

Single-photon dynamics of a telecom-band quantum dot emitter integrated with a double solid immersion lens

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Investigating single-photon dynamics is crucial for characterization of single-photon emitters. Here, we demonstrate a telecom-band quantum dot single-photon emitter integrated with a lithographically aligned double solid immersion lens structure, achieving a collection efficiency of 18(3)% at the first lens. Using two-time correlation measurements, we observed re-excitation-induced multiphoton emission arising from a long-lived, carrier-induced capture process under non-resonant excitation. Under quasi-resonant excitation, this effect was strongly suppressed, reducing the multiphoton emission probability within a 3 ns window from 0.052(1) to 0.0163(4). We further performed second-order quantum spectroscopy based on Fourier analysis of the Hong–Ou–Mandel interference, enabling direct extraction of the exciton fine-structure splitting. This work provides a direct characterization of re-excitation dynamics and coherence properties in a telecom-band single-photon emitter. © 2026 Optica Publishing Group under the terms of the Optica Open Access Publishing Agreement

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1. INTRODUCTION

Long-distance quantum communication requires single-photon emitters operating in the telecom band. While nonlinear photon-pair sources such as four-wave mixing [1–3] and spontaneous parametric down-conversion [4–8] generate single photons probabilistically via heralding from correlated photon pairs, semiconductor quantum dots (QDs) enable on-demand, deterministic emission [9]. Their performance has been well established at wavelengths around 780 and 900 nm, where integration with photonic nanostructures has enabled high extraction efficiency [10–13], high single-photon purity [14], and near-unity indistinguishability [12,15]. To date, a photon extraction efficiency as high as 85(3)% has been reported [10], while substantial progress has also been made in improving end-to-end efficiency [12,13]. To extend these advantageous properties to telecom wavelengths, one approach is to apply frequency conversion techniques that shift the emission into the telecom band. While such techniques can preserve the essential quantum optical characteristics, in practice, they incur photon losses of approximately 50% and add background

noise, which significantly limits overall efficiency and scalability [16,17].

A more direct approach is to employ QDs that emit photons directly in the C-band [18,19]. To date, the state-of-the-art collection efficiency from such devices has reached approximately 24% [20]. To realize efficient single-photon emitters, one major challenge lies in device fabrication, particularly for high-Q cavity structures that require precise spectral matching between the cavity mode and the QD emission, as well as accurate spatial alignment of the cavity around the QD [21,22]. In contrast, low-Q structures such as solid immersion lenses (SILs) offer a more fabrication-tolerant alternative [23–25]. These structures provide a practical and scalable platform for single-photon emitter integration [26–28].

Beyond device geometry, understanding the temporal dynamics of single-photon emission is essential for improving the performance of single-photon emitters in practical applications. Although conventional second-order correlation measurements $g_{\text{HBT}}^{(2)}(\tau)$, defined in terms of the time delay between detections $\tau = t_2 - t_1$, are widely used to quantify single-photon statistics,

they are formally valid for continuous wave emission only. For pulsed sources, they reflect time-averaged statistics and offer limited insight into transient processes such as re-excitation. This limitation calls for a more comprehensive approach to resolve these non-stationary dynamics and their impact on single-photon properties [29]. To this end, two-time correlation measurements $g_{\text{HBT}}^{(2)}(t_1, t_2)$ provide a powerful tool, enabling time-resolved characterization of the emission process in this non-stationary regime [29,30].

In addition to emission dynamics, accessing intrinsic coherence properties is important for optimizing single-photon emitters. For nearly degenerate states, conventional first-order spectroscopy is often limited by inhomogeneous broadening and temporal averaging, which obscure the tiny energy difference. An alternative spectroscopic approach that can access coherence properties beyond these limitations is therefore desirable.

We demonstrate a telecom-band single-photon emitter based on an InAs/InP QD integrated with a double SIL structure on top of a distributed Bragg reflector (DBR) to enhance photon extraction. The lithographically aligned InP and polymer SILs form a monolithic optical platform, achieving a collection efficiency of 18(3)% within a numerical aperture (NA) of 0.9 (number in parentheses is the uncertainty of one standard deviation).

We report the first demonstration of time-resolved characterization of re-excitation dynamics in a telecom-band QD emitter using two-time auto-correlation analysis, providing direct insight into carrier re-capture processes. Under non-resonant (NR) excitation, re-excitation arises from long-lived carrier capture during radiative decay, whereas it is effectively suppressed under quasi-resonant (QR) excitation. By considering two-time correlation measurements $g_{\text{HBT}}^{(2)}(t_1, t_2)$, we directly observe this underlying process and also find the range of times after the excitation when the emission is optimally single-photon-like. In particular, we see that within the first 3 ns after the initial excitation, the multiphoton emission probability decreases from 0.052(1) under NR excitation to 0.0163(4) under QR excitation. Furthermore, we perform second-order spectroscopy by applying Fourier analysis to the Hong–Ou–Mandel (HOM) interference, enabling direct extraction of the exciton fine-structure splitting (FSS) while suppressing slow environmental fluctuations through successive photon emissions. These results establish a practical and scalable platform for efficient single-photon generation in the telecom band, applicable to long-distance quantum communication and scalable quantum networks.

2. SAMPLE STRUCTURE

The QD wafer was grown by molecular beam epitaxy (MBE) on an InP/Fe substrate. After the growth of an InP buffer layer, 25 pairs of $\lambda/4$ -thick InP/InGaAlAs layers were grown to form a distributed Bragg reflector (DBR) with a design wavelength of 1550 nm. InAs QDs were grown on top of the DBR structure and embedded between InP layers. The nominal thicknesses of the InP spacer between the DBR and the QD layer and the InP capping layer above the QDs are 280 and 795 nm, respectively. Further details on the sample structure can be found in [31].

To enhance photon extraction from the QDs, a double-SIL structure was integrated above the QD layer. The double-SIL structure comprises an InP bottom SIL and a polymer

top SIL, which were fabricated and aligned through a two-step lithographic process. To fabricate the InP SIL, a circular negative-tone photoresist etch mask with a diameter of 2 μm and a thickness of 300 nm was patterned on the surface of the InP capping layer using a two-photon absorption (TPA) lithography process [24,32]. The patterned sample was etched down to the QD layer using an isotropic wet etchant composed of $\text{HCl}:\text{HBr}:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ (5:10:2:5). Due to the isotropic nature of the etching process, a rounded undercut was formed beneath the mask, while a sharp-edged tip remained at the apex of the etched InP SIL. After the etching process, the photoresist masks were removed using acetone and rinsed with isopropyl alcohol. After removal of the photoresist masks, a short additional isotropic etching step was performed without a mask to smooth the apex using an etchant with a reduced H_2O_2 concentration, resulting in a slower etch rate. The additional etch step effectively smoothed the apex, resulting in a near-Gaussian lens profile with minimal change in the overall height.

On top of the InP SIL, a second SIL was fabricated to form a double-SIL structure. The sample was coated with photoresist to a thickness of 2 μm . Using the TPA lithography process, the InP SIL was selectively exposed and developed to form a negative photoresist pattern on it. A subsequent thermal reflow process transformed the pattern into a hemispherical shape [24], resulting in a lithographically aligned double-SIL structure. The base diameters of both the InP and polymer SILs can be controlled by adjusting the diameter of the photoresist pattern.

The addition of the second SIL reduces the refractive-index contrast between InP and air by introducing an intermediate-index polymer layer, thereby increasing the critical angle for total internal reflection and reducing Fresnel reflection compared with a direct InP–air interface [33]. In addition, the smoothly curved polymer–air interface allows a larger fraction of the outward-propagating light to reach the surface at smaller local incidence angles than at a planar interface, thereby mitigating total internal reflection and facilitating outcoupling into air.

Figure 1(a) shows a scanning electron microscope image of the fabricated InP SIL structure. The InP SIL exhibits a Gaussian-like lens profile resulting from the wet-etching process. By etching the InP down to the QD layer, the height of the InP SIL approximately matched the thickness of the InP capping layer. Consequently, only QDs beneath the InP SIL remained intact, whereas those outside the InP SIL were either removed or became optically inactive. Figure 1(b) shows a scanning electron microscope image of the polymer SIL structure formed on top of the InP SIL, exhibiting a smooth hemispherical profile. The fabricated InP SIL has a base diameter of $\approx 1.8 \mu\text{m}$ and a height of $\approx 800 \text{ nm}$, while the polymer SIL has a base diameter of $\approx 3.5 \mu\text{m}$ and a height of $\approx 2 \mu\text{m}$. The polymer SIL enhances the photoluminescence (PL) intensity of the QD by a factor of approximately 1.75 (see Supplement 1) and also serves as a passivation layer for the underlying structure [24].

To design the double-SIL structure for operation in the near telecom C-band, we performed finite-difference time-domain (FDTD) simulations. The InP SIL was modeled with a Gaussian-shaped profile, with a bottom diameter of 1.8 μm and a height of 795 nm. The second polymer SIL was modeled as a hemi-elliptical structure with a base diameter of 3.5 μm , a height of 2 μm , and a refractive index of 1.6. A linearly polarized in-plane electric dipole source was located laterally at the center and vertically at the base plane of the Gaussian InP SIL, corresponding to the QD layer.

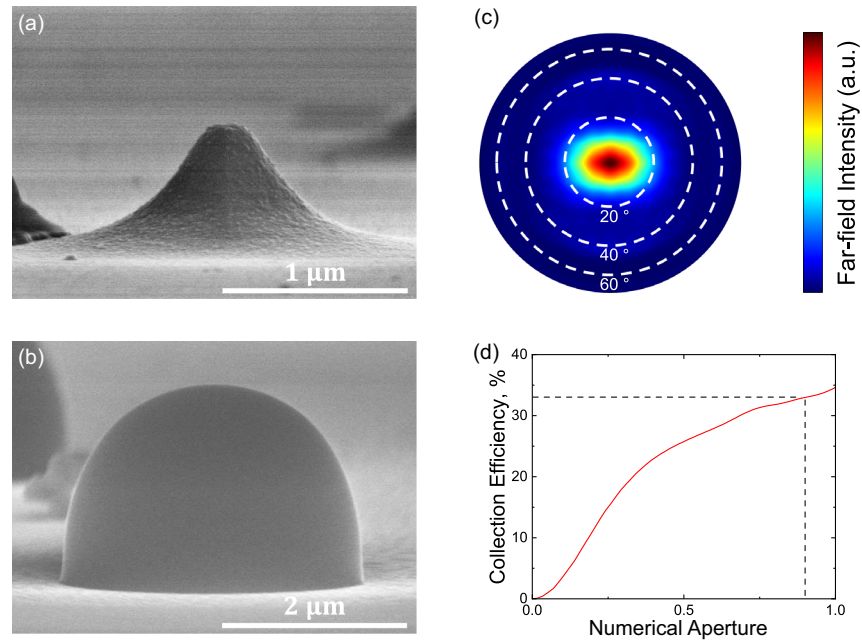


Fig. 1. Scanning electron microscope images of the fabricated (a) InP SIL structure and (b) polymer SIL structure. (c) Simulated far-field intensity distribution of the double SIL configuration. (d) Calculated collection efficiency at the emission wavelength as a function of the radiation half-angle.

Beneath the QD layer, a $\lambda/2$ -thick InP spacer and 25 pairs of $\lambda/4$ -thick InP/InGaAlAs layers (designed for a central wavelength of 1550 nm) were included in the simulation.

In Fig. 1(c), we present the calculated far-field intensity distribution at the emission wavelength of 1500 nm. The slight asymmetry in the far-field distribution originates from the anisotropic radiation pattern of the linearly polarized in-plane dipole source used in the simulation. The distribution shows that most of the radiation from the source is confined to small emission angles due to the enhanced directionality enabled by the double-SIL structure. Figure 1(d) shows the calculated collection efficiency as a function of NA. In the experiment, we used $NA = 0.9$ as

highlighted by a black dashed line. The expected collection efficiency of the structure under this condition is 33%.

3. OPTICAL EXPERIMENTAL SETUP

Figure 2 shows the experimental setup for the optical measurement. A supercontinuum pulsed laser with a repetition rate of 80 MHz was used as the excitation source. The laser light was spectrally filtered using a single diffraction grating, coupled into a single-mode fiber (SMF) and delivered to the cryostat. A dichroic mirror (DM) was used to separate the excitation and collection paths, reflecting the excitation beam while transmitting the QD

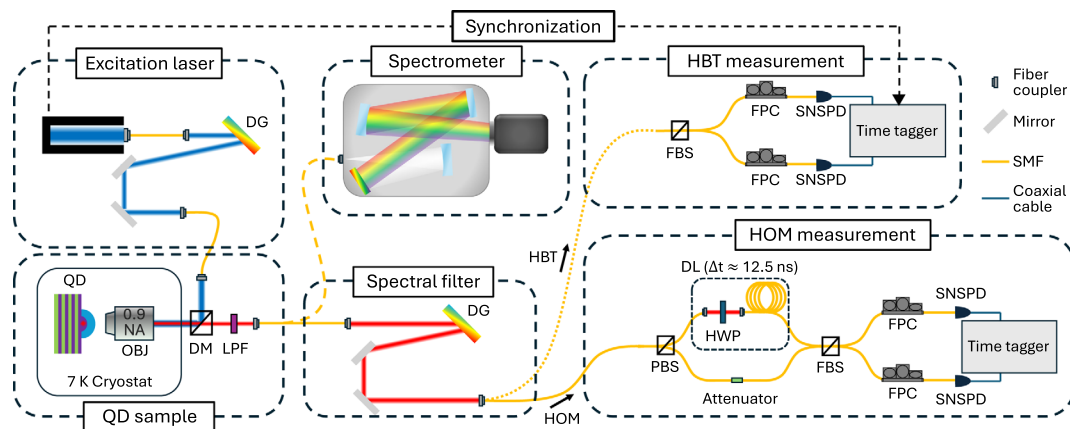


Fig. 2. Schematic of the experimental setup used for optical characterization of the QD double-SIL device. A spectrally filtered supercontinuum pulsed laser excites the QD. Emission from the QD is collected by an objective lens (OBJ), transmitted through a dichroic mirror (DM) and a long-pass filter (LPF), coupled into a single-mode fiber (SMF), and directed to either a spectrometer for spectral analysis or to a diffraction grating (DG) setup for spectral filtering. For photon-correlation measurements, the filtered signal is coupled into a fiber-based Hanbury-Brown-Twiss (HBT) or Hong-Ou-Mandel (HOM) interferometer, incorporating superconducting nanowire single-photon detectors (SNSPDs) and a time tagger. The HBT setup employs a non-polarizing fiber beam splitter (FBS), whereas the HOM setup includes both a polarizing beam splitter (PBS) and an FBS. In the HOM setup, a variable delay line (DL) introduces an optical delay of one laser repetition period (12.5 ns) in one arm, while a half-wave plate (HWP) is used to prepare orthogonal polarization states. Fiber polarization controllers (FPCs) are used to optimize the polarization of the input photons at the SNSPDs.

emission. After passing through a long-pass filter with a cut-on wavelength of 1500 nm, the QD emission was coupled into an SMF. For spectral characterization, the collected emission was directed to a spectrometer equipped with an InGaAs array detector.

For single-photon measurements, the emission was spectrally filtered by a ruled reflection grating combined with an SMF, providing an effective filtering bandwidth of approximately 1 nm. In HBT measurements, the filtered emission was split by a 45:55 beam splitter (BS), and each output was connected to a superconducting nanowire single-photon detector (SNSPD). To perform two-time correlation measurements, the detection times were collected using a time tagger synchronized with the excitation pulse. The arrival times of the photons were recorded over multiple pulses, and the two-dimensional correlation maps were reconstructed in post-processing.

For the HOM measurement, the filtered emission was sent to a polarization beam splitter (PBS). The PBS was used to divide the photon stream into two arms. One arm passed through a free-space delay line equipped with a half-wave plate to prepare orthogonal polarization states. The delay line was finely tuned using a manual translation stage with 3 ps resolution to match the pulse period of the excitation laser (12.5 ns). The other arm was attenuated using a fiber-based variable attenuator to balance the intensities of the two arms. The two arms were then recombined at a 45:55 FBS for interference.

4. RESULTS

A. Device Performance

Figure 3(a) shows the QD spectrum measured under QR excitation. An excitation wavelength of 1381 nm was used, resulting in a strong exciton peak at 1502.95 nm. The corresponding 71 meV detuning between the excitation and emission energies is well above the typical LO-phonon energy of InP (43 meV) [34] and is therefore assigned to p-shell excitation. The exciton emission line was spectrally selected using the grating filter for HBT and HOM measurements.

Figure 3(b) shows the detected single-photon count rate and the collection efficiency under NR and QR excitation. For the NR measurement, a 1270 nm laser was used to excite carriers into the continuum states above the QD energy levels but below the InP bandgap. In this measurement, the filtered emission was directly detected by a single SNSPD. The device reached saturation at an excitation power of 2 nW, with a count rate of 182,900(100) s⁻¹.

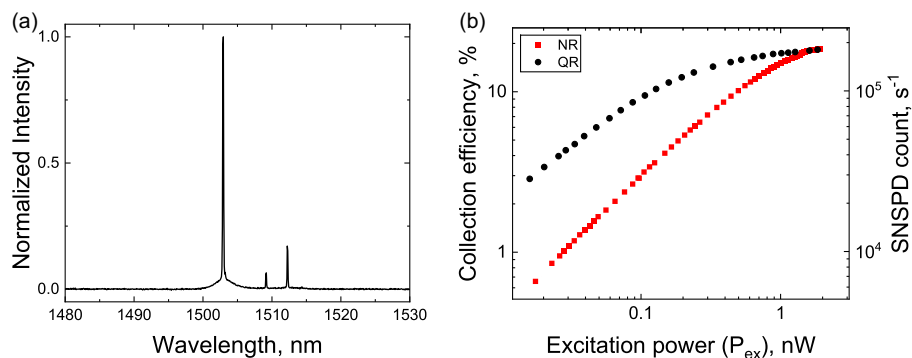


Fig. 3. (a) Measured photoluminescence spectrum of the QD double-SIL device under quasi-resonant (QR) excitation, showing a prominent exciton peak at 1502.95 nm. (b) Detected single-photon count rate and the corresponding collection efficiency at the first lens as a function of excitation power (P_{ex}) under non-resonant (NR) and QR excitation.

After accounting for the total optical transmission of the setup, detector quantum efficiency, and the laser repetition rate, we estimate a collection efficiency of 18(3)% at the first lens (see Table S1 of Supplement 1). The QD exhibited the same saturated count rate under NR and QR excitation within the relative uncertainty of the setup-transmission calibration.

The measured collection efficiency is lower than the simulated value of 33%. This discrepancy is primarily attributed to the non-deterministic fabrication process, which may result in lateral misalignment of the QD with respect to the optical axis of the lens structure, thereby reducing the effective coupling into the collection optics. This misalignment could be mitigated by employing deterministic QD positioning techniques optimized for telecom wavelengths [35]. Additionally, because the collection efficiency includes only the zero-phonon line transmitted through the approximately 1 nm spectral filter, the measured value represents a conservative lower bound due to the exclusion of phonon sideband emission (see Supplement 1).

Figure 4(a) shows the second-order auto-correlation measurement at the saturation power under NR excitation. Under both excitation schemes, the HBT histograms ($g_{HBT}^{(2)}(\tau)$) exhibit clear antibunching at zero delay between detection times at two detectors ($\tau = t_2 - t_1 = 0$), confirming that the QD operates as a single-photon emitter. Under NR excitation, however, a weak two-photon feature near zero delay is observed, which is attributed to re-excitation dynamics. Under QR excitation, this feature is significantly suppressed, as shown in Fig. 4(b).

Under NR excitation, carriers are generated in high-energy continuum states and subsequently relax before being captured by the QD. After radiative recombination, residual carriers may still be captured by the QD, resulting in a second photon emission within the same excitation cycle. In contrast, under QR excitation, most carriers are directly injected into higher-energy QD states, effectively suppressing the re-excitation process. We point out that the dip at $\tau = 0$ within the central peak, shown in Fig. 4(a), indicates this single-photon emission dynamics and can be viewed as an analog of the antibunching dip in CW measurements (c.f. Ref. [36]). We expect a different dynamic for QR excitation, Fig. 4(b), due to the lack of free excitation carriers, resulting in the nearly total suppression of the weak bunching feature near $\tau = 0$.

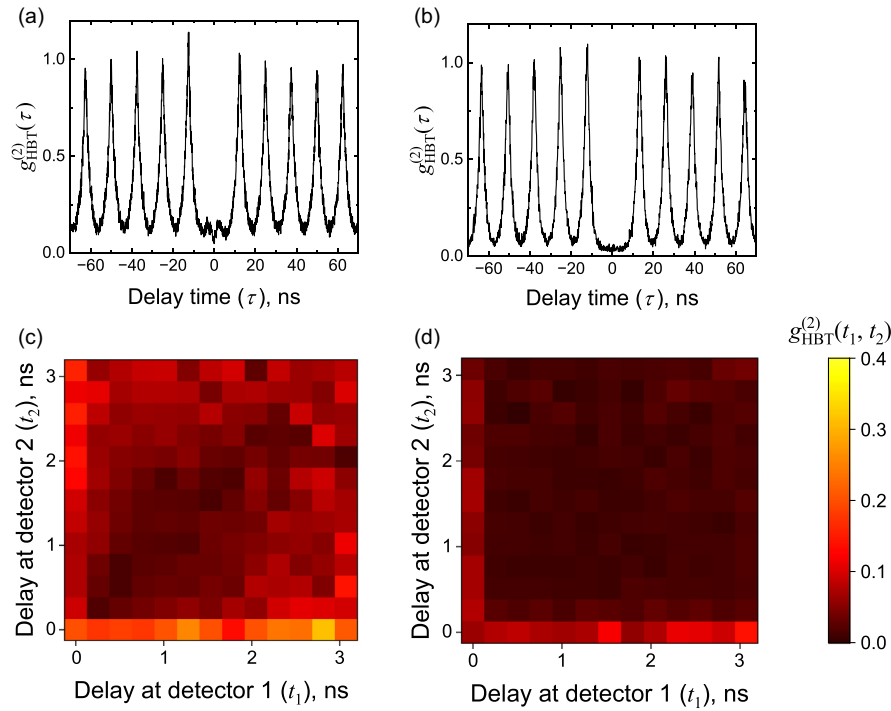


Fig. 4. Second-order correlation measurements $g_{\text{HBT}}^{(2)}(\tau)$ of the filtered emission line under (a) NR and (b) QR excitation. Both curves show antibunching behavior at zero delay time. Under NR excitation, a weak bunching near zero delay time is observed. (c) and (d) show normalized two-time second-order correlation maps $g_{\text{HBT}}^{(2)}(t_1, t_2)$ under NR and QR excitation, respectively. In (c), off-diagonal features reveal the temporal signature of re-excitation-induced multiphoton events, which are strongly suppressed in (d) under QR excitation.

B. Two-Time Correlation Analysis of Re-Excitation Dynamics

The antibunching behavior is clearly visualized in the two-time auto-correlation maps shown in Fig. 4(c) for NR excitation and Fig. 4(d) for QR excitation. In these measurements, t_1 and t_2 represent the photon arrival times recorded by the two SNSPDs measured with respect to the nearest laser pulse. If only time difference $\tau = t_2 - t_1$ is considered, corresponding to the x axis of the one-dimensional HBT histograms in Figs. 4(a) and 4(b), an additional integration of $g_{\text{HBT}}^{(2)}(t_1, t_2)$ is implicitly performed along diagonals $t_2 - t_1 = \text{const}$, which significantly obstructs the analysis of single-photon emission dynamics [29].

The two-time auto-correlation maps were obtained by normalizing the intra-pulse coincidence histogram, $G_{[0]}^{(2)}(t_1, t_2)$, using the average of the inter-pulse coincidence histograms, $\langle G_{[i]}^{(2)}(t_1, t_2) \rangle$, averaged over multiple pulse delays $i \neq 0$ to improve statistical accuracy:

$$g_{\text{HBT}}^{(2)}(t_1, t_2) = \frac{G_{[0]}^{(2)}(t_1, t_2)}{\langle G_{[i]}^{(2)}(t_1, t_2) \rangle}. \quad (1)$$

In the both two-time auto-correlation maps, the diagonal terms, where $t_1 \approx t_2$, exhibit low $g_{\text{HBT}}^{(2)}(t_1, t_2)$ values, consistent with the zero-delay antibunching ($g_{\text{HBT}}^{(2)}(0)$) observed in the one-dimensional HBT analysis in Figs. 4(a) and 4(b). However, under NR excitation, an increase in $g_{\text{HBT}}^{(2)}(t_1, t_2)$ is observed at off-diagonal times, particularly near $t_1 \approx 0$ or $t_2 \approx 0$, where one photon is detected early in the decay process and the other is emitted later. Furthermore, elevated off-diagonal $g_{\text{HBT}}^{(2)}(t_1, t_2)$ values at

$t_1 > 0$ or $t_2 > 0$ suggest that even when the first photon is generated later in the decay process, a second photon can still be emitted via carrier recapture. These observations indicate that secondary photon emission can still occur within the same excitation cycle.

This behavior is attributed to long-lived carriers in the reservoir states, whose population persists over the QD emission timescale. The long-lived carriers are re-captured into the QD, leading to subsequent photon emission observed by an increase of $g_{\text{HBT}}^{(2)}(t_1, t_2)$. Counterintuitively, $g_{\text{HBT}}^{(2)}(t_1, t_2)$ grows at longer times, especially in the NR excitation process. This growth happens because even though the overall rate of photons emitted by the dot and the number of reservoir carriers decrease exponentially with time, decay constants are different.

To quantify this effect, we employed rate-equation simulations that incorporate reservoir-mediated recapture processes (see Supplement 1). Under NR excitation, multiple reservoir and trap states may exist in the vicinity of the QD. To simplify the model, the reservoir and trap states were approximated as two effective states with different decay rates. Carriers in these states can be captured into the QD, leading to subsequent photon emission within the same excitation cycle.

From the fit to the experimental two-time auto-correlation map, we obtain fast and slow decay rates for the effective reservoir states. A fast decay component with a decay rate of 5.4(2) GHz dominates the early-time excitation dynamics immediately after the optical pulse, consistent with rapid carrier relaxation and capture from higher-energy reservoir or continuum-like states. In contrast, the slow decay component exhibits a decay rate of 0.5(1) GHz, which is comparable to, and possibly slightly lower than, the QD radiative decay rate of 0.67(1) GHz. This slow decay

component gives rise to delayed carrier recapture and re-excitation within the same excitation cycle.

In contrast, under QR excitation, $g_{\text{HBT}}^{(2)}(t_1, t_2)$ is nearly uniform and close to zero across the entire emission cycle. This strongly supports that the carrier re-capture process is effectively suppressed under QR excitation. A slight increase of $g_{\text{HBT}}^{(2)}(t_1, t_2)$ is observed in regions where $t_1 \approx 0$ or $t_2 \approx 0$, but the values remain below 0.14.

The use of the two-time correlation functions $g_{\text{HBT}}^{(2)}(t_1, t_2)$, instead of the time-delay auto-correlation function ($g_{\text{HBT}}^{(2)}(\tau)$), enables time-resolved quantification of the multiphoton emission probability within a selected time window. We quantified the multiphoton emission probability by integrating $G_{[i]}^{(2)}(t_1, t_2)$ over the region $t_1, t_2 \in (0, 3 \text{ ns})$, which contains most emission events given the measured radiative lifetime of approximately 1.5 ns. The integrated intra-pulse coincidences ($\sum G_{[0]}^{(2)}$) were normalized by the average of the integrated inter-pulse coincidences ($\sum \langle G_{[i]}^{(2)} \rangle$), yielding the multiphoton emission measurement within the window ($g_{\text{HBT}, 3 \text{ ns}}^{(2)}$):

$$g_{\text{HBT}, 3 \text{ ns}}^{(2)} = \frac{\sum G_{[0]}^{(2)}}{\sum \langle G_{[i]}^{(2)} \rangle}. \quad (2)$$

From the raw two-time correlation maps presented in Fig. S4 of Supplement 1, we extract $g_{\text{HBT}, 3 \text{ ns}}^{(2)} = 0.052(1)$ under NR excitation and 0.0163(4) under QR excitation. These results indicate that re-excitation-induced multiphoton emission is strongly suppressed under QR excitation. Furthermore, the analysis of the 2D window enables us to choose the interval of time, starting deterministically from the excitation moment, during which the dot generates a high number of single photons with higher purity. Although not done here, light can be optically blocked at later times, e.g., using an EOM [37,38].

C. HOM-Based Fourier Analysis of Exciton Fine-Structure Splitting

To characterize the indistinguishability and coherence properties of the source, we performed HOM interference measurements. HOM measurements provide access to temporal coherence and phase evolution that cannot be resolved by first-order spectroscopy. We performed second-order spectroscopy by applying Fourier analysis to the HOM interference between successively emitted single-photon pulses. This approach overcomes the limitations

of conventional first-order spectroscopy, which are intrinsically constrained by inhomogeneous broadening induced by slow environmental fluctuations [39].

In this measurement, the filtered exciton emission was used as the input without polarization alignment. The exciton consists of two orthogonal states, $|E_H\rangle$ and $|E_V\rangle$, separated by an FSS energy, $\Delta E_{\text{FSS}} = E_H - E_V$. The emission was directed to the PBS, which divided it into two optical paths, each containing a superposition of the fine-structure-split energy states. These two paths served as the input modes of the BS, given by

$$\psi_1 = \sqrt{1-B}|E_H\rangle + e^{-i\Delta E_{\text{FSS}}\tau/\hbar}\sqrt{B}|E_V\rangle, \quad (3)$$

$$\psi_2 = \sqrt{B}|E_H\rangle + e^{-i\Delta E_{\text{FSS}}\tau/\hbar}\sqrt{1-B}|E_V\rangle, \quad (4)$$

where B represents the relative population of the two energy states.

The HOM interference as a function of the delay time (τ) is described in Ref. [39]. Because our measurement uses consecutively emitted photon pairs that are subject to similar environmental fluctuations, the contribution from inhomogeneous broadening becomes negligible in this measurement. The resulting interference function is given by

$$g_{\text{HOM}, \parallel}^{(2)}(\tau) = A[e^{-|\tau|/T_1} - e^{-\gamma|\tau|}[(1-B) + B \cos(\Delta E_{\text{FSS}}\tau/\hbar)]] + G_0, \quad (5)$$

where A is the normalized amplitude, G_0 is multiphoton probability, and T_1 is the measured radiative lifetime (1.53(1) ns). The total dephasing rate is given by $\gamma = 1/T_1 + 2\Gamma^*$, which includes the pure dephasing rate Γ^* . The model assumes an ideal 50:50 beam splitter. B determines the modulation depth of the quantum beat arising from the interference between the two non-degenerate exciton states.

Figure 5(a) shows the normalized coincidence histograms for co-polarized (red) and cross-polarized (black) photons. The periodic pulses are separated by the laser repetition period of 12.5 ns over 13 pulse cycles. Figures 5(b) and 5(c) show magnified views of the central pulse near zero delay for the photons that are co-polarized and cross-polarized on a non-polarizing beam splitter (indicated as the FBS in the HOM measurement section of Fig. 2), respectively.

In Fig. 5(b), a clear HOM dip is observed for co-polarized photons, along with oscillatory beating arising from the exciton FSS. This oscillation reflects the coherent phase evolution between the two fine-structure-split states. Through second-order spectroscopic analysis, as shown in Fig. 5(d), the beating frequency

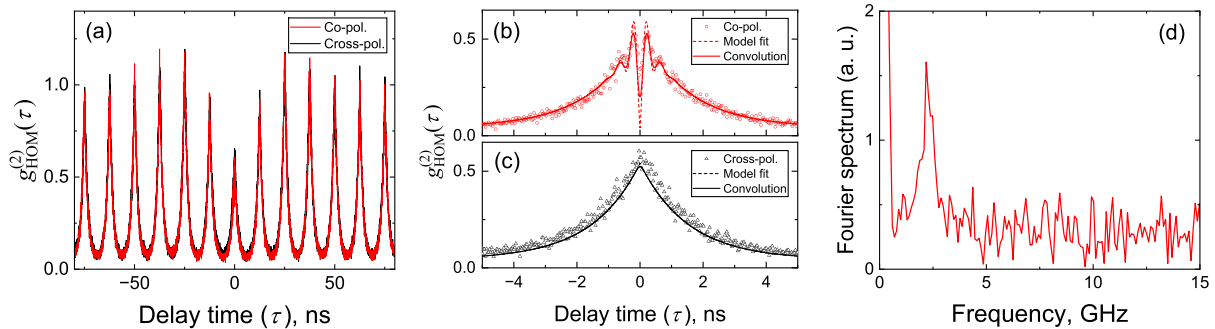


Fig. 5. HOM interference measurement under QR excitation. (a) Measured coincidence histogram over 13 pulse periods. Zoomed-in view of the measured data for (b) co-polarization (red circles) and (c) cross-polarization (black triangles), along with the fitted model curves near zero delay. The dashed and solid lines represent the theoretical model and its convolution with the instrument response function, respectively. (d) Fourier transform of the co-polarized interference in (b), revealing the FSS beating frequency.

becomes directly visible as a spectral peak at 2.26(2) GHz, corresponding to an exciton FSS of 9.35 μeV . Because this method relies on temporal correlations between successive single-photon pulses separated by 12.5 ns, it is inherently insensitive to slow drifts or long-term instabilities caused by environmental fluctuations such as charge noise.

To enable quantitative analysis, the HOM histogram of the co-polarized photons was fitted using Eq. (5). From the fit, the extracted parameters are $A = 0.498(9)$, $B = 0.77(4)$, $G_0 = 0.041(1)$, and $\gamma = 4.3(4)$ GHz, corresponding to a pure dephasing time $1/\Gamma^*$ of 550(40) ps. Using the measured exciton lifetime (T_1) and the extracted pure-dephasing rate (Γ^*), we obtain a coherence time $T_2 = [1/(2T_1) + \Gamma^*]^{-1} = 470(40)$ ps. The uncertainty of each fit parameter represents the standard error obtained from the weighted least-squares fit. G_0 is slightly elevated compared to the multiphoton probability obtained above, owing to background photon noise. Due to the timing jitter of our detection system, arising predominantly from the two SNSPDs, the expected features of the model are not fully resolved in our measurement. Therefore, we convoluted the theoretical model with the system response using a root-mean-square (RMS) timing jitter of approximately 64 ps, as shown by the solid curve in Fig. 5(b). For the cross-polarized photons, the interference term in Eq. (5) was removed, and the normalized histogram was fitted using the same parameters A and G_0 , as shown in Fig. 5(c). The full expression used for the cross-polarized fit is provided in Supplement 1.

To quantify the degree of photon indistinguishability, we calculated coalescence, defined as $\mathcal{C} = 1 - g_{\text{HOM}, \parallel}^{(2)}/g_{\text{HOM}, \perp}^{(2)}$ [40]. Using this expression with the values at $\tau = 0$, we obtain a measured post-selected coalescence of 0.48(9). To investigate the origin of this imperfect coalescence, we compare the experimental value with a theoretical model. The model yields a post-selected coalescence of 0.92(5) in the absence of the timing jitter, where the deviation from unity is attributed to the multiphoton probability and the background photon noise. When the RMS timing jitter is taken into account, the post-selected coalescence of the model is reduced to 0.61(3) because the FSS beating period is comparable to the timing jitter. The remaining discrepancy can be attributed to a combination of factors, including a slightly unbalanced beam splitter (45:55), minor polarization mismatch, and incoherent emission from the phonon sideband. We note that it is possible

to measure both $g_{\text{HOM}}^{(2)}$ and $g_{\text{HBT}}^{(2)}$ simultaneously, by employing photon number resolving detection in the HOM setup. A typical modification of the experiment is the use of four single-photon detectors—two at each HOM output. This method can therefore enable lower statistical uncertainty at the cost of increased experimental complexity [41].

As discussed above, the existing FSS together with the finite timing jitter of the detection system limits the coalescence in our two-photon interference measurements. For applications that require highly indistinguishable single photons, it is desirable to use a single exciton eigenstate or a transition that is intrinsically degenerate, such as a charged exciton state. Further enhancement of photon indistinguishability requires suppression of dephasing in the QD. One effective strategy is to stabilize the local charge environment using electrostatic gating, such as PIN diode structures, which reduce charge-noise-induced decoherence [42]. In addition, coherent excitation schemes including resonant excitation [14,15,43] or two-color excitation schemes [44,45] such as the swing-up of quantum emitter population (SUPER) [46,47] can mitigate dephasing during the relaxation process and suppress phonon-mediated broadening. These approaches improve the $T_2/(2T_1)$ ratio, thereby enhancing photon indistinguishability in both post-selected and non-post-selected regimes.

Table 1 compares the key device characteristics and performance metrics of the present work with those reported for representative quantum-dot single-photon sources operating near the telecom C-band. We note that the coalescence values shown in Table 1 are non-post-selected. For the present work, the coalescence value was estimated using the coherence-limited indistinguishability of the emitted photons ($T_2/(2T_1)$), to exclude the effect of FSS-induced oscillations.

5. SUMMARY AND CONCLUSION

We demonstrated a telecom-band single-photon source based on an InAs/InP QD integrated with a double-SIL structure on a DBR substrate, which enables precise characterization of emission dynamics and coherence. The broadband, lithographically aligned semiconductor-polymer SIL configuration was fabricated using simple wet etching and photolithography, without relying on high-precision tools such as e-beam lithography or dry etching. This

Table 1. Comparison of Key Characterization Metrics for Representative Quantum-Dot Single-Photon Sources Operating near the Telecom C-Band

Ref.	QD Type	Structure	FSS (μeV)	Collection Efficiency (%)	$g_{\text{HBT}}^{(2)}(0)$	Coalescence	T_1 (ns)	T_2 (ns)
[48]	InAs/InP	Mesa	—	13.3(20) (NA = 0.40)	0.000(83)	—	1.2–1.3	—
[49]	InAs/InGaAs (MMB)	Planar	N/A (CX)	—	0.023(19)	0.144(15)	1.01(1)	—
[50]	InAs/InGaAs (MMB)	CBG	N/A (CX)	17.4(9) (NA = 0.60)	0.0052(1)	0.081(338)	≈ 0.52	—
[51]	InAs/InP	Mesa	88(2)	—	0.005(4)	0.35(3)	0.34(3)	0.15(5)
[20]	InAs/InP	CBG	—	≈ 24 (NA = 0.65)	0.078(16)	$\approx 0.08^d$	0.775(1)	—
[35]	InAs/InP	CBG	N/A (CX)	16.6(27) (NA = 0.40)	0.0032(6)	0.193(26)	0.53(1)	0.176(9)
[52]	InAs/InAlGaAs	CBG	22.9(1)	—	0.0307(4)	0.719(2)	0.2575(2)	0.381(22)
[53]	InAs/InAlGaAs	CBG	N/A (CX)	—	0.017(1)	0.917(2)	—	—
This work	InAs/InP	Double SIL	9.35 (8)	18(3) (NA = 0.90)	0.0163(4)	0.15(1)	1.53(1)	0.47(4)

^dEstimated from [20] for a 4 ns time bin. MMB, metamorphic buffer; CBG, circular Bragg grating; CX, charged-exciton transition; N/A, not applicable.

fabrication approach provides a practical route toward scalable solid-state single-photon emitters. Experimentally, the double-SIL structure yields a collection efficiency of 18(3)% at the first lens.

To investigate photon emission dynamics, we employed two-time correlation measurements, which revealed that a long-lived, carrier-induced capture process leads to re-excitation and subsequent multiphoton emission under NR excitation, whereas such re-excitation is strongly suppressed under QR excitation. As a result, the multiphoton emission probability within a 3 ns window immediately following the excitation ($g_{\text{HBT}, 3 \text{ ns}}^{(2)}$) was reduced from 0.052(1) under NR excitation to 0.0163(4) under QR excitation, indicating more than a threefold improvement over the emission cycle.

Furthermore, we performed HOM interference measurements to characterize the coherence properties of the source. Fourier analysis of the HOM interference enables second-order spectroscopy that resolves the exciton fine-structure splitting beyond the inhomogeneous-broadening limit. This method allows characterization of μeV -level FSS without requiring a high-resolution spectrometer or Fabry–Perot interferometer.

These results highlight the critical role of excitation control in mitigating re-excitation dynamics in telecom-band QDs. Two-time correlation analysis provides direct access to transient multiphoton processes, while HOM-based second-order spectroscopy reveals coherence properties and an intrinsic excitonic structure. Combined with efficient photon extraction, this platform offers a scalable and fiber-compatible solution for advancing quantum networks and integrated photonic technologies.

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Data availability. The experimental datasets of the two-time correlation maps will be available at NIST Data Repository in Ref. [54].

Supplemental document. See Supplement 1 for supporting content.

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