Transfer-printed single-photon sources coupled to wire waveguides: supplementary material

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1. Sample Fabrication

PhC airbridge nanobeam cavities were fabricated into a 130 nm-thick GaAs slab containing a layer of self-assembled InAs QDs grown by molecular beam epitaxy. The areal density of the InAs QDs is 2×10⁹ cm⁻². We employed conventional nanofabrication processes including electron beam lithography and both wet and dry etching. We simply used the same process conditions as those used when studying high Q III-V nanobeam cavities [1,2], which in principle could be further optimized individually.

Transfer printing was performed with a homemade printing apparatus, a photograph of which is shown in Fig S1(a). The system is composed of two movable stages and an optical microscope. The left stage (highlighted in green) holds a glass plate, on which a transparent rubber stamp is attached. The stamp is made of polydimethylsiloxane (PDMS, Sylgard184, Dow Coming). The PDMS stamp has 1-μm-thick square bumps with a side length of 30 μm for selective sample pick up. The pillar-like structure mitigates unwanted strain on the stamp by reducing the...
contact area with the sample substrate, resulting in an improved positioning accuracy during the transfer process. The position of the stamp can be controlled with fine adjusters in the three axes. With the top stage, the pitch and roll of the stamp can also be controlled. The right stage (blue) holds SPS and waveguide samples on the top, the positions of which can be finely tuned by the combinations of fine adjusters and piezo actuators. The sample rotation can also be corrected using an incorporated rotational stage. The sample image was obtained by the microscope, the magnification of which can be switched by rotating the turret equipping objective lenses.

For the transfer printing, first, we attached a PDMS stamp to an appropriate airbridge nanobeam cavity under the microscope, as shown in Fig. S1(b). Then, we quickly peeled the stamp off by moving an actuator in the vertical direction (Fig. S1(c)). The peeling speed is roughly 3 mm/s. The success probability of this picking up process is about 70–80% in the current setup and condition. Then, we brought the lifted nanobeam cavity onto to a target waveguide. Subsequently, the cavity was carefully loaded above the waveguide manually using the piezo actuators (Fig. S1(d)). During the loading process, we paid attention to the cross markers patterned in both the coupons respectively containing the cavity and the waveguide. The same cross markers are patterned to both the sides of the waveguide: a part of one of them can be seen in Fig. 3(a) in the main text (see also Fig. S1(f)). The top cross markers on the cavity coupon are slightly enlarged compared to that on the waveguide coupon and thus the image contrast formed between the two elements served as a guide for sample positioning. Figure S1(e) shows a picture during the nanocavity release by slowly peeling the stamp off. We succeeded in this release step almost without fail in the current transfer condition. A microscope image of a completed sample is shown in Fig. 3(a) in the main text. The transferred SPS is bonded tightly on the waveguide wafer via van der Waals force [3]. When integrating two nanocavities into a waveguide as shown in Fig. 5(a), we did not see significant disturbance on the printing process by the pre-selected nanocavity. This suggests the possibility for dense integration of a larger number of SPSs by transfer printing which would be required for realizing large-scale quantum PICs. In this regard, the parallel transfer of multiple photonic structures by transfer printing [4] will also be of importance for scalable integration.

In order to evaluate the printing accuracy, we fabricated 8 different printed nanocavities with the same design and measured them with high-resolution optical microscope. A photograph of a typical completed sample is shown in Fig. S1(g). After the digital edge enhancement of the picture, we deduced the perimeter of each element, which was employed to determine the center positions of the cavity and waveguide. The absolute positioning error between the two elements in the y direction (normal to the waveguide) was estimated to be ~60 nm on average. The standard deviation of the error was evaluated to be ~40 nm. Also from the pictures, unwanted sample rotations are found to be less than 1 degree.

In the current work, we did not pre-select a suitable nanobeam cavity. Therefore, only one out of three to four samples contain QDs resonating with the cavity mode. The sample discussed in the main text is one of such samples. For the sample with two SPSs on the single waveguide, we prepared 8 pairs of such structure. One of them has QDs in each cavity and has been used for the discussion in the main text. This randomness in the SPS fabrication can be easily avoided by pre-selecting suitable QD SPSs by optical experiments prior to the transfer processes.

We used transfer printing for the fabrication of glass-cladded wire waveguides. For this purpose, first, we prepared airbridge wire waveguides with grating exit ports [5] into a 130 nm-thick GaAs. The waveguide width was chosen to be 220 nm as discussed in the supplementary section 4. We placed the waveguides on a glass substrate by transfer printing. We then formed an upper clad on the waveguide by a spin-on-process (FOX15, Dow Corning). The clad surface above the waveguide was evaluated using an atomic force microscope and was found to be smooth with a root-mean-square roughness of only 0.4 nm. The thickness of the glass above the waveguide (= d) was precisely controlled to be 300 nm for the first sample shown in Fig. 3(a) by tuning the amount of solvent in the liquid glass material and the spin speed. For the experiments in Fig 5(a), d = 270 nm was used.

2. Device design

We optimized the SPS based on the PhC nanobeam cavity on a glass-cladded wire waveguide [6] so as to maximize the single photon coupling efficiency into the waveguide. Hereafter, we conducted all the electromagnetic simulations by using the three dimensional finite difference time domain (FDTD) method. First, we designed the PhC nanobeam cavity on a flat glass substrate [7]. We considered a GaAs nanobeam with a width of 370 nm and a thickness of 130 nm. The air holes were patterned with a period (a) of 230 nm and radii of 53 nm. The lattice period was modulated near the cavity center so as to support a very high Q-factor of over 5 million for the fundamental cavity mode at the normalized frequency (a/λ) of 0.249. The polarization of the fundamental mode is mainly transverse electric (electric field parallel to the substrate). Details of the nanocavity design are described in the supplementary section 3. Then, we simulated light coupling into the glass-cladded waveguide placed directly below the cavity with separation d. We set the waveguide width and thickness to be 220 nm and 130 nm, respectively. These parameters were chosen so as to maximize the cavity-waveguide coupling strength for a given d (see the supplementary section 4): this optimization is essential to increase the maximum possible cavity-waveguide coupling efficiency (η) in design. The calculation of η starts with the simulation of the investigated cavity mode until reaching to its steady state by FDTD method. Then, we measured all the light leakage from the simulator, together with that from the waveguide. In this way, we can deduce η by the ratio of waveguide light leakage to that from the whole domain.

In an analytical fashion, we can describe η by the following equation:

$$\eta = \frac{Q_{w}^{-1}}{Q_{0}^{-1} + Q_{w}^{-1} + Q_{scatter}^{-1}}, \#(1)$$

where Q0 and Qw are the design cavity Q without and with the waveguide, respectively. 1/Qscatter expresses the additional photon loss into free space due to the introduction of the waveguide. From the equation, for realizing a high η, it is vital to design a very high Q0 and a low Qw while suppressing 1/Qscatter. The high Q0 (>5 million) of our PhC nanobeam cavity is highly suitable for increasing η. The reduction of 1/Qscatter is possible by taking a large enough d, which in turn exponentially increases Qw. We overcame this difficulty by optimizing the waveguide parameters so as to minimize Qw to 1,300 for d = 300 nm (see the supplementary section 4). In this design, 1/Qscatter becomes negligible and η reaches to be 99.4%. In contrast, for ds much smaller than 300 nm, the above discussion based on the perturbation theory (coupled mode theory) does not hold anymore, since the index modulation by the waveguide becomes too strong to treat as a perturbation for the cavity mode. In this case, the significant cavity-to-free space leakage is turned
on, resulting in a high $1/Q_{water}$ value and reduced $\eta_s$, as plotted in Fig 2(c) in the main text.

For evaluating the emitter-cavity coupling efficiency ($\beta$), we assumed that the spontaneous emission from the QD occurs into either the cavity mode or free space. The average spontaneous emission rate of QDs in unprocessed area ($\gamma$) was measured to be $\gamma = 1$ GHz. The nanocavity enables fast spontaneous emission into the cavity mode with a rate of $F_0\gamma$, where $F_0$ is the Purcell factor proportional to the value of $Q/V$ of the cavity mode. Meanwhile, the photonic bandgap effect in the one-dimensional nanobeams PhC suppresses the spontaneous emission rate of embedded QDs [2]. Consistent with the previous work, we experimentally measured $\gamma_{other}$ to be $\sim 0.5\gamma$. With these parameters, $\beta$ can be calculated from the following equation:

$$\beta = \frac{F_0\gamma}{F_0\gamma + \gamma_{other}}, \#(2)$$

For the designed SPS with an overall cavity Q-factor of 1,300 at $d = 300$ nm, the maximum possible $F_0$ is 250, resulting in a near-unity $\beta$ of 99.7%. Overall, the total single photon coupling efficiency to the waveguide ($\eta\beta$) becomes a near-ideal value of 99.2%. Such high $\eta\beta$s are also confirmed in direct simulations of them using a dipole source emulating the single QD (see the supplementary section 5). It is noteworthy that our design strategy for near-unity $\eta\beta$ can be applied to different material systems such as those using Si and Si$_3$N$_4$ (see the supplementary section 6). Moreover, the design is robust against the misalignment between the cavity and the waveguide: a 200-nm cavity position deviation reduces the total efficiency by less than 1% (see the supplementary section 7). From these results, our waveguide-coupled SPS design compatible with the transfer printing process could be regarded as one of the most viable routes to introduce single photons into diverse PIC platforms, regardless of material combinations. It is also noteworthy that the nanobeam-based cavity design can be extended to a crossed nanobeam cavity that can support doubly degenerated cavity modes suitable for entangled photon generation [8].

3. Details of the nanocavity design

We designed the PhC nanobeam cavity so as to possess an ultra-high Q-factor when being placed on flat glass [7] (refractive index $n = 1.45$). A schematic of the design is drawn in Fig S2. In the design, we considered a GaAs-based ($n=3.4$) nanobeam with a width ($w$) of 370 nm and a height ($h$) of 130 nm. The nanobeam is patterned with air holes with radii ($r$) of 59.8 nm and a period ($a$) of 230 nm. For the cavity formation, we disturbed the period of the air holes quadratically: $a_1, a_2, a_3, a_4, a_5$ and $a_6$ equals to 0.84$a$, 0.844$a$, 0.858$a$, 0.88$a$, 0.911$a$ and 0.951$a$, respectively. We assumed the thickness of the glass to be 1.5 µm in the model. We computed properties of the fundamental cavity mode resonating at a normalized frequency of 0.249 $a/\lambda$ by the FDTD method. We obtained a high Q-factor of $5.4 \times 10^6$ and a small mode volume of 0.434($\lambda/n$)$^3$.

![Fig. S2. Detailed schematic of the cavity design.](image)

4. Maximizing the cavity-waveguide coupling strength for a given $d$

As we discussed in the main text, it is essential for realizing high $\eta$ to achieve the maximum possible coupling between the PhC nanobeam cavity and the waveguide for a given cavity-waveguide distance, $d$. In the current work, we optimized the waveguide width so as to maximize the coupling [6]. Figure S3 shows an evolution of calculated cavity Q-factors as a function of the waveguide width for the case with $d = 300$ nm. By changing the width, cavity Q-factors increase or decrease and have its minimum value around the width of 220 nm. The reduction of $Q$ predominantly stems from the cavity-waveguide coupling, rather than the cavity-to-free space leakage. Indeed, we confirmed near unity $\eta_s$ for the cases using waveguide widths around 220 nm by directly calculating $\eta_s$ through the radiation power distribution: $\eta$ for the width of 220 nm was found to be 99.5%. In the current work, we set the waveguide width to be 220 nm.

We interpreted that the maximum coupling was obtained when achieving the largest overlap integral between the confined cavity mode and the propagating waveguide mode in the sense of the coupled mode theory [9]. From a different point of view, this can be understood as a result of phase matching between the two modes. Namely, by modifying the width, the waveguide dispersion was adjusted to cross the cavity frequency around the bandage of the PhC nanobeam, the field components around which, in this case, predominantly constitute the cavity mode.

5. Direct simulation of $\eta\beta$ by a dipole source

For further verifying the high total single photon coupling efficiencies, $\eta\beta$s, we performed direct numerical simulations of them by using a point dipole as a source of the radiation [10]. In this way, we can directly simulate $\eta\beta$ by monitoring the power distribution to the waveguide compared to the whole radiated power. Here, the dipole source was assumed to be linearly polarized (parallel to the slab and perpendicular to the guiding direction of the nanobeam), tuned to the resonance of the fundamental cavity mode and positioned to the cavity center, where the electric field of the fundamental mode is the strongest. We consider that the dipole source reasonably emulates our QDs, which are thin-disk-like in shape and hence possess strong optical transition dipole parallel to the slab (normal to the growth direction). Strong linear polarizations are available for e.g. neutral exciton states subjected to an anisotropic electron hole exchange interaction. The upper panel in Fig S4 shows a comparison of the directly calculated $\eta\beta$ (red) with those by the separated calculations as discussed above (black). The two curves match very well each other, confirming the validity of the separated simulations of $\eta$ and $\beta$ for estimating $\eta\beta$. For $d = 350$ nm, the simulation using the point dipole source results in $\eta\beta = 99.8%$. The remaining deviations between the two curves are considered to be due to the finite simulation accuracy in the FDTD method (which is limited by the spatial grid size and time length of the calculation,
6. Simulated single photon coupling efficiencies into waveguides made of Si and Si$_3$N$_4$

Our SPS design strategy is versatile and robust for the change in material platform. We examined this by considering waveguides made of Si ($n = 3.5$) and Si$_3$N$_4$ ($n = 2.0$), both of which are standard material for the fabrication of PICs.

For Si waveguide, we re-designed an InP-based ($n = 3.5$) nanobeam cavity such that it resonates within the telecom wavelength band at 1.55 μm, where Si is transparent. A design schematic is shown in Fig. 5(a). In the cavity design, we set $a = 380$ nm, $r = 99$ nm, $w = 640$ nm and $h = 220$ nm, while employing the same modulation rule of the air hole periods described above for defining the defect cavity region. Without the waveguide, the nanobeam cavity on plane glass exhibits a very high $Q$-factor of $5.2 \times 10^6$ and a small $V$ of $0.463(\lambda/n)^{3}$. For the waveguide coupling, we assumed a Si waveguide width and thickness of 400 and 210 nm, respectively. By setting the cavity-waveguide distance $d$ to be 500 nm, a near-unity $\eta$ of 99.5% was deduced based on power distributions obtained in FDTD simulations. A field profile of the simulated mode at the steady state is shown in Fig. 5(b). The cavity $Q$ with the waveguide was 2,310, which results in an $\eta$ of 99.9% and well explains the simulated $\eta$. Using the calculated $Q$ and $V$, a very high $\beta$ of 99.8% can be deduced. Overall, a very high single photon coupling efficiency $\eta\beta$ of 99.3% was obtained in these simulations. Meanwhile, for Si$_3$N$_4$ systems, we used the same nanobeam cavity design used in Fig. 2(a) in the main text. A design schematic for this structure is shown in Fig. 5(c). The Si$_3$N$_4$ waveguide are assumed to have a width of 1,000 nm and a thickness of 400 nm. With $d = 200$ nm, the designed SPS exhibits a very high $\eta$ of 99.1%, together with a $Q$ of 7,900. In this case, $\beta$ results in 99.9% and thereby $\eta\beta$ was deduced to be 99.0%. A computed field profile at the steady state is shown in Fig. 5(d).

These results clearly demonstrate that our design strategy is suitable for the introduction of highly efficient SPSs into diverse PIC material platforms. We emphasize that transfer printing enables the separated optimization of the fabrication processes for the SPSs and the waveguides, opening the way to high quality assembly of SPSs on PICs.
7. Effect of misalignment of the cavity with respect to the waveguide

The designed SPSs can keep the high $\eta$s even under the presence of misalignment of the cavity to the waveguide. First, we examined the robustness against the simple in-plane deviation, $\delta$, which is defined by the center-to-center distance between the cavity nanobeam and waveguide. Calculated Q-factors are shown in Fig S6(a). Up to $\delta = 200$ nm, we observed moderate Q-factors below 4,000, which is low enough to support high $\eta$s over 99%. Indeed, the low Q is predominantly due to the waveguide coupling and a high $\eta$ of 99.5% for $\delta = 200$ nm was confirmed by numerically calculated power distributions by FDTD method.

Then, we checked the design robustness against the rotation, which is quantified by the angle between the cavity and the waveguide, $\theta$. Figure S6(b) summarizes the simulated device Q-factors as a function of $\theta$. Again, we did not find a significant increase of the Q-factor, suggesting that the high $\eta$ is well maintained. For $\theta = 10$ degrees, we confirmed a high $\eta$ over 99% by the FDTD method.

We also confirmed the situations in which both finite $\delta$ and $\theta$ exist. Figure S6(c) summarizes the cases for $\delta = 100$ and 200 nm with $\theta$ from 0 to 10 degrees. Apparently, low Qs are still supported even under the existence of the combined misalignments. For $\delta = 200$ nm and $\theta = 10$ degrees, we confirmed a high $\eta$ of 99.1%. Assuming the experimentally observed misalignment of $\delta$ smaller than 100 nm and of $\theta$ less than 1 degree, we can conclude that the near-unity $\eta$ over 99% can be achieved even by the current transfer printing technology, if we can experimentally achieve $Q_0$ over 50,000.

8. Single photon transport under the presence of two cavities on a waveguide

We simulated light transport for the case that the two cavities are simultaneously integrated onto an individual waveguide. We used two different PbC nanobeam cavities: they differ in $a$ (230 nm and 235 nm), while share the same $r/a = 0.26$, $w = 370$ nm and $h = 130$ nm. The two cavities resonate at 924 nm for $a = 230$ nm and 937 nm for $a = 235$ nm in the simulation. For investigating the light propagation, we selectively excite one of the two cavities and computed its evolution until reaching to the steady state in our numerical simulator. Figures S7(a) and (b) show the calculated field profiles at the steady states. It is clearly seen that the light transport did not significantly disturbed even with the presence of the other cavity. By monitoring the power distribution into the waveguide, we deduced $\eta$s over 99% for the waveguide coupling from the two cavities. The minimal disturbance on the light transport is largely due to the large-enough frequency detuning between the two cavity modes.

9. Optical measurement setup

The PL measurements in the main text were conducted with a low-temperature micro-PL setup. The sample was fixed in a helium flow cryostat having a built-in heater for temperature control. We used an objective lens with a numerical aperture of 0.65 for sample imaging, pump laser beam focusing and collecting PL signal. The collected PL was analyzed with a grating spectrometer equipped with a Si CCD camera. For measuring the PL image in Fig 3(b), we used a continuous wave titanium sapphire laser oscillating at 819 nm with a pump power of 25 $\mu$W (measured before the objective lens), which was focused onto the cavity center. In this experiment, we inserted a bandpass filter centered at 900 nm in front of an imaging camera for extracting the contribution of the cavity mode emission. For measuring the spectra in Fig 3(c), we switched the pump source to a pulse laser (pulse width = $\sim$ 1 ps, repetition rate = 80.3 MHz) oscillating at 815 nm with an average pump power of 20 $\mu$W. We limit the area of PL collection (spatial filtering) around one of the exit ports by narrowing the entrance slit of the spectrometer and the region of interest of the CCD, which roughly corresponds to the detection area of a few $\mu$m$^2$. The PL spectra in Fig 4(a) was measured with the CW laser (wavelength = 849 nm, power = 87 nW). The temperature was controlled using the heater and the QD-cavity resonance condition was achieved at 46 K. The results in Fig 4(b) and (c) were obtained with the pulsed laser (815 nm, 20 nW). The time resolved spectra were measured with a time-correlated single photon counting technique with a silicon avalanche photodiode (overall time resolution = 0.4 ns). We used the spectrometer as a bandpass filter of PL signal. Fitting to the time-resolved spectra was done with double exponential decay curves convolved with a function reflecting the system time response. Among the two deduced time constants, we treated the faster decay rate as the experimental value in the discussion. For the intensity correlation measurements, we added a beamsplitter and
another avalanche photodiode to build a Hanbury Brown-Twiss interferometer. The $g^2(0)$ values were deduced by dividing the area of the time zero peak by the averaged area of the remaining peaks. The results in Figs. 5 were taken at 3 K using the pulse laser (831 nm, 3.8 µW).

10. Experimental estimation of $\eta$ and $\beta$.

The estimation of experimental cavity-waveguide coupling efficiencies ($\eta_{exp}$) was done based on the measured cavity Q-factors. First, we measured 9 nanobeam cavities that were placed on flat glass and did not coupled to the waveguide. By fitting the measured PL peaks with Lorentzian function, we deduced an average cavity Q-factor on flat glass ($Q_{ave}$) to be 13,000. The standard deviation of the Q values was estimated to be $\sim 1,000$. In addition, the emission spectrum measured for the cavity mode coupled to the waveguide was fitted to deduce the experimental Q-factor ($Q_{exp}$) of 3,600. The larger $Q_{exp}$ than the designed $Q$ of 1,300 for $d\approx 300$ nm can be explained by the deviation of the structural parameters in the fabricated device: in particular, the change in the cavity resonance wavelength disturbs the phase matching between the cavity and waveguide and degrades their coupling strength. Using the measured cavity Q-factors, we deduced an $\eta_{exp}$ of 72% based on the following equation:

$$\eta_{exp} = \frac{Q_{ave}^{-1} - Q_{exp}^{-1}}{Q_{ave}^{-1}}. \#(3)$$

This equation assumes that the observed reduction of the Q-factor when introducing the waveguide is dominated by the leakage of photons into the waveguide. This assumption is fairly reasonable in the current situation where $d$ is large enough to suppress the additional cavity photon leakage into free space, as confirmed in the numerical simulations (see the supplementary section 2). Even with fabrication imperfections, we can expect the dominance of the waveguide loss: from the view point of the cavity, the largest index perturbation inducing its photon leakage is provided by the waveguide itself. Indeed, we have experimentally confirmed that the significantly-suppressed free space radiation from the cavity after coupling to the waveguide, as discussed using the measured spectra in Fig. 3(c) in the main text.

For the case when loading the two cavities to the single waveguide, we measured a Q-factor of 1,000 (950) for the left (right) cavity, resulting in $\eta_{exp}$ of 92% (93%). In this case, $\eta_{exp}$ improved due to the slight reduction of $d$ to 270 nm, which reduces the cavity Q-factors and increases the coupling between the cavities and the waveguide. We note that a more direct measurement of $\eta_{exp}$ will be possible by measuring the transmission spectra of the waveguide after coupling to the cavity [6].

Regarding the estimation of the experimental $\beta$ ($\beta_{exp}$), we performed time-resolved PL measurements. First, we measured emission decay rates of several single QDs that were embedded in PhC nanobeam on plane glass and decoupled from any cavity modes. The average decay rate was measured to be 0.5 GHz (= $\gamma_{other}$), which is roughly half of that for QDs in an unprocessed region of the sample. This reduction of the decay rate stems from partial photonic bandgap effect in the PhC nanobeam [2]. Then, we measured emission decay rates of the investigated QD emission peaks coupled to the cavity mode ($\gamma_{exp}$). For deducing $\beta_{exp}$, we performed fitting for the measured PL decay curves using a model consisting of a 3-level QD [11]. We fit the whole decay curve including the initial intensity rise for better lifetime estimation. In the model, the QD characteristic is described with two decay time constants, composed of carrier relaxation time from the upmost level to the middle radiative state and spontaneous emission time to the lowest level. An important note here is that, in this fitting model, the two time constants equally impact on the shape of PL decay curve in essence. There, slower time constant always determines the slope of the PL decay irrespective of the assignment of the two time constants to the actual physical processes. As such, one should keep in mind that there is a possibility that the decay slope is determined by the carrier injection process [11]. Whereas, we know that our similar QD exhibits a very fast carrier decay within a time less than 50 ps [12]. Given this previous observation, we treated the slower time constant in the deduced values as the spontaneous emission rate in the following discussion. With the decay rate values for spontaneous emission, we deduced $\beta_{exp}$ by the following equation [13]:

$$\beta_{exp} = \frac{\gamma_{exp} - \gamma_{other}}{\gamma_{exp}}. \#(4)$$

For the QD discussed in Fig. 4(b) in the main text, $\gamma_{exp}$ was measured to be 3.9 GHz at the resonance, resulting in $\beta_{exp}$ of 87%. For the QD in the left (right) cavity in Fig. 4(d)(e) in the main text, $\gamma_{exp}$ was measured to be 2.2 (1.2) GHz at 3 K, at which the QD is detuned from the cavity resonance by 2.0 (1.8) nm. The resulting $\beta_{exp}$ was 77% (58%). The experimental single photon coupling efficiencies into the waveguide were simply obtained by multiplying the two efficiencies, that is $\eta_{exp}\beta_{exp}$. It is noteworthy that the estimation of $\beta_{exp}$ by the lifetime measurements can exclude the contribution of photon emission from the other QDs. This is important since our QD SPs exhibit certain levels of background cavity emission that is probably supplied by other QDs present in the cavity (~2 QDs on average with a rough estimation).

11. Achievable single photon coupling efficiency with current technology

In the current demonstration, $\beta_{exp}$ did not reach to the maximum possible value probably due to the deviation of the QD position from the cavity field maximum, which degrades the Purcell effect enhancement. If the QD position was optimum, the maximum Q-factor reached to that of the state-of-the-art PhC nanocavities [14]. With this fabrication quality, it would be possible to achieve a total single photon coupling efficiency of $\eta\beta > 95.7\%$ even under the presence of the nanocavity fabrication. Meanwhile, we have already demonstrated a cavity Q-factor over 50,000 for PhC nanocavities [14]. With this fabrication quality, it would be possible to achieve $\eta\beta > 98.4\%$ with $d = 250$ nm. Moreover, if the Q-factor reached to that of the state-of-the-art PhC nanobeam cavity (~ one million), the maximum possible $\eta\beta$ would become 99.6% for $d = 300$ nm. These estimations imply that the near-unity coupling of single photons into the waveguide is already within reach of the current process technology. It is noteworthy that the optimum $d$ for realizing the highest possible $\eta\beta$ varies with the achievable cavity Q-factor when not coupled to the waveguide, since $\eta\beta$ is determined between the waveguide coupling and the Purcell effect which increase or decrease depending on the total Q-factor.

12. Measured evolution of spontaneous emission rates as a function of detuning

Figure S8 shows measured spontaneous emission rates plotted as a function of cavity-QD detuning for the SPS discussed in Fig.
4(b) in the main text. The fastest emission rate of 3.8 ns$^{-1}$ is achieved at the emitter-cavity resonance. The emission rates become slower when detuned from the resonance. These behaviors support our conclusion that the emission rate enhancement originates from the Purcell effect within the nanocavity. The solid line in the figure shows a Lorentzian peak with the same linewidth of the cavity mode ($Q = 3,600$). The emission rate evolution does not match with the Lorentzian peak, being apart from the expectation from the conventional theory of the Purcell effect in cavity. We consider that this discrepancy is due to coupling of the QD to acoustic phonons. The phonon-assisted Purcell effect in QDs is known to support a broad range of the emission rate enhancement [15]. Indeed, the widened rate enhancement curve with a full width half maximum of 1.5 nm (2.3 meV) reasonably match with those discussed in the literature.

Fig. S8. Detuning dependence of the decay rates of the QD emission.

13. Comparing emission from the two exit ports

Figure S9 shows a comparison of two emission spectra of a QD SPS coupled to a waveguide, respectively measured from the two grating output ports. Each spectrum was measured by changing the position of the PL detection at the spectrometer. This was done by moving the sample such that the detection position is directly under the microscope. For all detection positions, the pump is directed at the nanocavity center. The pump source was an 819-nm continuous wave laser with an average power of 750 μW. We obtained almost the same emission spectra regardless of the measurement port, suggesting beam splitting at the moment that the cavity couples to the waveguide. Meanwhile, in the current work, we performed the second order intensity correlation measurements (which often require a beam splitter) using the emission from a single grating out-coupler and a bulk beam splitter added to the detection path. This is due to the limitation in our PL measurement setup. Our single photon counters with a small area of detection are located far away (> 5 m) from the microscope accessing the sample. As such, the field of views at the locations of the single photon detectors are too small to detect the emission from both the exit ports at once (the two ports are separated by 24 μm).

Fig. S9. Comparison of two emission spectra of a QD SPS coupled to a waveguide, respectively measured from the two grating output ports.

References

1. R. Ohta, Y. Ota, M. Nomura, N. Kumagai, S. Ishida, S. Iwamoto, and Y. Arakawa, "Strong coupling between a photonic crystal nanobeam cavity and a single quantum dot," Appl. Phys. Lett. 98, 173104 (2011).
2. Y. Ota, R. Ohta, N. Kumagai, S. Iwamoto, and Y. Arakawa, "Vacuum Rabi Spectra of a Single Quantum Emitter," Phys. Rev. Lett. 114, 143603 (2015).
3. J. Justice, C. Bower, M. Meitl, M. B. Mooney, M. a. Gubbins, and B. Corbett, "Wafer-scale integration of group III–V lasers on silicon using transfer printing of epitaxial layers," Nat. Photonics 6, 612–616 (2012).
4. S.-I. Park, Y. Xiong, R.-H. Kim, P. Elvikis, M. Meitl, D.-H. Kim, J. Wu, J. Yoon, C.-J. Yu, Z. Liu, Y. Huang, K.-c. Hwang, P. Ferreira, X. Li, K. Choquette, and J. A. Rogers, "Printed Assemblies of Inorganic Light-Emitting Diodes for Deformable and Semitransparent Displays," Science (80-. ). 325, 977–981 (2009).
5. A. Farao, I. Fushman, D. Englund, N. Stoltz, P. Petroff, and J. Vuckovic, "Dipole induced transparency in waveguide coupled photonic crystal cavities," Opt. Express 16, 12154 (2008).
6. Y. Hailoua, A. Bazin, P. Monnier, T. J. Karle, G. Roelkens, I. Sagnes, R. Raj, and F. Raineri, "Hybrid III-V semiconductor/silicon nanolasers.," Opt. Express 19, 9221–31 (2011).
7. E. Kuramochi, H. Taniyama, T. Tanabe, K. Kawasaki, Y.-G. Roh, and M. Notomi, "Ultrahigh-Q one-dimensional photonic crystal nanocavities with modulated mode-gap barriers on SiO2 claddings and on air claddings.," Opt. Express 18, 15859–15869 (2010).
8. K. Rivoire, S. Buckley, and J. Vuckovic, "Multiply resonant photonic crystal nanocavities for nonlinear frequency conversion," Opt. Express 19, 22198 (2011).
9. E. Waks and J. Vuckovic, "Coupled mode theory for photonic crystal cavity-waveguide interaction.," Opt. Express 13, 5064–73 (2005).
10. Y. Xu, J. Vuckovic, R. Lee, O. Painter, A. Scherer, and A. Yariv, "Finite-difference time-domain calculation of spontaneous emission lifetime in a microcavity," JOSA B 16, 465–474 (1999).
11. J.-P. Jahn, M. Munsch, L. Béguin, A. V. Kuhlmann, M. Renggli, Y. Huo, F. Ding, R. Trotta, M. Reindl, O. G. Schmidt, A. Rastelli, P. Treutlein, and R. J. Warburton, "An artificial Rb atom in a semiconductor with lifetime-limited linewidth," Phys. Rev. B 92, 245439 (2015).
12. K. Kuruma, Y. Ota, M. Kakuda, S. Iwamoto, and Y. Arakawa, "Time-resolved vacuum Rabi oscillations in a quantum dot-nanocavity system," arXiv 1803.05618 (2018).
13. M. Arcari, I. Sollner, A. Javadi, S. Lindskov Hansen, S. Mahmoodian, J. Liu, H. Thyresson, E. H. Lee, J. D. Song, S. Stobbe, and P. Lodahl, "Near-Unity Coupling Efficiency of a Quantum Emitter to a Photonic Crystal Waveguide," Phys. Rev. Lett. 113, 93603 (2014).
14. Y. Ota, S. Iwamoto, N. Kumagai, and Y. Arakawa, "Spontaneous Two-Photon Emission from a Single Quantum Dot," Phys. Rev. Lett. 107, 233602 (2011).

15. U. Hohenester, A. Laucht, M. Kaniber, N. Hauke, A. Neumann, A. Mohtashami, M. Seliger, M. Bichler, and J. J. Finley, "Phonon-assisted transitions from quantum dot excitons to cavity photons," Phys. Rev. B 80, 201311 (2009).