

*This manuscript has been previously reviewed at another Nature Research journal. This document only contains reviewer comments and rebuttal letters for versions considered at Communications Physics.*

Reviewers' comments:

Reviewer #1 (Remarks to the Author):

The authors show the implementation of a tunable LED emitting telecom-wavelength entangled photons and its use in a fibre network installed in a city. I found this work interesting, in particular due to the thorough description of the conditions necessary to implement an experiment out of the laboratory.

The manuscript is well written, and the data carefully analysed.

I will be happy to see it published in communications physics.

Before that, I would like to propose few changes that may help the reader appreciating even more this study:

1) I think it will be beneficial to add in the text the fabrication yield for this LED. Indeed, since the manuscript is device oriented, it is important to state reproducibility for future reference, in order to know how many devices and dots one needs to check before finding the suitable one

2) The approach followed to realize such an emitting diode is very interesting. In my opinion it does not matter if the photon emission arises from the direct recombination of electrically injected carriers or, as here, from the optical pumping of the dot via an external diode, being on the same chip. Nevertheless, it is important to remark that the excitation process is still optical so it would be interesting to compare these performances with optically excited.

3) I really appreciate the level of details in the sample description. Can the authors add the doping levels and profile?

4) For the study, a value of FSS of around 5 micro eV has been used. Is there a reason why the authors did not use a smaller FSS value? This can impact the post-selection window width

5) On a similar note, do the authors have an idea on the photon coherence? Is a post-selection window of 48 ps enough for realistic implementation of complex networks?

I will be very happy to support publication after having clarified these few points.

Reviewer #2 (Remarks to the Author):

I am surprised that the manuscript was hardly changed in response to the many points raised by the reviewers. Hence, most of the criticism is still relevant and remain to be dealt with by the authors.

For instance (and I only mean for instance), yield and reproducibility have not been clarified in the manuscript, although the authors have given a good and valuable response in their response letter. Hence, without providing data on yield and reproducibility in the manuscript the work should not(!) be published.

Another „for instance”: In the introduction the authors say "Good suppression of multi-photon emission is one of the cornerstones for the next level of high-speed quantum network applications, going beyond conventional quantum key distribution (QKD)". The second part of this sentence is noteworthy, as the authors argue in their response in a contradictory fashion: "photon indistinguishability is an important parameter for photonic quantum information processing and all-photon quantum repeater schemes" but it is "much less important for simpler quantum

network applications such as direct QKD, using entangled photon-pair sources.

So what do the authors want to claim? Some technology that goes beyond simple QKD or a concept that stays with easy technology?

In any case, the authors need to discuss photon indistinguishability and other parameters which are crucial for advanced quantum network applications.

This also includes the non-resonant excitation scheme used in the present work which might not be suitable for deterministic operation of scalable quantum networks.

The authors should revisit their introduction and capture recent progress in basic demonstrations of quantum dot based quantum communication schemes and technology, which are relevant to the present work (e.g. PRL 123, 160501 (2019); PRL 123, 160502 (2019)).

If the authors address all points raised above I am more than happy to recommend this work for publications.

Dear editors, dear reviewers,

We would again like to express our gratitude to the reviewers in examining our manuscript in this second round of revision, providing a fair judgement of our work. Based on the comments, we have prepared a revised version of the manuscript, with changes highlighted in the text.

In the following we provide further details for the changes in a point-to-point response to the reviewers' comments.

Kind regards,

Jan Huwer and co-workers

Reviewer 1:

*I think it will be beneficial to add in the text the fabrication yield for this LED. Indeed, since the manuscript is device oriented, it is important to state reproducibility for future reference, in order to know how many devices and dots one needs to check before finding the suitable*

Reviewer 2:

*For instance (and I only mean for instance), yield and reproducibility have not been clarified in the manuscript, although the authors have given a good and valuable response in their response letter. Hence, without providing data on yield and reproducibility in the manuscript the work should not(!) be published.*

We have added information about yield at the end of the first paragraph in section “Tuneable ELED”, at the end of page 2 and beginning of page 3.

Reviewer 1:

*The approach followed to realize such an emitting diode is very interesting. In my opinion it does not matter if the photon emission arises from the direct recombination of electrically injected carriers or, as here, from the optical pumping of the dot via an external diode, being on the same chip. Nevertheless, it is important to remark that the excitation process is still optical so it would be interesting to compare these performances with optically excited.*

Main focus of the work was network integration of a tuneable telecom quantum light emitter, therefore we have not extensively studied the comparison between on-chip optical excitation and various external optical excitation schemes. Important for our study was, that the device performance was as good as what we typically see with non-resonantly excited QDs from the same wafer. To make the reader aware of this, we made changes on page 5 in the first sentence at the very top and in the last sentence of the second paragraph.

Reviewer 1:

*I really appreciate the level of details in the sample description. Can the authors add the doping levels and profile?*

We have added more details about doping levels and profile in the text at the end of the second paragraph of the “Tuneable ELED” section, at the end of page 3 and beginning of page 4.

Reviewer 1:

*For the study, a value of FSS of around 5 micro eV has been used. Is there a reason why the authors did not use a smaller FSS value? This can impact the post-selection window width.*

This is of course correct. The reason for the choice of bias setting was not to set a specific FSS value but to tune the emission wavelength to exactly 1310.00nm, the centre of the O-band. To make this clearer in the manuscript, we have changed the wording of the last sentence of the “Tuneable ELED” section on page 5.

Reviewer 1:

*On a similar note, do the authors have an idea on the photon coherence? Is a post-selection window of 48 ps enough for realistic implementation of complex networks?*

We have an idea of photon coherence in these devices and it is currently not sufficient for high-level quantum network schemes that rely on high indistinguishability. This is mainly limited by the type of QD used in the current study (S-K + telecom wavelength emission) and not by the general device structure. We are very optimistic that the issue could be solved by using telecom wavelength droplet epitaxy QDs which have in the past shown excellent coherence properties for non-resonant optical excitation. We have made changes to the manuscript at several positions to address this discussion.

We changed the second paragraph in the introduction (on page 1) to make it clearer that there is a benefit for advanced QComm applications just from availability of sub-Poissonian entangled photon pair sources. High photon indistinguishability is a parameter which is in addition required for scalable high-level schemes.

In the second paragraph on page 5 we added information about the coherence time of the source used in this work and discuss that it is not relevant for the present study about field deployment and network integration of entangled photon pairs.

We added an additional paragraph at the end of the discussion, explaining how the current device properties could be improved to make it suitable for high-level QComm applications.

Regarding the post-selection window, we chose 48ps because it gives a good resolution of the quantum beat in polarisation correlations and highlights the excellent polarization contrast in all polarization bases. For realistic implementations (gated APDs as they are commonly used in QKD systems), gate windows around 170ps are pretty standard. To address this point, we analysed the data for a post-selection window size of 200ps which results in a fidelity of 92% and included this information at the end of the first paragraph of the discussion, on page 8.

*Reviewer 2:*

*Another „for instance”: In the introduction the authors say "Good suppression of multi-photon emission is one of the cornerstones for the next level of high-speed quantum network applications, going beyond conventional quantum key distribution (QKD)". The second part of this sentence is noteworthy, as the authors argue in their response in a contradictory fashion: "photon indistinguishability is an important parameter for photonic quantum information processing and all-photonic quantum repeater schemes" but it is "much less important for simpler quantum network applications such as direct QKD, using entangled photon-pair sources.*

*So what do the authors want to claim? Some technology that goes beyond simple QKD or a concept that stays with easy technology?*

We agree that the motivation given in the introduction was lacking clarity regarding what to our understanding are next-level QNetwork applications, which are still simple compared to high-level schemes such as repeaters and relays. Next-level applications are everything that goes beyond what is currently commercially available, which is point-to-point QKD systems based on weak coherent laser sources. We completely changed the second paragraph in the introduction to clarify that there are two categories of QNetwork applications that might benefit from sub-Poissonian entangled photon pair sources. The ones that are less sensitive to and the ones that heavily rely on photon indistinguishability. The purpose of our work is to shed light onto the fact that electrical operation, tuneability and emission in the O-band are extremely important factors to consider when it comes to network integration of quantum light sources, not matter if these are for simpler or more complex applications.

*Reviewer 2:*

*In any case, the authors need to discuss photon indistinguishability and other parameters which*

*are crucial for advanced quantum network applications.*

*This also includes the non-resonant excitation scheme used in the present work which might not be suitable for deterministic operation of scalable quantum networks.*

We have addressed the reviewer's concerns by discussing the importance of photon indistinguishability and efficiency in the new second paragraph of the introduction. In the third paragraph of the introduction, we further added a discussion about different common excitation schemes for QD quantum light sources and their advantages and limitations for applications. As already mentioned in the reply to the first reviewer's comments, we now provide information about coherence limitations in the current device. We further discuss how these and other limitations can be solved in the future for applying the technology in scalable QNetwork schemes in the new final paragraph of the discussion.

*Reviewer 2:*

*The authors should revisit their introduction and capture recent progress in basic demonstrations of quantum dot based quantum communication schemes and technology, which are relevant to the present work (e.g. PRL 123, 160501 (2019); PRL 123, 160502 (2019)).*

We have extended the introduction based on the reviewer's suggestion and included recent progress regarding QNetwork related experiments based on QD entangled photon pair sources. The changes are done in the second and third paragraph of the introduction.

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors addressed my questions in a satisfactory way. The manuscript increased in clarity and more information interesting for the reader is now included.

I support publication.

Reviewer #2 (Remarks to the Author):

The authors have replied in a good way to my comments. Prior to publication, they should provide the extraction efficiency for their source as requested previously by R#3. If they have this number at hand it would be nice. If not, they should provide a realistic estimate.



Dear editors, dear reviewers,

We are pleased with the positive feedback from both reviewers for the revised version of the manuscript. For the final submission we made one more modification as requested during review.

Reviewer 2 requested to provide a value for the extraction efficiency for the source:

*“The authors have replied in a good way to my comments. Prior to publication, they should provide the extraction efficiency for their source as requested previously by R#3. If they have this number at hand it would be nice. If not, they should provide a realistic estimate.”*

Unfortunately we don't have a measured value for the extraction efficiency as this is challenging to properly characterise with continuously non-resonantly excited quantum dots. Relevant for the current study was the rate of detected photons, which was high enough to carry out experiments with good statistics and which we provide in the Methods section “Photon rates”. However, from experience with pulsed devices with similar weak broadband DBR cavities in the same experimental setup as used in this study and from numerical simulations regarding broadband DBR structures performed in the past, we roughly estimate the extraction efficiency of emitted photons from the device into single mode fibre to be around 3%. We now added this estimate in the Methods section about photon rates and hope that it gives the interested reader a better idea about the great potential for improvement of this kind of source when incorporating photonic structures designed for high efficiency photon extraction in the future.

Kind regards,

Jan Huwer and co-workers