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Time-multiplexed heralded single-photon source

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Photons have proven to be excellent carriers of quantum information and play essential roles in numerous quantum information processing (QIP) applications. In particular, heralded single-photon sources via spontaneous parametric-down conversion (SPDC) have been a key technology for demonstrating small-scale QIP, yet their low generation efficiency is a critical limitation to furthering the scale-up of optical QIP technology. In order to efficiently overcome the probabilistic nature of SPDC, here we demonstrate time multiplexing for up to 30 time slots of a periodically pumped heralded single-photon source using a switchable low-loss optical storage cavity. We observe a maximum single-photon probability of 38.6 ± 0.4% in periodic output time windows, corresponding to ∼6 times enhancement over a nonmultiplexed source but with no increase in the contribution of unwanted multiphoton events. Combining this time-multiplexing technique with a heralded source producing pure single-photon states should enable larger-scale optical QIP systems than previously realized.

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Realizing and scaling up optical QIP systems [1–3] requires on-demand preparation of quantum states of light such as single-photon and definite multiphoton states. Single atoms, ions, and solid-state single-emitter sources such as color centers in diamond and semiconductor quantum dots can generate true single-photon states, and solid-state systems have especially great potential for integration. However, while high indistinguishability [4,5] and somewhat high (50%–80%) collection efficiency [6] have been reported in different single-emitter systems, achieving both simultaneously remains a challenge. Moreover, most single-emitter sources generate single photons with narrow bandwidths (5–100 MHz) that may be unsuitable for pursuing high-speed applications (e.g., a 5-MHz bandwidth source can produce nonoverlapping single-photon Gaussian wavepackets of duration 90 ns at a maximum rate of ∼10 MHz).

SPDC is another approach that has been conventionally and widely used for generating entangled photon pairs, multiphoton entangled states, and small-scale quantum algorithms [7]. A photon pair generated via SPDC can also be used for generating a "heralded" single-photon state [8]; detecting one of the photons "heralds" the presence of the other. Moreover, current technology has realized photons with very high coupling efficiency into single-mode optical fibers [9,10] and controlled two-photon spectral shapes [11,12]. However, the photon-pair generation process via SPDC is probabilistic: one cannot obtain a photon pair or a heralded single photon on demand. Unfortunately, indefinitely increasing the mean number of photon pairs per pump pulse p also increases the likelihood of unwanted k photon pairs ($\sim p^k$) by higher-order processes.

To overcome the probabilistic nature of photon-pair generation, time-multiplexing techniques were first proposed and demonstrated by Pittman, Jacobs, and Franson [13] in 2002. The method has since been extended and theoretically analyzed [14–17]. A related approach uses spatial multiplexing [18–22], but this is much more resource intensive—a source analogous to ours would need ∼30 sources (either using independent SPDC crystals or by extracting multiple photon-pair sources from a single crystal [18]), low-loss binary (2 to 1) switchyard elements, and detectors. The basic idea is shown in Fig. 1(a). A laser pulse train with period τ pumps a $\chi^{(2)}$ nonlinear crystal, generating photon pairs (i.e., signal and idler photons) in one or more time slots. Each signal photon is sent to a single-photon detector (SPD) whose firing heralds in which time slot the corresponding idler photon is present. By using a switchable storage cavity with the matched cycle length τ, any one of the time slots heralded to contain an idler photon can be multiplexed onto a single-output time window [see Fig. 1(b)]. Thus, the multiplexed single-photon probability $P_M(1)$ during the output time window is increased according to the number of pump pulses (time slots) N used for one cycle of the multiplexing. Moreover, if N is large, the probability of generating unwanted multiple pairs in a given time slot can be made arbitrarily small, because the total pump energy through the multiplexing cycle is distributed over the N time slots and the ratio of the single- and multiphoton probability is as low

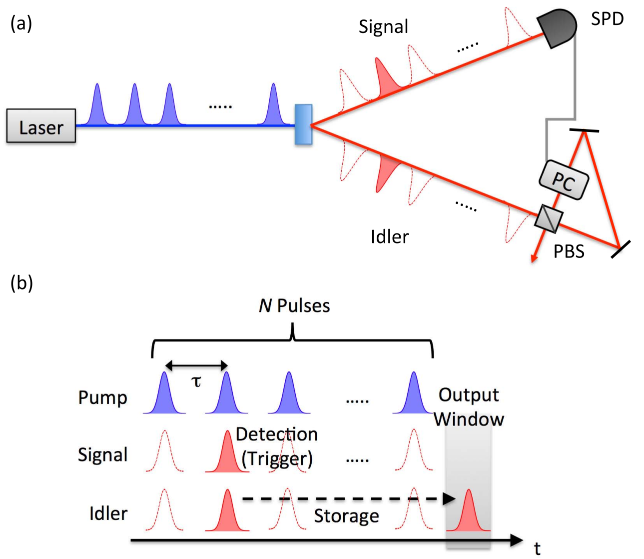

Fig. 1. (a) Simplified schematic diagram of a time-multiplexed heralded single-photon source. (b) Timing diagram of pump, signal, and idler photons in the time multiplexing. In our system, when the idler photon enters the storage cavity via a polarizing beam-splitter (PBS), a Pockels cell (PC) in the cavity is fired, rotating the photon polarization by 90° and thereby storing the photon in the cavity loop until its polarization is switched back. The single-pass delay of the cavity is set to match τ so that the time slots where idler photons may be present are temporally and spatially overlapped with each other in the cavity. The idler photon is then released from the cavity in the desired output time slot by a second switching of the PC.

as the one for a single (nonmultiplexed) heralded single-photon source. Hence, assuming losses can be kept low, the multiplexed heralded single-photon source can work as a pseudo-on-demand single-photon source (i.e., $P_M(1) \rightarrow 1$) by using sufficiently low pump pulse energy ($p < 0.1$) and large cycle number N. A detailed mathematical calculation of $P_M(1)$, accounting for loss and inefficiencies of SPDs, PC, and the SPDC source is discussed in [14,23] and in Supplement 1. Roughly speaking, we find that substantial (i.e., >5) enhancements to the single-photon probability are only possible if the losses per cycle can be kept below 20%. This may pose a challenge for implementations not using low-loss bulk optics [24], although proof-of-principle demonstrations of quantum storage and retrieval by light–matter interfaces have been reported (e.g., see [25]).

A schematic diagram of our experimental setup is shown in Fig. 2. We implemented the setup with a low-loss heralded single-photon source and photon storage cavity (see Supplement 1). However, in practice, many repeated passes through the storage cavity attenuate the stored idler photons; for the case that multiple time slots within N are heralded, photons stored later—closer to the output time window—experience less loss. In order to select only the last-produced and therefore lowest-loss photon, we introduced a low-loss Herriott-cell-type optical delay line [26] (between the SPDC crystal and the switchable storage cavity) whose delay Δt_{DL} is long enough to contain idler photons from all N of the pump pulses. The long optical delay makes it possible to determine the time slot of the last-detected signal photon, and to only switch the corresponding idler photon into the storage cavity. For our largest delay, Δt_{DL} is ~400 ns, sufficiently longer than the ~120 ns

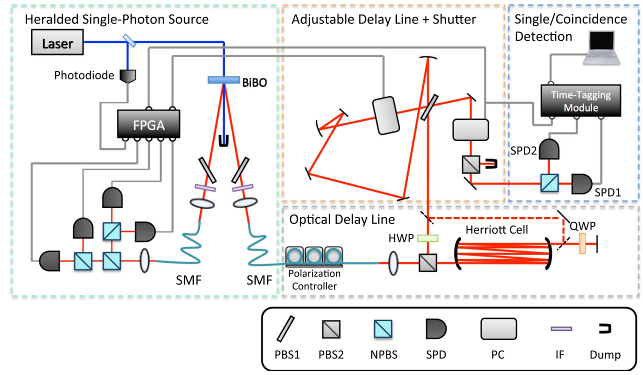

Fig. 2. Schematic diagram of experimental setup. PBS1, Brewster-angled polarizing beam splitter; PBS2, cube polarizing beam splitter; NPBS, nonpolarizing beam splitter; SPD, single-photon detector; PC, Pockels cell; IF, interference filter ($\Delta\lambda = 20$ nm); HWP, half-wave plate; QWP, quarter-wave plate; FPGA, field-programmable gate array. Dashed red line shows the optical path when the optical delay is shortened to $\Delta t_{\mathrm{DL}} \sim 200$ ns.

electronics latency (from detecting signal photons to the PC driver) to hold idler photons from up to $N \sim 30$ ($30 \times \tau = 250$ ns for $\tau = 8.33$ ns in our experiment). Using flippable mirrors, we can also reduce Δt_{DL} to ~200 ns, which is still longer than the electronics latency but not enough to store the latest heralded time slot for larger N. This allows us to compare the effect of storing the photons in the latest and earliest heralded time slots.

We studied time multiplexing with two different pump powers: A high pump power (such that $p = 0.35$) is used so that the heralding signal rate H is nearly saturated, i.e., H is close to the repetition rate of the multiplexed source $R = 50$ kHz for $N = 30$ [see blue circles and red triangles in Fig. 3(a)]. With a low pump power ($p = 0.07$), H increases almost linearly with N up to 30 [see green squares and purple diamonds in Fig. 3(a)]. Note that R for this proof-of-principle multiplexed source is limited by the duty cycle of the PC drivers. Figure 3(b) shows our experimental results for single photons in periodic output time slot $P_M(1)$ versus N. $P_M(1)$ is estimated by

$$P_M(1) = \frac{S_1 + S_2}{R\eta_{Di}}, \tag{1}$$

where S_1 and S_2 are the single-photon count rates measured by SPD1 and SPD2 at the output time windows, and η_{Di} is the system-detection efficiency for the multiplexed photons (see Supplement 1). For all the measurement in our experiment, we clearly observed an enhancement in $P_M(1)$ above the single-cycle probability: We observed $P_M(1) = 38.6 \pm 0.4\%$ for $p = 0.35$ and $N = 30$ [see blue dots in Fig. 3(b)], corresponding ~6 times enhancement over the nonmultiplexed heralded photons (for $N = 1$, $P_M(1) = 6.8 \pm 0.4\%$). The enhancement factor was even larger for $p = 0.07$ [~16, see green squares in Fig. 3(b)], because H increases as N up to 30. To our knowledge, these single-photon probability and enhancement factors are superior to all previous demonstrations [19,20] of multiplexed heralded single photons (that achieved $P_M(1) < 1\%$ with enhancement factor of 1.6–4). For the results with the 200 ns delay line [red triangles and purple diamonds in Fig. 3(b)], as expected, $P_M(1)$ starts to decrease after $N \sim 15$, due to increased loss for photons stored in the earlier heralded time slots. Our results are in

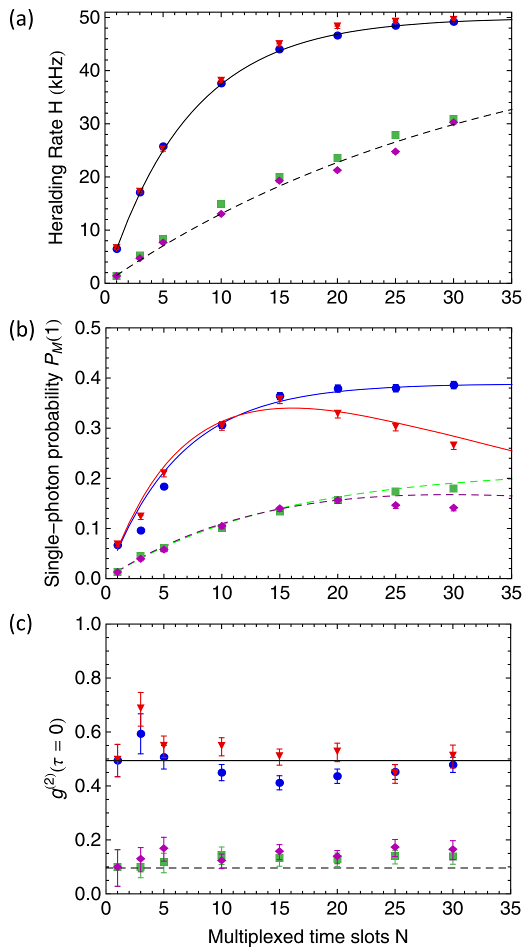

Fig. 3. Experimental results. (a) Heralding rate H, (b) single-photon probability $P_M(1)$, and (c) the second-order correlation function $g^{(2)}(0)$ versus number of multiplexed time slots N. Blue circles: $p = 0.35$, $\Delta t_{DL} \sim 400$ ns. Red triangles: $p = 0.35$, $\Delta t_{DL} \sim 200$ ns. Green squares: $p = 0.07$, $\Delta t_{DL} \sim 400$ ns. Purple diamonds: $p = 0.07$, $\Delta t_{DL} \sim 200$ ns. Error bars are estimated by Poissonian photon counting statistics. For (a) and (b), solid and dashed curves show theoretical predictions for the measurement with $p = 0.35$ and 0.07, taking into account the measured experimental parameters (p, T_c, T_i, η_{Ds}) and using Eq. (S1) in Supplement 1. Solid and dashed lines in (c) indicate the values of $g^{(2)}(0)$ measured without multiplexing ($N = 1$) for $p = 0.35$ and 0.07.

excellent agreement with our theoretical prediction [solid and dashed curves in Fig. 3(b)], except the observed single-photon probabilities with the 200 ns delay line for $N > 20$. The difference may be caused by slight spatial-mode mismatching between the output of the delay line and the switchable storage cavity—a 1% mismatch would be sufficient to make slight beam clipping at the PC in the storage cavity for $N \gtrsim 20$ and to account for the observed discrepancy.

We characterized the ratio of single- and multiphoton probabilities via the second-order correlation function at zero time delay between the signals from SPD1 and SPD2 [27]:

$$g^{(2)}(0) = \frac{C_{12}H}{S_1 S_2}, \quad (2)$$

where C_{12} is the coincidence count rate between SPD1 and SPD2. The observed $g^{(2)}(0) < 1$ [see Fig. 3(c)] is expected for a nonclassical light source. Moreover, while the single-photon probability is greatly enhanced by multiplexing, the observed $g^{(2)}(0)$ is nearly constant versus N for the same p: the contribution of the two-photon probability relative to the single-photon one is approximately independent of the time multiplexing. As expected [solid and dashed lines in Fig. 3(c)], $g^{(2)}(0)$ is higher for $p = 0.35$, because of the higher likelihood of multipair emissions compared to the case for $p = 0.07$. Nevertheless, our results are still better than what one could achieve even from an ideal heralded SPDC source (e.g., with 100% efficient trigger detection and perfect coupling into lossless optics, see Table 1), which predicts $P_M(1) = 36.8\%$ (25.0%) for a completely mixed (pure) single-photon state according to Poissonian (thermal) photon-number statistics [28].

Table 1. Comparison Between Multiplexed Sources (MUX) and Ideal Nonmultiplexed Sources (NMUX)[a]

		$P_M(1)$	$g^{(2)}(0)$
MUX	This work	$38.6 \pm 0.4\%$	0.479 ± 0.028
	With efficient components	>80%	<0.05
NMUX	Mixed state	36.8%	0
	Pure state	25.0%	0

[a]The ideal nonmultiplexed sources assume photon-pair sources with perfect heralding efficiency and 100% efficient detectors with photon-number-resolving functionality. For the time-multiplexed source with efficient components, the values are predicted by feasible parameters ($p = 0.1$, $T_c = 99\%$, $T_i = 95\%$, $\eta_{Ds} = 90\%$) using recent state-of-the-art technologies and Eq. (S1) in Supplement 1.

There are several straightforward improvements for the time-multiplexed source. First, we observed a low purity (0.05) of the heralded idler-photon state (using the method proposed in [28]), because of strong spectral entanglement. Since many QIP applications utilize multiphoton interference effects, which require pure states [29], our SPDC source must be changed to one that heralds single photons in a pure quantum state, i.e., without spectral entanglement between the signal and idler photons. Sources that herald intrinsically pure single photons without narrowband filtering have been reported [11,12,30]; combined with temporal multiplexing, these have the potential for both high single-photon probability and purity. (Note that the probability of higher-order emissions can actually be higher for pure heralded single-photon sources than for ones generating mixed states because of their different photon-number statistics, i.e., thermal for a single-mode SPDC source versus Poissonian for multimode states [28]; multiplexing is consequently even more important to suppress unwanted multiple-photon events).

Beyond preparing pure photons, it is important to maintain this purity throughout the time-multiplexing process. In particular, group velocity dispersion (GVD) in the storage cavity needs to be negligibly small, lest the cycle-dependent GVD disturbs the spectral-temporal mode purity. Thus, more careful dispersion management in the storage cavity is required for heralded photons with shorter pulse durations ($\lesssim$100 fs). Moreover, the fluctuation of the storage cavity length introduces timing jitter, which in turn reduces the temporal purity of the multiplexed photons. Therefore, active locking of the storage cavity length may be necessary to stabilize the timing jitter to be much smaller than the coherence length of the heralded single photons. Note, however, that we do not need to have phase stabilization (which would be much more stringent) since typical two-photon interference effects are insensitive to phase. Thus, the required level of path length precision is much less, on the order of 10 μm, which can be achieved without active stabilization. Finally, SPDs with higher detection efficiencies would better detect unwanted multiple photons in the signal mode, improving the likelihood of heralding true single-photon states. Recent state-of-the-art detector technologies, such as visible-light photon counters [31] and arrays of superconducting nanowire detectors [32], have achieved >90% detection efficiencies and timing resolutions below 100 ps.

With feasible values for collection (95%) and detector efficiency (90%), and delay-line (1%) and switchable cavity losses (1%), we anticipate single-photon probability up to 80%, with a $g^{(2)}(0)$ as low as 0.05 (see Table 1). Despite our current source rate being only 50 kHz, such performance would already be advantageous for building up larger photon numbers; for example, the generation rate of an eight-photon state would be $0.8^8 \times 50$ kHz ~ 8000 per second by using the multiplexing technique, while recent eight-photon experiments [7] with nonmultiplexed SPDC sources generated only ∼1 per second.

In conclusion, we have experimentally demonstrated a time-multiplexed heralded single-photon source. Our experiment is implemented by a highly efficient SPDC source, low-loss fixed optical delay line, and adjustable storage cavity with fast polarization switches. We observed large enhancements in single-photon probabilities by multiplexing up to 30 time slots of the heralded single-photon source. Despite the great enhancement in the single-photon probability, the observed second-order correlation function of the output photons showed that the ratio of single-photon and unwanted two-photon probabilities for the multiplexed source was as low as for a nonmultiplexed one. We anticipate that incorporating a bright and pure heralded single-photon source and state-of-the-art photon-number-resolving detectors will enable a periodic and near-deterministic single-photon source that will be a critical component for larger-scale optical QIP applications.

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See Supplement 1 for supporting content.

REFERENCES

1. N. Gisin, G. Ribordy, W. Tittel, and H. Zbinden, Rev. Mod. Phys. **74**, 145 (2002).
2. J. L. O'Brien, Science **318**, 1567 (2007).
3. A. M. Childs, D. Gosset, and Z. Webb, Science **339**, 791 (2013).
4. A. Sipahigil, K. D. Jahnke, L. J. Rogers, T. Teraji, J. Isoya, A. S. Zibrov, F. Jelezko, and M. D. Lukin, Phys. Rev. Lett. **113**, 113602 (2014).
5. Y.-J. Wei, Y.-M. He, M.-C. Chen, Y.-N. Hu, Y. He, D. Wu, C. Schneider, M. Kamp, S. Höfling, C.-Y. Lu, and J.-W. Pan, Nano Lett. **14**, 6515 (2014).
6. O. Gazzano, S. M. de Vasconcellos, C. Arnold, A. Nowak, E. Galopin, I. Sagnes, L. Lanco, A. Lemaître, and P. Senellart, Nat. Commun. **4**, 1425 (2013).
7. J.-W. Pan, Z.-B. Chen, C.-Y. Lu, H. Weinfurter, A. Zeilinger, and M. Żukowski, Rev. Mod. Phys. **84**, 777 (2012).
8. C. Hong and L. Mandel, Phys. Rev. Lett. **56**, 58 (1986).
9. M. C. Pereira, F. E. Becerra, B. L. Glebov, J. Fan, S. W. Nam, and A. Migdall, Opt. Lett. **38**, 1609 (2013).
10. B. G. Christensen, K. T. McCusker, J. Altepeter, B. Calkins, T. Gerrits, A. E. Lita, A. Miller, L. K. Shalm, Y. Zhang, S. W. Nam, N. Brunner, C. C. W. Lim, N. Gisin, and P. G. Kwiat, Phys. Rev. Lett. **111**, 130406 (2013).
11. P. J. Mosley, J. S. Lundeen, B. J. Smith, and I. A. Walmsley, New J. Phys. **10**, 093011 (2008).
12. P. G. Evans, R. S. Bennink, W. P. Grice, T. S. Humble, and J. Schaake, Phys. Rev. Lett. **105**, 253601 (2010).
13. T. Pittman, B. Jacobs, and J. Franson, Phys. Rev. A **66**, 042303 (2002).
14. E. Jeffrey, N. A. Peters, and P. G. Kwiat, New J. Phys. **6**, 100 (2004).
15. K. McCusker and P. G. Kwiat, Phys. Rev. Lett. **103**, 163602 (2009).
16. B. L. Glebov, J. Fan, and A. L. Migdall, Appl. Phys. Lett. **103**, 031115 (2013).
17. J. Mower and D. Englund, Phys. Rev. A **84**, 052326 (2011).
18. A. L. Migdall, D. Branning, and S. Castelletto, Phys. Rev. A **66**, 053805 (2002).
19. X. Ma, S. Zotter, J. Kofler, T. Jennewein, and A. Zeilinger, Phys. Rev. A **83**, 043814 (2011).
20. M. J. Collins, C. Xiong, I. H. Rey, T. D. Vo, J. He, S. Shahnia, C. Reardon, T. F. Krauss, M. J. Steel, A. S. Clark, and B. J. Eggleton, Nat. Commun. **4**, 2582 (2013).
21. R. J. A. Francis-Jones and P. J. Mosley, "Exploring the limits of multiplexed photon-pair sources for the preparation of pure single-photon states," arXiv:1409.1394 (2014).
22. D. Bonneau, G. J. Mendoza, J. L. O'Brien, and M. G. Thompson, New J. Phys. **17**, 043057 (2015).
23. K. T. McCusker, "Efficient quantum optical state engineering and applications," Ph.D. Thesis (University of Illinois at Urbana-Champaign, 2012).
24. G. J. Mendoza, R. Santagati, J. Munns, E. Hemsley, M. Piekarek, E. Martín-López, G. D. Marshall, D. Bonneau, M. G. Thompson, and J. L. O'Brien, "Active temporal multiplexing of photons," arXiv: 1503.01215 (2015).
25. A. I. Lvovsky, B. C. Sanders, and W. Tittel, Nat. Photonics **3**, 706 (2009).
26. C. Robert, Appl. Opt. **46**, 5408 (2007).
27. R. Loudon, *The Quantum Theory of Light*, 3rd ed. (Oxford University, 2000).
28. A. Christ, K. Laiho, A. Eckstein, K. N. Cassemiro, and C. Silberhorn, New J. Phys. **13**, 033027 (2011).
29. C. Hong, Z. Ou, and L. Mandel, Phys. Rev. Lett. **59**, 2044 (1987).
30. J. B. Spring, P. S. Salter, B. J. Metcalf, P. C. Humphreys, M. Moore, N. Thomas-Peter, M. Barbieri, X.-M. Jin, N. K. Langford, W. S. Kolthammer, M. J. Booth, and I. A. Walmsley, Opt. Express **21**, 13522 (2013).
31. J. Kim, K. S. McKay, P. G. Kwiat, K. Zielnicki, and E. J. Gansen, Exp. Methods Phys. Sci. **45**, 147 (2013).
32. F. Marsili, V. B. Verma, J. A. Stern, S. Harrington, A. E. Lita, T. Gerrits, I. Vayshenker, B. Baek, M. D. Shaw, R. P. Mirin, and S. W. Nam, Nat. Photonics **7**, 210 (2013).