

Ultrastable near-unity-fidelity dynamic polarization encoding of deterministically generated single photons

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The ability to reliably inscribe information on single photons is a crucial requirement for quantum applications such as quantum communication and measurement-based photonic quantum computation. Experimental implementations generally employ phase modulators in single-pass or Mach-Zehnder-interferometer configurations to encode information on photonic qubits. However, these approaches are intrinsically sensitive to environmental influences, which limits the achievable quantum error rates in practice, posing a major bottleneck in the transition of quantum applications with deterministic sources from the laboratory to the field. Inspired by the adaptation of Sagnac interferometer encoders for laser-based applications, we report a demonstration of a polarization encoder for single-photon qubits based on a free-space Sagnac interferometer. The device showcases inherent phase stability and overcomes previous error-rate limitations: Telecom-wavelength photons emitted by a quantum dot are modulated at a rate of 152 MHz and with a quantum bit error rate of $0.69 \pm 0.02\%$, marking the lowest value reported to date for MHz-rate information encoding on single photons by a factor of > 3 . This combination of low error rate, high modulation speed, stability, and operation with telecom-wavelength sub-Poissonian photons is an essential requirement for bringing quantum applications based on deterministic photon sources from the laboratory to the field and a significant step toward unlocking the full potential of a future quantum Internet.

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I. INTRODUCTION

The deterministic inscription of information onto individual qubits is a foundational capability for quantum information technologies. In particular, the ability to prepare photonic qubits in well-defined quantum states and to perform measurements in well-defined bases is essential for a broad range of applications. These include measurement-based quantum computing [1,2] and quantum-cryptographic schemes such as quantum key distribution (QKD) [3,4] and quantum bit commitment [5,6]. Such schemes are expected to play a pivotal role

in securing future digital infrastructures by enabling communication protected by information-theoretically unbreakable encryption. Beyond secure communication, these capabilities also open avenues for other quantum applications such as quantum secure coin flipping (QSCF) [3] and secure voting systems [7].

To date, QKD remains the most extensively tested and mature application of photonic quantum cryptography. It has been demonstrated across a wide range of protocols and sources, including weak coherent pulses (WCP) in decoy-state QKD [8–14], entanglement sources [15–17], and true single-photon sources (SPSs) [18–25]. While decoy-state QKD systems are currently ahead in terms of secure key rate (SKR) [14] and are already commercially available, SPSs offer distinct advantages for the establishment of scalable quantum networks [26–30]. For instance, protocols such as measurement-device-independent QKD [31] are expected to be carried out with SPSs, which offer potential performance advantages over WCP implementations [32]. Recent theoretical and experimental studies

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have also shown that SPSs can surpass the bits-per-pulse transmission limit both in QKD [33] and QSCF [34]. The performance of SPSs has improved significantly in recent years [35], particularly with respect to brightness [36] and single-photon purity [37–39], allowing for long-distance QKD in both laboratory settings [20,23] and real-world field trials [25,40]. Nevertheless, encoding information on sub-Poissonian photons with a performance comparable to that of other systems has proven difficult, constituting a bottleneck to the use of SPSs in practical applications. Meanwhile, the desire for long-term stable encoding has prompted the proposal of Sagnac interferometer encoders [41–45] and their implementation in WCP-QKD experiments [10,12,46–49]. Only recently, this technique has been applied in an SPS-QKD experiment [50], but the performance gap has thus far persisted.

In this work, we close this gap by presenting a free-space Sagnac interferometer (FSSI) BB84 polarization encoder and demonstrating real-time polarization encoding of single photons from a quantum dot (QD). A quantum bit error rate (QBER) of $0.69 \pm 0.02\%$ and an encoding agreement of $96.4 \pm 0.02\%$ with the theoretically expected polarization states are obtained from the polarization projection measurement. The reported values represent the highest performance to date for dynamic information encoding with an SPS. These results are achieved through high-quality free-space polarization optics, built-in interferometer balance tunability, and a low V_π electro-optical phase modulator (PM) driven by well-defined electrical pulses from an arbitrary waveform generator (AWG) operating at 152 MHz. Finally, we demonstrate the stability of this encoder over a 60-h period.

II. METHODS

A. Source excitation and characterization

In Fig. 1(a), the excitation setup is depicted. Our SPS consists of an InGaAs QD embedded in a circular Bragg grating cavity [36] and placed inside a cryostat (attoDRY 1100) at 3.8 K. The QD emits directly in the telecom C-band, making our setup suitable for use in data transmission over optical fiber. A mode-locked laser (PriTel UOC) with a repetition rate of 152 MHz, a pulse duration of 40 ps, and a wavelength of 1533.8 ± 0.1 nm is used for p -shell excitation of the QD after passing through a tunable bandpass filter (not shown) to suppress laser background at the QD emission wavelength. The emission from the QD is spectrally filtered using three volume Bragg gratings, two of which act as notch filters suppressing remaining laser light reflected by the sample [only one shown in Fig. 1(a)], while the third reflects only the QD emission to eliminate remaining background. Since the QD emission is only partially polarized due to cavity asymmetry [36], the photons are additionally sent through a Glan-Thompson polarizer to obtain a fixed

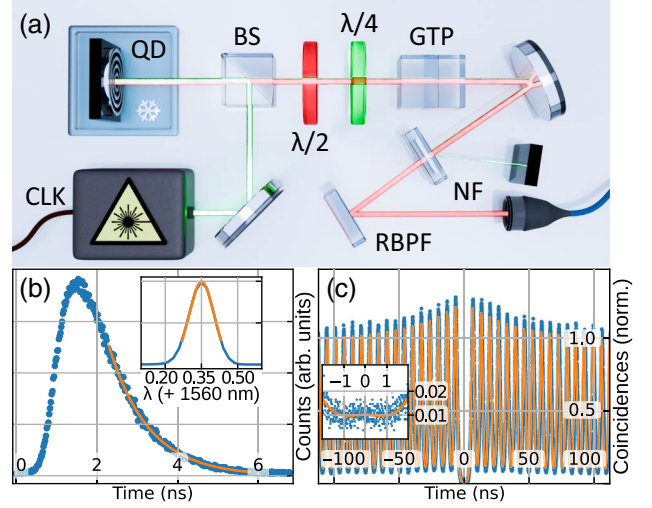


FIG. 1. Excitation, photoluminescence extraction, and characterization of the QD-SPS. (a) Excitation and photoluminescence extraction setup. The emitted photons are collected by an objective (not shown) with numerical aperture 0.7, polarized, spectrally filtered, and sent to the encoder module. BS, 1/99 (R/T) beamsplitter; GTP, Glan-Thompson polarizer; NF, notch filter; RBPF, reflecting bandpass filter; CLK, clock. (b) Time-resolved fluorescence measurement of the QD. An exponential decay fit yields $\tau = 990 \pm 7$ ps. Inset: filtered, polarized emission spectrum of the QD (blue). A Lorentzian fit (orange, ignoring the sides of the peak due to spectral cutoff by the RBPF) yields $\lambda = 1560.35 \pm 0.01$ nm and FWHM = 0.19 ± 0.01 nm. (c) Fit (orange) and data (blue) for a second-order coherence measurement. The fit yields a value of $g^{(2)}(0) = 0.55 \pm 0.08\%$ (see Appendix A for details).

starting polarization state. The polarizer and waveplates are used to maximize counts while aligning the output with the slow axis of a polarization-maintaining fiber, which is then connected to the encoder module. This keeps the initial polarization state stable over time.

For characterization, the photons were instead coupled to a single-mode fiber and sent directly to a superconducting nanowire single-photon detector (SNSPD) (Pixel Photonics PCU) or spectrometer (Princeton Instruments SpectraPro). A count rate of 3.2 Mcps s^{-1} of spectrally filtered and polarized photons (including an estimated 85% fiber coupling efficiency and a 37% nominal SNSPD detection efficiency) is achieved for an excitation power of 7 μ W measured directly above the objective. Second-order autocorrelation (radiative decay) data are obtained by temporally correlating detection times between two SNSPD channels in a Hanbury Brown and Twiss [51] setup (between one channel and a reference signal from the AWG) and shown in Figs. 1(b) and 1(c).

B. Encoding

For all measurements, the emitted photons are routed through a fiber circulator to the FSSI. The input state is

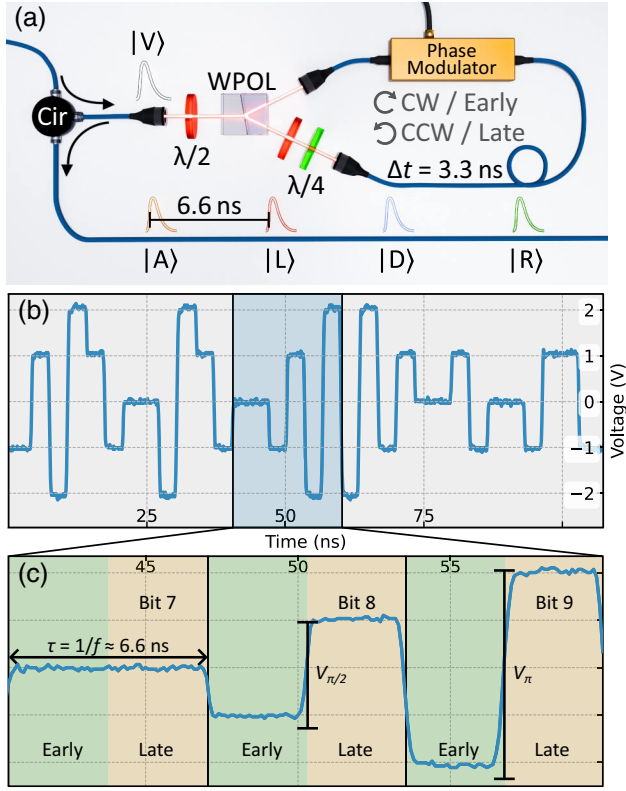


FIG. 2. Polarization encoding method. (a) Polarization encoding setup. Photons coming from the extraction setup are coupled to a polarization-maintaining circulator, which directs them to the Sagnac loop and, after propagation through the loop, to the output fiber. The arbitrary waveform generator that drives the phase modulator also drives the excitation laser, ensuring continuous synchronization between excitation and encoding. WPOL, Wollaston polarizer; Cir, circulator; CW, clockwise; CCW, counterclockwise. (b) Voltage signal applied to the phase modulator to encode a repeating 16-bit polarization sequence, as measured on an oscilloscope. (c) Close-up view of the shaded area in (b). Each time slot is split into an early and a late part, corresponding to the presence of CW and CCW photons within the PM.

prepared by rotating the $\lambda/2$ waveplate [see Fig. 2(a)] such that the two outputs of the Wollaston polarizer receive exactly equal power, as calibrated with a continuous-wave laser (Toptica CTL-1550) set to the QD emission wavelength. This precise tunability is key to achieving the reported low error rate, as it allows the precise creation of equal $|H\rangle - |V\rangle$ superpositions. We label the input state as the $|D\rangle$ state (with a relative phase $\varphi = 0$) for convenience and without loss of generality. Accordingly, we label the other three states $|R\rangle$ ($\varphi = \pi/2$), $|A\rangle$ ($\varphi = \pi$), and $|L\rangle$ ($\varphi = -\pi/2$).

Each polarizer output is then coupled to a polarization-maintaining fiber connected to the PM (Eospace PM-DS5), and on each side, a pair of waveplates (only one pair shown in Fig. 2) is used to align the polarization with the slow fiber axis. This constitutes another advantage

of the free-space architecture, eliminating misalignment at fiber connectors.

Because of an additional $\Delta T \approx 3.3 \text{ ns} \approx (2 \times 152 \text{ MHz})^{-1}$ delay in one arm, the early/CW and late/CCW photon components arrive at the PM at different times, and their relative phase φ can be modulated by changing the applied voltage in between. For our PM, $V_\pi = 4.2 \text{ V}$ and $V_{\pm\pi/2} = \pm 2.1 \text{ V}$ are applied in a repeating 16-bit sequence, an oscilloscope trace of which is shown in Figs. 2(b) and 2(c). Finally, the two paths merge at the polarizer and exit through the circulator, with the polarization determined by φ .

The Wollaston polarizer is a key element in achieving low QBERs: a nominal extinction ratio of 10^6 makes its contribution to the QBER negligible with proper alignment. It acts not only as an initial polarizing beamsplitter but also as a filter upon merging the paths again, as photons with incorrect polarization are refracted away from the output path. This double functionality makes the setup robust to polarization misalignment within the loop, as deviations from the optimal polarization states always affect both propagation directions equally and therefore do not result in higher error rates but only in reduced transmission efficiency.

C. Decoding

To demonstrate the successful encoding, the encoded photons are sent to a home-built BB84 polarization decoding setup [see Fig. 3(a)]. After they pass through a fiber polarization controller (GeneralPhotonics PCD-M02) to compensate for fiber-induced rotations, the basis choice is made passively by a 50/50 beam splitter. In each basis, states are spatially separated by a Wollaston polarizer and measured by SNSPDs. Finally, detected events are temporally correlated with a timing reference from the AWG marking the beginning of each sequence.

A nonmodulated QBER of $0.11 \pm 0.01\%$ is obtained, in agreement with the expectation that the contribution of the Wollaston polarizers is negligible given proper alignment and limited by the SNSPD dark count rate of approximately 160 cts/s. In order to confirm the expected stability of the output, the polarization state of an unmodulated continuous-wave laser was measured using a polarimeter (Thorlabs PAX1000IR2) after passing through the encoder. More details are provided in the Appendix D.

III. RESULTS AND DISCUSSION

A. Encoding of single photons

The single-photon encoding performance of the system is examined using a repeating pseudorandom 16-state sequence. In Fig. 3(b), the resulting temporal correlations between the respective decoder output channels and an electronic reference signal from the AWG (sent at the beginning of each sequence) are shown. They demonstrate

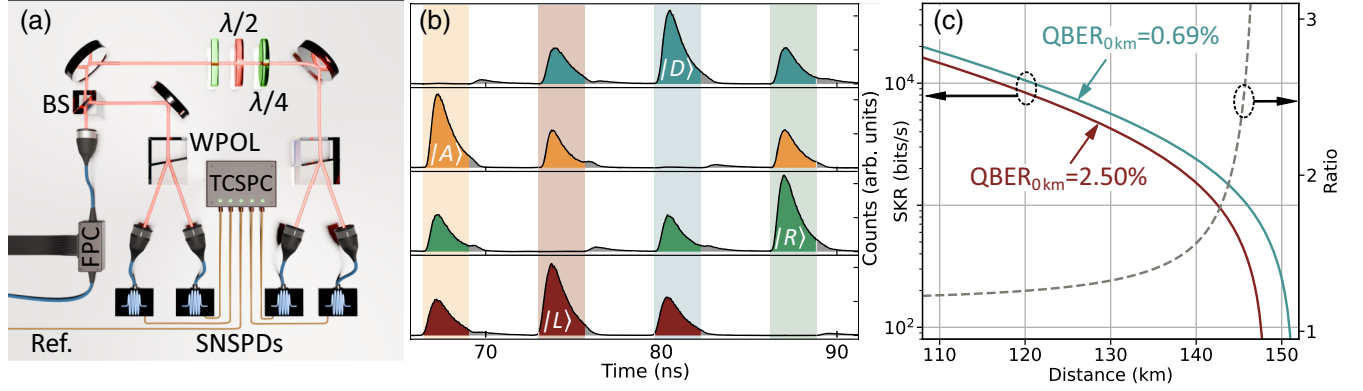


FIG. 3. Polarization encoding and decoding. (a) Decoder module. FPC, fiber polarization controller; BS, 50/50 beam splitter; TCSPC, time-correlated single-photon counter; Ref., reference signal from the AWG. (b) Detection times for all channels across four bits of the sequence, relative to the reference signal. Acceptance windows are highlighted. (c) Influence of the QBER on the asymptotic SKR in a simulated BB84 experiment (see Appendix C for details). Dashed line: relative increase in SKR for a reduction in error rate from 2.50% to 0.69%.

that the polarization is encoded as desired. Calculating the QBER for the entire sequence yields a mean value of $0.69 \pm 0.02\%$ ($0.43 \pm 0.02\%$ for the X -basis, $0.96 \pm 0.01\%$ for the Y -basis). Reconstructing the experimental

TABLE I. Relevant parameters of involved optical components. All values were measured with a cw laser at the QD emission wavelength.

Parameter	Description	Value (dB)
$L_{\text{circ},12}$	Circulator insertion loss (port 1 $\rightarrow$ 2)	1.21 ± 0.05
$L_{\text{circ},23}$	Circulator insertion loss (port 2 $\rightarrow$ 3)	0.86 ± 0.04
L_{PM}	PM insertion loss	2.29 ± 0.05
L_C	Estimated total fiber coupling loss	1.3 ± 0.1
L_{tot}	Total encoder loss	5.17 ± 0.05
ER_{PM}	PM extinction ratio	27.7 ± 0.03

encoded state matrix from the measured data and comparing it to the theoretically expected one yields an encoding agreement of $96.4 \pm 0.2\%$. We include this quantity since it additionally provides information about the basis splitting ratio and efficiency mismatches, which are similarly relevant in security considerations. Calculations are described in more detail in the Appendix B.

Transmission efficiencies are $\eta_{\text{dec}} = 81.3\%$ for the decoder (including the FPC) and $\eta_{\text{enc}} = 30.4\%$ for the encoder. An overview of relevant parameters is provided in Table I.

Figure 3(c) shows an exemplary simulation for the asymptotic SKR [40,55] in a hypothetical BB84 QKD experiment. For otherwise equal parameters, a zero-distance QBER of 0.69% yields more than 19% increase in SKR for all distances and an increase of 0.63 dB in maximum tolerable loss. The reference QBER of 2.50%

TABLE II. Comparison of our setup to other reported, comparable SPS-encoding experiments. Reference [52] is included for completeness, although they report $g^{(2)}(0) > 0.5$. Therefore, the reported value is not considered in Fig. 3(c). Reference [50] reports an in-lab QBER of 0.9%, but it is not mentioned if this value is measured or estimated.

References	Source	Protocol	Encoding type	Encoding method	Rate (MHz)	QBER (%)	Channel loss
This work	QD (C-band)	BB84	Polarization	Sagnac	151.894	0.69	...
[53]	QD	BB84	Polarization	Single-pass	76	2.5	...
[18,19]	QD (O-band)	BB84	Time-bin	MZI	1	5.9	12.8 dB
[52]	QD (894 nm)	BB84	Polarization	Single-pass	40	1.2	...
[54]	QD (897 nm)	BB84	Polarization	Single-pass	200	3.8	...
[20]	QD (L-band)	BB84	Time-bin	MZI	62.5	2.3 (est.)	...
[22]	hBN defects	B92	Polarization	Single-pass	1	8.95	...
[24]	hBN defects	BB84	Polarization	Single-pass	0.5	≥ 3	...
[25]	QD (924 nm)	BB84	Polarization	Single-pass	72.6	≥ 3.25	9.6 dB
[33]	QD (885 nm)	BB84	Polarization	Single-pass	76.13	2.54	...
[34]	QD (921 nm)	QSCF	Polarization	Single-pass	80	2.8	...
[50]	GaN defects (1310 nm)	BB84	Polarization	Sagnac	80	3.2	11.2 dB

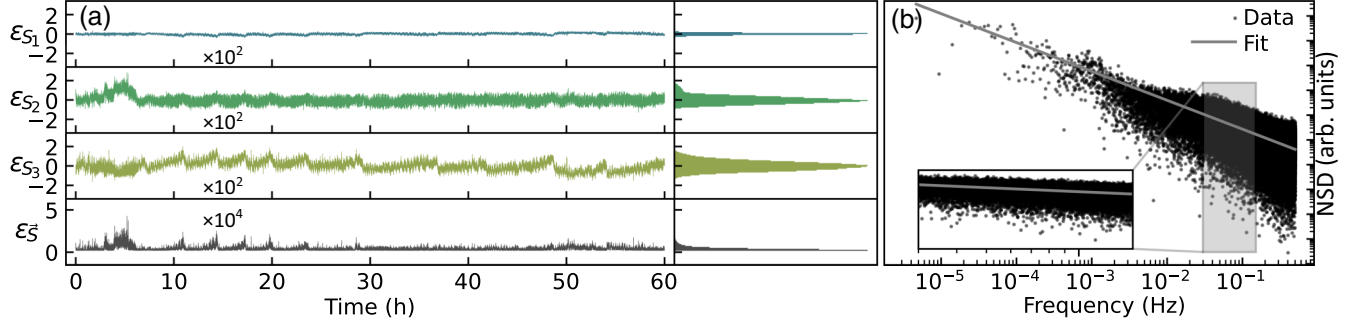


FIG. 4. Polarization stability measurements. (a) Deviations in normalized Stokes components over time, $\varepsilon_{S_i}(t) = S_i(t) - S_{i,\text{avg}}$. Bottom: $\varepsilon_S(t) = 1 - \vec{S}(t) \cdot \vec{S}_{\text{avg}}$. (b) Polarization noise spectral density of ε_S (double-logarithmic scale). A logarithmically weighted fit according to $c \times f^{-\beta}$ yields $\beta = 1.16$, showing that the noise spectrum is dominated by flicker noise (for which $\beta = 1$).

was chosen as a lower bound of values reported for high-speed SPS encoding experiments (see Table II).

B. Stability

In Fig. 4, the temporal evolution of the output polarization of the encoder module is shown. This measurement was conducted over a period of 60 h and highlights the stability of the module without any need for active temperature control or mechanical isolation. In Fig. 4(a), the quantity $\varepsilon_S(t)$ is used as a measure of the error in the output polarization of the setup. The average polarization error measured is 4×10^{-5} , and the maximum is 4.3×10^{-4} . In Fig. 4(b), a Fourier transform of this quantity reveals that the noise present in the signal is dominated by flicker noise proportional to f^{-1} , and that no particularly strong noise frequency is present in the signal, even at low frequencies.

IV. CONCLUSION

We present an encoding module for single photons at telecom wavelength based on a novel free-space Sagnac-loop architecture. This demonstration of such a free-space system achieves a high encoding agreement of $96.4 \pm 0.2\%$ and a QBER of $0.69 \pm 0.02\%$ for a 152 MHz excitation rate, representing the best results for dynamic information inscription onto single photons to date. Still, the system's performance has potential for improvement: (i) By employing direct real-time feedback on the QBER, human uncertainty could be drastically reduced. (ii) An improved, basis-agnostic alignment routine could mitigate the imbalance between the X - and Y -basis QBERs, which poses a security threat. A further reduction of the QBER in both bases to approximately 0.3%–0.4% is deemed possible by addressing these issues. (iii) The repetition rate of the system could, in principle, be increased further, as long as intersymbol interference is taken care of (see Appendix E).

We have also demonstrated the long-term stability of the output states over a time span of 2.5 days of continuous

operation, without the need for active mechanical or thermal stabilization. This operational simplicity is desirable for practical applications. Additionally, an encoder loss reduction of approximately 2 dB can be reasonably anticipated by deploying a free-space circulator. This approach facilitates direct free-space coupling into the fiber-based PM and the integration of the single-photon collection setup with the encoding module in free space.

Beyond polarization encoding, we envision three additional potential applications of this encoding protocol. First, all used components have integrated photonics counterparts [8,11,56], rendering the setup feasible for future on-chip integration. Second, the current architecture could easily be adapted for phase and time-bin encoding [41] while retaining the aforementioned performance. Third, the system can operate as an active single-photon decoder of equivalent performance by simply reversing the input and output ports, enabling, for instance, QKD protocols with adaptable, asymmetric basis choice [57] or reference-frame-independent QKD [43].

In summary, the presented technique provides a combination of operational simplicity, long-term stability, and information encoding quality, surmounting a long-standing obstacle in photonic information encoding. It is applicable to a wide range of quantum communication techniques, marks a significant advancement in the field of single-photon information processing, and positions itself as a strong candidate for application in future quantum networks based on deterministic sources.

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The authors declare no conflicts of interest.

DATA AVAILABILITY

The data that support the findings of this article are openly available [58].

APPENDIX A: SECOND-ORDER AUTOCORRELATION

For computing the value of $g^{(2)}(0)$ presented above, the recorded second-order autocorrelation data were fitted with a function consisting of side-peak terms $f_{S,i}$, a central-peak term f_C , and a bunching term f_B . Each side-peak term consists of a convolution of a Gaussian to model the bi-detector instrument response function and a two-sided exponential decay,

$$f_{S,i}(t) = A_S (\exp(-t^2/(2\sigma_i^2)) * \exp(-|t - t_0 + i/f_{\text{sys}}|/T_D)), \quad (\text{A1})$$

where A_S is the peak amplitude, σ_i is the Gaussian standard deviation, t_0 accounts for the potential offset of the measurement data in the t direction, $f_{\text{sys}} = 151.894$ MHz is the system repetition rate, $i \neq 0$ is the position of the side peak, and T_D represents the decay time of the QD emission. The term f_C is largely identical, but has $i = 0$ and an independent amplitude A_C instead of A_S . Finally, the bunching term is of the form

$$f_B = 1 + A_b \exp(-|t - t_0|/T_B), \quad (\text{A2})$$

where T_B is the bunching time (we find $T_B = (38 \pm 12)$ ns). The full fit function is then of the form

$$g^{(2)}(t) = \left(f_C(t) + \sum_i f_{S,i} \right) \times f_B, \quad (\text{A3})$$

and the value of $g^{(2)}(0)$ is calculated as

$$g^{(2)}(0) = \int f_C(t) dt / \int f_{S,0}(t) dt, \quad (\text{A4})$$

with both terms centered at $t = 0$ and integration limits of ± 100 ns. The bunching term corresponds to the normalization of the autocorrelation function as derived in Ref. [59]. As the direct fit uncertainty proved highly sensitive to the initial fit conditions, the upper (lower) uncertainty of the final value is instead estimated by using the upper (lower) bound for A_C and the lower (upper) bound for A_S (where the bounds were given by the 1σ fit uncertainties) in the f_C ($f_{S,0}$) term in Eq. (A4), respectively.

APPENDIX B: QUANTUM BIT ERROR RATE AND ENCODING AGREEMENT

The QBER and encoding agreement are calculated as follows. First, integrating the counts in each channel over a 2.65-ns temporal filtering window within each time slot i yields a total of 64 values $n_{|\psi\rangle,i}$, where $|\psi\rangle \in \{|D\rangle, |A\rangle, |R\rangle, |L\rangle\}$ represents the possible polarization states and $i = 1, 2, \dots, 16$ represents the respective bit in the sequence. The QBER is computed for each time slot individually by only considering the counts $c_{|\psi\rangle,i}$ in the expected measurement basis for that slot, for instance

$$\text{QBER}_7 = c_{|A\rangle,7} / (c_{|D\rangle,7} + c_{|A\rangle,7}), \quad (\text{B1})$$

for bit 7 in which the $|D\rangle$ state is encoded. When averaging over all bits in the sequence, this yields the presented mean QBER of $0.69 \pm 0.02\%$. A value of $0.43 \pm 0.02\%$ is obtained when averaging only over events where the X -basis was encoded, $0.96 \pm 0.01\%$ for the Y -basis.

For the encoding agreement, the same 64 values obtained after temporal filtering and integration serve as a starting point. First, four experimental four-dimensional state vectors $|\psi\rangle_{\text{exp}}$, one for each encoded state, are constructed from the data. This is done by adding up measured counts from each channel only for events where that specific state was encoded. For instance, the experimental vector $|D\rangle_{\text{exp}}$ is computed as

$$|D\rangle_{\text{exp}} = \sum_{i=4,7,12,14} \begin{pmatrix} c_{|D\rangle,i} \\ c_{|A\rangle,i} \\ c_{|R\rangle,i} \\ c_{|L\rangle,i} \end{pmatrix}. \quad (\text{B2})$$

For each of the four channels, counts that were detected in that channel during the measurement duration (and not discarded due to temporal filtering) are added up to form one entry of the state vector—but, in case of the $|D\rangle$ state, only bits 4, 7, 12, and 14 of the sequence are considered, since that state is encoded in those bits only. These state vectors are then normalized, and the experimental encoding matrix M_{exp} is constructed from them simply by using each state vector as one column.

The theoretical encoding matrix M_{theo} is obtained likewise from the normalized theoretically expected state vectors $|\psi\rangle_{\text{theo}}$ (in the corresponding order), where

$$|D\rangle_{\text{theo}} = \sqrt{2/3} \begin{pmatrix} 1 \\ 0 \\ 1/2 \\ 1/2 \end{pmatrix}, \quad (\text{B3})$$

and so on. Finally, the encoding agreement is computed as

$$F = 1 - \sqrt{\sum_{i=1}^4 \sum_{j=1}^4 (M_{\text{exp}}^{i,j} - M_{\text{theo}}^{i,j})^2} / \sqrt{\sum_{i=1}^4 \sum_{j=1}^4 (M_{\text{theo}}^{i,j})^2}. \quad (\text{B4})$$

The subtracted term describes the distance between the experimental and theoretical matrices in terms of the Frobenius norm, relative to that same norm applied to the theoretical matrix.

APPENDIX C: SECURE KEY RATE SIMULATIONS

The asymptotic SKR A is calculated the same way as in Ref. [40], namely as

$$A = R \times p_{\text{sift}} \times \left\{ \underline{p}_c^{(1)} \times (1 - h(\bar{e}_1)) - f_{\text{EC}} \times p_c \times h(e_{\text{tot}}) \right\}, \quad (\text{C1})$$

where $R = 151.894$ MHz is the system repetition rate, $p_{\text{sift}} = 0.5$, $\underline{p}_c^{(1)}$ is the lower bound of single-photon event

TABLE III. Parameters for asymptotic SKR simulations. Note that the detector efficiency is higher than that in the experiment, to more closely represent the state of the art in SNSPDs and enable a more accurate comparison to other recent experiments.

Parameter	Value	Parameter	Value
η_E	0.34	η_C	0.18 dB/km
η_D	0.8	η_S	0.8
$\langle n \rangle$	0.138	$g^{(2)}(0)$	0.005

detection probability per time slot, $\bar{e}_1$ is the upper QBER bound for single-photon states, $f_{\text{EC}} = 1.16$ is the error correction efficiency, p_c is the total detection probability per time slot across all photon number states, e_{tot} is the total QBER across all photon number states, and $h(\times)$ is the binary entropy function.

Assuming that n -photon events are negligible for $n > 2$, we get

$$p_2 = \frac{\langle n \rangle^2 g^{(2)}(0)}{2}, \quad p_1 = \langle n \rangle - p_2, \quad p_0 = 1 - p_1 - p_2. \quad (\text{C2})$$

The detector click probability for an n -photon state (neglecting dead times) is then given as

$$p_c^{(n)} = p_n [1 - (1 - p_{\text{dc}}) \times (1 - \eta_E \eta_C \eta_D \eta_S)^n], \quad (\text{C3})$$

where $p_{\text{dc}} = 50/R$ is the probability to detect a dark count in a given time slot, and $\eta_{E(C,D,S)}$ is the transmission efficiency of the encoder module (fiber channel, decoder module, and single-photon detector). Then,

$$e_n = \frac{p_{\text{dc}}/2 + p_{\text{mis}} \times (1 - (1 - \eta_E \eta_C \eta_D \eta_S)^n)}{1 - (1 - p_{\text{dc}}) \times (1 - \eta_E \eta_C \eta_D \eta_S)^n}, \quad (\text{C4})$$

$$e_{\text{tot}} = \frac{1}{p_c} \sum_{n=0}^2 e_n p_n (1 - (1 - p_{\text{dc}}) \times (1 - \eta_E \eta_C \eta_D \eta_S)^n), \quad (\text{C5})$$

$$\bar{e}_1 \leq \frac{e_{\text{tot}} p_c - p_0 p_{\text{dc}}/2}{1 - (1 - p_{\text{dc}}) \times (1 - \eta_E \eta_C \eta_D \eta_S)}, \text{ and} \quad (\text{C6})$$

$$\underline{p}_c^{(1)} \geq p_c - p_0 p_{\text{dc}} - p_2. \quad (\text{C7})$$

In Fig. 3, the quantity p_{mis} is varied between 0.69% and 2.50%. Although this quantity is not strictly equal to the QBER, the QBER provides an upper bound and constitutes a good approximation to p_{mis} as long as the ratio between signal counts and detector dark counts is sufficiently large. The remaining parameters in the simulations are given in Table III.

APPENDIX D: MEASUREMENT DETAILS

For the stability measurement, an additional free-space 50/50 beamsplitter was inserted into the encoder between the input and output coupler and the $\lambda/2$ waveplate. Two additional mirrors were then used to redirect the output light from the Sagnac loop to a polarimeter. Because of the limited sensitivity and time resolution of the polarimeter, an unmodulated continuous-wave laser signal tuned to the QD emission wavelength was used for this measurement. This configuration was chosen since it avoided all fibers outside of the Sagnac loop during the measurement, such that the actual encoding stability itself could be measured isolated from fiber-induced polarization fluctuations. In practical scenarios, this isolated encoding stability is the quantity of interest: Variations induced by fibers after the Sagnac loop can be easily corrected, but those originating from the encoder itself (for instance due to uneven splitting between CW and CCW components) cannot.

All measurements were conducted in a temperature-regulated laboratory and with the module placed on a vibration-isolated optical table. However, along the stability measurement's 60-h measurement duration, regular laboratory work was performed in the same room and on the same optical table, and even the input fiber of the encoder was moved, creating disturbances much stronger than, e.g., an MZI could typically tolerate. While changes in the polarization state are visible (especially within the first approximately 6 h of measurement), they are negligible compared to other sources of error in our setup, such as imperfections in the electronic pulses or human inaccuracy during manual optimization. Additionally, they appear to be reversible in time, as all measured parameters continuously tend back toward their mean.

We attribute the observed flicker noise to the photodiode inside the polarimeter [60]. The three leftmost datapoints are ignored in the fit to avoid skew by unproportional weighting. All data were recorded using a cw laser and an inactive phase modulator ($|D\rangle$ state), and datapoints were acquired in 1 s intervals at a power of 200 μW , as measured by the polarimeter.

APPENDIX E: SECURITY CONSIDERATIONS

Temporal filtering is used to avoid intersymbol interference, meaning the possibility that late-arriving CCW photons are modulated as CW ones and vice versa. While it discards roughly 10% of events, this is not factored into the transmission efficiency, as it is not inherent to the encoding module but rather a limitation of the SPS and repetition rate. In principle, it could be avoided by choosing a lower repetition rate. We acknowledge that single-pass or MZI encoders would support higher repetition rates than Sagnac-based ones before being met with this limitation.

We also acknowledge that in the setting described here, temporal filtering may induce a potential security risk.

Recently, a study revealed the threat of temporal side-channel information leakage in Sagnac-based information encoders using weak coherent sources [61]. We note that even when reducing the system repetition rate to eliminate intersymbol interference, the finite extinction ratio of excitation pulses may lead to photon emission background, potentially leaving the system vulnerable. Therefore, while the results of Ref. [61] cannot be directly transferred to our work, time-dependent side channel vulnerabilities are potentially present, and we encourage further research on this topic.

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- [1] F. M. Spedalieri, H. Lee, and J. P. Dowling, High-fidelity linear optical quantum computing with polarization encoding, *Phys. Rev. A* **73**, 012334 (2006).
 - [2] J. L. O'Brien, Optical quantum computing, *Science* **318**, 1567 (2007).
 - [3] C. H. Bennett and G. Brassard, Quantum cryptography: Public key distribution and coin tossing, *Theor. Comput. Sci.* **560**, 7 (2014).
 - [4] H.-K. Lo, M. Curty, and B. Qi, Measurement-device-independent quantum key distribution, *Phys. Rev. Lett.* **108**, 130503 (2012).
 - [5] G. Brassard, C. Crepeau, R. Jozsa, and D. Langlois, A quantum bit commitment scheme provably unbreakable by both parties, in *Proceedings of 1993 IEEE 34th Annual Foundations of Computer Science* (IEEE, Palo Alto, CA, USA, 1993), pp. 362–371.
 - [6] A. Kent, Unconditionally secure bit commitment by transmitting measurement outcomes, *Phys. Rev. Lett.* **109**, 130501 (2012).
 - [7] A. Broadbent and A. Tapp, Information-theoretically secure voting without an honest majority, *cryptology*, [eprint:2008/266](https://eprint.iacr.org/2008/266).
 - [8] P. Sibson, J. E. Kennard, S. Stanisic, C. Erven, J. L. O'Brien, and M. G. Thompson, Integrated silicon photonics for high-speed quantum key distribution, *Optica* **4**, 172 (2017).
 - [9] F. Gr nenfelder, A. Boaron, D. Rusca, A. Martin, and H. Zbinden, Simple and high-speed polarization-based QKD, *Appl. Phys. Lett.* **112**, 051108 (2018).
 - [10] M. Avesani, L. Calderaro, G. Foletto, C. Agnesi, F. Picciariello, F. Santagiustina, A. Scriminich, A. Stanco, F. Vedovato, M. Zahidy, G. Vallone, and P. Villoresi, A resource-effective QKD field-trial in Padua with the iPOGNAC encoder, in *2021 OFC Conference and Exhibition* (Optica Publishing Group, Washington, DC, USA, 2021), pp. 1–3.
 - [11] M. Avesani, L. Calderaro, M. Schiavon, A. Stanco, C. Agnesi, A. Santamato, M. Zahidy, A. Scriminich, G. Foletto, G. Contestabile, M. Chiesa, D. Rotta, M. Artiglia, A. Montanaro, M. Romagnoli, V. Sorianello, F. Vedovato, G. Vallone, and P. Villoresi, Full daylight quantum-key-distribution at 1550 nm enabled by integrated silicon photonics, *npj Quantum Inf.* **7**, 1 (2021).
 - [12] G.-J. Fan-Yuan, F.-Y. Lu, S. Wang, Z.-Q. Yin, D.-Y. He, W. Chen, Z. Zhou, Z.-H. Wang, J. Teng, G.-C. Guo, and

- Z.-F. Han, Robust and adaptable quantum key distribution network without trusted nodes, *Optica* **9**, 812 (2022).
- [13] S. Wang, Z.-Q. Yin, D.-Y. He, W. Chen, R.-Q. Wang, P. Ye, Y. Zhou, G.-J. Fan-Yuan, F.-X. Wang, W. Chen, Y.-G. Zhu, P. V. Morozov, A. V. Divochiy, Z. Zhou, G.-C. Guo, and Z.-F. Han, Twin-field quantum key distribution over 830-km fibre, *Nat. Photonics* **16**, 154 (2022).
- [14] W. Li, L. Zhang, H. Tan, Y. Lu, S.-K. Liao, J. Huang, H. Li, Z. Wang, H.-K. Mao, B. Yan, Q. Li, Y. Liu, Q. Zhang, C.-Z. Peng, L. You, F. Xu, and J.-W. Pan, High-rate quantum key distribution exceeding 110 Mb s^{-1} , *Nat. Photonics* **17**, 416 (2023).
- [15] F. Steinlechner, S. Ecker, M. Fink, B. Liu, J. Bavaresco, M. Huber, T. Scheidl, and R. Ursin, Distribution of high-dimensional entanglement via an Intra-city free-space link, *Nat. Commun* **8**, 15971 (2017).
- [16] Y. Shi, S. Moe Thar, H. S. Poh, J. A. Grieve, C. Kurtsiefer, and A. Ling, Stable polarization entanglement based quantum key distribution over a deployed metropolitan fiber, *Appl. Phys. Lett.* **117**, 124002 (2020).
- [17] Z.-Q. Zhong, X.-H. Zhan, J.-L. Chen, S. Wang, Z.-Q. Yin, J.-Q. Geng, D.-Y. He, W. Chen, G.-C. Guo, and Z.-F. Han, Hyperentanglement quantum communication over a 50 km noisy fiber channel, *Optica* **11**, 1056 (2024).
- [18] P. M. Intallura, M. B. Ward, O. Z. Karimov, Z. L. Yuan, P. See, A. J. Shields, P. Atkinson, and D. A. Ritchie, Quantum key distribution using a triggered quantum dot source emitting near $1.3 \text{ }\mu\text{m}$, *Appl. Phys. Lett.* **91**, 161103 (2007).
- [19] P. M. Intallura, M. B. Ward, O. Z. Karimov, Z. L. Yuan, P. See, P. Atkinson, D. A. Ritchie, and A. J. Shields, Quantum communication using single photons from a semiconductor quantum dot emitting at a telecommunication wavelength, *J. Opt. A* **11**, 054005 (2009).
- [20] K. Takemoto, Y. Nambu, T. Miyazawa, Y. Sakuma, T. Yamamoto, S. Yoroza, and Y. Arakawa, Quantum key distribution over 120 km using ultrahigh purity single-photon source and superconducting single-photon detectors, *Sci. Rep.* **5**, 14383 (2015).
- [21] T. Gao, L. Rickert, F. Urban, J. Große, N. Srocka, S. Rodt, A. Musiał, K. Żołnacz, P. Mergo, K. Dybka, W. Urbaniak, G. Sęk, S. Burger, S. Reitzenstein, and T. Heindel, A quantum key distribution testbed using a plug&play telecom-wavelength single-photon source, *Appl. Phys. Rev.* **9**, 011412 (2022).
- [22] Çağlar Samaner, S. Paçal, Gökem Mutlu, Kıvanç Uyanık, and S. Ateş, Free-space quantum key distribution with single photons from defects in hexagonal boron nitride, *Adv. Quantum Technol.* **5**, 2200059 (2022).
- [23] C. L. Morrison, R. G. Pousa, F. Graffitti, Z. X. Koong, P. Barrow, N. G. Stoltz, D. Bouwmeester, J. Jeffers, D. K. L. Oi, B. D. Gerardot, and A. Fedrizzi, Single-emitter quantum key distribution over 175 km of fibre with optimised finite key rates, *Nat. Commun.* **14**, 3573 (2023).
- [24] A. Al-Juboori, H. Z. J. Zeng, M. A. P. Nguyen, X. Ai, A. Laucht, A. Solntsev, M. Toth, R. Malaney, and I. Aharonovich, Quantum key distribution using a quantum emitter in hexagonal boron nitride, *Adv. Quantum Technol.* **6**, 2300038 (2023).
- [25] M. Zahidy, M. T. Mikkelsen, R. Müller, B. Da Lio, M. Krehbiel, Y. Wang, N. Bart, A. D. Wieck, A. Ludwig, M. Galili, S. Forchhammer, P. Lodahl, L. K. Oxenløwe, D. Bacco, and L. Midolo, Quantum key distribution using deterministic single-photon sources over a field-installed fibre link, *npj Quantum Inf.* **10**, 1 (2024).
- [26] H. J. Kimble, The quantum internet, *Nature (London)* **453**, 1023 (2008).
- [27] S. Wehner, D. Elkouss, and R. Hanson, Quantum internet: A vision for the road ahead, *Science* **362**, eaam9288 (2018).
- [28] M. Zopf, R. Keil, Y. Chen, J. Yang, D. Chen, F. Ding, and O. G. Schmidt, Entanglement swapping with semiconductor-generated photons violates bell's inequality, *Phys. Rev. Lett.* **123**, 160502 (2019).
- [29] F. Basso Basset, M. B. Rota, C. Schimpf, D. Tedeschi, K. D. Zeuner, S. F. Covre da Silva, M. Reindl, V. Zwiller, K. D. Jöns, A. Rastelli, and R. Trotta, Entanglement swapping with photons generated on demand by a quantum dot, *Phys. Rev. Lett.* **123**, 160501 (2019).
- [30] P. van Loock, W. Alt, C. Becher, O. Benson, H. Boche, C. Deppe, J. C. Eschner, S. Höfling, D. Meschede, P. Michler, F. Schmidt, and H. Weinfurter, Extending quantum links: Modules for fiber- and memory-based quantum repeaters, *Adv. Quantum Technol.* **3**, 1900141 (2020).
- [31] K. A. Owen, Towards MDI QKD using quantum dot single photon sources, Ph.D. thesis, University of Calgary, 2021.
- [32] Y.-H. Zhou, Z.-W. Yu, A. Li, X.-L. Hu, C. Jiang, and X.-B. Wang, Measurement-device-independent quantum key distribution via quantum blockade, *Sci. Rep.* **8**, 4115 (2018).
- [33] Y. Zhang, X. Ding, Y. Li, L. Zhang, Y.-P. Guo, G.-Q. Wang, Z. Ning, M.-C. Xu, R.-Z. Liu, J.-Y. Zhao, G.-Y. Zou, H. Wang, Y. Cao, Y.-M. He, C.-Z. Peng, Y.-H. Huo, S.-K. Liao, C.-Y. Lu, F. Xu, and J.-W. Pan, Experimental single-photon quantum key distribution surpassing the fundamental weak coherent-state rate limit, *Phys. Rev. Lett.* **134**, 210801 (2025).
- [34] D. A. Vajner, K. Kaymazlar, F. Drauschke, L. Rickert, M. von Helversen, H. Liu, S. Li, H. Ni, Z. Niu, A. Pappa, and T. Heindel, Single-photon advantage in quantum cryptography beyond QKD, *arXiv:2412.14993*.
- [35] M. Bozzio, M. Vvylecka, M. Cosacchi, C. Nawrath, T. Seidelmann, J. C. Lored, S. L. Portalupi, V. M. Axt, P. Michler, and P. Walther, Enhancing quantum cryptography with quantum dot single-photon sources, *npj Quantum Inf.* **8**, 104 (2022).
- [36] C. Nawrath, R. Joos, S. Kolatschek, S. Bauer, P. Pruy, F. Hornung, J. Fischer, J. Huang, P. Vijayan, R. Sittig, M. Jetter, S. L. Portalupi, and P. Michler, Bright source of purcell-enhanced, triggered, single photons in the telecom C-band, *Adv. Quantum Technol.* **6**, 2300111 (2023).
- [37] L. Schweickert, K. D. Jöns, K. D. Zeuner, S. F. Covre da Silva, H. Huang, T. Lettner, M. Reindl, J. Zichi, R. Trotta, A. Rastelli, and V. Zwiller, On-demand generation of background-free single photons from a solid-state source, *Appl. Phys. Lett.* **112**, 093106 (2018).
- [38] M. Reindl, J. H. Weber, D. Huber, C. Schimpf, S. F. Covre da Silva, S. L. Portalupi, R. Trotta, P. Michler, and A. Rastelli, Highly indistinguishable single photons from incoherently excited quantum dots, *Phys. Rev. B* **100**, 155420 (2019).

- [39] N. Tömm, A. Javadi, N. O. Antoniadis, D. Najer, M. C. Löbl, A. R. Korsch, R. C. Schott, S. R.é Valentin, A. D. Wieck, A. Ludwig, and R. J. Warburton, A bright and fast source of coherent single photons, *Nat. Nanotechnol.* **16**, 399 (2021).
- [40] J. Yang, Z. Jiang, F. Benthin, J. Hanel, T. Fandrich, R. Joos, S. Bauer, S. Kolatschek, A. Hreibi, E. P. Rugeramigabo, M. Jetter, S. L. Portalupi, M. Zopf, P. Michler, S. Kück, and F. Ding, High-rate intercity quantum key distribution with a semiconductor single-photon source, *Light Sci. Appl.* **13**, 150 (2024).
- [41] S. Wang, W. Chen, Z.-Q. Yin, D.-Y. He, C. Hui, P.-L. Hao, G.-J. Fan-Yuan, C. Wang, L.-J. Zhang, J. Kuang, S.-F. Liu, Z. Zhou, Y.-G. Wang, G.-C. Guo, and Z.-F. Han, Practical gigahertz quantum key distribution robust against channel disturbance, *Opt. Lett.* **43**, 2030 (2018).
- [42] C. Agnesi, M. Avesani, A. Stanco, P. Villoresi, and G. Vallone, All-fiber self-compensating polarization encoder for quantum key distribution, *Opt. Lett.* **44**, 2398 (2019).
- [43] Y.-P. Li, W. Chen, F.-X. Wang, Z.-Q. Yin, L. Zhang, H. Liu, S. Wang, D.-Y. He, Z. Zhou, G.-C. Guo, and Z.-F. Han, Experimental realization of a reference-frame-independent decoy BB84 quantum key distribution based on sagnac interferometer, *Opt. Lett.* **44**, 4523 (2019).
- [44] Y. Li, Y.-H. Li, H.-B. Xie, Z.-P. Li, X. Jiang, W.-Q. Cai, J.-G. Ren, J. Yin, S.-K. Liao, and C.-Z. Peng, High-speed robust polarization modulation for quantum key distribution, *Opt. Lett.* **44**, 5262 (2019).
- [45] M. Avesani, C. Agnesi, A. Stanco, G. Vallone, and P. Villoresi, Stable, low-error, and calibration-free polarization encoder for free-space quantum communication, *Opt. Lett.* **45**, 4706 (2020).
- [46] H. Liu, J. Wang, H. Ma, and S. Sun, Polarization-multiplexing-based measurement-device-independent quantum key distribution without phase Reference calibration, *Optica* **5**, 902 (2018).
- [47] Y.-A. Chen *et al.*, An integrated space-to-ground quantum communication network over 4,600 kilometres, *Nature (London)* **589**, 214 (2021).
- [48] D. Ma, X. Liu, C. Huang, H. Chen, H. Lin, and K. Wei, Simple quantum key distribution using a stable transmitter-receiver scheme, *Opt. Lett.* **46**, 2152 (2021).
- [49] Y.-L. Tang, C. Zhou, D.-D. Li, Z.-L. Xie, M.-L. Xu, J. Sun, Z.-X. Zhang, L.-J. Jiang, L.-W. Wang, G.-Q. Liu, K. Wu, Y. Ma, B.-R. Zheng, M.-S. Jiang, Y. Wang, Y.-K. Zhao, Q.-L. Ma, D. Zhang, M.-S. Zhao, W.-S. Bao, and S.-B. Tang, Time-bin phase-encoding quantum key distribution using Sagnac-based optics and compatible electronics, *Opt. Express* **31**, 26335 (2023).
- [50] X. Zhang, H. Zhang, R. M. Chua, J. Eng, M. Meunier, J. A. Grieve, W.-B. Gao, and A. Ling, Polarization-encoded quantum key distribution with a room-temperature telecom single-photon emitter, *Natl. Sci. Rev.* **12**, nwaf147 (2025).
- [51] R. Hanbury Brown and R. Q. Twiss, A test of a new type of stellar interferometer on sirius, *Nature (London)* **178**, 1046 (1956).
- [52] R. J. Collins, P. J. Clarke, V. Fernández, K. J. Gordon, M. N. Makhonin, J. A. Timpson, A. Tahaoui, M. Hopkinson, A. M. Fox, M. S. Skolnick, and G. S. Buller, Quantum key distribution system in standard telecommunications fiber using a short wavelength single photon source, *J. Appl. Phys.* **107**, 073102 (2010).
- [53] E. Waks, K. Inoue, C. Santori, D. Fattal, J. Vuckovic, G. S. Solomon, and Y. Yamamoto, Quantum cryptography with a photon turnstile, *Nature (London)* **420**, 762 (2002).
- [54] T. Heindel, C. A. Kessler, M. Rau, C. Schneider, M. Fürst, F. Hargart, W.-M. Schulz, M. Eichfelder, R. Roßbach, S. Nauerth, M. Lerner, H. Weier, M. Jetter, M. Kamp, S. Reitzenstein, S. Höfling, P. Michler, H. Weinfurter, and A. Forchel, Quantum key distribution using quantum dot single-photon emitting diodes in the red and near infrared spectral range, *New J. Phys.* **14**, 083001 (2012).
- [55] D. Gottesman, H.-K. Lo, N. Lutkenhaus, and J. Preskill, Security of quantum key distribution with imperfect devices, in *International Symposium on Information Theory, 2004. ISIT 2004. Proceedings* (IEEE, Chicago, IL, USA, 2004), p. 136.
- [56] Z. Su, E. Timurdogan, E. S. Hosseini, J. Sun, G. Leake, D. D. Coolbaugh, and M. R. Watts, Four-port integrated polarizing beam splitter, *Opt. Lett.* **39**, 965 (2014).
- [57] H.-K. Lo, H. F. Chau, and M. Ardehali, Efficient quantum key distribution scheme and a proof of its unconditional security, *J. Cryptol.* **18**, 133 (2005).
- [58] J. Hanel, Z. Jiang, J. Wang, F. Benthin, T. Fandrich, E. P. Rugeramigabo, R. Joos, M. Jetter, S. L. Portalupi, J. Yang, M. Zopf, P. Michler, and F. Ding, Ultrastable, low-error dynamic polarization encoding of deterministically generated single photons (2025), [10.25835/6D7NDUCZ](https://arxiv.org/abs/10.25835/6D7NDUCZ)
- [59] S. Machlup, Noise in semiconductors: Spectrum of a two-parameter random signal, *J. Appl. Phys.* **25**, 341 (1954).
- [60] M. B. Weissman, $1/f$ noise and other slow, nonexponential kinetics in condensed matter, *Rev. Mod. Phys.* **60**, 537 (1988).
- [61] H. Tan, W. Zhang, L. Han, S.-K. Liao, and F. Xu, Experimental study of time-dependent side channels in quantum key distribution, *Phys. Rev. A* **111**, 042622 (2025).