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Corresponding author:
Sebastian Brandhofer;
Email: sebastian.brandhofer@iti.uni-stuttgart.de

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Multiplexed pseudo-deterministic photon source with asymmetric switching elements

Sebastian Brandhofer[1,2], Casey R. Myers[3,4], Simon Devitt[5] and Ilia Polian[1,2]

[1]Institute of Computer Architecture and Computer Engineering, University of Stuttgart, Stuttgart, Germany; [2]Center for Integrated Quantum Science and Technology, University of Stuttgart, Stuttgart, Germany; [3]Silicon Quantum Computing, UNSW Sydney, Kensington, NSW, Australia; [4]School of Computing and Information Systems, Faculty of Engineering and Information Technology, The University of Melbourne, Melbourne, VIC, Australia and [5]Center for Quantum Software and Information, University of Technology Sydney, Ultimo, NSW, Australia

Abstract

The reliable, deterministic production of trustworthy high-quality single photons is a critical component of discrete variable, optical quantum technology. For single-photon based fully error-corrected quantum computing systems, it is estimated that photon sources will be required to produce a reliable stream of photons at rates exceeding 1 GHz (Vigliar et al., 2021). Photon multiplexing, where low probability sources are combined with switching networks to route successful production events to an output, are a potential solution but requires extremely fast single-photon switching with ultra-low-loss rates. In this paper, we examine the specific properties of the switching elements and present a new design that exploits the general one-way properties of common switching elements such as thermal pads. By introducing multiple switches to a basic, temporal multiplexing device, we can use slow switching elements in a multiplexed source being pumped at much faster rates. We model this design under multiple error channels and show that anticipated performance is now limited by the intrinsic loss rate of the optical waveguides within integrated photonic chipsets. While the developed design does not achieve the necessary 1 GHz photon rate, we demonstrate design elements that could become useful when underlying technology improves.

Linear optical quantum computing was one of the earliest success stories in quantum computing research (O'Brien, 2007). Since the groundbreaking paper of Knill, Laflamme and Milburn in 2000, which demonstrated that linear optics and post-selected measurements (Knill et al., 2001) could be used to realise universal scalable quantum logic in discrete photonics, experimental demonstrations of small-scale quantum algorithms have become routine around the world (Bouwmeester et al., 1999; Lu et al., 2007; Lanyon et al., 2007; Alberto et al., 2010; Stefanie et al., 2012; Jacques et al., 2015). Bulk optical experiments in the laboratory were replaced with more stable integrated optical photonic chips and algorithms consisting of up to 12 photonic qubits have been performed in a controlled manner (Zhong et al., 2018). In recent years, photonic quantum computing systems have been adopted by several startups worldwide (Kaczmarek et al., 2020; Bartolucci et al., 2021), with the promise of building scalable single-photon-based quantum computers (Rudolph, 2017).

However, quantum computing platforms based on single photons have traditionally suffered from the reliable generation of on-demand single photons. The vast majority of experimental demonstrations of optical quantum computing use sources that are probabilistic, producing individual photons from the down-conversion of low amplitude coherent states from pulsed lasers (henceforth called weak laser pulse) (Jacques et al., 2015). These non-deterministic sources are a major limiting factor for the demonstration of larger quantum algorithms in photonic platforms when millions or more photons are required in a temporally synchronous manner. The push to build a scalable quantum computing system in optics is dependent on solving the source problem and constructing devices that can produce high-quality, identical, on-demand single photons.

In this paper, we detail a design for a new type of multiplexed source that exploits a specific property of integrated optical switches, namely their asymmetric switching properties. Single-photon switches, based on Mach-Zehnder interferometers and phase modulators, often have anti-symmetric phase profiles as a function of the control parameter – that is they effectively have different time scales associated with "turning-on" and "turning-off" (Liu et al., 2022). For example, using thermal pads to phase modulate a wave-guide in doped silicon can be switched "on" quickly by adding thermal energy to the system, but removing that thermal energy to switch "off" the modulator takes up to five times as long (Liu et al., 2021; Sabouri et al., 2021).

Our new design – dubbed the racetrack source – considers this effect and allows for the construction of a multiplexed source where individual switches are only used once. This allows for fast multiplexing using hardware switching that may be slow. We perform detailed error modelling and illustrate that a high-probability multiplexed source can be constructed.

Background

Multiple approaches have been proposed for building a device with the capability of producing high-quality photons on-demand. They can be broken down into two broad categories.

- *Single-photon emitters*: Matter-based quantum systems (such as atoms or quantum dots) that can be controlled and pulsed to emit single photons deterministically as the result of an energy transition (Ding et al., 2016; Aharonovich et al., 2016; Senellart et al., 2017; Huber et al., 2017; Awschalom et al., 2018; Ding et al., 2023).
- *Multiplexing*: Combining a large number of probabilistic sources with an active switching network to route successful photon generation events to the output of the device (Pittman et al., 2002; Ma et al., 2011; Mower and Englund, 2011; Collins et al., 2013; Bonneau et al., 2015; Kaneda and Kwiat, 2019; Meyer-Scott et al., 2020).

While single-photon emitters may ultimately prove to be a more effective means of producing photons for quantum computing and communication applications in the future, they currently come with several drawbacks. The first is the ability to produce identical photons in artificial atoms such as quantum dots. For individual photons to be useful in optical quantum processing chipsets, they must interfere with high fidelity when mixed together on linear optical elements, such as beamsplitters. For this to occur, individual photons must be close to 100% indistinguishable in all degrees of freedom. This is still difficult to achieve. The physical fabrication of the solid-state emitter, its local environment and control inaccuracies all influence the ability to produce individual photons from distinct emitter sources that interfere with high accuracy on linear optical components. Additionally, the integration of these components into linear optical quantum technology often diminishes the benefits of the optical platform as they are comparatively difficult and costly to fabricate at scale, can require complex infrastructure, such as dilution refrigeration cooling to operate, and are not always compatible with telecom frequencies when utilising long-range optical fibre systems as low-loss quantum memories for scalable designs (Bombin et al., 2021).

The current method of choice for photon production remains probabilistic down-conversion processes such as in Spontaneous Parametric Down Conversion (SPDC) or Spontaneous Four Wave Mixing (SFWM) sources (Jacques et al., 2015) the latter of which has already been incorporated into integrated optical chipsets and experimentally utilised). These sources take a weak coherent laser source of frequency (ω) and, through a weak optical nonlinearity, probabilistically generate a pair of lower frequency photons ($\omega_1 + \omega_2 = \omega$). The probability of success for these single-photon sources is dictated by the power used in the pump laser. The general output Gaussian state given a weak laser pulse input can be described by the sum over Fock states,

$$\sqrt{1-|\zeta|^2}\left(|vac\rangle_s|vac\rangle_i + \sum_{n=1}^{\infty}\zeta^N|n\rangle_s|n\rangle_i\right). \quad (1)$$

The subscripts s and i refer to the signal and idler photons and $|\zeta| < 1$ parameterises the strength of the non-linearity in the source and the power used in the pump, $|\zeta| = \tanh(cP)$, where P is the power in mW and c is the coupling constant of the optical non-linearity in units of $\mathrm{mW}^{-1/2}$ (Walls and Milburn, 2012).

The output of the source is consequently not a perfect single photon; we instead always get a superposition of the vacuum state and all Fock states. As $|\zeta| < 1$, the higher-order Fock terms drop off exponentially. Therefore, good single-photon sources are highly probabilistic. This creates a scaling problem. For the production of two photons at the same time, two down-conversion sources must succeed at the same time, occurring with a probability of p^2. If each source succeeds with a probability of 1/100, then two photons can only be produced with a probability of 1/10,000. This continues to decrease exponentially, such that producing N photons at the same time for a quantum algorithm occurs with a probability of p^N.

The solution to this problem is the concept of multiplexing: A large number of probabilistic sources are integrated with an active switching network so that when the device is triggered, on average, one of the probabilistic sources will be successful and the switching network can be configured, in real-time, such that the resultant photon can be routed to the output of the device. However, the utility of this device to produce on-demand single photons is contingent on very accurate and fast single-photon switches. These switches are difficult to fabricate reliably, and often a choice needs to be made between fast, lossy, switches *versus* precise slow switches. This is often due to the intrinsic asymmetry of the switches themselves. While switches built, for example, from waveguide thermal pads (Jacques et al., 2015) can be switched on very quickly (by dumping a large amount of thermal energy onto a chip in a very short time), they cannot be switched off quickly – essentially the system has to be allowed to cool through thermal dissipation. This limits either the speed or reliability of the switch itself and limits its use in a multiplexed source.

Research has been ongoing to use different physical effects to induce the modulation needed to build a single-photon switch – most notably electro-optical modulation in materials such as Lithium Niobate (Wooten et al., 2000) – but these systems are still in their technological infancy and are not straightforwardly compatible with the CMOS manufacturing. This is important as CMOS compatibility and the ability to leverage global silicon manufacturing infrastructure for quantum technology is a big advantage for the utility of optics as a quantum hardware system.

In addition to intrinsic waveguide loss, inaccurate switching in these multiplexed sources is a large contributing factor to photon loss. High loss rates or slow production of on-demand photons renders multiplexed photon sources effectively useless in the current generation of integrated optical systems, especially without the existence of high-quality and low-loss single-photon memories. Photons need to be produced quickly, such that small amounts of fibre loops are sufficient to temporally synchronise photons as input to integrated optical computing chips and the pseudo-determinism of such a device has to be high to move into a regime where the probability of generating N photons for an experiment scales at worst polynomially rather than exponentially in N.

Our goal is to redesign a multiplexed switch specifically with this asymmetry in mind, using the CMOS-compatible thermal pad system to prototype a new design that operates each switch in the multiplexed system in a “one-way” fashion. As each switch is fast and accurate when switched “on” from a previously “off” position,

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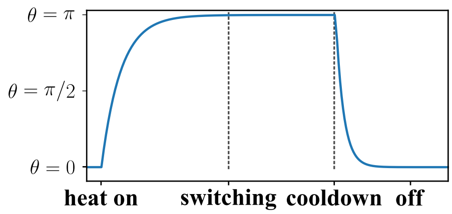

Figure 1. Schematic switching profile of switches based on thermo-optic effect.

we will construct a multiplexed switch where this is the only operation allowed for each switch in the device. This leads to a source design that resembles a racetrack, with an array of switches coupling an inner waveguide loop to an outer loop that contains an array of probabilistic sources and heralding detectors. The key insight is that each switch in the system can only be used ONCE, sidestepping the fundamental problem that makes switches in a multiplexed source either too unreliable or too slow.

In this work, we present a novel multiplexed single-photon source that addresses asymmetric configuration delays and corresponding error characteristics to produce high-quality photons with a high probability.

Asymmetric switch

In our proposed single-photon source each switch is configured at most twice. This enables the exploitation of asymmetric configuration delays for switches with a specific switching profile as sketched in Figure 1.

For currently available switches based on thermo-optic effects, the switch configuration can often be changed once quickly for example, by turning on a heat pad or by active cooling (Liu et al., 2022). However, as soon as the switch is configured once, reverting to the previous configuration requires a larger configuration delay. According to the literature, the configuration delay T_{sr} incurred by turning on a heat pad in thermo-optic switches may be approximately 3 times smaller to 4 times larger than T_{sf}, the configuration delay incurred by cooling down the heat pad (Liu et al., 2022). Regardless of T_{sr} or T_{sf} requiring more time, the polarity of the switches can be reversed to exploit the asymmetric configuration delays for switching in the proposed single-photon source. For the remainder of the paper, we assume that the time required to turn on a heat pad in a thermo-optic switch requires significantly less time than its cooldown.

Thermo-optic switches

A single-photon switch is a two-input, two-output device that allows for a single photon to be routed from either of the two inputs to either of the two outputs. It has a generic structure shown in Figure 2, which is drawn in the context of an integrated optics chipset.

In Figure 2, we have three components, two directional couplers that work as single-photon beamsplitters and a single device, known as a phase shifter, that acts to impart a relative phase on any photon that passes through the waveguides underneath. See for example, Walls and Milburn (2008) for a derivation of the transmission function of this Mach-Zehnder modulator.

Thermo-optic switches can be used in Figure 2 that contain two thermal pads, each applicable to one of the connected waveguides separately. The induced phase shift θ can be manipulated by each heat pad individually. The initial switch configuration can be reverted in time T_{sr} by activating the second heat pad. However, changing the switch configuration a third time would then require the cooldown of one or both heat pads, leading to the delay T_{sf}. The manufacturing of the proposed double-padded switches has been demonstrated in Liu et al. (2022). However, a characterisation of its exact switching profile and asymmetric error characteristics is pending.

Multiplexed single-photon source

The proposed novel multiplexed single-photon source exploits asymmetric configuration delays of switches while combining time- and space-multiplexing to improve the fidelity and excitation probability of photons. The components of the proposed photon source are available with current technology, can be manufactured at scale and are compatible with CMOS transistors as well as telecom frequencies (Jacques et al., 2015; Xiong et al., 2016). Therefore the photon source presents itself as an ideal candidate for the demonstration of large-scale quantum computations with linear optics.

The proposed photon source consists of one or more SPDC sources, which are connected to the same pump laser, single- and double-padded switches, non-photon-number-resolving detectors, delays and logic elements for processing the detector signals, for example, CMOS transistors. Figure 3 shows the developed photon source with two SPDC sources that are connected via switches to an inner delay loop and the output. Each SPDC source is connected to a detector and to the inner loop via multiple switches that are configured at most twice. In each pump cycle of one SPDC source, a photon pair can be generated with probability p. When the attached detector indicates that one photon pair was generated at its corresponding SPDC source, one photon in the photon pair is absorbed by the detector and the other enters the inner loop by configuring the first switch that has not been used by the proposed source, yet. For instance, the first of the down-converted photons enters the inner loop by configuring switch S_1 in Figure 3, the second generated photon is entered by switch S_2, and so on. The delay element directly attached to each SPDC source delays a passing photon by

$$T = T_d + T_c + T_{sr}, \tag{2}$$

where T_d is the detector delay, T_c is the classical processing delay and T_{sr} is the previously defined switch configuration delay. After the photon has entered into the inner loop by a switch S_i, the same switch S_i is configured to forward newly generated photons along the outer loop to the next switch S_{i+1} before the newly inserted photon traverses the inner loop once. This is facilitated by the inner loop delay $T - \varepsilon$, where T is the previously defined sum of delays and ε is the time a photon requires to traverse the inner loop once (without being delayed by ε). When another photon is generated, it will be forwarded to the next double-padded switch S_{i+1} that is configured to switch the inner loop photons to the outer loop where the photon is discarded or output. The newly generated photon is switched into the inner loop by switch S_{i+1} at the same time. Then, the same double-padded switch (S_{i+1}) is configured to keep the photon in the inner loop, and the next switch S_{i+2} is used when a new photon is generated. This is repeated until all switches of a photon source are exhausted. The extension to multiple SPDC sources is straightforward: all detector signals are attached to classical processing, for example, CMOS gates, to select the generated photon of one SPDC source that is forwarded to the inner loop. After a fixed number of pump cycles, or when the component at the output of the proposed source requests, the photon from the inner loop is switched to the output. With this

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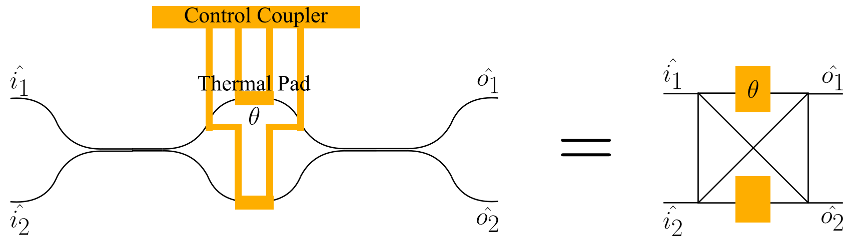

Figure 2. Switch based on thermo-optic effects with two thermal pads that can be activated individually.

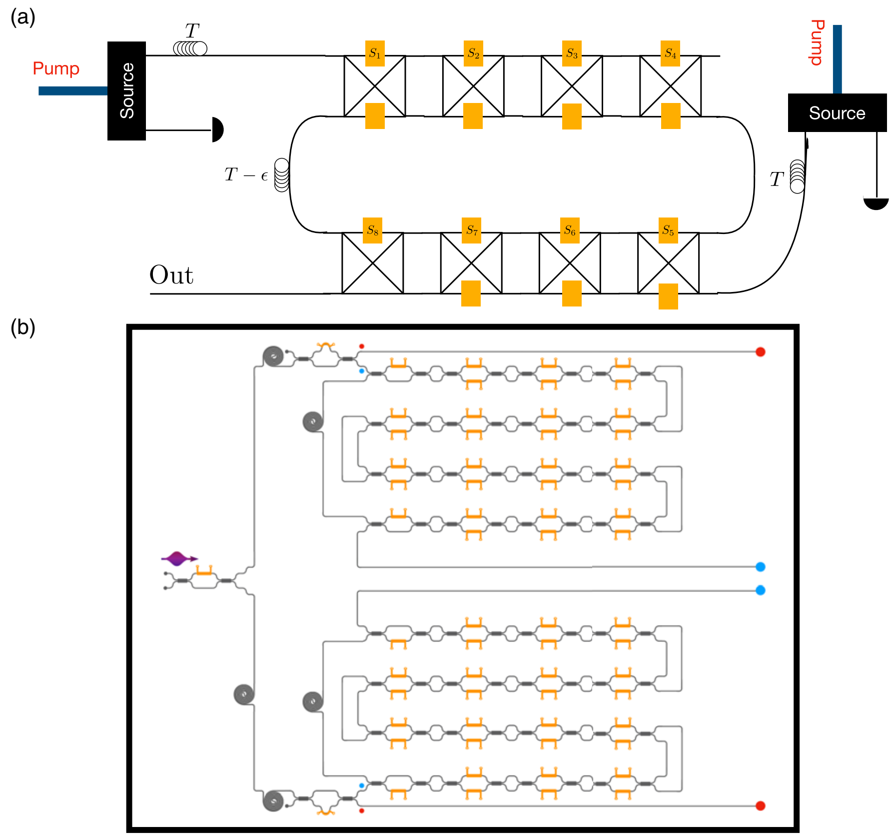

Figure 3. Developed photon source with two SPDC sources, seven double-padded switches that connect the sources to an inner delay loop and one single-padded switch S_8 that connects the inner loop to the output. figure 3(b)) is a more accurate representation of what figure 3(a)) would look like as an actual device. While figure 3(a)) demonstrates the developed design abstractly, figure 3(b)) examines the layout for two parallel sources, each with 16 switches, as it would appear if it were fabricated. figure 3(c)) serves as a key that maps the components in the schematic as depicted in figure 3(a)) to the components in an actual device depicted in figure 3(b)).

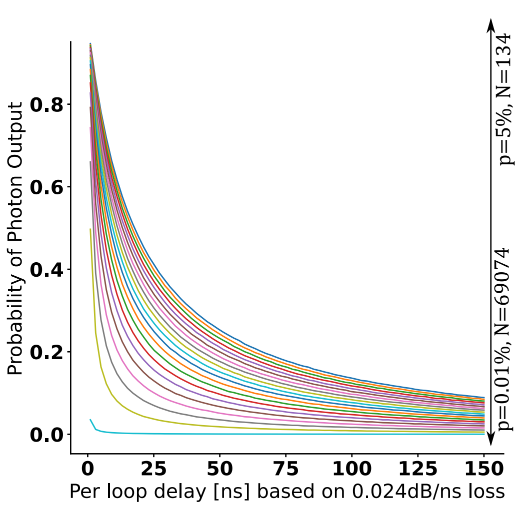

Figure 4. Photon output probability as a function of inner loop delay, number of pump cycles N and photon generation probability p with p ranging from 0.01% to 5% and $N = \frac{\log(1.0-0.999)}{\log(1.0-p)}$. The photon output probability p is increased by the value of 0.237% for each of the depicted curves.

setup, each switch is reconfigured at most twice, which takes full advantage of asymmetric switch configuration delays.

At some point during the operation of the proposed single-photon source, a large number of switches have been configured which warrants a reset of the photon source. During the reset, the photon source cannot output any photon and the switches are reverted to their default configuration state, which requires a technology-dependent delay T_{sf}. While the delay T_{sf} may be large, the proposed single-photon source can be designed to alleviate it by reducing the rate at which a reset is necessary. The reset rate can be reduced by either connecting each SPDC source through additional switches or by using multiple single-photon sources. Both strategies extend the period after which a reset is necessary. If the detector delay T_d is larger than the switch configuration delay T_{sr}, detector multiplexing can be employed to reduce T_d to T_{sr}.

The pump frequency is given by T^{-1}, where T represents the interval between pumping each probabilistic source and is bounded by the response time of the heralding detector, the classical processing time and the switching time (see Equation 2). However, after a full sequence of N pumping cycles is completed, the entire single-photon source must be reset. All thermal pads on all switches are deactivated and set to the default configuration. For

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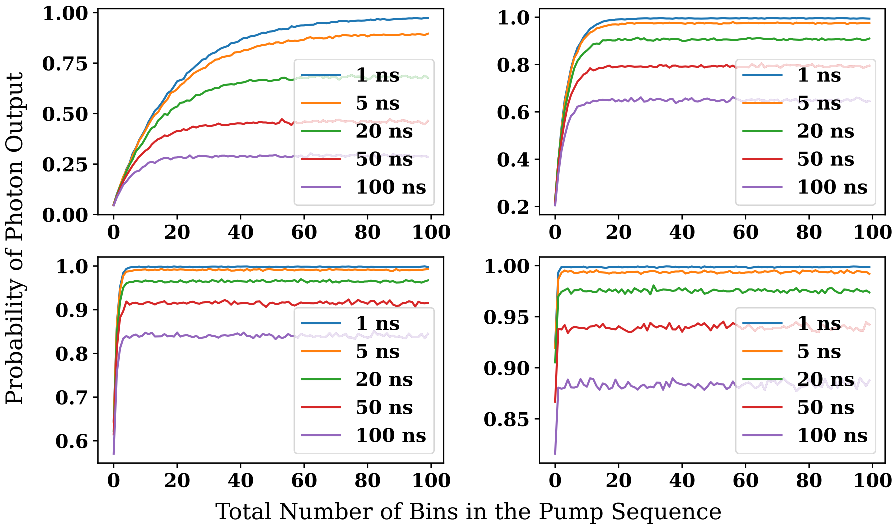

Figure 5. Photon output probability for $S \in \{1, 5, 20, 50\}$ photon sources (top left, top right, bottom left, bottom right) and a loop delay of $T \in \{1, 5, 20, 50, 100\}$ns at a waveguide loss of 0.024 dB/ns.

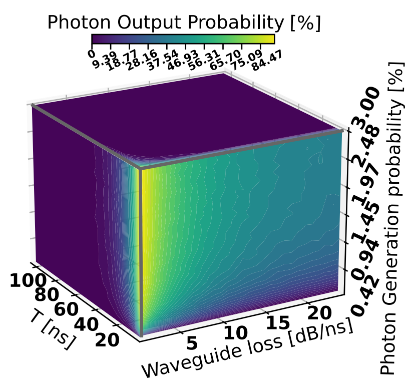

Figure 6. 3D plot of several configurations of 150 SPDC sources running for 150 pump cycles showing the achievable photon output probability as a colour from dark blue to yellow for an inner loop delay ranging from 1 ns to 100 ns, a waveguide loss ranging from 0.001 dB/ns to 24 dB/ns, and a photon generation probability of a single SPDC source ranging from 0.01% to 3%.

this reset time, $T_{sf} \gg T_{sr}$ can be chosen to ensure that all switches have cleanly returned to the $\theta = 0$ state without error.

As the multiplexed photon source must be reset periodically, the total repetition rate of the source can be much lower than the cycling time T^{-1} of the pumped source. The reset repetition rate ${t_{\mathrm{rmux}}}^{-1}$ of the source is determined by

$$t_{\mathrm{rmux}} = N \times T + T_{sf} = \frac{\log(1 - p_N)}{\log(1 - p)} \times T + T_{sf}. \qquad (3)$$

By prolonging t_{rmux} the frequency of resets can be reduced and thus the total repetition rate of the source can be improved. The quantity t_{rmux} can be increased by adding more switches to the inner loop that enable the routing of photons from SPDC sources to the inner loop or from the inner loop to the output.

Each photon source is attached to m switches that can be used to switch a generated photon into the inner loop of the racetrack. The number of attached switches m should be minimal to reduce the cost of manufacturing the proposed multiplexed photon source. At the same time, m must be large enough to allow a large portion of photons generated by the single-photon sources to be switched into the inner loop of the proposed multiplexed photon source. The error simulation performed in this work assumes that a sufficient number of switches are attached for each single-photon source. The minimum number of switches m can be derived by evaluating the inverse cumulative distribution function of the following binomial distribution

$$f(k, N, p) = Pr(X = k) = \binom{N}{k} p^k (1 - p)^{N-k}, \qquad (4)$$

where N is the number of pump cycles, p is a given photon generation probability and $f(k,n,p)$ is the probability of one photon source generating exactly k output photons in N pump cycles. If all k generated photons should be switched into the inner loop, the photon source requires $m := k$ switches. Hence, we can use the binomial distribution to determine an upper bound on the required number of switches such that each photon generated by a single-photon source has a large chance of getting switched into the inner loop.

We can compute the probability of generating at most k photons in N pump cycles, that is, the probability that a photon source requires $m := k$ switches by computing the cumulative distribution function of that binomial distribution

$$\widehat{\mathcal{F}}(k, N, p) = \sum_{i=0}^{k} \binom{N}{i} p^i (1 - p)^{N-i}. \qquad (5)$$

Finally, we can determine the minimum number m for a specified photon generation probability p and the number of pump cycles N as

$$m = \hat{F}^{-1}(q, N, p), \qquad (6)$$

where the inverse CDF $\hat{F}^{-1}$ returns the number m that is minimal such that

$$q \leq \sum_{i=0}^{m} \binom{N}{i} p^i (1 - p)^{N-i}, \qquad (7)$$

with q being the probability of being able to switch all generated photons of one SPDC source during the N pump cycles into the inner loop of the racetrack. The inverse cumulative distribution function $\hat{F}^{-1}$ can be evaluated numerically (Virtanen et al., 2020).

The data for Figures 4, 5 and 6 has been obtained via simulation: First, a random number r between zero and one is drawn for each

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considered SPDC source and pump cycle. Then, the pump cycle is determined at which the last photon in the multiplexed photon source has been generated. The pump cycle is determined by comparing each randomly drawn number r against the photon generation probability given for that simulation. In the last step, the number of pump cycles, the waveguide loss and the loop delay given for that simulation are considered to determine the probability of the most recently generated photon exiting the multiplexed photon source as described in the following section.

We show the photon output probability in Figure 4 as a function of inner loop delay $T-\varepsilon$, number of considered pump cycles N and photon generation probability p for one SPDC source attached to the outer loop. For a decreasing photon generation probability and increasing inner loop delay, the photon output probability diminishes exponentially as detailed in Figure 4. At a photon generation probability of 5% and an inner loop delay of 9ns the photon output probability is roughly at 66% when performing 134 pump cycles. This exponential decrease in photon output probability can be mitigated by introducing additional SPDC sources to the inner loop.

In Figure 5, the photon output probability of the proposed single-photon source is shown as a function of attached SPDC sources and pump cycles. The number of pump cycles is shown on the x-axis and the probability of photon output is given on the y-axis. The different lines indicate an inner loop delay ranging from 1 ns to 100 ns.

For the lowest considered inner loop delay of 1ns, the photon output probability converges to 100% for 5, 20 and 50 SPDC sources. At one SPDC source, it reaches up to 95%. For more than one considered SPDC source, a sharp rise in photon output probability is observable in the region of one to ten pump cycles. At higher inner loop delays, the photon loss increases and yields a diminished photon output probability. At 5 ns inner loop delay the photon loss leads to a photon output probability of less than 90% for one source, whereas the photon output probability converges to 23% for an inner loop delay of 100 ns. At 5, 2, and 50 SPDC sources this effect is reduced; a 100 ns inner loop delay leads to a photon output probability of 62% for 5 SPDC sources, 83% for 20 SPDC sources and slightly over 88% for 50 SPDC sources. At an increasingly larger number of SPDC sources, the depicted curves become less smooth. This is because of the probabilistic nature of our simulation and a finite sampling of ten thousand repetitions per data point.

Figure 6 shows a 3D plot where the inner loop delay on the x-axis, the waveguide loss per nanosecond on the y-axis and the photon generation probability of the SPDC sources on the z-axis is varied. The colour encodes the photon output probability of a racetrack design subject to a value assignment of the three parameters as given on their respective axes. The number of SPDC sources and number of pump cycles is set to 150 for all data points. It can be observed that a higher inner loop delay can mostly be compensated by a higher photon generation probability of the SPDC sources for an inner loop delay of less than 40 ns. Above an inner loop delay of 40 ns, the photon output probability converges to a lower value regardless of the photon generation probability. The top face of the cube shows that the waveguide loss, inner loop delay and photon generation probability must be in a very restricted region: to allow for photon output probabilities of more than 84%, the waveguide loss must be less than 5db/ns and the inner loop delay must be less than 10 ns at a photon generation probability of 3%. The photon output probability converges quickly to zero for an increasing waveguide loss and inner loop delay.

Error modelling

The inner loop delay T incurs photon loss. We modelled this photon loss by the power law, that is

$$e^{-T\cdot I\cdot L}, \tag{8}$$

gives the probability that a photon is not lost while traversing the inner loop I times at a waveguide loss of L. The range of values investigated in the parameters of the results figures are justified by values reported in experimental setups of previous art (Lee et al., 2012; Bauters et al., 2013; Vigliar et al., 2021; Lita et al. 2008; Kaneda and Kwiat, 2019; Meyer-Scott et al., 2020; Sabouri et al., 2021; Liu et al., 2021, 2022). The work in Bauters et al. (2013) and Lee et al. (2012) reports a waveguide loss of 0.024 dB/ns, while Vigliar et al., (2021) reports a waveguide loss of 16 dB/ns. We have chosen a detector efficiency of 90% in all of our simulations; in (Vigliar et al., 2021) a detection efficiency of 78% ±5% and in (Lita et al., 2008) a detector efficiency of 95% is reported. Works in Kaneda and Kwiat (2019) and Meyer-Scott et al. (2020) report a photon generation probability of 1%, whereas the work in Vigliar et al. (2021) reports a photon generation probability of 3%. As we are looking at the single-photon source in the context of fault-tolerant optical quantum computing, multi-photon contamination "purity" has to be bounded as the error correction in fault-tolerant optical quantum computing is not designed to handle multi-photon events. The probability of success also allows us to bound the amplitude of the multi-photon terms in Equation 1. At approximately a 1% success probability (i.e. $\zeta^2 \approx 1\%$ in Equation 1), the next higher order term occurs with a probability of $\zeta^4 \approx 10^{-4}$, which is comfortably below threshold for surface-code and Raussendorf lattice-based error correction schemes (Fowler et al., 2012).

Works in Liu et al. (2022); Liu et al. (2021); Sabouri et al. (2021) report a switch configuration delay of 50 ns for the first and second configuration (T_{sr}) and a delay of 950ns for the cooldown required for a third configuration. While thermo-optic switches can be comparatively slow, they also exhibit extremely low-loss rates as soon as they are set. A larger number of switches in the inner loop, however, requires a larger waveguide length and thus leads to larger loss rates due to the intrinsic loss of photons. Photon detectors are expected to have a photon absorption delay of several picoseconds, which is negligible. However, photon detectors are also assumed to have a relatively large dead (or: reset) time that is on the order of the switch-off time. Classical processing is expected to be handled with CMOS gates, which incur a negligible delay of a few hundred picoseconds.

Conclusion

We have presented a multiplexed single-photon source that combines space- and time-multiplexing to amplify the photon output probability. Depending on the underlying technology parameters, the proposed single-photon source can be tuned to use more time steps (pump cycles) or more SPDC sources. The proposed single-photon source can be manufactured at scale with currently available technology. The source can exploit asymmetric configuration delays by using thermo-optic switches with two heat pads at most twice during its operation. Simulations have shown that the proposed source can reach a photon output probability of almost 87% at an inner loop delay of 20 ns and five single-photon sources attached to the inner loop. This work reinforces the fact

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that loss is by far the most dominant source of error that needs to be overcome before any scheme to improve probabilistic sources of photons can be realised.

Our goal was to examine a redesign that we initially hypothesised could lead to potentially ultrafast operations with comparatively low speed and low-loss heating pad modulators. While we did show, theoretically, an improvement over naive approaches to optical multiplexing, the ultimate goal of producing a 1 GHz pseudo-deterministic source under realistic loss models was not achieved. Still, the ideas presented in this work may prove useful in multiplexed photon source design in the future, when new materials (especially for low-loss waveguides and fast electro-optical modulation are demonstrated).

Data availability statement. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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Connections references

Ingleby S, McGilligan J (2023) Can the microfabrication of atomic and optical components open new capabilities in quantum technologies? *Research Directions: Quantum Technologies*, **1**, e1. https://doi.org/10.1017/qut.2022.3.

References

Aharonovich I, Englund D and Toth M (2016) Solid-state single-photon emitters. *Nature Photonics* **10**(10), 631–641. https://doi.org/10.1038/nphoton.2016.186.

Peruzzo A, Lobino M, Matthews J C F, Matsuda N, Politi A, Poulios K, Zhou X-Q, Lahini Y, Ismail N, Wörhoff K, Bromberg Y, Silberberg Y, Thompson M G, OBrien J L (2010) Quantum walks of correlated photons. *Science* **329**(5998), 1500–1503. https://doi.org/10.1126/science.1193515.

Awschalom DD, Hanson R, Wrachtrup J and Zhou BB (2018) Quantum technologies with optically interfaced solid-state spins. *Nature Photonics* **12**(9), 516–527. https://doi.org/10.1038/s41566-018-0232-2.

Bartolucci S, Bichall P, Bombin H, Cabal H, Dawson C, Gimeno-Segovia M, Johnston E, Kieling K, Nickerson N, Pant M, Pastawski F, Rudolph T and Sparrow C (2021) Fusion-based quantum computation, arXiv: 2101.09310.

Bauters JF, Davenport ML, Heck MJR, Doylend JK, Arnold Chen, Fang AW and Bowers JE (2013) Silicon on ultra-low-loss waveguide photonic integration platform. *Optics Express* **21**(1), 544–555. https://doi.org/10.1364/OE.21.000544.

Bombin H, Kim IH, Litinski D, Nickerson N, Pant M, Pastawski F, Roberts S and Rudolph T (2021) Interleaving: Modular architectures for fault-tolerant photonic quantum computing, arXiv: 2103.08612.

Bonneau D, Mendoza GJ, OBrien JL and Thompson MG (2015) Effect of loss on multiplexed single-photon sources. *New Journal of Physics* **17**, 043057–043057. https://doi.org/10.1088/1367-2630/17/4/043057.

Bouwmeester D, Pan J-W, Daniell M, Weinfurter H and Zeilinger A (1999) Observation of three-photon Greenberger-Horne-Zeilinger entanglement. *Physical Review Letters* **82**(7), 1345–1349. https://doi.org/10.1103/PhysRevLett.82.1345.

Collins M J, Xiong C, Rey I H, Vo T D, He J, Shahnia S, Reardon C, Krauss T F, Steel M J, Clark A S, Eggleton B J (2013) Integrated spatial multiplexing of heralded single-photon sources. *Nature Communications* **4**(1), 2582. https://doi.org/10.1038/ncomms3582.

Ding X, Guo Y-P, Xu M-C, Liu R-Z, G-Yn Zou, Zhao J-Y, Ge Z-X, *et al.* (2023) High-efficiency single-photon source above the loss-tolerant threshold for efficient linear optical quantum computing, arXiv: 2311.08347 [quant-ph].

Ding X, He Y, Duan Z-C, Gregersen N, Chen M-C, Unsleber S, Maier S, Schneider C, Kamp M, Höfling S, Lu C-Y, Pan J-W (2016) On-demand single photons with high extraction efficiency and near-unity indistinguishability from a resonantly driven quantum dot in a micropillar. *Physical Review Letters* **116**(2), 020401–. https://doi.org/10.1103/PhysRevLett.116.020401.

Fowler AG, Mariantoni M, Martinis JM and Cleland AN (2012) Surface codes: towards practical large-scale quantum computation. *Physical Review A* **86**(3), 032324. https://doi.org/10.1103/PhysRevA.86.032324.

Huber D, Reindl M, Huo Y, Huang H, Wildmann JS, Schmidt OG, Rastelli A and Trotta R (2017) Highly indistinguishable and strongly entangled photons from symmetric gaas quantum dots. *Nature Communications* **8**(1), 15506. https://doi.org/10.1038/ncomms15506.

Carolan J, Harrold C, Sparrow C, Martín-López E, Russell N J, Silverstone J W, Shadbolt P J, Matsuda N, Oguma M, Itoh M, Marshall G D, Thompson M G, Matthews J C F, Hashimoto T, O'Brien J L, Laing A (2015) Universal linear optics. *Science* **349**(6249), 711–716. https://doi.org/10.1126/science.aab3642.

Kaczmarek K, Nunn J, Poem E and Peizpour A (2020, Quantum Memory Device, **10**, United States Patent US 10,600,482 B2.

Kaneda F and Kwiat PG (2019) High-efficiency single-photon generation via large-scale active time multiplexing. *Science Advances* **5**(10), eaaw8586. https://doi.org/10.1126/sciadv.aaw8586.

Knill E, Laflamme R and Milburn GJ (2001) A scheme for efficient quantum computation with linear optics. *Nature* **409**(6816), 46–52. https://doi.org/10.1038/35051009.

Lanyon BP, Weinhold TJ, Langford NK, Barbieri M, James DFV, Gilchrist A and White AG (2007) Experimental demonstration of a compiled version of shor's algorithm with quantum entanglement. *Physical Review Letters* **99**(25), 250505. https://doi.org/10.1103/PhysRevLett.99.250505.

Lee H, Chen T, Li J, Painter O and Vahala KJ (2012) Ultra-low-loss optical delay line on a silicon chip. *Nature Communications* **3**, 1–7.

Lita Adriana E, Miller Aaron J and SaeWoo N (2008) Counting near-infrared single-photons with 95% efficiency. *Optics Express* **16**(5), 3032–3040.

Liu S, Feng J, Tian Y, Zhao H, Jin L, Ouyang B, Zhu J and Guo J (2022) Thermo-optic phase shifters based on silicon-on-insulator platform: state-of-the-art and a review. *Frontiers of Optoelectronics* **15**(1), 1–21.

Liu S, Tian Y, Lu Y and Feng J (2021) Comparison of thermo-optic phase-shifters implemented on cumec silicon photonics platform. In *Seventh Symposium on Novel Photoelectronic Detection Technology and Applications 11763, SPIE*, pages 1889–1895.

Lu C-Y, Zhou X-Q, Gühne O, Gao W-B, Zhang J, Yuan Z-S, Goebel A, Yang T and Pan J-W (2007) Experimental entanglement of six photons in graph states. *Nature Physics* **3**(2), 91–95. https://doi.org/10.1038/nphys507.

Ma X, Zotter S, Kofler J, Jennewein T and Zeilinger A (2011) Experimental generation of single photons via active multiplexing. *Physical Review A* **83**(4), 043814. https://doi.org/10.1103/PhysRevA.83.043814.

Meyer-Scott E, Silberhorn C and Migdall A (2020) Single-photon sources: approaching the ideal through multiplexing. *Review of Scientific Instruments* **91**(4), 041101. https://doi.org/10.1063/5.0003320.

Mower J and Englund D (2011) Efficient generation of single and entangled photons on a silicon photonic integrated chip. *Physical Review A* **84**(5), 052326–. https://doi.org/10.1103/PhysRevA.84.052326.

O'Brien JL (2007) Optical quantum computing. *Science* **318**(5856), 1567–1570. https://doi.org/10.1126/science.1142892.

Pittman TB, Jacobs BC and Franson JD (2002) Single photons on pseudodemand from stored parametric down-conversion. *Physical Review A* **66**(4), 042303. https://doi.org/10.1103/PhysRevA.66.042303.

https://doi.org/10.1017/qut.2024.4 Published online by Cambridge University Press

Rudolph T (2017) Why I am optimistic about the silicon-photonic route to quantum computing. *APL Photonics* **2**(3), 030901. https://doi.org/10.1063/1.4976737.

Sabouri S, Angel Mendoza Velasco L, Catuneanu M, Namdari M and Jamshidi K (2021) Thermo optical phase shifter with low thermal crosstalk for soi strip waveguide. *IEEE Photonics Journal* **13**(2), 1–12. https://doi.org/10.1109/JPHOT.2021.3056902.

Senellart P, Solomon G and White A (2017) High-performance semiconductor quantum-dot single-photon sources. *Nature Nanotechnology* **12**(11), 1026–1039. https://doi.org/10.1038/nnano.2017.218.

Stefanie B, Elham K, Anne B, Joseph FF, Anton Z and Philip W (2012) Demonstration of blind quantum computing. *Science* **335**(6066), 303–308. https://doi.org/10.1126/science.1214707.

Vigliar C, Paesani S, Ding Y, Adcock J C, Wang J, Morley-Short S, Bacco D, Oxenløwe L K, Thompson M G, Rarity J G, Laing A (2021) Error-protected qubits in a silicon photonic chip. *Nature Physics* **17**(10), 1137–1143. https://doi.org/10.1038/s41567-021-01333-w.

Virtanen P, Gommers R, Oliphant TE, Haberland M, Reddy T, Cournapeau D, Burovski E, Peterson P, Weckesser W, Bright J, *et al.* (2020) Scipy 1.0: fundamental algorithms for scientific computing in python. *Nature Methods* **17**(3), 261–272. https://doi.org/10.1038/s41592-019-0686-2.

Walls DF and Milburn GJ (2008) Bose-einstein condensation, In *Quantum Optics*. Springer, pp. 397–420.

Walls DF and Milburn GJ (2012) *Quantum Optics*. Berlin Heidelberg: Springer Study Edition.

Wooten EL, Kissa KM, Yi-Yan A, Murphy EJ, Lafaw DA, Hallemeier PF, Maack D, *et al.* (2000) A review of lithium niobate modulators for fiber-optic communications systems. *IEEE Journal of Selected Topics in Quantum Electronics* **6**(1), 69–82. https://doi.org/10.1109/2944.826874.

Xiong C, Bell B and Eggleton BJ (2016) CMOS-compatible photonic devices for singlephoton generation. *Nanophotonics* **5**(3), 427–439. https://doi.org/10.1515/nanoph-2016-0022.

Zhong H-S, Li Y, Li W, Peng L-C, Su Z-E, Hu Y, He Y-M, Ding X, Zhang W, Li H, Zhang L, Wang Z, You L, Wang X-L, Jiang X, Li L, Chen Y-A, Liu N-L, Lu C-Y, Pan J-W (2018) 12-photon entanglement and scalable scattershot boson sampling with optimal entangled-photon pairs fromparametric down-conversion. *Physical Review Letters* **121**(25), 250505. https://doi.org/10.1103/PhysRevLett.121.250505.

https://doi.org/10.1017/qut.2024.4 Published online by Cambridge University Press