Near-unity coupling efficiency of a quantum emitter to a photonic-crystal waveguide

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A quantum emitter efficiently coupled to a nanophotonic waveguide constitutes a promising system for the realization of single-photon transistors, quantum-logic gates based on giant single-photon nonlinearities, and high bit-rate deterministic single-photon sources. The key figure of merit for such devices is the β-factor, which is the probability for an emitted single photon to be channeled into a desired waveguide mode. Here we report on the experimental achievement of \( \beta = 98.43 \pm 0.04\% \) for a quantum dot coupled to a photonic-crystal waveguide. This constitutes a nearly ideal photon-matter interface where the quantum dot acts effectively as a 1D "artificial" atom since it interacts almost exclusively with just a single propagating optical mode. The β-factor is found to be remarkably robust to variations in position and emission wavelength of the quantum dots. Our work demonstrates the extraordinary potential of photonic-crystal waveguides for highly efficient single-photon generation and on-chip photon-photon interaction.

The proposals of quantum communication [1] and linear-optics quantum computing [2] have been major driving forces for the development of efficient single-photon (SP) sources [3, 4, 5]. Furthermore, the access to photon nonlinearities that are sensitive at the SP level [6, 7] would open for novel opportunities of constructing highly efficient deterministic quantum gates [7, 8, 9, 10, 11, 12, 13]. A single quantum emitter that is efficiently coupled to a photonic waveguide [14] would facilitate such a SP nonlinearity, enabling the realization of single-photon switches and diodes [14, 5, 6], as well as serve as a highly efficient single-photon source. So far, experimental progress has been limited to superconducting qubit systems where the generation of nonclassical states at microwave frequencies was reported [15]. Waveguide-based schemes offer highly efficient and broadband channeling of SPs into a directly usable propagating mode where even the photon detection can be integrated on-chip [16]. The associated SP nonlinearity constitutes a very promising and robust alternative to the technologically demanding schemes based on the anharmonicity of the strongly-coupled emitter-cavity system [17, 18, 19, 20].

In the present work we consider a single quantum dot (QD) embedded in a photonic-crystal waveguide (PCW). The important figure of merit is the β-factor:

\[
\beta = \frac{\Gamma_{\text{wg}}}{\Gamma_{\text{wg}} + \Gamma_{\text{rad}} + \Gamma_{\text{nr}}} = \frac{\Gamma_{\text{c}} - \Gamma_{\text{uc}}}{\Gamma_{\text{c}}},
\]

(1)
which gives the probability for a single exciton in the QD to recombine by emitting a single photon into the waveguide mode. \( \Gamma_{wg} \) and \( \Gamma_{rad} \) are the rate of decay of the QD into either the guided mode or non-guided radiation modes, whereas \( \Gamma_{nr} \) denotes the intrinsic nonradiative decay rate of the QD. Experimentally, the \( \beta \)-factor can be obtained by recording the decay rate of a QD that is coupled to the waveguide \( \Gamma_c = \Gamma_{wg} + \Gamma_{rad} + \Gamma_{nr} \) and the rate of an uncoupled QD \( \Gamma_{uc} = \Gamma_{rad} + \Gamma_{nr} \) in the case where the difference between the total loss rates \( (\Gamma_{rad} + \Gamma_{nr}) \) of the two QDs is negligible.

Recent proposals have indicated that the \( \beta \)-factor in PCWs may approach unity \([21, 22]\). However, measuring a near-unity \( \beta \)-factor is experimentally challenging, because the reliable extraction of \( \Gamma_{uc} \) is not straightforward. A proper measurement of the \( \beta \)-factor requires the precise determination of \( \Gamma_{uc} \) for a QD that is coupled to the waveguide. In previous work \([23, 24, 25, 26, 27]\) \( \Gamma_{uc} \) was estimated either from QDs spectrally tuned to the band gap of the photonic crystal, or from QDs positioned outside the waveguide region (for a more detailed discussion of the previous experimental methods, see Supplementary Information). The drawback of both approaches is that the modifications in the coupling to the non-guided modes from the presence of the waveguide are not accounted for, which may lead to largely incorrect estimates of the \( \beta \)-factor as is revealed by numerical simulations.

In the present work, the \( \beta \)-factor is experimentally determined by comparing the decay rate of a QD coupled to the waveguide mode \( \Gamma_c \) to that of a very weakly coupled QD, which constitutes an upper bound of \( \Gamma_{uc} \). One of the key differences to previous work is that both \( \Gamma_c \) and \( \Gamma_{uc} \) are obtained by directly detecting the propagating waveguide mode, hence all measured QDs are spatially positioned in the waveguide. This guarantees that the spatial and spectral dependence of the coupling to radiation modes due to the presence of the PCW are correctly taken into account, which is essential for the analysis. The validity of our experimental method is confirmed by numerical simulations of the position and frequency dependence of \( \Gamma_{rad} \) in the PCW structure. We experimentally demonstrate a SP channelling efficiency of \( \beta = 98.43 \pm 0.04\% \) for a QD in a PCW, which significantly surpasses previously reported results exploiting atoms \([28, 29]\), nitrogen vacancy centres \([30]\), single molecules \([3]\), or quantum dots \([4, 23, 31]\) as the photon sources in photonic-waveguide structures. Such a high coupling efficiency matches the level achievable with superconducting microwave circuits, widely considered one of the most mature platforms for scalable quantum-information processing available today, and will lead to novel opportunities for photonic quantum-information processing \([32]\).

A near-unity \( \beta \)-factor PCW SP source is illustrated in Figure 1: a deterministic train of SPs in the waveguide can be obtained since the excited QD will emit a photon into the waveguide with probability \( \beta \), while out-of-plane photon loss is strongly suppressed. High \( \beta \)-factors are achievable due to the combination of two effects: a broadband Purcell enhancement of the rate \( \Gamma_{wg} \) of coupling into the waveguide and the strong suppression of the loss rate \( \Gamma_{rad} \) due to the photonic-crystal membrane structure. Different physical systems have been proposed for obtaining a large \( \beta \)-factor: plasmonic nanowires rely on the Purcell enhancement thereby increasing \( \Gamma_{wg} \) \([31]\), while dielectric nanowires \([4, 30]\) mainly suppress the coupling to radiation modes, i.e., decrease \( \Gamma_{rad} \). In PCWs the beneficial combination of the Purcell enhancement of the PCW mode and the pronounced reduction of radiation modes enables a near-unity \( \beta \)-factor.

Results

Numerical simulations of the \( \beta \)-factor.

In PCWs the Purcell enhancement is proportional to the group index or slow-down factor \( n_g = c/v_g \), where \( c \) is the speed of light in vacuum. The group velocity of light, \( v_g \), is the slope of the waveguide
band, see Figure 1b, which decreases at the waveguide band edge. We have measured \( n_g > 50 \) close to the band edge, leading to expected Purcell factors close to 10 \( \frac{21}{21} \). Furthermore, the photonic-crystal band gap strongly inhibits the in-plane radiative loss rate of the dipole emitter, while total internal reflection limits the decay by out-of-plane radiation.

The calculated position dependent \( \beta \)-factor for a dipole emitter in proximity of the band edge \( (n_g = 58) \) and close to the light line \( (n_g = 5) \) is shown in Figure 1e. The fraction of the emission coupled to the waveguide and to the radiation modes can be determined numerically and \( \Gamma_{\text{wg}} \) and \( \Gamma_{\text{rad}} \) are obtained by multiplying by the measured average radiative decay rate of QDs in a homogeneous medium \( \Gamma_{\text{hom}} = 0.91 \pm 0.08 \) ns\(^{-1} \). The measured average nonradiative decay rate is \( \Gamma_{\text{nr}} = 0.030 \pm 0.018 \) ns\(^{-1} \). In the slow-light regime \( (n_g = 58) \), \( \beta \)-factors exceeding 95% are predicted for dipole positions close to the field maxima of the waveguide mode (Figure 1d), with a maximum \( \beta \)-factor of 99.4%. In agreement with previous results \( \frac{21}{22} \), even outside the slow-light regime \( (n_g = 5) \), \( \beta \)-factors exceeding 90% are predicted for many positions in the waveguide, illustrating the extremely broadband coupling. The position dependence of the \( \beta \)-factor, that is displayed in Figure 1f, is determined by the spatial mode profiles of the guided modes shown in Figure 1c-d.

**\( \beta \)-factor measurements.** We investigate light emission from a single layer of self-assembled InAs QDs embedded in a GaAs PCW (see Methods for sample description). In order to efficiently collect the photons from the propagating waveguide mode, either second-order Bragg gratings \( \frac{33}{33} \) or inverse tapered mode adapters \( \frac{34}{34} \) are used. A numerical study of the coupling efficiency of the two outcoupling methods is presented in the Supplementary Information. Scanning-electron microscope images of typical devices are shown in Figure 2a-b. Since the mode adapters are designed to work in the regime of low \( n_g \), a transition region is introduced in the photonic crystal in order to couple from the high-\( n_g \) waveguide mode into the low-\( n_g \) mode \( \frac{35}{35} \). The length of the high-\( n_g \) region varies between 5.1 and 8.3 \( \mu \)m for different samples; a short sample length is chosen to eliminate the formation of Anderson-localized modes \( \frac{36}{36} \), which are detrimental for obtaining a high waveguide transmission. The averaged extinction length for light propagation in similar waveguides was measured to be \( l \simeq 30 \) \( \mu \)m \( \frac{37}{37} \).

Figure 2 shows a high-power photoluminescence spectrum of the waveguide mode collected from the grating under non-resonant excitation, which is used to characterize the waveguide samples. The applied power is approximately two orders of magnitude higher than the saturation power of single excitons, i.e., single QD lines can not be distinguished in this case. The spectrum displays a cut-off at 925 nm due to the waveguide band edge and a transmission bandwidth of 35 nm. Similar spectra were obtained when collecting the emission from the inverse tapers. We also investigated waveguide structures where a change in parameters of the gratings led to high reflectivity and the formation of sharp Fabry-Pérot (FP) resonances within the waveguide bandwidth, as shown in Figure 2e. In these structures the coupling to the waveguide mode for QDs spectrally positioned in-between two resonances is very weak, implying that the measured \( \Gamma_{\text{uc}} \) is close to the lower limit of \( \Gamma_{\text{rad}} + \Gamma_{\text{nr}} \).

Time-resolved photoluminescence spectroscopy is employed to characterize the dynamics of QDs in a 20 nm range, blue-detuned from the band edge cut-off. For each QD line, decay curves are measured at an excitation power level well below saturation, see Figure 2f. For details on how the decay curves are modeled, see the Supplementary Information. We extract Purcell-enhanced decay rates of up to \( \Gamma_c = 6.28 \pm 0.15 \) ns\(^{-1} \) in the high-\( n_g \) waveguide sections (Figure 2d) and inhibited decay rates down to \( \Gamma_{\text{uc}} = 0.098 \pm 0.001 \) ns\(^{-1} \) between two FP resonances in the low-\( n_g \) waveguide section (Figure 2f). This corresponds to \( \beta = 98.43 \pm 0.04\% \). In addition we measure \( \beta \)-factors above 90% for QDs up to 20 nm
spectrally detuned from the band edge, thus highlighting the robustness of these devices. We measured the β-factor for a total of 71 QDs within the 20 nm tuning range; the additional data can be found in the Supplementary Information. In the following we will focus on the highest β-factors found for QDs in the proximity of the band edge. The SP nature of the emission lines is confirmed by recording the normally ordered second order intensity correlation function $g^{(2)}(\tau) = \langle : \hat{I}(t) \hat{I}(t + \tau) : \rangle / \langle \hat{I}(t) \rangle^2$ under pulsed excitation. An example of a measurement for the highest β-factor QD of Figure 2d is shown in Figure 2h, where $g^{(2)}(0) = 0.20$ is found at 0.63 of saturation power. For further details about the analysis of $g^{(2)}(\tau)$, see the Supplementary Information. Even stronger antibunching has been observed for QDs in spectrally very clean regions of the waveguide mode reaching $g^{(2)}(0) < 0.05$ at excitation powers below the saturation level.

Spatial and spectral dependence of the loss rate. The applied method for extracting the β-factor by comparing $\Gamma_c$ and $\Gamma_{uc}$ of two different QDs is valid since the variation of the total loss rate $\Gamma_{rad} + \Gamma_{nr}$ between different QDs is small. Indeed, the variations in $\Gamma_{nr}$ over the wavelength range of relevance can be neglected while the spatial variation of $\Gamma_{rad}$ has been calculated as shown in Figure 3b for an efficiently ($n_g = 58$) and weakly coupled ($n_g = 7$) QD. The chosen values of $n_g$ correspond to the cases of the QDs shown in Figure 2d,f. For most positions, $\Gamma_{rad}$ is found to be lower than the experimental estimate based on $\Gamma_{rad} = \Gamma_{uc} - \Gamma_{nr}$ (indicated by the dashed line in Figure 3a), which is expected since residual coupling to the waveguide will increase the rate. At a few spatial positions in Figure 3b, the predicted $\Gamma_{rad}$ is found to be higher than the experimental rate. However, as displayed in Figure 3b these are not the positions where the large Purcell-enhanced decay rates observed in the experiment appear (experimental values indicated by the dashed line in Figure 3b), and we can thus exclude that the QDs with highest β-factor are positioned here, implying that the record-high β-factors constitute conservative estimates.

Discussion

The β-factor plays an important role in both probabilistic and deterministic all-solid-state quantum-information processing: the success probability of a linear-optics quantum computing algorithm is proportional to $\beta^n$, where $n$ is the number of SPs required. Since $n$ tends to be large in linear-optics protocols where ancillary photons are necessary, SP sources with near-unity β-factor are required. Additionally, a deterministic two-photon phase-gate can be implemented with a QD in a PCW by using the V-level scheme formed by the ground state and the two bright exciton states. It can be shown that the probability of flipping the internal state of the quantum emitter conditioned on the presence of a single photon in the first pulse equals $\beta$, in the limit of narrow-bandwidth optical pulses. We emphasize that such applications require the generation of highly coherent photons, which has recently been observed experimentally. The phase gate described above is one of the possible quantum-photonic devices that can be realized by exploiting the giant single-photon nonlinearity of a high-β-factor single QD. Furthermore, a highly-efficient SP source can be built by optimizing the outcoupling mode adapters of our structures, making the source immediately applicable for linear-optics quantum-computing experiments.

Methods

Sample fabrication. The samples consist of 160 nm thin GaAs (refractive index $n = 3.45$) photonic-crystal membranes with lattice constants of either $a = 238$ nm or $a = 235$ nm and respective hole
radii of $r = 0.29a$ or $r = 0.31a$. A waveguide is created by leaving out a single row of holes. A single layer of InAs self-assembled QDs, with a density of $\sim 100 \mu m^{-2}$ and an inhomogeneously broadened spectrum spanning the range of $920 \pm 25$ nm, was grown by molecular beam epitaxy in the center of the membrane. The photonic crystal structures were defined on a layer of resist (ZEP 520A) by electron-beam lithography and then transferred into the GaAs layer by using a chlorine based coupled plasma reactive-ion etching. Suspended membrane structures were formed by removing a 1-\mu m-thick AlGaAs sacrificial layer underneath the GaAs layer with hydrofluoric acid vapour.

**Optical measurements.** The QDs were pumped optically using a Ti:Sapphire laser, which provided 3-ps pulses at 800 nm with a repetition rate of 76 MHz. QDs with a slow decay rate were also investigated with a ps-pulse diode laser with a variable repetition rate operated at 20 and 40 MHz and an excitation wavelength of 785 nm. The grating samples were investigated in a helium-flow cryostat operated at 10 K. Both excitation and collection were performed with the same microscope objective (NA = 0.65), where the excitation beam was moved to the center of the waveguide while the collection was done from the grating. The tapered samples were mounted in a helium-bath cryostat operating at 4.2 K. The excitation beam was focused by a top microscope objective with NA = 0.5, and emission was collected from the taper with another microscope objective with NA = 0.65. The sample and the excitation objective were positioned by two stacks of piezoelectric stages enabling motion in all three dimensions. Emission was sent to a spectrometer (600 or 1200 grooves/mm grating), where a CCD was used for spectral measurements and avalanche photodiodes were used to record either the decay dynamics of the emitters as well as their intensity autocorrelation function.

**Simulation methods and results.** Numerical simulations using a finite-element method (FEM) in the frequency domain have been performed to model the coupling to radiation modes for a dipole emitter coupled to a PCW. The total power emitted by the dipole in the waveguide relative to the total emitted power in a homogeneous medium can be expressed as $P/P_{\text{hom}} = (\Gamma_{\text{wg}} + \Gamma_{\text{rad}})/\Gamma_{\text{hom}}$, where $\Gamma_{\text{hom}} = 0.91 \pm 0.08$ ns$^{-1}$ is the radiative decay rate of the QD in a homogeneous medium that is recorded experimentally. By computing the values of $\Gamma_{\text{wg}}$ and $\Gamma_{\text{rad}}$ (see below) for specific positions and dipole orientations, the radiative $\beta$-factor can be obtained from $\beta = \Gamma_{\text{wg}}/(\Gamma_{\text{wg}} + \Gamma_{\text{rad}})$, including the experimentally extracted value of $\Gamma_{\text{nr}}$ leads to Figure 1e.

The problem of defining appropriate boundary conditions for the waveguide mode in the numerical simulations has been overcome by applying a set of active boundary conditions at the two ends of the waveguide [22, 43]. The active boundary conditions absorb the propagating field with a mode profile given by the Bloch mode and a field amplitude extracted from eigenvalue simulations. Perfectly matched layers (PMLs) are used at all the boundaries of the simulation domain except for the two planes at the ends of the PCW, where active boundary conditions are applied. The total power radiated by the dipole, $P$, is extracted by integrating the power flowing out of a small cube surrounding the emitter. The power coupling to radiation modes, $P_{\text{rad}}$, is extracted with the same method, but using a box that surrounds the simulation domain. The yz-faces of this second box were left open to avoid including any contribution from the waveguide mode in the integration. Convergence tests have been performed to ensure the accuracy of the results with respect to mesh size, length of the waveguide, height of the active boundary conditions, and size of the box used for the power integration. The power emitted into the waveguide mode can be then extracted from $P_{\text{wg}} = P - P_{\text{rad}}$.

Using the above outlined method $\Gamma_{\text{rad}}$ is calculated for both x and y dipoles at different spatial
positions within the waveguide and the results are presented in Figure 3k. These calculations are performed for $n_g = 58$ and for $n_g = 7$ in structures corresponding to the high-$n_g$ and to the low-$n_g$ waveguide sections, respectively. In Figure 3b $\Gamma_{wg} + \Gamma_{rad}$ is shown for the same dipoles. The spectral positions within the respective waveguides were chosen to check the validity of the method used to extract the high $\beta$-factors from the measurements of QDs close to the band edge of the high-$n_g$ waveguide mode. An equivalent investigation was performed for a dipole far blue detuned from the waveguide mode band edge, $n_g = 5$, in structures corresponding to the high-$n_g$ waveguide section. These simulations were used to show the validity of our method for the QD detuned 20nm from the waveguide mode band edge and still exhibiting a $\beta$-factor above 90%. Finally the two simulations performed at $n_g = 58$ and $n_g = 5$ were combined to show the broadband nature of these structures, which is presented in Figure 4b.
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**Author contributions**

I.S., M.A., S.L.H. and H.T. carried out the experiment, M.A. and S.L.H. analyzed the data, I.S, J.L, and S.S. fabricated the sample, A.J. and S.M. provided the numerical simulations, E.H.L and J.D.S. grew the quantum dot wafer, S.S. and P.L. supervised the project, M.A., I.S. and P.L. wrote the paper with contributions from all authors.

**Additional information**

The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to I.S. and P.L.
Figure 1. High-β photonic-crystal waveguide single-photon source. a, Illustration of the device. A train of single-photon pulses (red pulses) are emitted from a triggered QD (yellow trapezoid). The photons are channeled with near-unity probability into the waveguide mode with a rate $\Gamma_{wg}$ while the weak rate $\Gamma_{rad}$ of coupling to radiation modes implies that only very few photons are lost. The guided photons can be efficiently extracted from the waveguide through a tapered mode adapter. b, Projected TE band structure of the PCW studied in the experiments displaying even (green) and odd (black) waveguide modes in the band gap. In the experiment only the even mode is studied. The shaded area of the dispersion diagram corresponds to the continuum of radiation modes. c,d, Electric field intensity spatial profiles $|E_x|^2$ (right) and $|E_y|^2$ (left) for two different spectral regions of the waveguide mode corresponding to two different group indices $n_g$. e, Maximum β-factor of the two orthogonal dipoles at $n_g = 58$ (red) and $n_g = 5$ (blue) calculated at the positions indicated in the inset. The maximum β-factor is the quantity measured in decay-dynamics experiments.

Figure 2. Measuring the β-factor. a-b, QDs are excited in an area centered on the PCW (green area), and the resulting emission is collected either from (a) the grating or (b) the tapered mode adapter (red areas). c, High-power emission spectrum displaying the mode of the high-$n_g$ waveguide section for a grating structure with weakly reflecting ends. d, Low-power spectrum with the corresponding decay rate $\Gamma_c$ and β-factor for a QD that is efficiently coupled to the waveguide. e, High-power emission spectrum for a low-$n_g$ waveguide section with a highly reflective grating mode adapter. f, Low power spectrum and decay rate $\Gamma_{uc}$ of a QD spectrally in-between two FP resonances. g, Decay curves of QD-lines shown in (d) (red curve) and in (f) (blue curve). h, Measured autocorrelation function of the QD in (d).

Figure 3. Spatial and spectral dependence of the rate of coupling to radiation modes. a, Position-dependent radiative loss rate for a y-polarized (squares) or x-polarized (circles) dipole emitting at either $n_g = 58$ in the high-$n_g$ waveguide section (red data) or $n_g = 7$ in the low-$n_g$ waveguide section (blue data). The shaded region indicates where the predicted $\Gamma_{rad}$ is above the experimentally extracted value of $0.063 \pm 0.008$ ns$^{-1}$. b, Calculated radiative rate as a function of position for a dipole aligned along the y-direction (squares) or the x-direction (circles) and emitting at $n_g = 58$. The corresponding emitter positions are indicated in the inset of Figure[1]. The shaded region indicates where the predicted decay rate is above the experimentally extracted value of $6.28 \pm 0.15$ ns$^{-1}$ for the high-β-factor QD.
Figure 1
Figure 2
Figure 3