Entanglement is a fundamental property of quantum mechanics, and is a primary resource in quantum information systems. Its manipulation remains a central challenge in the development of quantum technology. In this work, we demonstrate a device which can generate, manipulate, and analyse two-qubit entangled states, using miniature and mass-manufacturable silicon photonics. By combining four photon-pair sources with a reconfigurable six-mode interferometer, embedding a switchable entangling gate, we generate two-qubit entangled states, manipulate their entanglement, and analyse them, all in the same silicon chip. Using quantum state tomography, we show how our source can produce a range of entangled and separable states, and how our switchable controlled-Z gate operates on them, entangling them or making them separable depending on its configuration.

Keywords: silicon quantum photonics, integrated quantum information processing, entanglement, photonic qubits, quantum photonics
demonstrated with very high extinction. Finally, single-photon detectors, based on superconducting nanowires have shown excellent performance on silicon waveguides [35, 36]. The very high refractive index contrast of silicon-on-insulator waveguides yields micron-scale components (e.g. [37]), while miniature ring resonator SFWM sources [22], and quantum interferometric networks [38] facilitate devices on a very large scale.

The integration of entangled qubit sources with entangling quantum logic, together on a common platform, is an important next step. Here, we show a new method for generating path-encoded, variably entangled two-qubit states. We perform multi-qubit quantum logic on these states and study their entanglement. We implemented this scheme on a reconfigurable, silicon photonic device to generate a wide range of two-qubit states. We integrated this source with arbitrary state preparation, a switchable two-qubit gate, and an interferometer for tomographic analysis. The implemented quantum circuit is similar to the one reported in [39].

We tested the device’s quantum logic capabilities with several experiments. We analysed the source performance using reversed-Hong–Ou–Mandel-type (RHOM) [28, 40] quantum interference, and qubit tomography on a wide range...
of possible states. We followed this with an exploration of the
on-chip quantum logic, with the switchable two-qubit gate in
both entangling (\( \hat{c}z \)) and non-entangling (\( \hat{I} \)) configurations,
and using the purity (\( P \)) [41], the CHSH parameter (\( S \)) [42]
and the Schmidt number (\( K \)) [43] as diagnostic metrics.

2. Device structure and operation

A schematic of the device is shown in figure 1(a). It comprises a reconfigurable source of two path-encoded entangled
photons, controlled by the parameters \( \phi_0 \), \( \phi_T \) and \( \phi_B \). The
source is followed by a reconfigurable interferometer, able to
implement any two-qubit projector (including entangled
projections). This second part of the device can be divided
into three sections: arbitrary single qubit gates, a switchable
post-selected controlled-Z (\( cZ \)) gate [44], and final single-
qubit unitaries, used to implement projectors for quantum
state tomography, to reconstruct the output state.

The device comprised 500 \times 220 \text{ nm}^2 waveguides,
directional couplers (approximate length 45.9 \mu m), a wave-
guide crossing (>20 dB isolation), and resistive metallic
heaters (length 54.0 \mu m). It was coupled to fibre via edge
coupling, fibre lenses, and polymer spot-size converters.
Electrical connections were achieved through multi-contact
electrical probes and 200 \mu m pitch on-chip gold pads
(approximately 120 \times 200 \mu m^2). Fabrication of the device
proceeded as in [31].

The experimental setup is presented in figure 1(b). Pho-
ton pairs generation from the device, demultiplexed and separated from the pump using
dense wavelength-division multiplexers, detected using
superconducting nanowire detectors [46], and finally
converted into coincidence counts by a time-interval analyser.

2.1. Photon-pair generation

The strong nonlinear properties of silicon waveguides are
well known [47]. SFWM, an effect of the \( \chi^{(3)} \) nonlinearity, is
now commonly used to produce photon pairs in silicon
quantum photonic devices [21, 28].

Figure 2. Quantum interference for the two sources, measuring
coincidences from the outputs \( \text{OUT}_T \) and \( \text{OUT}_B \), obtained by
pumping each RHOM source and scanning the source internal phase,
\( \phi_T \) or \( \phi_B \). The imperfect interference can be explained in terms of
imbalance in the on-chip evanescent coupler beam splitters.

Figure 3. Two-qubit state properties, direct from the source, as a
function of the input state control phase, \( \phi_p \). (a) Balance between the
\( \text{C} = 72.9\% \) and the \( \text{C} = 93.2\% \) components of the state, see equation (2).
(b) Schmidt number. (c) CHSH parameter. Maximal entanglement
occurs when the state is balanced, when \( \phi_p = \pi/2 \). Error bars were
computed as one standard deviation of 200 trials around each
tomographic measurement, each with a random sampling of Poisson
photon noise. We assume a control phase uncertainty of \( \pm \pi/50 \).
In the non-degenerate SFWM process used here, two photons from a bright pump are annihilated, producing two correlated photons with different wavelengths (figure 1(a)). The two generated photons, ‘signal’ and ‘idler’, emerge spectrally on either side of the pump, conserving energy and momentum. In our experiment, spiralled 21 mm long waveguides were used to produce photon-pairs, with the pump, signal, and idler photon wavelengths being 1551, 1547 and 1555 nm. These photons were generated in a continuous spectrum and the chosen wavelengths were post-selected by the off-chip demultiplexers.

2.2. Entangled qubits generation

Our device uses a new scheme to generate entangled path-encoded states, which can subsequently be interfered, using pairs of non-degenerate photons. Pump laser is distributed between two reverse-HOM structures using a reconfigurable power splitter (splitting ratio $f_b = \sin^2 2\phi_f$). Each RHOM contains two spiralled waveguides and a thermal phase shifter, as in [28]. The internal RHOM phases ($\phi_T$ and $\phi_B$) were set to $\pi/2$, such that the produced photon-pairs emerged deterministically split, one in each output waveguide, and in a state symmetrical between signal and idler photons. $f_b$ allows us to control the balance of photon-pair emission between the two RHOM structures, and so to control the entanglement present in the two-qubit output state.

Following figure 1(b), if $\phi_b = \pi$, photons will be generated only in the top RHOM, and the photon number output state, after the waveguide crossing, will be $|0101\rangle$ or $|00\rangle$ in the qubit basis. On the other hand, if $\phi_b = 0$, only the bottom RHOM generates photons, leading to $|0101\rangle = |11\rangle$. Finally, if $\phi_b = \pi/2$, we obtain the maximally entangled state:

$$|\psi\rangle = \sqrt{\beta} |00\rangle + e^{i\theta} \sqrt{1-\beta} |11\rangle$$

which can be continuously varied across a wide range of separable and entangled states, depending on the balance parameter, $\beta$. The balance depends on the square of the power division of the state control Mach–Zehnder interferometers (MZI) (controlled by the phase $\phi_b$), due to the two-photon dependence of SFWM:

$$\beta = \left| \frac{\sin^2(\phi_b/2)}{\sqrt{\sin^2(\phi_b/2) + \cos^2(\phi_b/2)}} \right|^2.$$

2.3. Quantum logic and analysis

The state $|\psi\rangle$ is fed into a two-qubit circuit, composed of single-qubit rotations, and a switchable entangling gate. We implemented the arbitrary rotations on each qubit by cascading phase-shifters and MZI. These were used to realise $\hat{R}_z$ and $\hat{R}_y$ rotations, respectively, obtaining an arbitrary SU(2) with the combination $\hat{R}_z \cdot \hat{R}_y \cdot \hat{R}_z$. 

![Figure 4. Reconstructed output states for various source and gate configurations. States (a), (c), (e) are seeded by an entangled source state, while (b), (d), (f) are seeded by a $|11\rangle$ source state. States (a), (b) bypass the gate; (c), (d) pass through the gate set to $\hat{I}$; and (e), (f) pass through the gate set to $\hat{c}_2$, and include the phase information, below. State properties are compiled in table 1. Device configurations producing each set of states are shown at right.](image-url)
Table 1. Purity, Schmidt number, CHSH parameters and fidelity for a variety of measured states. The Schmidt number and CHSH parameter indicate entanglement. $S > 2$ indicates the presence of non-local correlations [43], while $K$ indicates the number of coefficients in the Schmidt decomposition of the state [43]. The fidelities $F'$ reported are computed against the ideal state optimised over local $R_i$ rotations, to compensate for the intrinsic random phase factor on each qubit.

| Source state | Gate | Purity $P$ | Schmidt number $K$ | CHSH $S$ | Fidelity $F'$ |
|--------------|------|------------|-------------------|-----------|--------------|
| $|00\rangle$ | Bypassed | $0.995 \pm 0.012$ | $1.012 \pm 0.011$ | $1.577 \pm 0.072$ | $0.973 \pm 0.011$ |
| $|00\rangle$ | $\hat{I}$ | $0.946 \pm 0.031$ | $1.034 \pm 0.017$ | $1.465 \pm 0.064$ | $0.962 \pm 0.016$ |
| $|11\rangle$ | Bypassed | $0.998 \pm 0.008$ | $1.004 \pm 0.006$ | $1.511 \pm 0.049$ | $0.984 \pm 0.007$ |
| $|11\rangle$ | $\hat{I}$ | $0.949 \pm 0.055$ | $1.048 \pm 0.037$ | $1.601 \pm 0.121$ | $0.948 \pm 0.031$ |
| $(|00\rangle + |11\rangle)/\sqrt{2}$ | Bypassed | $0.864 \pm 0.019$ | $1.905 \pm 0.022$ | $2.560 \pm 0.037$ | $0.909 \pm 0.028$ |
| $(|00\rangle + |11\rangle)/\sqrt{2}$ | $\hat{I}$ | $0.832 \pm 0.040$ | $1.936 \pm 0.025$ | $2.538 \pm 0.072$ | $0.900 \pm 0.026$ |
| $|\pm\rangle$ | $\hat{c}_z$ | $0.931 \pm 0.036$ | $1.657 \pm 0.045$ | $2.560 \pm 0.078$ | $0.873 \pm 0.038$ |
| $(|00\rangle + |11\rangle)/\sqrt{2}$ | $\hat{c}_z$ | $0.900 \pm 0.071$ | $1.166 \pm 0.055$ | $1.907 \pm 0.137$ | $0.839 \pm 0.013$ |

We implemented a switchable entangling gate using a scheme based on [44], but replacing the $1/3$ beam-splitters with tunable-reflectivity MZIs. In this way, we can switch the gate’s controlled-$Z$ operation on and off. When on, the $\hat{c}_z$ operation succeeds with probability $1/9$. In the remaining $8/9$ cases, non-qubit states are generated, which are filtered by the coincidence-counting post-selection. Note that only the on ($\cos(t_d) = 1/3$) and off ($\cos(t_d) = -1$) gate configurations produce unitary operations. The two qubit gate is followed by rotations (parametrised by $\theta_{M_3}$, $\theta_{M_2}$, $M \in \{T, B\}$) used to implement quantum state tomography, via the method described in [48].

2.4. Calibration

Since the phase shifter parameters (phase-per-electrical-power, and phase offset) varied between phase modulators, a calibration process was essential. Measuring the bright-light transmission from the inputs (IN and IN') to the outputs (OUT$_T$, OUT$_B$, OUT$_T'$, OUT$_B'$), we were able to characterise the electro-optic parameters of each thermal phase shifter, in a similar way to that described in [49]. We learned the parameters associated with each phase according to the scheme:

$$\begin{align*}
\text{IN'} & \rightarrow \text{OUT}_T', \ \text{OUT}_B' : \phi_B, \theta_{B_1}, \theta_{C_{ZB}}, \theta_{T_{1z}}, \theta_{C_{ZT}} \\
\text{IN} & \rightarrow \text{OUT}_T, \ \text{OUT}_B : \phi_J, \phi_T, \theta_{T_{1z}}, \theta_{B_1} \\
\text{IN} & \rightarrow \text{OUT}_T: \theta_{C_{ZC}}, \theta_{T_{2z}}, \theta_{T_{3z}} \\
\text{IN} & \rightarrow \text{OUT}_B : \theta_{B_2}, \theta_{B_2}, \theta_{B_3}.
\end{align*}$$

We observed instabilities in the calibration data, due to changes in electrical contact resistance between our probe card and the on-chip gold pads. To mitigate this, we periodically recalibrated the on-chip parameters. Metallurgical wire-bonded contacts can prevent this in future. Low levels of thermal and common-ground crosstalk were observed but not compensated. Recent results suggest that crosstalk can be reduced through efficiency improvements, passive compensation methods, and by current driving of the thermal phase shifters [38, 49, 50].

The offsets of the tomographic $z$-rotation phases ($\theta_{T_{2z}}$, $\theta_{B_3}$) were left at zero, meaning that additional random (fixed) $z$ rotations were applied to each qubit before measurement. This choice was necessitated by the combined difficulty of:

1. calibrating the nonlinear source phase with bright light, and
2. doing this for each setting of the gate, in the device’s finite stability time.

3. Results

3.1. Source performance

One of the key metrics of a photon-pair source is its pair-generation efficiency [51]. This quantity is obtained from the photon-pair detection rate as a function of the input power, accounting for loss and detector efficiency. Inside the $1\text{ mm}$ wide signal and idler spectral bands, we measured a brightness of $20 \text{ kHz mW}^{-2}$.

The indistinguishability between photon-pair sources is also important. The contrast of the RHOM block’s quantum interference fringes indicates the indistinguishability of the block’s constituent photon-pair sources. We measured RHOM quantum interference fringes on each source by configuring the chip to maximise photon flux at the OUT$_T$ and OUT$_B$ outputs, then varying $\phi_T$ and $\phi_B$ to obtain the fringes of figure 2. We pumped the bottom source via the auxiliary input IN', and the top source via IN and the state-control MZI, integrating each point for 5 s. We observed $C = 93.2\% \pm 1.4\%$ and $72.9\% \pm 0.8\%$ fringe contrasts, respectively, for the top and bottom sources. Here, $C = (N_{\text{max}} - N_{\text{min}})/(N_{\text{max}} + N_{\text{min}})$, where $N_{\text{max}}$ and $N_{\text{min}}$ are the accidental-subtracted maximum and minimum fitted count rates. The reduced contrasts can be explained by deviations (from the ideal $\eta = 50\%$) in the input evanescent couplers of each RHOM structure; they are compatible with reflectivity values of $\eta \approx 43\%$ and $\eta \approx 36\%$ for the top and bottom sources, respectively.

3.2. Quantum logic

We next quantified the device’s control over entanglement. Quantum state tomography was used to extract the purity ($P = \text{Tr}(\rho^2)$) [41]), the CHSH parameter, a strict measurement of quantum correlations, and the Schmidt number, analogous to the number of pure states represented in a given density.
between 0 and π to prepare variably entangled states in the form of (1). When β = 0 or 1, separable states result, while 
when β = 1/2, a maximally entangled state is produced. 
States obtained directly from the source (bypassing the gate) 
showed good agreement with (1). These were measured using the 
OUT\(x\)' and OUT\(y\)' auxiliary outputs (see figure 1(b)). 
Measured and calculated variations of the balance, Schmidt 
number, and CHSH parameter are plotted in figure 3, versus 
the state control parameter \(\phi\).

In figure 4 we show a sample of density matrices arising 
from the main device configurations, and we list their prop-
erties (purity, Schmidt number, CHSH parameter, and fidelity 
with the ideal z-rotated state) in table 1. Errors were obtained 
from Monte-Carlo simulations, based on 200 samples of 
Poissonian photon noise and accompanying tomographic 
reconstructions [54]. As expected, the \(\bar{I}\)-mode gate did not 
substantially affect the properties of the input states. The 
\(cz\)-mode gate, however, acted to entangle separable states, 
and separate entangled states, though it also degraded the 
purity. The limited contrast in the quantum interference of the 
two RHOM sources contributed to this reduction, by occa-
sionally depositing two photons into one ‘qubit’. Gate and 
tomography calibration errors likely also contributed.

Since the entangling gate operates on the input state’s 
phase, we must examine with care the phase of the output 
state, \(\text{arg}\[\hat{\rho}\]\). The intrinsic and uncalibrated 
\(z\)-rotations on each qubit result in complicated phase pictures (figures 4(e) and (f)). To compare these to their ideal counterparts, we 
computationally applied \(\hat{R}_c(\zeta_y) \otimes \hat{R}_c(\zeta_x)\) to the reconstructed 
output state, and optimised the fidelity over local \(z\)-rotations 
via \(\zeta_y\) and \(\zeta_x\). The resulting fidelities are listed in table 1 and 
the process is shown visually in figure 5.

4. Discussion

We have presented a silicon-on-insulator quantum photonic 
device which embeds capabilities for the generation, manip-
ulation, and analysis of two-qubit entangled states, by lever-
aging on-chip linear and nonlinear optics. We showed how 
the device can prepare a variety of entangled and separable 
states, and operate on them using a switchable entangling 
gate. We demonstrated a new reconfigurable source of vari-
ably path-entangled non-degenerate photon pairs, using 
RHOM quantum interference, and used on-chip quantum 
state tomography to measure its performance. The integration 
of this source with a complex integrated linear optical net-
work enabled both the entanglement and disentanglement of 
the on-chip generated quantum states.

Device performance was hindered by imperfect beam-
splitters and high coupling losses, leading to issues with 
stability, and ultimately limiting the measurable purity and 
entanglement. However, the use of more advanced fibre 
couplers, such as those based on ultra-low loss gratings [55], together with adaptive methods, employing multiple imper-
fect MZIs for the realisation of a very high-quality one [34], 
can overcome these limitations, and enable high-performance,
large-scale silicon photonic quantum devices in the near future.

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**Author contributions statement**

RS and JWS contributed equally to this work. They conceived and designed the device, performed the experiments, and analysed the data. MJS and M Sorel. fabricated the device. SM, TY, MF, M Sasaki, and HT provided the superconducting detectors and M G Tanner, CMN, and RHH built the detector system. M G Thompson supervised the work. All authors contributed to the manuscript.

**Data availability**

The data that support the plots within the paper and other findings of the study are available from the open data repository Figshare in https://doi.org/10.6084/m9.figshare.5464381.v1.

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**References**

[1] O’Brien J L, Furusawa A and Vuckovic J 2009 Photonic quantum technologies *Nat. Photon.* 3 687–95
[2] Latmiral L, Spagnolo N and Sciarrino F 2016 Towards quantum supremacy with lossy scattershot boson sampling *New J. Phys.* 18 113008
[3] Politi A, Cryan M J, Rarity J G, Yu S and O’Brien J L 2008 Silica-on-silicon waveguide quantum circuits *Science* 320 646–9
[4] Metcalf B J et al 2014 Quantum teleportation on a photonic chip *Nat. Photon.* 8 770–4
[5] Minkov M and Savona V 2016 A compact, integrated silicon device for the generation of spectrally filtered, pair-correlated photons *J. Opt.* 18 054012
[6] Matsuda N et al 2014 On-chip generation and demultiplexing of quantum correlated photons using a silicon-silica monolithic photonic integration platform *Opt. Express* 22 22831–40
[7] Reimer C et al 2015 Cross-polarized photon-pair generation and bi-chromatically pumped optical parametric oscillation on a chip *Nat. Commun.* 6 9236
[8] Carolan J et al 2015 Universal linear optics *Science* 349 711–6
[9] Sansoni L et al 2010 Polarization entangled state measurement on a chip *Phys. Rev. Lett.* 105 200503
[10] Tillmann M et al 2013 Experimental boson sampling *Nat. Photon.* 7 540–4
[11] Flamini F et al 2015 Thermally reconfigurable quantum photonic circuits at telecom wavelength by femtosecond laser micromachining *Light Sci. Appl.* 4 354
[12] Bentivegna M et al 2015 Experimental scattershot boson sampling *Sci. Adv.* 1 1400255
[13] Spring J B et al 2017 Chip-based array of near-identical, pure, heralded single-photon sources *Optica* 4 90–6
[14] Vergyris P et al 2016 On-chip generation of heralded photon-number states *Sci. Rep.* 6 1500
[15] Alibart O et al 2016 Quantum photonics at telecom wavelengths based on lithium niobate waveguides *J. Opt.* 18 104001
[16] Lenzini F et al 2017 Active demultiplexing of single photons from a solid-state source *Laser Photon. Res.* 11 1600297
[17] Sansoni L et al 2017 A two-channel, spectrally degenerate polarization entangled source on chip *npj Quantum Inf.* 3 5
[18] Zhang X, Zhang Y, Xiong C and Eggleton B J 2016 Correlated photon pair generation in low-loss double-stripe silicon nitride waveguides *J. Opt.* 18 074016
[19] Moss D J, Morandotti R, Gaeta A L and Lipson M 2013 New CMOS-compatible platforms based on silicon nitride and Hydex for nonlinear optics *Nat. Photon.* 7 597–607
[20] Silverstone J W, Bonneau D, O’Brien J L and Thompson M G 2016 Silicon quantum photonics *IEEE J. Sel. Top. Quantum Electron.* 22 6700113
[21] Sharpe J E et al 2006 Generation of correlated photons in nanoscale silicon waveguides *Opt. Express* 14 12388–93
[22] Azzini S et al 2012 Ultra-low power generation of twin photons in a compact silicon ring resonator *Opt. Express* 20 23100–7
[23] Matsuda N et al 2012 A monolithically integrated polarization entangled photon pair source on a silicon chip *Sci. Rep.* 2 00817
[24] Olislager L et al 2013 Silicon-on-insulator integrated source of polarization-entangled photons *Opt. Lett.* 38 1960–2
[25] Collins M J et al 2013 Integrated spatial multiplexing of heralded single-photon sources *Nat. Commun.* 4 2582
[26] Xiong C et al 2016 Active temporal multiplexing of indistinguishable heralded single photons *Nat. Commun.* 7 10853
[27] Harada K et al 2011 Indistinguishable photon pair generation using two independent silicon wire waveguides *New J. Phys.* 13 065005
[28] Silverstone J W et al 2013 On-chip quantum interference between silicon photon-pair sources *Nat. Photon.* 8 104–8
[29] Takesue H, Matsuda N, Kuramochi E and Notomi M 2014 Entangled photons from on-chip slow light Sci. Rep. 4 448

[30] Xu X et al 2013 Near-infrared Hong–Ou–Mandel interference on a silicon quantum photonic chip Opt. Express 21 5014–24

[31] Silverstone J W et al 2015 Qubit entanglement between ring-resonator photon-pair sources on a silicon chip Nat. Commun. 6 7948

[32] Harris N C et al 2014 Integrated source of spectrally filtered correlated photons for large-scale quantum photonic systems Phys. Rev. X 4 041047

[33] Piekarek M, Bonneau D, Miki S and Yamashita T 2016 High-extinction ratio integrated photonic filters for silicon quantum photonics Opt. Lett. 42 815

[34] Wilkes C M et al 2016 60 dB high-extinction auto-configured Mach–Zehnder interferometer Opt. Lett. 41 5318–21

[35] Najafi F et al 2015 On-chip detection of non-classical light by scalable integration of single-photon detectors Nat. Commun. 6 5873

[36] Pernice W H P et al 2012 High-speed and high-efficiency travelling wave single-photon detectors embedded in nanophotonic circuits Nat. Commun. 3 1325

[37] Xu Q, Fattal D and Beausoleil R G 2008 Silicon microring resonators with 1.5 μm radius Opt. Express 16 4309

[38] Harris N C et al 2014 Efficient, compact and low loss thermo-optic phase shifter in silicon Opt. Express 22 10487–93

[39] Shadbolt P J et al 2012 Generating, manipulating and measuring entanglement and mixture with a reconfigurable photonic circuit Nat. Photon. 6 45–9

[40] Chen J, Lee K F and Kumar P 2007 Deterministic quantum splitter based on time-reversed Hong–Ou–Mandel interference Phys. Rev. A 76 031804

[41] Gamel O and James D F V 2012 Measures of quantum state purity and classical degree of polarization Phys. Rev. A 86 033830

[42] Horodecki R, Horodecki M and Horodecki K 2009 Quantum entanglement Rev. Mod. Phys. 81 865–942

[43] Terhal B M and Horodecki P 2000 Schmidt number for density matrices Phys. Rev. A 61 040301

[44] Ralph T, Langford N K, Bell T B and White A G 2002 Linear optical controlled-NOT gate in the coincidence basis Phys. Rev. A 65 062324

[45] Trinh P D, Yegnanarayanan S and Jalali B 1995 Integrated optical directional couplers in silicon-on-insulator Electron. Lett. 31 2097–8

[46] Miki S, Yamashita T, Terai H and Wang Z 2013 High performance fiber-coupled NbTiN superconducting nanowire single photon detectors with Gifford-McMahon cryocooler Opt. Express 21 10208–14

[47] Leuthold J, Koos C and Freude W 2010 Nonlinear silicon photonics Nat. Photon. 4 535–44

[48] James D F V, Kow G, Munro W J and White A G 2001 Measurement of qubits Phys. Rev. A 64 052312

[49] Santagati R et al 2016 Witnessing eigenstates for quantum simulation of Hamiltonian spectra arXiv:1611.03511

[50] Paesani S et al 2017 Experimental Bayesian quantum phase estimation on a silicon photonic chip Phys. Rev. Lett. 118 100503

[51] Savanier M, Kumar R and Mookherjea S 2016 Photon pair generation from compact silicon microring resonators using microwatt-level pump powers Opt. Express 24 3313–28

[52] Aspect A, Grangier P and Roger G 1982 Experimental realization of Einstein–Podolsky–Rosen–Bohm gedankenexperiment: a new violation of Bell’s inequalities Phys. Rev. Lett. 49 91–4

[53] Sperling J and Vogel W 2011 The Schmidt number as a universal entanglement measure Phys. Scr. 83 045002

[54] Roos C F et al 2004 Bell states of atoms with ultralong lifetimes and their tomographic state analysis Phys. Rev. Lett. 92 220402

[55] Ding Y, Ou H and Peucheret C 2013 Ultra-high-efficiency apodized grating coupler using fully etched photonic crystals Opt. Lett. 38 2732–4