NANO LETTERS

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Letter

Gigahertz-Clocked Generation of Highly Indistinguishable Photons at C-Band Wavelengths

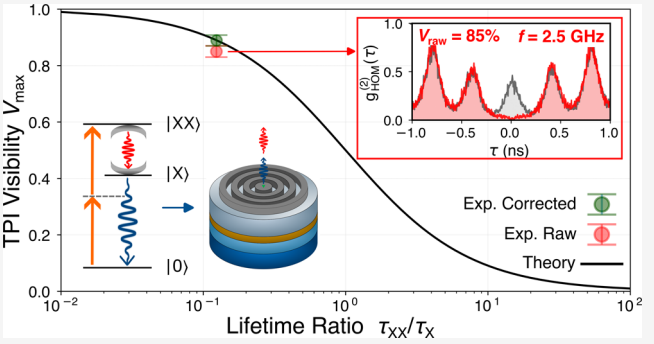
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Cite This: https://doi.org/10.1021/acs.nanolett.6c01800

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ABSTRACT: High-performance single-photon sources at telecom C-band wavelengths are key building blocks for applications in long-distance quantum communication. Here, we report the generation of highly indistinguishable single photons at a clock rate of 2.5 GHz. This is achieved by coherently driving the biexciton transition ($T_1^{XX} = 64(1)$ps) of a semiconductor quantum dot embedded in a microcavity with strong asymmetric Purcell enhancement. Employing pulsed two-photon resonant excitation, strong multiphoton suppression with $g^{(2)}(0) < 4\%$ and high two-photon-interference visibility of $V_{raw} > 85\%$ are observed. The observed photon indistinguishability is close to the theoretical limit expected for the photonically engineered radiative cascade and matches values obtained at lower repetition rates. Our results show a substantial advancement toward interference-based quantum information protocols at unprecedented data rates in the telecom C-band.



KEYWORDS: *single-photon source, quantum dot, purcell enhancement, telecom C-band, two-photon interference*

Semiconductor quantum dots (QDs)[1,2] are at the forefront of solid-state based platforms for state-of-the-art quantum light sources in terms of multiphoton suppression,[3] two-photon indistinguishability[4] and end-to-end efficiency.[5,6] While all of these benchmarks were achieved at near-infrared wavelengths below 1 μm, improvements in QD growth over the past decade yielded single photon emission at telecom C-band wavelengths.[7−11] This is highly desirable for long haul applications requiring lowest attenuation in existing deployed fiber backbones.[12]

A particular challenge for C-band emitting QDs was the generation of indistinguishable photons for InAs/GaAs QDs with metamorphic buffers,[13,14] and InAs/InP QDs,[15] which has recently been overcome by optimized growth in the InAs/InGaAlAs/InP material system in combination with Purcell enhancement.[16,17] Using these devices, two-photon interference (TPI) visibilities of ∼90% have been reported very recently, employing coherent LA-phonon assisted excitation[18] and two-photon resonant excitation (TPE)[19] at standard excitation repetition rates of 80 and 100 MHz, respectively. At shorter wavelengths, on the other hand, first quantum optical studies have been conducted at clock rates of ≥1 GHz,[20,21] using intrinsically fast decaying GaAs/AlGaAs QDs at ∼780 nm[22] and strongly Purcell-enhanced InAs/GaAs QDs at ∼920 nm,[23,24] both reporting high photon indistinguishabilities in that spectral range. Such high-clock-rate experiments, which have been elusive in the telecom wavelength range until now, become crucial for advancing the field toward applications in high-performance quantum networks.

In this work, we report the GHz-clocked generation of single photons with high photon indistinguishability in the telecom C-band using a Purcell-enhanced QD with strong asymmetric Purcell enhancement. Using TPE at a clock rate of 2.5 GHz, we observe multiphoton suppression of <4%, with raw TPI visibilities of >85%, paving the way for fiber-compatible interference-based quantum information protocols at unprecedented rates.

The InAs/$In_{0.53}Al_{0.23}Ga_{0.24}As$/InP QD used in this work is grown by molecular-beam epitaxy and integrated in a hybrid circular Bragg grating resonator. More information on sample growth and device fabrication can be found in refs 16 and 25. To enable GHz clock speed in our experiments, two ingredients are essential: first, a QD excitonic state with sufficiently fast emission decay time and, second, a high-

Received: April 16, 2026
Revised: September 30, 2026
Accepted: September 30, 2026

ACS Publications
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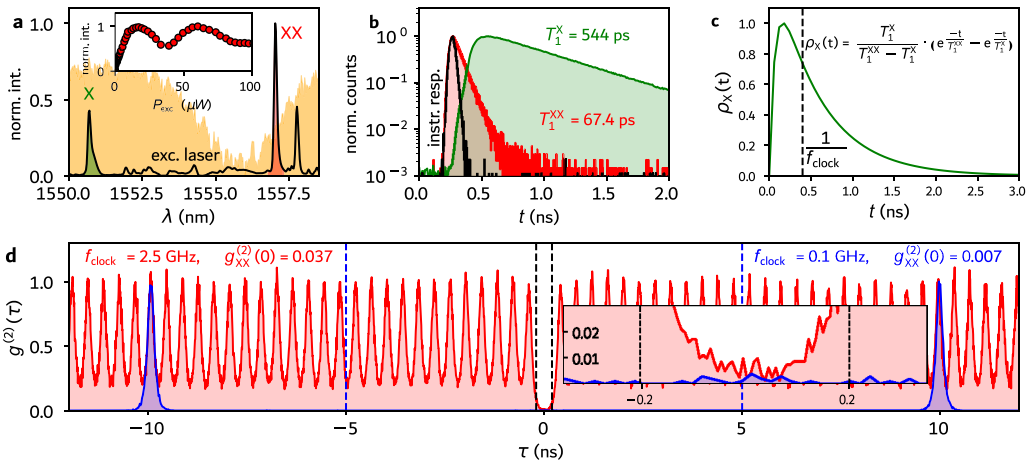


Figure 1. (a) QD spectrum under 2.5 GHz clocked TPE. Neutral exciton (X), neutral biexciton (XX), as well as the excitation laser wavelength are indicated. The cavity's reflection signal using a broadband source is depicted in orange. The inset shows the power dependent photoluminescence (PL) signal of the XX state under 2.5 GHz clocked TPE revealing Rabi rotations. (b) Time resolved X and XX PL signal with decay times extracted from monoexponential fits. (c) Theoretical time-dependent X emission $\rho_X(t)$ based on the convolved XX and X decays. The dashed line indicates the time interval between the excitation pulses. (d) Second order autocorrelation function $g^{(2)}(\tau)$ of the XX state under 2.5 GHz (red) and 0.1 GHz (blue) clocked TPE, with integrated respective $g^{(2)}(0)$-values. The inset shows a zoom-in of the histogram around $\tau = 0$. The integration window of the GHz-clocked measurement is indicated by black dashed lines.

repetition-rate laser is required. For pumping the QD at GHz rates, we used a pulsed laser with a repetition rate of $f_{rep} = 2.5$ GHz, a central emission wavelength of ∼1560nm, and <250fs pulse width. TPE is implemented using a pulse slicer to shape pulses with half of the $|G\rangle-|XX\rangle$ transition energy, where $|G\rangle$ is defined as the ground state. Additional reference experiments at a lower repetition rate were performed using a fiber-laser with $f_{rep} = 0.1$ GHz. Figure 1(a) shows the photoluminescence (PL) spectrum of the QD device under 2.5 GHz clocked TPE, with the XX emission line at ∼1557 nm, as well as the cavity's reflection signal (orange) using a broadband source, with an extracted Q-factor of $Q = 462 \pm 4$.

The inset shows the PL signal of the XX state as a function of excitation power P_{exc}, where Rabi oscillations up to a pulse area of 3π prove the coherent nature of the excitation.

For all subsequent measurements, the detected photons are spectrally filtered using three consecutive notch filters (λ_c = 1555 nm, $\Delta\lambda$ = 0.1 nm, OD3) based on a volume Bragg grating, followed by a spectrometer resulting in a spectral detection window of 70 μeV (0.14 nm). Fitting the emission line yields a resolution-limited full width at half-maximum (fwhm) of 36 μeV (0.07 nm). This setup filters the phonon sideband of the XX transition but leaves its zero phonon line unfiltered. The decay dynamics of X and XX are shown as time-resolved PL measurements in Figure 1(b), which yield decay times of ∼544 ps and ∼68 ps for the X- and XX-state, respectively. Note that the latter is still well-resolved by our detection system, with an instrument response function of 57.9 ps fwhm. Deconvoluting with the detector resolution yields a radiative lifetime of the XX-state of $T_1^{XX} = 64(1)$ ps. We achieve a detected photon rate of 2.2 MHz, representing an ∼12-fold increase in the count rate under 2.5 GHz clocked excitation, compared to 100 MHz clocked excitation. Figure 1(c) shows the theoretical time-resolved X emission as a convolution of both XX and X exponential decays[26] as

$$\rho_X(t) = \frac{T_1^X}{T_1^{XX} - T_1^X} \cdot (e^{-t/T_1^{XX}} - e^{-t/T_1^X}) \quad (1)$$

By integrating these emission events within the $1/f_{clock}$ = 400 ps time window and comparing to the remaining events on infinite time scales, we can determine the fraction of still populated $|X\rangle$-states, which prevent the population of $|XX\rangle$-states for the following excitation pulses at 2.5 GHz clock-rate. Furthermore, we obtain an estimated lifetime-limited increase in count rate between 100 MHz and 2.5 GHz excitation rate by a factor of 13.5, assuming a cascade preparation probability of 80% extracted from the performed second-order cross-correlation measurements (see the Supporting Information (SI) for more information), which is in good agreement with the above-mentioned 12-fold observation in the experiment. We thus attribute the limited gain mostly to the slow radiative decay of the intermediate X state, which prevents the excitation of the cascade if the system has not fully relaxed to the ground state between pulses. The remaining discrepancy could stem from altered blinking-contributions or a further reduced cascade preparation probability at these high clock-rates.

Figure 1(d) shows the second order autocorrelation $g^{(2)}(\tau)$ obtained for the XX photons in Hanbury Brown-Twiss (HBT) experiments under TPE at 2.5 GHz (red lines) and 0.1 GHz TPE (blue lines), respectively. The antibunching values $g^{(2)}(0)$ are extracted from the coincidence histograms by comparing the respective areas A_0 in the time interval ± 200 ps to the average peak area of the surrounding peaks A_n, $n \neq 0$, with all peak areas evaluated over time windows of ± 200 ps. From the blinking corrected data (see S.I. for more information), an integrated multiphoton suppression of $g_{XX}^{(2)}(0) = (3.7 \pm 0.7)\%$ is obtained for the f_{rep} = 2.5 GHz measurement, while the slower f_{rep} = 0.1 GHz measurement yields a value of $g_{XX}^{(2)}(0) = (0.7 \pm 0.1)\%$. The higher multiphoton contribution at GHz clock-rates is mainly attributed to residual pulse overlap in the time bin $\tau = 0^{+0.2ns}_{-0.2ns}$, due to the finite XX decay time. Further, we want to point out that by analyzing the blinking behavior, we extract an off-on ratio of 16.6(7)% between the two states of the investigated QD causing the blinking effect, which further reduces the overall extraction efficiency. The second-order autocorrelation measurement

https://doi.org/10.1021/acs.nanolett.6c01800
Nano Lett. XXXX, XXX, XXX−XXX

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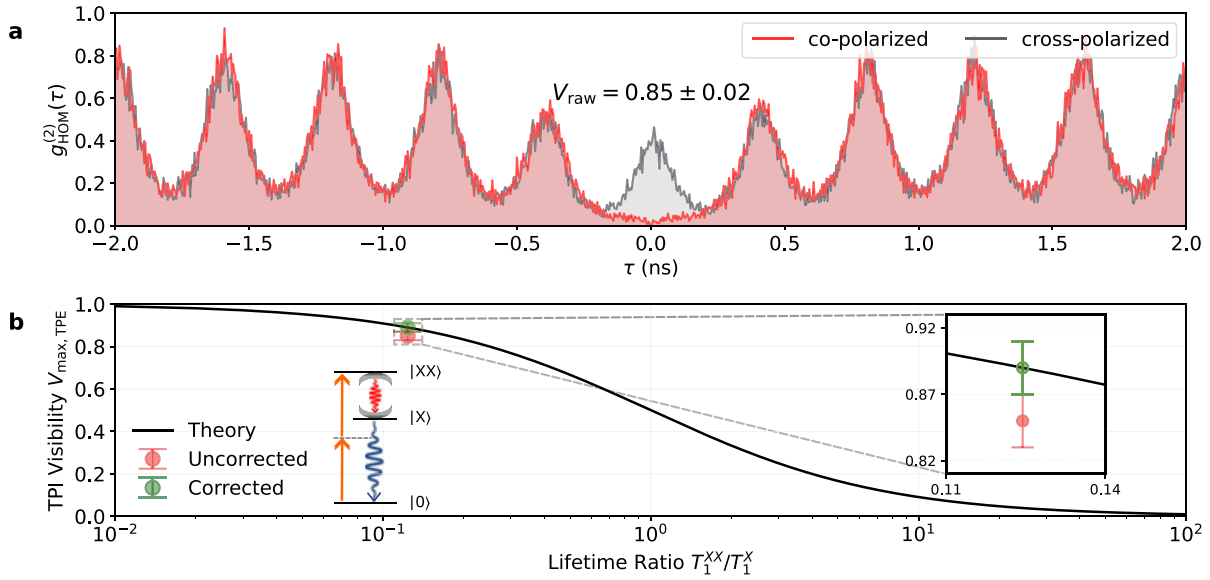


Figure 2. (a)Hong-Ou-Mandel (HOM) autocorrelation measurement $g^{(2)}_{HOM}(\tau)$ of the XX state under 2.5 GHz clocked TPE. The photon time delay corresponds to $1/f_{rep}$ = 400 ps. The maximally distinguishable cross-polarized measurement is shown in grey, the maximally indistinguishable copolarized measurement in red. (b) Dependence of TPI visibility on the radiative lifetime ratio. The solid black curve represents the theoretical maximum visibility $V_{max,TPE}$, as a function of the ratio between biexciton (T_1^{XX}) and exciton (T_1^X) lifetimes. The experimental corrected result (green circle) shows excellent agreement with the theoretical limit, while the uncorrected result (red circle) shows a slight deviation from the theoretical maximum, due to the residual pulse overlap.

confirms that the cavity enhanced XX transition maintains its excellent single photon emitter properties also under GHz optical pump. Moreover, these values compare favorably with results obtained at lower GHz repetition rates for quasi-resonantly excited InAs/GaAs QDs at f_{rep} = 1.28 GHz[23,24] as well as InP based InAs droplet-epitaxy QDs at f_{rep} = 1.07 GHz.[27] Interestingly, since there are no other comparable reports on optical excitation at GHz rates in the telecom C-band to our knowledge, our observed $g^{(2)}(0)$-values clearly surpass the performance of QD devices using electrical GHz excitation, both at short[20,28] and C-band wavelengths,[29] highlighting the advantages of coherent optical excitation compared to off-resonant electrical pumping. Also note that previous work on GHz-clocked TPE using non-Purcell-enhanced GaAs QDs reported multiphoton suppression values of 0.3%,[22] which was obtained at less than half the excitation frequency of our experiments. Remaining limitations in the current multiphoton suppression for the QD investigated here might arise from the remaining dark counts on the used telecom SNSPDs, as well as uncorrelated photons from the cavity mode in close resonance to the XX transition. We further note that pioneering early work on GHz-clocked QD single-photon sources even reported $g^{(2)}(0) = 0$,[30] the simulations underlying this claim, however, lacked a consistent validation from our viewpoint.

In order to check for the indistinguishability of the emitted photons under 2.5 GHz TPE, the TPI visibility V of consecutively emitted photons is probed in Hong-Ou-Mandel-type experiments,[31] where the time delay between the two photons is set to $1/f_{rep}$ = 0.4 ns. Figure 2(a) presents the resulting autocorrelation histograms $g^{(2)}_{HOM}(\tau)$ in co- and cross-polarized measurement configuration. Both histograms are corrected for blinking to ensure proper normalization (see the SI). The raw, blinking-corrected TPI visibility from the integrated events in the time interval $\pm 1/f_{rep}$, of co- and cross-polarized measurements is obtained according to eq 2

$$V_{raw} = 1 - \frac{A_{co}(\tau = 0)}{A_{cross}(\tau = 0)} = 0.85(2) \quad (2)$$

As discussed above in the context of $g^{(2)}(\tau)$, this raw value is impaired by the finite overlap of neighboring coincidence peaks within $\pm 1/f_{rep}$ due to the high clock-speed. Accounting for this in the HOM measurement analysis, we fit the data with a sum of exponential functions, modeling both the central peak and the adjacent side peaks, to quantify their contribution to their respective neighboring time bins (see the SI). We obtain an extracted corrected visibility of V_{corr} = 0.89(2). As shown in Figure 2(b), this value is in excellent agreement with the theoretical limit of $V_{theo} \approx 0.89$ expected for the decay time ratio of XX and X state extracted from our experimental data in Figure 1(b).[32,33] The TPI results reported above surpass previous measurements on QD indistinguishability both in employed excitation clock rate and observed visibility,[22−24] while also achieving these performances for fiber-compatible C-band emission.

In summary, we demonstrated the generation of highly indistinguishable single photons at 2.5 GHz optical clock rate from a semiconductor QD directly emitting in the telecom C-band. Employing TPE at the π-pulse, we achieved a multiphoton suppression of $g^{(2)}_{XX}(0) = (3.7 \pm 0.7)\%$, a raw TPI visibility of $V_{raw} > 85\%$, and a corrected TPI visibility matching the theoretical limit. This confirms that high photon indistinguishability from QD sources is maintained under unprecedented clock speeds, showing up prospects for substantial leaps in the performance of QD-based telecom quantum light sources for interference-based photonic quantum information applications.

https://doi.org/10.1021/acs.nanolett.6c01800
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Remaining limitations in our study concern the residual pulse overlap due to the finite XX lifetime, affecting the multiphoton suppression as well as the TPI visibility, and the relatively slow X decay, limiting the achievable single photon flux. To overcome these limitations in future work, efforts may focus on the following two routes: Route A could focus on achieving an asymmetric Purcell enhancement of XX and X states with a factor of 10 or higher, e.g., by enhancing the XX state with a Purcell of 50, and the X state with a Purcell of 5. This would reduce the pulse overlap for the XX photons at the employed clock rates, further increase the achievable count-rate by limiting the influence of the X intermediate state, and maintain the high TPI visibility under TPE excitation. These Purcell enhancements would require a deterministic integration technique with very high accuracy.[23,34] Route B would focus on collecting the photons from a deterministically Purcell-enhanced X state with a Purcell factor of >25 in combination with stimulated TPE[19,26,35,36] at optical excitation rates of >1 GHz This would overcome the TPI limitations of the XX−X cascade and provide highly indistinguishable X-photons at GHz clock rates with the benefit of a two-photon excitation process for reduced re-excitation and high multi-photon suppression.

■ ASSOCIATED CONTENT

Data Availability Statement

The data presented in this work will be made available on a public repository upon peer-reviewed publication.

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.nanolett.6c01800.

Data evaluation methods for blinking and pulse overlap correction (PDF)

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Funding

The authors acknowledge financial support by the German Federal Ministry of Research, Technology and Space (BMFTR) via the project "QuSecure" (Grant No. 13N14876) within the funding program Photonic Research Germany, the BMFTR joint projects "tubLAN Q.0" (Grant No. 16KISQ087 K), the project "NetiQueT" (Grant No. 16KIS1912), the project "QuNET+ICLink" (Grant No. 16KIS1967) in the context of the federal government's research framework in IT-security "Digital. Secure. Sovereign.", and the project "PhotonQ" (Grant No. 13N15759). The authors further acknowledge funding by the State of Bavaria. T.H.-L. acknowledges financial support by the BMFTR via the project "Qecs" (Grant No. 13N16272). A.P. acknowledges funding by the BMFTR via the project "Ferro35" (Grant No. 13N17641). (Grant No. 16KIS1967) in the context of the federal government's research framework in IT-security "Digital. Secure. Sovereign.".

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We gratefully acknowledge expert sample fabrication by M. Emmerling and thank Menhir Photonics AG for providing the laser system used for the experiments in this work.

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