

# C-band plug-and-play all-fiber single-photon source based on InAs/InP quantum dots integrated via microtransfer printing

Marek G. Mikulicz<sup>1,2,3,\*</sup>, Paweł Mrowiński<sup>1</sup>, Paweł Holewa<sup>2,3</sup>, Kresten Yvind<sup>2,3</sup>,  
Marcin Syperek<sup>1</sup>, and Elizaveta Semenova<sup>2,3</sup>

<sup>1</sup>*Department of Experimental Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Science and Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland*

<sup>2</sup>*DTU Electro, Technical University of Denmark, 2800 Kongens Lyngby, Denmark*

<sup>3</sup>*NanoPhoton - Center for Nanophotonics, Technical University of Denmark, 2800 Kongens Lyngby, Denmark*



(Received 26 November 2024; revised 3 March 2025; accepted 5 June 2025; published 11 July 2025)

Fiber-based long-haul quantum communication would greatly benefit from a robust and deterministically integrated source of quantum states. Here, we report the design, fabrication, and optical characterization of InAs/InP quantum dots in the InP H1 point-defect 2D photonic crystal cavity, integrated with a standard single-mode fiber employing microtransfer printing. The device is placed in a compact cryocooler maintaining a cryogenic temperature of 15 K, and it exhibits a low multiphoton contribution to emission, with  $g^{(2)}(0) = 0.14(14)$  in the all-fiber-based optical link between two laboratory nodes. In this way, we demonstrate a plug-and-play all-fiber single-photon source operating in the third telecom window, where standard telecommunication fiber networks can be used as a low-loss medium.

DOI: [10.1103/128x-4731](https://doi.org/10.1103/128x-4731)

## I. INTRODUCTION

Progress in solid-state system fabrication methods has significantly improved the quality of single-photon sources based on self-assembled semiconductor quantum dots (QDs) [1]. These sources have reached very high levels of performance in quantum technology [2–4]. High-throughput processing of photonic micro- and nanostructures, which enables integration of single-QD emitters in a modified photonic environment [5], can enhance radiative recombination rates and emission directionality (contributing to overall source brightness [6]), reduce multiphoton contributions [7–10], improve the indistinguishability of consecutively emitted photons [4,11–15], or strengthen light-matter coupling [16], with the possibility of creating entangled quantum states of light [17–24]. Nanostructures exploiting an increase in local density of states are typically realized by fabricating mesas [25–27], microlenses [2,28], microdiscs, 3D-printed micro-objectives [25], photonic wires [3,29–33], micropillar cavities [4,34,35], photonic crystals [5,36,37], circular Bragg gratings [34,38–41], tuneable cavities [6,42], and

hybrid structures [43,44]. Alternatively, to improve the strength of light-matter coupling, i.e., the ratio between the quality factor ( $Q$ ) and the volume of the cavity mode, a cavity with extreme dielectric confinement can be used [45]. This modified photonic environment enables the realization of quantum communication [19,46–48], quantum teleportation [49], and the generation of quantum states as inputs for photonic quantum computing [50,51].

An advantage of QDs is that they can be synthesized to emit light tuned to telecommunications windows. Connecting them directly to optical fibers is especially attractive because it eliminates bulky coupling setups, allowing the fabrication of compact devices [52–55]. Although collecting a signal from a QD with a microscope objective has been shown to be highly efficient [6,56], devices integrated with a fiber typically show lower extraction efficiency [53,57–60], being limited by numerical aperture (NA) and mode matching to the cavity mode, which must be optimal to reach high collection efficiency; however, gluing the fiber directly can enable more effortless operation. Moreover, access to numerous emitters on a single chip via a directly coupled fiber array also contributes to increased scalability. For all-fiber configurations, the most straightforward approach is to directly integrate the QD chip with an optical fiber [61]. To increase coupling efficiency, the emitter (or a cavity with an emitter) can be integrated with a standard, high-NA, or lensed fiber or a GRIN-lens assembly [43], or it can be glued to the micro-objective [62]. For more advanced structures, this approach can be improved

\*Contact author: [marek.mikulicz@pwr.edu.pl](mailto:marek.mikulicz@pwr.edu.pl)

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with preselection of the most suitable emitter before integration. The emitter can be deterministically integrated with a fiber, for example, using a focused ion beam (FIB) [63], a modified 2D circular Bragg grating transferred via microtransfer printing ( $\mu$ TP) [57], or using interferometric positioning over the mesa structure to attach the fiber core; this does, however, limit the yield to only one structure per chip [54,55]. With the use of the  $\mu$ TP technique, it is in principle possible to integrate all structures from the source wafer, enabling a high fabrication yield (high integration densities and efficient material utilization [64]) and selectivity of precharacterized devices; this also allows for more versatile integrated platforms.

Quantum communication protocols can operate in the telecoms regions, and multiple approaches are used to target the 900-nm wavelength range [43,62] and the second telecom window [54,55,57,63], where GaSb/AlGaSb QDs are potentially attractive for long spin-coherence times [65]; however, all-fiber demonstrations at 1550 nm are still missing. In this context, InAs/InP quantum dots are especially attractive, as they do not require substantial modifications to the growth conditions required for GaAs-based system, such as strain control [66,67] or metamorphic buffer layers [68–70], to fit the 1550-nm window [71]. InAs/InP QDs are characterized by their low multiphoton contributions to single-photon-generation processes [10], high photon indistinguishability [41,72], and the emission of polarization-entangled photon pairs [73]. For the third telecom window, advanced metropolitan quantum networks have already been established [74] using InAs/GaAs quantum dots, and InP-based sources with ultralow multiphoton contributions are also used [75], although they are not directly coupled to fibers. In this telecom window, InAs QDs can also be interfaced with an atomic quantum memory [76] to create scalable quantum networks. Direct integration with an optical fiber allows the use of cost-effective and compact cryocoolers that are commercially available. Despite inevitable internal vibrations that hinder the use of free-space optics, QD sources directly coupled to optical fibers are necessary.

Here, we report on the design, fabrication, and optical investigation of an all-fiber coupled single-photon source operating in the telecom C-band based on InAs/InP quantum dots integrated with an H1 point-defect photonic crystal (PhC) cavity. The device was created using  $\mu$ TP with a standard single-mode optical fiber and placed in a compact cryocooler at 15 K, and it exhibited triggered single-photon operation.

## II. DEVICE DESIGN AND FABRICATION

### A. Device design

To increase QD photon-extraction efficiency and accelerate the QD emission process through the Purcell effect,

sources are typically placed in a resonator that can be realized in the form of an H- or L-type 2D photonic crystal cavity [77,78]. The fabrication of the H1 PhC cavity shown in Fig. 2 was preceded by the use of finite-difference time-domain (FDTD) numerical simulations [79], in which a regular hole pattern was defined with a hole missing in the center. This enabled the numerical examination of light transmission through the integrated structure by resolving Maxwell's equations in the time domain, focusing on finding the fundamental cavity mode centered at around 1550-nm wavelength with a Purcell factor of up to 50 (a  $Q$  factor of around 250). Simulation of the QD emission was realized by placing the in-plane dipole source at the center of the cavity structure. The boundary conditions surrounding the simulation area were defined as a perfectly matched layer [80]. The thicknesses of the layers were fixed at values described in Sec. II B, and these matched the fabricated sample. A vertical cross section of the cavity and an intensity profile of the electric field in the simulation model are shown in Fig. 1(a). The field is mostly localized in the center of the cavity and is reflected from the Al mirror toward the core of the fiber. A fundamental mode at around 1550 nm, with a Purcell factor of about 50, was found for a cavity with a period ( $a$ ) of 420 nm and a hole radius ( $r$ ) of 93 nm, which is highlighted in Fig. 1(c) with white dashed lines. Figures 1(c) and 1(d) show the corresponding calculated resonances as functions of period and hole size (radius). The calculated transmission of the dipole field in resonance with the cavity mode to the fundamental mode of the fiber core is around 27%; however, both this and the high Purcell factor in the experimental realization are limited by the spatial overlap between the QD dipole and the cavity mode [78]. When scanning the parameter space, we observe other resonances with weaker Purcell factors in addition to the fundamental cavity mode, to which the dense QD emission lines can also couple.

### B. Chip fabrication

In our device design, the emitter is an InAs/InP quantum dot grown by metal-organic vapor-phase epitaxy (MOVPE) [71,81]. During growth on a (001)-oriented InP substrate at 610 °C, a 500-nm-thick InP buffer layer is deposited, followed by a 200-nm-thick  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  sacrificial layer lattice matched to InP and a 244-nm-thick InP layer. This is then followed by 0.93 monolayers of InAs for nucleation of QDs in the subcritical regime Stranski-Krastanov growth mode, achieving a high density ( $10^{10} \text{ cm}^{-2}$ ). By tuning the V/III ratio, the density of QDs can be controlled. The deposition of a 244-nm-thick InP cap layer finishes the growth. A 500-nm-thick  $\text{SiO}_2$  release layer is deposited by plasma-enhanced chemical vapor deposition, and with an e-beam evaporator, 120 nm of Al is deposited. These two layers serve a dual function: first, after the etching process, they allow separation

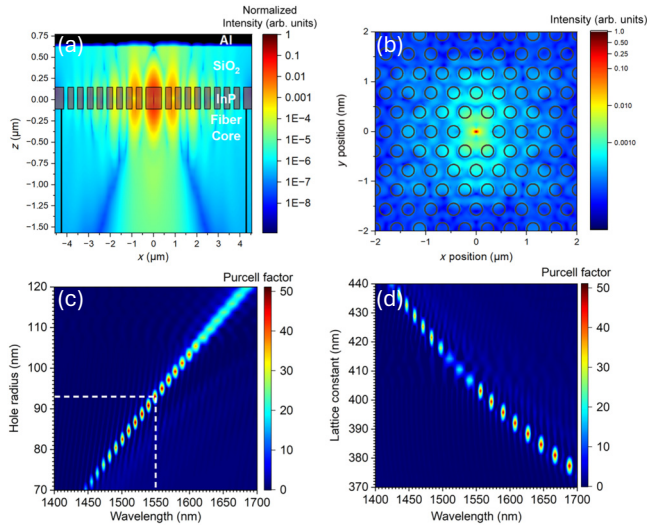


FIG. 1. FDTD simulations: cross section of the electric field intensity distribution in the logarithmic scale showing (a) the directional emission to the fiber core in the  $z$  direction and (b) the light distribution in the plane of the H1 PhC cavity. Dependence of the Purcell factor on (c) the hole radius (calculated for  $a = 420$  nm) and (d) the lattice period (calculated for  $r = 80$  nm).

of the device from the source wafer; second,  $\text{SiO}_2$ , which is transparent at  $1.55 \mu\text{m}$ , enables prospective 2D imaging [41]. The wafer is spin-coated with benzocyclobutene (BCB) and then bonded to the Si wafer with high force (2 kN) at  $250^\circ\text{C}$  under vacuum conditions in the wafer bonder. After bonding, the InP substrate and  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  stop layer are removed using HCl and  $(10\%)\text{H}_2\text{SO}_4\text{:H}_2\text{O}_2$ , respectively [82]. A 96-nm-thick SiN layer is deposited on the InP membrane. This layer acts not only as a mask for

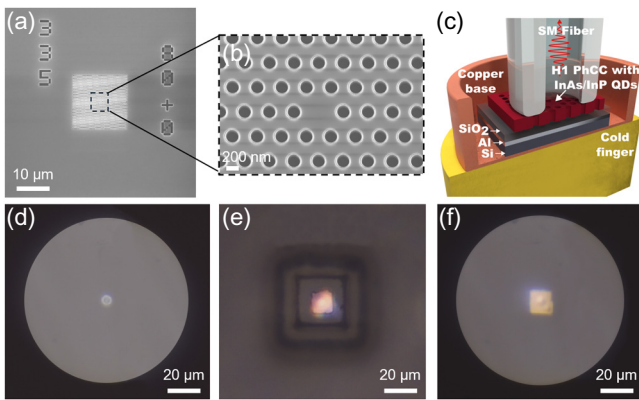


FIG. 2. Integration of a single 2D photonic microstructure into a cleaved single-mode fiber. (a), (b) SEM images of a fabricated H1 2D PhC cavity prior to membranization. (c) Conceptual visualization of the cross section of the fabricated device. (d) View of the fiber core before microtransfer without PDMS stamp. (e) View of the structure on the PDMS stamp during transfer. (f) Image of the structure transferred to the fiber core.

electron-beam lithography but also as a stress-management layer by introducing tensile stress. Consecutively, a series of designed H1 point-defect 2D PhC cavities is patterned with electron-beam lithography. The hole radius was set to 80, 100, or 120 nm, and the lattice constant was varied in the range from 335 to 435 nm with a step of 10 nm. After dry etching of InP with HBr using inductively coupled plasma reactive-ion etching, the structure was released by removing the underlying  $\text{SiO}_2$  release layer in a BHF wet etch, resulting in a suspended membrane (membranization) underneath a defined coupon area. Scanning electron microscope (SEM) images of an exemplary PhC cavity taken before membranization are shown in Fig. 2. After membranization, the cavities were characterized at room temperature in a  $\mu\text{PL}$  setup, with specific results for a device with a hole radius of 80 nm and a lattice constant of 405 nm described in Sec. III B.

### C. Microtransfer printing

In recent years, a highly deterministic approach to heterogeneous integration has been demonstrated via the pick-and-place technique, in which an individual structure is picked from a source and placed onto a target structure [64,83,84]. A potential method for the integration of III-V materials with a fiber is  $\mu\text{TP}$ , which involves the pickup and transfer of millimeter- to micrometer-sized elements from a source wafer to a target wafer with high alignment accuracy using a polydimethylsiloxane (PDMS) stamp [85,86]. The thickness of these elements may vary from the submicrometer scale to  $20 \mu\text{m}$ . This technique offers benefits such as high integration densities and efficient material utilization [64]; however, careful material selection and processing are essential due to the risk of mechanical-stress-induced damage to fragile released epitaxial layers during the transfer process, which can result in device degradation and collapse of the coupons. Typically, a release interlayer is used, such as InGaAs, InAlAs, or  $\text{SiO}_2$  [64,87].

The fabricated membrane is placed on a fiber without any adhesive, although BCB is commonly spin-coated onto the target wafer to increase the surface flatness and to serve as an adhesive for bonding [88]. Alternatively, if the released surface exhibits sufficient flatness and smoothness, typically with an  $R_q$  value (the root-mean-square average of height deviation taken from the mean image data plane) of less than 1 nm, the devices can be integrated directly onto the target substrate by van der Waals adhesion forces [89]. This adhesive-free approach facilitates potential electrical connections and increases heat dissipation for the devices. Using atomic force microscopy, we investigated the bottom of a nonperforated part of our structure, and this showed  $R_q$  values from 1.0 to 1.8 nm. In the case of our design, our transfer yield is close to 100%, with 20 out of 21 devices successfully transferred. Additionally,

the use of BCB can decrease the  $Q$  factor of the H1 2D PhC cavity by approximately a factor of 2 due to decreasing the refractive-index contrast [90].

Microtransfer printing was carried out using a commercially available X-Celeprint machine. Preselected 2D PhC cavities were picked up with a  $50 \times 50 \mu\text{m}^2$  PDMS stamp and placed on a fiber core, which was cleaved and cleaned before transfer with isopropanol. The PhC cavity structure is placed directly on a standard Corning SMF-28 fiber (core diameter  $8.2 \mu\text{m}$ ). The mode wavelength of the selected cavities at room temperature was around  $1.57$  to  $1.58 \mu\text{m}$ , to compensate for low-temperature blueshift. The fiber cable can be illuminated from the opposite end to increase the contrast between the core and the cladding and to facilitate cavity alignment. The microscope images taken at different steps of this  $\mu\text{TP}$  process are shown in Figs. 2(d)–2(f). The high magnification and stability of our setup allow for precise placement of the structure on top of the fiber core with an accuracy and precision greater than  $200 \text{ nm}$ . In a specially modified setup, the  $\mu\text{TP}$  accuracy can be as good as  $50 \text{ nm}$  [91] and can even allow direct docking contact in two axes [92], depending on the integration method.

After microtransfer printing, the fiber with PhC cavity was further secured to the Si chip using a temporary bonding adhesive (Crystalbond 555), which had  $0.5\text{-}\mu\text{m}$   $\text{SiO}_2$  and  $120\text{-nm}$  Al layers acting as a transparent spacer and backreflection layer (to control interference). A conceptual layer cross-section image is shown in Fig. 2(c). To introduce structural robustness for fiber manipulation and installation in a cryocooler, we subsequently secured the chip to the fiber with ultraviolet-cured epoxy and bonded the whole assembly to a copper base using aluminum epoxy. This additionally allows efficient heat transfer to the cryocooler's cold finger and better temperature stability.

### III. DEVICE CHARACTERIZATION

#### A. Experimental setup

For low-temperature microphotoluminescence spectroscopy, the sample was kept in a closed-cycle cryocooler at  $15 \text{ K}$ . The sample was excited with a fiber-coupled  $805\text{-nm}$  pulsed laser (PicoQuant LDH-D-C-810) with a repetition rate of up to  $80 \text{ MHz}$  ( $50\text{-ps}$ -long pulses). For continuous-wave experiments, the sample was excited with a  $787\text{-nm}$  laser (Coherent CUBE), which was also fiber-coupled. For high excitation powers, spectral analysis was conducted on a  $0.5\text{-m}$  focal-length monochromator (Princeton Instruments) with an InGaAs multichannel array detector. For the measurements that employed the superconducting nanowire single-photon (SNSPD) detectors, laser-diode background emission in the longer wavelengths was filtered with a shortpass ( $1000 \text{ nm}$ ) filter mounted onto a fiber-to-fiber U-Bench, directly

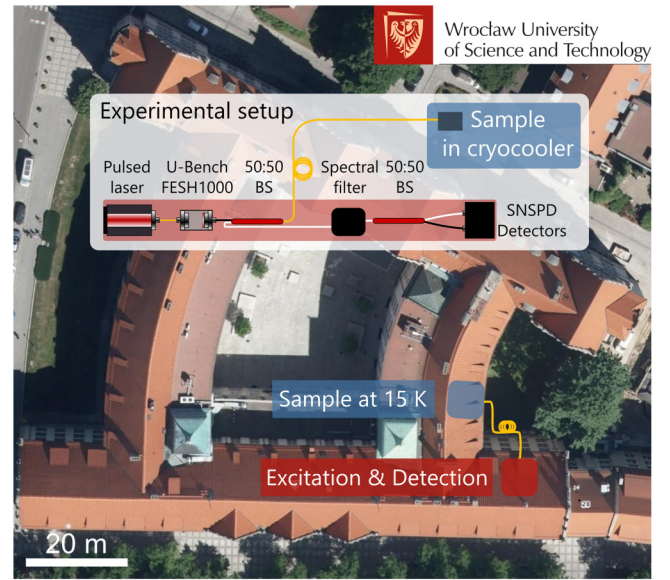


FIG. 3. All-fiber experimental setup with coupled single-photon system. The background photograph shows the location of the two laboratory nodes used for the experiment. The inset shows a schematic of the all-fiber path from the excitation laser to the source and to the detectors.

after the pulsed laser. The fiber-coupled laser was connected to a  $50:50$   $1 \times 2$  wideband fiber coupler (Thorlabs TW1550R5F1) and to a  $30\text{-m}$ -long stainless-steel-shielded single-mode fiber (SMF-28-J9) that was guided outside the building, connecting two laboratory nodes. In a different laboratory, the shielded fiber was connected to a cryocooler (CTI-Cryogenics, with internal dimensions of  $30 \times 40 \times 25 \text{ cm}^3$ ) that housed the sample mounted inside, accessed via a fiber feed-through. The cryocooler was connected to a water-cooled compressor and evacuated with a turbo pump. The emission was collected from the other arm of the  $50:50$  beam splitter at the excitation and detection node, and the spectra were filtered with a polarization-insensitive electric tunable fiber optical filter of  $0.4 \text{ nm}$  (Gaussian-shaped) FWHM bandwidth over the tuning range  $1520\text{--}1580 \text{ nm}$  centered at  $1550 \text{ nm}$  and detected on the SNSPD detectors. The autocorrelation measurement was performed in the Hanbury-Brown-Twiss configuration, where the signal after the fiber filter was split into two detection channels with an additional  $1 \times 2$   $50:50$  fiber beam splitter. A schematic of the experimental setup is shown in the inset of Fig. 3.

#### B. Optical characterization

We first investigated the device using a high excitation power. The temperature series is shown in Fig. 4(a). At room temperature, we observed both the broad emission from the QD ensemble and the resonant cavity mode at  $1573.4 \text{ nm}$ . Although in this device we do not observe

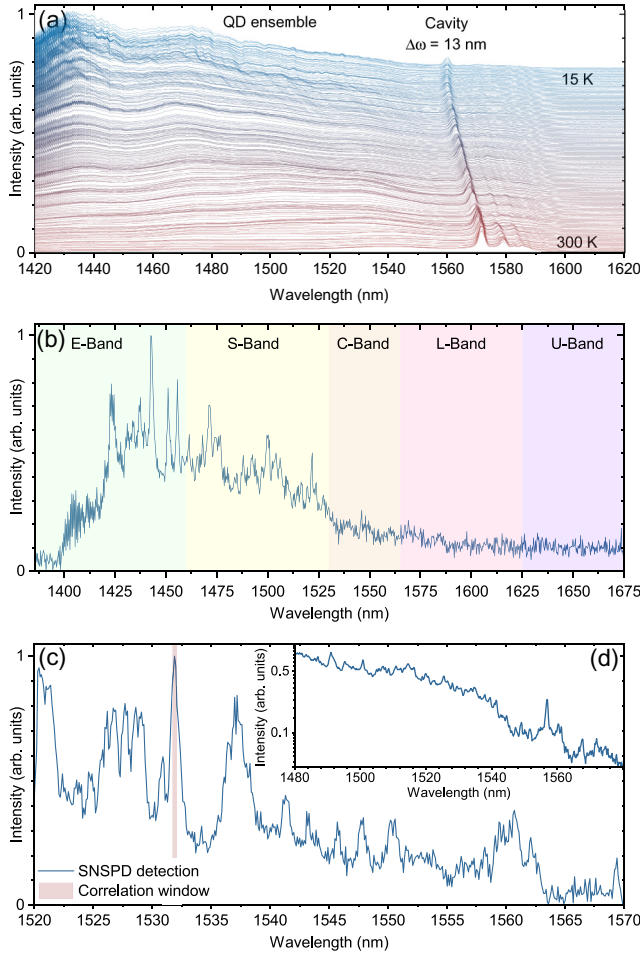


FIG. 4. Optical characterization of the device. (a) Temperature-driven evolution of the photoluminescence (PL) spectrum in the range from 15 to 300 K under high excitation power. (b) PL spectrum at  $T = 15$  K and low excitation power for a fiber-integrated PhC cavity. (c) Higher-resolution spectra of the same device as in panel (b), recorded using SNSPD. (d) A different device with a transition on the cavity mode exhibiting a linewidth more than twice as narrow as that of the cavity mode.

higher-order cavity modes, for some devices, they were identified in the spectra at shorter wavelengths. Upon cooling the structure to 15 K, we observe a blueshift of the QD emission due to Varshni-like changes in the band gap of the QD material and a blueshift of the cavity mode by approximately 13 nm. The blueshift in the cavity mode is due to the temperature-dependent change in the refractive index [93] and thermal shrinkage of the cavity. Furthermore, at 15 K, we observe an increase in the cavity's  $Q$  factor (frequency-to-bandwidth ratio) from 620 to 750.

At  $T = 15$  K, the excitation power was reduced to observe individual QD transitions in the telecom bands, as shown in Fig. 4(b). To characterize the source in time-resolved experiments, the average laser power was set to 146 nW before the cryocooler fiber feedthrough, and the

integrated spectrum was measured on the SNSPD detector, as shown in Fig. 4(c). Due to the diverse range of excited and ground states of high-density QDs, the number of excitonic transitions blends into a quasicontinuous spectrum, leading to emission of quantum-dot background radiation that undesirably feeds the fundamental mode of the cavity [94]. Figure 4(d) shows the spectra from a different device with a Purcell-enhanced QD transition, which exhibits a linewidth less than half that of the cavity mode. This measurement was taken with a higher excitation power than in Fig. 4(c).

The QD emission line at 1532 nm marked in Fig. 4(c) was selected for autocorrelation measurements. The high signal-to-noise ratio, the higher intensity than other lines, and the C-band operation make it an optimum choice. It also matches the parameters of the  $^4I_{13/2} \rightarrow ^4I_{15/2}$  transition of erbium(III) ions [95]. The intensity of the measured line during the autocorrelation measurement in counts per second was  $\sim 2$  kHz, which is relatively low but comparable to the intensity of the nontransferred device. For the emission line in Fig. 4(d), the uncorrelated background contributes to multiphoton events and hinders the demonstration of its single-photon emission; the low density of QDs is expected to overcome this constraint and allow single-photon Purcell-enhanced emission from a single QD. For the line at 1532 nm, to characterize the multiphoton contribution to the emission, which is one of the limiting factors in the application of quantum computation and communication devices [33,96,97], we used nonresonant pulsed excitation. The measurement of photoluminescence decay, as shown in Fig. 5(b), reveals biexponential decay with fast (0.9 ns) and slow (6.6 ns) components. With typical lifetimes for InAs/InP QD ensembles being around 2.0 ns [41,78,81], one possible explanation for a lifetime shorter than 1.0 ns is that the QD transition might be coupling to a cavity resonance with a weak Purcell factor of around 2.

Due to the presence of a long photoluminescence decay component, which may originate from the uncorrelated background emission [94], we examined the Hanbury-Brown-Twiss experiment with a laser repetition rate of 40 MHz to avoid overlap of subsequent correlation peaks. The line was filtered with a tunable fiber-based filter, so the investigated window was within the spectral range marked by the pink area in Fig. 4(c). The histogram data were fitted with a periodic exponential decay using the following formula [10]:

$$g_{\text{fit}}^{(2)}(\tau) = C_{\text{bg}} + g^{(2)}(0)e^{\frac{-|\tau|}{\tau_d}} + \alpha \sum_{n \neq 0} e^{\frac{-|\tau \pm nT|}{\tau_d}}. \quad (1)$$

From the normalized histogram of coincidences shown in Fig. 5(a), we subtracted the coincidences caused by the background contribution  $C_{\text{bg}}$ . In the equation,  $\alpha$  is the amplitude of pulses outside the zero delay and  $\tau_d$  is the

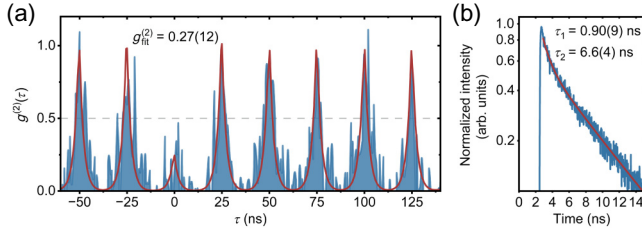


FIG. 5. Time-resolved experiments. (a) Second-order autocorrelation measurement with pulsed (triggered) optical excitation at 146 nW and 40 MHz repetition rate with background subtracted. The dip at zero delay time confirms that the emitter is a single-photon emitter. The blue curve is the experimental data and the red lines correspond to fitted curves showing  $g_{\text{fit}}^{(2)}(0) = 0.27(12)$ . (b) Measured transition decay profile of the quantum emitter within the same spectral window as for the autocorrelation measurement. The decay curve is fitted using a double exponential function to estimate the decay constants of fast 0.90(9) ns and slow 6.6(4) ns.

time constant describing decay, which has a value of 2.2 ns from the histogram fit. The value of  $g_{\text{fit}}^{(2)}(0)$  from the histogram fit is then 0.27(12). The measurement was carried out with an optical power close to the saturation level, which allows for prompt observation of the minimum at  $g^{(2)}(0)$  given the large background emission. The histogram in Fig. 5(a) is normalized by intensity, meaning that it is unaffected by the vacuum-state contribution, which here is large due to the low end-to-end efficiency of the device.

Under these experimental conditions, the fitted value of  $g_{\text{fit}}^{(2)}(0)$  is rather high, and with a power reduction, we expect a reduction of  $g_{\text{fit}}^{(2)}(0)$  [54]. Nonetheless, a decrease in optical excitation power and, consequently, in the signal-to-noise ratio introduces difficulty in obtaining an accurate measurement. The  $g_{\text{fit}}^{(2)}(0)$  value does not reach the pure single-photon state with a value of  $g_{\text{fit}}^{(2)}(0) = 0$ , and the background contribution can be accounted for using the formula

$$g_{\text{corrected}}^{(2)}(0) = \frac{C_N(\tau) - (1 - \rho^2)}{\rho^2}, \quad (2)$$

with a  $\rho = (S)/(S + B)$  value of 0.7, where  $S$  and  $B$  represent the signal and background count rates, respectively, of the observed line [98], and where  $C_N(\tau)$  is the measured number of coincidences normalized by the expected number of coincidences for a Poissonian source with the same intensity. This parameter enables determination of the corrected value of  $g_{\text{corrected}}^{(2)}(0) = 0.14(14)$  without the background contribution. It should be noted that due to the low end-to-end efficiency and high background contribution, the uncertainty in  $g^{(2)}(0)$  is large. Before background subtraction, the histogram coincidences were 152 for  $C_{\text{bg}}$  and 237 for the average peak height outside zero delay time.

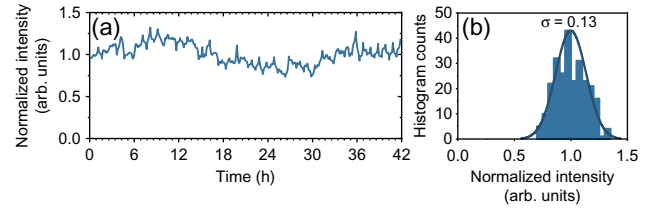


FIG. 6. (a) Intensity plot of the normalized count rate of the device. (b) Histogram of the normalized intensity, showing the distribution of the signal intensity with a standard-deviation value  $\sigma = 0.13$ .

A fiber-coupled QD source's stability and operational readiness are important for real-world applications. We tested the stability of our device by monitoring the photon flux for more than 40 hours, and the normalized intensity plot is shown in Fig. 6(a). This reveals long-time-scale fluctuations, possibly caused by thermal fluctuations of the cryocooler and spectral wandering of the autocorrelated line partially out of the spectral-filter range. The intensity of the source remains unchanged after the cryocooler's thermal cycle. A histogram of the signal distribution is shown in Fig. 5(b); this was fitted with a Gaussian function with a standard deviation  $\sigma = 0.13$ . After eliminating the long-time-scale component, the calculated signal fluctuation is reduced to  $\sigma = 0.09$ .

#### IV. RESULTS AND DISCUSSION

In this work, we have detailed the design, fabrication, and optical characterization of a triggered all-fiber single-photon source operating in the third telecom window based on high-density InAs/InP quantum dots. We used an H1 point-defect 2D PhC cavity to enhance photon coupling to the standard single-mode fiber, along with a metallic back-reflector and a  $\text{SiO}_2$  layer spacer. The structures were integrated using the microtransfer printing technique with a high yield. Operating between two distant laboratory nodes connected via commercially available single-mode fiber, the device was found to maintain long-term emission and reliable performance through a cooling cycle, demonstrating real-world applicability while focusing on the telecom C-band. The device showed a low multiphoton contribution of  $g_{\text{fit}}^{(2)}(0) = 0.27(12)$  and, without background contribution,  $g_{\text{corrected}}^{(2)}(0) = 0.14(14)$ . It should be noted that to demonstrate a pure single-photon state (unlike this device, which has a large vacuum-state contribution),  $g^{(2)}(0)$  should be zero, and the vacuum contribution must be measured or a negative Wigner function should be observed [99,100].

Before transfer printing, the use of a  $\text{SiO}_2$  release layer and a metallic mirror at the bottom of the chip have the potential for 2D imaging and deterministic localization of a single QD [41]. This would allow one to define a cavity with a preselected single QD in its center, which, along

with using QDs with lower density, would decrease the number of spectral lines (a decrease in QD density by a factor of 10 would give approximately one QD transition matched to a cavity mode), thus decreasing the background contribution [101] and improving the single-photon purity of the device. Reduction of the background emission and improvement of the single-photon purity can also be achieved using the quasiresonant excitation scheme [55]. In addition, the efficiency of light coupling can be increased with improved surface quality (fiber end polishing) [102] and a more optimized cavity design. Compared to FIB integration, microtransfer printing allows for the introduction of a feedback loop during the alignment of the structure, where the fundamental mode of the cavity can be observed from the other side of the fiber in real time and microtransfer printing can be adjusted to maximize coupling efficiency.

Our design preserves the ability of the device to generate single photons despite advanced processing, overcoming the challenges of precise alignment, mode mismatch, and mechanical stress when coupling to a fiber. This makes our integration framework suitable for applications beyond single-photon sources (which can be used for quantum key distribution, quantum metrology, or photon-based simulations) that also require alignment with a fiber core or multiple cores and stable operation, such as lab-on-fiber sensing [103,104], highly sensitive measurement of refractive index and temperature [105,106], and Raman-scattering detection [107].

## ACKNOWLEDGMENTS

We acknowledge financial support from the National Science Centre (Poland) within Project No. 2023/50/E/ST7/00581, from the Danish National Research Foundation via the Research Centers of Excellence NanoPhoton (DNRF147), and from the European Union's Horizon Europe Research and Innovation Programme under the QPIC 1550 project (Grant Agreement No. 101135785). M.S. acknowledges financial support in realizing quantum optics experiments from the QuanterERA II European Union's Horizon 2020 research and innovation programme under the EQUAISE project, supervised by the National Centre for Research and Development in Poland.

## DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

- [1] P. Senellart, G. Solomon, and A. White, High-performance semiconductor quantum-dot single-photon sources, *Nat. Nanotechnol.* **12**, 1026 (2017).

- [2] M. Gschrey, A. Thoma, P. Schnauber, M. Seifried, R. Schmidt, B. Wohlfeil, L. Krüger, J. H. Schulze, T. Heindel, S. Burger, F. Schmidt, A. Strittmatter, S. Rodt, and S. Reitzenstein, Highly indistinguishable photons from deterministic quantum-dot microlenses utilizing three-dimensional in situ electron-beam lithography, *Nat. Commun.* **6**, 7662 (2015).
- [3] J. Claudon, J. Bleuse, N. S. Malik, M. Bazin, P. Jaffrennou, N. Gregersen, C. Sauvan, P. Lalanne, and J.-M. Gérard, A highly efficient single-photon source based on a quantum dot in a photonic nanowire, *Nat. Photonics* **4**, 174 (2010).
- [4] N. Somaschi, V. Giesz, L. D. Santis, J. C. Loredó, M. P. Almeida, G. Hornecker, S. L. Portalupi, T. Grange, C. Antón, J. Demory, C. Gómez, I. Sagnes, N. D. Lanzillotti-Kimura, A. Lemaitre, A. Auffeves, A. G. White, L. Lanco, and P. Senellart, Near-optimal single-photon sources in the solid state, *Nat. Photonics* **10**, 340 (2016).
- [5] P. Lodahl, A. Floris van Driel, I. S. Nikolaev, A. Imman, K. Overgaag, D. Vanmaekelbergh, and W. L. Vos, Controlling the dynamics of spontaneous emission from quantum dots by photonic crystals, *Nature* **430**, 654 (2004).
- [6] N. Tomm, A. Javadi, N. O. Antoniadis, D. Najer, M. C. Löbl, A. R. Korsch, R. Schott, S. R. Valentin, A. D. Wieck, A. Ludwig, and R. J. Warburton, A bright and fast source of coherent single photons, *Nat. Nanotechnol.* **16**, 399 (2021).
- [7] P. Michler, A. Imamoglu, A. Kiraz, C. Becher, M. Mason, P. Carson, G. Strouse, S. Buratto, W. Schoenfeld, and P. Petroff, Nonclassical radiation from a single quantum dot, *Phys. Status Solidi (b)* **229**, 399 (2002).
- [8] P. Michler, A. Kiraz, C. Becher, W. V. Schoenfeld, P. M. Petroff, L. Zhang, E. Hu, and A. Imamoglu, A quantum dot single-photon turnstile device, *Science* **290**, 2282 (2000).
- [9] 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).
- [10] T. Miyazawa, K. Takemoto, Y. Nambu, S. Miki, T. Yamashita, H. Terai, M. Fujiwara, M. Sasaki, Y. Sakuma, M. Takatsu, T. Yamamoto, and Y. Arakawa, Single-photon emission at 1.5  $\mu\text{m}$  from an InAs/InP quantum dot with highly suppressed multi-photon emission probabilities, *Appl. Phys. Lett.* **109**, 132106 (2016).
- [11] C. Santori, D. Fattal, J. Vučković, G. S. Solomon, and Y. Yamamoto, Indistinguishable photons from a single-photon device, *Nature* **419**, 594 (2002).
- [12] C. K. Hong, Z. Y. Ou, and L. Mandel, Measurement of subpicosecond time intervals between two photons by interference, *Phys. Rev. Lett.* **59**, 2044 (1987).
- [13] X. Ding, Y. He, Z.-C. Duan, N. Gregersen, M.-C. Chen, S. Unsleber, S. Maier, C. Schneider, M. Kamp, S. Höfling, C.-Y. Lu, and J.-W. Pan, On-demand single photons with high extraction efficiency and near-unity indistinguishability from a resonantly driven quantum dot in a micropillar, *Phys. Rev. Lett.* **116**, 020401 (2016).
- [14] Y.-J. Wei, Y.-M. He, M.-C. Chen, Y.-N. Hu, Y. He, D. Wu, C. Schneider, M. Kamp, S. Höfling, C.-Y. Lu, and J.-W. Pan, Deterministic and robust generation of single photons from a single quantum dot with 99.5% indistinguishability using adiabatic rapid passage, *Nano Lett.* **14**, 6515 (2014).

- [15] A. Thoma, P. Schnauber, M. Gschrey, M. Seifried, J. Wolters, J.-H. Schulze, A. Strittmatter, S. Rodt, A. Carmele, A. Knorr, T. Heindel, and S. Reitzenstein, Exploring dephasing of a solid-state quantum emitter via time- and temperature-dependent Hong-Ou-Mandel experiments, *Phys. Rev. Lett.* **116**, 033601 (2016).
- [16] P. Lodahl and S. Stobbe, Solid-state quantum optics with quantum dots in photonic nanostructures, *Nanophotonics* **2**, 39 (2013).
- [17] A. K. Ekert, Quantum cryptography based on Bell's theorem, *Phys. Rev. Lett.* **67**, 661 (1991).
- [18] H.-J. Briegel, W. Dür, J. I. Cirac, and P. Zoller, Quantum repeaters: The role of imperfect local operations in quantum communication, *Phys. Rev. Lett.* **81**, 5932 (1998).
- [19] N. Gisin and R. Thew, Quantum communication, *Nat. Photonics* **1**, 165 (2007).
- [20] C. Simon, H. de Riedmatten, M. Afzelius, N. Sangouard, H. Zbinden, and N. Gisin, Quantum repeaters with photon pair sources and multimode memories, *Phys. Rev. Lett.* **98**, 190503 (2007).
- [21] J. Mower, Z. Zhang, P. Desjardins, C. Lee, J. H. Shapiro, and D. Englund, High-dimensional quantum key distribution using dispersive optics, *Phys. Rev. A* **87**, 062322 (2013).
- [22] O. Benson, C. Santori, M. Pelton, and Y. Yamamoto, Regulated and entangled photons from a single quantum dot, *Phys. Rev. Lett.* **84**, 2513 (2000).
- [23] E. Moreau, I. Robert, L. Manin, V. Thierry-Mieg, J. M. Gérard, and I. Abram, Quantum cascade of photons in semiconductor quantum dots, *Phys. Rev. Lett.* **87**, 183601 (2001).
- [24] R. M. Stevenson, R. J. Young, P. Atkinson, K. Cooper, D. A. Ritchie, and A. J. Shields, A semiconductor source of triggered entangled photon pairs, *Nature* **439**, 179 (2006).
- [25] S. Fischbach, A. Kaganskiy, E. B. Y. Tauscher, F. Gericke, A. Thoma, R. Schmidt, A. Strittmatter, T. Heindel, S. Rodt, and S. Reitzenstein, Efficient single-photon source based on a deterministically fabricated single quantum dot—microstructure with backside gold mirror, *Appl. Phys. Lett.* **111**, 011106 (2017).
- [26] L. Bremer, C. Jimenez, S. Thiele, K. Weber, T. Huber, S. Rodt, A. Herkommer, S. Burger, S. Höfling, H. Giessen, and S. Reitzenstein, Numerical optimization of single-mode fiber-coupled single-photon sources based on semiconductor quantum dots, *Opt. Express* **30**, 15913 (2022).
- [27] P.-I. Schneider, N. Sročka, S. Rodt, L. Zschiedrich, S. Reitzenstein, and S. Burger, Numerical optimization of the extraction efficiency of a quantum-dot based single-photon emitter into a single-mode fiber, *Opt. Express* **26**, 8479 (2018).
- [28] M. Sartison, K. Weber, S. Thiele, L. Bremer, S. Fischbach, T. Herzog, S. Kolatschek, M. Jetter, S. Reitzenstein, A. Herkommer, P. Michler, S. L. Portalupi, and H. Giessen, 3D printed micro-optics for quantum technology: Optimised coupling of single quantum dot emission into a single-mode fibre, *Light: Adv. Manuf.* **2**, 103 (2021).
- [29] S. Bounouar, M. Elouneq-Jamroz, M. D. Hertog, C. Morchutt, E. Bellet-Amalric, R. André, C. Bougerol, Y. Genuist, J.-P. Poizat, S. Tatarenko, and K. Kheng, Ultrafast room temperature single-photon source from nanowire-quantum dots, *Nano Lett.* **12**, 2977 (2012).
- [30] M. Munsch, N. S. Malik, E. Dupuy, A. Delga, J. Bleuse, J.-M. Gérard, J. Claudon, N. Gregersen, and J. Mørk, Dielectric GaAs antenna ensuring an efficient broadband coupling between an InAs quantum dot and a gaussian optical beam, *Phys. Rev. Lett.* **110**, 177402 (2013).
- [31] K. D. Jöns, L. Schweickert, M. A. M. Versteegh, D. Dalacu, P. J. Poole, A. Gulinatti, A. Giudice, V. Zwiller, and M. E. Reimer, Bright nanoscale source of deterministic entangled photon pairs violating Bell's inequality, *Sci. Rep.* **7**, 1700 (2017).
- [32] G. Bulgarini, M. E. Reimer, M. Bouwes Bavinck, K. D. Jöns, D. Dalacu, P. J. Poole, E. P. A. M. Bakkers, and V. Zwiller, Nanowire waveguides launching single photons in a Gaussian mode for ideal fiber coupling, *Nano Lett.* **14**, 4102 (2014).
- [33] M. J. Holmes, K. Choi, S. Kako, M. Arita, and Y. Arakawa, Room-temperature triggered single photon emission from a III-Nitride site-controlled nanowire quantum dot, *Nano Lett.* **14**, 982 (2014).
- [34] J. Wang, F. Sciarrino, A. Laing, and M. G. Thompson, Integrated photonic quantum technologies, *Nat. Photonics* **14**, 273 (2019).
- [35] S. E. Thomas, M. Billard, N. Coste, S. C. Wein, Priya, H. Ollivier, O. Krebs, L. Tazaïrt, A. Harouri, A. Lemaitre, I. Sagnes, C. Anton, L. Lanco, N. Somaschi, J. C. Lored, and P. Senellart, Bright polarized single-photon source based on a linear dipole, *Phys. Rev. Lett.* **126**, 233601 (2021).
- [36] W. H. P. Pernice, C. Xiong, C. Schuck, and H. X. Tang, High- $Q$  aluminum nitride photonic crystal nanobeam cavities, *Appl. Phys. Lett.* **100**, 091105 (2012).
- [37] T. Schröder, M. Walsh, J. Zheng, S. Mouradian, L. Li, G. Malladi, H. Bakhru, M. Lu, A. Stein, M. Heuck, and D. Englund, Scalable fabrication of coupled NV center—photonic crystal cavity systems by self-aligned N ion implantation, *Opt. Mater. Express* **7**, 1514 (2017).
- [38] S. Ates, L. Sapienza, M. Davanco, A. Badolato, and K. Srinivasan, Bright single-photon emission from a quantum dot in a circular Bragg grating microcavity, *IEEE J. Sel. Top. Quantum Electron.* **18**, 1711 (2012).
- [39] J. Liu, R. Su, Y. Wei, B. Yao, S. F. C. D. 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).
- [40] A. Barbiero, J. Huwer, J. Skiba-Szymanska, T. Müller, R. M. Stevenson, and A. J. Shields, Design study for an efficient semiconductor quantum light source operating in the telecom C-band based on an electrically-driven circular Bragg grating, *Opt. Express* **30**, 10919 (2022).
- [41] P. Holewa, D. A. Vajner, E. Zięba-Ostó, M. Wasiluk, B. Gaál, A. Sakanas, M. Burakowski, P. Mrowiński, B. Krajnik, M. Xiong, K. Yvind, N. Gregersen, A. Musiał, A. Huck, T. Heindel, M. Syper, and E. Semenova, High-throughput quantum photonic devices emitting indistinguishable photons in the telecom C-band, *Nat. Commun.* **15**, 3358 (2024).

- [42] D. Najer, I. Söllner, P. Sekatski, V. Dolique, M. C. Löbl, D. Riedel, R. Schott, S. Starsielec, S. R. Valentin, A. D. Wieck, N. Sangouard, A. Ludwig, and R. J. Warburton, A gated quantum dot strongly coupled to an optical microcavity, *Nature* **575**, 622 (2019).
- [43] D. B. Northeast, D. Dalacu, J. F. Weber, J. Phoenix, J. Lapointe, G. C. Aers, P. J. Poole, and R. L. Williams, Optical fibre-based single photon source using InAsP quantum dot nanowires and gradient-index lens collection, *Sci. Rep.* **11**, 22878 (2021).
- [44] H. Abudayyeh, B. Lubotzky, A. Blake, J. Wang, S. Majumder, Z. Hu, Y. Kim, H. Htoon, R. Bose, A. V. Malko, J. A. Hollingsworth, and R. Rapaport, Single photon sources with near unity collection efficiencies by deterministic placement of quantum dots in nanoantennas, *APL Photonics* **6**, 036109 (2021).
- [45] F. Wang, R. E. Christiansen, Y. Yu, J. Mørk, and O. Sigmond, Maximizing the quality factor to mode volume ratio for ultra-small photonic crystal cavities, *Appl. Phys. Lett.* **113**, 241101 (2018).
- [46] D. A. Vajner, L. Rickert, T. Gao, K. Kaymazlar, and T. Heindel, Quantum communication using semiconductor quantum dots, *Adv. Quantum Technol.* **5**, 2100116 (2022).
- [47] F. Flamini, N. Spagnolo, and F. Sciarrino, Photonic quantum information processing: A review, *Rep. Progr. Phys.* **82**, 016001 (2018).
- [48] T. E. Northup and R. Blatt, Quantum information transfer using photons, *Nat. Photonics* **8**, 356 (2014).
- [49] F. Basso Basset, F. Salusti, L. Schweickert, M. B. Rota, D. Tedeschi, S. F. Covre da Silva, E. Roccia, V. Zwiller, K. D. Jöns, A. Rastelli, and R. Trotta, Quantum teleportation with imperfect quantum dots, *npj Quantum Inf.* **7**, 7 (2021).
- [50] T. D. Ladd, F. Jelezko, R. Laflamme, Y. Nakamura, C. Monroe, and J. L. O'Brien, Quantum computers, *Nature* **464**, 45 (2010).
- [51] E. Knill, R. Laflamme, and G. J. Milburn, A scheme for efficient quantum computation with linear optics, *Nature* **409**, 46 (2001).
- [52] A. Schlehahn, L. Krüger, M. Gschrey, J.-H. Schulze, S. Rodt, A. Strittmatter, T. Heindel, and S. Reitzenstein, Operating single quantum emitters with a compact Stirling cryocooler, *Review of Scientific Instruments* **86**, 013113 (2015).
- [53] A. Schlehahn, S. Fischbach, R. Schmidt, A. Kaganskiy, A. Strittmatter, S. Rodt, T. Heindel, and S. Reitzenstein, A stand-alone fiber-coupled single-photon source, *Sci. Rep.* **8**, 1340 (2018).
- [54] A. Musiał, *et al.*, Plug&play fiber-coupled 73 kHz single-photon source operating in the telecom O-band, *Adv. Quantum Technol.* **3**, 2000018 (2020).
- [55] T. Gao, L. Rickert, F. Urban, J. Große, N. Srocka, S. Rodt, A. Musiał, K. Żołnacz, P. Mergo, K. Dybka, W. Urbańczyk, 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).
- [56] J. Yang, Y. Chen, Z. Rao, Z. Zheng, C. Song, Y. Chen, K. Xiong, P. Chen, C. Zhang, W. Wu, Y. Yu, and S. Yu, Tunable quantum dots in monolithic Fabry-Perot microcavities for high-performance single-photon sources, *Light: Sci. Appl.* **13**, 33 (2024).
- [57] W. B. Jeon, J. S. Moon, K. Kim, Y. Ko, C. J. K. Richardson, E. Waks, and J. Kim, Plug-and-play single-photon devices with efficient fiber-quantum dot interface, *Adv. Quantum Technol.* **5**, 2200022 (2022).
- [58] L. Rickert, K. Żołnacz, D. A. Vajner, M. von Helversen, S. Rodt, S. Reitzenstein, H. Liu, S. Li, H. Ni, P. Wyborski, G. Sęk, A. Musiał, Z. Niu, and T. Heindel, A fiber-pigtailed quantum dot device generating indistinguishable photons at GHz clock-rates, *Nanophotonics* **14**, 1795 (2025).
- [59] L. Rickert, F. Schröder, T. Gao, C. Schneider, S. Höfling, and T. Heindel, Fiber-pigtail quantum-dot cavity-enhanced light emitting diodes, *Appl. Phys. Lett.* **119**, 131104 (2021).
- [60] H. Snijders, J. A. Frey, J. Norman, V. P. Post, A. C. Gosard, J. E. Bowers, M. P. van Exter, W. Löffler, and D. Bouwmeester, Fiber-coupled cavity-QED source of identical single photons, *Phys. Rev. Appl.* **9**, 031002 (2018).
- [61] X. Xu, I. Toft, R. T. Phillips, J. Mar, K. Hammura, and D. A. Williams, "Plug and play" single-photon sources, *Appl. Phys. Lett.* **90**, 061103 (2007).
- [62] L. Bremer, K. Weber, S. Fischbach, S. Thiele, M. Schmidt, A. Kaganskiy, S. Rodt, A. Herkommer, M. Sartison, S. L. Portalupi, P. Michler, H. Giessen, and S. Reitzenstein, Quantum dot single-photon emission coupled into single-mode fibers with 3D printed micro-objectives, *APL Photonics* **5**, 106101 (2020).
- [63] C.-M. Lee, M. A. Buyukkaya, S. Aghaeimeibodi, A. Karasahin, C. J. K. Richardson, and E. Waks, A fiber-integrated nanobeam single photon source emitting at telecom wavelengths, *Appl. Phys. Lett.* **114**, 171101 (2019).
- [64] J. Zhang, *et al.*, III-V-on-Si photonic integrated circuits realized using micro-transfer-printing, *APL Photonics* **4**, 110803 (2019).
- [65] J. Michl, G. Peniakov, A. Pfenning, J. Hilska, A. Chellu, A. Bader, M. Guina, S. Höfling, T. Hakkarainen, and T. Huber-Loyola, Strain-free GaSb quantum dots as single-photon sources in the telecom S-band, *Advanced Quantum Technologies* **6**, 2300180 (2023).
- [66] F. Guffarth, R. Heitz, A. Schliwa, O. Stier, N. N. Ledentsov, A. R. Kovsh, V. M. Ustinov, and D. Bimberg, Strain engineering of self-organized InAs quantum dots, *Phys. Rev. B* **64**, 085305 (2001).
- [67] J. Tatebayashi, M. Nishioka, and Y. Arakawa, Over 1.5  $\mu\text{m}$  light emission from InAs quantum dots embedded in InGaAs strain-reducing layer grown by metalorganic chemical vapor deposition, *Appl. Phys. Lett.* **78**, 3469 (2001).
- [68] E. S. Semenova, R. Hostein, G. Patriarche, O. Mauguin, L. Largeau, I. Robert-Philip, A. Beveratos, and A. Lemaître, Metamorphic approach to single quantum dot emission at 1.55  $\mu\text{m}$  on GaAs substrate, *J. Appl. Phys.* **103**, 103533 (2008).
- [69] M. Paul, F. Olbrich, J. Höschele, S. Schreier, J. Kettler, S. L. Portalupi, M. Jetter, and P. Michler, Single-photon emission at 1.55  $\mu\text{m}$  from MOVPE-grown InAs quantum dots on InGaAs/GaAs metamorphic buffers, *Appl. Phys. Lett.* **111**, 033102 (2017).

- [70] S. L. Portalupi, M. Jetter, and P. Michler, InAs quantum dots grown on metamorphic buffers as non-classical light sources at telecom C-band: A review, *Semicond. Sci. Technol.* **34**, 053001 (2019).
- [71] Y. Berdnikov, P. Holewa, S. Kadhodazadeh, J. M. Śmigiel, A. Sakanas, A. Frackowiak, K. Yvind, M. Syperrek, and E. Semenova, Near-critical Stranski-Krastanov growth of InAs/InP quantum dots, *Sci. Rep.* **14**, 23697 (2024).
- [72] M. H. Rahaman, S. Harper, C.-M. Lee, K.-Y. Kim, M. A. Buyukkaya, V. J. Patel, S. D. Hawkins, J.-H. Kim, S. Addamane, and E. Waks, Efficient, indistinguishable telecom C-band photons using a tapered nanobeam waveguide, *ACS Photonics* **11**, 2738 (2024).
- [73] A. Kors, J. P. Reithmaier, and M. Benyoucef, Telecom wavelength single quantum dots with very small excitonic fine-structure splitting, *Appl. Phys. Lett.* **112**, 172102 (2018).
- [74] S. Gyger, K. D. Zeuner, T. Lettner, S. Bensoussan, M. Carlñäs, L. Ekemar, L. Schweickert, C. R. Hedlund, M. Hammar, T. Nilsson, J. Almlöf, S. Steinhauer, G. V. Lloera, and V. Zwiller, Metropolitan single-photon distribution at 1550 nm for random number generation, *Appl. Phys. Lett.* **121**, 194003 (2022).
- [75] K. Takemoto, Y. Nambu, T. Miyazawa, Y. Sakuma, T. Yamamoto, S. Yorozu, 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).
- [76] S. E. Thomas, L. Wagner, R. Joos, R. Sittig, C. Nawrath, P. Burdekin, I. M. de Buy Wenniger, M. J. Rasiah, T. Huber-Loyola, S. Sagona-Stopfel, S. Höfling, M. Jetter, P. Michler, I. A. Walmsley, S. L. Portalupi, and P. M. Ledingham, Deterministic storage and retrieval of telecom light from a quantum dot single-photon source interfaced with an atomic quantum memory, *Sci. Adv.* **10**, eadi7346 (2024).
- [77] M. Saldutti, M. Xiong, E. Dimopoulos, Y. Yu, M. Gioannini, and J. Mørk, Modal properties of photonic crystal cavities and applications to lasers, *Nanomaterials* **11**, 3030 (2021).
- [78] C. L. Phillips, A. J. Brash, M. Godslan, N. J. Martin, A. Foster, A. Tomlinson, R. Dost, N. Babazadeh, E. M. Sala, L. Wilson, J. Heffernan, M. S. Skolnick, and A. M. Fox, Purcell-enhanced single photons at telecom wavelengths from a quantum dot in a photonic crystal cavity, *Sci. Rep.* **14**, 4450 (2024).
- [79] I. Lumerical Solutions, Lumerical Solutions, Inc., 2024, <https://www.ansys.com/products/optics/fdtd>, accessed: 2024-10-01.
- [80] J.-P. Béranger, *Perfectly Matched Layer (PML) for Computational Electromagnetics* (Springer International Publishing, Cham, 2007).
- [81] P. Holewa, M. Gawelczyk, C. Ciostek, P. Wyborski, S. Kadhodazadeh, E. Semenova, and M. Syperrek, Optical and electronic properties of low-density InAs/InP quantum-dot-like structures designed for single-photon emitters at telecom wavelengths, *Phys. Rev. B* **101**, 195304 (2020).
- [82] P. Holewa, A. Sakanas, U. M. Gür, P. Mrowiński, A. Huck, B.-Y. Wang, A. Musiał, K. Yvind, N. Gregersen, M. Syperrek, and E. Semenova, Bright quantum dot single-photon emitters at telecom bands heterogeneously integrated on Si, *ACS Photonics* **9**, 2273 (2022).
- [83] J. Yoon, S. Lee, D. Kang, M. A. Meitl, C. A. Bower, and J. A. Rogers, Heterogeneously integrated optoelectronic devices enabled by micro-transfer printing, *Adv. Opt. Mater.* **3**, 1313 (2015).
- [84] G. Roelkens, *et al.*, Micro-transfer printing for heterogeneous Si photonic integrated circuits, *IEEE J. Sel. Top. Quantum Electron.* **29**, 1 (2023).
- [85] E. Menard, K. J. Lee, D.-Y. Khang, R. G. Nuzzo, and J. A. Rogers, A printable form of silicon for high performance thin film transistors on plastic substrates, *Appl. Phys. Lett.* **84**, 5398 (2004).
- [86] M. A. Meitl, Z.-T. Zhu, V. Kumar, K. J. Lee, X. Feng, Y. Y. Huang, I. Adesida, R. G. Nuzzo, and J. A. Rogers, Transfer printing by kinetic control of adhesion to an elastomeric stamp, *Nat. Mater.* **5**, 33 (2005).
- [87] J. O'Callaghan, R. Loi, E. E. Mura, B. Roycroft, A. J. Trindade, K. Thomas, A. Gocalinska, E. Pelucchi, J. Zhang, G. Roelkens, C. A. Bower, and B. Corbett, Comparison of InGaAs and InAlAs sacrificial layers for release of InP-based devices, *Opt. Mater. Express* **7**, 4408 (2017).
- [88] F. Niklaus, G. Stemme, J. Q. Lu, and R. J. Gutmann, Adhesive wafer bonding, *J. Appl. Phys.* **99**, 031101 (2006).
- [89] R. Loi, J. O'Callaghan, B. Roycroft, C. Robert, A. Fecioru, A. J. Trindade, A. Gocalinska, E. Pelucchi, C. A. Bower, and B. Corbett, Transfer printing of AlGaInAs/InP etched facet lasers to Si Substrates, *IEEE Photonics. J.* **8**, 1 (2016).
- [90] H. H. J. E. Kicken, I. Barbu, J. Gabriels, R. W. van der Heijden, R. Notzel, F. Karouta, H. W. M. Salemink, and E. van der Drift, in *2008 20th International Conference on Indium Phosphide and Related Materials* (IEEE, Versailles, 2008).
- [91] R. Katsumi, Y. Ota, M. Kakuda, S. Iwamoto, and Y. Arakawa, Transfer-printed single-photon sources coupled to wire waveguides, *Optica* **5**, 691 (2018).
- [92] T.-W. Lu, Y.-C. Lin, and P.-T. Lee, Highly accurate docking of a photonic crystal nanolaser to a SiN<sub>x</sub> Waveguide by Transfer Printing, *ACS Photonics* **10**, 2679 (2023).
- [93] M. Mikulicz, T. Smółka, M. Rygała, M. Badura, W. Kijaszek, A. Łozińska, M. Kamp, and M. Motyka, Temperature dependence of refractive indices of InP, GaAs, AlAs, and In<sub>0.53</sub>Ga<sub>0.47</sub>As in the midinfrared spectral range determined by combined ellipsometry and Fourier-transform spectroscopy, *Phys. Rev. Appl.* **21**, 044001 (2024).
- [94] M. Winger, T. Volz, G. Tarel, S. Portolan, A. Badolato, K. J. Hennessy, E. L. Hu, A. Beveratos, J. Finley, V. Savona, and A. Imamoğlu, Explanation of photon correlations in the far-off-resonance optical emission from a quantum-dot-cavity system, *Phys. Rev. Lett.* **103**, 207403 (2009).
- [95] W. H. Wong, E. Y. B. Pun, and K. S. Chan, Er<sup>3+</sup>–Yb<sup>3+</sup> codoped polymeric optical waveguide amplifiers, *Appl. Phys. Lett.* **84**, 176 (2004).

- [96] C. Santori, M. Pelton, G. Solomon, Y. Dale, and Y. Yamamoto, Triggered single photons from a quantum dot, *Phys. Rev. Lett.* **86**, 1502 (2001).
- [97] C. Brunel, B. Lounis, P. Tamarat, and M. Orrit, Triggered source of single photons based on controlled single molecule fluorescence, *Phys. Rev. Lett.* **83**, 2722 (1999).
- [98] R. Brouri, A. Beveratos, J.-P. Poizat, and P. Grangier, Photon antibunching in the fluorescence of individual color centers in diamond, *Opt. Lett.* **25**, 1294 (2000).
- [99] J. S. Neergaard-Nielsen, B. M. Nielsen, H. Takahashi, A. I. Vistnes, and E. S. Polzik, High purity bright single photon source, *Opt. Express* **15**, 7940 (2007).
- [100] A. Predojević, M. Ježek, T. Huber, H. Jayakumar, T. Kauten, G. S. Solomon, R. Filip, and G. Weihs, Efficiency vs multi-photon contribution test for quantum dots, *Opt. Express* **22**, 4789 (2014).
- [101] M. Winger, T. Volz, G. Tarel, S. Portolan, A. Badolati, K. J. Hennessy, E. L. Hu, A. Beveratos, J. Finley, V. Savona, and A. Imamoglu, Explanation of photon correlations in the far-off-resonance optical emission from a quantum-dot-cavity system, *Phys. Rev. Lett.* **103**, 207403 (2009).
- [102] Y. A. Gharbia, G. Milton, and J. Katupitiya, in *Optical Fabrication, Testing, and Metrology*, edited by R. Geyl, D. Rimmer, and L. Wang (SPIE, St. Etienne, France, 2004).
- [103] L. Picelli, A. van Klinken, G. Lindgren, K. D. Hakkel, F. Pagliano, N. Fiaschi, I. Sersic-Vollenbroek, P. J. van Veldhoven, R. W. van der Heijden, and A. Fiore, Scalable wafer-to-fiber transfer method for lab-on-fiber sensing, *Appl. Phys. Lett.* **117**, 151101 (2020).
- [104] P. Vaiano, B. Carotenuto, M. Pisco, A. Ricciardi, G. Quero, M. Consales, A. Crescitelli, E. Esposito, and A. Cusano, Lab on fiber technology for biological sensing applications, *Laser Photonics Rev.* **10**, 922 (2016).
- [105] I. W. Jung, B. Park, J. Provine, R. T. Howe, and O. Solgaard, Highly sensitive monolithic silicon photonic crystal fiber tip sensor for simultaneous measurement of refractive index and temperature, *J. Lightwave Technol.* **29**, 1367 (2011).
- [106] B. Park, I. W. Jung, J. Provine, A. Gellineau, J. Landry, R. T. Howe, and O. Solgaard, Double-layer silicon photonic crystal fiber-tip temperature sensors, *IEEE Photonics Technol. Lett.* **26**, 900 (2014).
- [107] E. J. Smythe, M. D. Dickey, J. Bao, G. M. Whitesides, and F. Capasso, Optical antenna arrays on a fiber facet for in situ surface-enhanced Raman scattering detection, *Nano Lett.* **9**, 1132 (2009).