A Pure and Indistinguishable Single-Photon Source at Telecommunication Wavelength

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On-demand single-photon sources emitting pure and indistinguishable photons at the telecommunication wavelength are critical assets toward the deployment of fiber-based quantum networks. Indeed, single photons may serve as flying qubits, allowing communication of quantum information over long distances. Self-assembled InAs quantum dots embedded in GaAs constitute an excellent nearly deterministic source of high-quality single photons, but the vast majority of sources operate in the 900–950 nm wavelength range, precluding their adoption in a quantum network. A quantum frequency conversion scheme is presented here for converting single photons from quantum dots to the telecommunication C band, around 1550 nm, achieving 40.8% end-to-end efficiency, while maintaining both high purity and a high degree of indistinguishability during conversion with measured values of $g^{(2)}(0) = 2.4\%$ and $V^{(\text{corr})} = 94.8\%$, respectively.

1. Introduction

Single photons at telecommunication wavelengths constitute a key resource for quantum communication, enabling transmission of quantum information over long distances across optical fiber networks without loss of coherence. A complete quantum network would require the ability to exchange information between matter qubits and photons with high fidelity. This demands a deterministic emitter-photon interface capable of realizing photon generation and entanglement in a scalable manner. In combination with mature foundry-based silicon photonic integrated circuit technology, the realization of a scalable quantum photonic technology is within reach. A solid-state quantum emitter deterministically coupled to a cavity or waveguide is an attractive source of on-demand single photons. In particular, self-assembled InAs quantum dots (QDs) in GaAs offer a mature technology for photon generation and a platform for interfacing electron spin and photons in which the decoherence and noise processes have been identified and reduced. Despite the excellent performance, a major drawback of InAs-based QD emitters is that the emission wavelength is typically in the range of 900–950 nm. However, standard single mode fibers experience the lowest attenuation coefficient of 0.16–0.2 dB km$^{-1}$ at around 1550 nm, while the attenuation in the 900–950 nm range is severely limited by Rayleigh scattering to about 1–1.5 dB km$^{-1}$. Hence, the QDs typical emission wavelength reduces their applications to communication over only short distances and impedes interfacing to advanced quantum photonic integrated circuits on the silicon-on-insulator platform.

Controlling the epitaxial growth of self-assembled QDs does enable shifting the wavelength of the emitters to longer wavelengths, that is, to the telecommunications O-band (1300 nm) and C-band (1550 nm), by providing a deeper electron–hole confinement. However, InAs QDs in pseudomorphically strained InGaAs quantum wells or grown by metalorganic vapor-phase epitaxy typically suffer from high dislocation densities or large background impurity concentration, resulting in higher charge noise, blinking, or low internal quantum efficiency from non-radiative decay channels. In fact, to date, several demonstrations of single-photon emission at telecommunication wavelengths exist, but there are only few reports on the photon indistinguishability where temporal post-selection was implemented at the cost of reduced source efficiency. These works are important stepping stones toward the realization of a quantum network, and indeed prepare-and-measure

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quantum key distribution protocols have already been implemented with such sources, as they do not require indistinguishable photons.\cite{25–29} However, the full potential of the technology, that is, in device-independent quantum key distribution or one-way quantum repeaters, is only realized with high-efficiency on-demand sources of indistinguishable photons in the telecom range.

An alternative route to reach this goal exploits quantum frequency conversion (QFC) of the emitted single photons to the C-band, thereby bridging the gap between the mature InAs emitter and quantum communications applications. Previous works have shown efficient QFC to either the O-band\cite{30} or the C-band\cite{31,32} while maintaining the purity of the single-photon source. Recently, Morrison et al.\cite{33} also analyzed the indistinguishability after QFC and reported two-photon interferometry and quantum communications applications. Preliminary works have shown efficient QFC to either the O-band\cite{30} or the C-band\cite{31,32}, while maintaining the purity of the single-photon source. Recently, Morrison et al.\cite{33} also analyzed the indistinguishability after QFC and reported two-photon interference of up to (67 ± 2)\%.

In this work, we report stable and efficient QFC of single photons from QDs to the telecommunication C-band, with a total (40.8 ± 0.8)\% system efficiency and simultaneously low multi-photon probability of (2.4 ± 0.2)\% and high degree of indistinguishability (94.8 ± 1.6)\% of the converted photons, without implementing any post selection. The conversion method uses difference-frequency generation in periodically poled lithium niobate (ppLN) waveguides, approaching near-unity internal conversion efficiency, which is only limited by fabrication imperfections (e.g., non uniform waveguide cross-section), mode matching between the three waves, and scattering. Our QFC scheme enables implementing single-photon-based protocols for quantum key distribution over long distances and combining high-quality on-demand single-photon sources with photonic integrated circuits based on silicon photonics.

2. Experimental Setup Characterization

The frequency conversion process implemented in this work is based on difference frequency generation (DFG). DFG is a second-order non-linear process in which photons from two input wavelengths, \(\lambda_1\) and \(\lambda_2\), are combined to produce output photons at a third wavelength \(\lambda_3\) that is, at the difference of the input frequencies. Since the InAs/GaAs QDs emit photons in the range of 900 to 950 nm (\(\lambda_1\)), and the goal is to convert them to the telecommunication C-band around 1550 nm (\(\lambda_3\)), a pump laser source at around 2100-2500 nm (\(\lambda_2\)) is required. In this work, we used a 48 nm long ppLN waveguide with 26 μm poling period. A schematic representation of the setup used for DFG is shown in Figure 1a. The setup consists of one input fiber for photons at 940 nm (subsequently collimated to a free-space beam), free-space optics to optimally couple to the desired ppLN waveguide, and an output fiber where converted telecommunication photons are coupled into. We define the system, or end-to-end, efficiency as measured from fiber to fiber. At the input of the ppLN waveguide, single photons from the QD are mixed with light from a high-power continuous-wave pump laser. At the output, the converted 1550 nm wavelength photons are spectrally filtered and directed to the output fiber. Spectral filtering is crucial to achieve a low-noise process, as required to reach high purity and indistinguishability. Here, we use a longpass filter to remove residual input photons and second harmonic generation from the pump and a blazed grating acts as a narrow bandpass filter to extinguish the pump from the converted output. Further details on the experimental setup are reported in Supporting Information.

The system efficiency is characterized with a classical light beam at the input. We use a continuously tunable laser emitting...
In the second method, we compare the 940 nm laser transmission losses occurring at the input and output of the waveguide (e.g., arising from surface roughness), we are estimating the coupling efficiency (96%). As we neglect the potential scattering losses and from the propagation loss of the 1550 nm (with the uncertainty coming from the in- and out-coupling scenarios, which are estimated assuming 100% internal conversion efficiency and including the measured optical loss of the setup (with the uncertainty coming from the in- and out-coupling scattering losses and from the propagation loss of the 1550 nm photons in the waveguide). The measured values and the fit show that the maximum conversion efficiency is lower than in the ideal scenario and it is reached at higher pump power. The lower efficiency is explained by a non-unity internal conversion efficiency, which is mainly due to an imperfect coupling of the single photons to the fundamental mode of the waveguide, which supports several modes at 940 nm. We suspect that the requirement for higher pump power to reach saturation can be explained by assuming a varying waveguide cross-section along its length due to fabrication imperfections (see Supporting Information).

We estimate the internal conversion efficiency using two methods, with each method providing either the upper or the lower bounds. In the first method, we measure the input and output converted power right before and after the aspheric lenses used for in- and out-coupling and then factor out the aspheric lenses' insertion loss (6.5% at both 940 and 1550 nm) and the simulated coupling efficiency (96%). As we neglect the potential scattering losses occurring at the input and output of the waveguide (e.g., arising from surface roughness), we are estimating a lower bound for the actual internal conversion efficiency \( \eta_{\text{int}}^L \). In the second method, we compare the 940 nm laser transmission with pump laser on and off to estimate the depletion due to DFG. As we neglect the optical loss at 1550 nm, we are estimating the efficiency with an upper bound \( \eta_{\text{int}}^U \). We measured \( \eta_{\text{int}}^L = (86 \pm 0.3)\% \) and \( \eta_{\text{int}}^U = (95 \pm 1)\% \).

3. Quantum Frequency Conversion

The QFC experiment is performed with a QD source in a 1.6 K closed-cycle cryostat (see ref. [2] for a description of the source) emitting at 942 nm. The end-to-end efficiency of the QFC is obtained by comparing the single-photon rate at 1550 nm at the output of the setup with the single-photon rate at 942 nm at the input of the setup. Under \( x \)-pulse resonant excitation (with 73 MHz repetition rate and 20 ps pulse duration), we measure an in-fiber rate of \( N_{\text{in}} = (2.21 \pm 0.02) \) M counts s\(^{-1} \) at the fiber input of the frequency conversion setup. The achieved in-fiber count rate at the output of our setup is \( N_{\text{out}} = (905 \pm 15) \) kcounts s\(^{-1} \).

Both \( N_{\text{in}} \) and \( N_{\text{out}} \) are obtained measuring the photon rate with SNSPDs and correcting for the setup-to-detector fiber transmissions and detector efficiencies (see Supporting Information). This leads to an overall external conversion efficiency of \( \eta_{\text{ext}} = N_{\text{out}}/N_{\text{in}} = (40.8 \pm 0.8)\% \). The achieved \( \eta_{\text{ext}} \) is fully consistent with the value obtained for classical input light, as discussed previously, meaning that the bandwidth of the QD (measured to be around 500 MHz) is sufficiently narrow to be covered by the frequency conversion process bandwidth, whose full width half maximum is measured to be 115 GHz.

In a second experiment with a different QD source (operated in a 4 K closed-cycle cryostat) emitting at 945 nm, the quantum characteristics of the source were investigated both before and after the the QFC process. The output wavelength was moved to 1543 nm in order to completely eliminate the noise coming from the pump laser, either direct or Raman. Figure 3 on the left shows the measured lifetime of the source (measured with the setup shown in Figure 1b), the detector/instrument response function (IRF), and the fit with an exponential decay convolved with the IRF. From the fitted curve, we can extract a time constant of \( \tau_{945} = (0.271 \pm 0.016) \) ns. On the right, we report the same measurement carried out on the converted photons. We find \( \tau_{1543} = (0.269 \pm 0.004) \) ns, confirming no change in the lifetime of the frequency converted single-photons. To assess the purity of the source, we measured the second order correlation \( g^{(2)}(0) \) of the photons at 945 nm and at 1543 nm using a Hanbury Brown–Twiss (HBT) setup as shown in Figure 1c. The resulting coincidence counts are reported in Figure 3b in the left (right) plot before- (after-)QFC with an integration time of 10 (30) min. By fitting the data, we can compare the area of the central peak with the area of a far-away peak (at around 40 μs delay, see Supporting Information, for the long time scale behavior). This gives us \( g_{945}^{(2)}(0) = (2.0 \pm 0.3)\% \) and \( g_{1543}^{(2)}(0) = (2.4 \pm 0.2)\% \) in the two wavelength regimes. The two values and error ranges show that the QFC process does not increase the multi-photon probability, that is, the C-band single-photon source is only limited by the few percent impurity of the original QD source.

Finally, we characterize the indistinguishability of the source, before and after conversion, by measuring coincidence counts in a Hong–Ou–Mandel (HOM) setup, shown in Figure 1d. Two photons generated by consecutive excitation pulses are...
Figure 3. Measured lifetime and purity before (left) and after conversion (right). a) Lifetime measurements. The lifetime is measured and plotted in orange. The instrument response function (shown in yellow) is convolved with an exponential decay to precisely fit the single photon lifetime (fit shown in dashed black). b) Purity measurements. Coincidence counts are measured in a HBT setup. Data are shown with yellow points while the fit is shown in orange.

Figure 4. Measured indistinguishability before (left) and after conversion (right). a) Coincidence counts. Data, measured in a HOM setup, are shown in orange (yellow) for the co-polarized (cross-polarized) configuration. b) Zoom in view on the central peaks. Normalized data are shown with yellow points in the cross-polarized scheme (fit shown in orange), and with purple points in the co-polarized scheme (fit shown in blue). Each trace is first normalized to a far-away side peak area, and then both are normalized on the cross-polarization central peak for clarity.
interfered in an asymmetric Mach–Zehnder interferometer, and a half waveplate is used to cross-polarize the photons to make them distinguishable. The results are shown in Figure 4a. On the left, we report measurements from the QD source at 945 nm (with 10 min integration time per trace), and on the right similar measurements after conversion at 1543 nm (1 h integration time per trace). In both cases, the raw visibility is obtained by fitting the data, normalizing each trace with the area of a peak at a delay of approximately 500 ns, and then comparing the areas of the central peaks in the co- and cross-polarized cases, \( V_{\parallel}^{(\text{raw})} = (A_\parallel - A_\perp)/A_\parallel \). The normalized coincidence counts are shown in Figure 4b for both before and after conversion measurements for ease of comparison. The cross-polarized trace recorded after conversion suffers from an overall drop in counts compared to the co-polarized configuration. We attribute this to the high polarization dependence of the detectors and to the long acquisition time of the traces after conversion; indeed, the two traces have been recorded without realignment of the QD source or the QFC setup. The resulting raw visibilities are \( V_{\parallel}^{(\text{raw})} = 89.2 \pm 0.9\% \) and \( V_{\perp}^{(\text{raw})} = 88.8 \pm 1.4\% \). Taking into account the non zero \( g^{(2)}(0) \) (assuming it is due to indistinguishable photons) and the imperfections in the optical setups such as imperfect splitting ratios of the beam splitters and non-unity interference visibility (see Supporting Information), we extract the corrected visibility\[34] \( V_{\parallel}^{(\text{corr})} = 93.5 \pm 1.1\% \) and \( V_{\perp}^{(\text{corr})} = 94.8 \pm 1.6\% \) before and after conversion, respectively. Both the raw and corrected visibility data reveal a high degree of indistinguishability of the QD source, which is preserved after QFC. We observe a qualitatively different shape of the suppressed HOM peak for the two sets of data, which can be attributed to the fact that detector response time at 1543 nm is significantly faster than at 945 nm, which is evident in the IRF of the 945 and 1543 nm detectors in Figure 3a (further analysis in Supporting Information).

\[ V_{\parallel}^{(\text{raw})} = \frac{(A_\parallel - A_\perp)}{A_\parallel}, \quad V_{\perp}^{(\text{raw})} = \frac{(A_\perp - A_\parallel)}{A_\perp} \]

\[ V_{\parallel}^{(\text{corr})} = \frac{(V_{\parallel}^{(\text{raw})} - g^{(2)}(0))}{1 - g^{(2)}(0)}, \quad V_{\perp}^{(\text{corr})} = \frac{(V_{\perp}^{(\text{raw})} - g^{(2)}(0))}{1 - g^{(2)}(0)} \]

4. Conclusions

In conclusion, we have demonstrated frequency conversion of indistinguishable single photons emitted in the 900–950 nm to the telecommunication C-band around 1550 nm. We have shown simultaneously a high external efficiency of 40.8% and the low-noise behavior required to maintain the high purity and indistinguishability characteristic of the QDs used as sources, achieving \( g^{(2)}(0) = 2.4\% \) and \( V^{(\text{corr})} = 94.8\% \), respectively. The end-to-end conversion efficiency is currently limited by (apart from the optical loss of the setup components) the coupling of the converted C-band photons to the output fiber, and could be readily improved by tailoring the light wavefront to achieve better mode matching, for example, using spatial light modulators. Future work will address integrating QFC on-chip, using thin-film ppLN or GaAs waveguides\[35–37\] which are expected to further reduce the required pump power and allow to scale up the conversion to multiple emitters. The demonstrated low-noise QFC enables developing schemes for long-distance quantum communication, and it offers the possibility to compensate for the inhomogeneous broadening of the QD emission wavelength, as demonstrated by several works\[18,19\] recently achieving up to \((67 \pm 2)\%\) two-photon indistinguishability.\[40\] Moreover, our schemes could be used in combination with highly-efficient photonic integrated circuits to implement device-independent quantum key distribution protocols, where maintaining photon coherence after conversion is crucial to perform Bell-state measurements at a remote heralding station.\[41,42\] Finally, the QFC demonstrated here closes the gap between the single-photon source technology of InAs QDs in GaAs and the mature silicon-on-insulator photonic integrated circuit technology\[42–45\] enabling the modular integration of quantum communication, computing, and simulation.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

P.L. is founder and minority shareholder in the company Sparrow Quantum. The authors declare that there are no other competing interests.

Data Availability Statement

All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supporting Information. Additional data related to this paper are available from the corresponding author upon reasonable request.

Keywords

quantum frequency conversion, quantum photonics, single photon sources

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