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ABSTRACT

We review the rapid recent progress in single-photon sources based on multiplexing multiple probabilistic photon-creation events. Such multiplexing allows higher single-photon probabilities and lower contamination from higher-order photon states. We study the requirements for multiplexed sources and compare various approaches to multiplexing using different degrees of freedom.

I. INTRODUCTION

Single-photon sources, inherently nonclassical in their nature, are quite distinct from the light sources of a century ago. Since the first efforts toward building nonclassical sources of light a half century ago,[1,2] significant progress has been made. Now, sources that produce photons in pairs, allowing for the heralding of a single photon, are the workhorse for a wide array of applications from tests of fundamental physics[3,4] to metrology[5,6] and to even entanglement-enhanced microscopy.[7] Systems built from sources of photon pairs rely on either spontaneous parametric down-conversion (PDC) or spontaneous four-wave mixing (FWM) and can now reach production rates of millions of heralded single photons per second in controlled states[8] with tailored spectral properties[9,10] and near-perfect spatial modes.[11] However, because these nonlinear optical processes are probabilistic, they cannot simultaneously achieve a high probability of producing a photon and a high single-photon fidelity[12] (see the Appendix for detailed definitions). This inherent trade-off can be a severe constraint in many applications.

The multiplexing of many of these probabilistic single-photon sources offers a path to overcoming this trade-off. By having many low-probability, but high-fidelity, heralded single-photon sources, it is possible to create a system that boosts the probability of successfully generating an output while retaining high single-photon fidelity. Multiplexing in such sources is achieved through the use of time, space, and/or frequency degrees of freedom to parallelize the spontaneous photon creation in a number of different modes and then actively switch the photons into a single output mode based on feedback from heralding detection events.

We will review the history and recent rapid progress in this exciting field. From a few theoretical proposals near the year 2000, the field has sharply grown: numerous distinct multiplexing schemes have been proposed with ≈9 experiments realized in the last three years alone (plus many more relying on similar ideas or technologies) and that rate is increasing. It seems likely that through the use of source multiplexing, one can expect states with ten photons at rates of $\approx 10^3$/s and states of 50 photons in some finite time are no longer a pipe dream. This should be enough for a conclusive quantum advantage over classical computers.[13]

This paper is organized as follows: first, we discuss photon source issues, in general, and provide definitions for single-photon and related metrological parameters. Then, we give a brief history of the field of source multiplexing and show how and why multiplexing helps photon sources; next, we discuss requirements for multiplexed single-photon sources, including the required performance of the heralded sources, the switches, and the heralding detectors. Then, we compare the different degrees of freedom that allow multiplexing. Finally, we provide an outlook and possible future directions.

A. Single-photon sources

An ideal single-photon source is one that produces a single photon in a known single mode each and every time one is called for, and that mode must be identical each time. That is what is meant by an *on-demand* single-photon source. While this ideal source can never be achieved in the real world due to inevitable losses and nonzero multiphoton rates, there have been efforts at making better and better approximations to such an ideal source. There are two basic approaches to constructing single-photon sources (beyond the original approximation to single photons of strongly attenuated laser light,[14] which is limited to ≈37% fidelity due to the photon statistics of coherent states). Current single-photon sources (Fig. 1) are based either on the isolated single quantum systems that can only emit one photon at a time or on sources that emit photons in pairs so that the detection of one photon heralds the existence of the second photon. While the isolated quantum systems are often called *deterministic* sources (because they can, in principle, produce a single photon on demand with no other noise or higher-order photon terms), in practice, there is always some level of residual noise and the efficiency of photon collection is less than 100%. The difference between *deterministic* and *on-demand* sources is that the former produce photons at certain fixed times, whereas the latter can produce them at arbitrary times. This distinction can be blurred by reconfigurable delay lines or by pumping schemes or storage cavities that are necessarily periodic, e.g., mode-locked lasers. By contrast, the pair sources used to herald single photons are called *probabilistic* sources, since one cannot know even, in principle, when a heralding signal will come, but when and only when it does come, the existence of the output photon is guaranteed. In reality, the line between deterministic and probabilistic is rather a continuum. Deterministic sources become more probabilistic as extraction and coupling efficiencies to other systems (such as fibers) decrease, and probabilistic sources can become more deterministic by multiplexing.

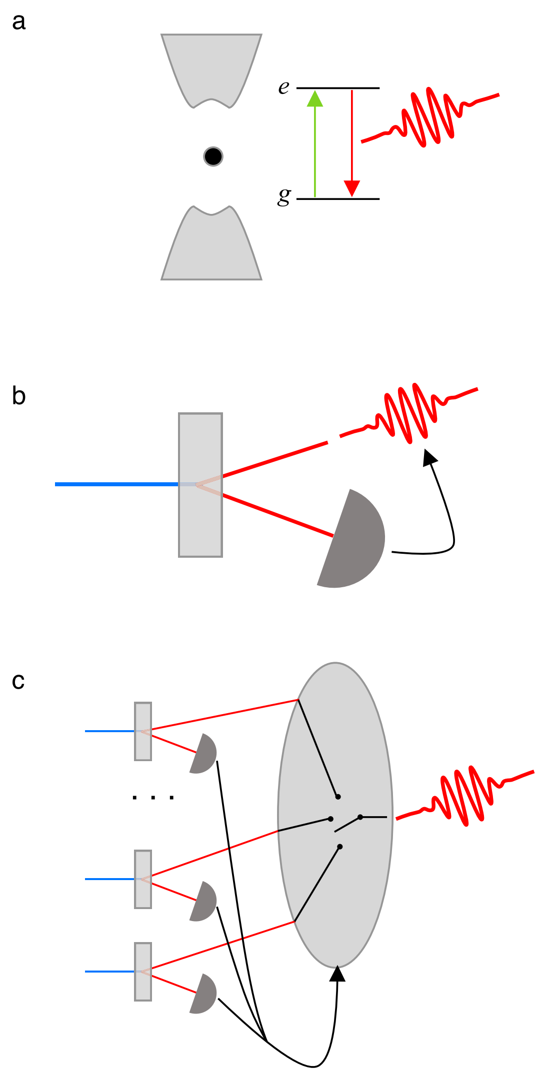

FIG. 1. Types of single-photon sources: (a) isolated quantum systems (e.g., a single particle in an optical cavity with ground *g* and excited *e* states), (b) heralded single-photon sources from photon pairs, and (c) multiplexed source (as one example, spatial multiplexing is shown).

Each of these approaches has advantages and drawbacks. With nonlinear-optical pair sources (and faint laser sources), the probability of one- and two-photon pair excitations is strongly linked, making optimization of both simultaneously impossible. Thus, these sources are usually operated in the regime of low excitation probability, meaning that the state generated is mostly vacuum, so when a photon is actually produced is unpredictable. However, unlike faint laser sources, the fidelity (after heralding to eliminate the vacuum contribution) of pair sources can be very near unity, as the multiphoton component can be made arbitrarily small,[15] and the indistinguishability can be made high through source engineering.[16] Of deterministic sources, those based on quantum dots suffer from lower indistinguishability and fidelity due to charge fluctuations in their local environment.[17] However, this problem is being addressed by techniques such as resonant pumping[18–21] and efficiencies that continue to increase,[22,23] leading closer to the ideal. There are also efforts to enable deterministic growth and/or placement within an integrated platform.[24] Nitrogen-vacancy and other color centers in crystals are also emerging as reliable quantum emitters,[25,26] though spectral drift in these systems still limits indistinguishability.[27] Single atoms and molecules have also shown promise[28,29] but are arguably more difficult to engineer and integrate than quantum dot-type emitters.

B. Single photons: Definitions

Single photons, that is, single excitations of modes of the electromagnetic field as solutions to Maxwell's equations, are useful in metrology,[5,30] quantum computing,[31,32] imaging,[33,34] quantum communication,[35,36] and randomness generation.[37] (Single-photon *detectors* are used in far wider applications as low-noise low-intensity detectors, but here we focus on applications requiring also single-photon *sources*.) An ideal single photon is in the state $|1\rangle_k$, where k defines the field mode (spatial mode, continuous-wave mode, or pulsed temporal mode) in which the photon resides.

While that is the ideal, often more than one photon will be produced by the source, and once produced, the state always encounters some nonzero optical loss before reaching the application, a transformation that results in a state that contains both vacuum and multiphoton components along with the desired single photon. Furthermore, the photon can also be spread over multiple modes in a superposition or mixture, requiring a sum or integral over k.

As the engineering of single-photon sources improves, the metrology of their performance characteristics becomes more challenging and more critical. While the need for good metrology obviously impacts comparisons of devices and schemes, its use as a diagnostic tool is also key to the advance of these sources.

In surveying the state of development of these devices, it clear that complete reporting of performance data is needed and something we strongly encourage. With that goal in mind, we provide a list of definitions (Appendix, Tables V–VII) and later present a table with performance results as best as can be determined from the available literature (Table III). Unfortunately, the published results are often incomplete and ill defined. Hopefully, this compendium of results will help clarify the progress in the field and suggest standards of reporting of results. Even the missing table entries serve a purpose, highlighting the need for better reporting of results.

For a wider look at single photons and their applications, we refer the reader to many excellent reviews.[38–48]

1. Single-photon fidelity and indistinguishability

One way to assess the quality of the output of a single-photon source is to measure its absolute fidelity to a single photon in a single mode, which is defined as the overlap of the reconstructed output density matrix with $|1\rangle_k$. For the most general case, this is an unheralded fidelity (i.e., without post-selection), which requires quantum state tomography by homodyning.[49] This can be difficult and time-consuming, so other single-photon metrics have been developed. For example, the normalized Glauber second-order correlation $g^{(2)}(0) = \frac{\langle a^\dagger a^\dagger a a\rangle}{\langle a^\dagger a\rangle^2}$ is particularly useful, as it quantifies, independent of losses, the multiphoton component of the state with respect to the single-photon component, i.e., $|n > 1\rangle$ vs $|1\rangle$. We also make use of the heralded fidelity F_{h}, which is the fidelity of the photon to $|1\rangle$ after heralding, but before any losses. This is assessed via the $g^{(2)}(0)$ as it is intrinsically insensitive to losses and, as such, is the fidelity in the subspace excluding the vacuum.

Another characteristic that needs consideration is *indistinguishability*, which is defined as the modal similarity of the photons (spectrum, time, polarization, and space). A subtle point is that this includes the purity of the photon in each of these degrees of freedom, as impure states imply the need for purifications that, in principle, provide distinguishing information. (Indistinguishability is sometimes also used to quantify the interference between two photons from the *same* pair, but we do not consider that here.) The indistinguishability between photons from different sources or between photons from the same source, but generated at different times, is critical for interference experiments. For single emitters, it is often much harder to achieve indistinguishability between different sources due to narrow spectra and differing electronic/magnetic environments, which can cause spectral variations and wandering. Indistinguishability is quantified using the visibility of the Hong–Ou–Mandel interference of the photons.[50,51] Single-photon sources should also not emit noise photons at unwanted or unheralded times. This can be quantified by the *output noise factor*, the ratio of unheralded or untriggered photons to the total photons emitted by the single-photon source.[15,52]

Regarding photon modes, ideal single photons, are in a well-defined spatial mode (e.g., of a single-mode fiber) and nicely behaved spectral-temporal modes (e.g., Fourier-transform-limited Gaussian modes). Unfortunately, photons are often emitted from sources that are spatially multimode, violating the ideal requirement and making coupling to fiber difficult. Photons are often also spectrally multimode, either due to spectral correlations between the two photons of a pair or due to electronic or other noise near the isolated quantum emitters. For the photon pair case, once one is detected, the other is left in a mixture of modes, whose natural basis is given by the Schmidt decomposition of the two-photon joint spectral amplitude.[53] The effective number of contributing modes is then given by the Schmidt number. For the rest of the paper, we assume that the photon has been engineered (meaning that the source is constructed in such a way as to produce intrinsically pure photons without subsequent filtering and the additional loss that comes with it) or filtered (meaning that the photons are strongly filtered to a single mode, decreasing brightness and heralding efficiency) to be spectrally and spatially single-mode.

We can also gain some information looking at the bandwidth and temporal duration of the photons: it is generally desirable to produce an output with a Fourier-transform-limited time-bandwidth product. For the heralded sources, a photon that is transform-limited is also spectrally single mode.[54] For the isolated quantum emitters, transform-limited photons indicate that the long-term noise near the emitter is controlled or eliminated, meaning that the emission frequency is not wandering with time.[18] In both cases, transform-limited photons enable interference applications.

2. Source brightness

The *brightness* of a single-photon source has taken different definitions in different communities, for example, for quantum dots, it is often the probability of receiving a photon per excitation event, while for photon pair sources, it is normally the number of photons per pump pulse or per second, normalized to pump power and sometimes to photon bandwidth. Here, we define it as the probability to have exactly one photon in a single-mode fiber at a given clock cycle, irrespective of whether a heralding detection is received or not. Thus, for a pulsed pair source, brightness can be written as

$$B(\text{unheralded}) = p_{\mathrm{h}} p_{(1|\mathrm{h})} \eta_{\mathrm{coupl}}, \tag{1}$$

where p_{h}, the heralding probability, is the probability of a heralding event per pulse and $p_{(1|\mathrm{h})}$ is the conditional probability of producing a single photon given a heralding event. The coupling from the source to single-mode fiber is η_{coupl}. For an isolated quantum emitter, the brightness is

$$B_{\mathrm{Q}} = p_1 \eta_{\mathrm{coupl}}, \tag{2}$$

as heralding is not relevant, so here we use simply p_1 as the single-photon probability. These two definitions, both defined in terms of a single spatial mode, allow for clear comparison between these two types of sources, at least in most applications. We note that for quantum dot emitters, η_{coupl} is often defined as the collection by the first lens, a much less useful definition than our single-mode-based definition.

The brightness can be assessed by measuring the detection rate in combination with the multiphoton component via $g^{(2)}(0)$. To find brightness from non-photon-number-resolving-detector count rates, we neglect terms beyond two photons such that the click probability in the heralded mode given a heralding signal is

$$p_{\rm click} = S_{\rm det}/S_{\rm h} \approx \eta_{\rm tot} p_{(1|{\rm h})} + \eta_{\rm tot}(2-\eta_{\rm tot}) p_{(2|{\rm h})}, \qquad (3)$$

where $S_{\rm det}$ is the rate of heralded single-photon detections, $S_{\rm h}$ is the heralding rate (or the repetition rate for quantum emitters), $\eta_{\rm tot} = \eta_{\rm coupl}\eta_{\rm det}$ is the total detection efficiency, composed of coupling and detector efficiencies, and $p_{(2|h)}$ is the conditional probability of generating two photons given a heralding event. In addition, the (heralded) second-order correlation can be measured with a 50:50 beamsplitter and two detectors as $g_{\rm h}^{(2)}(0) = \frac{C_{12}S_{\rm h}}{S_{1\rm h}S_{2\rm h}}$. Here, the heralded coincidence rate is C_{12}, and heralded singles rates are $S_{1\rm h(2h)}$. This directly gives $p_{(2|{\rm h})} \approx g_{\rm h}^{(2)}(0)/2$, since $\langle a^\dagger a^\dagger a a\rangle \approx 2p_{(2|{\rm h})}\eta_{\rm tot}^2$ and $\langle a^\dagger a\rangle \approx \eta_{\rm tot}$. Then, the brightness in terms of easily measurable quantities is

$$\begin{aligned} B &= p_{\rm h} p_{(1|{\rm h})}\eta_{\rm coupl} \\ &= p_{\rm h}(p_{\rm click}/\eta_{\rm tot} - (2-\eta_{\rm tot})p_{(2|{\rm h})})\eta_{\rm coupl} \\ &\approx p_{\rm h}(p_{\rm click}/\eta_{\rm tot} - (2-\eta_{\rm tot})g_{\rm h}^{(2)}(0)/2)\eta_{\rm coupl}, \end{aligned} \qquad (4)$$

which can be seen as the heralded click rate, corrected for detector efficiency, minus the fraction of the click rate that is made of two-photon events.

Of course, most applications require not just a single photon one time, but rather a stream of single photons. Thus, the source repetition rate (the rate of attempts to extract a single photon from the source, $R_{\rm src}$) is an important factor in source design with higher source repetition rates allowing, for example, faster experiments and better signal-to-noise ratios. The total rate of usable single photons out of the source is then $R_{\rm src}B$.

3. Efficiencies

In experiments, there are a number of efficiencies at play. For pair sources, the efficiency of transforming pump photons into photon pairs (conversion or generation efficiency) and the coupling efficiency $\eta_{\rm coupl}$ (i.e., loss due to coupling) for both the heralding photons and heralded photons into the single-mode fiber are of critical importance. The total efficiency of detecting a photon given a herald event (comprising coupling efficiency $\eta_{\rm coupl}$ and detector efficiency $\eta_{\rm det}$) is called the Klyshko, heralding, or total efficiency $\eta_{\rm tot}$, given in the low power regime by the ratio of coincidence counts to heralding counts.[55] For single emitters, the excitation efficiency, the quantum efficiency of emitting a photon given the dot is in the excited state, losses due to non-radiative decay,[56] and the coupling efficiency from the dot to the fiber largely determine the brightness.[45] The various sources of non-unit efficiency differ in origin between pair sources and quantum emitters, making comparisons difficult. Thus, we use the brightness to best compare the ultimate performance. To allow for fair comparisons, a delineation of where the source ends and where the transfer to the application begins needs to be clearly made,

II. THE ADVANTAGE OF MULTIPLEXING

In this work, we focus on transforming probabilistic sources (namely, sources based on photon-pair emission) into deterministic via multiplexing. It has been shown in theory[12] and experiment[57] that a single ideal photon-pair source cannot be used to herald single photons with *heralded* fidelity (fidelity to $|1\rangle$ after heralding but before any losses) $F_{\rm h} = 1$ with greater than $p_{\rm h} = 25\%$ heralding probability (i.e., unheralded fidelity $F < 25\%$), and this bound is only achieved if the heralding detector can perfectly resolve the photon number with perfect efficiency. For single-photon detectors that cannot resolve the photon number (bucket, click, or so-called photon-counting detectors that merely declare the presence of one or more photons), the fidelity and heralding probability are bounded[12] as $F_{\rm h} + p_{\rm h} = 1$. Only source multiplexing can break these bounds for the heralded photon sources.

Photon source multiplexing allows independent control of the amplitudes of the emitted photon numbers of the component sources. By allowing many low-probability chances to produce a single photon, the single-photon term for the multiplexed system can be increased without increasing the higher-order terms. To the first order, the output photons maintain the high fidelity of a single, weakly pumped heralded source while increasing the brightness linearly with the number of sources employed. We now examine these scaling arguments in detail.

The general structure of a multiplexed spontaneous source is shown in Fig. 1(c). Multiple pair sources are pumped simultaneously, and each one has its own heralding detector. If one heralding detector fires, the corresponding partner mode is actively routed to the output. If multiple detectors fire, just one of the partner modes is routed to the output, perhaps based on which path is the least lossy. It is key that the other modes, those not selected to route to the output, are removed and not allowed to propagate with the true output mode so that any photons produced in these modes do not pollute the single-photon state.

A. History of multiplexing

The first ideas for multiplexing many down-conversion events to engineer quantum states came as early as 2001.[58] The next year, multiplexing for single-photon generation was independently formalized by Pittman and colleagues for the temporal degree of freedom[59] and by Migdall and colleagues for the spatial degree of freedom.[60] Further theoretical refinements and schemes were provided by Kwiat and colleagues in 2004[61] and 2009,[62] and Shapiro and Wong in 2007,[63] and strong limits mentioned above on the heralding probability and fidelity for single PDC sources were shown to be surpassed with multiplexing in 2012.[12] The Pittman work already included a first experimental demonstration, but it was not until 2011 that a large number of experiments started. A selection of these experiments is summarized by performance in Fig. 2. So far, only quantum-dot sources and time-multiplexing schemes based on bulk optics have outperformed the bounds of non-multiplexed PDC sources.

B. Theory of multiplexing

The two-mode state emerging from a photon pair source is well-described by the squeezed vacuum state,[75]

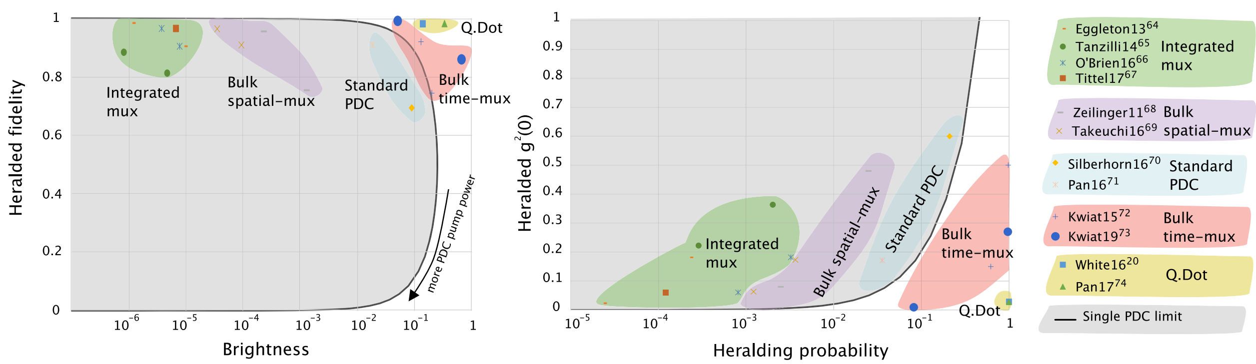

FIG. 2. Experimental source multiplexing (MUX) performance for state-of-the-art single-photon parametric down-conversion (PDC) sources. For comparison, quantum dot performance is also shown. Left: the heralded fidelity to a single photon vs the brightness (i.e., the probability of finding just one photon per pump laser pulse). Single-source PDC brightness is bounded by the black line and limited to the gray region. Optimal sources are toward the upper right, and PDC source multiplexing has outperformed the best quantum dots in brightness. Right: the heralded $g^{(2)}(0)$ (= 0 for ideal single photons) vs the heralding probability. For standard PDC, $g^{(2)}(0)$ is bounded by the black line and limited to the gray region. Currently only bulk time multiplexing and quantum dots have achieved $g^{(2)}(0)$ better than this limit. (Integrated mux.[64–67] Bulk spatial–mux.[68,69] Standard PDC.[70,71] Bulk time–mux.[72,73] Q.Dot.[20,74])

$$|\psi\rangle = \sqrt{1-\lambda^2}\sum_{n=0}^{\infty}\lambda^n|n,n\rangle, \tag{5}$$

with the squeezing parameter r contained in the squeezing strength[75] $\lambda = \tanh r$ and n being the number of signal and idler photons that are each in single mode. It is immediately clear that the probability of generating two photon pairs is directly linked to the probability of generating one, namely, its square. The heralding event by a click detector is represented by the positive operator-valued measure (POVM) element,

$$\hat{\Pi} = \sum_{n=0}^{\infty}\left[1-(1-\eta_{\mathrm{h}})^n\right]|n\rangle\langle n|, \tag{6}$$

where η_{h} is the detection efficiency of the herald including all optical coupling efficiencies and the heralding detector efficiency. Applying those efficiencies to one mode of the PDC state and tracing over the other give the heralding probability,

$$\begin{aligned} p_{\mathrm{h}} &= (1-\lambda^2)\sum_{n=0}^{\infty}[1-(1-\eta_{\mathrm{h}})n]\lambda^{2n} \\ &\approx \eta_{\mathrm{h}}\lambda^2 + (\eta_{\mathrm{h}}-\eta_{\mathrm{h}}^2)\lambda^4, \end{aligned} \tag{7}$$

and the heralded single-photon state,[12]

$$\begin{aligned} \rho &= \frac{1-\lambda^2}{p_{\mathrm{h}}}\sum_{n=0}^{\infty}\left[1-(1-\eta_{\mathrm{h}})^n\right]\lambda^{2n}|n\rangle\langle n| \\ &\approx \frac{\eta_{\mathrm{h}}\lambda^2(1-\lambda^2)|1\rangle\langle 1| + (2\eta_{\mathrm{h}}-\eta_{\mathrm{h}}^2)\lambda^4|2\rangle\langle 2|}{p_{\mathrm{h}}}, \end{aligned} \tag{8}$$

where in each second line, we keep only two orders in λ.

Before we look at the low-power approximation, we can check the fundamental limits of brightness and heralded fidelity for a standard single PDC source. Without optical or detector losses, the heralding probability for click detectors is $p_{\mathrm{h}} = \lambda^2$, then the brightness is $B = p_{\mathrm{h}}p_{(1|\mathrm{h})} = (1-\lambda^2)\lambda^2$ and the heralded fidelity is $F_{\mathrm{h}} = p_{(1|\mathrm{h})} = (1-\lambda^2)$, satisfying the limit $F_{\mathrm{h}} + p_{\mathrm{h}} = 1$, and allowing us to plot the single PDC source limit curves in Fig. 2. The heralded fidelity is lowered only due to multiphoton components and does not include losses on the heralded mode. These losses are instead captured in the brightness through η_{coupl}.

In the low power regime, in order to approach commonly measured quantities, we can directly extract the heralded probability of producing one and two photons as $p_{(1|\mathrm{h})} \approx \eta_{\mathrm{h}}\lambda^2/p_{\mathrm{h}}$ and $p_{(2|\mathrm{h})} \approx (2-\eta_{\mathrm{h}})\eta_{\mathrm{h}}\lambda^4/p_{\mathrm{h}}$, respectively. The brightness is $B = p_{\mathrm{h}}p_{(1|\mathrm{h})}\eta_{\mathrm{coupl}} \approx \eta_{\mathrm{h}}\lambda^2\eta_{\mathrm{coupl}}$, and to second order, the heralded fidelity is

$$F_{\mathrm{h}} = p_{(1|\mathrm{h})} \approx 1 - p_{(2|\mathrm{h})} \approx 1 - \frac{g_{\mathrm{h}}^{(2)}(0)}{2} \approx 1-(2-\eta_{\mathrm{h}})\lambda^2. \tag{9}$$

The heralded $g_{\mathrm{h}}^{(2)}(0)$ can also be related to the coincidences-to-accidentals ratio $CAR = (C-A)/A$, where C is the total number of measured coincidences and A is the measured accidentals,

$$g_{\mathrm{h}}^{(2)}(0) \approx 2(2-\eta_{\mathrm{h}})/CAR. \tag{10}$$

Again, for perfect heralding efficiency, $p_{\mathrm{h}} = \lambda^2$, so $p_{(1|\mathrm{h})} = 1-\lambda^2$, giving $F_{\mathrm{h}} + p_{\mathrm{h}} = p_{(1|\mathrm{h})} + p_{\mathrm{h}} = 1$. Then, the bound $F_{\mathrm{h}} + p_{\mathrm{h}} < 1$ applies for imperfect efficiency. Multiplexing can break this bound.

Instead of a single generated state $|\psi\rangle$, multiplexing uses many generated states, and routes to the output one whose corresponding heralding detector clicks. This K-source state is described by the tensor product,

$$|\psi\rangle^{\otimes K} = \bigotimes_{k=0}^{K}\sqrt{1-\lambda^2}\sum_{n=0}^{\infty}\lambda^n|n,n\rangle. \tag{11}$$

Now, we also have K heralding detectors, and since we want to actually switch the heralded photon to the output mode, we can accept any number >0 of detectors firing. From the geometric distribution, the heralding probability now is

$$\begin{aligned} p_{\mathrm{h,\,mux}} &= 1 - \left(1-(1-\lambda^2)\sum_{n=0}^{\infty}\left[1-(1-\eta_{\mathrm{h}})^n\right]\lambda^{2n}\right)^K \\ &\approx 1-\left(1-\eta_{\mathrm{h}}\lambda^2\right)^K, \end{aligned} \tag{12}$$

which can be interpreted as one minus the probability that none of the heralding detectors fires.

TABLE I. Heralded fidelity and heralding probability for the given source and detection parameters. The first row is the base case of a weakly pumped single source providing 99% heralded fidelity. The next two rows are for a very reachable number of sources of 10, the latter showing the effect of increasing the squeezing strength by a factor of 10. The next row shows what could be achieved with 100 sources. The last two rows show the number of multiplexed sources needed to reach simultaneously 99% fidelity and heralding probability without and with dark counts in the heralding detector, respectively.

Number of multiplexed sources K	Squeezing strength λ^2	Herald detection efficiency η_h (%)	Dark count probability d	Heralded fidelity F_h (%)	Heralding probability p_h (%)
1	0.0083	80	0	99	0.66
10	0.0083	80	0	99	6
10	0.083	80	0	90	50
100	0.0083	80	0	99	48
692	0.0083	80	0	99	99
845	0.0068	80	10^{-5}	99	99

The state after heralding and switching is identical to Eq. (8) and thus has the same heralded fidelity, but the brightness is directly improved with increasing number of sources. Again for lossless detectors, $F_h + p_h \approx 1 - \lambda^2 + K\lambda^2 > 1$, breaking the single-source bound. In fact, for $K \to \infty$ and $\lambda^2 \to 0$, F_h and p_h both approach 1. For a realistic efficiency of $\eta_h = 80\%$, to reach $p_h = F_h = 99\%$ with non-photon-number-resolving detectors requires $\lambda^2 = 0.0083$ and $K = 692$ sources, before any other losses are considered. These and some other cases are summarized in Table I. The large number of sources can also be reduced by using photon number-resolving detectors in the heralding arm, allowing stronger pumping while preserving the fidelity; for details, see Christ and Silberhorn.[12]

Next, we describe the physical requirements for multiplexed photon sources and the effects of imperfections.

III. REQUIREMENTS

A. Probabilistic single-photon sources

A good multiplexed single-photon source starts with a good photon pair source. As shown above, the fidelity of the multiplexed single photon is the same as the heralded single photon from a single source. Thus, photon pair sources used for multiplexing should be low-noise, i.e., their $g_h^{(2)}(0)$ should not exceed $2\lambda^2$, and they should be spatially and spectrally single-mode to allow multiphoton interference. Achieving single-mode operation remains a significant effort in source engineering, and many common sources do not fulfill this condition. Furthermore, the coupling efficiency from the source to the heralding detector and to the multiplexer should be high, as both significantly degrade the achievable improvement. Whether the sources must be bright depends on the application: for optimized single-photon fidelity, many sources of low squeezing strength are needed ($\lambda^2 < 0.01$) such that the multiphoton component of the output state is minimized. By contrast, for the highest rates, the emission probability of each source should also be large enough ($\lambda^2 \approx 0.1$) such that the probability to have a heralding event is high or the number of sources increased. The trade-off is that for high emission probability, the multiphoton component will be large, decreasing the output single-photon fidelity.

Many sources can satisfy these requirements, notably three-wave mixing sources based on bulk[10,76,77] and waveguided[9,78] potassium titanyl phosphate (KTP) [unlike periodically poled lithium niobate (PPLN), which does not produce spectrally single-mode states directly] and bulk potassium dihydrogen phosphate (KDP)[16] crystals. Resonator sources that restrict the photon pairs to single spectral modes are also good candidates.[79,80] Some integrated sources also show reasonably good performance, especially if photons would not have to be coupled off-chip for multiplexing, for example, four-wave mixing in silicon wire waveguides[81] and microdisks,[82] photonic crystals[83] and birefringent[84] fibers, and laser-written silica waveguides.[85]

B. Optical switches

Equally critical to source multiplexing is the switch or switches that receive a signal from the heralding detector to switch the heralded photon into the output mode. Multiplexing schemes have used the integrated switches, such as fast opto-ceramic switches[64,86,87] and electro-optic switches,[65,66] and bulk electro-optic polarization rotating switches, with[61,68] and without[59,69,72] polarization-independent interferometers. Spectral multiplexing requires frequency shifts rather than path switching, which has been accomplished with electro-optic modulators[67] and four-wave mixing.[88] In all cases, the heralded photons must be delayed to allow time to process the heralding signals and activate the switch. Most switching times are short enough that the needed optical delay is dominated by electronic processing time. Delay (or latency) times in source-multiplexing experiments range from 200 ns to 1000 ns, but none of these has been strongly optimized. If this required delay can be met by sending the heralded photons through the optical fiber, and if the photons are at telecom wavelengths, not much loss is encountered. However, in other cases and for scaling to applications, this delay time should be reduced significantly from its current average.

For spatial and temporal multiplexing, the photons pass through switches multiple times, making the insertion loss of the switch a critical parameter. Most integrated switches mentioned above have ≈1 dB loss, while the bulk polarization rotators can reach 0.03 dB.[73] This is one of the contributing factors why the integrated

TABLE II. Switch parameters used in source multiplexing experiments (the last one is relevant but has not yet been used for multiplexing). ∗ indicates the value inferred from similar devices. Other multiplexing works did not report these parameters. Further relevant parameters, such as switch contrast, fall time, maximum burst rate, and minimum on time are not reported.

Type	Rise time (ns)	Maximum rate (MHz)	Transmission (%)	References
Pigtailed electro-optic	300	0.5	79	O'Brien16[66]
Pigtailed ceramic	50	1	79	Mosley17[87]
Pigtailed phase mod.	0.25	...	32	Tittel17[67]
Bragg scattering	2.5	1	74	Gaeta18[88]
Bulk electro-optic	<10*	0.5	99.2	Kwiat18[73]
Cross-phase mod.	<0.4	5	79	Lee18[90]

implementations in Fig. 2 remain on the left part of the graph, as switching loss enters exponentially in the photon rate. However, the integrated switches can be faster than the bulk, allowing the source(s) to be pumped faster, creating a linear speedup in the photon rate. In current implementations, the speed advantage for the integrated switches is not yet large (e.g., 1 MHz[87] maximum repetition rate for the integrated switches vs 0.5 MHz[73] for the bulk), but this gap should grow with continued research. The contrast of the switches should also be high such that only the desired heralded mode is coupled to the output, suppressing unwanted counts from all other modes. This high contrast has been shown in a "multiplexing of one" scheme, wherein the output of a single source is physically gated based on the heralding signal, providing an extremely low output noise factor.[15,52,89] Switch parameters for a number of multiplexing experiments are shown in Table II. A promising new direction is the use of four-wave mixing in interferometers as a switch,[90] which promises rates up to 500 MHz (currently 5 MHz) with losses below 1 dB.

C. Heralding detector

The final important component in source multiplexing is the heralding detector(s), which must be efficient enough to detect a significant fraction of the herald photons, fast enough for high-rate pumping, and have low enough dark counts to avoid heralding the vacuum. In recent years, it is very common to use superconducting nanowire single-photon detectors,[91] as they have the highest overall figure of merit[38] $H = \eta_{\rm det}/(d_{\rm r}\Delta t)$ (defined as the detector efficiency divided by the dark count rate and the timing resolution) and satisfy the requirements above, albeit at the cost of cryogenic operation.

As seen above, the heralding probability for a single source is proportional to the efficiency of detecting the heralding photon. For a fixed pump power, the effect of herald detection efficiency on the heralding probability and heralded fidelity for $K = 20$ and $K = 50$ multiplexed sources is shown in Fig. 3. From Eqs. (9) and (12), we can approximate the number of sources required to surpass the single-source threshold of $F_{\rm h} + p_{\rm h} = 1$, given herald detection efficiency $\eta_{\rm h}$ as

$$K \approx \frac{2-\eta_{\rm h}}{\eta_{\rm h}}, \tag{13}$$

which shows that for lower herald detection efficiency, more sources are required. Assuming weak pumping, this threshold is independent of the pumping strength. Or equivalently, for K sources, a herald detection efficiency of

$$\eta_{\rm h} \approx 2/(K+1) \tag{14}$$

is needed to break the single-source bound.

The dark counts of the heralding detector also play a role. Adding dark counts to the detector POVM[92] [Eq. (6)] and recalculating the heralded single-photon state [Eq. (8)] give

$$\begin{aligned}\rho &= \frac{1-\lambda^2}{p_{\rm h}}\sum_{n=0}^{\infty}\big[1-(1-d)(1-\eta_{\rm h})^n\big]\lambda^{2n}|n\rangle\langle n| \\ &\approx \frac{d|0\rangle\langle 0| + \eta_{\rm h}\lambda^2|1\rangle\langle 1| + (2\eta_{\rm h}-\eta_{\rm h}^2)\lambda^4|2\rangle\langle 2|}{p_{\rm h}},\end{aligned} \tag{15}$$

where d is the dark count probability during the heralding coincidence window and in the limits $\lambda \ll 1$ and $d \ll \lambda$. Now, the heralded fidelity including the vacuum is

$$F_{\rm h} = \frac{\eta_{\rm h}\lambda^2}{p_{\rm h}} \approx \frac{\lambda^2}{d/\eta_{\rm h} + \lambda^2 + (2-\eta_{\rm h})\lambda^4}. \tag{16}$$

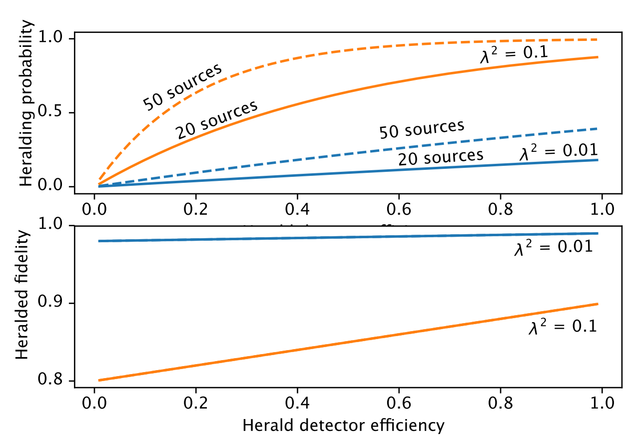

FIG. 3. (Upper) Heralding probability and heralded fidelity for a multiplexed single-photon source with $K = 20$ (solid) and $K = 50$ (dashed) sources vs the efficiency of the heralding detector $\eta_{\rm h}$ for two different squeezing strengths λ. (Lower) The fidelity is independent of the number of sources, while the heralding probability increases with the source number.

Reaching the same 99% fidelity now with $d = 10^{-5}$ instead of a noiseless detector requires decreasing the pump power (lowering the multiphoton contributions to compensate for the vacuum contribution) to $\lambda^2 = 0.0068$, increasing the number of sources required to reach heralding probability 99% from $K = 692$ to $K = 845$ (Table I). However, modern superconducting nanowire detectors have $d < 10^{-7}$ in a 1 ns window, making dark counts largely irrelevant.[91]

Finally, heralding detector dead time can decrease the heralding rate or require adopting detector multiplexing strategies.[93,94] Dead time arises from the need for suppressing afterpulses after the detector fires or, in the case of gated detectors, from the need to reset to a ready state even after a gate with no detection events.[94] Dead time is a bigger problem for temporally multiplexed sources, since just one detector is responsible for detecting all modes, whereas in other multiplexing methods, different detectors are coupled to different source modes.

D. Integrated vs bulk optics

Photon sources, switches, and detectors all exist in both bulk-optic and integrated forms. Integrated optics promise bright sources due to strong confinement and long interaction lengths (however, source engineering is essential to produce spatially and spectrally single-mode photons), high-speed switching enabled by low required voltages, and high-efficiency low-noise detectors due to small active areas and strong interactions. The integrated optics devices are also compact and robust, leading to easier adoptability in applications. However, so far the problems of coupling losses from the chips to external detectors and noise filtering have not been sufficiently solved to permit performance competitive with bulk optics with the notable exception of detection. Here, superconducting nanowire detectors outperform other types of detectors, especially in the telecommunication wavelength bands. They normally require coupling via the optical fiber, but the integration of detectors on waveguide structures is showing promise as the need for off-chip coupling is eliminated.[95,96]

The integrated sources, however, suffer from losses coupling between disparate elements, ≈1 dB (20% loss) per interface,[97] as well as waveguide losses in the source itself (e.g., ≈1 dB over the 196 nm long source waveguide in Ref. 86). Not only are integrated filters lossy, they tend to have low extinction (e.g., 2.8 dB loss for 40 dB extinction in Ref. 98), requiring cascading filters to achieve the required pump and noise suppression.[65] Nonetheless, strong gains are being made all the time in integrated quantum optics, which should allow surpassing bulk-optic performance in a few years, in particular, in scaling to many sources and many photons.[85]

IV. DEGREES OF FREEDOM AND MULTIPLEXING SCHEMES

Now, we present a survey of the various degrees of freedom that have been proposed for multiplexing, and the implementations using them, with experimental results summarized in Table III.

A. Spatial source multiplexing

Spatial multiplexing requires multiple down-conversion events to occur in separate spatial modes, either in the same crystal, e.g., in different directions, or in physically separate crystals (see Fig. 4). First proposed in 2002,[60] it was shown theoretically that it is possible to decouple the probability of producing one and more than one photon by pumping multiple sources simultaneously and placing a heralding detector on each one. When a detector fires, its corresponding partner photon is switched into the output. The first experiment using multiplexed spatial modes came nearly ten years later: Ma *et al.*[68] pumped two beta barium borate (BBO) crystals to produce photon pairs, and additionally polarization entanglement, effectively giving four PDC sources (two spatially separated sources and two polarizations for each source). A fast router based on Pockels cells directed the heralded photons to the output mode.

After this implementation, there were many theoretical refinements in spatial schemes, adding realistic experimental imperfections.[101,102] With an eye toward scalability, modularity was introduced, allowing the connection of many identical components into massive multiplexing setups,[63] particularly to reduce the average number of switches traversed[103–105] or to switch the pump instead to eliminate switching of the single photons entirely[106] and the associated switch loss. This last scheme is sometimes referred to as "dump the pump." A number of schemes combined spatial and temporal multiplexing, increasing the number of sources available to multiplex.[66,107,108] Applications of such sources include BosonSampling[109,110] and quantum key distribution.[111]

In parallel, partially integrated spatial multiplexing took off, pioneered in the Eggleton group, including discrete but waveguided sources and switches,[64,65,86] and fully fiber-based experiments.[98] However, due to high losses, these experiments have not yet approached the single-source limits. A great engineering push to reduce losses is ongoing across the integrated quantum optics community, and this will greatly benefit these multiplexed sources.

One new direction is the spatial multiplexing of atom-photon entanglement in a quantum memory.[112] This allows multiple excitations to be stored in parallel, heralded by the detection of a single photon correlated with each excitation on a single-photon camera. Then, the multiple stored excitations can be emitted simultaneously as a multiphoton state. Switching the arbitrary heralded spatial modes into desired modes remains a challenge.

B. Temporal source multiplexing

A proposal resembling temporal source multiplexing was published in 2001,[58] but the field really began with the experiment of Pittman, Jacobs, and Franson [Fig. 5(a)],[59] published just a month before the first spatial multiplexing proposal.[60] They showed the storage of heralded photons in a free-space loop conditioned on heralding events, with the purpose of providing photons on pseudo-demand. Pseudo-demand here means that the photons can come at any time, but then be stored for an integer number of the roundtrip times of the memory loop and released at a selected, albeit constrained, time. This was followed by analyses by Kwiat and colleagues to put the idea on solid theoretical footing comparable with the spatial case[61] and to introduce the production of Fock states with more than one photon by repeated down-conversion.[62]

Compared to spatial multiplexing, temporal multiplexing can claim a big advantage in the scaling of physical resources (as well

TABLE III. Parameters and metrics for source-multiplexing experiments. In the type of multiplexing, "int." denotes the integrated sources, switches, or both. Values that could not be extracted or estimated from published data are marked with ". . ." For papers with multiple data points, the values with the lowest and highest pump powers are given. The data from Eggleton13a[86] are for the dual-input device.

References	Type	Brightness	Coincidences-to-accidentals ratio	Coupling efficiency (%)	Detector efficiency (%)	Fidelity (heralded) to a single photon	Heralding probability (%)	Heralding rate (counts/s)	Indistinguishability (%)	Klyshko efficiency (%)	Number of multiplexed sources	Second-order correlation function (heralded)	Single-photon rate (counts/s)	Source repetition rate (MHz)	Squeezing strength	Total herald detection efficiency (%)
		B	CAR	η_{coupl}	η_{det}	F_h	p_h	S_h	I	η_{tot}	K	$g^{(2)}(0)$	S_{det}	R_{src}	λ^2	η_h
Franson02[59]	Temporal	. . .	. . .	. . .	. . .	. . .	. . .	3250	. . .	0.31	. . .	. . .	10	. . .	. . .	5
Zeilinger11[68]	Spatial	2.3×10^{-4}	. . .	. . .	. . .	0.96; 0.76	0.25; 2.5	20 000; 200 000	89	0.36	4	0.08; 0.48	714	80	. . .	10
Eggleton13a[86]	Spatial, int.	. . .	15	1	10	. . .	. . .	5000	. . .	0.10	2	. . .	5	. . .	. . .	1
Eggleton13[64]	Spatial, int.	1.2×10^{-6}	170; 22	5	10	0.99; 0.91	0.0024; 0.023	1200; 12 000	. . .	0.50	2	0.02; 0.18	6; 58	50	0.002; 0.023	0.5
Tanzilli14[65]	Spatial, int.	8.2×10^{-7}; 4.7×10^{-6}	18; 11	0.4	14	0.89; 0.82	0.029; 0.2	22 000; 150 000	. . .	0.05	4	0.22; 0.36	11; 77	76	0.007; 0.051	0.8
Kwiat15[72]	Temporal	0.13; 0.20	. . .	81	70	0.93; 0.75	62; 98	31 000; 49 000	. . .	57	30	0.15; 0.5	18 000; 28 000	0.05	0.021; 0.033	42
Eggleton16[99]	Temporal, int.	. . .	75; 21	. . .	. . .	0.97; 0.91	. . .	. . .	91	6.0	4	0.05; 0.18	160; 570	10	. . .	. . .
O'Brien16[66]	Temporal, spatial	3.8×10^{-6}; 7.8×10^{-6}	66; 22	0.5	25	0.97; 0.91	0.081; 0.33	65 000; 260 000	. . .	0.12	8	0.06	80; 190	80	0.048; 0.19	1.6
Takeuchi16[69]	Spatial	3.5×10^{-5}; 9.4×10^{-5}	. . .	3	16	0.97; 0.91	0.12; 0.37	100 000; 300 000	. . .	0.49	2	0.06; 0.17	6000; 18 000	82	. . .	. . .
Mosley16[98]	Spatial, int.	. . .	38; 10	. . .	. . .	0.95; . . .	. . .	. . .	86	. . .	2	0.11; . . .	130; 560	10	. . .	. . .
Mosley17[87]	Temporal, int.	. . .	. . .	. . .	. . .	. . .	3.6; 17	45 000; 210 000	. . .	0.11	4	. . .	50; 363	5	. . .	. . .
Tittel17[67]	Frequency	6.7×10^{-6}	. . .	6	60	0.97	0.012	9717	. . .	3.5	3	0.06	340	80	. . .	. . .
Gaeta18[88]	Frequency	. . .	720; 100	3	53	0.99; 0.97	. . .	170 000; 1 100 000	. . .	1.8	3	0.015; 0.07	3000; 24 000	. . .	. . .	. . .
Kwiat18[73]	Temporal	0.05; 0.67	. . .	31	80	0.996; 0.87	8.2; 97	41 000; 490 000	91	25	40	0.009; 0.27	10 000; 130 000	0.5	0.004; 0.18	55
White16[20]	Quantum dot	0.14	. . .	49	32	0.99	. . .	. . .	71	. . .	. . .	0.029	3.6×10^{6}	80	. . .	. . .
Pan17[74]	Quantum dot	0.34	. . .	. . .	25	0.987	1	. . .	94	. . .	. . .	0.027	6.5×10^{6}	76	. . .	. . .
Pan19[100]	Quantum dot	0.34	. . .	. . .	60–82	0.991	1	. . .	92.3	. . .	. . .	0.018	1.6×10^{7}	76	. . .	. . .

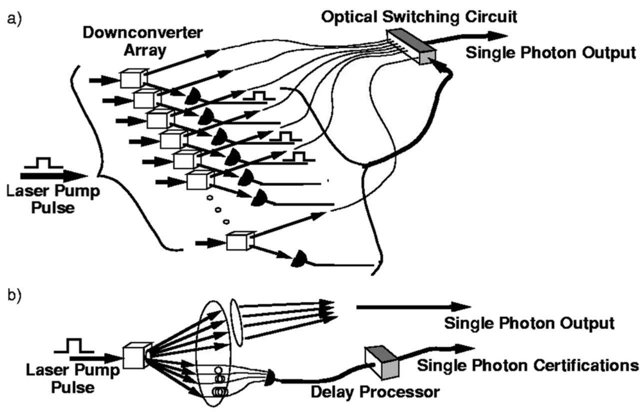

FIG. 4. Proposal for spatial source multiplexing, either using many distinct sources (a) or many spatial modes of a single source (b). Reproduced with permission from Pittman *et al.*, Phys. Rev. A **66**, 042303 (2002). Copyright 2002 American Physical Society.

as the experimental effort in alignment). Since the down-conversion events happen at different times rather than different locations, only one PDC crystal and a single pair of output ports are needed for an arbitrary number of multiplexed modes. This makes scaling to large

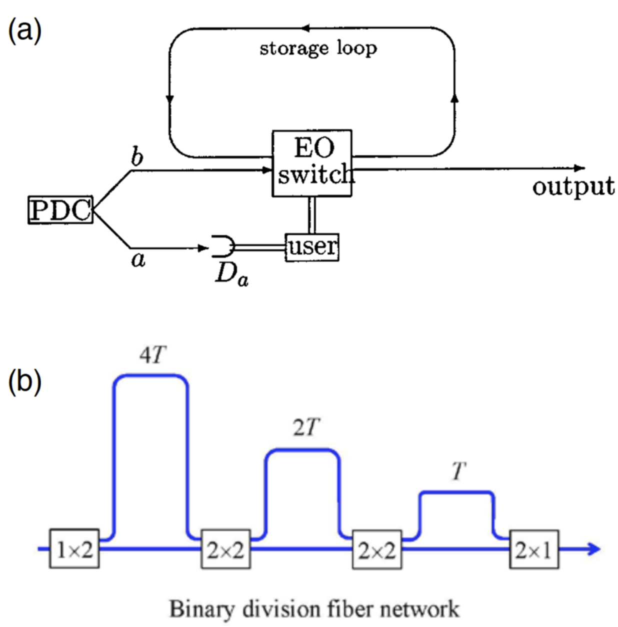

FIG. 5. (a) Schematic for temporal multiplexing using a storage loop, where many temporal modes are pumped, and the one with a herald event is synchronized using a selectable number of roundtrips of the storage loop to the output. Reproduced with permission from Pittman *et al.*, Phys. Rev. A **66**, 042303 (2002). Copyright 2002 American Physical Society. (b) An alternative synchronization method, binary division, where the photon takes the single path with the correct delay length through the fiber network. Reprinted with permission from Latypov *et al.*, J. Phys.: Conf. Ser. **613**, 012009 (2015). Copyright 2015 Author(s), licensed under a Creative Commons Attribution 3.0 Unported License.

multiplexing considerably easier experimentally. However, temporal schemes generally have to run at lower repetition rates than spatial ones, both for the fundamental reason of needing many temporal bins to generate photons and for the practical limitation of slow switching speeds. In the spatial case, any one switch has to operate on average less often than the rate at which photons are produced, but the temporal switch has to switch at least once for each photon.

Relative multiplexing[105,113] of photons, another multiplexing variant, allows multiple photons to synchronize not at a fixed clock time, but at some convenient common time bin, or in the spatial mode that requires least switching. This can improve both temporal and spatial schemes.

Temporal multiplexing can be divided into two main types: those based on networks of delay lines [Fig. 5(b)] and those based on storage cavities or loops [Fig. 5(a)]. Delay lines use a fixed number of fixed-length relative delays to align the heralded photon to an output clock, while storage loops use an arbitrary number of roundtrips in a single path. Examples of delay lines include both on-chip delays[114] and proposals[115] and implementations[66,99,113] using specific fiber lengths. Storage loops have been proposed[116,117] and implemented[87] using fiber loops, proposed with simple free-space linear cavities,[61] and implemented with free-space Herriot cells,[72] providing about the same delays but allowing the use of free-space Pockels cells that have much lower losses than the integrated switches. The best performance so far has come from short free-space ring cavities,[73] with output single-photon probabilities of up to 66.7%, and additionally spectrally engineered pure photons, giving up to $F_\mathrm{h} + p_\mathrm{h} \approx 1.83$, strongly outperforming the single-source limit. Values of $F_\mathrm{h} + p_\mathrm{h}$ for many multiplexing experiments are given in Table IV.

Related to storage loops are delay cavities, which use resonance of the photons for storage and release, rather than polarization or physical switches. These have found use in the continuous-variable community for narrowband photons[118–120] and also in a fully integrated proposal in silicon photonics.[121] Using true quantum memories based on Raman scattering or rare-earth ions has also been proposed to enable time multiplexing.[122] Finally, time multiplexing of spin-wave excitations has been shown to increase atom-photon entanglement rates in the field of quantum repeaters.[123,124]

There is an important point in the bookkeeping of the source repetition rate (the rate of attempts to extract a single photon from the source) of spatial vs temporal source multiplexing. In temporal multiplexing, the source repetition rate is chosen to be compatible with the maximum switching rate. (Note that the switching rate is not to be confused with the switching transition time, which is typically much faster.) In this case, the pump rate is many times faster than the maximum switching rate, which provides for the multiplexing of many pump pulses to one single-photon extraction attempt. In spatial multiplexing, the pump repetition rate equals the source repetition rate (since the multiplexing happens in space rather than in time). However, in current spatial multiplexing experiments, the source is pumped much faster than the maximum switching rate, and the maximum switching rate is enforced after the fact by a holdoff time programmed in switching logic after a heralding event. This holdoff time reduces the single-photon rate, but not the source repetition rate, which remains at the full laser repetition rate. This can be likened to making the photons available on pseudo-demand[59] because they come at random laser pulse times, rather than at

TABLE IV. Best values for the sum of heralding probability and heralded fidelity from multiplexed sources. All values are inferred from published data, the fidelity from the heralded $g^{(2)}(0)$ or CAR and the probability from the heralding rate and experiment clock rate. References where one of these parameters is not provided are not included.

Type	Heralding probability p_h (%)	Heralded fidelity F_h (%)	$p_h + F_h$	Reference
Bulk spatial	0.25	96	0.96	Zeilinger11[68]
Integrated spatial	0.0024	99	0.99	Eggleton13[64]
Integrated spatial	0.029	89	0.89	Tanzilli14[65]
Bulk storage loop	98	75	1.73	Kwiat15[72]
Integrated temporal + spatial	0.081	97	0.97	O'Brien16[66]
Bulk spatial	0.12	99	0.99	Takeuchi16[69]
Integrated spatial	0.091	95	0.95	Mosley16[98]
Integrated spectral	0.012	97	0.97	Tittel17[67]
Bulk storage loop	97	86	1.84	Kwiat19[73]

pre-chosen ones as in the temporal case. The way around this for spatial multiplexing is to select specific pulses (or pulse-pick) from the pump laser to a rate compatible with the switches. This will increase the brightness at the specified clock times, at the cost of lowering the overall per-second photon rate, which may not be a worthwhile trade-off until losses are reduced.

C. Spectral source multiplexing

The newest form of multiplexing uses the frequency degree of freedom, spectrally correlated photon pairs, and spectrally resolved detection of herald photons. For this form, frequency shifting of the heralded photons is employed to switch photons between modes as in Fig. 6. Spectral multiplexing was pioneered using a linear phase ramp from an integrated phase modulator to shift the frequency of the heralded photon depending on the frequency of the herald

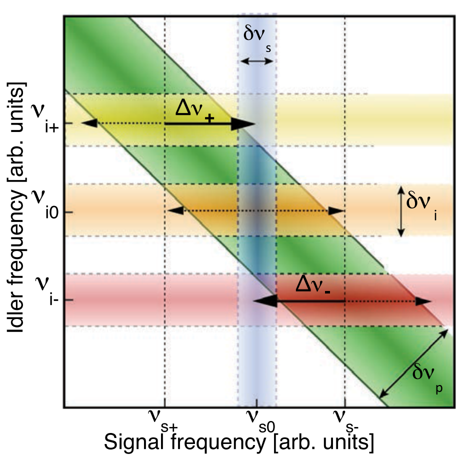

FIG. 6. Spectral source multiplexing. The idler photon, which shares a correlated joint spectrum with the signal photon, is detected with spectral resolution (ν_{i+}, ν_{i0}, or ν_{i-}), then the corresponding signal photon's frequency is shifted to the output spectral band ν_{s0}. Reproduced with permission from Grimau Puigibert *et al.*, Phys. Rev. Lett. **119**, 083601 (2017). Copyright 2017 American Physical Society.

for three discrete frequency bins.[67] The method has been extended to continuous frequency resolution[125] using a time-of-flight spectrometer.[10,126]

A different approach soon followed: frequency conversion of the heralded photon using four-wave mixing with different pump frequencies again for three frequency bins of the herald photon.[88] Both approaches to spectral multiplexing will face technical challenges in expanding to many sources, the phase ramp approach due to the limited bandwidth and depth of the modulators, and the four-wave mixing approach due to the need for a different pump laser for each frequency bin.

D. Related experiments

One of the main reasons for desiring single photons on demand is the production of multiple photons for interference-based applications.[74,100,106,127–130] The fast switching inherent in source multiplexing is additionally useful for synchronizing multiple sources or de-multiplexing a photon stream from a single source to multiple spatial modes. The former has been accomplished with two temporally multiplexed sources, relatively multiplexed to show an increase in the two-photon interference rate of ≈30 times over non-multiplexed sources using bulk components,[131] and ≈2 times compared to non-relative temporal multiplexing using the fiber-integrated components.[113] Both the previous experiments also demonstrated high indistinguishability of the multiplexed photons. As proposed in 2014,[115] de-multiplexing has been employed to take subsequently produced photons from a single quantum dot and route them to different spatial modes using the integrated switches,[132] passive (probabilistic) bulk optics,[129] and multiple free-space switches.[74] Finally, higher-order Fock states can be prepared using the ideas of multiplexing through repeated down-conversion[62] or simply storing higher-order heralded states until required.[133]

V. SUMMARY

It is clear that from the beginning, what were offered as ideal single-photon sources were woefully deficient in many characteristics, particularly for any application requiring more than two photons. It is also clear that there has been an increasing interest in multiplexing methods in terms of the degrees of freedom used and how to best use those degrees given limitations of existing components. One benefit of these efforts to implement multiplexed systems is that it has drawn attention to those component limitations and encouraged improvements. Advances in detector efficiency, dark count rate, and switch loss have all contributed to the improved operation of heralded sources and their multiplexing. In addition, the careful engineering of pair sources to generate pure photon states has taken great strides. All these advances have greatly improved single-photon rates and brightnesses to the point where experiments requiring handfuls of photons are possible and experiments requiring 15 or more are imaginable.

What is still clear is that while multiplexing is the only path to scalability, components of multiplexed photonic quantum systems also need to be scalable. This can be seen as heralded photon and quantum dot sources both use multiplexing to improve to achieve higher rates in multiphoton experiments. As a result, both must move to the integrated components as system size increases. With the emergence of numerous "quantum vendors," the development and advance of efficient integrated components will be interesting to watch. While the current leader in the highest photon experiments uses a single time-multiplexed quantum dot,[100] it remains to be seen if that lead will hold. What ultimately may tip the balance is the relative ease with which indistinguishable photons can made from separate heralded-photon sources vs the individual manipulation required to make two photons from separate dots indistinguishable. This will be a key factor in determining which approach succeeds and in which applications. Another important factor is the convenience of noncryogenic operation.

We have noted the continuing difficulty in comparing results and often the lack of clarity in defining and stating performance parameters. That was apparent to the authors in assembling results into Table III. To help, we have created a table of definitions and measurement protocols that we hope will be a convenience to subsequent authors and help promote clarity.

ACKNOWLEDGMENTS

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

APPENDIX: DEFINITION TABLES

TABLE V. Definitions of terms relevant for single-photon sources.

Term	Definition
Deterministic photon source	A photon source that can, in principle, produce a single photon with high probability at fixed, regular times. The isolated quantum emitters and multiplexed heralded sources seek to reach this goal
Heralded single-photon source	A source of single photons based on heralding one photon from a photon pair source by detecting its partner photon. This is a probabilistic source that can nevertheless produce high-quality photons, albeit at arbitrary times
Isolated quantum system	A source based on a single isolated quantum system, such as a single atom, color center, or quantum dot, which emits single photons after optical or electronic excitation
On-demand photon source	A photon source that can, in principle, produce a single photon with high probability at arbitrary times. The isolated quantum emitters and multiplexed heralded sources seek to reach this goal
Photon pair source	A source of photons based on nonlinear optics, either three-wave (parametric down-conversion) or four-wave mixing, where one or two pump photons decays to a pair of correlated photons. One photon can be directly detected to herald the presence of the other
Photon-counting (click) detector	A single-photon-sensitive detector that clicks when one or more photons are detected, thus "photon counting" is a misnomer
Photon number resolving detector	A single-photon-sensitive detector that reports the number of photons detected
Probabilistic photon source	A source of single photons that emits photons at various times with some probability, typically much lower than unity. Often these are pair sources, where detecting one photon at an arbitrary time heralds the presence of a coincident partner photon. The isolated quantum systems also become probabilistic under realistic losses
Transform limited	A photon source emits transform limited photons if they are in a single spectral-temporal mode without drift of the central frequency (for the isolated quantum systems) or mixedness across multiple Schmidt modes (for pair sources). Such photons are highly indistinguishable and are suitable for multiphoton interference

TABLE VI. Definitions of parameters and metrics relevant for single-photon sources.

Term	Symbol	Definition	How to measure
Brightness	B	Probability of exactly one photon in a single-mode fiber at a given clock time, irrespective of whether a heralding detection occurs or not. Applies equally well to quantum emitters and pair sources	Measure the ratio of detector clicks to clocks, then divide out the detector efficiency and downstream losses. Subtract the multiphoton component as estimated by the $g^{(2)}(0)$ (for pair sources, the heralded $g_h^{(2)}(0)$)
Coincidences-to-accidentals ratio	CAR	The ratio of true coincidence count rate to accidental coincidence count rate from a pair source: $CAR = (C - A)/A$, where C is the total coincidence rate and A is the measured accidentals rate, which can be approximated by the heralded $g_h^{(2)}(0)$ as $CAR \approx 2(2 - \eta_h)/g_h^{(2)}(0)$	Measure the raw coincidence rate, and measure the accidental rate by electronically delaying the coincidence window by a multiple of the repetition rate
Conditional photon probability	$p_{(n\|h)}$	Probability of producing n photons in a pair source given an heralding event	$p_{(1\|h)}$ can be approximated from click probabilities and $p_{(2\|h)}$ from the heralded $g^{(2)}(0)$ [see Eq. (3)]
Coupling efficiency	η_{coupl}	The efficiency to collect an emitted photon in a single-mode fiber from the photon source, including filtering and other losses. In this work, we include loss from the multiplexing process here	For pair sources, measure the Klyshko (heralding) efficiency and divide out the detector efficiency and downstream losses
Detector efficiency	η_{det}	The efficiency of a detector to produce an electrical output click when one photon is incident on the detector	Detector efficiency can be measured using calibrated attenuation of laser light
Klyshko efficiency [55], heralding efficiency, total efficiency	η_{tot}	For pair sources, the raw probability to detect heralded photon given a herald detection, $\eta_{tot} = \eta_{coupl}\eta_{det}$	For the signal's Klyshko/heralding/total efficiency, divide the coincidence rate by the idler singles rate, and vice versa
Total herald detection efficiency	η_h	For pair sources, the total detection efficiency (Klyshko efficiency) of the herald photon	Coincidence rate divided by singles rate in the other channel
Emission efficiency		The probability (normally for a single-emitter source) that a photon is emitted at the desired time, including the excitation probability	Measure the count rate then divide out all losses
Generation efficiency		The number of emitted photon pairs (for pair sources) per second per milliwatt of input pump power, sometimes also normalized per photon bandwidth	Measure the coincidence (C) and singles rates (S_1, S_2), then find the rate of emitted pairs as before any losses S_1S_2/C, then divide by pump power and possibly photon bandwidth
Dark count probability	d	The probability that a detector fires with no light incident per experiment time window	Block light to the detector and measure the dark count rate, then multiply by the experiment time window
Fidelity to a single photon	F	The overlap of the output state of a single-photon source to a single photon in a single mode	Reconstruct the Wigner function of the output mode using, e.g., homodyning, then compare with that of an ideal single photon
Fidelity (heralded) to a single photon	F_h	For photon pair sources, the overlap of the output state conditioned on a heralding event to a single photon: $F_h = \langle 1\|\rho\|1\rangle$, where ρ is the state after heralding. In this work, we neglect modes, but ideally this should be in a single mode	Can be approximated by measuring the heralded $g_h^{(2)}(0)$ as in Eq. (9)
Heralding probability	p_h	The probability per output clock (often, per pump pulse) to measure a heralding event from a pair source	Measure the heralding rate and divide by the source repetition rate

TABLE VII. Continuing definitions of parameters and metrics for single-photon sources.

Term	Symbol	Definition	How to measure
Heralding rate	S_{h}	The rate of measured heralding clicks from a pair source	Count the number of herald events per unit time
Hong–Ou–Mandel interference visibility[50]	V_{HOM}	The visibility of the HOM dip recorded when looking at the coincidence counts when two photons are incident on opposite ports of a 50:50 beam splitter and varied in distinguishability, most commonly by a relative time delay	Given the maximum and minimum coincidence rates ($C_{\max}$, $C_{\min}$) across the dip, $V_{\mathrm{HOM}} = (C_{\max} - C_{\min})/C_{\max}$
Indistinguishability	I	The indistinguishability of two photons from separate sources or from the same source at different times quantifies their ability to interfere. Perfect indistinguishability ($I = 1$) implies perfect interference visibility	Measure a Hong–Ou–Mandel dip[50] between the two modes. The indistinguishability is equal to the visibility of the dip: $I = V_{\mathrm{HOM}}$
Multiphoton component		The fraction of the total photon state made up of Fock states of more than one photon. A heuristic rather than precise quantity	A sense of the multiphoton component can be obtained from the $g^{(2)}(0)$ and similar correlation functions
Number of multiplexed sources	K	The number of sources whose outputs are combined through switching in a multiplexed single-photon source	Count the number of sources you have built
Output noise factor[52]		The ratio in the output mode of a photon source of the background counts to the total output counts (sum of background counts and true counts)	Use a coincidence timing histogram to identify the true, narrow, photon peak, and the broad background counts. Divide these background counts by the sum of true and background counts
Schmidt number	K_S	The effective number of optical modes (spatial and/or temporal-spectral) into which the photon pairs are emitted. Sources with the Schmidt number greater than 1 produce non-transform-limited photons	Measure the unheralded $g^{(2)}_{\mathrm{unh}}(0)$ for either photon of the pair, and find the Schmidt number $K_S \approx 1/\left(g^{(2)}_{\mathrm{unh}}(0) - 1\right)$
Second-order correlation function	$g^{(2)}(0)$ $g^{(2)}_{\mathrm{h}}(0)$ $g^{(2)}_{\mathrm{unh}}(0)$	In a single mode, gives information on the multiphoton component. Variants specific to pair sources are the heralded $g^{(2)}_{\mathrm{h}}(0)$, measured conditioned on a heralding event, and the unheralded $g^{(2)}_{\mathrm{unh}}(0)$, measured unconditionally	For a low multiphoton component, the $g^{(2)}(0)$ can be approximated as follows: split the mode on a 50:50 beamsplitter, and place single-photon detectors at each output, recording the singles on each detector S_1 and S_2 and the coincidences C. Then, $g^{(2)}(0) \approx S_1 S_2 / C$
Single-photon rate	S_{det}	The rate of single-photon detections that have been heralded by a herald event	Count the number of heralded single-photon detection events per unit time (i.e., coincidences between signal and idler)
Source repetition rate	R_{src}	The rate of attempts to extract a single photon from the source	For spatially multiplexed sources, generally the same as the pump laser repetition rate. For other cases, this source repetition rate is often much lower than the pump laser repetition rate, so take care in counting the number of attempts made
Squeezing strength	λ^2	The overall strength of the squeezing interaction or parametric down-conversion; depends on pump power, nonlinearity, crystal geometry, phase matching	Can be inferred from single-photon count rate in the low-squeezing regime. Related to the squeezing parameter r as $\lambda = \tanh r$

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