P. Poulin, B. C. Sanders, Coincidence landscapes for three-channel linear optical networks, Phys. Rev. Adoi:10.1103/PhysRevA.89.063819.
URL http://link.aps.org/doi/10.1103/PhysRevA.89.063819

[34] H. de Guise, D. Spivak, J. Kulp, I. Dhand, d-functions and immanants of unitary matrices and submatrices, J. Phys. A:Math. Theor. 49 (2016) 09LT01.

[35] Y.-S. Ra, M. C. Tichy, H.-T. Lim, O. Kwon, F. Mintert, A. Buchleitner, Y.-H. Kim, Nonmonotonic quantum-to-classical transition in multi-particle interference, Proceedings of the National Academy of Sciences 110 (4) (2013) 1227–1231. doi:10.1073/pnas.1206910110.
URL http://www.pnas.org/content/110/4/1227.abstract

[36] S. Agne, T. Kauten, J. Jin, E. Meyer-Scott, J. Z. Salvail, D. R. Hamel, K. J. Resch, G. Weihs, T. Jennewein, Observation of genuine three-photon interference, Phys. Rev. Lett.doi:10.1103/PhysRevLett.118.153602.
URL https://link.aps.org/doi/10.1103/PhysRevLett.118.153602

[37] A. J. Menssen, A. E. Jones, B. J. Metcalf, M. C. Tichy, S. Barz, W. S. Kolthammer, I. A. Walmsley, Distinguishability and many-particle interference, Phys. Rev. Lett.doi:10.1103/PhysRevLett.118.153603.
URL https://link.aps.org/doi/10.1103/PhysRevLett.118.153603

[38] L.-A. Wu, P. Walther, D. A. Lidar, No-go theorem for passive single-rail linear optical quantum computing, Scientific Reports 3 (2013) 1394 EP –.
URL http://dx.doi.org/10.1038/srep01394

[39] K. R. Motes, A. Gilchrist, J. P. Dowling, P. P. Rohde, Scalable boson sampling with time-bin encoding using a loop-based architecture, Phys. Rev. Lett.doi:10.1103/PhysRevLett.113.120501.
URL https://link.aps.org/doi/10.1103/PhysRevLett.113.120501

[40] B.-G. Englert, C. Kurtsiefer, H. Weinfurter, Universal unitary gate for single-photon two-qubit states, Phys. Rev. Adoi:10.1103/PhysRevA.63.032303.
URL https://link.aps.org/doi/10.1103/PhysRevA.63.032303

[41] A. Bouland, S. Aaronson, Generation of universal linear optics by any beam splitter, Phys. Rev. Adoi:10.1103/PhysRevA.89.062316.
URL https://link.aps.org/doi/10.1103/PhysRevA.89.062316

[42] I. Dhand, S. K. Goyal, Realization of arbitrary discrete unitary transformations using spatial and internal modes of light, Phys. Rev. Adoi:10.1103/PhysRevA.92.043813.
URL http://link.aps.org/doi/10.1103/PhysRevA.92.043813

[43] N. C. Harris, D. Bunandar, M. Pant, G. R. Steinbrecher, J. Mower, M. Prabhu, T. Baehr-Jones, M. Hochberg, D. Englund, Large-scale quantum photonic circuits in silicon, Nanophotonics 5.
URL https://www.degruyter.com/view/j/nanoph.ahead-of-print/nanoph-2015-0146/nanoph-2015-0146.xml

[44] A. Laing, J. O'Brien, Super-stable tomography of any linear optical device, arXiv: 1208.2868v1.

[45] I. Dhand, A. Khalid, H. Lu, B. C. Sanders, Accurate and precise characterization of linear optical interferometers, Journal of Optics 18 (3) (2016) 035204.
URL http://stacks.iop.org/2040-8986/18/i=3/a=035204

[46] N. Spagnolo, E. Maiorino, C. Vitelli, M. Bentivegna, A. Crespi, R. Ramponi, P. Mataloni, R. Osellame, F. Sciarrino, Learning an unknown transformation via a genetic approacharXiv:arXiv:1610.03291v1.

[47] M. Tillmann, C. Schmidt, P. Walther, On unitary reconstruction of linear optical networks, Journal of Optics 18 (11) (2016) 114002.
URL http://stacks.iop.org/2040-8986/18/i=11/a=114002

[48] S. Rahimi-Keshari, M. A. Broome, R. Fickler, A. Fedrizzi, T. C. Ralph, A. G. White, Direct characterization of linear-optical networks, Opt. Expressdoi:10.1364/OE.21.013450.
URL http://www.opticsexpress.org/abstract.cfm?URI=oe-21-11-13450

[49] R. Heilmann, M. Grfe, S. Nolte, A. Szameit, A novel integrated quantum circuit for high-order w-state generation and its highly precise characterization, Science Bulletindoi:http://doi.org/10.1007/s11434-014-0688-5.
URL http://www.sciencedirect.com/science/article/pii/S2095927316305400

[50] Y.-H. Kim, S. P. Kulik, Y. Shih, Bell-state preparation using pulsed nondegenerate two-photon entanglement, Phys. Rev. Adoi:10.1103/PhysRevA.63.060301.
URL https://link.aps.org/doi/10.1103/PhysRevA.63.060301

[51] T. B. Pittman, M. M. Donegan, M. J. Fitch, B. C. Jacobs, J. D. Franson, P. Kok, H. Lee, J. P. Dowling, Heralded two-photon entanglement from probabilistic quantum logic operations on multiple parametric down-conversion sources, IEEE Journal of Selected Topics in Quantum Electronicsdoi:10.1109/JSTQE.2003.820916.

[52] C. Śliwa, K. Banaszek, Conditional preparation of maximal polarization entanglement, Phys. Rev. Adoi:10.1103/PhysRevA.67.030101.
URL https://link.aps.org/doi/10.1103/PhysRevA.67.030101

[53] P. Walther, M. Aspelmeyer, A. Zeilinger, Heralded generation of multiphoton entanglement, Phys. Rev. Adoi:10.1103/PhysRevA.75.012313.
URL https://link.aps.org/doi/10.1103/PhysRevA.75.012313

[54] C. Wagenknecht, C.-M. Li, A. Reingruber, X.-H. Bao, A. Goebel, Y.-A. Chen, Q. Zhang, K. Chen, J.-W. Pan, Experimental demonstration of a heralded entanglement source, Nat Photon 4 (8) (2010) 549–552.
URL http://dx.doi.org/10.1038/nphoton.2010.123

[55] S. Barz, G. Cronenberg, A. Zeilinger, P. Walther, Heralded generation of entangled photon pairs, Nat Photon 4 (8) (2010) 553–556.
URL http://dx.doi.org/10.1038/nphoton.2010.156

[56] D. M. Greenberger, M. A. Horne, A. Z. (edited by M. Kafatos), Going beyond Bell's theorem, Kluwer Academic, Dordrecht, The Netherlands, 1989, p. 73.

[57] J.-W. Pan, D. Bouwmeester, M. Daniell, H. Weinfurter, A. Zeilinger, Experimental test of quantum nonlocality in three-photon greenberger-horne-zeilinger entanglement, Nature 403 (6769) (2000) 515–519.
URL http://dx.doi.org/10.1038/35000514

[58] C. Zhang, Y.-F. Huang, Z. Wang, B.-H. Liu, C.-F. Li, G.-C. Guo, Experimental greenberger-horne-zeilinger-type six-photon quantum nonlocality, Phys. Rev. Lett.doi:10.1103/PhysRevLett.115.260402.
URL https://link.aps.org/doi/10.1103/PhysRevLett.115.260402

[59] J.-W. Pan, Z.-B. Chen, C.-Y. Lu, H. Weinfurter, A. Zeilinger, M. Żukowski, Multiphoton entanglement and interferometry, Rev. Mod. Phys.doi:10.1103/RevModPhys.84.777.
URL https://link.aps.org/doi/10.1103/RevModPhys.84.777

[60] C.-Y. Lu, X.-Q. Zhou, O. Guhne, W.-B. Gao, J. Zhang, Z.-S. Yuan, A. Goebel, T. Yang, J.-W. Pan, Experimental entanglement of six photons in graph states, Nat Phys 3 (2) (2007) 91–95.
URL http://dx.doi.org/10.1038/nphys507

[61] Y.-F. Huang, B.-H. Liu, L. Peng, Y.-H. Li, L. Li, C.-F. Li, G.-C. Guo, Experimental generation of an eight-photon greenberger–horne–zeilinger state, Nature Communications 2 (2011) 546 EP –.
URL http://dx.doi.org/10.1038/ncomms1556

[62] X.-C. Yao, T.-X. Wang, P. Xu, H. Lu, G.-S. Pan, X.-H. Bao, C.-Z. Peng, C.-Y. Lu, Y.-A. Chen, J.-W. Pan, Observation of eight-photon entanglement, Nat Photon 6 (4) (2012) 225–228.
URL http://dx.doi.org/10.1038/nphoton.2011.354

[63] H. J. Briegel, R. Raussendorf, Persistent entanglement in arrays of interacting particles, Phys. Rev. Lett. 85 (2001) 910.

[64] R. Raussendorf, D. E. Browne, H. J. Briegel, Measurement-based quantum computation on cluster states, Phys. Rev. A 68 (2003) 022312.

[65] A. Mantri, T. F. Demarie, J. F. Fitzsimons, Universality of quantum computation with cluster states and (x, y)-plane measurements, Scientific Reports 7 (2017) 42861 EP –.
URL http://dx.doi.org/10.1038/srep42861

[66] P. Walther, K. J. Resch, T. Rudolph, E. Schenck, H. Weinfurter, V. Vedral, M. Aspelmeyer, A. Zeilinger, Experimental one-way quantum computing, Nature (London) 434 (2005) 169.

[67] R. Prevedel, P. Walther, F. Tiefenbacher, P. Bohi, R. Kaltenbaek, T. Jennewein, A. Zeilinger, High-speed linear optics quantum computing using active feed-forward, Nature 445 (7123) (2007) 65–69.
URL http://dx.doi.org/10.1038/nature05346

[68] Y. Tokunaga, S. Kuwashiro, T. Yamamoto, M. Koashi, N. Imoto, Generation of high-fidelity four-photon cluster state and quantum-domain demonstration of one-way quantum computing, Phys. Rev. Lett.doi:10.1103/PhysRevLett.100.210501.
URL https://link.aps.org/doi/10.1103/PhysRevLett.100.210501

[69] I. Schwartz, D. Cogan, E. R. Schmidgall, Y. Don, L. Gantz, O. Kenneth, N. H. Lindner, D. Gershoni, Deterministic generation of a cluster state of entangled photons, Sciencedoi:10.1126/science.aah4758.
URL http://science.sciencemag.org/content/early/2016/09/07/science.aah4758

[70] S. Yokoyama, R. Ukai, S. C. Armstrong, C. Sornphiphatphong, T. Kaji, S. Suzuki, J.-i. Yoshikawa, H. Yonezawa, N. C. Menicucci, A. Furusawa, Ultra-large-scale continuous-variable cluster states multiplexed in the time domain, Nat Photon 7 (12) (2013) 982–986.
URL http://dx.doi.org/10.1038/nphoton.2013.287

[71] P. P. Rohde, Simple scheme for universal linear-optics quantum computing with constant experimental complexity using fiber loops, Phys. Rev. Adoi:10.1103/PhysRevA.91.012306.
URL https://link.aps.org/doi/10.1103/PhysRevA.91.012306

[72] R. H. Hadfield, Single-photon detectors for optical quantum information applications, Nat Photon 3 (12) (2009) 696–705.
URL http://dx.doi.org/10.1038/nphoton.2009.230

[73] M. Eisaman, J. Fan, A. Migdall, S. Polyakov, Invited review article: Single-photon sources and detectors, Review of Scientific Instrumentsdoi:http://dx.doi.org/10.1063/1.3610677.
URL http://aip.scitation.org/doi/full/10.1063/1.3610677

[74] J. Sperling, W. Vogel, G. S. Agarwal, True photocounting statistics of multiple on-off detectors, Phys. Rev. Adoi:10.1103/PhysRevA.85.023820.
URL https://link.aps.org/doi/10.1103/PhysRevA.85.023820

[75] A. Divochiy, F. Marsili, D. Bitauld, A. Gaggero, R. Leoni, F. Mattioli, A. Korneev, V. Seleznev, N. Kaurova, O. Minaeva, G. Gol'tsman, K. G. Lagoudakis, M. Benkhaoul, F. Levy, A. Fiore, Superconducting nanowire photon-number-resolving detector at telecommunication wavelengths, Nat Photon 2 (5) (2008) 302–306.
URL http://dx.doi.org/10.1038/nphoton.2008.51

[76] D. A. Kalashnikov, S.-H. Tan, T. S. Iskhakov, M. V. Chekhova, L. A. Krivitsky, Measurement of two-mode squeezing with photon number resolving multipixel detectors, Opt. Lett.doi:10.1364/OL.37.002829.
URL http://ol.osa.org/abstract.cfm?URI=ol-37-14-2829

[77] R. Chrapkiewicz, W. Wasilewski, K. Banaszek, High-fidelity spatially resolved multiphoton counting for quantum imaging applications, Opt. Lett.doi:10.1364/OL.39.005090.
URL http://ol.osa.org/abstract.cfm?URI=ol-39-17-5090

[78] D. J. Brod, J. Combes, Passive cphase gate via cross-kerr nonlinearities, Phys. Rev. Lett.doi:10.1103/PhysRevLett.117.080502.
URL https://link.aps.org/doi/10.1103/PhysRevLett.117.080502

[79] P. Kok, W. J. Munro, K. Nemoto, T. C. Ralph, J. P. Dowling, G. J. Milburn, Linear optical quantum computing with photonic qubits, Rev. Mod. Phys. 79 (2005) 135.

[80] B. J. Metcalf, J. B. Spring, P. C. Humphreys, N. Thomas-Peter, M. Barbieri, W. S. Kolthammer, X.-M. Jin, N. K. Langford, D. Kundys, J. C. Gates, B. J. Smith, P. G. R. Smith, I. A. Walmsley, Quantum teleportation on a photonic chip, Nat Photon 8 (10) (2014) 770–774.
URL http://dx.doi.org/10.1038/nphoton.2014.217

[81] J. Carolan, C. Harrold, C. Sparrow, E. Martín-López, N. J. Russell, J. W. Silverstone, P. J. Shadbolt, N. Matsuda, M. Oguma, M. Itoh, G. D. Marshall, M. G. Thompson, J. C. F. Matthews, T. Hashimoto, J. L. O'Brien, A. Laing, Universal linear optics, Sciencedoi:10.1126/science.aab3642.
URL http://science.sciencemag.org/content/early/2015/07/08/science.aab3642

[82] X.-S. Ma, T. Herbst, T. Scheidl, D. Wang, S. Kropatschek, W. Naylor, B. Wittmann, A. Mech, J. Kofler, E. Anisimova, V. Makarov, T. Jennewein, R. Ursin, A. Zeilinger, Quantum teleportation over 143 kilometres using active feed-forward, Nature 489 (7415) (2012) 269–273.
URL http://dx.doi.org/10.1038/nature11472

[83] M. Miková, H. Fikerová, I. Straka, M. Mičuda, J. Fiurášek, M. Ježek, M. Dušek, Increasing efficiency of a linear-optical quantum gate using electronic feed-forward, Phys. Rev. Adoi:10.1103/PhysRevA.85.012305.
URL https://link.aps.org/doi/10.1103/PhysRevA.85.012305

[84] T.-M. Zhao, H. Zhang, J. Yang, Z.-R. Sang, X. Jiang, X.-H. Bao, J.-W. Pan, Entangling different-color photons via time-resolved measurement and active feed forward, Phys. Rev. Lett.doi:10.1103/PhysRevLett.112.103602.
URL https://link.aps.org/doi/10.1103/PhysRevLett.112.103602

[85] X.-Q. Zhou, T. C. Ralph, P. Kalasuwan, M. Zhang, A. Peruzzo, B. P. Lanyon, J. L. O'Brien, Adding control to arbitrary unknown quantum operations, Nature Communications 2 (2011) 413 EP –.
URL http://dx.doi.org/10.1038/ncomms1392

[86] B. P. Lanyon, M. Barbieri, M. P. Almeida, T. Jennewein, T. C. Ralph, K. J. Resch, G. J. Pryde, J. L. O/'Brien, A. Gilchrist, A. G. White, Simplifying quantum logic using higher-dimensional hilbert spaces, Nat Phys 5 (2) (2009) 134–140.
URL http://dx.doi.org/10.1038/nphys1150

[87] X.-L. Wang, X.-D. Cai, Z.-E. Su, M.-C. Chen, D. Wu, L. Li, N.-L. Liu, C.-Y. Lu, J.-W. Pan, Quantum teleportation of multiple degrees of freedom of a single photon, Nature 518 (7540) (2015) 516–519.
URL http://dx.doi.org/10.1038/nature14246

[88] M. Mičuda, M. Sedlák, I. Straka, M. Miková, M. Dušek, M. Ježek, J. Fiurášek, Efficient experimental estimation of fidelity of linear optical quantum toffoli gate, Phys. Rev. Lett.doi:10.1103/PhysRevLett.111.160407.

URL https://link.aps.org/doi/10.1103/PhysRevLett.111.160407

[89] R. B. Patel, J. Ho, F. Ferreyrol, T. C. Ralph, G. J. Pryde, A quantum fredkin gate, Science Advances 2 (3). doi:10.1126/sciadv.1501531.
URL http://advances.sciencemag.org/content/2/3/e1501531

[90] R. Stárek, M. Mičuda, M. Miková, I. Straka, M. Dušek, M. Ježek, J. Fiurášek, Experimental investigation of a four-qubit linear-optical quantum logic circuit, Scientific Reports 6 (2016) 33475 EP –.
URL http://dx.doi.org/10.1038/srep33475

[91] J. H. Shapiro, Single-photon kerr nonlinearities do not help quantum computation, Phys. Rev. Adoi:10.1103/PhysRevA.73.062305.
URL https://link.aps.org/doi/10.1103/PhysRevA.73.062305

[92] J. H. Shapiro, M. Razavi, Continuous-time cross-phase modulation and quantum computation, New J. Phys. 9 (2007) 16.

[93] J. Gea-Banacloche, Impossibility of large phase shifts via the giant kerr effect with single-photon wave packets, Phys. Rev. Adoi:10.1103/PhysRevA.81.043823.
URL https://link.aps.org/doi/10.1103/PhysRevA.81.043823

[94] I.-C. Hoi, A. F. Kockum, T. Palomaki, T. M. Stace, B. Fan, L. Tornberg, S. R. Sathyamoorthy, G. Johansson, P. Delsing, C. M. Wilson, Giant cross˜kerr effect for propagating microwaves induced by an artificial atom, Phys. Rev. Lett.doi:10.1103/PhysRevLett.111.053601.
URL https://link.aps.org/doi/10.1103/PhysRevLett.111.053601

[95] V. Venkataraman, K. Saha, A. L. Gaeta, Phase modulation at the few-photon level for weak-nonlinearity-based quantum computing, Nat Photon 7 (2) (2013) 138—141.
URL http://dx.doi.org/10.1038/nphoton.2012.283

[96] A. Feizpour, M. Hallaji, G. Dmochowski, A. M. Steinberg, Observation of the nonlinear phase shift due to single post-selected photons, Nat Phys 11 (11) (2015) 905–909.
URL http://dx.doi.org/10.1038/nphys3433

[97] K. M. Beck, M. Hosseini, Y. Duan, V. Vuleti?, Large conditional single-photon cross-phase modulation, Proceedings of the National Academy of Sciences 113 (35) (2016) 9740–9744. doi:10.1073/pnas.1524117113.
URL http://www.pnas.org/content/113/35/9740.abstract

[98] B. Peropadre, A. Aspuru-Guzik, J. J. García-Ripoll, Equivalence between spin hamiltonians and boson sampling, Phys. Rev. Adoi:10.1103/PhysRevA.95.032327.
URL https://link.aps.org/doi/10.1103/PhysRevA.95.032327

[99] A. Crespi, R. Osellame, R. Ramponi, D. J. Brod, E. F. Galvao, N. Spagnolo, C. Vitelli, E. Maiorino, P. Mataloni, F. Sciarrino, Integrated multimode interferometers with arbitrary designs for photonic boson sampling, Nat Photon 7 (7) (2013) 545–549.
URL http://dx.doi.org/10.1038/nphoton.2013.112

[100] A. P. Lund, A. Laing, S. Rahimi-Keshari, T. Rudolph, J. L. O'Brien, T. C. Ralph, Boson sampling from a gaussian state, Phys. Rev. Lett.doi:10.1103/PhysRevLett.113.100502.
URL https://link.aps.org/doi/10.1103/PhysRevLett.113.100502

[101] M. Bentivegna, N. Spagnolo, C. Vitelli, F. Flamini, N. Viggianiello, L. Latmiral, P. Mataloni, D. J. Brod, E. F. Galvão, A. Crespi, R. Ramponi, R. Osellame, F. Sciarrino, Experimental scattershot boson sampling, Science Advances 1 (3). doi:10.1126/sciadv.1400255.
URL http://advances.sciencemag.org/content/1/3/e1400255

[102] P. P. Rohde, K. R. Motes, P. A. Knott, J. Fitzsimons, W. J. Munro, J. P. Dowling, Evidence for the conjecture that sampling generalized cat states with linear optics is hard, Phys. Rev. Adoi:10.1103/PhysRevA.91.012342.
URL https://link.aps.org/doi/10.1103/PhysRevA.91.012342

[103] V. Tamma, S. Laibacher, Multiboson correlation interferometry with multimode thermal sources, Phys. Rev. Adoi:10.1103/PhysRevA.90.063836.
URL https://link.aps.org/doi/10.1103/PhysRevA.90.063836

[104] J. Huh, G. G. Guerreschi, B. Peropadre, J. R. McClean, A. Aspuru-Guzik, Boson sampling for molecular vibronic spectra, Nat Photon 9 (9) (2015) 615–620.
URL http://dx.doi.org/10.1038/nphoton.2015.153

[105] C. Gogolin, M. Kliesch, L. Aolita, J. Eisert, Boson-sampling in the light of sample complexityarXiv:arXiv:1306.3995.

[106] S. Aaronson, A. Arkhipov, Bosonsampling is far from uniformarXiv:arXiv:1309.7460.

[107] N. Spagnolo, C. Vitelli, M. Bentivegna, D. J. Brod, A. Crespi, F. Flamini, S. Giacomini, G. Milani, R. Ramponi, P. Mataloni, R. Osellame, E. F. Galvao, F. Sciarrino, Experimental validation of photonic boson sampling, Nat Photon 8 (8) (2014) 615–620.
URL http://dx.doi.org/10.1038/nphoton.2014.135

[108] J. Carolan, M. D. A., P. J. Shadbolt, N. J. Russell, N. Ismail, K. Wörhoff, T. Rudolph, M. G. Thompson, J. L. O'Brien, M. C. F., A. Laing, On the experimental verification of quantum complexity in linear optics, Nat Photon 8 (8) (2014) 621–626.
URL http://dx.doi.org/10.1038/nphoton.2014.152

[109] M. Walschaers, J. Kuipers, J.-D. Urbina, K. Mayer, M. C. Tichy, K. Richter, A. Buchleitner, Statistical benchmark for bosonsampling, New Journal of Physics 18 (3) (2016) 032001.
URL http://stacks.iop.org/1367-2630/18/i=3/a=032001

[110] M. C. Tichy, K. Mayer, A. Buchleitner, K. Mølmer, Stringent and efficient assessment of boson-sampling devices, Phys. Rev. Lett.doi:10.1103/PhysRevLett.113.020502.
URL https://link.aps.org/doi/10.1103/PhysRevLett.113.020502

[111] A. Crespi, R. Osellame, R. Ramponi, M. Bentivegna, F. Flamini, N. Spagnolo, N. Viggianiello, L. Innocenti, P. Mataloni, F. Sciarrino, Suppression law of quantum states in a 3d photonic fast fourier transform chip, Nature Communications 7 (2016) 10469 EP –.
URL http://dx.doi.org/10.1038/ncomms10469

[112] M.-H. Yung, X. Gao, J. Huh, Universal bound on sampling bosons in linear optics, arXiv:1608.00383.

[113] P. P. Rohde, T. C. Ralph, Error tolerance of the boson-sampling model for linear optics quantum computing, Phys. Rev. Adoi:10.1103/PhysRevA.85.022332.
URL https://link.aps.org/doi/10.1103/PhysRevA.85.022332

[114] A. Leverrier, R. García-Patrón, Analysis of circuit imperfections in bosonsampling, Quantum Information & Computation 15 0489–0512.

[115] V. S. Shchesnovich, Sufficient condition for the mode mismatch of single photons for scalability of the boson-sampling computer, Phys. Rev. A doi:10.1103/PhysRevA.89.022333.
URL https://link.aps.org/doi/10.1103/PhysRevA.89.022333

[116] V. Tamma, S. Laibacher, Boson sampling with non-identical single photons, Journal of Modern Optics 63 (1) (2016) 41–45. doi:10.1080/09500340.2015.1088096.
URL http://dx.doi.org/10.1080/09500340.2015.1088096

[117] M. C. Tichy, Sampling of partially distinguishable bosons and the relation to the multidimensional permanent, Phys. Rev. A doi:10.1103/PhysRevA.91.022316.
URL https://link.aps.org/doi/10.1103/PhysRevA.91.022316

[118] K. R. Motes, J. P. Dowling, A. Gilchrist, P. P. Rohde, Implementing bosonsampling with time-bin encoding: Analysis of loss, mode mismatch, and time jitter, Phys. Rev. A doi:10.1103/PhysRevA.92.052319.
URL https://link.aps.org/doi/10.1103/PhysRevA.92.052319

[119] I. M. Georgescu, S. Ashhab, F. Nori, Quantum simulation, Rev. Mod. Phys. doi:10.1103/RevModPhys.86.153.
URL https://link.aps.org/doi/10.1103/RevModPhys.86.153

[120] I. Buluta, F. Nori, Quantum simulators, Science 326 (5949) (2009) 108–111. doi:10.1126/science.1177838.
URL http://science.sciencemag.org/content/326/5949/108

[121] A. Aspuru-Guzik, P. Walther, Photonic quantum simulators, Nat Phys 8 (4) (2012) 285–291.
URL http://dx.doi.org/10.1038/nphys2253

[122] L. P., W. D., G. G., G. E., A. P., Kassal I., B. D., Mohseni M., P. J., Barbieri M., Aspuru-Guzik A., W. G., Towards quantum chemistry on a quantum computer, Nat Chem 2 (2) (2010) 106–111.
URL http://dx.doi.org/10.1038/nchem.483

[123] X.-s. Ma, B. Dakic, W. Naylor, A. Zeilinger, P. Walther, Quantum simulation of the wavefunction to probe frustrated heisenberg spin systems, Nat Phys 7 (5) (2011) 399–405.
URL http://dx.doi.org/10.1038/nphys1919

[124] D. González Olivares, B. Peropadre, A. Aspuru-Guzik, J. J. García-Ripoll, Quantum simulation with a boson sampling circuit, Phys. Rev. A doi:10.1103/PhysRevA.94.022319.
URL https://link.aps.org/doi/10.1103/PhysRevA.94.022319

[125] T. Kitagawa, M. A. Broome, A. Fedrizzi, M. S. Rudner, E. Berg, I. Kassal, A. Aspuru-Guzik, E. Demler, A. G. White, Observation of topologically protected bound states in photonic quantum walks 3 (2012) 882 EP –.
URL http://dx.doi.org/10.1038/ncomms1872

[126] A. Schreiber, K. N. Cassemiro, V. Potoček, A. Gábris, I. Jex, C. Silberhorn, Decoherence and disorder in quantum walks: From ballistic spread to localization, Phys. Rev. Lett. doi:10.1103/PhysRevLett.106.180403.
URL https://link.aps.org/doi/10.1103/PhysRevLett.106.180403

[127] L. Sansoni, F. Sciarrino, G. Vallone, P. Mataloni, A. Crespi, R. Ramponi, R. Osellame, Two-particle bosonic-fermionic quantum walk via integrated photonics, Phys. Rev. Lett. doi:10.1103/PhysRevLett.108.010502.
URL https://link.aps.org/doi/10.1103/PhysRevLett.108.010502

[128] J. C. F. Matthews, K. Poulios, J. D. A. Meinecke, A. Politi, A. Peruzzo, N. Ismail, K. Wörhoff, M. G. Thompson, J. L. O'Brien, Observing fermionic statistics with photons in arbitrary processes 3 (2013) 1539 EP –.
URL http://dx.doi.org/10.1038/srep01539

[129] R. Keil, C. Poli, M. Heinrich, J. Arkinstall, G. Weihs, H. Schomerus, A. Szameit, Universal sign control of coupling in tight-binding lattices, Phys. Rev. Lett. doi:10.1103/PhysRevLett.116.213901.
URL https://link.aps.org/doi/10.1103/PhysRevLett.116.213901

[130] Y.-J. Han, R. Raussendorf, L.-M. Duan, Scheme for demonstration of fractional statistics of anyons in an exactly solvable model, Phys. Rev. Lett. doi:10.1103/PhysRevLett.98.150404.
URL https://link.aps.org/doi/10.1103/PhysRevLett.98.150404

[131] J. K. Pachos, W. Wieczorek, C. Schmid, N. Kiesel, R. Pohlner, H. Weinfurter, Revealing anyonic features in a toric code quantum simulation, New Journal of Physics 11 (8) (2009) 083010.
URL http://stacks.iop.org/1367-2630/11/i=8/a=083010

[132] C.-Y. Lu, W.-B. Gao, O. Gühne, X.-Q. Zhou, Z.-B. Chen, J.-W. Pan, Demonstrating anyonic fractional statistics with a six-qubit quantum simulator, Phys. Rev. Lett. doi:10.1103/PhysRevLett.102.030502.
URL https://link.aps.org/doi/10.1103/PhysRevLett.102.030502

[133] F. Caruso, N. Spagnolo, C. Vitelli, F. Sciarrino, M. B. Plenio, Simulation of noise-assisted transport via optical cavity networks, Phys. Rev. A doi:10.1103/PhysRevA.83.013811.
URL https://link.aps.org/doi/10.1103/PhysRevA.83.013811

[134] S. Viciani, S. Gherardini, M. Lima, M. Bellini, F. Caruso, Disorder and dephasing as control knobs for light transport in optical fiber cavity networks 6 (2016) 37791 EP –.
URL http://dx.doi.org/10.1038/srep37791

[135] V. Giovannetti, S. Lloyd, L. Maccone, Quantum-enhanced measurements: Beating the standard quantum limit, Science 306 (5700) (2004) 1330–1336. doi:10.1126/science.1104149.
URL http://science.sciencemag.org/content/306/5700/1330

[136] J. P. Dowling, Quantum optical metrology–the lowdown on high-n00n states, Contemporary Physics 49 (2) (2008) 125–143. doi:10.1080/00107510802091298.
URL http://dx.doi.org/10.1080/00107510802091298

[137] V. Giovannetti, S. Lloyd, L. Maccone, Advances in quantum metrology, Nat Photon 5 (4) (2011) 222–229.
URL http://dx.doi.org/10.1038/nphoton.2011.35

[138] M. Szczykulska, T. Baumgratz, A. Datta, Multi-parameter quantum metrology, Advances in Physics: X 1 (4) (2016) 621–639. doi:10.1080/23746149.2016.1230476.

URL http://dx.doi.org/10.1080/23746149.2016.1230476

[139] T. Baumgratz, A. Datta, Quantum enhanced estimation of a multidimensional field, Phys. Rev. Lett.doi:10.1103/PhysRevLett.116.030801.
URL https://link.aps.org/doi/10.1103/PhysRevLett.116.030801

[140] M. A. Ciampini, N. Spagnolo, C. Vitelli, L. Pezzè, A. Smerzi, F. Sciarrino, Quantum-enhanced multiparameter estimation in multiarm interferometers, Scientific Reports 6 (2016) 28881 EP –.
URL http://dx.doi.org/10.1038/srep28881