On-demand source of dual-rail photon pairs based on chiral interaction in a nanophotonic waveguide

Pedersen, Freja Thilde; Gonzalez Ruiz, Eva Maria; Hauff, Nils Valentin; Wang, Ying; Wieck, Andreas D.; Ludwig, Arne; Schott, Rüdiger; Midolo, Leonardo; Sørensen, Anders Søndberg; Uppu, Ravitej; Lodahl, Peter

Published in:
PRX Quantum

DOI:
10.1103/PRXQuantum.3.020363

Publication date:
2022

Document version
Publisher's PDF, also known as Version of record

Document license:
CC BY

Citation for published version (APA):
Pedersen, F. T., Gonzalez Ruiz, E. M., Hauff, N. V., Wang, Y., Wieck, A. D., Ludwig, A., Schott, R., Midolo, L., Sørensen, A. S., Uppu, R., & Lodahl, P. (2022). On-demand source of dual-rail photon pairs based on chiral interaction in a nanophotonic waveguide. PRX Quantum, 3, [020363].
https://doi.org/10.1103/PRXQuantum.3.020363
On-Demand Source of Dual-Rail Photon Pairs Based on Chiral Interaction in a Nanophotonic Waveguide

Freja T. Østfeldt,1 Eva M. González-Ruiz,1 Nils Hauff,1 Ying Wang,1 Andreas D. Wieck,2 Arne Ludwig,2 Rüdiger Schott,2 Leonardo Midolo,1 Anders S. Sørensen,1 Ravitej Uppu,1,*,‡ and Peter Lodahl1,†

1 Center for Hybrid Quantum Networks (Hy-Q), Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, Copenhagen DK-2100, Denmark
2 Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität Bochum, Universitätsstrasse 150, Bochum D-44780, Germany

(Received 17 January 2022; revised 22 May 2022; accepted 8 June 2022; published 27 June 2022)

Entanglement is the fuel of advanced quantum technology, enabling, e.g., measurement-based quantum computing and loss-tolerant encoding of quantum information. In photonics, entanglement has traditionally been generated probabilistically, requiring massive multiplexing for scaling up to many photons. An alternative approach utilizing quantum emitters in nanophotonic devices can realize deterministic generation of entangled photons. However, such sources generate polarization entanglement that is incompatible with spatial dual-rail qubit encoding employed in scalable photonic quantum-computing platforms utilizing integrated circuits. Here we propose and experimentally realize an on-demand source of dual-rail photon pairs using a quantum dot in a planar nanophotonic waveguide. The source exploits the cascaded decay of a biexciton state and chiral light-matter coupling to achieve deterministic generation of spatial dual-rail Bell pairs with the amount of entanglement determined by the chirality. The operational principle can readily be extended to multiphoton entanglement generation required for efficient preparation of resource states for photonic quantum computing.

DOI: 10.1103/PRXQuantum.3.020363

I. INTRODUCTION

Quantum photonics has developed significantly in the last decade and many of the required tools for scaling up to advanced applications in quantum-information processing are already available [1,2]. Indeed, the advent of production-mature advanced planar photonic integrated circuits has been trumpeted as a major argument for photonic quantum computing [3]. Efficient photon sources, however, have remained challenging, and typically photon entanglement is heralded by multiplexing probabilistic sources [4]. An alternative approach exploits quantum emitters in photonic nanostructures that allow harvesting single-photon emission with near-unity efficiency [5,6].

This is the basis of deterministic photon sources that combined with optical switching can be demultiplexed to produce many simultaneous photons [7,8]. Quantum-dot (QD) sources can generate two-photon polarization-entangled Bell states on demand by exploiting the radiative decay of a biexciton state [9,10] to realize high entanglement fidelity and efficiency [11,12]. These sources exploit polarization correlations induced from the biexciton radiative decay, which is not compatible with the path encoding of quantum states typically employed in photonic integrated circuits [13]. Furthermore, rotationally symmetric (in the plane perpendicular to the QD growth axis) photonic nanostructures are required to ensure equal coupling of orthogonally polarized dipoles. This geometric constraint has restricted QD entanglement sources to the polarization degree of freedom, and most notably implied that the wide-bandwidth and highly efficient planar nanophotonic waveguide platform [5] is incompatible with biexciton entanglement generation. On-demand generation, however, requires that the emitter is radiatively coupled to only one spatial mode, which cannot be realized for polarization-entangled photons that necessitate at least two optical modes. We show that a chiral light-matter interface allows overcoming these limitations.
simultaneously by realizing directional coupling of circularly polarized QD transitions to obtain a (spatial) dual-rail encoded entanglement source.

The planar nanophotonic QD platform offers several salient features: it provides high-efficiency and broadband sources of highly indistinguishable photons [14] and is directly compatible with planar integrated photonic circuits for complex photonic processing [15]. Integrated on-demand entanglement sources have however, been unattainable, since the high source efficiency relies on the radiative coupling of the QD to a single spatial and polarization mode. This limitation can be overcome by exploiting polarization-dependent directional coupling [16] where the photons from the QD are emitted preferentially into a single-mode waveguide propagating to the left or the right, labeled as $A$ and $B$, respectively, as determined by the polarization ($\sigma^\pm$) of the optical transition, cf. Fig. 1(a). While glide-plane-symmetric photonic crystal waveguides (GPWs) [17] and nanobeam waveguides [18] have realized unidirectional coupling, residual backscattering of photons and multimode operation may adversely affect coherent quantum phenomena such as entanglement. In this paper, we exploit specially designed GPWs supporting a single TE-polarized mode and terminated with mode adapters for minimized back scattering [19,20] to transform the intrinsic polarization entanglement of the QD biexciton cascade into photon path entanglement. Hereby dual-rail path encoded entanglement sources can be realized, which may be readily interfaced with photonic integrated circuits for realizing advanced quantum processors, cf. Fig. 1(e).

II. PATH ENTANGLEMENT FROM CHIRAL INTERACTIONS

Figure 1(a) illustrates the operational principle of an on-demand source of path-entangled photons. The QD biexciton state is excited through two-photon resonant excitation using optical laser pulses and decays through a correlated $\sigma^\pm-\sigma^\mp$ cascade. The GPWs are single mode (TE polarized) and designed to feature simultaneously high directionality and coupling efficiency (i.e., $\beta$ factor) [17], as required for an on-demand entanglement source. For a chirally coupled QD, $\sigma^+$- and $\sigma^-$-polarized transitions emit photons coupled to opposite propagation directions (denoted by $A$ and $B$) of the waveguide mode leading to optimal path entangled state $|\Psi\rangle = 1/\sqrt{2}(|A_{XX}B_X\rangle + |B_{XX}A_X\rangle)$, where the subscripts denote biexciton $XX$ and exciton $X$ photons. The key governing parameter for

\[ (a) \quad (b) \quad (c) \quad (d) \quad (e) \]

**FIG. 1.** Operational principle of spatial dual-rail entanglement source in a planar photonic circuit. (a) Illustration of the device containing a QD in a glide-plane waveguide (GPW). The QD is optically excited to the biexciton state ($XX$) that recombines through a cascaded decay (level structure in inset) via the exciton states ($X_\pm$) emitting a circularly polarized entangled photon pair. In the GPW, circular-polarized photons with opposite helicity couples preferentially to only one of the directions, i.e., $A$ or $B$, which enables path entanglement generation. A nonzero fine-structure splitting $S$ induces temporal spin-flip oscillations between the exciton states, as illustrated in the inset. (b) Calculated local phase $\Phi$ between the $E_x$ and $E_y$ components of the electric field at different spatial locations within the unit cell of the GPW. $\Phi = \pm\pi/2$ correspond to the locations of ideal chiral coupling. Here, $a$ is the lattice parameter of the photonic crystal. (c) Experimental setup for projective exciton-biexciton cross-correlation measurements. Two sets of cross-correlation measurements along the same path ($A_{XX}A_X$) and different paths ($A_{XX}B_X$) are performed. If the photons are collected from the same path, we split the signal using a 50:50 fiber beam splitter as illustrated with the orange dashed line. (d) Predicted two-photon cross-correlation dynamics (coincidence detection probability) for the experimental parameters of $S = 2\pi \times 13$ GHz and exciton radiative decay rate $\gamma_X = 8.35$ ns$^{-1}$ and assuming ideal chiral coupling $\Phi = \pm\pi/2$. For details on the model see Sec. S5 within the Supplemental Material [21]. The experimental “tell tale” of path correlation is the phase offset of $2\Phi$ between the $(A_{XX}A_X)$ and $(A_{XX}B_X)$ correlation measurements. (e) Proposed integration of a waveguide spatial dual-rail entanglement source into an advanced photonic integrated circuit with phase shifters ($\theta$) and beam splitters for quantum-information processing applications.
between the electric fields in the $x$ and $y$ directions at the position of the QD within the GPW, with ideal directionality corresponding to $\Phi = \pm \pi/2$. QD asymmetries, however, introduce exciton fine structure, which modifies the dynamics and leads to a photon state of the form \[ |\psi(\tau)\rangle = \frac{1}{\sqrt{N}} \left( |\psi_{AXX}\rangle |AXX\rangle + |\psi_{AXY}\rangle |AXY\rangle \right) \]

\[ + |\psi_{BXX}\rangle |BXX\rangle + |\psi_{BXY}\rangle |BXY\rangle \],

\[ \text{where } N \text{ is the normalisation factor, } \tau \text{ is the time since excitation of the QD and the amplitudes are} \]

\[ |\psi_{AXX}\rangle = -\sqrt{2} \gamma_X e^{-\gamma_X \tau/2} \left( e^{-i(S\tau/2 + 2\Phi)} + e^{iS\tau/2} \right), \]

\[ |\psi_{AXY}\rangle = -\sqrt{2} \gamma_X e^{-\gamma_X \tau/2} \left( e^{-i(S\tau/2 - 2\Phi)} + e^{iS\tau/2} \right), \]

\[ |\psi_{BXX}\rangle = -2\sqrt{2} \gamma_X \cos(S\tau/2) e^{-i\gamma_X \tau/2}. \]

Here, $\gamma_X$ is the exciton radiative decay rate, $S$ is the QD fine-structure splitting (in cyclic frequency units), and we assume that the radiative decay rate of the biexciton is $2\gamma_X$. We further assume that both the exciton and biexciton transitions couple to the waveguide with the same phase ($\Phi_X = \Phi_{XX} = \Phi$), which is a consequence of the wide operation bandwidth of GPWs compared to the energy difference between the exciton and biexciton states. In the case of a QD with $S \neq 0$ positioned at a location with ideal chiral coupling ($\Phi = \pm \pi/2$), a maximally entangled path-encoded state is realized for all $\tau$, but oscillating between the two Bell states $|\Psirangle(\tau = 0) = 1/\sqrt{2}(|AXX\rangle |AXX\rangle + |BXX\rangle |BXX\rangle)$ and $|\Psirangle(\tau = 2\pi/S) = 1/\sqrt{2}(|AXX\rangle |AXX\rangle + |BXX\rangle |BXX\rangle)$. The oscillation can be suppressed either by eliminating the fine-structure splitting $S$ [23] or by implementing time gating [24]. In path-resolved exciton-$X$-biexciton ($XX$) photon correlation measurements, cf. Fig. 1(c), the two-photon coincidence probabilities $|\langle AXX |XX |\Psi(\tau)\rangle|^2$ and $|\langle AXX |XX |\Psi(\tau)\rangle|^2$ are predicted to oscillate with a phase difference of $2\Phi$. Figure 1(d) shows the predicted two-photon coincidence probabilities using a theoretical model presented in detail in Sec. S5 within the Supplemental Material [21]. In the absence of chiral coupling ($\Phi = 0$) a separable state is generated, e.g., $|\Psirangle(\tau = 0) = 1/2(|AXX\rangle + |BXX\rangle)(|AXX\rangle + |BXX\rangle)$ and the phase shift in the correlation measurements is absent. The observation of a phase shift consequent constitutes the “tell tale” for the generation of path-encoded entanglement mediated by the chiral coupling.

### III. IMPLEMENTATION

The experimental demonstration is realized with single QDs located in electrically contacted waveguide samples for low-noise performance [25] and Stark tuning of the charge states. We employ self-assembled indium arsenide (InAs) QDs epitaxially grown at the center of a suspended 170-nm gallium arsenide (GaAs) membrane comprising a $p$-$i$-$n$ diode for charge control of the QD, cf. Sec. S1 within the Supplemental Material [21] for details about the heterostructure. The QDs are located randomly across the sample with an average density of approximately equal to $1 \mu m^{-2}$. Figure 2(a) shows a scanning electron microscope image of the nanofabricated device in the GaAs membrane, which has a total footprint of $50 \times 25 \mu m^{-2}$. The central part of the device contains the GPW where the studied QD is located. The GPW is designed with a lattice constant of $a = 260 \text{ nm}$ and hole radius of $r = 69 \text{ nm}$. The glide plane geometry is made by shifting the holes by half a lattice constant ($a/2$) compared to a regular photonic crystal waveguide along the propagation direction ($x$). Additionally, the geometry is optimized for TE-polarized, single-mode operation, following the proposal of Ref. [19], by shifting rows 2–4 of the holes outwards (along $y$) by $0.25a\sqrt{3}/2$, $0.2a\sqrt{3}/2$, and $0.1a\sqrt{3}/2$, respectively, while the radii of the holes in rows 1–3 are also modified to $r_{1,2} = 1.17r$ and $r_3 = 0.8r$. The mode adapters [19] [see inset of Fig. 2(a)] are designed to minimize reflections at the nanobeam-GPW interface that occurs due to a large group-index mismatch. The nanobeam waveguides are terminated with two shallow-etched grating couplers [26] that are oriented by $90^\circ$ with respect to each other for orthogonally polarized free-space collection. The grating couplers are designed to diffract only the waveguide mode into a linearly polarized free-space mode with the polarization axis perpendicular to the waveguide. The orthogonal orientation of the two couplers $A$ and $B$ with respect to each other ensures that the collection ports are cross-polarized. We utilize this property to collect path-dependent emission at the couplers $A$ and $B$ without compromising the collection efficiency. Upon collection, the photons can be subsequently made co-polarized using a single half-wave plate in one of the collection ports.

The sample is cooled to $1.6 \text{ K}$ in a helium closed-cycle cryostat, with electrical and optical access. The excitation laser is focused to the sample using a high numerical aperture (NA = 0.81) microscope objective. A single QD is excited by a pulsed Ti:Sapphire laser (20- ps optical duration) whose frequency is tuned to satisfy the two-photon resonance condition of the QD biexciton. The emitted photons coupled to the GPW are directed out of plane at two grating couplers [$A$ and $B$ in Fig. 2(a)], and are collected by the same objective lens, and separated from the input excitation path using a 5:95 beam splitter. Using a set of quarter-wave and half-wave plates together with a polarizing beam splitter, we separate the emission from the grating couplers into two separate spatial modes, each collected by a single-mode optical fiber. The emission in these two collection fibers is spectrally filtered with
experimental characterization of QD coupled to a GPW. (a) Scanning electron microscope image of the device used for the measurements. The central section consists of a GPW (insets show close ups of the optimized waveguide design). The GPWs are connected to grating outcouplers A and B via nanobeam waveguides. The GPW-nanobeam interface features a mode adapter, as shown in the inset. (b) Spectrally resolved laser transmission shown in orange from gratings A to B for identifying the slow-light region. The curve is normalized to the transmission through a nanobeam waveguide (cf. Sec. S1 within the Supplemental Material [21]). The green curves are the simulated group index $n_g$ for the GPW (solid line) and a nanobeam waveguide (dotted line). The wavelengths of the $X$ and $XX$ transitions of the QD are marked as well. (c) Gate-voltage-dependent resonance fluorescence of the QD under two-photon pulsed excitation displaying the $X$ and $XX$ transitions. (d) Pulsed second-order correlation measurements of $X$ and $XX$ transitions after spectral filtering of each transition (22-GHz bandwidth). We extract $g_{XX}^{(2)}(0) = 0.006 \pm 0.002$ and $g_{XX}^{(2)}(0) = 0.009^{+0.014}_{-0.009}$ for the two transitions indicating excellent single-photon purity.

22-GHz bandpass filters and detected using superconducting nanowire single-photon detectors (SNSPDs) with a low timing jitter (full-width at half-maximum $\varsigma < 15$ ps). A time-tagging device is used to register the timestamps of the detection events in both paths with a resolution of 4 ps. The timestamps accumulated over an hour are processed using MATLAB to construct the photon correlation histograms shown in Figs. 3(a) and 3(b). The low timing jitter $\varsigma$ of the SNSPDs is crucial in resolving the rapid oscillations (period approximately equal to 80 ps) in the photon correlations induced by the fine-structure splitting of the QD excitons.

IV. RESULTS

A. QD characterization

The GPW device is characterized by spectrally resolved transmission measurements where a tunable diode laser beam is injected into the waveguide at port A and the transmitted light is measured at port B, cf. Fig. 2(b). More details and characterization measurements of the device can be found in Sec. S2 within the Supplemental Material [21]. From the optical excitation of the QD we identify the spectral distance of the $X$ and $XX$ emission from the high-group-index ($n_g$) region. The GPW experiences slow light with slow-down factors of 16 and 14 for the $XX$ and $X$ transitions, respectively. This gives rise to slow-light-induced Purcell enhancement and a near-unity coupling efficiency quantified through the $\beta$ factor. We measure a radiative decay rate of $\gamma_X = 8.35 \text{ ns}^{-1}$ corresponding to a Purcell factor of about 2 leading to $\beta > 95\%$, i.e., near-deterministic operation of the source [17,19], see Sec. S3 within the Supplemental Material [21] for more details and experimental data. Spectrally resolved emission is collected at the out-coupling grating $B$ as a function of applied gate voltage, see Fig. 2(c), whereby $X$ and $XX$ transitions can be identified from their similar charge tuning slopes. Distinct antibunching is observed in pulsed second-order correlation measurements [$g_{XX}^{(2)}(\tau)$] of both the $X$ and $XX$, cf. data in Fig. 2(d). This confirms the high-purity single-photon emission [$g_{XX}^{(2)}(0) < 1\%$] from each transition, which is a prerequisite for entangled photon pair generation.

B. Path-correlation measurements

We quantify the generation of path-entangled photon pairs by extracting the phase $\Phi$ from the resulting data displayed in Fig. 3(a). The experimental data (circles) are very well explained by the theoretical correlation function model (solid line) cf. Sec. S5 within the Supplemental Material [21]. The correlation function decays with the independently measured exciton radiative decay rate $\gamma_X$, while the fine-structure splitting $S$ and phase shift $\Phi$ are extracted from the analysis. A key aspect in order to extract the phase is to implement a high-precision time matching of photon-correlation datasets, cf. Sec. S4 within the Supplemental Material [21]. A pronounced phase shift of $\Phi = (0.12 \pm 0.01)\pi$ is extracted, which is the experimental
Figure 3. Observation of path-dependent correlations of the entangled state. (a) Path-dependent photon correlation measurements of QDs in GPW in two configurations, $A_{XX}B_X$ and $A_{XX}A_X$. Solid lines are fits to the theoretical model. The error in $\Phi$ is the 1σ confidence interval fitting error. (b) Similar measurements as (a) but from a QD in a regular photonic crystal waveguide with no significant chiral interaction. (c) Time-dependent measurable concurrence $C_m(\tau)$ accounting for detector timing jitter. The solid blue curve is calculated for a QD in the GPW under current experimental conditions ($\Phi_1 = 0.12\pi$, $S = 2\pi \times 13$ GHz, $\gamma_X = 8.35$ ns$^{-1}$, $\varsigma = 15$ ps). The blue dotted line uses a smaller $S = 2\pi \times 13$ GHz, corresponding to experimental parameters of a previously studied device [14]. The orange curves show both cases of $S$ but for the absence of back reflections where $\Phi = 0.32\pi$ (see main text). (d) Predicted QD position-dependent $C$ of the path-entangled state at time $\tau = 0$ within the GPW exhibiting wide areas of near-perfect entanglement. The concurrence is calculated using the theoretical model [22], and the simulated phase plotted in Fig. 1(b).

Evidence of chiral coupling resulting in path entanglement. For comparison, Fig. 3(b) displays the separable case of a QD in a regular photonic crystal waveguide, where we observe no pronounced phase shift. In a regular photonic crystal waveguide, the local electric field polarization is preferentially linear, and pronounced chiral coupling is not expected.

It is worth emphasizing that the experiment directly probes the phase of the local electric field inside a complex photonic nanostructure; a quantity that otherwise would have to be extracted from complex interferometric near-field measurements. The GPW is designed to maximize the probability of finding a QD positioned near points with $\Phi \approx \pi/2$ (corresponding to ideal directionality), cf. Fig. 1(b). We quantify that > 70% of the GPW unit-cell area has $|\Phi - \pi/2| \leq 0.15\pi$, which highlights the suitability of GPWs for path-entangled photon-pair generation. The measurements are repeated on two additional QDs (cf. Sec. S6 within the Supplemental Material [21]) both exhibiting $\Phi \approx 0.1\pi$. The observed low values of $\Phi$ is a consequence of the presence of residual back reflections from the outcoupling gratings due to nonoptimized mode impedance matching, as is elaborated below.

C. Analysis of path entanglement

The local phase $\Phi$ is a governing parameter determining the quality of the generated path entanglement. The degree of path entanglement is quantified by the concurrence $C$, where $C > 0$ is an entanglement criterion. The concurrence of the path-entangled state generated by the QD is given by

$$C(\tau) = \frac{\sin^2(\Phi)}{1 + \cos(S\tau)\cos^2(\Phi)},$$

where $\tau$ is the time difference between the emission of the first and the second photons [21]. We extract the time-averaged concurrence $\bar{C}$ [27] as the entanglement measure. In the experiment, timing jitter (quantified by the measured full-width at half-maximum $\varsigma$) in the detectors and coincidence measurement electronics reduces the $X$-$XX$ oscillations and thus the maximum concurrence expressed by Eq. (3). We model the impact of timing jitter on the $X$-$XX$ photon correlation by introducing a density matrix averaged over the timing jitter. Using the density matrix from this model, we define the measurable concurrence $C_m(\tau)$ and its time average $\bar{C}_m$ (cf. Sec. S5B within the Supplemental Material).

Figure 3(c) shows the modeled time evolution of $C_m(\tau)$ using the experimentally measured parameters ($S, \Phi, \varsigma$) as the solid blue curve in Fig. 3(c). $C_m(\tau)$ can be dramatically increased by improving the phase $\Phi \rightarrow 0.5\pi$, i.e., for an ideal chirally coupled QD. In the experiment, however, back reflections decrease the chirality. To investigate this we use a reference measurement and estimate the intensity.
reflectance to be $|r|^2 = 0.23 \pm 0.02$ at each grating, which gives rise to a standing-wave cavity between the outcouplers $A$ and $B$. We evaluate the impact of these back reflections on the chiral phase and extract $\Phi = 0.32 \pm 0.03 \pi$ upon correcting for their effect (cf. Sec. 6A within the Supplemental Material [21]). This value is compatible with the expected intrinsic chirality of the GPW, cf. Fig. 1(b) and shows that modifying the grating design would readily improve the chirality. The resulting concurrence and shows that modifying the grating design would readily improve the chirality. The resulting concurrence $C_m(\tau)$ for $\Phi = 0.32 \pi$ is plotted as the solid orange curve in Fig. 3(c), and is substantially higher. From Eq. (3) we also extract $\tilde{C}$, excluding the effect of the detector timing jitter, which improves from $0.26 \pm 0.01$ to $0.75 \pm 0.08$ in the absence of reflections. Gratings with significantly improved performance, i.e., suppressed back reflections, have been implemented in single-photon source devices used in Ref. [14]. Figure 3(d) shows the QD position dependence of the measurable concurrence in an ideal GPW, with no reflections, at $\tau = 0$ highlighting the potential wide area of near-perfect entanglement quality $[C_m(\tau = 0) > 0.9]$ enabled by GPWs.

Finally, for many applications of entanglement it would be desirable to produce a stable Bell state rather than the oscillating superposition of Bell states intrinsically produced by a QD source with nonzero fine-structure splitting. The oscillating period is directly determined by the fine-structure splitting. The dotted curves in Fig. 3(c) show the measurable concurrence that could be achieved with a smaller $S = 2\pi \times 5$ GHz, reported on a similar device platform [14]. QDs with vanishing fine-structure splitting have been reported in the literature [23] and experimental results on integrating these QDs in photonic nanostructures are under way [28]. An alternative approach erases the oscillation between Bell states by actively compensating the time-dependent phase shift introduced by $S$. This has been realized for polarization-entangled photon pairs using electro-optic modulators [29] and could be realized for a path-entangled state by employing a phase modulator.

V. CONCLUSION

In summary, we have proposed and experimentally implemented an on-demand planar nanophotonic waveguide source of dual-rail path-entangled photon pairs. The operation of the source is based on chiral coupling of a QD to the waveguide mode leading to directional emission. The operational principle is general, and could readily be extended also to multiphoton entanglement sources, e.g., for the generation of path-encoded photonic cluster states [30]. Such deterministic entanglement sources are much needed for advanced quantum-information processing applications [31,32]. For instance, in photonic quantum computing, the most demanding task is the generation of high-quality multiphoton entangled resource states [33] with photonic integrated circuits providing a realistic route for realizing quantum processors [34]. Consequently, interfacing QD path-entanglement sources with mature integrated photonic circuits, as sketched in Fig. 1(e), appears a resource-efficient approach. To this end, heterogeneous chip transfer processes may be applied in order to combine the active QD devices and the passive photonic circuits [35]. The generated path-encoded entangled states would enable easy integration with conventional integrated photonic circuits. Alternatively, upon generation, the entangled state can be converted back to polarization basis by interfering the two outputs of the waveguide at a polarizing beam splitter. This would allow implementation in dual-polarization waveguide circuits [36,37]. Either route would benefit from careful impedance matching in order to overcome any detrimental effects from back reflections. In scenarios where the entangled photon source is integrated with other material platforms such as silicon nitride or lithium niobate, high-efficiency mode matching can be achieved by incorporating inverted waveguide tapers [38,39].

The data presented in the figures of this study are available from the authors on request.

ACKNOWLEDGMENTS

We thank Single Quantum for giving us access to the ultralow timing-jitter superconducting nanowire single-photon detectors required for extracting the correlations. We gratefully acknowledge financial support from Danmarks Grundforskningsfond (DNRF 139, Hy-Q Center for Hybrid Quantum Networks). This project has received funding from the European Union’s Horizon 2020 research and innovation programmes under Grant Agreement No. 824140 (TOCHA, H2020-FETPROACT-01-2018) and under the Marie-Skłodowska-Curie Grant Agreement No. 801199. A.D.W. and A.L. acknowledge gratefully support of DFG-TRR160, BMBF—Q.Link.X 16KIS0867, and the DFH/UFA CDFA-05-06. We acknowledge Adam Knorr for initial sample characterization. We thank Matthew Broome for discussions in the early phase of the project.

[1] J. L. O’Brien, A. Furusawa, and J. Vučković, Photonic quantum technologies, Nat. Photonics 3, 687 (2009).
[2] R. Uppu, L. Midolo, X. Zhou, J. Carolan, and P. Lodahl, Quantum-dot-based deterministic photon–emitter interfaces for scalable photonic quantum technology, Nat. Nanotechnol. 16, 1308 (2021).
[3] T. Rudolph, Why I am optimistic about the silicon-photonic route to quantum computing, APL Photonics 2, 30901 (2017).
[4] H.-S. Zhong, et al., 12-Photon Entanglement and Scalable Scattershot Boson Sampling with Optimal Entangled-Photon Pairs from Parametric Down-Conversion, Phys. Rev. Lett. 121, 250505 (2018).
[5] P. Lodahl, S. Mahmoodian, and S. Stobbe, Interfacing single photons and single quantum dots with photonic nanostructures, Rev. Mod. Phys. 87, 347 (2015).

[6] P. Lodahl, A. Ludwig, and R. J. Warburton, A deterministic source of single photons, Phys. Today 75, 44 (2022).

[7] F. Lenzini, B. Haylock, J. C. Loredo, R. A. Abrahão, N. A. Zakaria, S. Kasture, I. Sagnes, A. Lemaître, H.-P. Phan, D. V. Dao, P. Senellart, M. P. Almeida, A. G. White, and M. Lobino, Active demultiplexing of single photons from a solid-state source, Laser Photonics Rev. 11, 1600297 (2017).

[8] H. Wang, Y. He, Y.-H. Li, Z.-E. Su, B. Li, H.-L. Huang, X. Ding, M.-C. Chen, C. Liu, J. Qin, J.-P. Li, H. Y.-M. C. Schneider, M. Kamp, C.-Z. Peng, S. Höfling, C.-Y. Lu, and J.-W. Pan, High-efficiency multiphoton boson sampling, Nat. Photonics 11, 361 (2017).

[9] O. Benson, C. Santori, M. Pelton, and Y. Yamamoto, Regulated and Entangled Photons from a Single Quantum Dot, Phys. Rev. Lett. 84, 2513 (2000).

[10] N. Akopian, N. H. Lindner, E. Poem, Y. Berlatzky, J. Avron, D. Gershoni, B. D. Gerardot, and P. M. Petroff, Entangled Photon Pairs from Semiconductor Quantum Dots, Phys. Rev. Lett. 96, 130501 (2006).

[11] D. Huber, M. Reindl, S. F. Covre Da Silva, C. Schimpf, J. Martin-Sánchez, H. Huang, G. Piredda, J. Edlinger, A. Rastelli, and R. Trotta, Strain-Tunable GaAs Quantum Dot: A Nearly Dephasing-Free Source of Entangled Photons on Demand, Phys. Rev. Lett. 121, 033902 (2018).

[12] J. Liu, R. Su, Y. Wei, B. Yao, S. F. C. da Silva, Y. Yu, J. Iles-Smith, K. Srinivasan, A. Rastelli, J. Li, and X. Wang, A solid-state source of strongly entangled photon pairs with high brightness and indistinguishability, Nat. Nanotechnol. 14, 586 (2019).

[13] A. Politi, J. C. Matthews, M. G. Thompson, and J. L. O'Brien, Integrated quantum photonics, IEEE J. Sel. Top. Quantum Electron. 15, 1673 (2009).

[14] R. Uppu, F. T. Pedersen, Y. Wang, C. T. Olesen, C. Papon, X. Zhou, L. Midolo, S. Scholz, A. D. Wieck, A. Ludwig, and P. Lodahl, Scalable integrated single-photon source, Sci. Adv. 6, eabc8268 (2020).

[15] W. Bogaerts, D. Pérez, J. Capmany, D. A. Miller, J. Poon, D. Englund, F. Morichetti, and P. Zoller, Programmable photonic circuits, Nature 586, 207 (2020).

[16] P. Lodahl, S. Mahmoodian, S. Stobbe, A. Rauschenbeutel, P. Schneeweiss, J. Volz, H. Pichler, and P. Zoller, Chiral quantum optics, Nature 541, 473 (2017).

[17] I. Söllner, S. Mahmoodian, S. L. Hansen, L. Midolo, A. Javadi, G. Kirşansk ̈e, T. Pregnolato, H. El-Ella, E. H. Lee, J. D. Song, S. Stobbe, and P. Lodahl, Deterministic photon-emitter coupling in chiral photonic circuits, Nat. Nanotechnol. 10, 775 (2015).

[18] R. J. Coles, D. M. Price, J. E. Dixon, B. Royall, E. Clarke, P. Kok, M. S. Skolnick, A. M. Fox, and M. N. Makhonin, Chirality of nanophotonic waveguide with embedded quantum emitter for unidirectional spin transfer, Nat. Commun. 7, 11183 (2016).

[19] S. Mahmoodian, K. Prindal-Nielsen, I. Söllner, S. Stobbe, and P. Lodahl, Engineering chiral light–matter interaction in photonic crystal waveguides with slow light, Opt. Mater. Express 7, 43 (2017).

[20] N. V. Hauff, H. Le Jeannic, P. Lodahl, S. Hughes, and N. Rotenberg, Chiral quantum optics in broken-symmetry and topological photonic crystal waveguides, Phys. Rev. Res. 4, 023082 (2022).

[21] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PRXQuantum.3.020363 for details on sample fabrication, characterization, and theoretical modeling, which includes Refs. [40–50].

[22] E. M. González-Ruiz, et al., in preparation (2021).

[23] Y. H. Huo, A. Rastelli, and O. G. Schmidt, Ultra-small excitonic fine structure splitting in highly symmetric quantum dots on GaAs (001) substrate, Appl. Phys. Lett. 102, 152105 (2013).

[24] T. Huber, A. Predojević, M. Khoshnegar, D. Dalacu, P. J. Poole, H. Majedi, and G. Weihs, Polarization entangled photons from quantum dots embedded in nanowires, Nano Lett. 14, 7107 (2014).

[25] F. T. Pedersen, Y. Wang, C. T. Olesen, S. Scholz, A. D. Wieck, A. Ludwig, M. C. Löbl, R. J. Warburton, L. Midolo, R. Uppu, and P. Lodahl, Near Transform-limited Quantum Dot Linewidths in a Broadband Photonic Crystal Waveguide, ACS Photonics 7, 2343 (2020).

[26] X. Zhou, I. Kulkova, T. Lund-Hansen, S. L. Hansen, P. Lodahl, and L. Midolo, High-efficiency shallow-etched grating on GaAs membranes for quantum photonic applications, Appl. Phys. Lett. 113, 251103 (2018).

[27] R. J. Young, R. M. Stevenson, P. Atkinson, M. N. Makhonin, and R. Trotta, Strain-Tunable GaAs Quantum Dots for One-Way Quantum Computing, Phys. Rev. Lett. 121, 020363 (2022).

[28] F. T. Pedersen, Ph.D. thesis, Niels Bohr Institute, University of Copenhagen, 2020.

[29] A. Fognini, A. Ahmadi, S. J. Daley, M. E. Reimer, and V. Zwiller, Universal fine-structure eraser for quantum dots, Opt. Express 26, 24487 (2018).

[30] N. H. Lindner and T. Rudolph, Proposal for Pulsed On-Demand Sources of Photonic Cluster State Strings, Phys. Rev. Lett. 103, 113602 (2009).

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

[32] K. Azuma, K. Tamaki, and H. K. Lo, All-photonic quantum repeaters, Nat. Commun. 6, 6787 (2015).

[33] S. Bartolucci, P. Bichir, H. Bombin, H. Cable, C. Dawson, M. Gimeno-Segovia, E. Johnston, K. Kielping, N. Nickerson, M. Pant, F. Pastawski, T. Rudolph, and C. Sparrow, Fusion-based quantum computation, ArXiv:2101.09310 (2021).

[34] A. W. Elshaari, W. Perrin, K. Srinivasan, O. Benson, and V. Zwiller, Hybrid integrated quantum photonic circuits, Nat. Photonics 14, 285 (2020).

[35] N. H. Wan, T.-J. Lu, K. C. Chen, M. P. Walsh, M. E. Trusheim, L. De Santis, E. A. Bersin, I. B. Harris, S. L. Mouradian, I. R. Christen, E. S. Bielejec, and D. Englund, Large-scale integration of artificial atoms in hybrid photonic circuits, Nature 583, 226 (2020).

[36] A. Crespi, R. Ramponi, R. Osellame, L. Sansoni, I. Bongioanni, F. Scirrino, G. Vallone, and P. Mataloni, Integrated photonic quantum gates for polarization qubits, Nat. Commun. 2, 1 (2011).
[37] L. Sansoni, F. Sciarrino, G. Vallone, P. Mataloni, A. Crespi, R. Ramponi, and R. Osellame, Two-Particle Bosonic-Fermionic Quantum Walk via Integrated Photonics, Phys. Rev. Lett. 108, 010502 (2012).

[38] J. Liu, A. S. Raja, M. H. Pfeiffer, C. Herkommer, H. Guo, M. Zervas, M. Geiselmann, and T. J. Kippenberg, Double inverse nanotapers for efficient light coupling to integrated photonic devices, Opt. Lett. 43, 3200 (2018).

[39] A. D. Uğurlu, H. Thyrrestrup, R. Uppu, C. Ouellet-Plamondon, R. Schott, A. D. Wieck, A. Ludwig, P. Lodahl, and L. Midolo, Suspended spot-size converters for scalable single-photon devices, Adv. Quantum Technol. 3, 1900076 (2020).

[40] L. Midolo, T. Pregnolato, G. Kiršanské, and S. Stobbe, Soft-mask fabrication of gallium arsenide nanomembranes for integrated quantum photonics, Nanotechnology 26, 484002 (2015).

[41] S. Adachi, GaAs, AlAs, and Al,Ga1−x: Material parameters for use in research and device applications, J. Appl. Phys. 58, R1 (1985).

[42] J. D. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, Molding the Flow of Light (Princeton University Press, Princeton, NJ, 2008).

[43] S. Hughes, L. Ramunno, J. F. Young, and J. E. Sipe, Extrinsic Optical Scattering Loss in Photonic Crystal Waveguides: Role of Fabrication Disorder and Photon Group Velocity, Phys. Rev. Lett. 94, 033903 (2005).

[44] M. Patterson, S. Hughes, S. Schulz, D. M. Beggs, T. P. White, L. O’Faolain, and T. F. Krauss, Disorder-induced incoherent scattering losses in photonic crystal waveguides: Bloch mode reshaping, multiple scattering, and breakdown of the Beer-Lambert law, Phys. Rev. B 80, 195305 (2009).

[45] T. Pregnolato, Ph.D. thesis, Niels Bohr Institute, University of Copenhagen, 2019.

[46] X.-L. Chu, T. Pregnolato, R. Schott, A. D. Wieck, A. Ludwig, N. Rotenberg, and P. Lodahl, Lifetimes and quantum efficiencies of quantum dots deterministically positioned in photonic-crystal waveguides, Adv. Quantum Technol. 3, 2000026 (2020).

[47] S. Das, L. Zhai, M. Čepulskovskis, A. Javadi, S. Mahmoodian, P. Lodahl, and A. S. Sørensen, A wave-function ansatz method for calculating field correlations and its application to the study of spectral filtering and quantum dynamics of multi-emitter systems, ArXiv:1912.08303 (2019).

[48] K. A. Fischer, R. Trivedi, V. Ramasesh, I. Siddiqi, and J. Vučković, Scattering into one-dimensional waveguides from a coherently-driven quantum-optical system, Quantum 2, 69 (2018).

[49] R. Trivedi, K. Fischer, S. Xu, S. Fan, and J. Vučkovic, Few-photon scattering and emission from low-dimensional quantum systems, Phys. Rev. B 98, 144112 (2018).

[50] T. Pregnolato, X.-L. Chu, T. Schröder, R. Schott, A. D. Wieck, A. Ludwig, P. Lodahl, and N. Rotenberg, Deterministic positioning of nanophotonic waveguides around single self-assembled quantum dots, APL Photonics 5, 086101 (2020).