Suspended Spot-Size Converters for Scalable Single-Photon Devices

Ugurlu, Asli D.; Thyrrestrup, Henri; Uppu, Ravitej; Ouellet-Plamondon, Clauderic; Schott, Ruediger; Wieck, Andreas D.; Ludwig, Arne; Lodahl, Peter; Midolo, Leonardo

Published in:
Advanced Quantum Technologies

DOI:
10.1002/qute.201900076

Publication date:
2020

Document version
Peer reviewed version

Citation for published version (APA):
Suspended Spot-Size Converters for Scalable Single-Photon Devices

Aslı D. Uğurlu,¹, a) Henri Thyrrestrup,¹ Ravitej Uppu,¹ Claudéric Ouellet-Plamondon,¹ Rüdiger Schott,² Andreas D. Wieck,² Arne Ludwig,² Peter Lodahl,¹ and Leonardo Midolo¹

¹) Center for Hybrid Quantum Networks (Hy-Q), Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, DK-2100 Copenhagen, Denmark

²) Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität, Universitätsstrasse 150, D-44780 Bochum, Germany

We report on the realization of a highly efficient optical spot-size converter for the end-face coupling of single photons from GaAs-based nanophotonic waveguides with embedded quantum dots. The converter is realized using an inverted taper and an epoxy polymer overlay providing a 1.3 µm output mode field diameter. We demonstrate the collection of single photons from a quantum dot into a lensed fiber with a rate of 5.84±0.01 MHz and estimate a chip-to-fiber coupling efficiency of ∼ 48%. The stability and compatibility with cryogenic temperatures make the epoxy waveguides a promising material to realize efficient and scalable interconnects between heterogeneous quantum photonic integrated circuits.

Keywords: single-photon sources; quantum dot devices; semiconductor materials; nanofabrication

a) Author to whom correspondence should be addressed: asli.ugurlu@nbi.ku.dk
1. INTRODUCTION

Single-photon devices such as emitters, routers, and detectors have been recently developed worldwide to extend the functionality of classical photonic integrated circuits towards on-chip quantum information processing.\(^1\) Chip-scale integration enables scaling up these devices to achieve multi-photon operation required for simulation and computing.\(^2,3\) To this end, quantum dots (QDs) in gallium arsenide (GaAs) waveguides\(^4\) provide an excellent platform for generating photons with high indistinguishability and efficiency.\(^5\) However, despite the excellent progress in routing and detecting photons on this platform,\(^6,7\) scaling quantum optics experiments with integrated circuits based exclusively on GaAs is rather challenging due to propagation loss. Interfacing QDs to a different material system could enable a whole new range of applications for ultra-fast switching, low-loss routing, and filtering. For example, in Refs.\(^8,9\) a nanowire QD single-photon source was integrated with silicon nitride waveguides enabling filtering and routing operation. Alternatively, GaAs waveguides have been epitaxially lifted-off, transferred to a SiN substrate and processed in-situ.\(^10-12\) These approaches are challenging as they require compatible substrate materials (such as SiN) and introduce additional fabrication complexity when building electrical gates to QDs, which are essential to control charge noise of the emitter.\(^13\) Modern three-dimensional nanofabrication techniques such as photonic bonding\(^14\) have also been proposed for interfacing photonic circuits and constitute a potentially scalable approach to multi-chip photonics.

An alternative approach exploits an optical device that allows for the end-fire coupling of single photons from the cleaved edge of a GaAs chip to another optical chip or into an optical fiber. Side-coupling from the chip edge requires suppressing back-reflections at the cleaved waveguide edge and, most importantly, enlarging the mode size to avoid field mismatch at the interface. While back-reflection can be controlled using anti-reflection coatings, angled cleaving, or by introducing inverted tapers,\(^15-17\) the mode matching requires designing spot-size converters (SSC) to expand the optical mode profile. Inverted tapers with an overlay polymer are often adopted in silicon-on-insulator technology\(^18-21\) to perform this task. However, the fabrication process requires a low-index substrate (silica), which can physically support the polymer structure without introducing additional loss. Planar GaAs devices with deterministic photon-emitter coupling, on the contrary, are fabricated on a high-index sacrificial layer (Al\(_x\)Ga\(_{1-x}\)As) which is subsequently removed to form suspended
waveguides.\textsuperscript{22} A cladded inverted taper for this platform has not yet been demonstrated. Although near-unity coupling efficiency has been achieved using tapered fibers directly in contact with the waveguide,\textsuperscript{23,24} such evanescent coupling scheme suffer from mechanical failures, and are difficult to scale.

We have developed a method to fabricate suspended converters to expand the optical spot size of a single-mode GaAs waveguide (refractive index $n = 3.48$ and width 300 nm) to a Gaussian mode with $1.3 \ \mu m$ field diameter, which can be expanded further by increasing the converter length. The materials and processes used ensure vacuum and cryogenic compatibility and sufficient stability during cool-down and operation. The converter has an estimated efficiency of $\sim 48\%$, resulting in up to $5.84 \pm 0.01 \ MHz$ single-photon rates into a lensed optical fiber. In the present work a single lensed fiber is used for characterization, but the developed SSC enables interfacing, e.g., multiple photonic chips as well, and can readily be scaled-up to multiple channels. As a further benefit of the fabricated device, it has been proposed that the polymer cladding may serve the dual purpose of efficiently suppressing limiting phonon decoherence processes.\textsuperscript{25} This paves the way for an on-demand fiber-coupled single-photon source with simultaneously near-unity degree of indistinguishability of the photons and near-unity coupling efficiency.

The SSC presented here consists of a GaAs waveguide and an epoxy-based optical polymer cladding waveguide depicted schematically in Figure 1a. The width of the GaAs waveguide ($w_{IT}$) is gradually reduced to enlarge the area of its fundamental transverse electric (TE\textsubscript{00}) mode [see inset of Figure 1a], which is transferred to the overlay polymer waveguide with a size matched to the focal spot of a lensed fiber. Unlike tapers without polymers,\textsuperscript{15–17} the adiabatic condition is easier to fulfil, resulting in virtually perfect spot-size conversion. Here we focus on the TE modes only, since the QD dipole is exclusively in-plane and thus does not couple to transverse magnetic modes.\textsuperscript{4} The taper angle $\theta_t$ is designed to achieve an adiabatic transition into the fundamental mode of the cladding, according to $\theta_t \ll \Delta n_{\text{eff}}$, where $\Delta n_{\text{eff}}$ is the difference between the effective indices between the first two modes of the cladding polymer. The adiabatic taper ensures a gradual decrease of the effective refractive index of TE\textsubscript{00} to match the low-index overlay epoxy polymer ($n_{Epo} = 1.52$) and suppressing back-reflections in the taper. Figure 1b shows the calculated effective index change in the fundamental modes of the SSC (red dotted line) and GaAs inverted taper (blue dotted line) as a function of the taper width ($w_{IT}$). The two horizontal lines indicate the effective indices
Figure 1. End-fire mode coupling between the SSC and a lensed fiber. a) Sketch of the SSC made of a GaAs inverted taper and a polymer cladding. The inverted taper width and length are denoted by $w_{IT}$ and $L_{IT}$, respectively. A lensed fiber (with $1.3 \, \mu m$ mode-field diameter measured at $1/e^2$) is placed at the edge of the chip according to its working distance. The insets show the evolution of simulated mode profile cross-sections of the fundamental transverse electric (TE) mode as it propagates along the SSC. b) Calculated effective refractive index of the fundamental TE modes of the SSC (red dotted line) and the GaAs inverted taper (blue dotted lines) as a function of $w_{IT}$. The light blue and green lines are effective indices of the fundamental and the first order TE modes of the overlay polymer waveguide, respectively (with their corresponding mode profiles). c) Scanning electron microscope (SEM) image shows the fabricated spot-size converter. The highlighted blue shaded area is the overlay polymer.

of the fundamental and second-order (odd) mode, whose profiles are shown in the inset. The calculated difference $\Delta n_{\text{eff}} \simeq 0.1$ requires a maximum taper angle well below $5^\circ$. It should be noted that larger mode diameters are in principle achievable with wider polymer waveguides, provided that smaller angles and longer tapers can be accurately patterned and fabricated. In the present work, we have chosen an angle below $1^\circ$ (taper length $L_{IT}$ around $10 \, \mu m$), which is achievable with electron beam lithography and fulfills the adiabatic condition.
Figure 2. Fabrication process flow. a) The layer structure of the wafer used for fabricating the SSC. b) Ti/Au alignment markers are defined by e-beam evaporation and lift-off. c) e-beam lithography followed by reactive ion etching (RIE) is used to define GaAs nanostructures on the membrane. d) An epoxy polymer resin is spin coated on the substrate in order to form the overlay cladding and support structures by e-beam lithography. e) Scanning-electron micrograph of the fabricated inverse taper with a 60 nm tip width before the deposition of the polymer cladding.

1.1. Device fabrication

The suspended epoxy couplers, shown in the scanning electron microscope (SEM) image of Figure 1c, are fabricated on a GaAs wafer with the layer structure given in Figure 2a, grown by molecular beam epitaxy. The wafer contains a layer of self-assembled InAs QDs density 1-10 dots $/\mu m^2$ emitting at around 920 nm wavelength, located in the center of a 160-nm-thick membrane to ensure coupling to TE modes. Ti/Au marks are initially patterned and deposited on the wafer for precise alignment of the GaAs waveguides to the epoxy polymer (cf. Figure 2b). The GaAs waveguide circuit is fabricated by means of electron beam (e-beam) lithography, followed by dry and wet etching. The tapers are patterned on a 200-nm-thick CSAR 9 positive e-beam resist. A thin ($\sim 20 \text{ Å}$) Ti layer is
used as adhesion promoter to achieve narrow isolated lines of around 60 nm width. We have noticed that without proper adhesion, the resist tends to peel off at the tapered tip when the width is smaller than 100 nm. A slow-rate (35 nm/min) reactive ion etching (RIE) process (BCl3/Ar with 1:2 flow ratio) is used in combination with end-point detection to etch the membrane a few tens of nm into the sacrificial layer, cf. Figure 2c. This ensures that the spin-coating of the epoxy resin is sufficiently planar and that the bottom face of the epoxy waveguide is aligned to the GaAs waveguide. Figure 2e shows an SEM image of the GaAs waveguide taper before the polymer deposition.

A commercial epoxy polymer resin EpoCore2 (Microresist Gmbh) is used to coat the wafer with a final thickness of 1.15 µm. The polymer acts as a negative resist with sensitivity to both ultra-violet light (i-line) and electron beams.26,27 Here, we used electron beam lithography in an Elionix F-125 system (acceleration voltage 125 keV and a uniform dose of 9 µC/cm²) enabling smooth and vertical patterning of the waveguide with small (<20 nm) alignment errors. After patterning, the polymer is hard baked to make it adhere permanently on the substrate. Leftover residues from the epoxy are removed with an oxygen plasma step. Before undercut in a hydrofluoric acid solution (HF 5%), as shown in Figure 2d, the sample is cleaved to leave a flat polymer interface at the edge. Since the suspended structure can bend or collapse onto the substrate after the undercut due to capillary forces, the polymer is patterned with side tethers perpendicular to the propagation direction, in order to support it without adding significant loss (−0.025 dB) as confirmed by numerical simulations. A small bending, likely caused by strain relaxation, is observed on longer polymer structures.

1.2. Numerical analysis of the spot-size converter

The design of the SSC is optimized by three-dimensional (3D) finite-element calculations. Figure 3a shows the distribution of the simulated y-component of the fundamental TE mode (Ey) plotted on the central cross-section of the device, and at a wavelength of 930 nm. The power transmitted over the SSC is evaluated using a scattering matrix (S-matrix) formalism to estimate the transmission efficiency of the SSC ηSSC. The efficiency depends on the length of the linear inverted taper LIT and the width of the waveguide at the tip. As mentioned above, the smallest achievable tip in the fabrication process has a width of 60 nm, which is sufficient to achieve negligible mode mismatch (cf. the last two mode profiles in the inset
Figure 3. Numerical analysis of the SSC efficiency. a) Cross-section of the 3D optical simulation showing the cut view of the inverted taper SSC, where the waveguide width is tapered from 200 nm to 60 nm over 15 µm length and the polymer height is 1.15 µm. b) Calculated transmission efficiency $\eta_{SSC}$ as a function of the taper length. c) Calculated transmission efficiency as a function of wavelength for material’ refractive indices at cryogenic (4.2 K) and room temperature (293 K) at $L_{IT} = 15$ µm.

The transmission efficiency $\eta_{SSC}$ is plotted in Figure 3b as a function of the taper length. Near-unity ($\eta_{SSC} = 98.9\%$) is predicted when $L_{IT} = 15$ µm. Figure 3c shows the calculated efficiency for $L_{IT} = 15$ µm as a function of wavelength at room and cryogenic temperature. No significant deviation from the optimal coupling is observed over a 50 nm bandwidth, indicating that the coupler is very broadband. To avoid excessive bending of the structures after undercut, the samples are designed with 11 µm taper length, which results in slightly lower efficiency of $\eta_{SSC} = 94.6\%$.

The SSC transmission efficiency $\eta_{SSC}$ is the theoretical maximum power transfer that the device would achieve in case of direct face-to-face coupling to a waveguide of same refractive index and mode profile (i.e., neglecting any additional index or mode mismatch related to the coupling). In this work, we have calculated the coupling efficiency for a lensed fiber with 1.3 µm mode-field diameter (MFD), which is positioned at a working distance of 4.5 µm from the end face of the chip. Such characterization method utilizing lensed fibers introduces additional loss related to the polymer-air-glass interfaces and to the alignment (displacement and angle) of the lensed fiber [the alignment scheme is illustrated in Figure 4a].
in Figure 4b and 4c show the calculated far-field distribution (two-dimensional map and cross-sections, respectively) of the optical mode emerging from the end face of the polymer, which appears nearly Gaussian.

We estimated the mode overlap by a normalized overlap integral between the complex electric field of the waveguide out-coupler \(E_{y,oc}\) and the fiber \(E_{y,fiber}\) as follows:\textsuperscript{28–30}

\[
\eta_{\text{Overlap}} = \frac{\left| \iint E_{y,oc}^* E_{y,fiber} \, dy \, dz \right|^2}{\iint |E_{y,oc}|^2 \, dy \, dz \cdot \iint |E_{y,fiber}|^2 \, dy \, dz},
\]

where the fundamental TE mode of the out-coupler \(E_{y,oc}\) is computed numerically and the circular Gaussian mode of the single mode lensed fiber \(E_{y,fiber}\) is approximated by a perfect Gaussian profile with an MFD of 1.3 \(\mu m\). When the SSC is perfectly aligned to the focal plane of the lensed fiber the theoretical overlap efficiency is found to be 80.4\%, indicating that the square profile of the epoxy waveguide introduces diffraction that is not captured by an ideal lensed fiber. Making wider polymer waveguides and considering the overlap to a size-matched Gaussian profile is expected to mitigate this issue as confirmed by numerical simulations (> 97\% mode overlap for 3-um-wide polymers).

The overlap integral of Equation 1 allows us to estimate the alignment tolerance between the out-coupler and the lensed fiber. Figure 4d and Figure 4e show the coupling efficiency as a function of the lateral and angular fiber offset, respectively. We identify a 3 dB loss in the coupling efficiency for a lateral misalignment exceeding 0.5 \(\mu m\) or angular deviations around 25 \(^\circ\). In our experiments, the fiber is mounted on nano-positioners with a sub-nm positioning resolution and 5 nm repeatability, which suggests that the lateral misalignment is not an issue. Angular deviations, however, are much more difficult to control as they require stages with rotational degrees of freedom. Additionally, the taper itself can slightly bend during cool-down due to thermal stress. We estimate that our total angle misalignment does not exceed 10 \(^\circ\) by inspecting the setup with an optical microscope.

An additional loss term is caused by the reflection at the facet of the epoxy polymer out-coupler. We estimate them using the Fresnel coefficient for a polymer-air interface at normal incidence, resulting in approximately 4\% loss \(R_{\text{polymer}} = 4\%\). In summary, the theoretical chip-to-fiber coupling efficiency of the SSC has been estimated numerically to be 73\% and is given by the product of the taper transmission efficiency \(\eta_{\text{SSC}} \simeq 94.6\%\), the transmission across polymer-air interface \(T_{\text{polymer}} = 1-R_{\text{polymer}} (96\%)\), and the mode matching to a fiber, which in the ideal case is \(\eta_{\text{Overlap}} = 80.4\%\).
2. CHARACTERIZATION AND RESULTS

The sample is mounted on a piezo stack and cooled down to 4.2 K in a bath cryostat. A lensed fiber is mounted next to the sample on a separate piezo stack, fed through the cryostat using a hermetic sealing, and finally spliced to another single-mode fiber and interfaced to the detection setup. A microscope objective is used to excite the QDs from the top, and the photoluminescence (PL) is collected on the fiber by manually optimizing its alignment. We investigated a QD placed in a nanobeam waveguide, as shown in Figure 5a, terminated by
an out-coupler. The QD line is pumped via above-band excitation using an 810 nm pulsed laser source with a repetition rate of 76 MHz. The QD integrated intensity as a function of the excitation power (from 0.2 µW to 40 µW) is shown in Figure 5b. The saturation power $P_{\text{sat}} = 1.78 \pm 0.25$ µW is extracted at a 95% confidence interval by fitting the peak counts of the QD with the function $I = I_{\text{max}}(1 - \exp(-P/P_{\text{sat}}))$ (solid red line). The spectrum of the QD is successively recorded by a cooled CCD camera (spectral resolution $\sim 20$ pm).

Figure 5c shows the excitonic line of the QD for an excitation power $P = 1$ µW. In order to characterize the single-photon nature of the light emitted by the QD, we carried out an auto-correlation measurement using a Hanbury Brown-Twiss setup. The QD is pumped at 0.56$P_{\text{sat}}$ and subsequently filtered with a grating setup (300 pm spectral bandwidth). The filtered signal is split by a 50:50 fiber beam-splitter whose outputs are connected to two fiber-coupled silicon avalanche photo-diodes (APDs). A time-tagging module (PicoHarp 300) is used to record correlation events between the two detectors. The result of the auto-correlation experiment is shown in Figure 5d, where the coincident counts are plotted as a function of the delay time between the two APDs. The plot reveals a strong anti-bunching at zero time delay, $g^{(2)}(0) = 0.015 \pm 0.002$, confirming the single-photon nature of the QD emission. Figure 5e shows the auto-correlation experiment at 1.68$P_{\text{sat}}$ (3 µW), where the source generates single photons with a probability of multiphoton emission of 11 ± 0.3%. The data are fitted with two-sided exponentials and the $g^{(2)}$ value is obtained by dividing the area of the central peak to the peak around a time delay of 250 ns on account of blinking over short timescales. The purity of the source could be improved even further by fabricating the structures on a sample with lower QD density or by adopting different excitation schemes such as p-shell or resonant excitation.\textsuperscript{32,33}

3. CHARACTERIZATION OF THE COUPLING EFFICIENCY OF THE DEVICE

The recorded single-photon emission rate from the QD can be further scrutinized in order to experimentally extract the efficiency of the SSC. We record in total a single-photon count rate of 167 kHz on the APD at the saturation. Based on this number we can extract the photon rate inside the fiber to be 5.84 ± 0.01 MHz by accounting for the measured transmission efficiency of the various components of the detection setup: (i) collection optics.
Figure 5. Measurement of single-photon collection from the SSC. a) Scanning electron microscope image of the nanobeam waveguide terminated by the SSC. The QD coupled to the waveguide is excited from the top by the pump laser and single photons are collected horizontally from the SSC at the edge of the sample. b) Detected single-photon rate as a function of the pump power exciting the QD from which the saturation power is extracted. c) Photoluminescence spectrum of a QD emitting at 913.1 nm under above-band excitation with a pulsed laser. d) Auto-correlation measurement of the QD emission line in (c) taken at pump power of 1 µW (0.56x$P_{sat}$). The coincidence count histograms are fitted with exponential decays in order to extract $g^{(2)}(0) = 0.015 \pm 0.002$. e) Auto-correlation measurement of the QD emission line in c) taken at pump power of 3 µW (1.68x$P_{sat}$). The coincidence count histograms are fitted with exponential decays in order to extract $g^{(2)}(0) = 0.11 \pm 0.003$.

To get to the chip-to-fiber efficiency of the SSC we estimate the rate of single photons...
present inside the GaAs waveguide and compare that to the measured value of single photons in the fiber. Time-resolved PL (not shown) reveals two-time exponential decay, typical of neutral exciton emission. The fast decay rate, associated with the bright exciton, is 1.75 ns$^{-1}$ while the slow rate of 0.27 ns$^{-1}$ is associated with dark exciton recombination in the form of either non-radiative recombination or dark-bright spin flips.\textsuperscript{31} For the above-band excitation scheme applied here, the spin-flip rate was previously found to be several orders of magnitude slower than the total recombination time, i.e., the dark state primarily recombines non-radiatively.\textsuperscript{31} Consequently, the occupation of dark excitons leads to an effective preparation efficiency of the source of $\eta_{\text{QD}} \sim 50\%$. Furthermore, since the waveguide is two-sided only half of the coupled photons are collected leading to $\beta_{\text{directional}} \sim 40\%$ based on the calculated average $\beta$-factor for a $y$-oriented dipole in a 300 nm wide waveguide.\textsuperscript{17,25} Finally propagation loss in the 117 $\mu$m-long nanobeam waveguide amounts to $\eta_{\text{nb}} = 81 \pm 2\%$,\textsuperscript{6} leading to an overall photon rate at the entrance of the SSC of 5.84$\pm$0.01 MHz.

Based on the above analysis, we can quantify the overall efficiency of the fiber-coupling comprising of both the SSC and the aligned tapered fiber. We estimate the chip-to-fiber coupling efficiency to be $\sim 48\%$. The minor discrepancy between experimental estimate and theory can likely be attributed to the angular deviations in the alignment of the fiber or fabrication imperfections influencing the taper tip.

4. CONCLUSIONS

We reported the design, fabrication, and characterization of a suspended spot-size converter for the end-face coupling of single photons from QDs. The device holds great promise as a building block for scalable quantum information processing and for the realization of photonic quantum networks. The measured efficiency of $\sim 48\%$ is currently limited by the characterization method, which is based on a lensed fiber. Direct coupling to a second chip could lead to better alignment and would increase the single-photon rate further. Moreover, the design allows for the straightforward scaling of the number of couplers to multiple ports, thereby enabling multi-photon protocols. The efficiency of the device could readily be improved further by: (i) the termination of the waveguide on one side with a mirror will double the photon collection efficiency; (ii) integrating quantum dot embedded photonic crystal waveguides with the presented spot-size converter can boost the single-photon generation
### TABLE I. Transmission efficiencies and performances of the single-photon source out-coupled to a lensed fiber via the SSC. Part I: theoretical coupling efficiency of the spot-size converter is a product of the SSC transmission efficiency (based on 3D FEM simulations), transmission efficiency of the polymer overlay waveguide as a result of reflection losses due to the Fresnel reflectivity at the cladding facet, mode overlap efficiency at far-field. Part II: off-chip efficiencies for detecting, filtering, collection optics. Part III: on-chip efficiencies of the QD excitation and single-photon transmission. Part IV: experimentally calculated chip-to-fiber coupling efficiency.

<table>
<thead>
<tr>
<th>I</th>
<th>Theoretical transmission efficiency $\eta_{SSC}$</th>
<th>94.6%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theoretical polymer transmittance $T_{\text{polymer}}$</td>
<td>96%</td>
</tr>
<tr>
<td></td>
<td>Theoretical mode overlap efficiency $\eta_{\text{Overlap}}$</td>
<td>80.4%</td>
</tr>
<tr>
<td></td>
<td>Theoretical coupling efficiency</td>
<td>73%</td>
</tr>
<tr>
<td>II</td>
<td>APD count rate</td>
<td>0.167 MHz</td>
</tr>
<tr>
<td></td>
<td>Detector efficiency $\eta_{\text{APD}}$</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>Spectral filter efficiency $\eta_{F}$</td>
<td>30 ± 1%</td>
</tr>
<tr>
<td></td>
<td>Collection optics efficiency $T$</td>
<td>32 ± 2%</td>
</tr>
<tr>
<td></td>
<td>Single-photon rate at the lensed fiber</td>
<td>5.84 ± 0.01 MHz</td>
</tr>
<tr>
<td>III</td>
<td>Laser repetition rate</td>
<td>76 MHz</td>
</tr>
<tr>
<td></td>
<td>Preparation efficiency $\eta_{\text{QD}}$</td>
<td>$\sim$ 50%</td>
</tr>
<tr>
<td></td>
<td>Waveguide $\beta_{\text{directional}}$</td>
<td>$\sim$ 40%</td>
</tr>
<tr>
<td></td>
<td>Nanobeam transmission efficiency $\eta_{\text{nb}}$</td>
<td>81 ± 2%</td>
</tr>
<tr>
<td></td>
<td>Single-photon rate at the SSC input</td>
<td>$\sim$ 12 MHz</td>
</tr>
<tr>
<td>IV</td>
<td>Chip-to-fiber coupling efficiency</td>
<td>$\sim$ 48%</td>
</tr>
</tbody>
</table>

efficiency to near-unity; \cite{34} (iii) resonant excitation of the QD could improve the preparation...
efficiency to unity; (iv) developing longer tapers on the waveguide and performing direct end-face coupling to a cleaved fiber with matched mode-field diameter would increase the SSC efficiency further up to > 95%. It is expected that any alignment imperfections of the fiber could be overcome chip-to-chip or chip-to-fiber coupling using the SSCs. For instance the SSC is readily applicable in a hybrid approach to quantum-information processing using two different photonic chips, where one is a source chip delivering deterministic photonic qubits and the other is a processing chip implementing, e.g., a complex quantum algorithm.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Xiaoyan Zhou for fruitful discussions about the numerical simulations and Zhe Liu for the helpful comments on the fabrication. We gratefully acknowledge financial support from the European Research Council (ERC Advanced Grant 'SCALE'), Danish National Research Foundation (Center of Excellence 'Hy-Q'), Innovation Fund Denmark (Quantum Innovation Center 'Qubiz'), Styrelsen for Forskning og Innovation (FI)(5072-00016B QUANTECH), Bundesministerium für Bildung und Forschung (BMBF) (16KIS0867, Q.Link.X), Deutsche Forschungsgemeinschaft (DFG) (TRR 160).

REFERENCES


